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Tide Gauge Observations of 2004–2007 Indian Ocean Tsunamis from Sri Lanka and Western Australia

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Abstract—Tide gauge data collected from Sri Lanka (three stations) and Western Australia (eleven stations) during the Indian Ocean tsunamis, which occurred in December 2004, March 2005, July 2006, and September 2007, and incorporated five tsunamis, were examined to determine tsunami behaviour during these events. During the December 2004 tsunami, maximum wave heights of 3.87 m and 1.75 m were recorded at Colombo (Sri Lanka) and Bunbury (Western Australia), respectively. The results indicated that although the relative magnitudes of the tsunamis varied, the tsunami behaviour at each station was similar. This was due to the effect of the local and regional topography. At all tide gauges, the spectral energy corresponding to periods between 20 and 85 minutes increased during the tsunami. The sea-level data obtained from the west and south coasts of Sri Lanka (Colombo and Kirinda) indicated the importance of wave reflections from the Maldives Island chain, which produced the maximum wave two to three hours after the arrival of the first wave. In contrast, Trincomalee on the east coast did not show evidence of a reflected wave. Similarly, along the west coast of Australia, the highest waves occurred 15 hours after the arrival of the first wave. Here, based on travel times, we postulated that the waves were reflected from the Mascarene Ridge and/or the Island of Madagascar. Reflected waves were not present in the 2006 tsunami, where the primary waves propagated away from topographic features. One of the main influences of the tsunami was to set up oscillations at the local resonance frequency. Because Sri Lanka and Western Australia have relatively straight coastlines, these oscillations were related to the fundamental period of the shelf oscillation. For Colombo, this corresponded to 75-minute period, whereas in Geraldton and Busselton (Australia), the four-hour period was most prominent; at Jurien Bay and Fremantle, the resonance period was 2.7 hours.

Key words: Tide gauge, Sri Lanka, Western Australia, tsunami, wave reflection, seiches.

1. *Introduction*

The Indian Ocean experienced its most devastating natural disaster through the action of a tsunami resulting from an earthquake off the coast of Sumatra on 26 December 2004, which caused widespread damage to property and human lives, with over 250,000 deaths in the region and millions left homeless (WALTER, 2005). This event revealed the destructive effects of tsunamis, with a maximum runup exceeding 30 m in Banda Aceh

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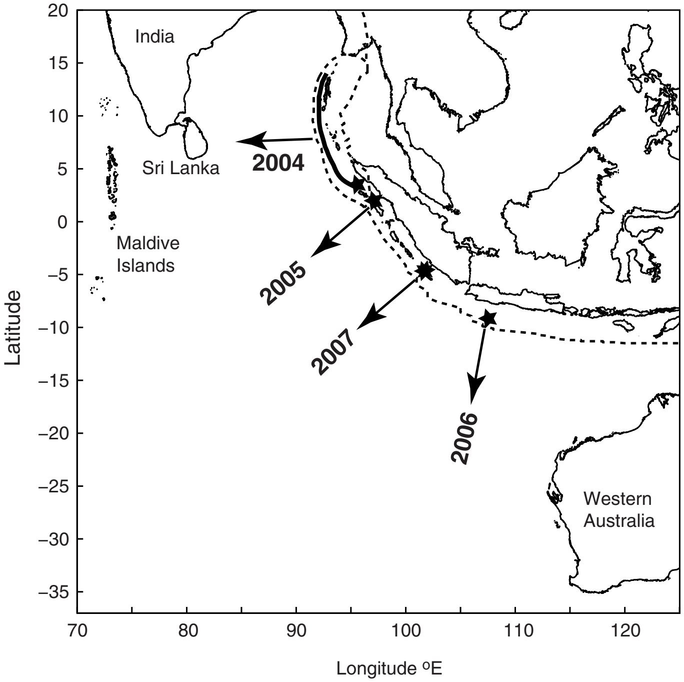


Figure 1
Map of the eastern Indian Ocean showing the location of the earthquake epicentres (indicated by stars) and direction of the primary wave propagation for the 2004, 2005, 2006, and 2007 tsunamis. Note that there were two earthquakes in September 2007 within 12 hours. The dashed line indicates the plate boundary; the thick black line indicates the area of rupture for the 2004 tsunami.

and 10 m at several sites in Sri Lanka (Inoue *et al.*, 2007); in Western Australia, the impact was much less, with a maximum total water level of 2.6 m recorded at Geraldton. The December 2004 tsunami was followed by considerably smaller basin-wide tsunamis in 2005, 2006, and 2007 (Fig. 1; Table 1). Although these tsunamis caused loss of lives and damage to property in the immediate vicinity of the tsunami generation region in Indonesia, regions located far from the earthquake epicentre (e.g., Sri Lanka, Western

Table 1

Details of Indian Ocean tsunamis 2004–2007 (see Figure 1 for locations)

Year	Date	Time of earthquake (UTC)	Earthquake magnitude	Epicentre location
2004	26 December	00:58	9.1	3.32° N 95.854° E
2005	28 March	16:09	8.6	2.07° N 97.01° E
2006	17 July	08:19	7.7	9.22° S 107.32° E
2007	12 September	11:10	8.5	4.52° N 101.37° E
		23:49	7.9	2.51° N 100.91° E

Australia) did not experience the tsunami's damaging impacts; however, local sea-level recording stations documented the characteristics of each tsunami.

Tsunamis in the Indian Ocean are rare, with ~24 tsunamis reported over a 2000-year period prior to 2004 (DOMINEY-HOWES *et al.*, 2007). The 2004 tsunami is considered to be the third tsunami recorded globally, i.e., observed in oceans other than the ocean where the tsunami was generated (RABINOVICH and THOMSON, 2007). The globally recorded tsunamis were: (1) The Krakatoa volcanic explosion in 1883 (CHOI *et al.*, 2003); (2) the Chilean tsunami in 1960 (RABINOVICH and THOMSON, 2007); and, (3) the December 2004 event, which was recorded in most of the global sea-level measurement stations across all the major oceans (TITOV *et al.*, 2005; MERRIFIELD *et al.*, 2005; WOODWORTH *et al.*, 2005; DRAGANI *et al.*, 2006; NAGARAJAN *et al.*, 2006; RABINOVICH and THOMSON, 2007). RABINOVICH and THOMSON (2007) presented detailed analyses of the sea-level records from the Indian Ocean region for the 2004 event. In this paper, we present previously unreported data from the 2004 event from tide gauges from Sri Lanka and Western Australia (the Colombo tide record was reconstructed using an offshore tide gauge) together with data from Indian Ocean tsunami events, which occurred in 2005, 2006, and 2007.

The destructive effects of tsunamis in coastal regions are usually limited to several hours. However, a much neglected tsunami effect is the set-up of coastal oscillations (seiches), which can last for three to five days after the impact of the tsunami and affect port operations and coastal sea levels. These oscillations were predominant in all of the sea-level time series presented in this paper, and the nature of these oscillations was also examined.

This paper is organised as follows: Section 2 presents background information on tsunami impacts and tidal characteristics of the study regions (Sri Lanka and Western Australia); methods are presented in Section 3, followed by analysis of the sea-level records for the tsunami events from 2004 to 2007 in Section 4; Section 5 presents an analysis of the continental shelf seiches induced by the tsunami.

2. *Study Regions*

2.1. *Sri Lanka*

Sri Lanka is located off the southern tip of India (Fig. 1). The island has a length of 445 km, a width of 225 km, a total area of 65,610 km^2, and a coastline of 1760 km, which mainly consists of sandy materials with intermittent stretches of granite rock or sandstone. It has a population of over 20 million, of which 4.85 million people live within 1 km of the coast, which makes up only 4% of the land mass.

