Tsunamis

A Large-Scale Earth and Ocean Phenomenon

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Tsunamis are surface gravity waves that are triggered due to perturbation of the ocean floor. The tsunamis that occurred in the Indian Ocean on 26 December 2004 were due to an earthquake off the coast of Sumatra. Sea level variations associated with this event are summarized after a brief introduction to tsunamis.

1. Introduction

On 26 December 2004, at about 9 am, many parts of the east coast of India experienced sudden changes in water level. As the waters rose, they moved inland with a ferocity unusual to the region to flatten structures that stood in their way. Fifteen to twenty minutes later, the waters receded, only to rise again some time later. Similar variation in sea level was noticed at different times and with different intensities at other coastal locations of the country: Car Nicobar in the Nicobar Islands, Port Blair in the Andaman Islands, along the southwest coast of India, etc. Similar behaviour was also noticed in parts of other south Asian countries: Sumatra in Indonesia, Thailand, Myanmar, Sri Lanka, and the Maldives.

The fluctuations in sea level observed along these coasts were due to a natural phenomenon rare in the region: the arrival of ocean waves known as tsunamis. The word tsunami is Japanese and means "harbour waves". The waves are also known as tidal waves and seismic waves. It turns out that none of these names is satisfactory. Tsunamis have very little to do with harbours or with tides, and are not always linked to seismic activity.

Keywords
Tsunami, shallow-water waves, earthquakes, sea-level, North Indian Ocean.

Tsunamis are a special class of surface gravity waves. This article first examines what surface gravity waves are, then discusses special features of tsunamis, including their generation, and finally examines the events of 26 December 2004.

2. Surface Gravity Waves

One of the most common sights seen from a beach, or from a ship in marine waters, or from a boat in a lake, is the undulation of the water surface. The undulations increase when the wind picks up, have a distinct wavy pattern, and are known as wind waves. They form a class of surface gravity waves distinct from the tsunamis. Wind waves are *deep-water waves* because they are normally found in waters that are deeper than half their wavelengths. The pattern associated with the waves moves with a phase velocity of 1-100 m/s, their wavelengths are in the range 1-1,000 m, and their periods vary from seconds to minutes. The waves are dispersive, i.e. their phase velocity depends on the wavelength. When the wind-wave field is weak (for example, when there are no breaking waves seen anywhere), the particle speeds associated with the motion due to the wind-wave field are much smaller than the phase velocity, and individual particles trace vertical circles. The size of the circle traced by a particle, as also its speed, decreases with depth, and beyond a certain depth, the motion associated with the wave decays to a negligible value.

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Wind waves are called surface gravity waves because the gravitational pull of the Earth plays an important role in their dynamics. In a motionless water body, the surface remains flat and in stable configuration. The action of the wind on the surface perturbs it from the equilibrium by introducing kinetic energy into the water body, and particles start moving. Earth's gravity pulls the water particles back towards equilibrium. In the resulting motion, the sum of the kinetic energy and potential energy due to gravitational pull of the Earth is conserved.

Another kind of surface gravity waves that occur in the oceans is called *shallow-water waves*. They are called so because they occur in waters that are shallower than half of the wavelength associated with the waves. The ocean, on average, is 4,000 m deep.

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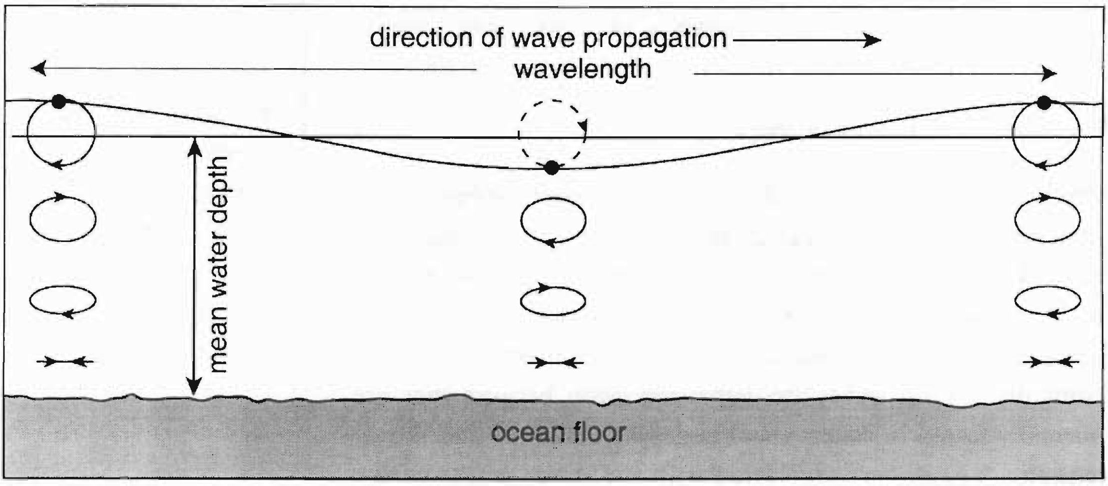

