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The Indian Ocean Disaster: Tsunami Physics and Early Warning Dilemmas

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Understanding the physics of tsunamis may save lives, especially near the epicenter of a large earthquake where the danger is highest and early warning is least likely to be effective.

Normal modes of Earth are standing waves of the Love (toroidal) or the Rayleigh (spheroidal) variety. The Indian Ocean tsunami may have been partly or wholly caused by low-order spheroidal modes of the Earth such as ${}_0S_2$, ${}_0S_3$, and ${}_0S_4$, that may have excited a waveguide—a layer that confines and guides a propagating wave—in the ocean.

The Indian Ocean tsunami of 26 December 2004 caused an estimated 250,000 or more deaths and extensive damage due to run-up, landward inundation, and wave-structure interactions. Scientists are developing three-dimensional numerical models, which include coastal run-up and overland flow. However, the tectonic motion of the seabed, which is believed to be responsible for generating the tsunami waves in the first place, cannot be derived reasonably from the available seismic data. The seismic rupture occurred at more than 20 km depth and did not break the surface. The parameters of models of tsunami generation must be inferred from geodetic deformations onshore. It is easy to see why early warning is, so to speak, on shaky ground.

The Indian Ocean tsunami was attributed to an impulsive upheaval of the ocean floor by up to 10 meters. A back-of-the-envelope calculation shows that the kinetic-to-potential energy ratio is $R = V^2/(2gh)$, where V is the velocity, h is the elevation of the bulge, and g is the acceleration of gravity [see, e.g., *Feynman*, 1963]. But near-field peak ground accelerations in large subduction earthquakes are mostly around 0.25 g. Such low values suggest $R < 0.001$, and possibly as low as 10^{-6}. Thus, the assumption of an impulsive source could overestimate the kinetic energy by a factor of up to a million. "All numerical studies...must make valid assumptions on the correlation of the initial water displacements to tsunami wave length and period regardless of the generative mechanism" [*Pararas-Carayannis*, 2002].

BY C. LOMNITZ AND S. NILSEN-HOFSETH

Could the Tsunami Have Been Caused by Spheroidal Normal Modes?

What other sources of kinetic energy are there for this event? One is the earthquake itself. Large earthquakes can excite free oscillations, much as a hammer blow can excite the normal modes of a bell [*Lognonné and Clévédé*, 2002; *Stein and Wysession*, 2003]. The wavelengths are comparable with the circumference of the planet.

Can spheroidal normal modes of Earth generate water waves? Toroidal modes do not alter the shape of the Earth, but spheroidal modes do (Figure 2). They excite ionospheric oscillations [*Lognonné et al.*, 1998; *Artru et al.*, 2001] and oscillations of the seafloor [*Suda et al.*, 1998; *Rhie and Romanowicz*, 2004]. They cause the epicentral region to move up and down in the gravity field. The vertical component is in phase only at the epicenter.

Large subduction earthquakes are known to generate a significant fraction of their total energy (estimated at 1.1×10^{17} Nm in the Sumatra earthquake) in low-order normal modes of the Earth. *Gower* [2005] found a