Sri Lanka has a narrow continental shelf (range: 2.5–25 km), with a mean distance between the coast and the 200-m-depth contour of 20 km; at some locations, especially along the southern coast, this distance is reduced to < 3 km (Fig. 2a). The shelf is

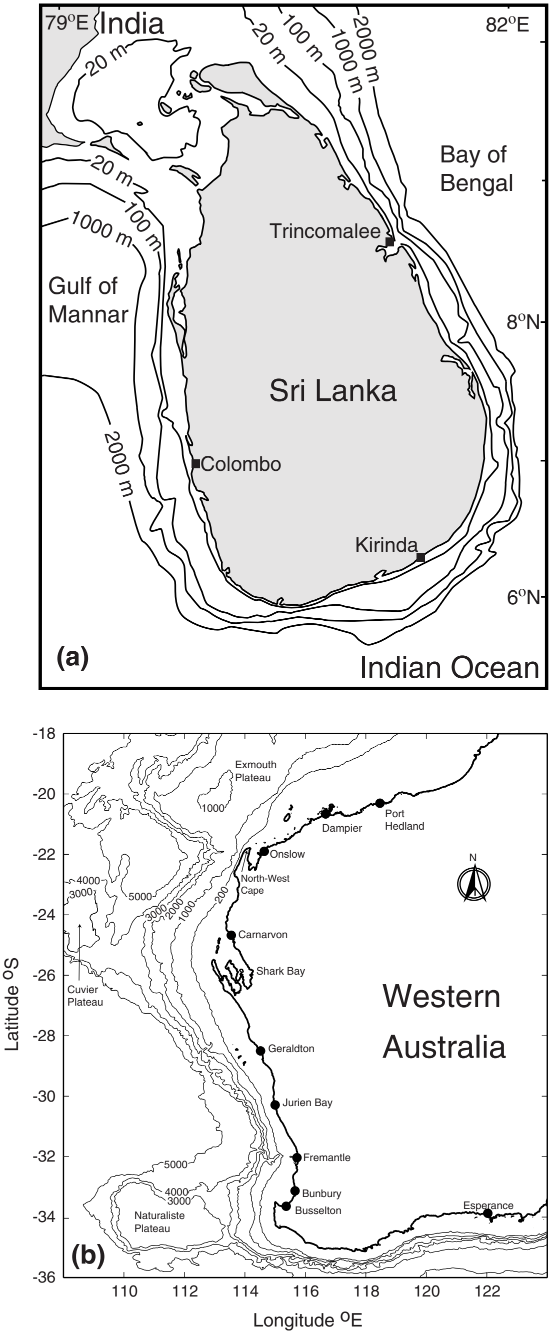


Figure 2

Locations of the tide gauges in (a) Sri Lanka and (b) Western Australia. Bathymetry contours are in metres.

narrowest around the southern part of Sri Lanka and broadens to merge with the Indian continental shelf towards the north and northeast. The continental shelf is also shallower (30–90 m) than the mean global shelf depth (75–125 m). The continental slope is steep, with a rapid increase in water depth to ~4000 m. The narrow continental shelf and the steep continental slope mean Sri Lanka is extremely vulnerable to the action of tsunamis, as the shoaling effect occurs over a shorter distance and there is a negligible amount of energy dissipated over the continental shelf region. Sri Lanka is most vulnerable to tsunamis generated from the Sunda Arc region, located approximately 1500 km to the east (Fig. 1). There are also no major submarine topographic features between the tsunami source region and Sri Lanka to dissipate or refract the tsunami waves. As a result, Sri Lanka was the second-most affected country for the 2004 tsunami event.

Sri Lanka has a semi-diurnal, micro-tidal regime with a maximum tidal range of ~0.5 m along the entire coast. The tides around Sri Lanka are controlled by the oceanic tides of the Arabian Sea (west coast) and the Bay of Bengal (east coast), which results in a phase difference in the tides between the east and west coasts. For example, the tides in Trincomalee are exactly out-of-phase with the tides in Colombo, with low water in Colombo corresponding to high water at Trincomalee.

Although Sri Lanka lies in the direct path of a tsunami from the Sunda Arc, the only documented impact of a tsunami, prior to 2004, was due to the 1883 Krakatoa eruption (CHOI *et al.*, 2003). The resulting tsunami was reported in newspaper articles in Sri Lanka, with impacts reported from Galle, Negombo, and Arugam Bay where there was one casualty. The reported maximum wave height was 1 m, and the tsunami impacted Sri Lanka five to seven hours after the eruption (CHOI *et al.*, 2003). It is likely Sri Lanka was affected by the tsunamis in the Bay of Bengal in 1881 (ORTIZ and BILLHAM, 2003), 1941 (MURTY and RAFIQ, 1991), and 1994 (SYNOLAKIS *et al.*, 1995), but the effects of a small tsunami would not have caused any damage and thus would have been undetected. The 1994 East Java earthquake, which occurred on 3 June 1994, was recorded in tide gauges in Oman (B. Kilonsky, pers. comm., 2005). As Sri Lanka lies between the source region and Oman, the tsunami would have propagated past Sri Lanka; however, no tide records from Sri Lanka exist to confirm this.

2.2. *Western Australia*

Western Australia's coast is over 20,000 km and comprises one-third of the Australian continent. The northern section of Western Australia (east of Onslow, Fig. 2a) has a wide continental shelf. Although this region is closest to the Sunda Arc region (Fig. 1), the wide continental shelf has a large influence on tsunami impacts at the shoreline (PATTIARATCHI and WOO, 2000). The presence of the Exmouth Plateau influences tsunami propagation through refraction, with a concentration of energy along the coastline (LEGGET, 2006). The continental shelf is narrowest (< 20 km) at North-West Cape (Fig. 2b); its width increases to the south of North-West Cape to Shark Bay (where it is up to 80 km), decreases to Jurien Bay (Fig. 2b), and then increases to the south.

Along the west coast, the narrowest shelf is at Jurien Bay; thus the tsunami's arrival was first recorded at this location.

The location of Cuvier Plateau to the west of Shark Bay strongly influenced deep water tsunami propagation through refraction (Legget, 2006). Here, the presence of the plateau causes the refraction of tsunami wave energy onshore, concentrating energy in the region between Geraldton and the offshore regions of Shark Bay (Fig. 2b).

There is a large variation in the tidal chacteristics along the coast, with the northern section (east of Onslow, Fig. 2b) experiencing semi-diurnal tides, with a maximum spring tidal range exceeding 10 m to the east of Port Hedland (Fig. 2b). The section between Onslow and Carnarvon (Fig. 2b) experiences mixed tidal conditions, with a maximum tidal range of 2–3 m. The coastline between Geraldton and Esperance (Fig. 2b) expriences diurnal tides, with a maximum range of < 1 m. The low tidal range in this region means that even a small tsunami or seiche (> 0.25 m) results in a significant proportion of the local tidal range.

Western Australia is susceptible to the action of tsunamis generated by earthquakes in the Sunda Arc region (Fig. 1). Although there have been many earthquakes in the region (Dominey-Howes, 2007), tsunamis have been observed (either through visual records or tide gauges) only for the events in 1883 (Krakatoa), 1977 (Sumbawa), 1994 (East Java), and the 2004–2007 tsunami events described in this paper. A summary of these events is presented below (see also Pattiaratchi and Woo, 2000, and Dominey-Howes *et al.*, 2007).

- The 1883 tsunami was associated with the eruption of Krakatoa volcano on 27 August 1883. A maximum runup height of 1.5 m was observed at Cossack (near Dampier, Fig. 1). Tsunami waves corresponding to this volcanic explosion were also observed at Geraldton, Carnarvon, and Fremantle.
- The 1977 tsunami was due to the 7.9-magnitude Sumbawa earthquake, which occurred on 19 August, 1977. Gregson *et al.* (1979) described the tsunami associated with this earthquake. A 4-m-high wave was observed at Barrow Island by fishermen while the lighthouse keeper at Cape Leveque reported a 6-m-high wave. This is the highest tsunami-generated wave reported in Australia. At Point Samson, six to eight 4.6-m-high waves were observed, and in Dampier, four waves of 2–2.5 m in height were observed.
- The 1994 tsunami resulted from the 7.2-magnitude East Java earthquake, which occurred on 3 June, 1994. The time series from the water level recorders obtained from coastal stations along the northwest region indicated small changes in the water level. This was due to the fact that the tide gauges were set to record at 15-minute intervals and therefore may not have accurately measured the maximum wave heights. Examination of the damage resulting from the tsunami revealed the tsunami would have reached heights up to 4 m along the NorthWest Cape, with reduced values of 2–3 m between Exmouth and Dampier (Pattiaratchi and Woo, 2000).

