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Tide gauge observations of the Indian Ocean tsunami, December 26, 2004

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[1] The magnitude 9.0 earthquake centered off the west coast of northern Sumatra (3.307°N, 95.947°E) on December 26, 2004 at 00:59 UTC (United States Geological Survey (USGS) (2005), USGS Earthquake Hazards Program-Latest Earthquakes, Earthquake Hazards Program, http://earthquake.usgs.gov/eqinthenews/2004/usslav/, 2005) generated a series of tsunami waves that devastated coastal areas throughout the Indian Ocean. Tide gauges operated on behalf of national and international organizations recorded the wave form at a number of island and continental locations. This report summarizes the tide gauge observations of the tsunami in the Indian Ocean (available as of January 2005) and provides a recommendation for the use of the basin-wide tide gauge network for future warnings. **Citation:** Merrifield, M. A., et al. (2005), Tide gauge observations of the Indian Ocean tsunami, December 26, 2004, *Geophys. Res. Lett.*, *32*, L09603, doi:10.1029/2005GL022610.

1. Introduction

[2] Water level stations are an important component of the International Tsunami Warning System in the Pacific (coordinated by the United Nations Educational, Scientific, and Cultural Organization's Intergovernmental Oceanographic Commission (UNESCO IOC) [*IOC*, 1999; *McCreery*, 2004]). They provide real-time information on the development of a tsunami following a seismic event, and thus are critical for guiding the issuance of tsunami warnings and for canceling warnings when non-destructive tsunamis are observed. The majority of the Pacific network is made up of tide gauge stations designed for tsunami detection (fast sampling and near real-time reporting) as well as sea level measurement.

[3] There was no tsunami warning system in the Indian Ocean at the time of the December 26, 2004 tsunami. However, a number of the existing gauges recorded the Indian Ocean tsunami and reports were available within hours of the event. In anticipation of the development of an Indian Ocean Tsunami Warning System, we summarize the available tide gauge data and recommend upgrades that would build a basin-wide tsunami detection system.

[4] The sample rate of the gauges used in this study ranges from 1 to 10 minutes. Most of the tide gauges are float gauges in stilling wells located within harbors, bays, or lagoons (Table 1). Thus their measurements are not necessarily representative of conditions along exposed coasts. In addition, many of the sites are located on the western sides of islands, somewhat protected from the westward-propagating waves. Data from the gauges are filtered both mechanically and in time, and thus are not exactly representative of the absolute height of the tsunami.

2. Description of Tide Gauge Observations of the Tsunami

[5] The initial tsunami wave was measured with amplitudes of up to 2.17 m by tide gauges; in comparison, open ocean heights measured by satellite were about 0.60 m two hours after the earthquake [*National Oceanic and*

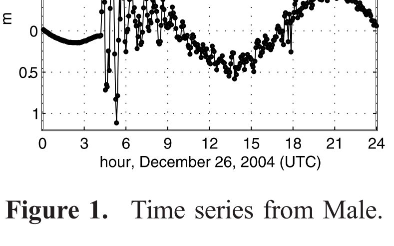

Figure 1. Time series from Male.

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Table 1. Tsunami Characteristics at Indian Ocean Stations[a]

Station	Travel Time	Height, m	Sampling Interval	Station Location
Belawan, Indonesia	00:41	0.51	10	harbor, NE Sumatra
Lembar, Indonesia	01:51	0.15	10	harbor, W Lombok
Panjang, Indonesia	03:00	0.11	30	harbor, SE Sumatra
Prigi, Indonesia	02:21	0.15	10	harbor, S Java
Sibolga, Indonesia	01:21	0.43	10	harbor, W Sumatra
Cocos Islands, Australia	02:18	0.33	1	atoll
Esperance, Aus.	07:58	−0.01	1	
Hillarys Aus.	06:29	0.35	1	
Portland, Aus.	09:49	0.17	1	
Dumont D'Urville, France	13:34	0.06	30	Antarctica
Colombo, Sri Lanka	02:53	2.17	2	harbor, W side
Gan, Maldives	03:21	0.88	4	inner lagoon, SE side
Hanimaadhoo, Maldives	03:33	1.71	2	inner lagoon, E side
Hulule, Male, Maldives	03:17	1.46	4	inner lagoon, SE side
Diego Garcia, UK	04:49	0.56	6	inner lagoon, W side
Port Louis, Mauritius	06:43–07:47		4	harbor, W side
Rodrigues, Mauritius	05:41+		2	harbor, NW side
Pt. La Rue, Seychelles	07:17	1.09	4	bay, NE side
Salalah, Oman	07:13	0.28	4	harbor, S side
Lamu, Kenya	08:57	0.28	4	W side of NW-SE channel between islands
Zanzibar, Tanzania	09:45	0.29	4	W side
Richard's Bay, South Africa	11:04	0.16	3	
Port Elizabeth, S. A.	12:22	0.26	3	

