

Tide gauge observations of the Indian ocean tsunami, December 26, 2004, in Buenos Aires coastal waters, Argentina

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Abstract

Sea level oscillations at the Buenos Aires province coastal waters were detected as a response to the magnitude 9.3 earthquake centered off the west coast of northern Sumatra (3.307°N, 95.947°E) on December 26, 2004 at 00:59 UTC. The aim of the present work is to report the first description on sea level oscillations in the Buenos Aires continental shelf generated by oceanic seismic activity. Sea level records gathered at three tide gauge stations located at Santa Teresita (36° 32'S, 56° 40'W), Mar del Plata (38° 05'S, 57° 30'W) and Puerto Belgrano (38° 54'S, 62° 06'W) were filtered and analyzed. The first arrival was measured at Mar del Plata (December 27, 2004, 00:15 UTC). At Santa Teresita and Puerto Belgrano, the tsunami reached the coast 33 min and 4.5 h later than at Mar del Plata, respectively. Maximum wave heights observed were 0.27, 0.15 and 0.20 m at Santa Teresita, Mar del Plata and Puerto Belgrano stations, respectively, and wave periods were detected in the range from 20 to 120 min. Wave amplitudes presented a remarkable temporal variability in the period immediately following tsunami wave arrival. After the first arrivals, waves lasted during the first 40 and 54 h at Mar del Plata and Santa Teresita, respectively. Even though, atmospherically forced sea level oscillations (in the tsunami frequency band) are frequently observed at different tide stations at locations on the Buenos Aires province coast, the weather patterns between December 24 and 27, 2004 showed no evidences of either frontal passages or atmospheric gravity waves. Thus sea level perturbations recorded at Santa Teresita, Mar del Plata and Puerto Belgrano stations can certainly be linked to the Indian Ocean tsunami.

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1. Introduction

Sea level stations located along the Buenos Aires province coast constitute a tide gauge network (maintained by the Servicio de Hidrografía Naval of

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Argentina) with the main purpose to record sea level heights associated not only with tides but also with the atmospheric forcing, which produces storm surges (D'Onofrio et al., 1999). Tides in the northern region of the Buenos Aires continental shelf (Fig. 1) present a mixed, primarily semidiurnal regime and, in the southern part of the continental shelf, they present a semidiurnal regime. Tides have a maximum spring range of 4.36 m at Puerto Belgrano (Bahía Blanca) and they are smaller to the north, 1.80 and 1.69 m at Mar del Plata and Santa Teresita, respectively (SHN, 2005). The coincidence of large or even moderate high tides and large meteorologically induced surges has historically caused catastrophic floods in many coastal areas of the Buenos Aires province (D'Onofrio et al., 1999). Sea level perturbations generated unambiguously by oceanic seismic activity have never been detected before December 27, 2004 either at the Buenos Aires province or in the Argentinian coastal waters. For this reason, there is no tsunami warning system along the Argentinian coast.

Sea level oscillations in the frequency band corresponding to tsunamis (from a few minutes to almost two hours) have been frequently observed at different tide stations on the Buenos Aires coast (Balay, 1955; Inman et al., 1962; Vara et al., 1977, 1978; Vara and Mazio, 1982). Dragani (1988)

studied a possible relationship between oceanic seismic activity and energetic sea level oscillation events detected at Pinamar (Fig. 1) but, due to the low correlation between both the phenomena, it was suggested that a different mechanism should be required to generate these sea level oscillations.

Dragani (1997) and Dragani et al. (2002) showed that, during high sea level activity, spectral peaks covered almost the whole frequency band between 1.1 and 4.7 cph (cycles per hour). Significant coherence values estimated between Mar de Ajó and Mar del Plata (172-km apart, Fig. 1) have clearly shown that this is a regional phenomenon. Atmospheric gravity waves are the most probable source of long ocean waves in the Buenos Aires continental shelf waters. This conclusion follows from the simultaneous occurrence of atmospheric gravity waves and long ocean wave events, the similarities of the spectral properties of both phenomena, and the high effectiveness in the atmospheric-ocean energy transfer demonstrated by numerical simulations (Dragani, 2006).