Figure 1. Particle motion in shallow-water waves, showing progressive flattening of orbits near the sea-bed (based on Figure 1.8(c) in [3]).

Hence, wavelengths associated with shallow-water waves are at least 8 km, but they can be as much as 1,000 km. The phase velocity of these waves is $\sqrt{gh}$, where g is the acceleration due to gravity (9.81 m/s^2) and h is the depth of water. As the phase velocity is independent of wavelength, these waves are non-dispersive. In the open sea, their phase velocity is about 200 m/s, i.e. about 750 km/hr. This is roughly the speed at which a jet aircraft normally cruises. The speed of particle motion associated with shallow water waves observed over the open sea is much weaker. For linear waves, it is of the order of $g\eta/\sqrt{gh}$, where η is the perturbation of the ocean surface. The particle motions associated with shallow-water waves are along ellipses (*Figure* 1). Unlike deep-water waves, the major axis of the ellipses associated with shallow-water water waves does not change with depth, and neither does the speed of the particles. In technical jargon, this kind of motion, in which the speed of the particle (the current) does not change with depth, is called *barotropic*.

The most common example of shallow-water waves observed in Nature are the waves due to tidal motion. They are generated by the gravitational pull of the Moon and the Sun. These motions have periods of about 12.5 hours and 24 hours. In the open sea, their wavelengths are in the range of 100-10,000 km.

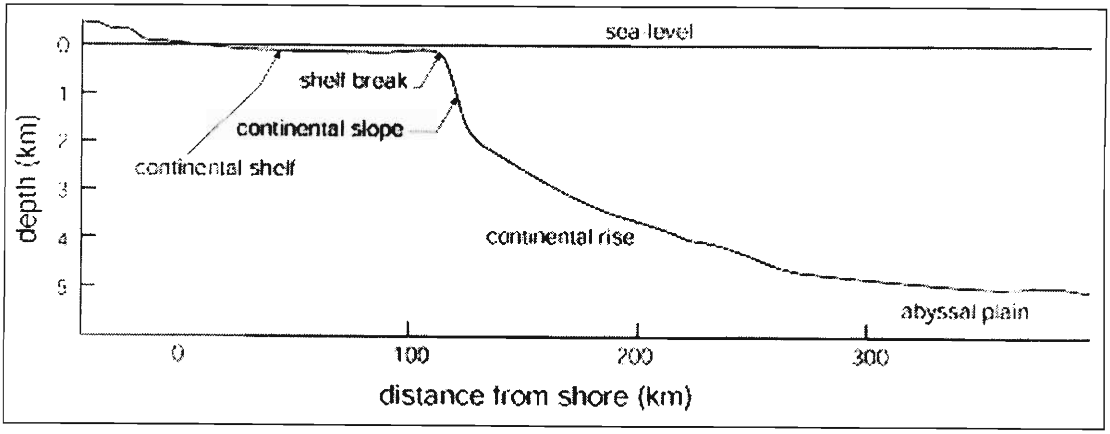

Figure 2. Typical variation of bottom topography in coastal areas (based on Figure 2.7 in [4])

3. Propagation of Tsunamis

Tsunamis over the open sea, i.e. in waters about 4,000 m deep, propagate as shallow-water surface gravity waves. They have typical periods of 100-3,000 seconds and wavelengths of 10-500 km. The surface perturbation due to these waves over the open sea is typically less than about half a metre, and particle velocities only a few centimetres per second. Such particle velocities and surface perturbations are much too insignificant for a passing ship to notice. Hence, tsunamis remain unreported while travelling in the open sea, unless special instrumentation specifically designed to look for them is in place.

