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Tsunami and Its Hazards in the Indian and Pacific Oceans

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Pure and Applied Geophysics

Tsunami and its Hazard in the Indian and Pacific Oceans: Introduction

K. SATAKE,[1] E. A. OKAL,[2] and J. C. BORRERO[3]

Abstract—The 2004 Indian Ocean tsunami caused an estimated 230,000 casualties, the worst tsunami disaster in history. A similar-sized tsunami in the Pacific Ocean, generated by the 1960 Chilean earthquake, commenced international collaborations on tsunami warning systems, and in the tsunami research community through the Tsunami Commission of International Union of Geodesy and Geophysics. The IUGG Tsunami Commission, established in 1960, has been holding the biannual International Tsunami Symposium (ITS). This volume contains selected papers mostly presented at the 22nd ITS, held in the summer of 2005. This introduction briefly summarizes the progress of tsunami and earthquake research as well as international cooperation on tsunami warning systems and the impact of the 2004 tsunami. Brief summaries of each paper are also presented.

Key words: Tsunami, Sumatra-Andaman earthquake, Indian Ocean, Pacific Ocean, seismology, tsunami warning system, IUGG Tsunami Commission.

1. *Introduction*

The 2004 Indian Ocean tsunami was the worst tsunami disaster in history. The tsunami, caused by the giant Sumatra-Andaman earthquake (M_w 9.3; STEIN and OKAL, 2005) on December 26, 2004, devastated the shores of the Indian Ocean. The total number of victims, dead and missing together, is estimated as 230,000 (INTERNATIONAL FEDERATION OF RED CROSS AND RED CRESCENT SOCIETIES, 2005); the largest in Indonesia (163,795), followed by Sri Lanka (35,399), India (16,389), Thailand (8,345), and Somalia (298).

In the Pacific Ocean, a similar, basin-wide tsunami occurred in 1960. This tsunami was generated by the giant Chilean earthquake, which remains the largest instrumentally-recorded earthquake on record (M_w 9.5). The tsunami caused more than 1,000 casualties along the Chilean coast, then propagated across the Pacific

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Ocean, taking 61 lives in Hawaii 15 hours later, and reaching the coast of Japan in 23 hours and claiming 142 more casualties. Following this Pacific-wide tsunami, international collaborations started on operational tsunami warning systems and scientific studies of tsunamis.

The Tsunami Commission of IUGG (International Union of Geodesy and Geophysics) was established immediately after the 1960 tsunami. The Tsunami Commission organizes the biannual International Tsunami Symposium (ITS). The 22nd ITS was held in Chania, Greece, from July 27 to 29, 2005, with approximately 90 participants from 20 countries. This volume contains selected papers presented at the meeting and a few other papers, and reflects tsunami research after the 2004 Indian Ocean tsunami.

In this introductory paper, Section 2 reviews international cooperation and progress on earthquake and tsunami research in the last half century. Section 3 describes the impacts of the 2004 Indian Ocean tsunami. Finally in Section 4 we briefly introduce the papers in the following categories; survey and research results on the 2004 and other recent tsunamis, geological studies of older tsunamis, and studies on tsunami hazard analysis.

2. Status Before the 2004 Tsunami

2.1. International Coordination on Tsunami Warning Systems

After the 1960 tsunami, which affected many countries around the Pacific Ocean, international coordination was initiated by the IOC (Intergovernmental Oceanographic Commission) under UNESCO (United Nations Educational, Scientific and Cultural Organization). In 1965, IOC set up ITIC (International Tsunami Information Center) in Hawaii with support from the USA NOAA (National Oceanic and Atmospheric Administration). With the mission of mitigating tsunami hazards around the Pacific, ITIC coordinates international activities on tsunami warning systems, helps countries to establish national warning and mitigation systems, collects publications and other materials on tsunami events, develops educational and awareness materials, and serves as an information resource on tsunamis. The ICG/ITSU (International Coordination Group for the Tsunami Warning System in the Pacific) was also established under the auspices of IOC, and first convened in 1968. The ICG/ITSU as of 2006 has 30 member countries and holds a biannual meeting to exchange information and coordinate international activities in the Pacific.

For operational tsunami monitoring and warning activities in the Pacific, three tsunami warning centers have been established. The PTWC (Pacific Tsunami Warning Center), established in 1949 following the 1946 Aleutian tsunami, serves as the international warning center for the Pacific. The WC/ATWC (West Coast/Alaska

Tsunami Warning Center), established in 1967 following the 1964 Alaska earthquake tsunami, serves as a sub-regional center for the western USA and Canada. In 2006, Japan commenced operation of the Northwest Pacific Tsunami Advisory Center to provide advisories to the northwest Pacific. These centers, operated by USA NOAA and Japan Meteorological Agency, monitor seismic activity around the Pacific, and issue tsunami warnings for the Pacific countries. All the centers share information and coordinate message content before issuing advisories.

2.2. International Collaboration in Research Community

The Tsunami Commission was established at the 12th general assembly of International Union of Geodesy and Geophysics (IUGG). The Tsunami Commission is closely related to three associations of the IUGG, IASPEI (International Association of Seismology and Physics of the Earth's Interior), IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior) and IAPSO (International Association for the Physical Sciences of the Oceans). The Tsunami Commission also organizes the biannual International Tsunami Symposium and publishes Proceedings with selected papers presented at the Symposium.

