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The Great Tsunami of 26 December 2004: A description based on tide-gauge data from the Indian subcontinent and surrounding areas

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The Great Tsunami of 26 December 2004 is described using data from seven tide gauges in India and others from surrounding areas in the Indian Ocean. The tsunami struck the Indian east coast around 0330 UTC. The amplitude was 2 m above the tide at Chennai, Paradip, and Colombo. The east coast of India (and of Sri Lanka) was hit shortly after high tide; Tuticorin and Colombo, however, were hit shortly after low tide. The tsunami wave propagated northward along the Indian west coast. All these gauges are to the west of the earthquake zone and the detided sea levels show first a rise in sea level with the arrival of the tsunami, and then a sharp decrease. Spectral and wavelet analysis of the detided series show that the maximum amplitude was at a period of 35–45 minutes, with another maximum around 20 minutes. Along the Indian east coast, however, there is another broad peak between 1–2 hours within the first few hours after the first tsunami wave.
Key words: Earthquake, tsunami, Sumatra, Andaman, tide gauge, wavelet.

1. Introduction

An earthquake with a moment magnitude $M_w = 9.3$ occurred at (3.307°N, 95.947°E) (255 km south-southeast of Banda Aceh, Sumatra, Indonesia) at 0059 UTC (all times reported in this paper are in UTC, unless otherwise stated) on 26 December 2004 (Bilham, 2005) (Fig. 1). This earthquake, which ruptured 1300 km of the eastern boundary of the Indian plate and is the second largest (after the Chile earthquake of 1960) instrumentally recorded (Bilham, 2005; Lay *et al.*, 2005), triggered a tsunami that devastated South and Southeast Asia. The death toll has exceeded 300,000 (Lay *et al.*, 2005), making this the biggest “killer” tsunami in recorded history (Bryant, 2001).

Though the tsunami was also observed in a timely pass of the altimetric satellite Jason I (http://www.noaanews.noaa.gov/stories2005/s2365.htm), the best instrumental records of the tsunami waves are contained in the tide gauges at coastal and island stations. Merrifield *et al.* (2005) described the tsunami as seen in tide gauges from the Indian Ocean, but this description did not include data from the Indian stations. We briefly describe the tsunami as seen in the tide-gauge records from India and from surrounding areas in the Indian Ocean. We first describe the progress of the tsunami in the Indian Ocean based on these data and then subject the data to spectral and wavelet analysis to determine the frequencies present.

2. Data

The Survey of India (SOI) maintains a network of tide gauges along the coast of India (Fig. 1). The tide gauge at Nagapattinam (south of Chennai), which was the worst affected region on the Indian mainland, did not survive the tsunami. It was damaged along with the housing, and the records could not be retrieved. Data are available for Paradip, Visakhapatnam, Chennai, Tuticorin, Kochi, Mormugao, and Okha. Data are not available from the Andaman and Nicobar islands; the tide gauge at Car Nicobar was destroyed by the tsunami and that at Port Blair was under repair at the time of the tsunami.

The SOI gauges are either mechanical float-type gauges or pressure-sensor gauges (see Table 1). The mechanical float-type gauges produce an analog record that has been digitised at an interval of 5 or 6 minutes for the tsunami event. The pressure-sensor gauges also record data at an interval of 5 or 6 minutes. The tsunami signal was obtained from these data by detiding the record using the TASK (Tidal Analysis Software Kit) package (Anonymous, 1996); data for 30 days were used for detiding.

Data from some other tide-gauge stations in the Indian Ocean (Fig. 2) are also available from the Sea-Level Centre at the University of Hawaii (UHSLC) (http://ilikai.soest.hawaii.edu/uhslc/iotd/index.html) under the GLOSS (Global Sea Level Observing System) Program (Woodworth *et al.*, 2003; Merrifield *et al.*, 2005). These are also pressure-sensor tide gauges, and detided data (residuals) were downloaded from the UHSLC web site.