3. Methods

Data were obtained from tide gauges in Sri Lanka and Western Australia (Fig. 2). In Sri Lanka, data were obtained from tide gauges operated and maintained by the National Aquatic Resources Research and Development Agency (NARA). The sea-level recording station at Colombo, within the Mutwal fishery boat harbour, was established as a global sea-level observing system (GLOSS) station in August 2004. The tide gauges consisted of two floats with a digital recording system, and were set to record measurements at two-minute intervals. During the 2004 tsunami, after recording the first wave, the floats were stuck at the bottom of the stilling well at 0430 UTC (1030 local time), 40 mins after the arrival of the intitial wave (Fig. 3) when the water level dropped below the lowest level of the well. The floats were reset by the second author (EMSW) and then recorded data from 1000 UTC (1400 local time). Thus data were missing for 3.5 hours, coinciding with the arrival of the highest waves. This is in contrast to the 5 hours 40 minutes reported by RABINOVICH and THOMSON (2007) who used the data archived by the University of Hawaii Sea Level Centre using data from a single encorder. Using data recorded by both encorders, we have decreased the amount of missing data. An offshore bottom mounted tide gauge (InterOcean S4DW wave and current recorder maintained by Lanka Hydraulic Institute, Ltd), located in 16-m-water depth, a distance 5 km from the coastline, recorded water levels at 10-minute intervals throughout the tsunami event.

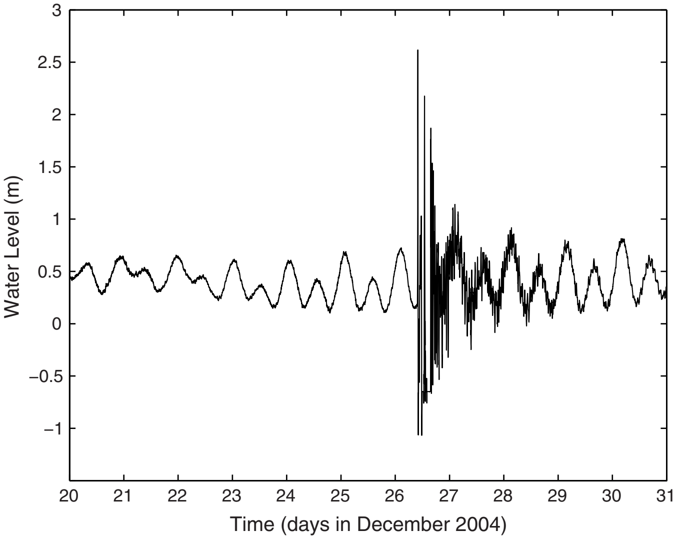


Figure 3
Time series of the water level record from Colombo, Sri Lanka, from 20 to 31 December, 2004 showing the scale of the tsunami with respect to the tidal range and also the presence of high frequency oscillations subsequent to the tsunami.

The S4DW water level data were used to determine the missing data from the Colombo tide gauge as follows: The Colombo data, for one day before and after the tsunami, were re-sampled at 10-minute intervals and compared with the S4DW water level record. The missing data were then interpolated with reference to the S4DW data, and the Colombo time series was re-sampled at 2-minute intervals (Fig. 4). Subsequent to reconstruction, the spectral characteristics of both series were found to be very similar (not shown). There was an excellent correspondence between the two-time series after the reconstruction of the Colombo data (Fig. 4a). It should be noted that the floats accurately recorded a single wave after the floats were partly dislodged at around 1200 (Fig. 4b), but were dislodged completely after the largest wave at 1330. After the 2004 tsunami, the sampling interval on the Colombo tide gauge was changed to one minute. The sea-level recording station at Trincomalee (Fig. 2), which was established in 2005 (subsequent to the March 2005 tsunami), also had a sampling interval of one minute.

A Coastal Leasing micro-tide pressure gauge located inside the Kirinda fishery harbour measured the March 2005 tsunami (Fig. 2). The instrument recorded the sea level at five-minute intervals, with an accuracy of ±1 cm.

In Western Australia, data were obtained from tide gauges that the Department for Planning and Infrastructure (http://www.dpi.wa.gov.au/) operates and maintains. All sea-level stations recorded the sea level at five-minute intervals. The residual time series were obtained by subtracting the predicted tide from the observed tide at each recording station.

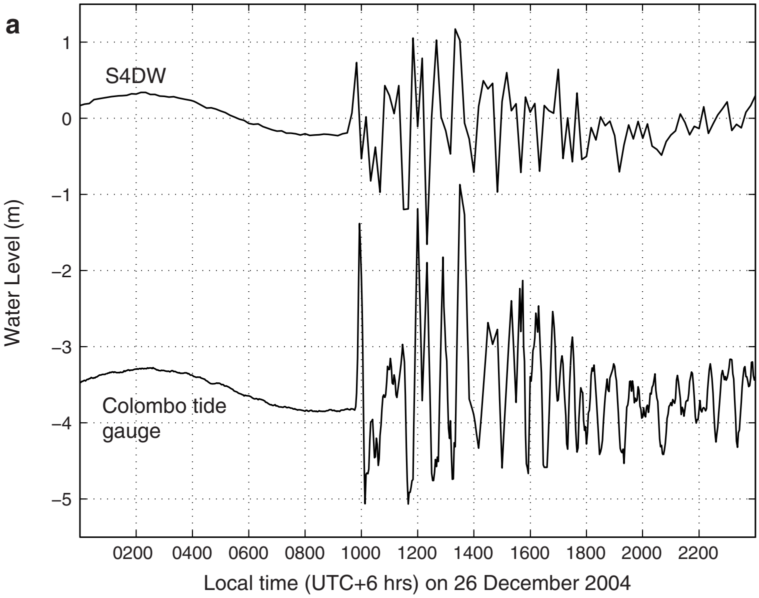
The tidal time series were subjected to Fourier analysis to identify the dominant frequencies in the records. This was undertaken in two ways: (1) the records for five consecutive days immediately before and after the tsunami were used to construct the auto-spectrum and identify the changes in the spectral energy before and after the tsunami; and (2) the auto-spectra were used to construct time–frequency plots and determine the longer-term changes in the spectral energy distribution. Here, time series of 2048 points were used to estimate power spectra using the 'Welch' method (Little and Shure, 1988) using Fast Fourier Transform (FFT) method. Subsequent spectra were calculated using a 50% overlap (i.e., 1024 points).

4. Tide Gauge Records of Tsunamis

4.1. December 2004 Tsunami

Sri Lanka. The Colombo tide gauge data indicated the tsunami arrived at 0352 UTC (0952 local time) as a leading elevation wave reaching a maximum height of 2.65 m over 10 minutes (Table 2); that is, the highest water level for the initial wave was reached at 0402 UTC (1002 local time).

During the tsunami, the float in the stilling well was stuck at bottom of the tide gauge; the missing data were reconstructed using an offshore tide gauge (see Section 3).



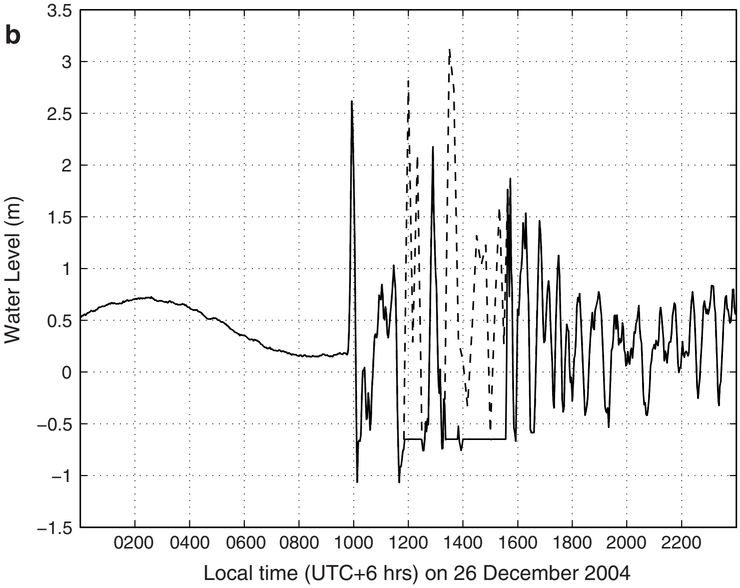


Figure 4

(a) Time series of the offshore S4DW tide gauge and Colombo tide gauge sea levels on 26 December, 2004. Note the Colombo data were offset by −4 m. (b) Time series of the reconstructed Colombo tide gauge sea level on 26 December, 2004. The dashed lines show the reconstructed data.

