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STATISTICAL AND SPECTRAL CHARACTERISTICS OF THE 2011 EAST JAPAN TSUNAMI SIGNAL IN ARRAIAL DO CABO, RJ, BRAZIL

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ABSTRACT. For the second time, the sign of a tsunami could be measured in Brazil. The waves generated by the M_W 9.0 earthquake in Japan on March 11, 2011, have spread across the Pacific Ocean and through Drake Passage reached the Atlantic Ocean, being recorded by at least three tide gauges. During the 2004 Sumatra event, the positioning of the tsunami source allowed the waves to propagate almost directly to the South American coast and the signal was recorded at many sites of the Argentinian, Uruguayan and Brazilian coast. This time, the path of the waves was much more complex, causing strong signal attenuation and making difficult the detection of the waves. Nevertheless, the tsunami signal was identified at Arraial do Cabo, RJ, mainly due to the low background noise level. This far-field record was used to estimate statistical and spectral characteristics of arriving tsunami waves.

Keywords: Japan tsunami, signal detection, Brazil.

RESUMO. Pela segunda vez, o sinal de um tsunami pôde ser registrado no Brasil. As ondas originadas pelo terremoto de magnitude 9,0 ocorrido no Japão, em 11 de março de 2011, se propagaram através do oceano Pacífico e, passando pelo Estreito de Drake, atingiram o oceano Atlântico, sendo registradas por, pelo menos, três marégrafos. No evento de 2004, a posição da fonte do tsunami permitiu a propagação quase direta das ondas até a costa sul americana e o sinal pôde ser registrado em diversos pontos na Argentina, Uruguai e Brasil. Dessa vez, o caminho das oscilações foi bem mais complexo, provocando forte atenuação do sinal e, assim, dificultando sua detecção. Apesar disso, foi possível detectar esse sinal em Arraial do Cabo, RJ, principalmente devido ao baixo nível de ruído de fundo no registro do nível do mar. O registro desses dados de campo distante foi utilizado para extrair características estatísticas e espectrais dos dados coletados.

Palavras-chave: tsunami do Japão, detecção do sinal, Brasil.

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INTRODUCTION

The giant thrust fault earthquake of 11 March 2011, at 05:46 UTM and coordinates 38°19'19"N, 142°22'08"E generated a highly destructive tsunami on the Pacific coast of Japan, with huge material losses and more than 18,500 fatalities. It was the first time that people were killed by a tsunami in Japan since the 1993 Okushiri tsunami (www.itic.ioc-unesco.org). After Sugawara et al. (2012), the wave heights near the coastlines of the Sendai Bay reached 40 m, and horizontal run-up distances (i.e., inundation area) extended more than 4 km. The earthquake took place off the Pacific coast of the Tohoku District, northeastern Honshu, Japan, being also called as the "Tokohu tsunami" for this reason.

The estimated magnitude was $M_w = 9.0$ and it was the largest earthquake ever observed in Japan and fourth largest earthquake in the world ever instrumentally recorded (Lay & Anamori, 2011).

The waves were recorded throughout the Pacific Ocean. Bressan & Tinti (2012) reported maximum heights of 205 cm at Caldera (Chile), 185 cm at Coquimbo (Chile) and 165 cm at Hilo (Hawaii), besides mentioning that at several stations, the maximum amplitudes could not be estimated precisely, due to the data loss or saturation meter, as at Crescent City, California, where the maximum value reached 245 cm.

Data analyses showed that in Drake Passage, at Vernadsky tidal station (65°14'45.6"S; 64°15'15"W) the maximum wave height was 19.8 cm. In the Atlantic Ocean, at the King Edward station – the South Sandwich Islands (54°23'16"S; 42°38'29"W), the maximum amplitude was 66.6 cm and at Port Stanley (51°50'30"S; 48°48'26"W), the Falklands/Malvinas Islands, it was 32.4 cm.

The waves were also recorded by a tide gauge operated by the Instituto de Estudos do Mar Almirante Paulo Moreira – IEAPM (22°58.3'S; 42°00.9'W), at Arraial do Cabo, RJ, widening the area influenced by the phenomenon. The objective of this work is to describe and analyze the statistical and spectral characteristics of these signals, the second tsunami in less than 7.5 years recorded on the Brazilian coast.

