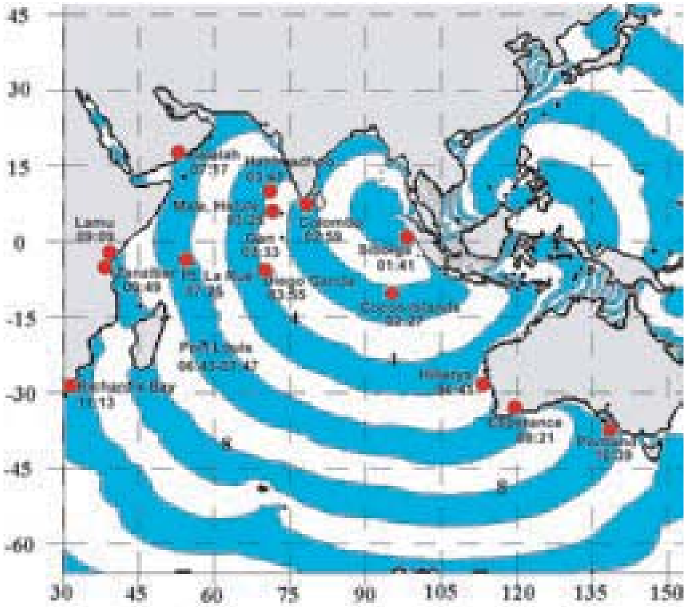
OFF NORTHERN SUMATRA, M_W=9.0, 26 DECEMBER 00:59 UTC



Above: Tsunami travel time map for the 26 December 2004 Indian Ocean Tsunami. Contour interval and color change every hour. The red dots show the locations of sea level stations which measured the tsunami in the Indian Ocean along with the observed tsunami travel time to each station.

Data from Tide Gauge Observations of the Indian Ocean Tsunami, December 26, 2004, Geophysical Research Letters, 32, L090603, doi:10.1029/2005GL022610; M. A. Merrifield, Y. L. Firing, G. Brundrit, R. Farre, B. Kilonsky, W. Knight, L. Kong, C. Magori, P. Manurung, C. McCreery, W. Mitchell, F. Shillington, E. M. S. Wijeratne, P. Caldwell, J. Jardin, S. Nakahara, F.-Y. Porter, and N. Turetsky.

Below: Arrival times correspond respectively to 1) the first change, and 2) the crest of the 1st wave, in hours:minutes, December 26, 2004 (UTC) (exceptions: at Belawan, Sibolga, Lembar, and Prigi, times correspond to the first trough and first crest; Rodrigues station was destroyed and time corresponds to the last transmitted data; Port Louis time range corresponds to the data gap), with the parenthesized number representing the sample rate in minutes. Travel time is the difference between the time of the earthquake (00:59 UTC) and the time of the arrival of the first crest (or trough). Absolute height is the height of the first crest above the mean for each station. Non-tidal height is the height above the mean when a tidal fit has been removed. Heights in parentheses correspond to the largest measured crest (when the the first was not the largest), and Max. time is the corresponding time (hours:minutes, December 26, 2004, UTC).

Tsunami Characteristics at Indian Ocean Stations

Station	Arrival time	Travel time	Absolute height (m)	Non-tidal height (m)	Max. time
Belawan	01:40, 03:30 (10)	00:41	0.23(1.30)	0.51(0.93)	09:30
Sibolga	02:40, 03:10 (10)	01:41	0.28(1.21)	0.43(1.32)	06:50
Lembar	03:20, 04:00 (10)	02:21	-0.24(1.02)	0.15(0.25)	15:10
Cocos Islands	03:17, 03:26 (1)	02:27	0.03	0.33	
Colombo	03:52, 03:58 (2)	02:59	1.92	2.17	
Prigi	04:10, 04:30 (10)	03:11	0.05(0.74)	0.15(0.28)	11:20
Hulule, Male	04:16, 04:24 (4)	03:25	1.42	1.46	
Panjang	04:29 (30)	03:30	-0.01(1.02)	0.11(0.45)	12:59
Gan	04:20, 04:32 (4)	03:33	0.80	0.88	
Hanimaadhoo	04:32, 04:40 (2)	03:41	1.83	1.71	
Diego Garcia	04:48, 04:54 (6)	03:55	0.34	0.56	
Rodrigues	06:40+ (2)	05:41+			
Hillarys	07:28, 07:40 (1)	06:41	0.41(0.87)	0.35(0.57)	10:25
Port Louis	07:42-08:46 (4)	06:43-07:47	(1.66)	(1.45)	09:26
Salalah	08:12, 08:16 (4)	07:17	-0.28(0.74)	0.28(1.64)	10:04
Pt. La Rue	08:16, 08:24 (4)	07:25	0.61(1.18)	1.09(1.58)	09:12
Esperance	08:57, 09:20 (1)	08:21	0.08(0.03)	-0.01(0.26)	22:25
Lamu	09:56, 10:08 (4)	09:09	-0.23(0.35)	0.28(0.50)	10:44
Zanzibar	10:44, 10:48 (4)	09:49	0.31(-0.79)	0.29(0.32)	18:12
Portland	10:48, 11:38 (1)	10:39	0.17(0.46)	0.17(0.58)	26:32
Richard’s Bay	12:03, 12:12 (3)	11:13	0.69(0.74)	0.16(0.79)	17:24
Port Elizabeth	13:21, 13:27 (3)	12:28	1.03(1.07)	0.26(1.81)	19:18