Table 2

Characteristics of the 26 December 2004 tsunami as recorded by tide gauges

Station	Initial wave		Maximum wave	
	Arrival time/date (UTC)	Wave height+	Elapsed time (number)	Wave height
Colombo	03:52 26/12/04	2.3 m	2 h 08 m (3)	3.87 m
			3 h 38 m (6)	3.87 m
Carnarvon	07:40 26/12/04	0.38 m	15 h 20 m (25)	1.14 m
Geraldton	07:20 26/12/04	0.13 m	15 h 15 m (19)	1.65 m
Jurien Bay	07:05 26/12/04	0.47 m	6 h 30 m (10)	0.90 m
Fremantle	07:40 26/12/04	0.33 m	7 h 20 m (9)	0.60 m
Bunbury	08:05 26/12/04	0.60 m	13 h 35 m (18)	1.75 m
Busselton	07:55 26/12/04	0.54 m	13 h 15 m (19)	1.15 m
Esperance	09:00 26/12/04	0.11 m	12 h 00 m (17)	0.44 m

+ Maximum wave height is listed as the trough to crest height.

The resulting time series (Fig. 4) showed that in Colombo, the highest water level of 3.13 m occurred during the sixth wave, 3.5 hours after the first wave at 0730 UTC (1330 local time). As a result of the previously missing data, many authors (e.g., Liu *et al.*, 2005) reported eyewitness accounts that the third wave along the west coast, which arrived at ~0600 UTC (1200 local time), was the highest. Inoue *et al.* (2007) reported that the arrival of the second wave was between 0400 and 0900 UTC (1000 and 1500 local time). The reconstructed sea-level record confirmed some of these findings with respect to Colombo (Table 2):

(1) The initial wave, which arrived at 0352 UTC, was a leading elevation wave with a maximum height of 2.65 m.
(2) The second highest water level of 2.81 m was reached at 0600 UTC (1200 local time).
(3) The highest water level of 3.13 m was reached at 0730 UTC (1330 local time).
(4) The maximum wave height (trough to crest) was 3.87 m, with the two waves at 0600 UTC and 0730 UTC having the same height.

The timings of the above waves could be confirmed by the personal experiences of the first author (CBP) who was present in Sri Lanka and experienced the first and subsequent waves along the coast while driving on a road (Galle Road) that runs parallel to the coast to the south of Colombo.

The above results suggested the waves along the west coast of Sri Lanka had many sources, with the highest waves reflected from the Maldives Island chain. The elapsed time for the tsunami's deep water propagation from Sri Lanka to the Maldives Island chain and return was ~two hours. Thus the second largest wave in the record, which occurred at 1200 (Fig. 4), could be attributed to the reflection from the Maldives Island chain. Kowalik *et al.* (2007) showed through numerical modelling that the reflected waves from Sri Lanka and the Maldives Island chain were often larger than the primary wave. The results from the Colombo tide gauge, where the highest waves were those resulting from the wave reflected from the Maldives Island chain, confirmed this finding.

Western Australia. The tide gauge data along the west coast indicated that the tsunami waves were first recorded at Jurien Bay at 0705 UTC, with a travel time of six hours and three minutes (Table 2). The continental shelf offshore Jurien is the narrowest along this part of the coast. The waves were then incident at Geraldton (0720), Carnarvon (0740), Fremantle (0740), Busselton (0755), Bunbury (0805), and Esperance (0900). Esperance is located along the southern coast (Fig. 2b) and is farthest away from the source region, which explained the late arrival time. The initial waves all indicated an increase in the water level, corresponding to leading elevation waves, and the heights along the west coast ranged from 0.33 m at Fremantle to 0.60 m at Bunbury (Fig. 5 and Table 2). Esperance recorded an initial wave height of 0.11 m.

Examination of the residual time series, maximum wave heights, and the elapsed time between the initial and maximum waves indicated several features:

(1) The maximum wave heights (Table 2), recorded at Carnarvon, Geraldton, Bunbury, and Busselton all exceeded the maximum spring tidal range at these locations.
(2) At Geraldton, although initial oscillations due to the tsunami waves were observed at 0720 UTC, there was a lag of five hours before the highest water level (2.6 m relative to datum) was reached at 1210 GMT, which coincided with the tidal high water (Fig. 6). However, the highest waves (trough to crest) were recorded ~10 hours later

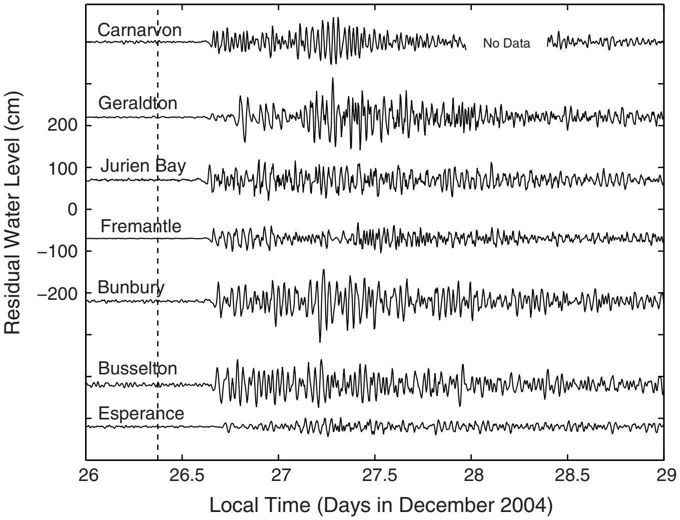


Figure 5
Time series of residual sea level from coastal stations located along the west coast of Australia. The dashed line shows the time of the earthquake. (Note: local time is +8 hrs UTC).

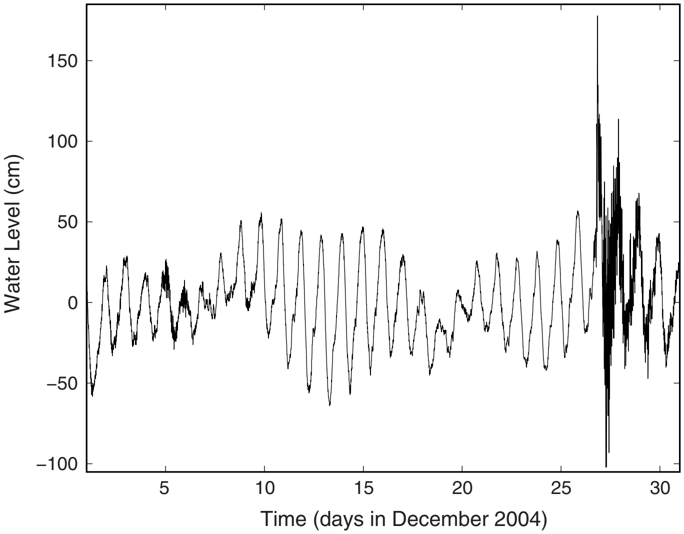


Figure 6
Time series of the water level record from Geraldton, Western Australia, for December, 2004 showing the scale of the tsunami with respect to the tidal range and also the presence of high frequency oscillations subsequent to the tsunami (also note the high frequency oscillations from 4 to 8 December).

and were associated with a wave group (see 3 below). The highest waves coincided with the low water and thus the lowest water level (−0.60 m) was recorded at this time (Fig. 6). The water levels recorded at Geraldton during this event were the highest and lowest levels recorded at this station, which has been in continuous operation for more than 40 years.