METHODOLOGY AND DATA DESCRIPTION

The tide gauge used is based on ultrasound technology, with temperature correction, 1-min time resolution, and vertical precision of 1 cm.

For the analyses, the astronomical tide were estimated using the least squares method of harmonic analysis and then subtracted from the original series. Additionally, the low frequency oscillations were suppressed by Kaiser-Bessel high pass filter, with cut-off period of 3 hours.

The criterion used to determine the arrival of the first wave was the sharp amplification of the waves, with well-defined dominant period. Therefore, it is crucial that the signal-to-noise ratio shows a favorable aspect, especially when the waves are small. A detailed description of the background noise interference in the tsunami wave detection can be found in Rabinovich et al. (2011).

Munk (1963) stated that the tsunami energy in the ocean decays much like sound intensity in an enclosed room. Following this suggestion, Van Dorn (1984) concluded that the energy decays in a uniformly exponential manner with the form

$$E(t) = E_0 \cdot e^{-\delta t}$$

where E_0 is the tsunami energy index, δ is the energy decay (attenuation) coefficient and $t_0 = \delta^{-1}$ is the "decay time". To compute the variance evolution, 6-h segments with 3-h overlap were used, resulting in one variance value at each 3 hours, and the decay line was set by least square method.

Two kinds of analysis were performed. First, the statistical characteristics of signal, such as the propagation time, variance evolution, maximum wave height, tsunami index and energy decay were determined. After that, the spectral features were investigated through spectral and time-frequency (wavelet-type) analysis. For the first one, the traditional FFT method was used, with 16 degrees of freedom. For the second one, the software package developed by Torrence (1998 – http://paos.colorado.edu/research/wavelets/) was employed, with 5 powers-of-two, and 8 sub-octaves each.

RESULTS AND DISCUSSION

Statistical characteristics

The original, de-tided and filtered series are presented in Figure 1(a, b, c). The first wave arrived at the gauge on the 12th, at 11:57 UTM (8:57 pm, official Brazilian time), totaling 31h 12 min propagation. Tsunami can be considered as shallow-water waves, because their lengths are always greater than ocean depth. Their speed is $c = \sqrt{gh}$, where g is the gravity acceleration and h is the depth. Taking $h \cong$ 4,000 m and $g \cong$ 10 m.s^{-2}, we get $c \cong$ 200 m.s^{-1} $\cong$ 720 km.h^{-1}. The trajectory estimated as a great circle from the source region to Arraial do Cabo is about 22,000 km, what is in reasonable agreement with the propagation time. In fact, tsunami waves are strongly influenced by the ocean topography, especially by the mid ocean ridges, which, as was shown by Titov et al. (2005) for the 2004 Sumatra event play a role of a wave guide.

Although the tsunami signal was weak, the signal-to-noise ratio was relatively high and the tsunami waves could be clearly