3. Description of Tide-gauge Records

The detided records for the tide-gauge stations along the Indian and Sri Lankan coast are shown in Fig. 2, the observed sea levels (including the tide) for some stations are shown in Fig. 3, and a summary of the observations is provided in Table 2. The stations on the Indian east coast were hit almost at the same time (around 0330 UTC or 0900 IST).

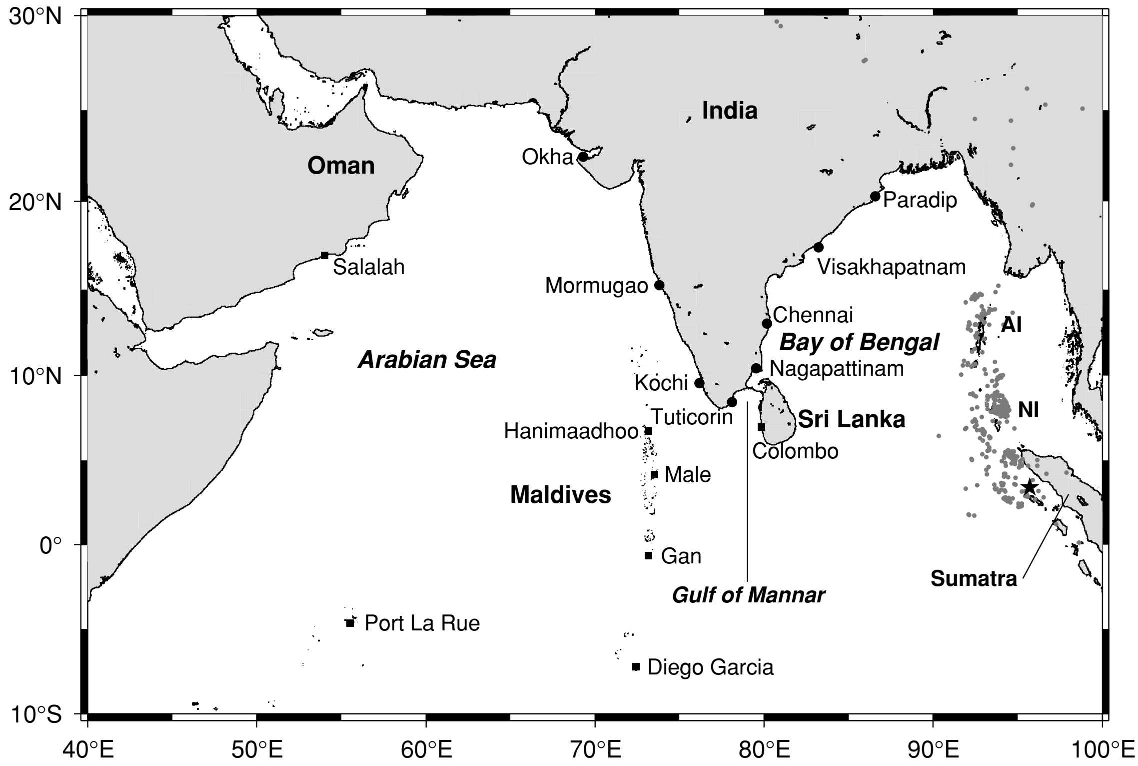

Fig. 1. Map of the Indian Ocean showing the epicentre of the 26 December earthquake (asterisk) and the locations of the aftershocks (grey circles) till 10 February 2005. The locations of the tide-gauge stations operated by the Survey of India are marked by filled circles; GLOSS stations are marked by filled squares. Data are not available for Nagapattinam, where the SOI tide gauge was destroyed by the tsunami. AI: Andaman Islands; NI: Nicobar Islands.

Table 1. Tide gauge stations operated by the Survey of India. FT: Float-type gauge; PT: Pressure-sensor type gauge. Column 3 gives the sampling (digitising) interval for PT (FT) gauges. For information on other stations, see Merrifield *et al*. (2005).