(3) The residual time series indicated the arrival of a group of waves with higher wave heights at all stations except at Fremantle and Jurien Bay (Fig. 5) some 13–15 hours after the arrival of the initial wave (Table 2). The maximum wave height (crest to trough) at each of these stations (Carnarvon, Geraldton, Bunbury, Busselton, and Esperance) was also recorded during the passage of this wave group. KOWALIK *et al.* (2007) examined the energy flux of the tsunami waves between Australia and Antarctica across longitude 140° onto the Pacific Ocean and predicted that the highest energy flux was ~21 hours after the source earthquake. The wave group at Bunbury, Busselton, and Esperance was recorded ~19 hours after the source earthquake. As the cross section (longitude 140°) at which the energy flux calculations were made was located to the east of these stations (Fig. 1), it is likely this wave group was responsible for the high energy flux predicted by KOWALIK *et al.* (2007). KOWALIK *et al.* (2007) attributed the source of this higher energy to reflected waves from the Maldives and Seychelles (Mascarene Ridge). However, the time lag of 13–15 hours suggested that the Island of Madagascar could also have been responsible for the reflection.

(4) The highest (trough to crest) wave was recorded at Bunbury (1.75 m; Table 2), which coincided with the arrival of the wave group. However, as the wave group arrived at Bunbury near to low water, the maximum water level was lower than that recorded at Geraldton (see 2 above).

4.2. March 2005 Tsunami

Sri Lanka. Tide gauges at Colombo and Kirinda (Fig. 2a) recorded initial tsunami wave heights of 0.3 m and 0.7 m, respectively, with the travel times to Colombo and Kirinda being two hours and 56 minutes and three hours and 24 minutes, respectively (Fig. 7; Table 3). At Kirinda, the first wave arrived almost at low tide; the wave heights then increased, reaching a maximum height of 2.7 m two hours and 24 minutes after the arrival of the first wave (Fig. 8). The approximate 2.5-hour time interval corresponded to the elapsed time from the tsunami wave reflected from the Maldives Island chain; hence, similar to the December 2004 tsunami, the highest waves were due to reflection from the Maldives Island chain. It should be noted that the wave height recorded at Kirinda was larger than wave heights recorded elsewhere in the region—Cocos Island (10–22 cm), the Maldives (10 cm)—and were similar to those recorded near the earthquake zone—3 m on the southern edge of Simeulue Island and 2 m recorded on the west coast of Nias Island (RASTOGI and JAISWAL, 2006).

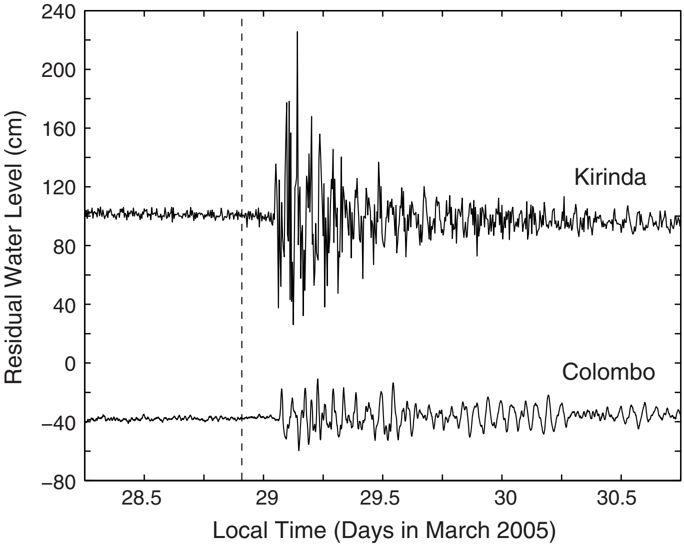


Figure 7
Time series of residual sea level from Kirinda and Colombo, Sri Lanka, 29 March, 2005.

Table 3

Characteristics of the 28 March 2005 tsunami as recorded by tide gauges

Station	Initial wave		Maximum wave	
	Arrival time/date (UTC)	Wave height	Elapsed time (number)	Wave height
Colombo	19:32 28/03/05	0.23	4 h 17 m (5)	0.43 m
Kirinda	19:05 28/03/05	0.56	2 h 24 m (7)	2.7 m
Carnarvon	22:20 28/03/05	0.07 m	14 h 45 m (25)	0.30 m
Geraldton	22:10 28/03/05	0.05 m	3 h 55 m (5)	0.40 m
Jurien Bay	21:45 28/03/05	0.08 m	12 h 35 m (11)	0.38 m
Fremantle	21:45 28/03/05	0.20 m	14 h 05 m (16)	0.32 m
Bunbury	22:15 28/03/05	0.17 m	12 h 45 m (10)	0.49 m
Busselton	22:20 28/03/05	0.19 m	15 h 25 m (16)	0.49 m
Esperance	01:45 29/03/05	0.05 m	3 h 00 m (4)	0.11 m

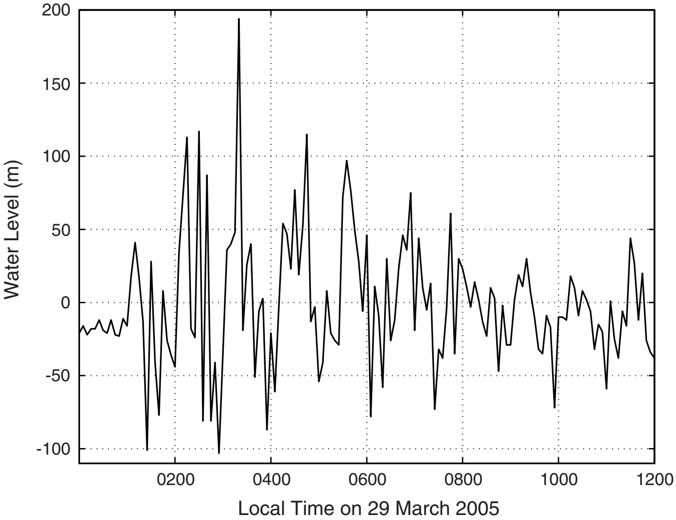


Figure 8
Time series of the water level record from Kirinda, Sri Lanka, on 29 March, 2005.

Western Australia. All the tide gauges along the WA coast recorded the tsunami waves (Fig. 9), but the waves had considerably smaller amplitudes than those in Sri Lanka, with heights ranging between 11% and 50% of the heights recorded for the December 2004 tsunami (Table 3). The maximum wave heights ranged between 0.11 m (Esperance) and 0.49 m (Bunbury and Busselton). However, the tsunami arrival patterns were similar to the 2004 event: The waves first arrived at Jurien Bay and Fremantle, followed by Geraldton, Bunbury, Busselton, Carnarvon, and Esperance.

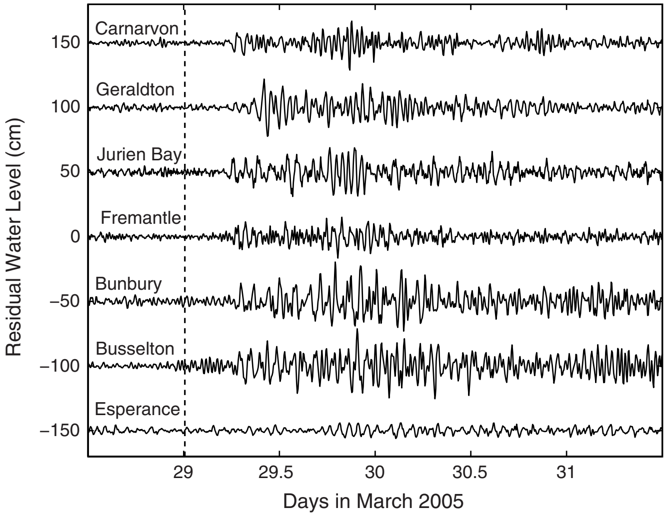


Figure 9
Time series of the residual water level records from Western Australia for 28 March to 1 April, 2005. The dashed line shows the time of the earthquake. (Note: local time is +8 hrs UTC).

The features identified during the 2004 events (see Section 4.1) were also observed. These included: (a) The lag of several hours (~four hours) before the arrival of the highest wave at Geraldton; and (b) the presence of a second group of waves 13–15 hours after the arrival of the initial wave at all stations (Fig. 9 and Table 3). The maximum wave heights (crest to trough) at all stations, except Geraldton and Esperance, were also recorded during the passage of this wave group. It should be noted that the second wave group, which was not clearly identified at Jurien Bay and Fremantle for the 2004 event, was present during the 2005 event (Fig. 9). KOWALIK *et al.* (2007) proposed the reflections from the Maldive Islands and/or the Mascarene Ridge caused the second group of waves. As the dominant wave direction in the 2005 event was not directed towards the Maldives and Sri Lanka (Fig. 1), we could discount the islands of Sri Lanka and the Maldives as possible sources for wave reflection. Hence it was likely the Mascarene Ridge and Madagascar were the source of the reflections.