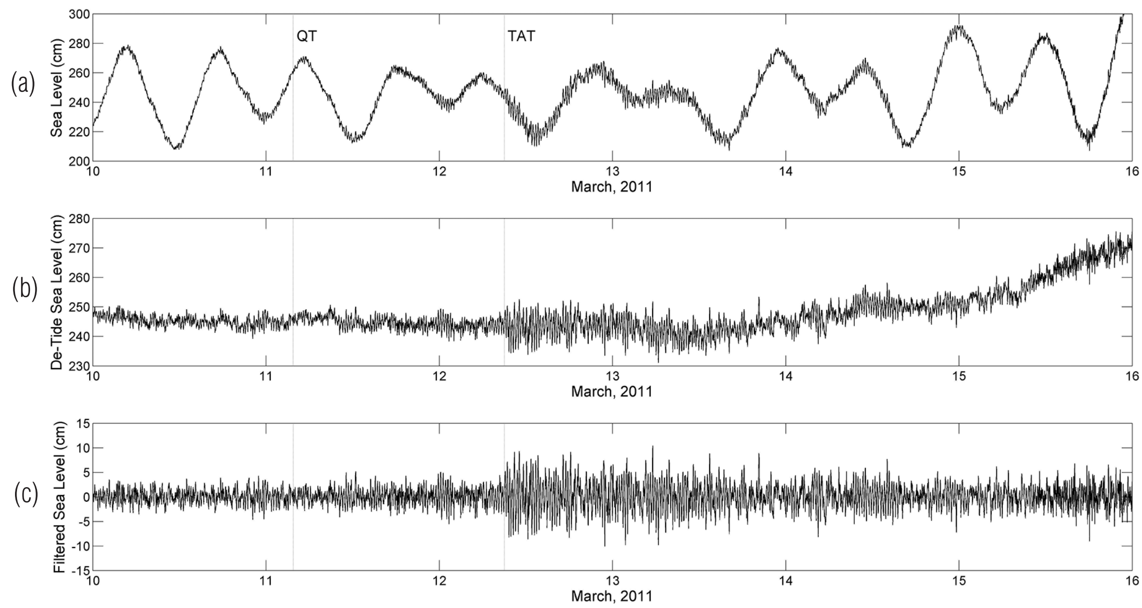

Figure 1 – Original (a), residual (de-tided) (b) and highpass filtered (cutoff period 3 h) (c) sea level oscillations recorded at Arraial do Cabo between March 10th and 17th, 2011.

identified. The maximum wave amplitude was 18 cm, showing that, as expected, there was a strong attenuation of the signal due to its intricate path.

The variance evolution of this event (Fig. 2) shows that the tsunami index (E_0) was 17 cm^2, much lower than the value of 242 cm^2 estimated for the 2004 tsunami (Rabinovich et al., 2011). Similarly, as was observed for the 2004 event, it is possible to identify well defined and succeeding wave trains. At this time, however, the low energy made these structures more evident and affecting directly the energy decay. In the same figure, the solid line indicates the exponential decay taken from E_0 to the point where the energy returns to the background level, implying that $T_0 \cong 28.7$ h, what is much higher than the value determined by Rabinovich et al. (2011) for the 2004 tsunami: $T_0 = 18.0$ h. Nonetheless, if the same procedure is applied for each of the wave trains (thinner lines), the mean T_0 value (18.6 h) would have approximately the same magnitude order. Rabinovich et al. (2011) also assumed that these trains of waves, with periods from 12 to 18 h between the groups are related to the energy reflection from the coasts of Africa and Antarctic. The same assumption can be made about the wave trains observed in Arraial do Cabo record of the 2011 tsunami.

Spectral characteristics

The wavelet graphic (Fig. 3) shows that the most energetic periods are in the range of 15 to 80 min, highlighting the main resonant oscillation period, around 19 min, given by

$$T_n = \frac{4L}{\left(2n + 1\sqrt{gh}\right)},$$

where $L = 3{,}500$ m is the length of the bay, $n = 0$ (fundamental or Helmholtz mode), g is the gravitational acceleration, and $h = 15$ m is the mean depth. This analysis shows that the tsunami ringing lasted for about three days (12, 13 and 14), similarly to what was indicated by the energy decay analysis.

Tsunami waves arriving from the open ocean are strongly modified by local topography and bathymetry, in particular by continental shelves and adjacent bays and harbors (Rabinovich, 1997). This author suggested an approach based on comparative analysis of tsunami and background spectra, estimating the ratio between them to get an invariant form that is independent from local topography and can be compared with the spectral characteristics of the tsunami source. In other words

$$S_{obs}(w) = S_t(w) + S_b(w)$$

where $S_{obs}(w)$ is the observed spectrum, $S_t(w)$ is tsunami spectrum, and $S_b(w)$ is the background spectrum.

In the present case, it was defined a segment of 1024 minutes ($\sim$17 hours) to be used for the analysis of the event and a 4096-min interval to determine the background spectrum. The size difference between sections is justified, since the analysis of a time greater than 17 hours could include oscillations unrelated