Sumatra, *continued.*

PTWC SPEAKS OUT AFTER 26 DECEMBER 2004 TSUNAMI

To put it simply ... "On 26 December 2004, there was no tsunami warning system in the Indian Ocean." Specifically, there was no warning center, inadequate regional seismic networks, no network of remotely reporting sea level gauges, no designated national authorities for tsunami warnings, no communications methods to reach potential authorities, no tsunami-educated emergency managers or local tsunami experts, no communications to disseminate warnings to coastal regions at risk, and painfully little tsunami awareness.

On that quiet afternoon of Christmas Day in Ewa Beach, Hawaii, the three PTWC staff who responded were confronted with an extraordinary event off northwestern Sumatra, Indonesia—one which evolved over hours and the next days to result in the world's worst tsunami catastrophe. The casualties and destruction occurred across the Indian Ocean basin, striking Indonesia then Thailand, Sri Lanka, India, and the Maldives, and then Somalia, northeastern Africa eight hours afterward. Altogether, it is estimated that nearly 250,000 people lost their lives in the great earthquake and ensuing tsunami, and it was these circumstances that immediately bolted the world's leaders on 6 January 2005 to call for the establishment a tsunami warning system to protect against this fatal, though infrequent hazard.

The following is a Comment by PTWC that was published in the American Geophysical Union's EOS weekly newspaper in July, 2005. Tsunami warnings are just one part of what must be in place to enable an effective tsunami response that will move people out of harm's way before the tsunami's arrival.

Comment on "A Strategy to Rapidly Determine the Magnitude of Great Earthquakes" by W. Menke and V. Levin

by S. A.Weinstein, C. McCreery, and B. Hirshorn,
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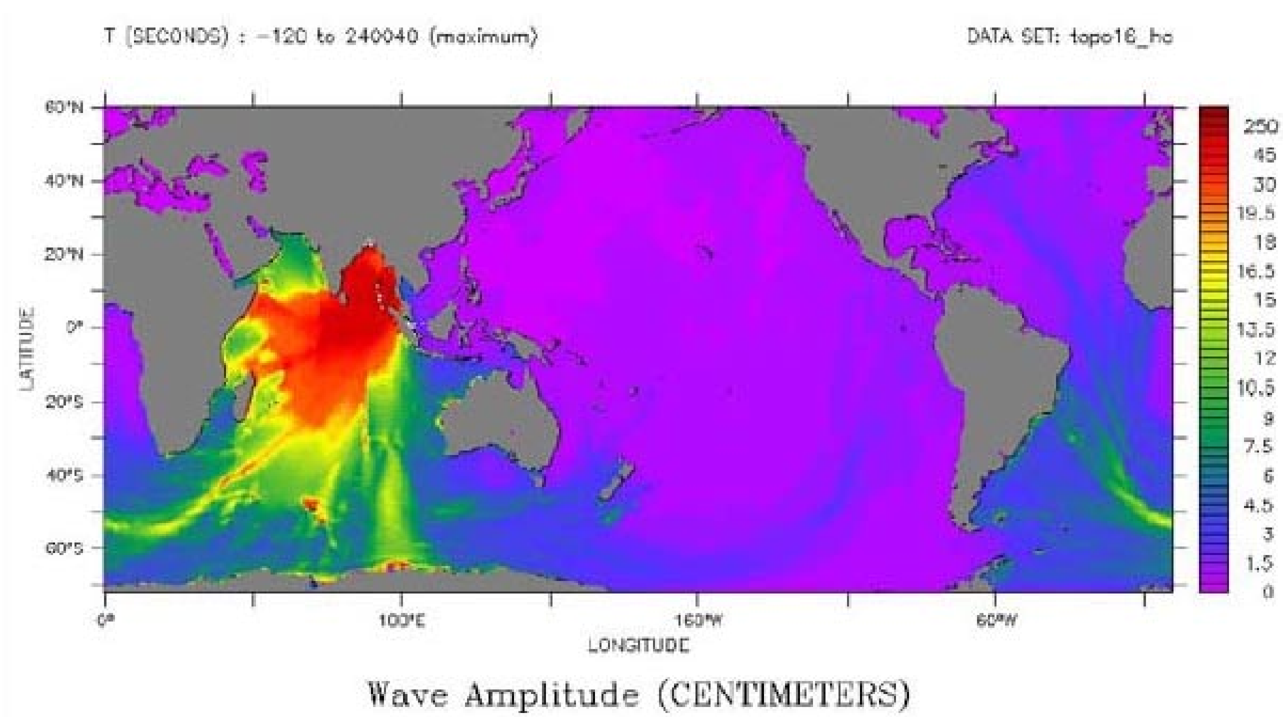
Eos, 86:28 (12 July 2005) p. 263-264.