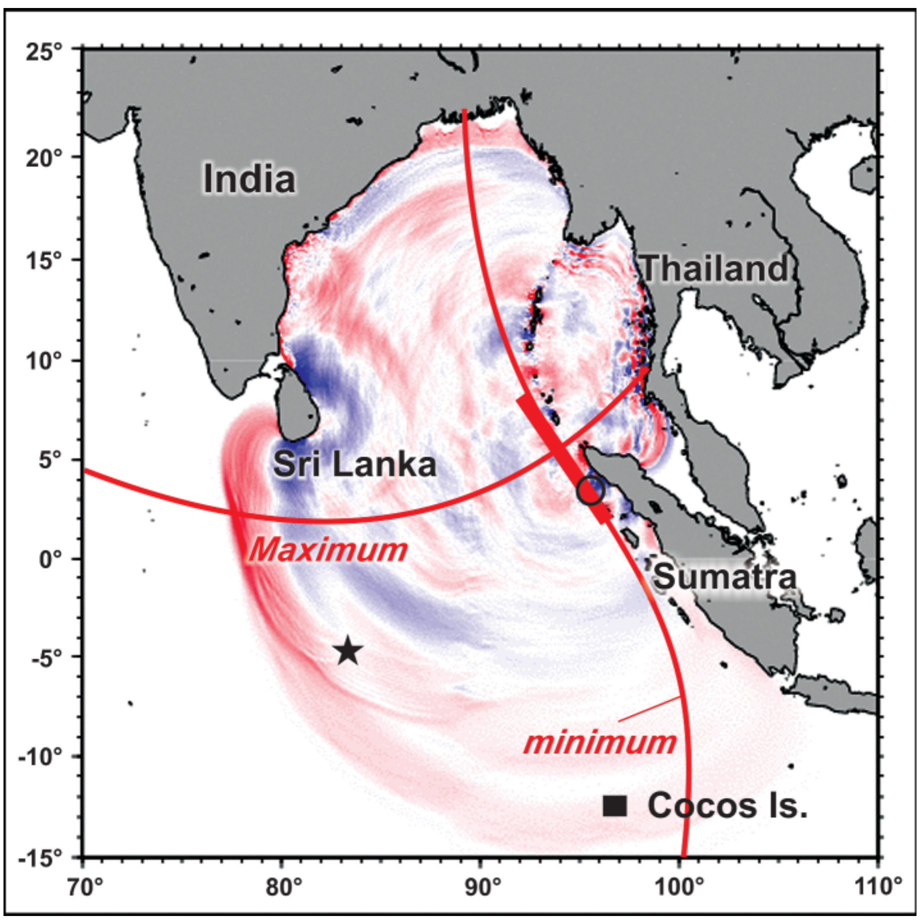

Fig. 1. The Indian Ocean tsunami of 26 December 2004. The map shows nodal lines of maximum and minimum tsunami intensity, assuming a waveguide propagation in the ocean. Star indicates initial location of the Jason 1 altimetry pass (see article). Base map courtesy of the U.S. National Oceanic and Atmospheric Administration.

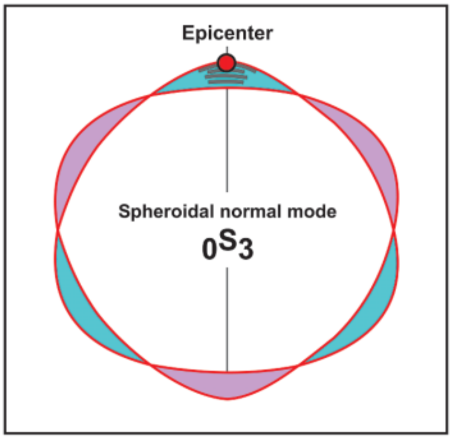

Fig. 2. Spheroidal normal mode $_0S_3$. The amplitude of the mode is greatly exaggerated.

period of t = 37 minutes for the leading tsunami wave from Jason 1 satellite altimeter observations (Figure 1). This value of t matches the period of normal mode $_0S_3$. The signature of normal modes should also be detectable in tide-gauge records. Unfortunately, the available recordings use a sampling interval of 6 minutes. As the lowest normal mode has a period of 54 minutes, there are less than 9 sample points per cycle. No near-field tide-gauge records are available, and stations in California had small amplitudes (Figure 3). Higher-order spheroidal modes suffered from aliasing.

Nevertheless, Fourier amplitude spectra of tide-gauge records at Jackson Bay, New Zealand and other far-field stations (Figure 3) show some significant maxima at frequencies near 0.31 and 0.46 mHz, corresponding to the frequencies of the two lowest-order spheroidal modes [*He and Tromp*, 1996]. These observations cannot be explained by bulge formation in the ocean floor.