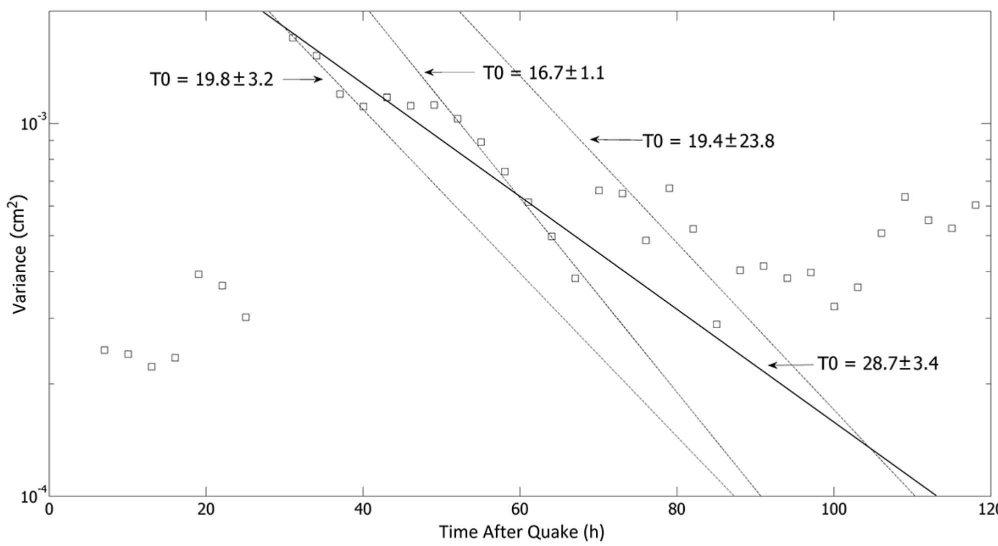

Figure 2 – Energy decay of the Japan tsunami recorded at Arraial do Cabo, showing the sea level variance changes with time. The secondary peaks of the variance are apparently associated with the wave trains reflected from the coasts of Africa and Antarctica.

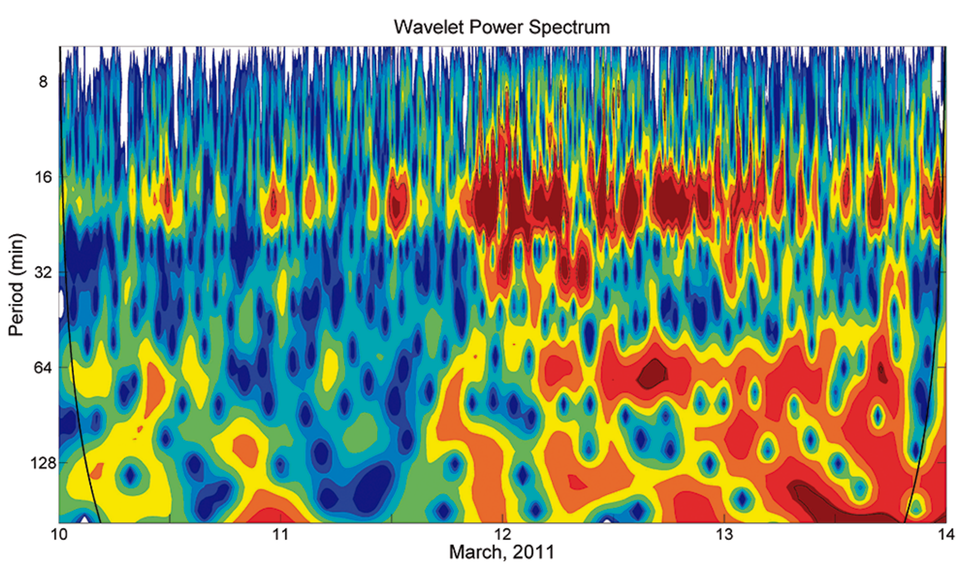

Figure 3 – The wavelet analysis showing the presence of the Tohoku tsunami waves in the sea level oscillations at Arraial do Cabo from March, 12 to March, 14.

to the tsunami. On the other hand, longer time to characterize the background energy tends to minimize influences of short duration atmospheric events.

Figure 4 shows both spectra (left panel) and the spectral ratio (right panel). It can be seen that the event had a broad frequency band with higher level of energy in all frequencies above 0.0125 cpm ($T<80$ min). This result agrees with the results of our preliminary analysis of the DART (Deep-ocean Assessment and Reporting of Tsunamis) records in the Pacific Ocean (in preparation). The area of the spectrum related to the tsunami in filled in gray color in the figure.