4.3. July 2006 Tsunami

Sri Lanka. The primary direction of the tsunami waves was southwards and away from Sri Lanka (Fig. 1); thus no evidence of the tsunami was detected in the Sri Lankan tide gauges.

Western Australia. The tide gauges along the WA coast, north of Geraldton, recorded the tsunami (Table 4), with the tsunami being most prominent at Dampier, which recorded a maximum wave height of 0.8 m (Fig. 10). The northern stations recorded higher water

Table 4

Characteristics of the 17 July 2006 tsunami as recorded by tide gauges

Station	Initial wave		Maximum wave	
	Arrival time/date (UTC)	Wave height	Elapsed time (number)	Wave height
Cape Lambert	12:30 17/07/06	0.09 m	40 m (3)	0.19 m
Dampier	12:30 17/07/06	0.27 m	40 m (3)	0.80 m
Carnarvon	12:40 17/07/06	0.19 m	35 m (3)	0.44 m
Geraldton	12:00 17/07/06	0.08 m	3 h 50 m (10)	0.36 m
Jurien Bay	12:10 17/07/06	0.12 m	10 m (3)	0.14 m
Fremantle	12:30 17/07/06	0.07 m	20 m (3)	0.09 m

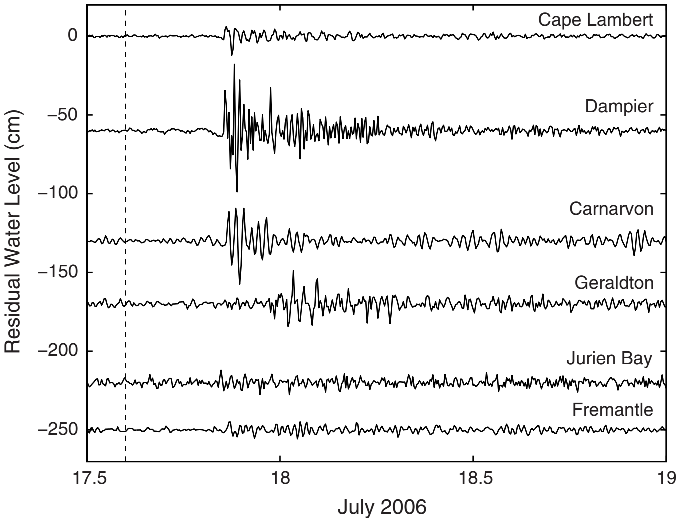


Figure 10
Time series of the residual water level records from Western Australia for 17–19 July, 2006. The dashed line shows the time of the earthquake. (Note: local time is +8 hrs UTC).

levels because the location of the earthquake epicentre was more eastward than it was during the 2004 and 2005 tsunamis. Thus the stations to the south of Geraldton were in the lee of the Cuvier Plateau (Fig. 2b). The existing shelf oscillations, unrelated to the tsunami, also obscured the tsunami signal at Jurien Bay, Fremantle, Bunbury, and Busselton (Figure 10—latter two stations are not shown).

The tsunami first arrived as a leading elevation wave at Geraldton, followed by Jurien Bay, Fremantle, Dampier, Cape Lambert, and Carnarvon. The maximum wave heights occurred within 10–40 minutes of the initial wave; the third wave was the highest at all stations except Geraldton. The absence of a second wave group was evident and could be attributed to the propagation of the primary wave in a southerly direction (Fig. 1) away from regions which could result in wave reflection. At Geraldton, the maximum wave height was recorded ~4 hours after the arrival of the initial wave. The delay in the arrival of the highest waves at Geraldton was also observed during the 2004 and 2005 events and appeared to be a phenomenon related to the local bathymetry: Geraldton has a complex offshore topography with a wide (~80 km) continental shelf and a string of offshore islands (the Houtman-Abrolhos Islands) located at the shelf break (Fig. 2b).

4.4. September 2007 Tsunami

Sri Lanka. Tide gauges at Trincomalee and Colombo (Fig. 2a) recorded the tsunami as a leading elevation wave with initial wave heights of 0.2 m and 0.3 m, respectively, and travel times to Trincomalee and Colombo of three hours and 48 minutes and four hours and two minutes, respectively (Fig. 11; Table 5). At Trincomalee, the second wave reached a maximum height of 0.6 m 52 minutes after the arrival of the first wave (Fig. 11). In contrast, at Colombo, the sixth wave (0.50 m), which arrived two hours and 38 minutes after the first wave, was the highest. This was in agreement with the 2004 and 2005 events and could be related to wave reflection from the Maldives Island chain. Trincomalee, along the east coast (Fig. 2a), was sheltered from the reflected wave and thus did not appear in the record.

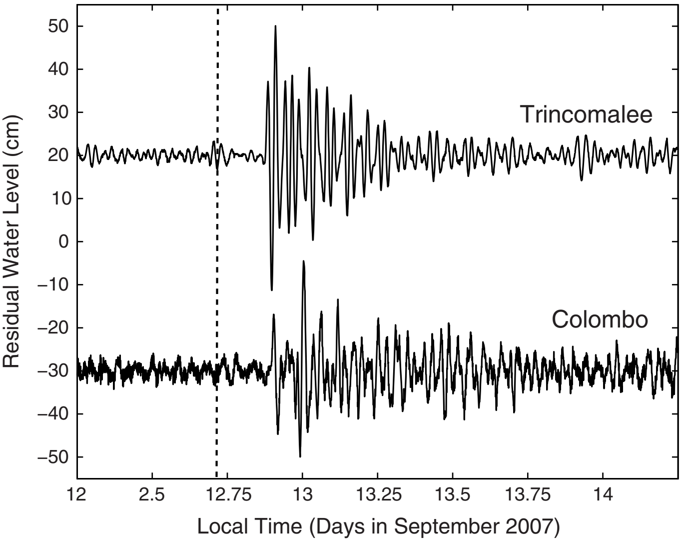


Figure 11
Time series of the residual water level records from Colombo and Trincomalee for 12–14 September, 2007. The dashed line shows the time of the earthquake. (Note: local time is +5.5 hrs UTC).

Table 5

Characteristics of the 12 September 2007 tsunami as recorded by tide gauges

Station	Initial wave		Maximum wave	
	Arrival time/date (UTC)	Wave height	Elapsed time (number)	Wave height
Colombo	15:12 12/09/07	0.3 m	2 h 38 m (6)	0.50 m
Trincomalee	14:58 12/09/07	0.2 m	52 m (2)	0.60 m
Onslow	15:55 12/09/07	0.15 m	5 h 15 m (7)	0.32 m
Carnarvon	16:25 12/09/07	0.09 m	6 h 25 m (11)	0.34 m
Geraldton	16:00 12/09/07	0.07 m	5 h 35 m (8)	0.64 m
Jurien Bay	15:35 12/09/07	0.13 m	1 h 20 m (2)	0.17 m
Fremantle*	-	-	-	-
Busselton	-	-	-	-

* Tsunami could not be identified because of background oscillations.

At both stations, there was no evidence of a tsunami generated by the second earthquake, which occurred ~12 hours after the first earthquake (Table 1). If a tsunami occurred, its effects were small and could not be identified because of the oscillations set up by the first tsunami.

Western Australia. The tide gauges along the WA coast recorded the tsunami; however, at Fremantle (Fig. 12), the effect of the tsunami was obscured because of the passage of a storm system prior to the earthquake, which set up oscillations of the same order as that due to the tsunami. These oscillations were also present at Busselton, but the tsunami could be identified as higher oscillations, which occurred at a similar time to the tsunami's arrival at Jurien Bay. The tsunami arrival patterns along the west coast were similar to those of the 2004, 2005, and 2006 tsunamis: the leading elevation waves first arrived at Jurien Bay, followed by Geraldton, Onslow, and Carnarvon (Table 5). The maximum wave height was recorded at Geraldton (0.64 m), with the maximum wave heights at Onslow and Carnarvon being of similar magnitudes (0.32 m and 0.34 m, respectively) (Table 5). As per previous tsunamis, there was a time lag (5.5 hours) between the arrival of the initial wave and the recorded maximum wave height at Geraldton.