Since 1992, many tsunamis have occurred in the world. The development of the internet has accelerated international collaboration through the 1990s. Immediately after the 1992 Nicaragua tsunami, an e-mail list, then called Nicaragua Bulletin Board, was set up, and has been used ever since as a forum for international collaboration and exchange of information. Now called the Tsunami Bulletin Board (TBB), this service is maintained by ITIC.

The Tsunami Commission has also performed successful international projects. The Tsunami Inundation Modeling Exchange (TIME) project distributed computer software, a support manual and conducted training programs to teach tsunami inundation modeling techniques using a numerical model developed at Tohoku University in Japan. Under the Historical Tsunami Data Base project, a repository of tsunami data has been established and is maintained through the joint efforts of the Institute of Computational Mathematics and Mathematical Geophysics, in Novosibirsk, Russia and the National Geophysical Data Center, Boulder, Colorado, USA, which also serves as the World Data Center – Solid Earth Geophysics – Tsunamis.

2.3. Scientific Developments

In 1960, when the giant Chilean earthquake generated a Pacific-wide tsunami, little was known about tsunami generation. Most of the current seismological concepts have been developed since the 1960s. Plate tectonic theory was introduced in the 1960s and now explains the mechanism of great or giant earthquakes. Mathematical models of earthquake source were developed in the 1960s to relate seismic moment and size of fault. On the observational side, the World Wide Standard Seismic Network was deployed in the 1960s.

In the 1970s, using these theories and observed data, fault parameters of many large earthquakes in the world were determined. The moment magnitude (M_w) scale, based on seismic moment, was also introduced. It took more than a decade to accurately estimate the size of the 1960 Chilean earthquake. Theoretical and computational developments made it possible to compute seafloor deformation from fault models and the tsunami propagation on actual bathymetry.

Since the 1980s, seismograms have been recorded digitally, which has improved data quality and reduced processing times. As a result, basic earthquake source parameters can be estimated quickly and almost automatically. Heterogeneous slip distributions (asperities) on the fault also have been studied. Large-scale numerical simulations of tsunamis also became popular in the 1980s.

In the 1990s, developments in computer networking have made it possible to share the results of seismic wave analysis and tsunami numerical simulations in real time through the internet. In addition to instrumental seismology, historical and geological studies of past earthquakes and tsunamis have made important discoveries around the Pacific, advancing our understanding of tsunami hazards and recurrence intervals.

At present, after a large earthquake, globally observed seismological and sea-level data, as well as initial estimation of earthquake source parameters, are available within minutes through the internet. Based on these data and information, more seismological and tsunami studies are made and the results are also shared in real time. The development of the internet thus made positive feedback and accelerated tsunami research.

3. Impacts of the 2004 Tsunami

3.1. International Activities

The lack of a tsunami warning system in the Indian Ocean contributed to the severity of the 2004 Indian Ocean tsunami. At the 2005 IOC general assembly, it was proposed and adopted to organize ICGs (Intergovernmental Coordination Groups) in oceans and basins other than the Pacific. They are ICG/IOTWS (ICG for the Indian Ocean Tsunami Warning and Mitigation System), ICG/NEAMTWC (ICG for the Tsunami Early Warning and Mitigation System in the northeastern Atlantic, the Mediterranean and connected seas), and ICG/CARIBE-EWS (ICG for Tsunami and Coastal Hazards Warning System for the Caribbean and Adjacent Regions). The ICG/ITSU for the Pacific has been renamed as ICG/PTWS (ICG for the Pacific Tsunami Warning and Mitigation System). ICG/PTWC performed the first international tsunami drill for issuing and transmitting tsunami warning messages in May 2006.

Among the scientific community, information on tsunami damage, survey plans and obtained data or research results have been exchanged and discussed through Tsunami Bulletin Board (TBB). Within a month after December 26, about 500 mails were posted to the TBB. Through such coordination, hundreds of tsunami scientists around the world participated in tsunami surveys, most of them consisting of international teams, to document the 2004 tsunami. The survey data were also shared through the Tsunami Bulletin Board and individual websites. The surveys showed that tsunami heights were very large around Band Aceh (maximum 30 m) on Sumatra Island. They were 5 to 15 m along Thailand and Sri Lanka coast, but much smaller in Myanmar ($<$ 3 m) or the Andaman Islands ($<$ 5 m).

At the business meeting held during the 22nd ITS, the Tsunami Commission decided to publish collections of selected papers presented at the Symposium. The Commission also organized Working Groups to collect field data, survey results, tide gauges and satellite data on the 2004 Indian Ocean tsunami.

3.2. Scientific Impacts

There are several new lines of scientific progress resulting from the 2004 Indian Ocean tsunami. Numerical simulations were made immediately; with several groups performing the numerical simulations within hours after the event and posting the results on websites.

Sea-level monitoring stations, namely GLOSS (Global Sea Level Observation System) stations and stations in Australia, the Pacific and Atlantic Oceans recorded the 2004 tsunami (RABINOVICH and THOMSON, 2007). For tsunami recording, higher sampling interval (1 min) than ordinary tide (typically 6 min) is required. Such digital data were provided to researchers through websites in real- or semi-real-time.

High-resolution satellite images, taken before and after the tsunami, made it possible to estimate the tsunami damage in the hardest-hit areas such as Banda Aceh (e.g., BORRERO, 2005). Snapshots of nearshore tsunamis (e.g., on Sri Lanka coasts) were recorded in high-resolution satellite images. Tsunami propagation across the Indian Ocean was also captured by satellite altimeter (JASON-1) data (e.g., FUJII and SATAKE, 2007).