Sea level oscillations in Buenos Aires coastal waters were measured after the occurrence of the $M_w = 9.3$ earthquake (Stein and Okal, 2005) centered off the west coast of northern Sumatra (3.307°N, 95.947°E) on December 26, 2004 at 00:59 UTC. The aim of the present work is to report first evidence of sea level oscillations in

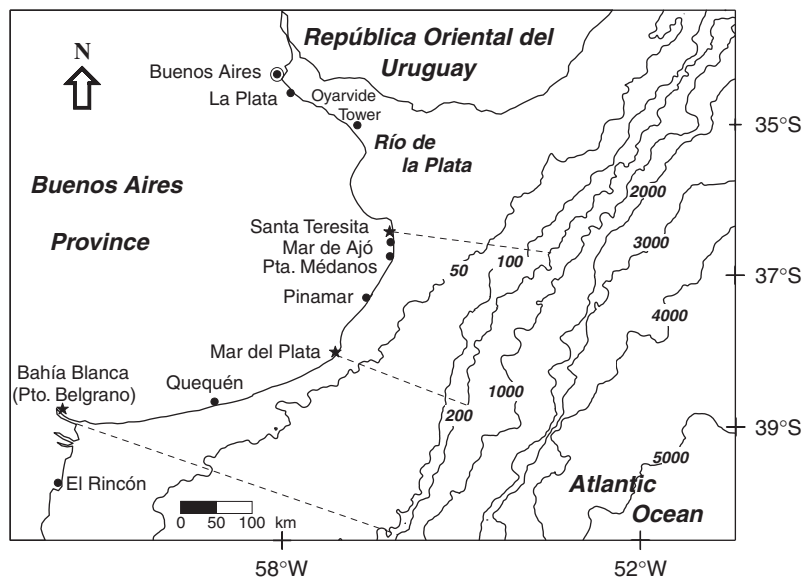


Fig. 1. Buenos Aires coastal region (Argentina) and its locations in the southwestern Atlantic Ocean. Bathymetry contours are in meters. Source: nautical charts SHN (1992, 1993). Also depicted are transects (dashed lines) where depth profiles were obtained.

Buenos Aires continental shelf waters generated by tsunami waves arriving from the Indian Ocean. In Section 2, sea level measurements gathered at Santa Teresita, Mar del Plata and Puerto Belgrano tide stations are shown, briefly described and analyzed. The weather patterns during the sea level oscillation events are described in Section 3. Finally, discussion and conclusions are presented in Section 4.

2. Data

Sea level records for three tide gauge stations located along the coast of Buenos Aires province were analyzed. The stations are located at Santa Teresita ($36^{\circ} 32'S$, $56^{\circ} 40'W$), Mar del Plata ($38^{\circ} 05'S$, $57^{\circ} 30'W$) and Puerto Belgrano ($38^{\circ} 54'S$, $62^{\circ} 06'W$) (Fig. 1). Santa Teresita and Mar del Plata stations are exposed to the open sea; Mar del Plata is about 200 km south–southwest of Santa Teresita and about 430 km east–northeast of Puerto Belgrano. The Puerto Belgrano station is located 50 km up the Bahía Blanca estuary and is connected to the ocean through a narrow 10–15 m deep navigation channel.

At Mar del Plata and Puerto Belgrano stations, sea levels were measured by conventional tide gauges with a float and a counterweight inside a vertical tube (UNESCO, 1985). In general, tide gauges work with an accuracy of ± 0.01 m. An additional error of ± 0.01 m was assumed to be associated with the digitizing procedure. Consequently, it was assumed that heights obtained from analog records from a tide gauge have a total error equal to ± 0.02 m. A water level recorder (pressure sensor fixed 1.5 m below the tidal datum) was located at the head of Santa Teresita fishermen's pier (150 m long). The accuracy given by the pressure sensor is approximately $\pm 0.1\%$ of the instrument depth (± 0.003 m). This instrument was set with a sampling interval of 6 min.

Sea level oscillations from December 27–28, 2004, recorded at Santa Teresita, Mar del Plata and Puerto Belgrano are shown in Fig. 2. It can be noted that the tide gauge at Puerto Belgrano did not work after December 28 2004, 02:00 UTC. Thus, the evolution of sea level oscillations cannot be completely analyzed at this location.