Station	Gauge type	Interval (minutes)
Paradip	PT	6
Visakhapatnam	FT	5
Chennai	FT	5
Tuticorin	PT	6
Kochi	PT	5
Mormugao	FT	5
Okha	FT	6

Colombo, which lies on the west coast of Sri Lanka in the Gulf of Mannar, was hit at 0352 UTC; Tuticorin, which lies on the other side of the gulf, was hit at 0423 UTC. The first tsunami wave may have arrived earlier at the southeastern coast of India (in the neighbourhood of Nagapattinam) and the east coast of Sri Lanka, but no instrumental data exist to confirm this.

Though hardly any damage was reported from Paradip (or from its vicinity), the data show that the tsunami wave was highest there (note that data for Nagapattinam are not available); the maximum amplitude there was comparable to that at Colombo. At none of the three Indian east-coast stations was the first wave the highest (Fig. 2, Table 2), but the amplitude of the first wave as well as the maximum recorded amplitude were highest at Paradip. The first wave struck the Indian east coast around high tide; the maximum amplitude of the tsunami was, however, recorded around low tide, and this was also the maximum water level recorded at the three stations.

There is a gap in the tide-gauge record at Colombo as the water regressed after the first wave struck. This was also the maximum amplitude and water level recorded. At Tuticorin, the amplitude was less (~100 cm), but the first wave was the highest; this may have been so at Colombo too. There is a difference in the behaviour of the tsunami in the Gulf of Mannar and north of it. That the tsunami wave struck Tuticorin around low tide (Fig. 3) also helps explain the lack of damage recorded in this region of the Indian coast.

In the Maldive Islands, the first wave, which occurred between low and high tide, was the highest and its amplitude increased from south (Gan Island) to north (Hanimaadhoo). Male was hit first; both Hanimaadhoo and Gan Island were hit shortly thereafter (Table 2). The amplitude continued to decrease southward along the Chagos-Laccadive Ridge, with the southernmost station of Diego Garcia recording an amplitude of ~60 cm.

Kochi, on the Indian west coast, was hit over an hour after the Maldive Islands. The amplitude here was less than half that at Hanimaadhoo, and the amplitude continued to decrease as the wave propagated north to Mormugao and Okha. As at most of the Indian stations, the first wave was not the highest (Table 2): the maximum amplitude and maximum water level occurred much later than the first wave. The tsunami wave propagated into the Arabian

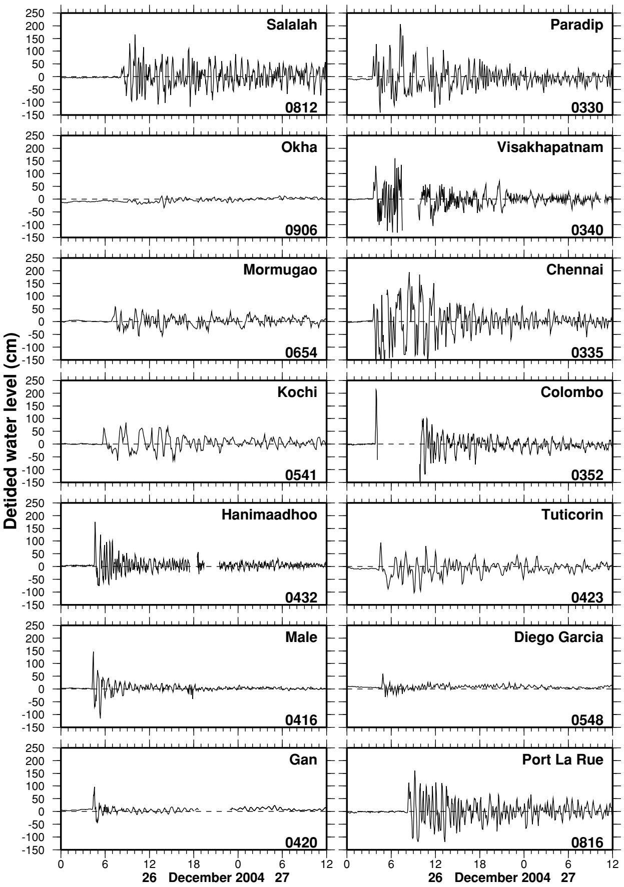

Fig. 2. Detided water levels (cm) from the tide-gauge records. The tsunami arrival time (UTC) is given in the bottom right corner.