As the waves propagate towards a coast, two changes take place: the depth decreases and so does the wavelength. Due to the decrease in depth, the energy in the water column has to be accommodated over a smaller height. *Figure* 2 gives the typical variation in water depth from the open sea to a coast. The shelf break in the Indian coastal region occurs at a depth of about 200 m. At this depth the wave energy that was earlier distributed over about 4,000 m of the water column has to be squeezed into 200 m. The decrease in depth also leads to a decrease in phase velocity and hence in wavelength. This means the wave energy also has to be accommodated over a smaller distance horizontally. The two effects, decrease in height and in wavelength, lead to a rapid increase in available mechanical energy per unit

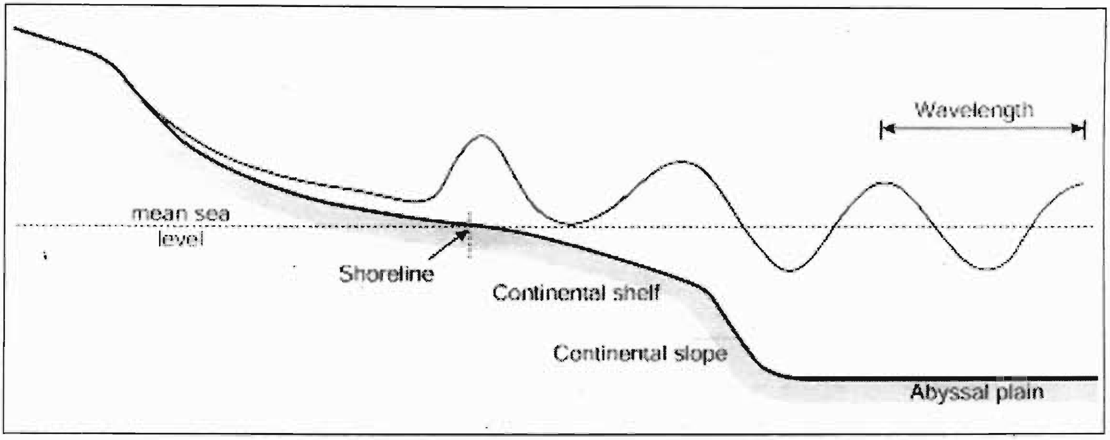

Figure 3. Transformation of a shallow-water wave as it approaches a shoreline (based on Figure 2.2 in [1]).

volume of water as it propagates towards shallow areas. In other words, the energy density of the tsunami wave increases.

The increase in energy density leads to a transition of the wave from its linear version to a non-linear state. *Figure* 3 provides a schematic of this transition, which is marked by a decrease in phase velocity and in wavelength, and by an increase in wave height and in particle velocity. According to the highly informative book *Tsunami* by E Bryant, about 60% of the increase in wave height takes place in the last 20 m depth change near the coast. Particle velocities near the coast reach a value of about 7 m/s (~ 25 km/hr). It is with such velocities that the waters associated with a tsunami move towards a beach. To an observer on the beach, the wave appears as a wall of water (in contrast to the spatially undulating surface seen in wind waves). As pointed out earlier, tsunamis have periods ranging from minutes to tens of minutes. The periods of the incoming waves determine how rapidly the waters on a beach will rise, peak, and recede, but only to rise again. This goes on generally for about 2-3 days (the largest amplitudes being on the first day) until the energy contained in the packet of tsunami waves is exhausted.

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4. Generation of Tsunamis

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There are three mechanisms that can lead to such a perturbation:

(a) earthquakes with epicenters located below the ocean floor can make the floor vibrate;
(b) mudslides on the ocean floor, particularly on the continental slope (*Figure* 2), can suddenly change shape of the ocean floor; and
(c) volcanic explosions, either on the ocean floor or on the nearby continent, can lead to shaking of the floor, or huge quantities of ash that accompanies an explosion can flow rapidly on the ocean floor.

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Each of the above perturbations of the ocean floor can lead to a perturbation of the ocean surface, which then propagates as a shallow-water wave.