Analog tidal records gathered at tide gauge stations at Mar del Plata and Puerto Belgrano were digitized at a rate of 15 samples per hour. Sea level data contain diurnal and semidiurnal tides and higher-frequency oscillations ranging from a few

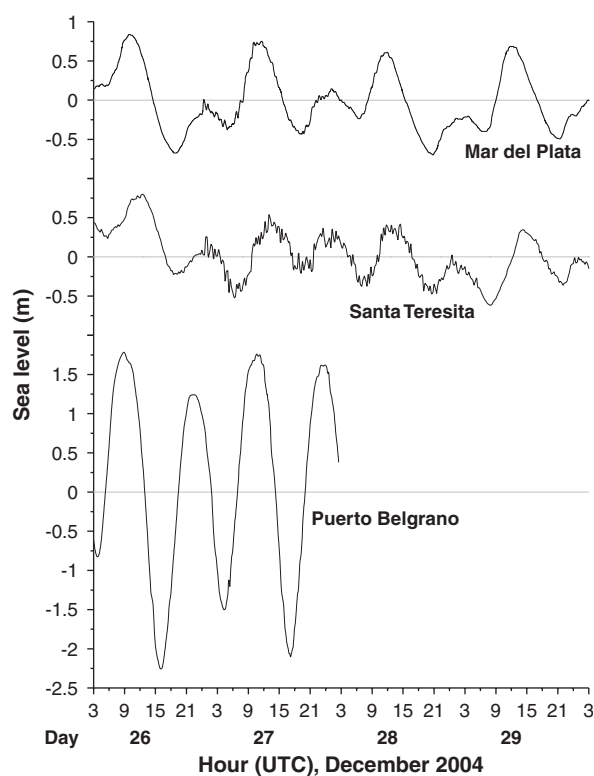


Fig. 2. Sea level records at Santa Teresita, Mar del Plata and Puerto Belgrano. Time in hours from December 26, 2004, 03:00 UTC.

minutes to almost 2 h. Digitized data (Mar del Plata and Puerto Belgrano records, 4-min sampling interval) and digital data (Santa Teresita record, 6-min sampling interval) were convoluted by means of Kaiser–Bessel bandpass filters, which select periods of approximately 12–180 min, and provide an attenuation factor of 100 dB outside that range (Hamming, 1977; Harris, 1978).

Filtered sea level oscillations recorded at Santa Teresita, Mar del Plata and Puerto Belgrano are shown in Fig. 3. At Mar del Plata, Santa Teresita and Puerto Belgrano, the Indian Ocean tsunami first arrived as a trough and the perturbations persisted approximately 2 days after the initial arrival. Initial waves were not the largest ones in the group. At Mar del Plata and Santa Teresita the largest waves were not observed until 7.8 and 17.8 h after the first arrival, respectively. We estimate arrival times by the first measured increase or decrease before the crest or trough. The first arrival detected was at Mar del Plata on December 27, 2004, at 00:15 UTC. At Santa Teresita and Puerto Belgrano, the tsunami reached the coast 33 min and 4.5 h, respectively,

after the arrival at Mar del Plata. Maximum wave height (distance from trough to crest or vice versa) determined at Santa Teresita, Mar del Plata and Puerto Belgrano stations were 0.27, 0.15 and 0.20 m, respectively. Amplitudes and periods (ranging from 20 to 120 min) presented noticeable temporal variability while the oscillations persist. Oscillations lasted 40 h at Mar del Plata and the perturbation

was longer at Santa Teresita (54 h). The main characteristics of the recorded tsunami waves at Mar del Plata, Santa Teresita and Puerto Belgrano (arrival time, travel time, maximum wave height and duration of the sea level activity) are summarized in Table 1.

Filtered sea level wavelet transform (Torrence and Compo, 1998) for Mar del Plata and Santa Teresita are shown in Figs. 4 and 5, respectively. Mar del Plata wavelet power spectrum (Fig. 4) shows two lapses of high sea level oscillation activity: from 0 to 11 h and from 18 to 23 h (UTC), December 27. Periods ranged from 30 min to almost 2 h, within the first lapse, and from 1 to 2 h, within the second one. Sea level activity in Mar del Plata ended at 16:00 (UTC), December 28. Sea level oscillations are more regular at Santa Teresita even though larger oscillations showed up within the middle part of the record. Wavelet power spectrum (Fig. 5) shows the lapse of highest sea level oscillation activity occurred between 0 and 23 h (UTC), December 27, with variable periods, which ranged from 30 min to 2 h. Sea level activity ended at 6:00 (UTC), December 29.