We appreciate W. Menke and L. Levin's comments (*Eos, 86:19 (10 May 2005), p.185+,*) on the need to develop new seismological techniques to more accurately determine the magnitude of great earthquakes quickly. However, in the first few paragraphs, Menke and Levin suggest that the many thousands of people died because an accurate assessment of the true nature of the 26 December 2004 Sumatra earthquake was not known within the first hour after it occurred. Although this may serve as a wake-up call to seismologists on the importance of better and more rapid magnitude estimation procedures, it should not be used to obscure the most urgent need, which is to establish an effective global tsunami warning system.



Maximum calculated global wave heights (cm) from the December 26, 2004 Indian Ocean tsunami. Waves were recorded on sea level gauges in Antarctica, and along the coasts of South and North America and Canada in both the Pacific and Atlantic Oceans. (NOAA Pacific Marine Environmental Laboratory)

Sumatra, *continued.*

Photo Mosaic of Banda Aceh, Indonesia

The primary reason many thousands of lives were lost in the Sumatra tsunami is that there was no tsunami warning system for the Indian Ocean. Rather than focusing on the failure of seismologists to accurately estimate the magnitude of the 26 December earthquake, we should understand that what the world needs to prevent another tsunami tragedy on this scale is, first and foremost, a global tsunami warning system. Faster seismological techniques for more accurate magnitude estimation and source characterization will certainly help the warning system. However, such improvements will be of little benefit to nations or regions where there is still no tsunami warning system.

In the aftermath of the Sumatra tsunami, there was considerable confusion about what exactly a tsunami warning system is. Many people still seem to believe that warning centers themselves are the warning system. This is a misconception that we are trying to dispel.

A successful warning system is composed of three main components: tsunami hazard and risk assessment, warning guidance, and preparedness. Each component must be functioning; otherwise the system collapses.

Warning centers are the trip wires; the centers' responsibilities include determining the location and magnitude of an earthquake as quickly as possible, evaluating potential tsunami threat, issuing message products, and monitoring sea level gauges for evidence of tsunami activity.

Emergency managers evaluate warning center message products (with the help of local tsunami advisors, when possible), plan evacuation routes and shelters, and develop a communications system to alert the public to a tsunami emergency.

Tsunami awareness also is vital. The public needs to be educated about what actions to take to save their lives during a tsunami emergency. For example, if you are near the shore and feel a strong earthquake, you should immediately head inland and/or uphill. Likewise, a proper understanding of some basic properties of tsunamis and their causes can save lives, even in the epicentral region. One sure sign of an approaching tsunami is the ocean draw-down, i.e., when the ocean recedes in an unnatural way.

How would the Pacific tsunami warning system react if a 26 December type event were to occur in the Pacific Basin? With an initial Mw estimate of 8.0, and based on predetermined conservative criteria, the U.S. National Oceanic and Atmospheric Administration's Richard H. Hagemeyer Pacific Tsunami Warning Center (NOAA PTWC) and the agency's West Coast/Alaska Tsunami Warning Center would issue warnings, watches, and advisories to their respective clients in the Pacific.

(NOAA's tsunami warning centers work with a number of U.S. agencies, including the U.S. Geological Survey and other NOAA organizations. Internationally, the warning centers work with Australia's National Tidal Center, Chile's Servicio Hidrográfico y Oceanográfi co de la Armada, the Japan Meteorological Agency, and other organizations. Through such collaborations, NOAA's warning centers obtain the information needed to provide timely tsunami threat warnings.)