CONCLUSIONS

In 2004, the Sumatra tsunami signal was recorded along almost the entire Atlantic coast of South America (Candella et al., 2008), with maximum waves ranging roughly from 0.5 to 1.5 m. In 2011 another event of the same type was again registered. The tsunami generated in Japan, in March 2011, was recorded by the gauge

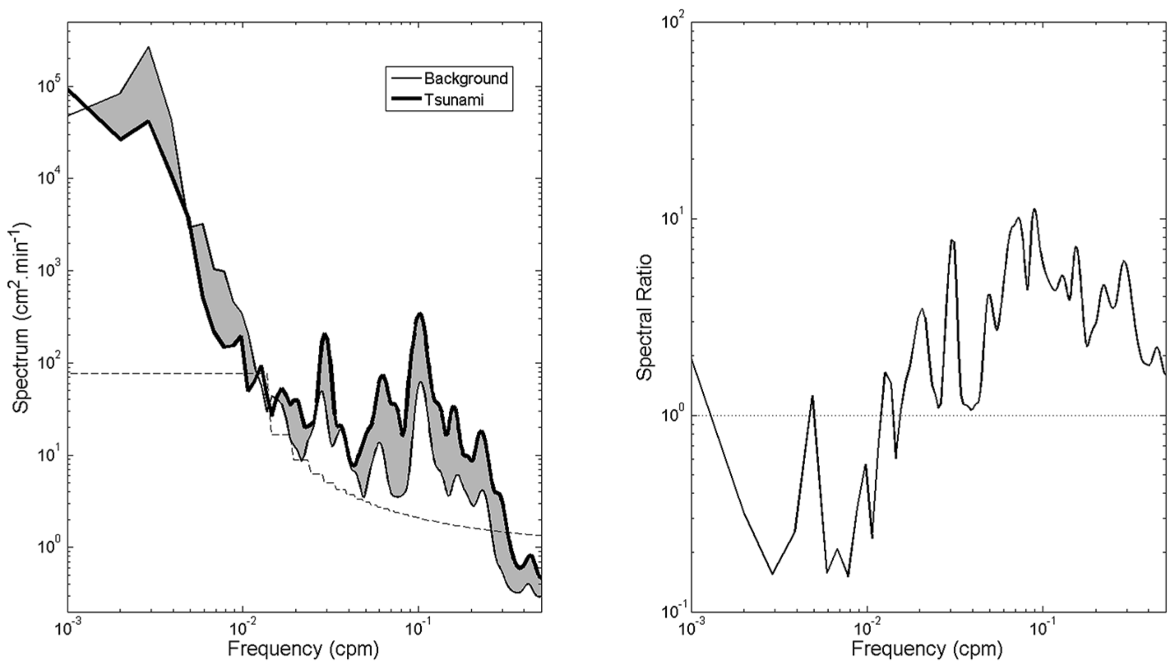

Figure 4 – Background (thin line) and tsunami (thick line) spectra estimated from the record of the Arraial do Cabo tide gauge (left panel). Spectral ratio (right panel) shows that the energy of tsunami was larger than the background in all frequencies above 0.0125 cpm.

located in Arraial do Cabo about 30 hours after the quake, which is the time consistent with the distance and the theoretical estimates for the propagation time.

Despite the enormous energy released in the quake and the huge waves that occurred in the Pacific Ocean, the amplitudes recorded in Arraial do Cabo were relatively small, on the order of 20 cm, due to the large distance between the source and the tide gauge and mainly due to its complex path of propagation. Nevertheless, the tsunami waves could clearly be identified because of the low level of the background noise.

The evolution of the variance clearly showed a succession of wave trains and the general decay time (T_0) for this event is much longer than the decay time estimated by Rabinovich et al. (2011) for the 2004 tsunami record at Arraial do Cabo. This T_0 value computed for each wave train independently is very close to our estimate of T_0 for the entire time period. We can conclude that the effect of wave trains on the energy decay is insignificant for the events with high energy, but they strongly affect the decay times in situations of the low-energy events like the 2011 Tohoku tsunami recorded on the far-field Atlantic coast of Brazil.

The spectrum of the tsunami occupies a broadband frequency range, with considerable energy in all frequencies above 0.0125 cpm. This result agrees with the preliminary analyses carried out for the DART records in the Pacific Ocean.

The record of this event suggests that the waves of past tsunamis could had reached the South America East Coast, but may not be perceived due to the low resolution of tide gauges used until recently and/or had been masked by the background noise.

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