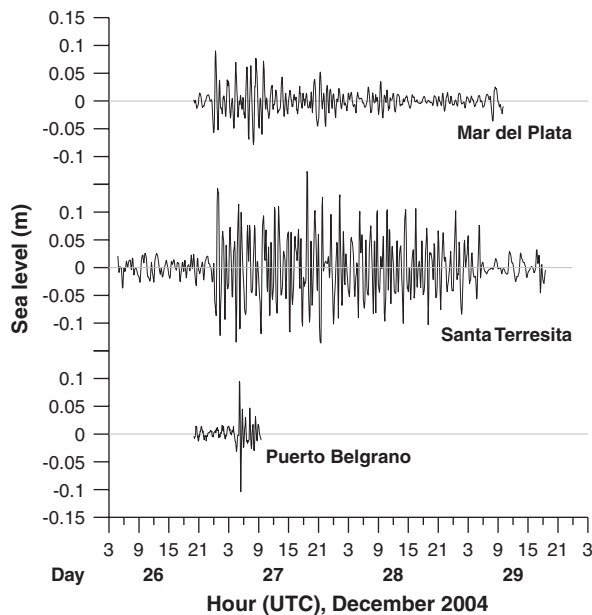


Fig. 3. Passband filtered sea level records at Santa Teresita, Mar del Plata and Puerto Belgrano. Time in hours from December 26, 2004, 03:00 UTC.

3. Weather patterns during a typical (atmospherically forced) sea level oscillation event at the Buenos Aires province coastal waters

Dragani (1997) described the typical synoptic situation during sea level oscillation events in the Buenos Aires province coastal waters. Low-level atmospheric cyclonic circulation and the passage of

Table 1

Arrival time (UTC), travel time (h), maximum wave height (m) and duration of sea level activity (h) obtained from of sea level records gathered at stations located in the Southwestern South Atlantic Ocean

Station	Arrival time (UTC)	Travel time (h)	Maximum wave height (m)	Duration of sea level activity (h)
Cananeira, Brazil (Franca and de Mezquita, 2006)	Dec. 26, 20:45	19.77	0.20	54
Ubatuba, Brazil (Franca and de Mezquita, 2006)	Dec. 26, 22:00	21.02	1.20	53
Port Stanley (Woodworth, 2005)	Dec. 26, 22:23	21.40	0.44	~48
Arraial do Cabo, Brazil (22°57'S, 42°01'W) (Candella, 2005) ^a	Dec. 26, 22:57	21.97	~0.90	~48
Mar del Plata	Dec. 27, 00:15	23.27	0.15	40
Santa Teresita	Dec. 27, 00:48	23.82	0.27	54
Imbituba Port (28°13'S, 48°39'W)(Mello and Rocha, 2005) ^b	Dec. 27, 03:20	26.35	1.22	~40
Puerto Belgrano	Dec. 27, 04:45	27.77	0.20	^c

^a<http://www.pmel.noaa.gov/tsunami/indo20041226/IEAPM.html>

^b<http://www.pmel.noaa.gov/tsunami/indo20041226/tsunami-southernbrazil.pdf>

^cTruncated record—the tide gauge did not work after December 28, 2004, 02:00 UTC.