As seen from *Table* 1, the generation of tsunamis from any of the above three causes is rather rare in the Indian and the Atlantic Ocean. The Pacific Ocean and its rim areas account for most of the tsunamis recorded so far. Accounts of tsunamis dating back to 4,000 years ago can be found in China and to 1,300 years in Japan (E Bryant [1]). In contrast, there seem to be no such accounts in India. In fact, a word equivalent to 'tsunami' does not seem to occur in any of the Indian languages.

Location	Percentage
Atlantic East Coast	1.6
Mediterranean	10.1
Bay of Bengal	0.8
East Indies	20.3
Pacific Ocean	25.4
Japan Russia	18.6
Pacific East Coast	8.9
Caribbean	13.8
Atlantic West Coast	0.4

Table 1. Percentage of occurrence of tsunamis in different locations of the world. (Source: [1])

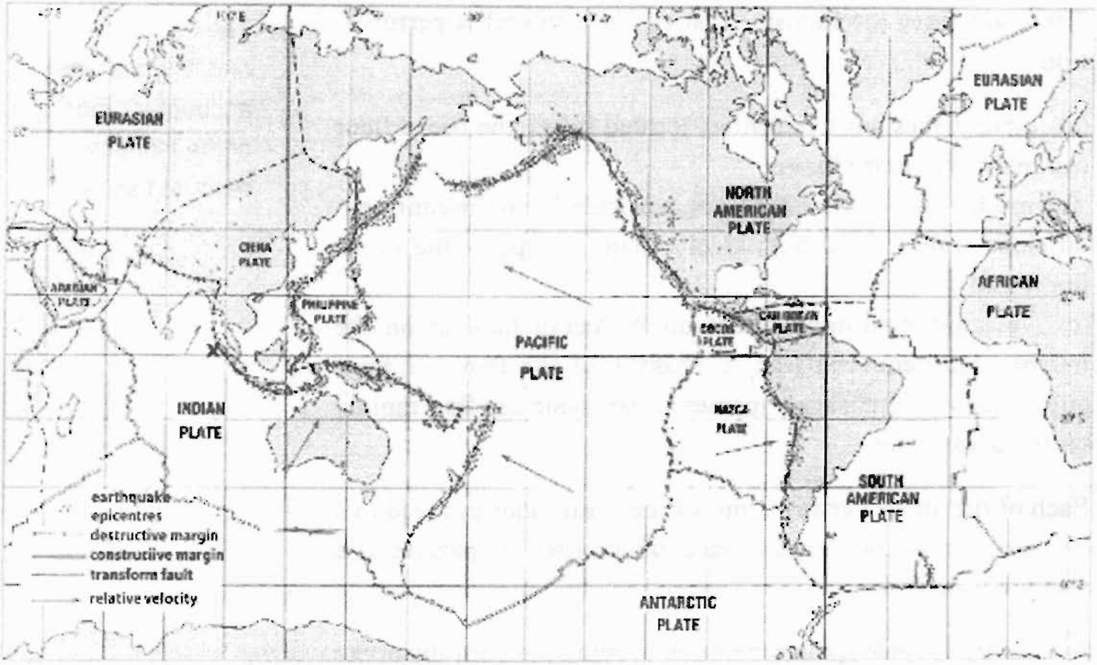


Figure 4. ***The 'cross' off the coast of Sumatra on the Indian Plate shows the location of the earthquake of 26 December 2004. The dots mark positions of past earthquakes. The meaning of other symbols is given in the lower left hand corner. (Based on Figure 2.1 in [4]).***

Of all the tsunamis that have been recorded in the Indian Ocean, about 80% have been triggered by earthquakes. Tsunamis are more frequent in the Pacific because earthquakes on the ocean floor are more frequent there. This is a consequence of plate tectonics and sea-floor spreading that determine the movement of continents on the surface of the earth through geological time scale (refer to earlier articles on this subject in *Resonance*[1]). Earthquakes on the ocean floor occur most often when an oceanic plate subducts under a continental plate. The entire rim of the Pacific experiences subduction of this sort and hence earthquakes on the ocean floor are common there. This has earned the rim the name *rim of fire*. This can be appreciated from *Figure* 4, which shows the distribution of earthquakes on the ocean floor and the boundaries of the plates that make up the Earth's continents and ocean floor. Note in this figure that there is a subduction zone along the eastern rim of the Indian Ocean.