Numerous reports and papers have been published regarding the 2004 earthquake and tsunami, and it is almost impossible to list all of them. Here we only refer to special issues of other scientific journals. A special section in *Science* on May 20, 2005 (BILHAM, 2005) contains papers mostly on the seismological aspects. The special issue of *Earth, Planets and Space* (vol. 58, no. 2) contains 20 papers on various aspects such as GPS measurements or tsunami surveys (TANIOKA *et al.*, 2006). The June 2006 issue of *Earthquake Spectra* contains 44 reports, mostly on tsunami field surveys and societal responses (IWAN, 2006). A special issue of *Bulletin* *of Seismological Society of America* contains 22 papers on seismological and tsunami analysis (BILEK *et al.*, 2007).

3.3. Future Improvements

Despite the advances mentioned in the previous subsection, we still need to improve our scientific understanding of tsunamis. We are still unable to accurately forecast coastal tsunami heights in real time. Initial numerical simulations made after the Sumatra earthquakes in December 2004 and March 2005 assumed a generalized source mechanism and computed tsunami propagation over the relatively coarse ETOPO2, 2 min gridded bathymetry data (SMITH and SANDWELL, 1997). Although these data are accurate for deep oceans, shallow bathymetry is not accurate enough to be used for reliable tsunami forecasting. Hence the numerical simulations reproduce the overall features of tsunami propagation but cannot predict accurate arrival times and amplitudes. Nearshore tsunami effects can be accurately reproduced using available numerical codes for tsunami generation, propagation and inundation, however the results depend heavily on detailed information on the source mechanism as well as on local bathymetric and topographic features.

Since it is unlikely that the detailed analysis of the seismic signals will accelerate significantly nor will there ever be established a comprehensive database of detailed bathymetry for every coast in the world, it is important that we develop the technology to continuously monitor the tsunamigenic regions of the world and directly observe tsunami generation and propagation. Offshore tsunameters (buoys) capable of relaying real-time information to warning centers are essential for determining whether or not a tsunami has been generated and how big the wave will be when it reaches the coast. Dense networks of costal sea-level gauges in tsunami-prone areas provide important confirmation of a tsunami's generation, so that more distant communities can be warned. All of these will enable more informed evacuation decisions, as well as eliminate costly and potentially dangerous false evacuations. Satellite technology should also be improved to allow for targeted tsunami observation and rapid damage assessment for remote or inaccessible locations. Of course, the real-time availability and exchange of these data are essential to improving our understanding of a tsunami event as it unfolds and for saving lives and property. It is also important to urge port and harbor officials to install or upgrade tide measuring stations to record water levels at a higher sampling rate (1-minute or shorter) on a continuous or event-triggerred basis.

For long-term forecast of future tsunamis, probabilistic estimation can be made based on the study of past tsunamis, using historical and geological data. Paleoseismological work in the Nicobar and Andaman Islands would help us to understand the occurrence and recurrence of great earthquakes in the Indian Ocean since prehistoric time.

4. *Contents of this Issue*

4.1. *On the 2004 Indian Ocean Tsunami*

As a part of the Tsunami Commission Working Group on tide gauge data, RABINOVICH and THOMSON (2007) collected and compiled about 50 tide gauge records around the Indian Ocean and provided analysis such as arrival times, maximum amplitude and spectral components.

Tsunami was also recorded on hydrophones or seismometers. OKAL *et al.* (2007) analyzed the hydrophone records at Diego Garcia and showed that the tsunami signal is detected in a very wide period range (about 90 s to 3000 s), beyond the shallow-water approximation. The dispersion character was modeled by normal mode theory. OKAL (2007) shows that the 2004 Indian Ocean tsunami and other recent tsunamis are recorded on horizontal components of seismometers. The seismic detection of a tsunami can be modeled by using normal mode theory of the Earth including the tsunami mode, thus leading to estimate the seismic moment of parent earthquake from tsunami records.

OKAL and TITOV (2007) proposed a new magnitude scale, M_{TSU}, from spectral amplitude of tsunami. Similar to the mantle magnitude, M_m, the method is based on normal-mode theory and uses variable frequency, hence it is free from saturation. They demonstrate that the new magnitude scale recovers the seismic moment within a factor of two (0.2 in magnitude scale) from DART tsunameter records, and from satellite sea-surface data obtained for the 2004 tsunami in the Indian Ocean.

The 2004 tsunami was also detected in the Atlantic and Pacific Oceans. KOWALIK *et al.* (2007) carried out a tsunami simulation on the global ocean while monitoring energy flux. They found many important features of the tsunami. Reflection from the coasts of Sri Lanka and Maldives were larger than the direct wave; the tsunami entered the Pacific Ocean through various routes; the amplified tsunami energy arrived much later than the first arrival.

INOUE *et al.* (2007) reports tsunami heights, arrival times and damage along the Sri Lankan coast. A damaging tsunami had never been observed on this island country, and then the 2004 tsunami resulted in about 36,000 victims. KELLETAT *et al.* (2007) examined the geological effects of the 2004 tsunami on the Thai coast. They found minimal geomorphological changes and tsunami traces in their survey immediately after the tsunami. Based on their observations, they concluded that the 2004 tsunami was considerably smaller than the paleo-tsunami events in the Atlantic Ocean or Caribbean Sea that transported boulders.