The residual time series, particularly for Onslow, Carnarvon, and Geraldton, indicated the occurrence of several wave groups. Here it should be noted that a second earthquake occurred at almost the same location (~250 km to the south; Table 1) ~12 hours later. Through examining the time lags for the first tsunami and the arrival of the initial wave at the sea-level recording stations, the tsunami generated by the second earthquake could be identified (Fig. 12). The presence of secondary wave groups between the first and second tsunami could also be clearly identified in the residual times series (Fig. 12); however, the time lag between the arrival of the initial wave and the maximum wave in the wave group varied between five and six hours, which was much less than the ~15 hours recorded during the 2004 and 2005 tsunamis. This indicated that local phenomena, rather

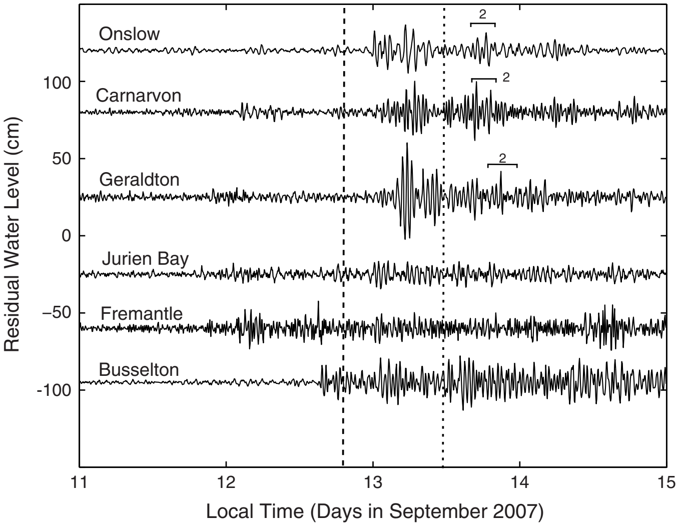


Figure 12
Time series of the residual water level records from Western Australia for 11–15 July, 2006. The dashed lines indicate the times of the earthquakes. The brackets and number 2 denote the tsunami due to the second earthquake. (Note: local time is +8 hrs UTC).

than wave reflection from distant sources, such as the Mascarene Ridge or Madagascar, caused these wave groups.

5. Tsunami-induced Seiches

A free oscillation in an enclosed or semi-enclosed body of water, similar to the oscillation of a pendulum where the oscillation continues after the initial force has stopped, is defined as a seiche (MILES, 1974). Several factors cause the initial displacement of water from a level surface, and the restoring force is gravity, which tends to maintain a level surface. Once formed, the oscillations are characteristic only of the system's geometry (length and depth) and may persist for many cycles before decaying under the influence of friction.

A common feature of the time series plots shown in Figures 3 to 12 is the presence of high frequency oscillations with periods ranging from minutes to hours, which persisted for several days after the tsunami. As a result of the tsunami impact, the energy contained in these periods increased by two to three orders of magnitude (RABINOVICH and THOMSON, 2007); this is illustrated in the spectra obtained from the Colombo and Geraldton tide gauge records (Fig. 13). These oscillations mainly consisted of two types: (1) Waves that comprise the tsunami. These waves are usually identified in tide gauge records during the first few hours of a tsunami. For the 2004 tsunami, these waves had energy in the periods

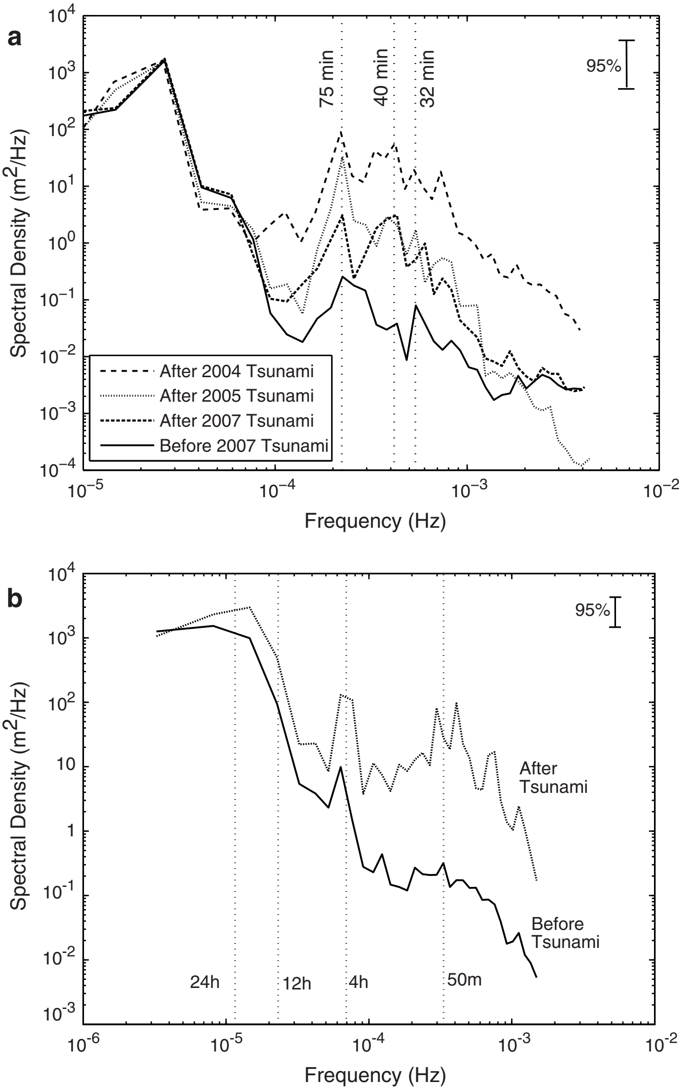


Figure 13

(a) Water level spectra from the Colombo tide record for the 2004, 2005 and 2007 tsunamis showing the spectral energy after the tsunami. Spectral energy before the 2007 tsunami is also shown. (b) Water level spectra from the Geraldton tide record for the December 2004 tsunami showing the spectral energy before and after the tsunami.

ranging from 20 to 85 minutes, with peak values ranging between 35 and 60 minutes (Rabinovich and Thomson, 2007). This was also reflected in the data recorded at Colombo and Geraldton (and other stations in Western Australia, not shown), where a significant increase in the spectral energy in this range of periods occurred subsequent to the tsunami (Fig. 13); (2) oscillations that are set up by the tsunami but whose periods are governed by the local topography. These oscillations may continue for several days after the tsunami's impact, with energy in a particular period enhanced because of the tsunami. Examples of these oscillations were seen at Colombo, where the energy at the 75-minute period increased after the tsunami (for all tsunamis recorded in 2004, 2005 and 2007, Fig. 13a), and at Geraldton, where the oscillations at a period of four hours were enhanced (Fig. 13). We will now examine the features of these oscillations in more detail.

Several studies have been undertaken to examine water level oscillations with periods of O (hours) on the continental shelf. These studies showed atmospheric effects mainly generated these oscillations. Cartwright and Young (1974) demonstrated that along the east Shetland coast (Scotland, UK), standing edge waves were generated through the passage of weather systems. Heath (1982) indicated that along the east coast of New Zealand, atmospheric forcing, tsunamis, and edge waves along the continental shelf and slope caused sea-level oscillations with periods of two to three hours. Similarly, shelf oscillations off the Argentine coast (Dragani, 2007), Strait of Sicily (Candela *et al.*, 1999), and in the Balearic Islands (Rabinovich and Monserrat, 1998) have been attributed to meteorological forcing.