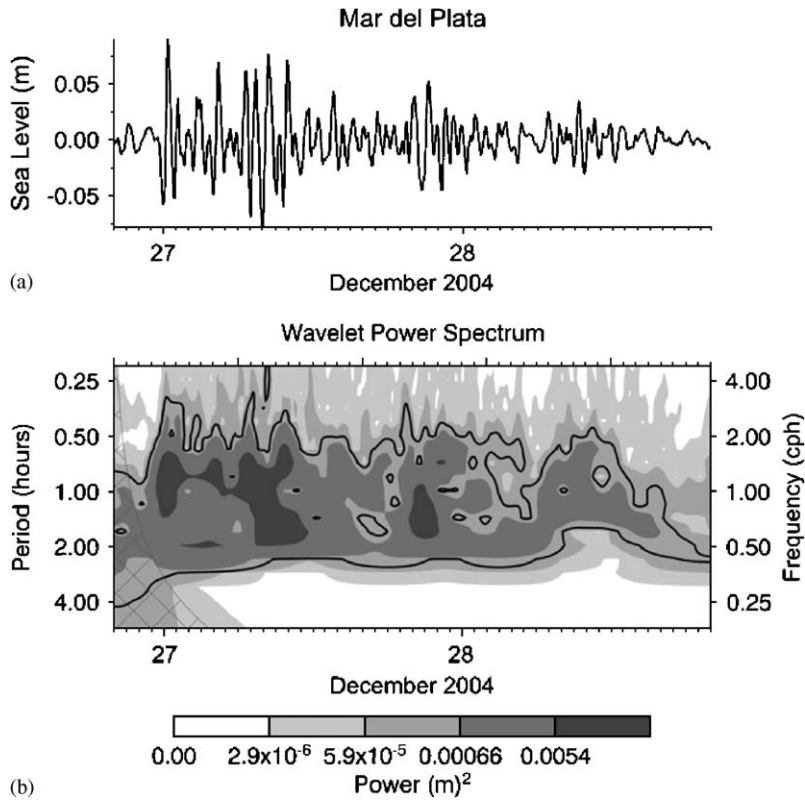


Fig. 4. (a) Mar del Plata filtered sea level record. (b) The wavelet power spectrum. Levels of color palette from white to dark gray have been chosen so that 75%, 50%, 25% and 5% of the wavelet power is above each level, respectively. The cross-hatched region on the left side is the “cone of influence”—where edge effects become important (Torrence and Compo, 1998). The lack of a “cone of influence” on the right-hand side of the figure is due to the fact that even though the wavelet spectrum was obtained from the complete sea level data series (shown in Fig. 3) this panel depicts the wave activity period. Black contour is the 95% significance level.

atmospheric fronts were always present prior to and during those events. Upper-air soundings obtained at Bahía Blanca meteorological station 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).

Weather patterns during the events described in this paper observed over the Buenos Aires continental shelf were completely different to the one described by Nuñez et al. (1998). The mean (December 25–27, 2004) sea level pressure field is presented in Fig. 6 (NOAA-CIRES/Climatic Diagnostics Center, www.cdc.noaa.gov). A low-pressure cell located east of the Río de la Plata estuary and a high-pressure cell located south of the low cell, at 50°S, can be seen in this figure. During December 25–27, easterlies prevailed in the lower troposphere

over the whole Buenos Aires province coastal area. This weather pattern is completely different to the ones associated with frontal passages over the Buenos Aires province. The tropospheric inversion necessary for the development of atmospheric gravity waves (capable of generating sea level oscillations) was not present in the region. Thus, we can confirm that sea level perturbations recorded at Santa Teresita, Mar del Plata and Puerto Belgrano on December 27–28, 2004, were almost certainly not forced by atmospheric gravity waves.

4. Discussion and conclusions

At 00:59 UTC on 26 December 2004, a moment magnitude (M_W) 9.3 megathrust earthquake occurred along 1300 km of the oceanic subduction zone located 100 km west of Sumatra and the Nicobar and Andaman Island in the eastern Indian Ocean. The waves recorded around the world

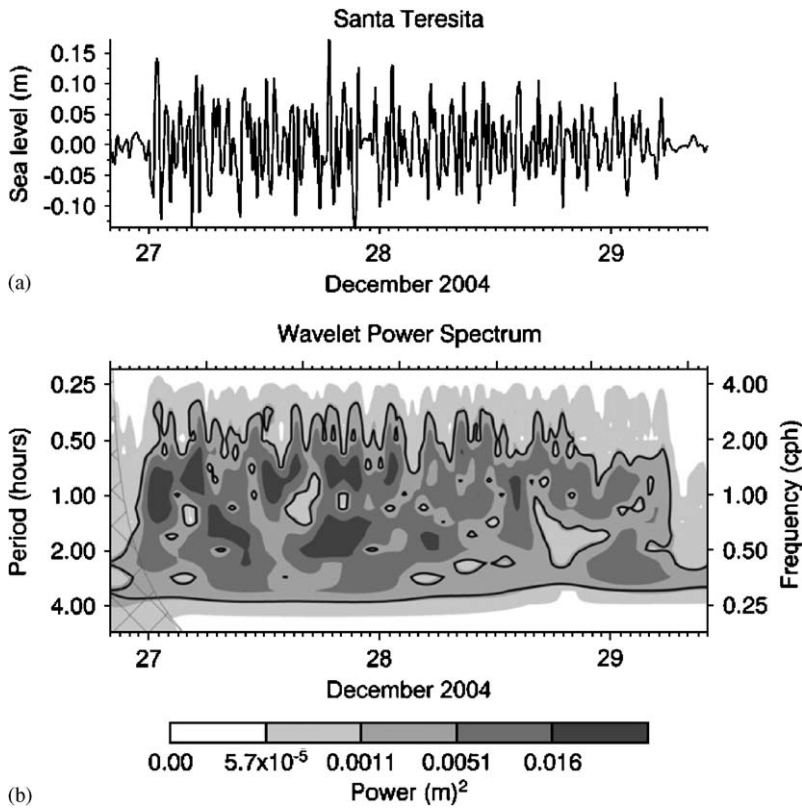


Fig. 5. (a) Santa Teresita filtered sea level record. (b) The wavelet power spectrum. Levels of color palette from white to dark gray have been chosen so that 75%, 50%, 25% and 5% of the wavelet power is above each level, respectively. The cross-hatched region on the left side is the “cone of influence”—where edge effects become important (Torrence and Compo, 1998). The lack of a “cone of influence” on the right hand side of the figure is due to the fact that even though the wavelet spectrum was obtained from the complete sea level data series (shown in Fig. 3) this panel depicts the wave activity period. Black contour is the 95% significance level.