[a] Travel times correspond to the difference between the time of the earthquake (00:59 UTC) and the time of the first water level change of the tsunami, in hours:minutes (exceptions: Rodrigues station was destroyed and time corresponds to the last transmitted data; Port Louis time range corresponds to the data gap). Height is the height of the first crest above the mean tide. The sampling interval is given in minutes.

Atmospheric Administration (*NOAA*), 2005]. At all locations west of the earthquake center, the tsunami first arrived as a crest. To the east of the center the tsunami first appeared as a wave trough. This trough was most distinct at Sibolga, where the drop recorded was about 0.25 m over 10 minutes; the following crest raised the water level by 0.82 m from this point. The time series at Male (Figure 1) exemplifies the dramatic increase in water level at western stations on the arrival of the first wave. Initial wave periods ranged from 40 to 120 min.

[6] At most locations, the waves continued for hours to days after the initial arrival (Figures 2, 3, and 4). At Male, Gan, and Diego Garcia, the amplitude of the ringing was very small compared to the initial waves. At Salalah, Pt. La Rue, Cocos, Hillarys, and Port Elizabeth, in contrast, oscillations of nearly the same amplitude persisted for one to two days. The period, generally between 20 and 45 minutes, varied with location (most locations did not show one clear frequency). This suggests that the tsunami caused resonant oscillations which varied with local bathymetry. The lack of a strong persistent signal at some of the more exposed sites (e.g. Male and Gan) reinforces this notion. Wave reflection from the boundaries of the Indian Ocean may also have contributed to the persistent oscillations. Satellite altimeter measurements of the tsunami indicate the importance of wave reflections [*NOAA*, 2005]. *Van Dorn* [1984, 1987] has considered the decay characteristics of tsunamis in tide gauge records in relation to basin-wide reflections and energy dissipation.

[7] Wave amplitudes tend to decrease towards the west as the wave form spreads. High wave energy propagated to the east and west, with comparatively weak amplitudes to the southeast (Lembar, Prigi) and southwest (Cocos). Sumatra also may have sheltered stations located to the southeast. Although not included here, stations located along the

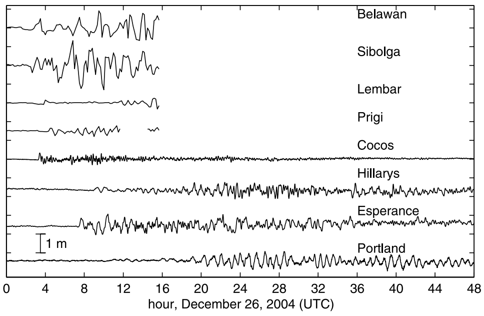

Figure 2. Time series with tidal contributions removed from eastern stations.

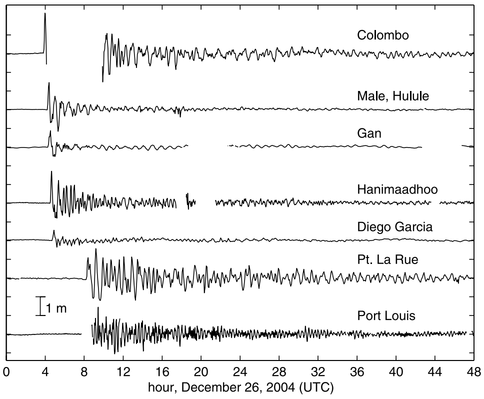

Figure 3. Time series with tidal contributions removed from island stations.

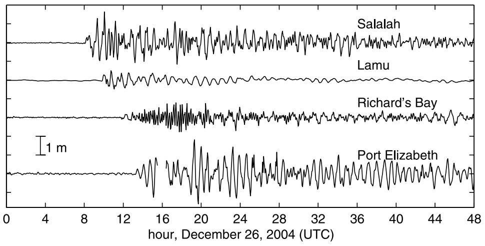

Figure 4. Time series with tidal contributions removed from African stations.