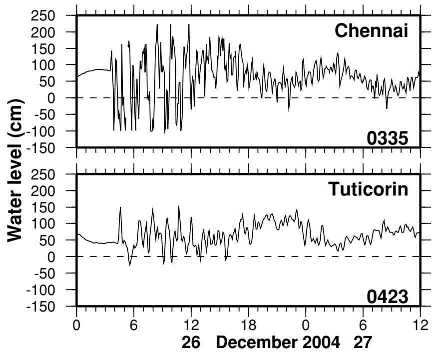

Fig. 3. Water level (cm) measured by the tide gauges at Tuticorin and Chennai; the curve plotted includes both the tide and the tsunami. The tsunami arrival time (UTC) is given in the bottom right corner.

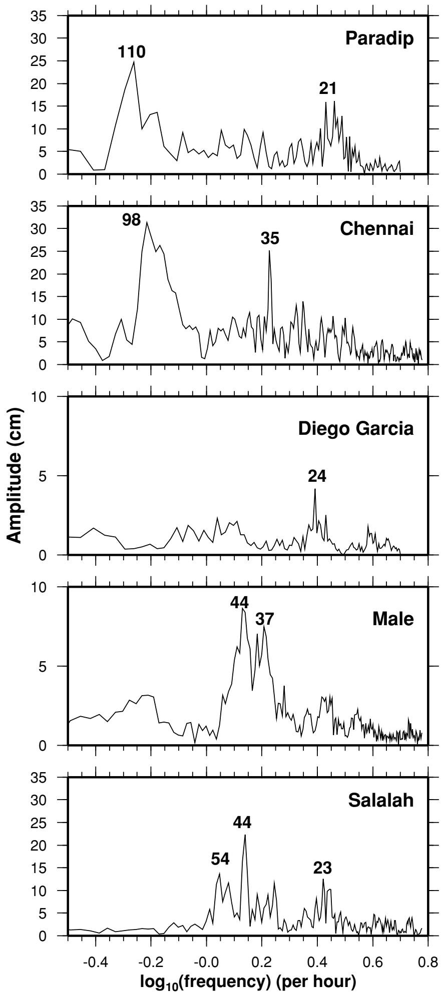

Fig. 4. Spectral analysis (FFT) of the detided water level records. The abscissa is $\log_{10}$(frequency) (per hour) and the ordinate is the amplitude (cm). The period corresponding to the prominent peaks is shown by the numbers (in minutes).

Sea from the south. On the western side of the Arabian Sea, at the Omani port of Salalah, the first tsunami wave was observed at 0812 UTC; its amplitude was comparable to that at Mormugao. The highest amplitude at Salalah, however, was for the third wave and was much higher than that along the Indian west coast; the 165 cm amplitude of the third wave here is comparable to that recorded in the Maldive Islands.

The wave propagated into the southern Indian Ocean and was recorded by the tide gauges at both island and coastal stations (Table 2, Fig. 2). The maximum amplitude was at Port La Rue. At all stations, the first wave was not the highest (unlike at the islands in the Chagos-Laccadive Ridge): the maximum water level was recorded around high tide.

At almost all stations, water level dropped sharply after the first wave; an exception is Paradip, where the big drop occurred instead after the second wave.

4. Spectral and Wavelet Analysis

A Fast Fourier Transform (FFT) of the detided records shows that a dominant period is ∼35–45 minutes at most stations (Fig. 4), with another peak at ∼20 minutes at some stations; this was also noted by Merrifield *et al.* (2005). At Diego Garcia, however, only the ∼20-minute period is seen. The stations on the Indian east coast (Paradip, Visakhapatnam, Chennai, and Tuticorin) also show a broad peak between 1–2 hours.