To provide timely warnings, the earthquake must be evaluated as fast as possible. Warning centers understand that evaluating the first 100 seconds of signal may not indicate the size of a great earthquake with a rupture time of several hundred seconds.

IKONOS satellite images before and after the tsunami over Banda Aceh, northeast tip of Sumatra island, Indonesia. The coastal plain was fully inundated, all vegetation stripped and mud and sediment deposited. Some area still remain flooded 3 days after the event when this image was taken. The region was formerly used for aquaculture, settlements, and agriculture.

Sumatra, *continued.*

However, the initial estimate can be used to determine if an earthquake is over a warning threshold.

Had the 26 December event occurred in the Pacific, all regions within three hours of tsunami travel time would have been placed in a tsunami warning status based on the initial determination of an M_W of 7.9 or greater. More limited regional warning bulletins are issued for earthquakes in the Pacific with an M_W as small as 7.55, and local warnings are issued for earthquakes with an M_W as small as 6.8.

Although destructive tsunamis resulting from an earthquake with an M_W as small as 6.8 are extremely rare, they are not impossible. For example, such an earthquake could potentially trigger landslides, or the earthquake could be a slow earthquake (sometimes referred to as a tsunami earthquake) resulting in a much larger than expected tsunami given the earthquake's seismic moment.

Fortunately, the tsunami warning system of the Pacific has an extensive network of over 130 remotely reporting sea level gauges including several deep-ocean pressure sensors. These gauges are a critical asset for tsunami warning that was completely missing in the Indian Ocean on 26 December.

The Pacific network of sea level gauges allows warning centers to confirm the existence or nonexistence of tsunami waves following a warning based solely on the seismic data. Most Pacific warnings are canceled within 2–3 hours after they are issued, based on the sea level data. Without the network of sea level gauges, the entire Pacific Basin would have unnecessarily been placed in a warning status many times during the past 40 years over which the tsunami warning system of the Pacific has been operational.

Aside from causing a significant disruption to normal activities in coastal zones, frequent false warnings cause them to be discredited, and make warnings of real threats ineffective.

On 26 December 2004, there was no tsunami warning system in the Indian Ocean: there was no warning center, inadequate regional seismic networks, no network of remotely reporting sea level gauges, no designated national authorities for tsunami warnings, no communications methods to reach potential authorities, no tsunami-educated emergency managers or local tsunami experts, no communications to disseminate warnings to coastal regions at risk, and painfully little tsunami awareness.

We hope we have made it clear that what is vitally important is a functioning tsunami warning system. Better seismology for such events is something that can help; but with respect to mitigating loss of life from tsunamis, it is of secondary importance to the establishment of a global tsunami warning system.

We are always seeking ways to improve the warning system. Currently, the tsunami warning centers employ the M_{wp}, M_m, and M_s methods to estimate the size of earthquakes at teleseismic distances. In particular, the M_{wp} (P-wave moment method, *Tsuboi et al., 1995*) and M_m (mantle magnitude method, *Okal and Talandier, 1988*) are methods that are designed to reduce the effects of saturation (underestimation of the earthquake magnitude when source duration significantly exceeds the seismic wave period at which the magnitude is measured) and yield quality seismic moment estimates of great earthquakes in near real time. While these methods underestimated the 26 December earthquake, they performed superbly for the 28 March 2005 earthquake, a Harvard Seismology CMT magnitude M_W = 8.6 event as estimated by Harvard Seismology that the Pacific Tsunami Warning Center reported in its initial bulletin as an M_W 8.5 just 19 min after the event. Further analysis by Weinstein and Okal (2005) shows that extending the M_m method to longer periods gives a value for the 26 December Sumatra earthquake of 8.9.

We appreciate Menke and Levin's efforts directed at developing new seismological techniques that could improve the warning system's capability to more accurately assess great earthquakes in a timely fashion, and look forward to any other such advances that may emerge from the scientific community at large in the wake of the 26 December event.

References

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Tsuboi, S., Abe, K.,Takano, K. and Y. Yamanaka, Rapid determination of M_W from broadband P waveforms, Bull. Seismol. Soc. Am., 85, 606–613, 1995.

Weinstein, S.A., and E. A. Okal, The mantle magnitude M_m and the slowness parameter Θ: Five years of real-time use in the context of tsunami warning, Bull. Seismol. Soc. Am., 95, 779–799, 2005.