[1] Ramesh Chander, Wegener and his theory of continental drift, *Resonance*, Vol.4, No.7, p.24, 1999.
A B Roy, Assembly and breakup of supercontinents, *Resonance*, Vol.4, No.7, p.42, 1999.

5. The Event of 26 December 2004

At 6.29 am (IST) on 26 December 2004, an earthquake measur-

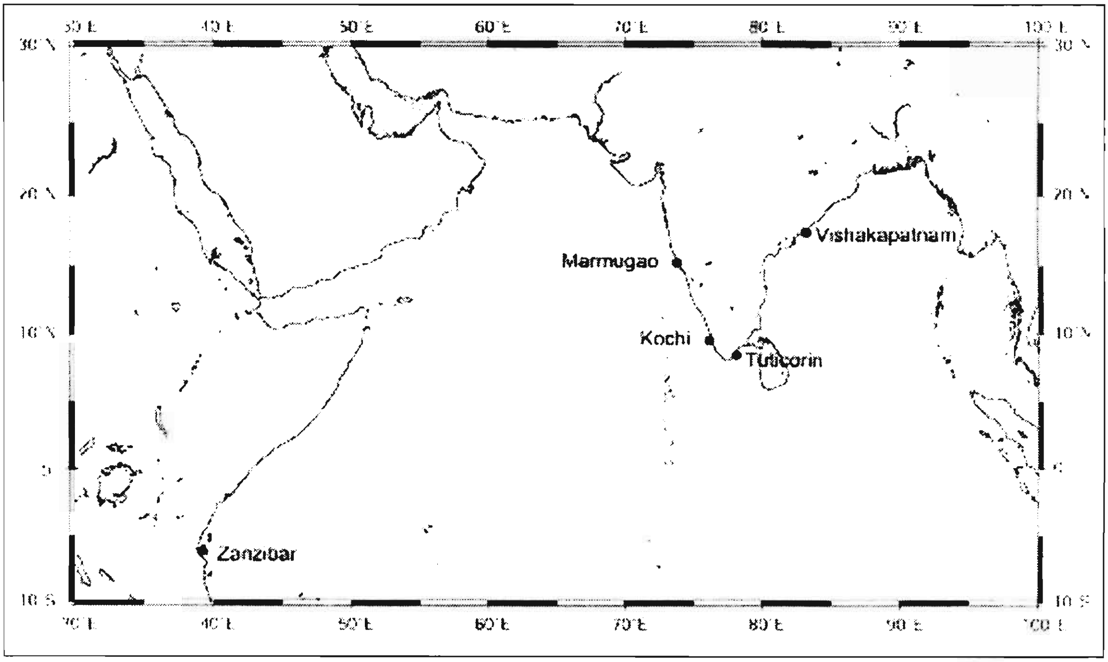


Figure 5. Location of the tide gauges whose data are shown in Figures 6a and b.

ing 9.0 on the Richter Scale occurred at latitude/longitude 3.4 N and 95.7 E off the coast of Sumatra, Indonesia (this location has been marked in *Figure* 4). The earthquake seems to have triggered some slumping of the ocean floor west of the Andaman and Nicobar chain of Islands. The earthquake and the slumping perturbed the ocean floor over a distance of about a thousand kilometers. This, in turn, perturbed the ocean surface, triggering a train of tsunamis that propagated outward from the region of their generation.

Signatures of the arrival of these tsunamis were recorded by tide gauges (water-level recorders) that are usually located in major ports. *Figures* 5 and 6 give the locations of the gauges and the sea level observed respectively, during 26-31 December 2004. Notice in *Figure* 6a that the normal tidal variation (oscillations with periods of 12.5 and 24 hours) are perturbed by tsunamis, which had periods of 20-40 minutes. The data from Indian locations are taken from the tide-gauge network of the Survey of India (see http://www. nio.org). Data from Zanzibar (*Figure* 6b) are from the website http://ilikai.soest.hawaii.edu/uhslc/iotd/.