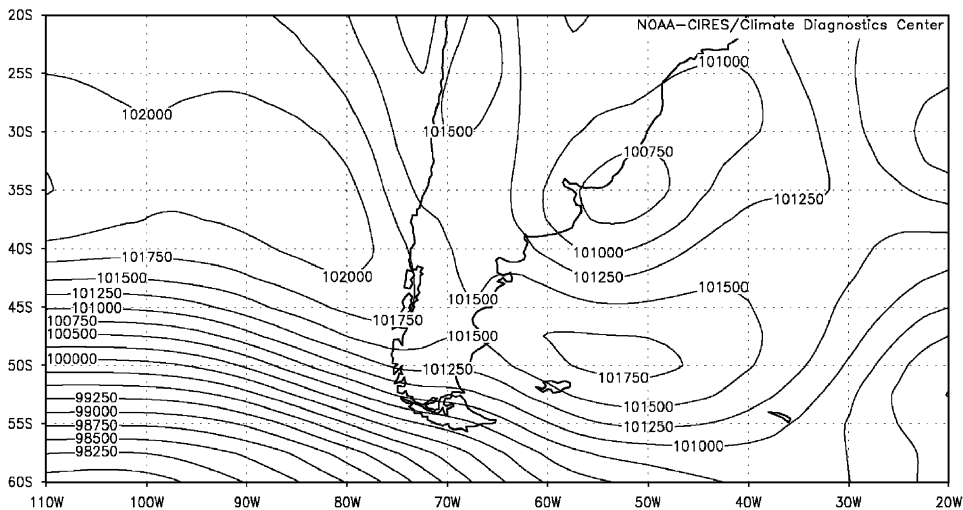


Fig. 6. Averaged sea level pressure (December 25–27, 2004). Contours in Pascals. Source: NOAA-CIRES/Climate Diagnostics Center (www.cdc.noaa.gov).

revealed unprecedented, truly global reach of the waves generated on December 26 (Titov et al., 2005). This tsunami is the first for which there are high-quality worldwide tide-gauge measurements. Tsunami amplitudes along many Indian Ocean coast-lines were measured in meters, and in some cases the waves were large enough to destroy the tide-gauge-recording equipment (Merriehfield et al., 2005). All these records, together with those from other countries, demonstrate that this particular tsunami was a truly global event (Woodworth et al., 2005).

Model simulations of tsunamis provide insight into open-ocean wave propagation that cannot be determined from tide-gauge recording alone. This is especially important for open-ocean regions (e.g., the Atlantic coast of Africa and South America) for which there are very little available data. Results obtained by Titov et al. (2005) show that submarine ridges act as wave guides. For example, these authors pointed out that the sharp bend of the Mid Atlantic Ridge in the South Atlantic results in the tsunami ray leaving the waveguide near 40°S and hitting the Atlantic coast of South America with relatively high wave amplitudes. Sea level measurements along the southeastern Brazilian coast, between 20 and 30°S, show the effect of the Indian Ocean tsunami (Franca and de Mesquita, 2006). Two records from stations, one (Cananeia station) located inside an estuary and other one (Río de Janeiro station) inside the Guanabara Bay, show oscillations of about 0.20 m range. One additional record from Ubatuba station facing the open sea shows up to 1.2 m range oscillation. These oscillations have around 45 min period, starting 20–22 h after the Indian earthquake, and lasting for 2 days (Franca and de Mesquita, 2006). The travel times predicted by the West Coast/Alaska Tsunami Warning Center tsunami model (West Coast Alaska Tsunami Warning Center (WC/ATWC), Tsunami Models, WC/ATWC Communications and Networking Architecture, <http://wcatwc.arh.noaa.gov/IndianOSite/IndianO12-26-04.htm>, 2005) show that the oceanic wave front arrived parallel to the Buenos Aires continental shelf slope approximately 20–21 h after the occurrence of the earthquake in the Indian Ocean. Sea level oscillations generated in the Indian Ocean propagated westward from the epicenter, traveled westward between South Africa and the Antarctica and then throughout the South Atlantic Ocean reaching the Argentinian continental shelf almost 1 day after the earthquake. At Port