Australian northwest shelf showed little indication of the tsunami.

[8] The initial wave was not always the largest in the group. At several sites (Hillarys, Salalah, Pt. La Rue, and Lamu), the second or third wave was the largest. At other sites (Zanzibar, Richard's Bay, and Port Elizabeth) the largest waves were not observed until 6–8 hours after the first arrivals. At Portland, there was a distinct increase in wave size about 9 hours after the initial wave; the largest wave was measured about 15 hours after the first arrival. The tide gauge records at Richard's Bay and Port Elizabeth, separated by ~840 km along the South African Coast, are surprisingly different in both amplitude and frequency. We presume that local shelf interactions are somehow responsible.

[9] The tsunami was superimposed on a mixed (diurnal plus semidiurnal) tidal signal which ranged in amplitude from about 1 m in Indonesia to 0.5 m in the central Indian Ocean to 1.5 m along the central African coast. In general, the tsunami arrival coincided with low or mid-tide (e.g., Figure 1). The exceptions among the stations discussed here are Port Louis, Richard's Bay, Port Elizabeth, and Esperance, where the arrivals coincided with high tide. In addition, we note that the tidal phase on the east coast of Sri Lanka is opposite to that on the west coast (where Colombo is located). On the east coast, the tsunami arrived near high tide during a period of spring tides and near the seasonal sea level maximum.

[10] We estimate arrival times by the first measured increase or decrease before the crest or trough. The first measured arrival was at Belawan, Indonesia, at 1:40 UTC (Table 1), corresponding to a travel time of 41 minutes from the earthquake center 318 km away (Figure 5). The wave reached the coast of Africa about 9 hours after the earthquake (Table 1). Based on the travel times and distances (excluding stations in Indonesia and Mauritius), a typical speed for the tsunami was ~187 m/s. Around Indonesia, the wave was traveling in relatively shallow water. Travel times to Indonesian locations were unusually long compared with the others (average speed of 160 m/s). The travel times predicted by the West Coast/Alaska Tsunami Warning Center tsunami model (West Coast/Alaska Tsunami Warning Center (WC/ATWC), Tsunami Models, WC/ATWC Com-