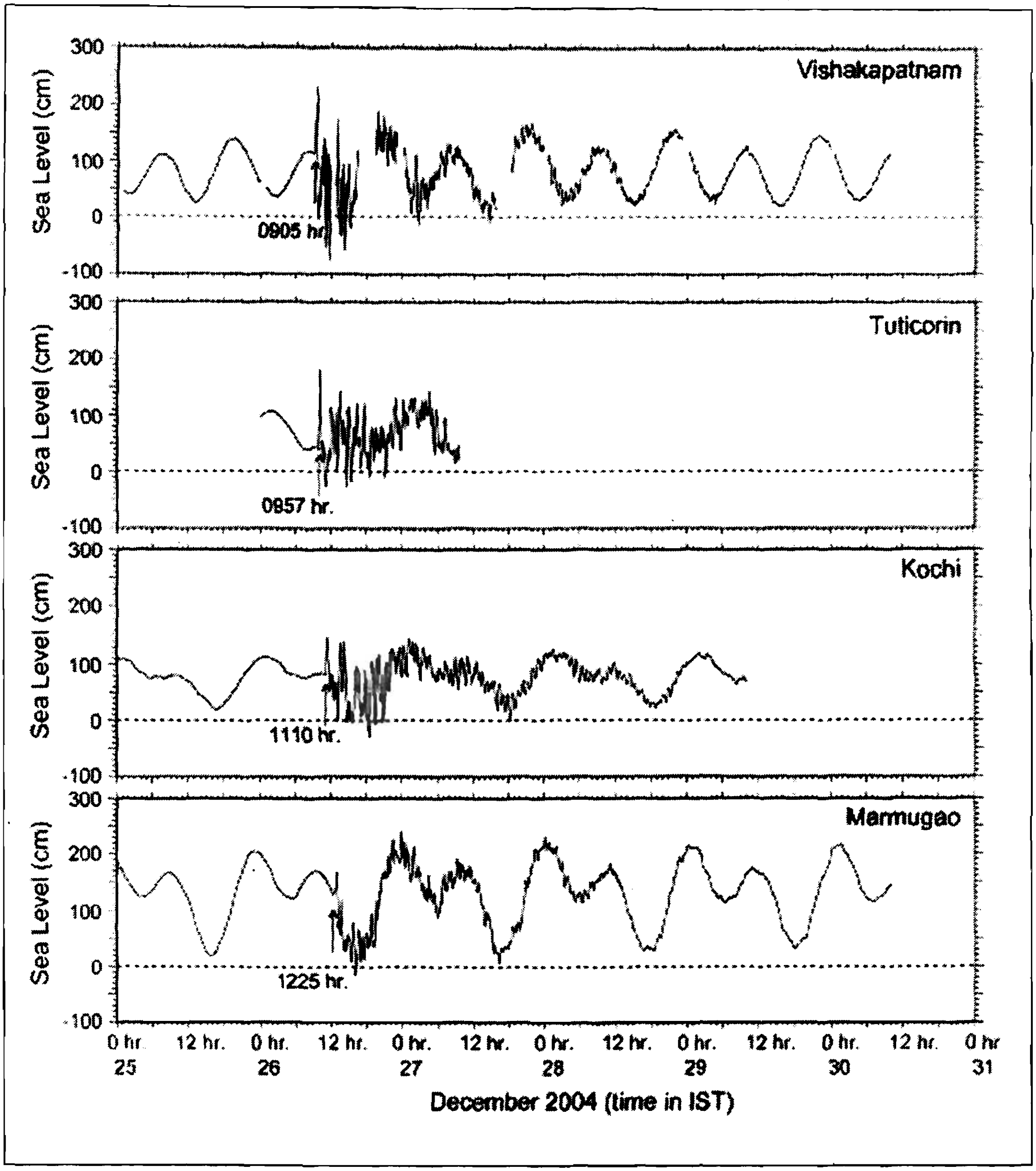


Figure 6a. Survey of India tide-gauge data from the Indian stations shown in Figure 5. The time marked with an arrow in each figure indicates the arrival time (Indian Standard Time) of the first of the tsunamis. These waves perturbed the sea level from the normal smooth variation seen due to tides. Note that the earthquake occurred at 0629 IST. (Source: www.nio.org)