Stanley station, in the Southwestern Atlantic Ocean, sea level rose by 0.09 m at nearly 23:00 UTC, fell 0.24 m just after 23:00 UTC and rose 0.19 m shortly before midnight (Woodworth et al., 2005). First arrival in Mar del Plata was detected almost 2 h after the arrival in Port Stanley. Even though a tsunami warning system would be not necessary in the Buenos Aires coastal area, the observation of real-time Port Stanley data (which can be made available through the www.pol.ac.uk/ntslf/networks.html) could be useful within a real-time surge warning system for this region of South America.

The main characteristics of recorded tsunami waves at eight locations of the southwestern South Atlantic Ocean: Cananeira, Ubatuba, Port Stanley, Arraial do Cabo (Brazil), Mar del Plata, Santa Teresita, Imbituba Port (Brazil) and Puerto Belgrano, are summarized in Table 1. In this table, the locations have been ordered by arrival times. The largest amplitudes were observed at Imbituba Port (1.22 m) and Ubatuba (1.20 m) and the minimum amplitude at Mar del Plata (0.20 m). Duration of sea level activity associated to the tsunami ranged from 40 to 54 h.

Lags detected in the times of first arrivals (33 min and 4.5 h after Mar del Plata at Santa Teresita and Puerto Belgrano, respectively) were satisfactorily computed considering the tsunami wave speed across continental shelf waters. The continental shelf (Fig. 1) is 250, 180 and 480 km wide off Santa Teresita, Mar del Plata and Puerto Belgrano, respectively. Depth distributions through each section (Fig. 1) were obtained from nautical charts SHN (1992, 1993). The wave speed, c , of long ocean waves could be reasonably approximated by $(gh)^{1/2}$ (e.g., Dean and Dalrymple, 1984), where g is the acceleration due to gravity and h the local depth. According to the expression for c and using the corresponding continental shelf widths and depths, the computed time lags between Mar del Plata and Santa Teresita and Mar del Plata and Puerto Belgrano tide stations resulted in 33 min and 4.83 h, respectively. Therefore, the calculated time lags match very well with the observed time presented in Section 2. However the arrival is still several hours late compared to the models. The Indian Ocean tsunami was firstly measured at Mar del Plata, secondly at Santa Teresita (located north of Mar del Plata) and finally at Puerto Belgrano (located west–southwest of Mar del Plata). This propagation is completely different to the typical one associated with atmospherically forced sea level

oscillations. Atmospherically forced perturbations are frequently observed first at Mar del Plata and, subsequently, further north (at Pinamar and Mar de Ajó, Fig. 1) associated with the direction of propagation of the atmospheric perturbation (Dragani et al., 2002).

Water level perturbations associated with the Indian oceanic tsunami were not recorded in the Río de la Plata estuary. There could be, at least, two reasons to explain this. First, both tide gauges operating in the Río de la Plata estuary have a sampling interval of 60 min, one located on the coast of Buenos Aires City ($34^{\circ} 34'S$, $58^{\circ} 23'W$) and another at Oyarvide Tower station ($35^{\circ} 06'S$, $57^{\circ} 08'W$). This sampling interval is too long to resolve the signals corresponding to the tsunami. The second reason is related to the shallowness of the estuary. In the middle of the Río de la Plata, the mean depth is less than 5 m and, in the inner part of the estuary, the mean depth is less than 3 m. Consequently, long ocean waves could be significantly attenuated due to reflection by the shallow-waters within the shelf/estuary zone and by friction dissipation effects.