The tide-gauge station at Cocos Island at a distance of 1754 km south of the epicenter (Figure 1) may have been close to a nodal line of the tsunami (see below). The peak-to-trough amplitude was only 42 cm even when the town of Galle in southern Sri Lanka, roughly at the same distance, was destroyed.

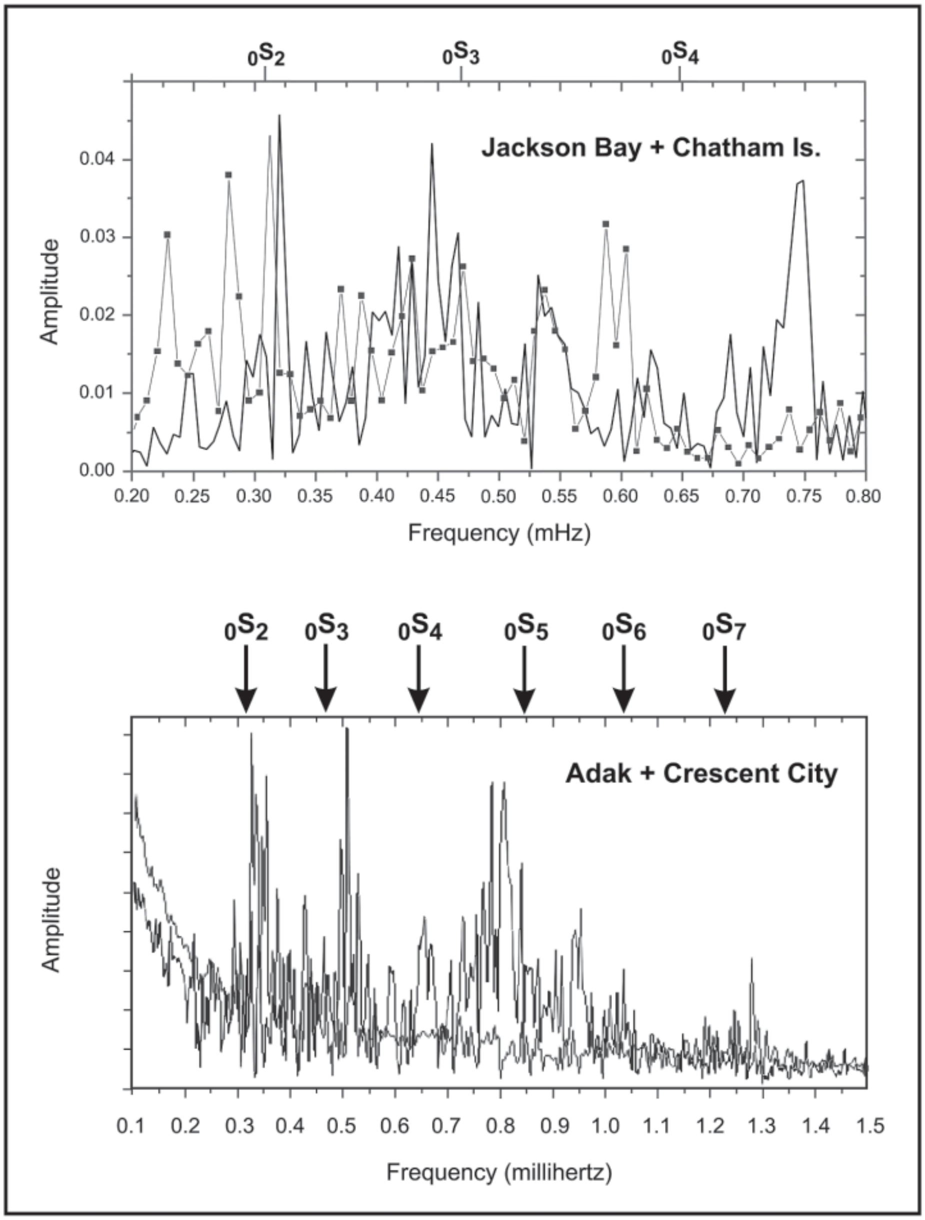

Fig. 3. Fourier amplitude spectra of tide-gauge records of the Indian Ocean tsunami. Top: Jackson Bay and Chatham Island (marked), New Zealand. Bottom: Adak, Alaska, and Crescent City, California.