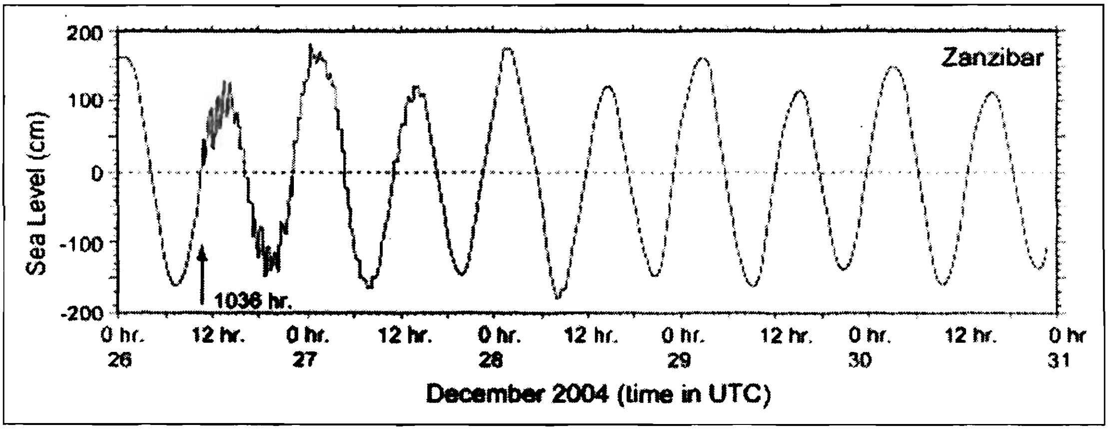


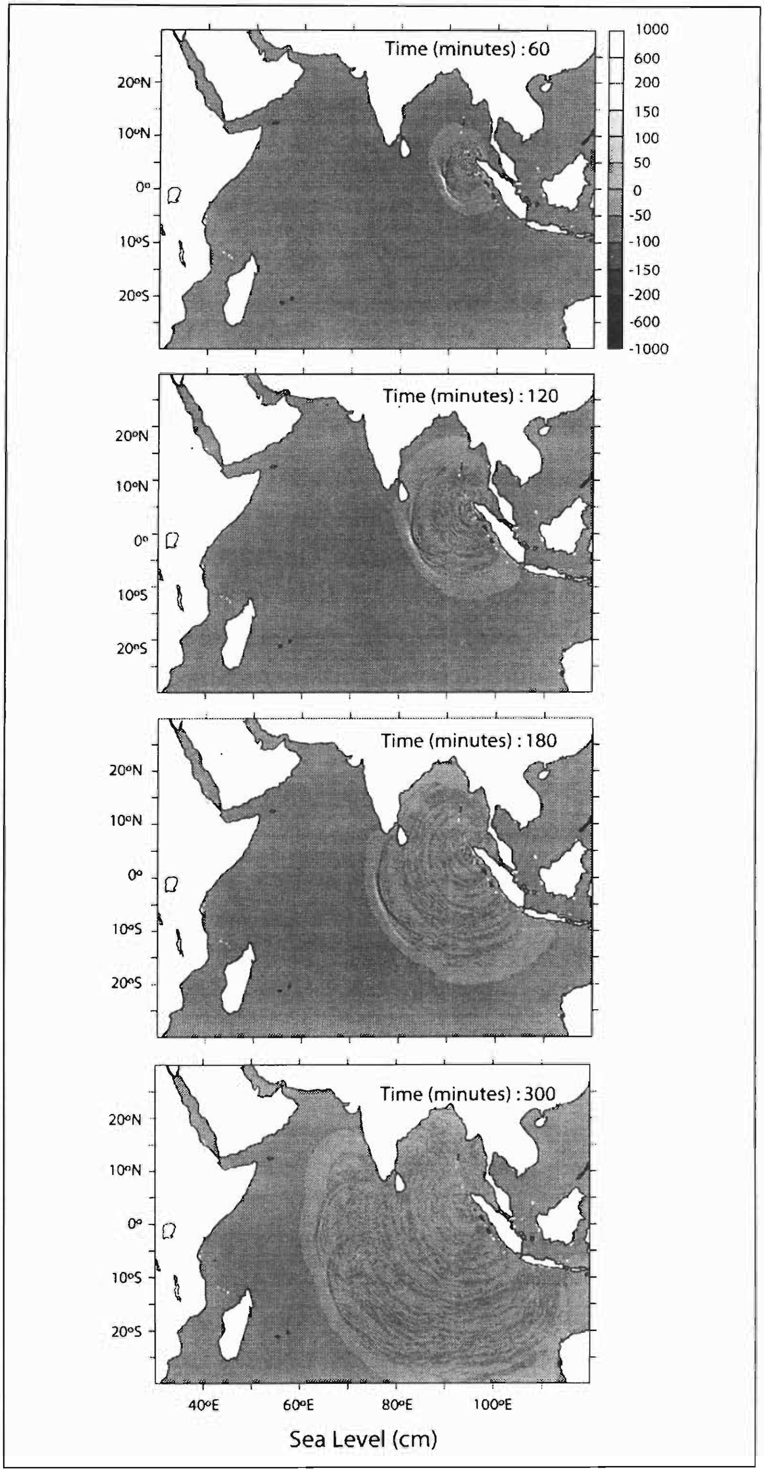
Figure 6b. Sea-level data from Zanzibar (see Figure 5) tide-gauge. The horizontal axis gives time in Universal Time which lags IST by 330 minutes. (Source: http://ilikai.soest.hawaii.edu/uhslc/iotd/)