Wavelet analysis of the residual data shows (Fig. 5) that the 1–2-hour peak is the result of a low-frequency oscillation along the Indian east coast within the first 6–7 hours of the first tsunami wave (between 0330 and 1100 UTC), with the peak occurring around noon (0630 UTC) in the northern stations (Paradip and Visakhapatnam) and in the afternoon

Table 2. Description of the tsunami. Column 2 gives the arrival time (AT, UTC), column 3 the amplitude of the first wave (residual) (FW,cm), and column 4 the maximum amplitude over the tide (residual) (Max, cm). Other acronyms are as follows: FW, first wave; HT, high tide; LT, low tide; MWL, maximum water level; and MDW, maximum detided water level.

Station	AT	FW	Max	Remarks
Paradip	0330	89	215	FW just after HT, max just before LT (also MWL)
Visakhapatnam	0340	65	159	FW around HT, max close to LT (also MWL)
Chennai	0335	64	190	FW around HT, max around LT (also MWL)
Tuticorin	0423	100	100	FW after LT (also MWL)
Kochi	0541	64	84	FW around HT (MWL), MDW during intermediate tide
Mormugao	0654	57	57	FW during intermediate tide, MWL near HT in the night
Okha	0906	7	—	—
Colombo	0352	217	—	FW just after LT
Male	0416	146	146	FW during intermediate tide
Hanimaadhoo	0432	171	171	FW just before HT
Gan Island	0420	88	88	FW during intermediate tide
Diego Garcia	0448	60	60	FW during intermediate tide, MWL during HT
Salalah	0812	29	165	FW during intermediate tide, MDW just before LT, MWL during HT