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References

- Balay, M., 1955. La determinación del nivel medio del Mar Argentino, influencias de las oscilaciones del mar no causadas por la marea, Dir. Gral. de Nav. Hidrog., Min. de Marina, 46pp.
- Dean, R.G., Dalrymple, R.A., 1984. *Water Wave Mechanics for Engineers and Scientists*. Prentice-Hall, Englewood Cliffs, NJ, 353pp.
- D'Onofrio, E.E., Fiore, M.M.E., Romero, S.I., 1999. Return periods of extreme water levels estimated for some vulnerable areas of Buenos Aires. *Continental Shelf Research* 19, 1681–1693.
- Dragani, W.C., 1988. Análisis del proceso físico generador de ondas largas en la costa bonaerense argentina, Thesis, Inst. Tec. Bs. As., Buenos Aires, 65pp.
- Dragani, W.C., 1997. Una explicación del proceso físico generador de ondas de largo período en la costa bonaerense argentina, Doctoral Thesis, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, 222pp.
- Dragani, W.C., 2006. Numerical experiments of the generation of long ocean waves in coastal waters of the Buenos Aires Province, Argentina, submitted to *Continental Shelf Research*.
- Dragani, W.C., Mazio, C.A., Nuñez, M.N., 2002. Sea level oscillations in coastal waters of the Buenos Aires Province, Argentina. *Continental Shelf Research* 22, 779–790.
- Franca, C.A.S., de Mesquita, A.R., 2006. The December 26th 2004 tsunami recorded along the southeastern coast of Brazil, accepted by *Natural Hazards*.
- Hamming, R.W., 1977. *Digital Filters*, Signal Processing Series. Prentice Hall, Englewood Cliffs, NJ, 221pp.
- Harris, F.J., 1978. Of the use of windows for harmonics analysis with the discrete Fourier Transform. *Proceedings of the IEEE* 66, 51–83.
- Inman, D., Munk, W., Balay, M., 1962. Spectra of low frequency ocean waves along the Argentine shelf. *Deep-Sea Research* 8, 155–164.
- Merrifield, M.A., Firing, Y.L., Aarup, T., Agricole, W., Brundrit, G., Chang-Seng, D., Farre, R., Kilonsky, B., Knight, W., Kong, L., Magori, C., Manurung, P., McCreery, C., Mitchell, W., Pillay, S., Schindele, F., Shillington, F., Testut, L., Wijeratne, E.M.S., Caldwell, P., Jardin, J., Nakahara, S., Porter, F.-Y., Turetsky, N., 2005. Tide gauge observations of the Indian Ocean tsunami, December 26, 2004. *Geophysical Research Letters* 32, L09603.
- Nuñez, M.N., Mazio, C.A., Dragani, W.C., 1998. Estudio espectral de un lapso de intensa actividad de ondas de gravedad atmosféricas registradas en la costa bonaerense argentina. *Meteorológica* 23 (1 and 2), 47–54.
- SHN, 1992. Nautical Chart H-1: Acceso al Río de la Plata, Serv. Hidrog. Nav., Buenos Aires.
- SHN, 1993. Nautical Chart H-2: El Rincón, Golfos San Matías y Nuevo, Serv. Hidrog. Nav., Buenos Aires.
- SHN, 2005. Tablas de Marea, H-610, Serv. Hidrog. Nav., Buenos Aires.
- Stein, S., Okal, E.A., 2005. Speed and size of the Sumatra earthquake. *Nature* 434, 581–582.
- Titov, V., Rabinovich, A.B., Mofjeld, H.O., Thomson, R.E., González, F.I., 2005. The global reach of the 26 December 2004 Sumatra tsunami. *Science* 309, 2045–2048.
- Torrence, C., Compo, G.P., 1998. A practical guide to wavelet analysis. *Bulletin of the American Meteorology Society* 71, 61–78.
- UNESCO, 1985. *Manual on Sea Level Measurement and Interpretation*. Intergovernmental Oceanographic Commission, 83pp.
- Vara, C.D., Mazio, C.A., 1982. Espectro de ondas largas en Pinamar, Tech. Rep. 54, Dpto. Oceanog., Serv. Hidrog. Nav., Buenos Aires, 39pp.
- Vara, C.D., Mazio, C.A., D'Onofrio, E.E., Weischelbaun, M.L.D., 1977. Oscilaciones de largo período en el área de Punta Médanos, Parte I, Tech. Rep. 11, Dpto. Oceanog., Serv. Hidrog. Nav., Buenos Aires, 24pp.
- Vara, C.D., Mazio, C.A., D'Onofrio, E.E., 1978. Oscilaciones de largo período en el área de Punta Médanos, Parte II: Análisis espectral, Tech. Rep. 21, Dpto. Oceanog., Serv. Hidrog. Nav., Buenos Aires, 20pp.
- Woodworth, P.L., Blackman, D.L., Foden, P., Holgate, S., Horsburgh, K., Knight, P.J., Smith, D.E., Macleod, E.A., Bradshaw, E., 2005. Evidence for the Indonesian Tsunami in British tidal records. *Weather* 60 (9), 263–267.