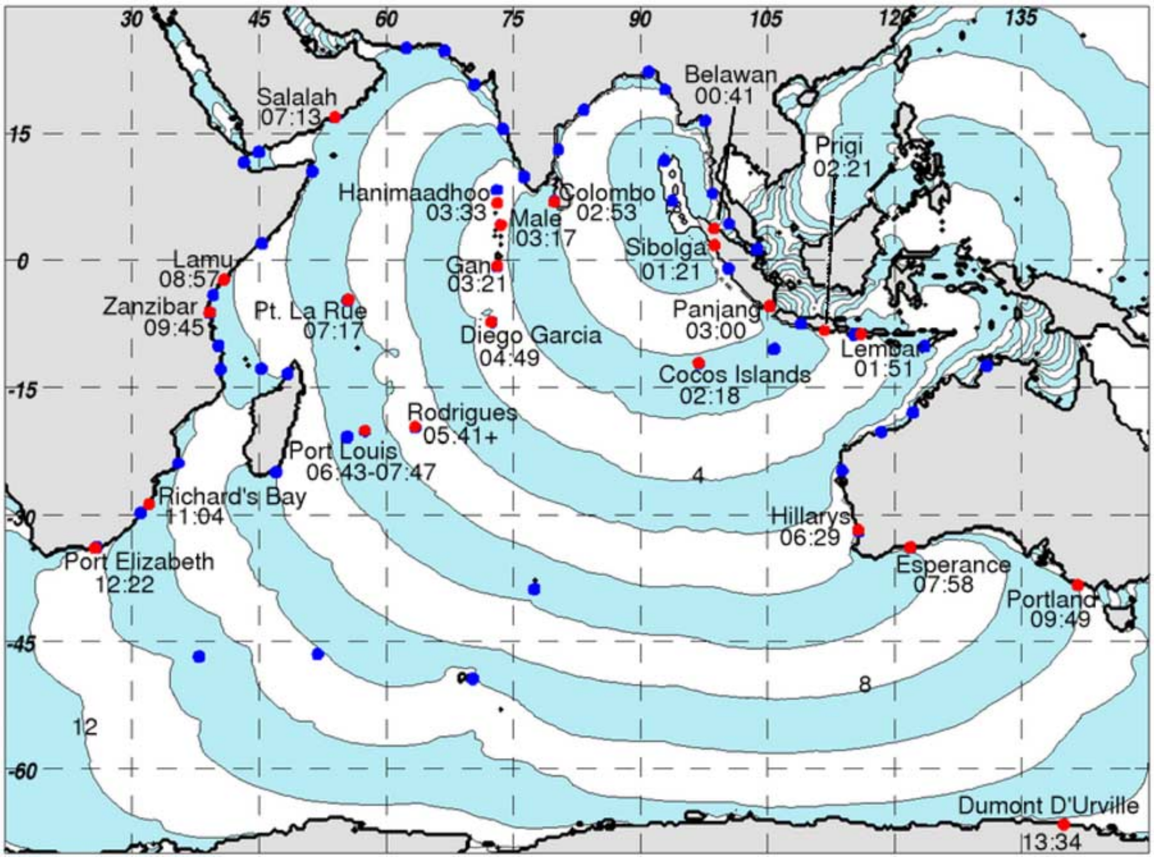

Figure 5. Tsunami travel times to Indian Ocean tide gauge stations, in hours:minutes. The contours show predicted travel times (hours) from the WC/ATWC model. The red dots show the locations of stations used in this paper (some of which are GLOSS). The blue dots represent the other GLOSS stations.

munications and Networking Architecture, http://wcatwc.arh.noaa.gov/IndianOSite/IndianO12-26-04.htm, 2005) compare favorably with the observations (Figure 5).

3. Steps Toward a Basin-Wide Tsunami Water Level Network

[11] The data summarized above illustrate the potential of tide gauges to be used for tsunami warning in the Indian Ocean. The majority of the stations transmitted data at hourly intervals. At this transmission rate, confirmation of the tsunami at Cocos Islands could have provided an advance warning to the Maldives and locations farther west if a warning system had been in place. Similar transmitting stations in Thailand and Indonesia would have allowed for significantly faster issuance of a warning for much of the Indian Ocean.

[12] The implementation of a tsunami warning system in the Indian Ocean will require the deployment of a sea level monitoring network with real-time transmissions to a regional tsunami warning center. Many of the stations examined in this report are part of the Global Sea Level Observing System (GLOSS) run by the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the World Meteorological Organisation (WMO) and the UNESCO IOC [*IOC*, 1997]. Sea level data acquired through GLOSS are freely available and used for climate, oceanographic and coastal sea level research, and for operational purposes [*Woodworth et al.*, 2002, 2003]. The existing GLOSS network, with suitable upgrades, can be used for tsunami detection (Figure 5). The majority of stations require modification for faster sampling rates (1–2 minutes) and near real-time transmission of data (hourly or more frequent) via satellite. Approximately 13 stations are not functioning and require major investments [*Woodworth and Aarup*, 2003]. A reliance on multiple-use water level stations that can be used to detect tsunamis and storm surge, as well as monitoring long-term changes in sea level, would maximize the likelihood of maintenance and sustained operation of the network. Moreover a small expansion of the array of tide gauges to carefully selected islands may also offer a cost-effective supplement to an array of deep-sea pressure sensors and moorings. While additional stations are required, particularly near Sumatra where large earthquakes associated with subduction along the Sunda Trench will continue to occur, the GLOSS stations provide a starting point for the implementation of an Indian Ocean tsunami detection network.

[13] **Acknowledgments.** Data providers include the National Tidal Center, Australia (NTC); LEGOS, France; the National Coordinating Agency for Surveys and Mapping, Indonesia (BAKOSURTANAL); the Kenya Marine and Fisheries Institute; the Department of Meteorology, Republic of Maldives; Meteorological Services, Mauritius; the Directorate of Civil Aviation, Republic of Seychelles; the National Aquatic Resources Research and Development Agency, Sri Lanka (NARA); the Director of Meteorology CIVAIR, Sultanate of Oman; the South African Navy Hydrographic Office, South Africa; the Commission of Lands and Environment, Tanzania; and the University of Hawaii Sea Level Center (UHSLC), USA. Data can be obtained from the UHSLC. Support for the UHSLC was provided by the Office of Global Programs, National Oceanic and Atmospheric Administration (NA17RJ1230).

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