4.2. *Analysis and Simulations for other Tsunamis*

The last disastrous tsunami prior to the 2004 tsunami was the 1998 tsunami in Papua New Guinea. This event generated tsunami waves as large as 15 m around

Sissano Lagoon near the epicenter and casualties estimated at 2,200. JOKU *et al.* (2007) report on their follow-up surveys of eyewitness accounts of this tsunami on the coast west of the tsunami source region. They also summarize the experiences of coastal residents from historical tsunamis since 1940.

Large tsunamis, including the 2004 event, demonstrate strong directivity; the largest tsunami heights were in directions perpendicular to the source, e.g., Sumatra, Thai and Sri Lankan coasts. ABE (2007) found that in the direction of the long axis of the tsunami source, or in the direction where the smallest tsunami amplitudes are observed, the source length is represented well by the period of the initial tsunami wave. Through examinations of tide gauge records from four large Japanese earthquakes in the last few decades, he measured the periods of the initial tsunami wave, estimated the source length assuming that the observed period is equal to the tsunami travel time across the source, and found that they are well correlated with the earthquake magnitudes.

CHERNIAWSKY *et al.* (2007) carried out numerical simulations of tsunamis in the southern Vancouver Islands from possible scenario earthquakes in the Cascadia region of the Pacific Northwest. A very fine bathymetry grid, as small as 10 m, is used in their simulation, and tsunami run-up on land is considered. The computed coastal tsunami heights are mostly 5–8 m, with the maximum of 16 m, and larger than those inferred from paleoseismological studies. The simulation also predicts very fast current velocity up to 17 m/s (33 knots).

4.3. Geological Studies of old Tsunamis

Geological records or tsunami deposits have been studied around the Pacific Ocean for the last two decades. KOMATSUBARA and FUJIWARA (2007) provide an overview of such studies carried out in southwestern Japan along Nankai, Suruga and Sagami troughs. Many studies of tsunami deposits have been carried out in the last 15 years but most of them were reported in Japanese language and not known to the international community. The geological records cover a much longer time range than the historical records. The inferred recurrence interval is variable; the shortest ones are similar to those estimated from historical records.

In the Cascadia subduction zone, off the Pacific Northwest of the USA and Canada, the recurrence of giant earthquakes similar in size to the 2004 event has been inferred from geological and historical records. KILFEATHER *et al.* (2007) extended such studies on tsunami deposits by examining micro-structures in thin sections. They found millimeter-scale stratigraphic features indicating multiple waves of tsunamis, that are not visible on a macro-scale in the field.

FREUNDT *et al.* (2007) examined geological traces of past tsunamis around two lakes in Nicaragua, Lake Nicaragua and Lake Managua. These tsunamis were of volcanic origin, generated by pyroclastic flows or debris avalanches from flank collapse of nearby volcanoes. They emphasize that the tsunamis in shallow lakes can be highly disastrous, not only in Nicaragua but also in other countries.

4.4. Tsunami Hazard Analysis

Probabilistic models have been developed to estimate coastal tsunami heights from future earthquakes. Such methods have been widely used for seismic hazard (Probabilistic Seismic Hazard Analysis), but only recently applied to tsunamis. POWER *et al.* (2007) developed a Probabilistic Tsunami Hazard Analysis (PTHA) method and applied it for estimating probabilistic tsunami heights from distant earthquakes. The end result is a map showing expected maximum tsunami heights in the next 500 years around New Zealand from earthquakes off South America.

A method for evaluating tsunami risk at nuclear power facilities in Japan is proposed by YANAGISAWA *et al.* (2007). Their method is based on a parametric study, in which numerical simulations are repeated for element tsunamis with various fault parameters, and the element tsunami with the greatest influence is selected as the design tsunami. The design tsunami is further compared with the historical data to ensure that it produces tsunami heights larger than those historically recorded. ANNAKA *et al.* (2007) proposed a logic-tree approach for PTHA. Their end product is a hazard curve, a relationship between coastal tsunami heights and the probability of exceedance at a particular site. The hazard curve is obtained by integration over the aleatory uncertainties, whereas a large number of hazard curves are obtained for different branches of logic-trees representing epistemic uncertainty, such as tsunami sources, size and frequency of tsunamigenic earthquakes, standard errors of estimated tsunami heights.

ORFANOGIANNAKI and PAPADOPOULOS (2007) examined the stochastic methods to compute the probability of tsunami generation from historical data of tsunami and earthquakes. Two methods, based on the conditional probability of tsunami occurrence and the total probability theorem, are compared to estimate the probabilities in three regions around the Pacific: South America, Kuril-Kamchatka and Japan.

FARRERAS *et al.* (2007) reports developments of the Mexican national program for tsunami hazard reduction. It consists of a sea-level monitoring system with real-time data access, deployment of a numerical simulation to construct tsunami inundation maps for coastal communities, and publication and distribution of educational material on tsunamis. These efforts cover the three important areas, warning guidance, hazard assessment and mitigation of tsunami hazard reduction on both national and international levels.

The coastal behavior of tsunamis, such as wave fission or wave breaking, can be studied by laboratory experiments. MATSUYAMA *et al.* (2007) report their experiments on tsunami wave fission and wave-breaking in large-scale undistorted experiments.

REFERENCES

ABE, K. (2007), *Phases representing source lengths of tsunamis in tide gauge records*, Pure Appl. Geophys. *164*, 453–463.

ANNAKA, T., SATAKE, K., SAKAKIYAMA, T., YANAGISAWA, K., and SHUTO, N. (2007), *Logic-tree approach for probabilistic tsunami hazard analysis and its applications to the Japanese coasts*, Pure Appl. Geophys. *164*, 577–592.