In Colombo, after the first packet of waves from the December 2004 tsunami, enhanced high frequency oscillations superimposed on the tidal record were present for four to five days (Fig. 3). Spectral analysis of five days of data obtained before and immediately after each of the tsunamis in 2004, 2005 and 2007 indicated high frequency energy (e.g., at 75 minutes) was enhanced after the tsunami (Fig. 13a). Although the tide gauge was located in a harbour, the 75-minute oscillations were related to the study region's entire continental shelf, whose fundamental period is given by Merian's formula for an open system (Pugh, 1987):

$$T_n = \frac{1}{n}\frac{4L}{\sqrt{gh}},$$

where L is the width of the continental shelf; h is the mean water depth; g is acceleration due to gravity; and n is the mode number ($=1$ for the fundamental mode). The continental shelf adjacent to Colombo has a mean depth of 40 m and a width (to the 200-m contour where the shelf break occurs) of 22 km. Thus the tsunami enhanced the existing natural oscillation of the entire continental shelf. The time–frequency plot (Fig. 14) indicated higher frequency energy at the 75-minute band before the tsunami. During the tsunami, spectral energy increased across all frequencies, and subsequent to the tsunami, the energy at the higher frequencies decreased, nonetheless the energy at the 75-minute frequency band continued for almost 10 days (Fig. 14).

A similar pattern was found along the Western Australian coast (Fig. 2b). After the first packet of waves from the December 2004 tsunami, enhanced high frequency oscillations superimposed on the tidal record were present for four to five days (Fig. 5). At Geraldton, spectral analysis of five days of data obtained before and immediately after the tsunami showed the energy at the four-hour frequency band was enhanced after the

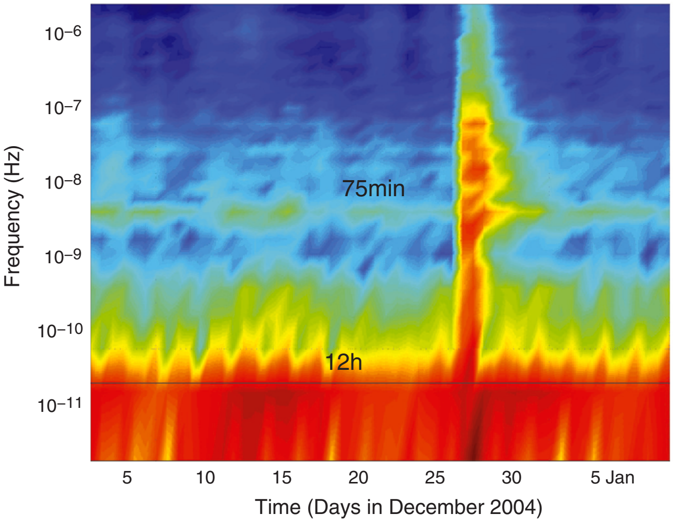


Figure 14
Time–frequency plot of the tidal record from Colombo for December 2004.

tsunami (Fig. 13b). The four-hour oscillations were related to the first mode of the study region's entire continental shelf. Here the continental shelf has a mean depth of 50 m and a width (to the 200-m contour) of 80 km; hence the tsunami enhanced the existing natural oscillation of the whole continental shelf.

The time–frequency plot (Fig. 15a) showed the presence of the enhanced energy at the four-hour band (before the tsunami) and the increased energy along all frequencies (during the tsunami). After the tsunami, the energy at the higher frequencies decreased, however the energy at the four-hour frequency band continued (Fig. 15a). Similarly, oscillations at 2.7 hours (Figs. 15c and 15d) were seen at Jurien Bay and Fremantle. A decrease in the shelf width caused these decreased period (cf. Geraldton), whereas further south at Busselton, the increase in shelf width increased the fundamental frequency to four hours (Fig. 15d).

The time–frequency plot also indicated events that caused higher energy levels across all the frequencies, similar to what was observed during the tsunami, although the maximum energy was lower than it was during the tsunami. In Western Australia, these events occurred on 5–6 December 2004, 9–10 January 2005, and 19–20 January 2005 (Fig. 15). These periods coincided with the passage of pressure systems, which enhanced the onshore (westerly) winds at the site. These results confirmed the findings of Rabinovich and Stephenson (2004), who analysed sea-level records from the British Columbia coast and concluded that the oscillation periods identified from the sea-level records were related to the resonant properties of the local topography rather than the source characteristics and were the same as the background oscillations at each site.

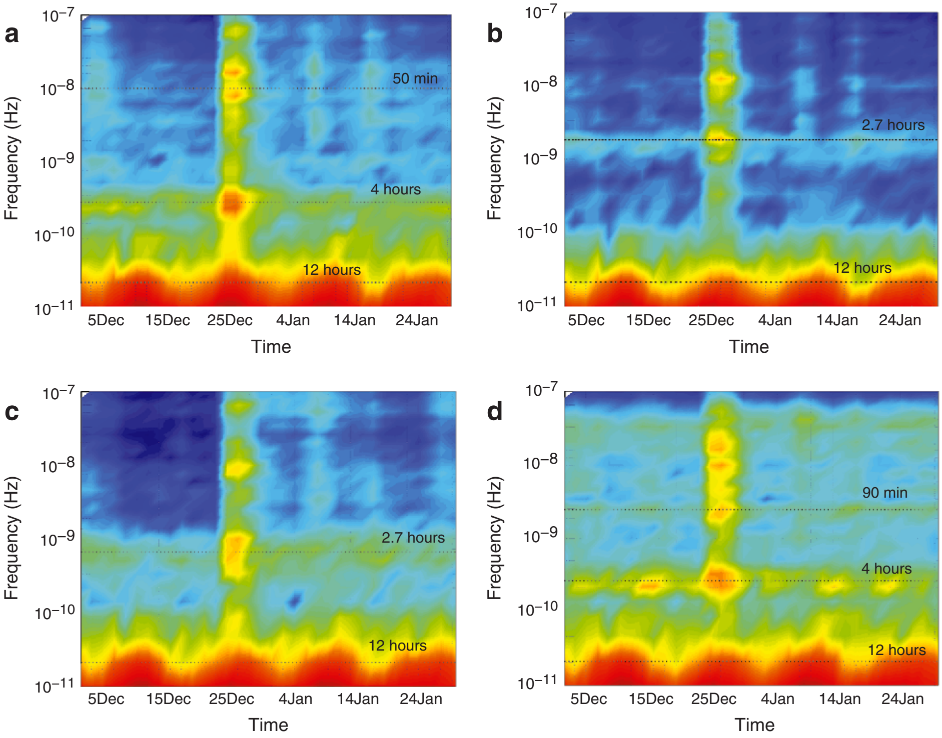


Figure 15

(a) Time–frequency plot of the tidal record from Geraldton for December 2004. (b) Time–frequency plot of the tidal record from Jurien Bay for December 2004. (c) Time–frequency plot of the tidal record from Fremantle for December 2004. (d) Time–frequency plot of the tidal record from Busselton for December 2004.

Thus the effect of the tsunami was to set up oscillations at the local resonance frequency. Because Sri Lanka and Western Australia have relatively straight coastlines, these oscillations were related to the fundamental period of the shelf oscillation. The actual nature of these oscillations in terms of standing or progressive edge waves trapped on the continental shelf (e.g., BRICKER *et al.*, 2007) was beyond the scope of this study.

6. Conclusions

Tide gauge data collected from Sri Lanka and Western Australia during five tsunamis—December 2004, March 2005, July 2006, and September 2007 (two tsunamis)—which occurred in the Indian Ocean, indicated that although the relative magnitudes of the tsunamis changed, the tsunami behaviour at each station was similar.

This was because the local and regional topography mainly controlled the tsunami characteristics at each station. Other major findings could be summarised as follows:

- At all stations in Sri Lanka and Western Australia, spectral energy corresponding to periods between 20 and 85 minutes increased during the tsunami.
- The sea-level data obtained from the west and south coasts of Sri Lanka (Colombo and Kirinda) indicated the importance of wave reflections from the Maldives Island chain, which produced the highest wave two to three hours after the first wave. In contrast, Trincomalee on the east coast did not show evidence of a reflected wave.
- Along the west coast of Australia, the highest waves occurred 15 hours after the arrival of the first wave. Here, based on travel times, we postulated that the waves were reflected from the Mascarene Ridge and/or the Island of Madagascar. Reflected waves were not present in the 2006 tsunami, in which the primary waves were propagated from topographic features.
- The effect of the tsunami was to set up oscillations at the local resonance frequency. Because Sri Lanka and Western Australia have relatively straight coastlines, these oscillations were related to the fundamental period of the shelf oscillation. For Colombo, this corresponded to the 75-minute period, whereas in Geraldton and Busselton (Australia), the four-hour period was most prominent; at Jurien Bay and Fremantle, the resonance period was 2.7 hours.

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