Could the Tsunami Have Propagated in a Waveguide?

Tsunami waves are assumed to propagate as solitons, or nonlinear solitary waves, over distances of thousands of kilometers. But their wavelength is much greater than the depth of the ocean, so there should be significant bottom friction. Propagation across the Indian Ocean was strongly directional (Figure 1). Along-trench paths from Sumatra produced very small amplitudes, as at Cocos Island or the coast of Bangladesh, yet the ocean-floor bulge would have followed the trend of aftershock occurrence, parallel to the Sumatra coast.

An alternative, greatly simplified explanation for efficient tsunami wave propagation may be derived from waveguide theory. The canonical waveguide in the oceans is well known since World War II [*Ewing et al.*, 1957]. It is modulated by internal waves caused by small horizontal density variations [*Pond and Pickard*, 1978].

Internal waves may thus form a diffraction grating similar to the anomalies discovered in 1902 by Robert W. Wood (1868–1955). Wood's anomalies can enable a waveguide to trap and propagate selected modes [S. Nilsen-Hofseth and C. Lomnitz, Mexico City, San Francisco: Truant modes, resonant Wood's anomalies, and the physics of earthquake damage, manuscript in preparation, 2005]. This mechanism could enable a waveguide in the ocean to trap and transmit tsunami energy at minimal dissipation. Because internal waves are produced by tidal currents flowing over the sloping seafloor, and the gradients tend to slope normal to the coast, such a mechanism will be directional normally to the trench (Figure 1).

It is concluded that available observations of the Indian Ocean tsunami may be compatible with a physical mechanism of causation and propagation involving coupling to the vertical components of low-order spheroidal normal modes. The observed frequency content of tsunami waves suggests that most of the energy may be due to the two lowest-order normal modes, $_0S_2$ and $_0S_3$. The low dissipation and the directionality of tsunamis may be attributable to waveguide propagation.

Could Early Warnings Be Made More Reliable?

Independent of whether these new ideas are ultimately proved correct, a revision of the logic of early tsunami warning is overdue. When scientists were first alerted that a M 9.0 earthquake had occurred on Sunday, 26 December 2004 at 0058:49 UTC off the west coast of northern Sumatra, they had no way of knowing that it had generated a devastating tsunami. According to news reports, "scientists do not have the tools to tell when an earthquake has created a tsunami" [*Kayal and Wald*, 2004]. The *U.S. Geological Survey* [2004] has stated that "the only way to know for certain if a tsunami has been generated is to directly measure the height and propagation of the ensuing wave."

A warning strategy based on tide-gauge readings in the path of the tsunami is unsatisfactory. After the waves have hit the coast, it is too late to warn the population. Advance warning can be effective in Hawaii or Japan, where local alert systems are operational; but, in general, tsunami diagnosis should not depend on sea level readings taken while a disaster is in progress.

Better tsunami physics is the answer. The 2004 Sumatra earthquake was the largest earthquake recorded anywhere since 1964. Every seismic station should have the means to detect whether such an earthquake has generated low-order spheroidal modes, especially ${}_0S_2$ and ${}_0S_3$. Observations can be made within minutes. In principle, a tsunami alert could be issued from any seismic station.