BILHAM, R. (2005), *A flying start, then a slow slip*, Science *308*, 1126–7.

BILEK, S.L., SATAKE. K., and SIEH, K. (2007), *Preface to the issue dedicated to the 2004 Sumatra-Andaman earthquake*, Bull. Seismol. Soc. Am. *97*, 1–5.

BORRERO, J.C. (2005), *Field data and satellite imagery of tsunami effects in Banda Aceh*, Science *308*, 1596.

CHERNIAWSKY, J.Y., TITOV, V.V., WANG, K., and LI, J.-Y. (2007), *Numerical simulations of tsunami waves and currents for southern Vancouver Island from a Cascadia megathrust earthquake*, Pure Appl. Geophys. *164*, 465–492.

FUJII, Y. and SATAKE, K. (2007), *Tsunami source of the 2004 Sumatra-Andaman earthquake inferred from tide gauge and satellite data*, Bull. Seismol. Soc. Am. *97*, 192–207.

FARRERAS, S., ORTIZ, M., and GONZALEZ, J.I. (2007), *Steps towards the implementation of a tsunami detection, warning, mitigation and preparedness program for southwestern coastal areas of Mexico*, Pure Appl. Geophys. *164*, 605–616.

FREUNDT, A., STRAUCH, W., KUTTEROLF, S., and SCHMINCKE, H.-U. (2007), *Volcanogenic tsunamis in lakes: examples from Nicaragua and general implications*, Pure Appl. Geophys. *164*, 527–545.

INOUE, S., WIJEYEWICKREMA, A.C., MATSUMOTO, H., MIURA, H., GUNARATNA, P., MADURAPPERUMA, M., and SEKIGUCHI, T. (2007), *Field survey of tsunami effects in Sri Lanka due to the Sumatra-Andaman earthquake of December 26, 2004*, Pure Appl. Geophys. *164*, 395–411.

INTERNATIONAL FEDERATION of RED CROSS and RED CRESCENT SOCIETIES, *World Disasters Report*. (Kumarian Press, 2005), 246 p.

IWAN, W.D. (2006), *Preface to the Issue dedicated to the 2004 Sumatra-Andaman earthquake*, Earthq. Spectra *22*, S3, xi.

JOKU, G.N., DAVIES, J.M., and DAVIES, H.L. (2007), *Eye-witness accounts of the impact of the 1998 Aitape tsunami, and of other tsunamis in living memory, in the region from Jayapura, Indonesia, to Vanimo, Papua New Guinea*, Pure Appl. Geophys. *164*, 433–452.

KELLETAT, D., SCHEFFERS, S., and SCHEFFERS, A. (2007), *Field signatures of the SE-Asian mega-tsunami along the West Coast of Thailand compared to holocene paleo-tsunami from the atlantic region*, Pure Appl. Geophys. *164*, 413–431.

KILFEATHER, A.A., BLACKFORD, J.J., and VAN DER MEER, J.J.M. (2007), *Micromorphological analysis of coastal sediments from Willapa Bay, Washington, USA: A technique for analysing inferred tsunami deposits*, Pure Appl. Geophys. *164*, 509–525.

KOMATSUBARA, J. and FUJIWARA, O. (2007), *Overview of Holocene tsunami deposits along the nankai, Suruga, and Sagami Troughs, southwest Japan*, Pure Appl. Geophys. *164*, 493–507.

KOWALIK, Z., KNIGHT, W., LOGAN, T., and WHITMORE, P. (2007), *The tsunami of 26 December 2004: Numerical modeling and energy considerations*, Pure Appl. Geophys. *164*, 379–393.

MATSUYAMA, M., IKENO, M., SAKAKIYAMA, T., and TAKEDA, T. (2007), *A study on tsunami wave fission in an undistorted experiment*, Pure Appl. Geophys. *164*, 617–631.

OKAL, E.A. (2007), *Seismic records of the 2004 Sumatra and other tsunamis: A quantitative study*, Pure Appl. Geophys. *164*, 325–353.

OKAL, E.A., TALANDIER, J., and REYMOND, D. (2007), *Quantification of Hydrophone records of the 2004 Sumatra tsunami*, Pure Appl. Geophys. *164*, 309–323.

OKAL, E.A. and TITOV, V.V. (2007), *M_{TSU}: Recovering seismic moments from tsunameter records*, Pure Appl. Geophys. *164*, 355–378.

ORFANOGIANNAKI, K. and PAPADOPOULOS, G.A. (2007), *Conditional probability approach of the assessment of tsunami potential: application in three tsunamigenic regions of the Pacific Ocean*, Pure Appl. Geophys. *164*, 593–603.

POWER, P., DOWNES, G., and STIRLING, M. (2007), *Estimation of tsunami hazard in New Zealand due to South American earthquakes*, Pure Appl. Geophys. *164*, 547–564.

RABINOVICH, A.B. and THOMSON, R.E. (2007), *The 26 December 2004 Sumatra tsunami: analysis of tide gauge data from the World Ocean: Part 1. Indian Ocean and South Africa*, Pure Appl. Geophys. *164*, 261–308.

SMITH, W.H.F. and SANDWELL, D.T. (1997), *Global sea floor topography from satellite altimetry and ship depth soundings*, Science *277*, 1956–1962.

STEIN, S. and OKAL, E.A. (2005), *Speed and size of the Sumatra earthquake*, Nature *434*, 581–582.