The data in *Figures* 6a and b provide many interesting features of how the tsunamis propagated. Models of tsunami propagation help us to understand these features. One such feature is that the tsunamis reached the entire east coast of India more or less simultaneously, whereas along the west coast of India, the waves propagated from south to north, with increasing delay in arrival time from south to north. A numerical model developed by S Neetu and D Shankar at the National Institute of Oceanography does reproduce this feature. The model uses a code that was earlier used by Unnikrishnan *et. al.* [5] to study tides in the coastal waters of India. *Figure* 7 gives a few glimpses of the propagation of the sea-level perturbation due to the tsunamis. The model uses equations for shallow-water waves. In their simplest form these equations reduce to the following equation for the sea level perturbation, η:

$$\frac{\partial^2 \eta}{\partial t^2} - gh\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\eta = 0 ,$$

where t is the time and x and y are, respectively, eastward and northward distance. This equation is well known and represents propagation of many kinds of waves including optical waves. As in the optical waves, the shallow-water waves can reflect, refract, and get trapped. In the above equation depth plays a role analogous to refractive index in optical waves. It is through such

Figure 7. ***Propagation of tsunamis as simulated in a model developed by S Neetu, AS Unnikrishnan, D Shankar, and others at the National Institute of Oceanography, Goa. The grey-scale at the upper right-hand corner gives sea level perturbation in centimeters.***
(Source: www.nio.org).



processes of reflection, refraction, and trapping that the tsunamis reached the west coast of India and propagated northward. These processes also help us understand why some areas received a higher dose of energy from the tsunamis, whereas others escaped unhurt.

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6. Epilogue

It turned out that the Great Earthquake and the accompanying Tsunami of 26 December 2004 is the largest killer tsunami on record. As of now, the number of dead have been put at more than 2,50,000. This is indeed a devastating loss. It has occurred in a region where the frequency of tsunamis is small, because of which no warning system exists in the region. The only ocean that has a tsunami warning system is the Pacific. The Great Tsunami, though an event with a low probability of occurrence, was a high-impact event. One cannot but compare this event with what happened in 1755 along the east coast of the North Atlantic, another low-probability location for the occurrence of tsunamis. That year, one of the largest earthquakes ever was recorded near Lisbon, Portugal, setting off huge tsunamis and causing devastation along the east coast of the Atlantic. As in 1755, in 2004 Nature once again asserted its complexity through a low-probability but high-impact event.

Suggested Reading

[1] Edward Bryant, *Tsunami: The Underrated Hazard*, Cambridge University Press, Cambridge, UK, 2001.

[2] Walter Dudley and Min Lee, *Tsunami!*, University of Hawaii Press, Honolulu, USA, 1998.

[3] The Oceanography Course Team, *Waves, Tides and Shallow-Water Processes*, The Open University, UK, 1994.

[4] The Oceanography Course Team, *The Ocean Basins: Their Structure and Evolution*, The Open University, UK, 1994.

[5] A S Unnikrishnan, S R Shetye, and G S Michael, Tidal Propagation in the Gulf of Khambat, Bombay High, and Surrounding Areas, *Proc. Indian Acad. Sci.* (Earth Planet. Sci.), Vol. 108, No.3, pp.155-177, 1999.

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