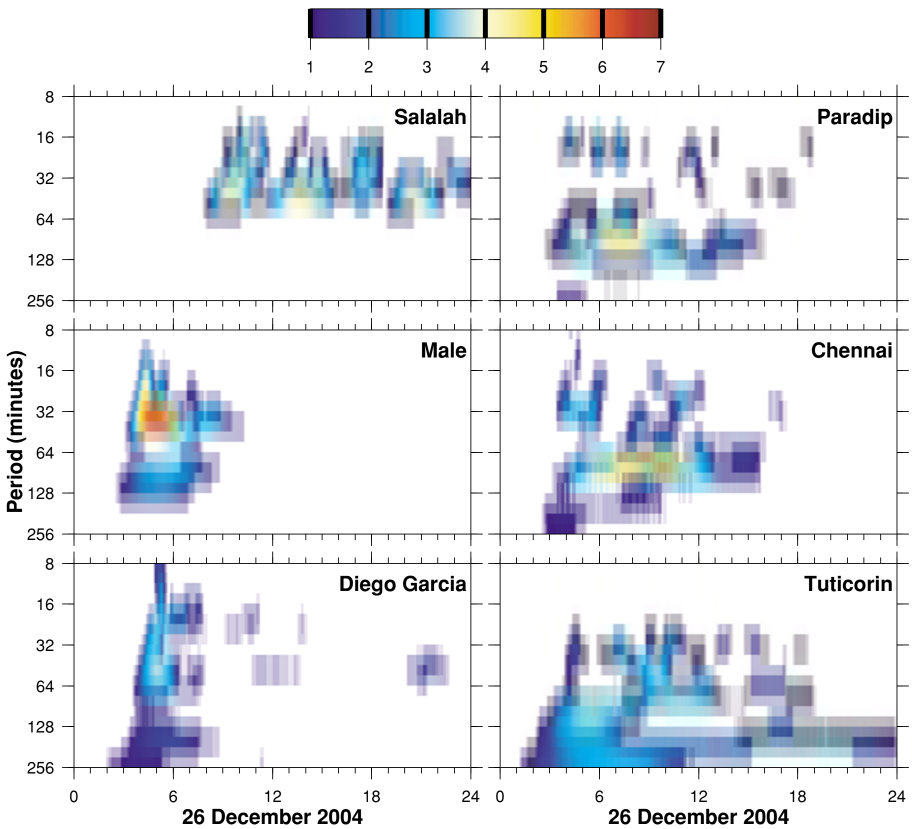

Fig. 5. Wavelet analysis of the detided water level records. The Morlet wavelet was used because its wavelet scale is almost equal to the Fourier period, enabling easy comparison with the FFT results. The abscissa is the time (UTC) during 26 December 2004, and the ordinate is the period (minutes); note that the ordinate is plotted on a $\log_2$ scale. The shading gives the wavelet power spectrum (cm^2); $\log_2$(wavelet power) is shaded and each successive shade indicates doubling of the wavelet power. Note that more power is present at the stations along the Indian east coast (Paradip, Chennai, and Tuticorin) in the 1–2-hour period range and that this low-frequency band decays after ~1000 UTC (or in the afternoon; Indian Standard Time is 5:30 hours ahead of UTC).

(~0930 UTC) at the southern stations (Chennai and Tuticorin).

Wavelet power is manifest at this period at Male in the Maldives too, but it is short-lived and weaker than in the 40-minute band, and it peaks within an hour of the first tsunami wave. This peak is very weak at Diego Garcia and is not seen at Salalah (Fig. 5). This peak is weak at Colombo, for which the wavelet analysis was done for the data after the gap (figure not shown), by when this peak had weakened along the Indian east coast.

5. Discussion

We have used tide-gauge data from stations to the west of the rupture zone to describe the tsunami. At all these stations, the water level first rose, then fell. Available data from Indonesia show that stations to the east first saw a drop in water level (Merrifield *et al.*, 2005).

Spectral and wavelet analysis pick the 35–45 minutes and $\sim$20 minutes bands as the prominent periodicities. Along the Indian east coast, there is another prominent peak between 1–2 hours. Given that this signal is seen clearly at Tuticorin, even though it is weaker here than at Chennai, it is likely that this periodicity would have also been evident at Colombo if there were no gap in the record when this signal peaks along the Indian coast. The signal occurs in both float-type (Visakhapatnam and Chennai) and pressure-sensor (Paradip and Tuticorin) tide gauges. The pressure sensors, however, are also located in the stilling well of the earlier float-type gauges at Paradip and Tuticorin. In spite of this, the low-frequency oscillations at periods exceeding an hour are not due to the nonlinear response characteristic of such tide wells (Noye, 1974). This is due to two reasons. First, this low-frequency peak is much higher than the other peaks along the Indian east coast. Second, the difference of the other two prominent frequencies observed for this tsunami (corresponding to $\sim$20 and 40–45 minutes), which can be produced by the nonlinear response (Noye, 1974), is still much greater than the low frequency along the Indian coast. This low frequency is much weaker at the stations in the Maldives and is not seen at Diego Garcia, an isolated island station. It is also absent at Salalah.

One possible cause of this low-frequency peak along the Indian east coast is coastally trapped edge waves triggered by the reflection of the shallow-water tsunami waves. Such edge waves have been shown to produce a low-frequency response distinct from the higher frequencies of deep-water waves and shallow-water tsunami waves (González *et al.*, 1995). It needs to be seen if edge-wave trapping can explain the differential frequency response seen in the tide gauges, or if this "anisotropy" in the spectrum is because the lower frequencies triggered by the rupture propagated more to the north-northwest towards the Indian coast. Available geophysical evidence suggests that such an anisotropy existed in the forcing: the propagation speed and rate of slip were not uniform along the rupture arc (Bilham, 2005).

In conclusion, we note that both float-type and pressure-sensor-type tide gauges were able to measure the tsunami signal. The data from the former, however, are normally digitised at 1-hour interval for tidal analysis and prediction. It is necessary to digitise them at a finer interval (5–6 minutes seems to be acceptable); carrying out this exercise with the data archived at SOI should enable detection of past tsunamis along the Indian coast because continuous tide-gauge records are available at Chennai and Visakhapatnam from the 1940s.

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