TANIOKA, Y., GEIST, E.L., and PUSPITO, N.T. (2006), *Preface to special issue* "The 2004 great Sumatra earthquake and tsunami", Earth, Planet Space *58*, 111.

YANAGISAWA, K., IMAMURA, F., SAKAKIYAMA, T., ANNAKA, T., TAKEDA, T., and SHUTO, N. (2007), *Tsunami assessment for risk management at nuclear power facilities in Japan*, Pure Appl. Geophys *164*, 565–576.

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Pure and Applied Geophysics

The 26 December 2004 Sumatra Tsunami: Analysis of Tide Gauge Data from the World Ocean Part 1. Indian Ocean and South Africa

ALEXANDER B. RABINOVICH,[1,2] and RICHARD E. THOMSON[1]

Abstract—The $M_w = 9.3$ megathrust earthquake of December 26, 2004 off the northwest coast of Sumatra in the Indian Ocean generated a catastrophic tsunami that was recorded by a large number of tide gauges throughout the World Ocean. Part 1 of our study of this event examines tide gauge measurements from the Indian Ocean region, at sites located from a few hundred to several thousand kilometers from the source area. Statistical characteristics of the tsunami waves, including wave height, duration, and arrival time, are determined, along with spectral properties of the tsunami records.

Key words: 2004 Sumatra tsunami, tide gauge records, Sumatra earthquake, Indian Ocean, tsunami travel time, spectral analysis.

1. Introduction

At 07:59 Local Indonesian Time (00:59 UTC) on December 26, 2004, a magnitude $M_w = 9.3$ megathrust earthquake occurred along 1300 km of the oceanic subduction zone from northwestern Sumatra Island to the Andaman Islands in the eastern Indian Ocean (STEIN and OKAL, 2005; LAY *et al.*, 2005a). The earthquake generated highly destructive tsunami waves that severely damaged the coastal regions of the Indian Ocean and killed more than 226,000 people (INTERNATIONAL FEDERATION OF RED CROSS AND RED CRESCENT SOCIETIES, 2005). Because of international tourism, many countries far removed from the major disaster areas lost citizens, triggering the largest international aid and relief effort in history. Tsunami waves recorded around the world revealed the unprecedented global reach of the 2004 tsunami (TITOV *et al.*, 2005).

The December 2004 tsunami is one of very few well documented global-scale tsunamis for which waves generated in one ocean propagate into other oceans. The first known global tsunami — that associated with the Krakatau Volcano explosion

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of 27 August 1883 (cf., MURTY, 1977) — was generated in the same region (the Indonesian Archipelago), demonstrating the potential of this region as a major source for worldwide catastrophic tsunamis. The 1883 Krakatau tsunami was recorded by 35 tide gauges, including gauges in Le Havre (France), Kodiak Island (Alaska) and San Francisco (SYMONS, 1888; PELINOVSKY *et al.*, 2005). However, a common opinion (cf., EWING and PRESS, 1955; GARRETT, 1970) is that tsunami waves recorded at far-field sites originated from coupling between the ocean surface and the eruption-induced atmospheric waves (that circuited the globe three times, see MURTY, 1977) rather than from direct water waves propagated from the source area. The limited quality of the analog records available for the 1883 tsunami, and the sketchy information on the source characteristics for the waves, do not allow a thorough quantitative analysis of the tsunami wave properties and global propagation pattern. An interesting attempt to model the global effect of this tsunami is presented by CHOI *et al.* (2003).

The second known global tsunami was the Chilean tsunami of May 22, 1960. The $M_w = 9.5$ earthquake off the coast of South Central Chile (the strongest ever recorded) generated one of the most destructive trans-Pacific tsunamis. The tsunami was measured by about 250 tide gauges in the Pacific Ocean (BERKMAN and SYMONS, 1960; WIGEN, 1960; TAKAHASHI and HATORI, 1961). Tsunami waves observed at many far-field sites (ten thousand kilometers from the source area) were very strong: For example, tsunami trough-to-crest of heights recorded at Attu Island (Alaska), Crescent City and Santa Monica (both California), were more than 3–4 m (BERKMAN and SYMONS, 1960). However, all these records were analog records in which the crests and troughs of the largest waves (i.e., those most important for analysis) were frequently chopped off because the instruments of the day were not designed to measure such strong oscillations. Moreover, it appears that no attention was paid to possible recordings of this tsunami outside of the Pacific Ocean; the single exception being the records at Fremantle and Port MacDonnell on the Indian Ocean coast of Australia (these records were assembled along with Australian records for the Pacific coast; cf., BERKMAN and SYMONS, 1960). Evidence that the 1960 Chilean tsunami was a global-scale event was provided over 25 years later when VAN DORN (1987) examined British and other hydrographic archives and located a few records of this tsunami at sites in the Indian Ocean (Bunbury, Australia; Mossel Bay, South Africa; and Mauritius Island) and Atlantic Ocean (Luderitz, South Africa; Newlyn, UK; and Bermuda).