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Unveiling the Mystery of North Pacific Intermediate Water Formation

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How were the sources of the subtropical North Pacific Intermediate Water (NPIW), which has a core density of $26.8\sigma_\theta$, formed in the subpolar region, given that the maximum surface density in the late winter (density reaches a maximum in March due to successive cooling through the winter) of the entire North Pacific is only $26.5\sigma_\theta$? How, then, did these sources cross the broad subarctic-tropical frontal zone (SATFZ) (which is about 800 km in width and has predominantly eastward flowing currents) and enter the subtropical gyre southward, forming the NPIW? These questions have been addressed recently. This article provides an update.

The previously conjectured pathway (a path of NPIW's source water en route to the subtropical gyre from the formation region, the Okhotsk Sea) was a shortcut directly from the western subpolar gyre into the subtropical gyre. Such a pathway required an isopycnal (along a constant density surface) salinity minimum that is not found immediately south of the SATFZ in the northwestern subtropical gyre.

The newly proposed pathway follows a lengthy transpacific path, and enters the subtropical gyre from the northeastern North Pacific. The new pathway is dynamically consistent with the gyre circulation and distribution of NPIW.

By Y. You

North Pacific Intermediate Water, an intriguing class of intermediate water in the world oceans, is confined only to the subtropical gyre of the North Pacific Ocean, and has a narrow density range of about 26.7–$26.9\sigma_\theta$ [*Sverdrup et al.*, 1942; *Reid*, 1965; *Talley*, 1993]. Unlike the Antarctic Intermediate Water (AAIW), whose core density outcrops at its formation region near Antarctica, the NPIW's core density of $26.8\sigma_\theta$ is not found in the winter surface density of the entire North Pacific. This suggests that NPIW is not formed by open-ocean convection in winter but instead by slow interior processes.

AAIW is characterized by a salinity minimum tongue (34.0–34.4) coincident with a distinct oxygen maximum tongue (240–280 μ mol kg^{-1}) reminiscent of the last contact with the atmosphere in the formation region. However, NPIW has no oxygen maximum tongue; instead it is characterized by a rather low oxygen core of about 130 μ mol kg^{-1} with strong stratification, which suggests a different formation mechanism. This unventilated nature of NPIW formation is the reason why some usually effective chemical tracers, such as chlorofluorocarbons

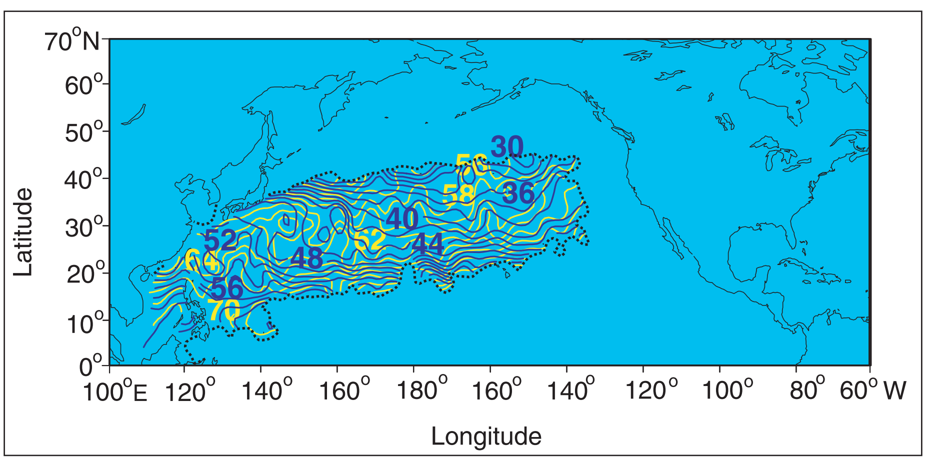

Fig. 1. Water-mass age (years) on the neutral density surfaces $\sigma_N = 26.5$ (blue curve) (in the upper boundary of North Pacific Intermediate Water; NPIW) and $\sigma_N = 26.9$ (yellow curve) (at the NPIW core). Dotted curve marks the subtropical extent of NPIW. Adapted from You *[2003b, Figure 3f].*