The 2004 Sumatra tsunami was the third known global-scale tsunami, but the first to occur during the ''instrumental era,'' and it was clearly recorded by a large number of tide gauges throughout the World Ocean, including tide gauges located in the North Pacific and North Atlantic (RABINOVICH *et al.*, 2006). Global tsunami propagation models (TITOV *et al.*, 2005; KOWALIK *et al.*, 2005) demonstrate that mid-ocean ridges served as waveguides to the 2004 event, efficiently transmitting tsunami energy from the source area to far-field regions of the Pacific and Atlantic coasts of North America. The 2004 Sumatra tsunami is now recognized as the most globally distributed and accurately measured tsunami in recorded history. More than 200 digital records of this tsunami are available (cf., Institute of Ocean Sciences http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/tsunami/tsunamiasia_e.htm) and months after the event, tsunami measurements were still being collected and archived. Some of these data have been previously examined (cf., MERRIFIELD *et al.*, 2005; WOODWORTH *et al.*, 2005; TITOV *et al.*, 2005; NAGARAJAN *et al.*, 2006; TSUJI *et al.*, 2006; RABINOVICH *et al.*, 2006; FUJII and SATAKE, 2007). However, most of the data remain unexamined and unpublished. The purpose of our three-part study is to provide an overview of all available records for the 2004 Sumatra tsunami and to present fundamental statistical characteristics of these records. This study was initiated by the Working Group on Tide Gauge Measurements of the 2004 Sumatra Tsunami, IUGG Tsunami Commission. This first part focuses on the Indian Ocean; the second part will deal with the Atlantic Ocean, and the third part, with the Pacific Ocean.

In general, our ability to detect tsunami waves in a tide gauge record depends strongly on the signal/noise ratio of the data. For example, for the North Pacific and North Atlantic records, the 2004 Sumatra tsunami signal-to-background noise ratio typically ranged from 4:1 to 1:1, and was even lower at some sites, making tsunami detection difficult (RABINOVICH *et al.*, 2006). In contrast, for the Indian Ocean this ratio ranged from 40:1 to 20:1, so detection was straightforward. The main problems with the Indian Ocean records are the inadequate quality of some instruments, the overly long sampling interval (up to 1 hour at Kerguelen and St. Paul islands), extensive gaps in the data due to instrument and transmission problems, and damage from tsunami waves (some of the gauges were totally destroyed). In the present study, we filled gaps in the residual (de-tided) series with zeros. Data processing is similar to that described by RABINOVICH *et al.* (2006), including: (1) preliminary analysis, verification and correction of the original data; (2) de-tiding; (3) tsunami detection and statistical analysis; (4) high-frequency filtering (only for plotting purposes); (5) spectral analysis (except for the poor quality records or records with a sampling interval $\geqslant$ 30 min); and (6) time-frequency (wavelet-type) analysis. Published material has been used for those sites (in Thailand and at Port Blair, Andaman Islands, India) for which we do not have the original time series records.

Because tide gauge records available for the various sites had markedly different durations, sampling intervals and quality (some series had numerous gaps), we were required to select series with differing lengths for statistical, spectral and time-frequency analysis. We also had to take into account the actual length of the "ringing" (the duration of tsunami oscillations with significant wave heights) which was of much shorter duration for sites located relatively close to the source area (e.g., for the Maldives stations) than for the distant sites (e.g., South African stations). Despite these constraints, we tried to be consistent in our analysis by keeping the same analysis format and by assembling stations into comparable groups.

Known tide gauge records of the 2004 Sumatra tsunami in the Indian Ocean were separated into five groups (Fig. 1). The first group (Section 2) included records from stations in the Tropical Indian Ocean, specifically ten digital GLOSS stations and two digital Australian stations (the Cocos Islands and Hillarys). These records were probably the best known and widely used (cf., MERRIFIELD *et al.*, 2005; LAY *et al.*, 2005a; FINE *et al.*, 2005; FUJII and SATAKE, 2007). Most of the instruments for these sites were located on isolated islands. As a result, the records were not significantly affected by local topography and are, therefore, especially valuable for the analysis of the source parameters and for comparison with numerical modeling of the tsunami. The second group of records (Section 3) consists of records from nine Indian sites: eight from mainland tide gauges and one from Port Blair on the Andaman Islands. We do not have the Port Blair record, so the statistical information on this record is mainly from NEETU *et al.* (2005) and SINGH *et al.* (2006). Focus in Section 4 is on the near-field instruments located on the coasts of Indonesia and Thailand (Group 3).

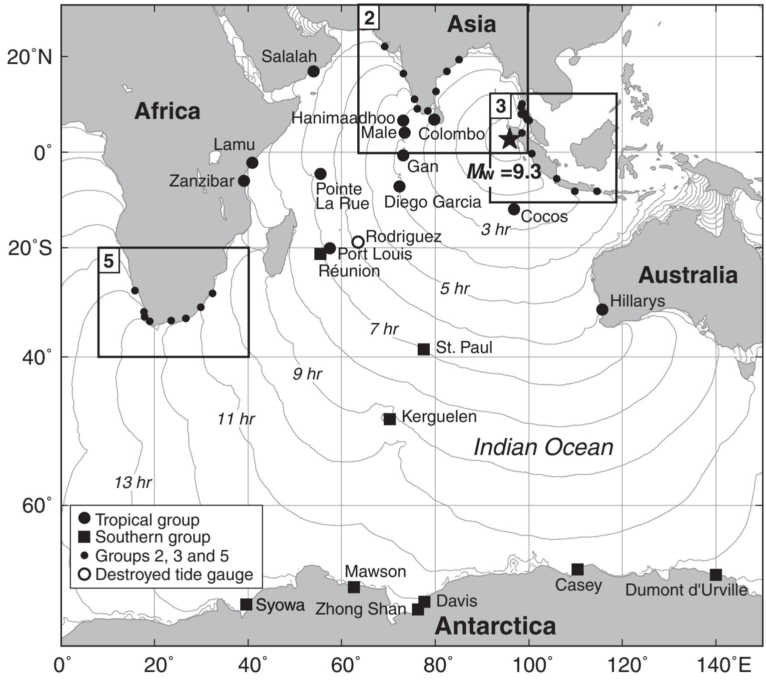

Figure 1

Map of the Indian Ocean showing the location of the $M_w = 9.3$ earthquake epicenter (star) and positions of tide gauges. Also shown are locations of the "India" (2), "Thailand and Indonesia" (3), and "South Africa" (5) boxes and the approximate positions of tide gauges for the corresponding groups (Groups, 2, 3 and 5, respectively). The names of the stations for these groups and more exact positions are presented in Figures 5, 9, and 17. Solid thin lines are the hourly isochrones of the tsunami travel time from the source area.

A preliminary analysis of the analog records from these tide gauges was provided by MERRIFIELD *et al.* (2005), TSUJI *et al.* (2006) and TANIOKA *et al.* (2006). The Indonesian records have now been re-digitized and made available for processing. Section 5 describes the records from the southern part of the Indian Ocean and the Antarctic coast (Group 4), specifically from three French stations located on La Réunion, Kerguelen and St. Paul islands and the French Antarctic station Dumont d'Urville, and four stations from the Australian Antarctic Division (Casey, Davis, Zhong Shan, and Mawson). This section also examines the record from the Japanese Antarctic station Syowa (Showa). Finally, the records from eight South African stations (Group 5) are presented and analyzed in Section 6. Although four of these stations are actually located on the Atlantic coast of South Africa, we decided to include the South African records from all eight stations into one group and describe them in Part 1 of this study rather than separate them into Indian Ocean and Atlantic units. Section 7 provides a discussion of the main results and a comparison between different groups of stations.

2. *Tropical Indian Ocean Stations*

The 2004 Sumatra tsunami was accurately recorded by ten digital Global Sea Level Observing System (GLOSS) stations located in the central and western parts of the Tropical Indian Ocean; one other GLOSS station located at Rodriguez Island (Mauritius) was destroyed by the first tsunami wave that arrived. Most of these stations were float tide gauges in stilling wells located in harbors, bays and lagoons (MERRIFIELD *et al.*, 2005). Data for the GLOSS stations were obtained from the University of Hawaii's (Honolulu) Sea Level Center database http://ilikai.soest.hawaii.edu/uhslc/iotd. Three of the GLOSS gauges, Colombo (Sri Lanka), Hanimaadhoo (Maldives), and Port Louis (Mauritius), had sampling intervals $\Delta t = 2\,\mathrm{min}$; station Diego Garcia (UK) had 6 min sampling, and six other stations had 4 min sampling (Table 1). In this group, we have included two Australian stations: Hillarys (west coast of Australia) and the Cocos Islands (Fig. 1). The digital tide gauge data for these stations (with 1-min sampling) were provided by the Australian Bureau of Meteorology. The tsunami arrival times for the GLOSS stations and the Cocos Islands were used by LAY *et al.* (2005a), FINE *et al.* (2005) and FUJII and SATAKE (2007) in inverse wave-tracing algorithms to delineate the source region for the 2004 event; the estimates were in good agreement with geophysical delineations of the source region (cf., STEIN and OKAL, 2005; TSAI *et al.*, 2005). The 2004 tsunami was also recorded by several other tide gauges along the mainland coast of Australia, including tide gauges on the southern coast of Australia that are officially designated as Indian Ocean sites (stations west of 147°E). However, all mainland stations from the south, east and north coasts of Australia, except Hillarys, will be examined in Part 3 of our study for the Pacific Ocean.

Table 1

Tsunami characteristics estimated from tide gauge records in the Tropical Indian Ocean. The number appearing in the brackets in column six denotes which wave in the sequence of incoming waves was highest

No	Station	Country	Coordinates	Sampling interval (min)	Maximum wave height (cm); number	First wave	
						Sign, arrival time (UTC)	Travel time
1	Cocos Islands	Australia	12.13°S; 96.88°E	1	59 (1)	(+) 03:17	2hr 18min
2	Colombo	Sri Lanka	06.93°N; 79.83°E	2	> 300 (2?)*	(+) 03:49	2hr 50min
3	Hanimaadhoo	Maldives	06.77°N; 73.18°E	2	217 (1)	(+) 04:30	3hr 31min
4	Male	Maldives	04.18°N; 73.52°E	4	215 (1)	(+) 04:14	3hr 15min
5	Gan	Maldives	00.68°S; 73.17°E	4	139 (1)	(+) 04:16	3hr 17min
6	Diego Garcia	UK	07.30°S; 72.38°E	6	90 (1)	(+) 04:45	3hr 46min
7	Rodriguez I.	Mauritius	19.67°S; 63.42°E	2	?	(?) 06:40	5hr 41min
8	Port Louis	Mauritius	20.15°S; 57.50°E	2	195 (?)	(?) 07:46	6hr 47min
9	La Réunion	France	20.92°S; 55.30°E	0.5*	70 (13)	(+) 07:55	6hr 56min
10	Hillarys	Australia	31.82°S; 115.73°E	1	108 (4)	(+) 07:14	6hr 15min
11	Salalah	Oman	17.00°N; 54.00°E	4	261 (3)	(+) 08:08	7hr 09min
12	Pointe La Rue	Seychelles	04.68°S; 55.53°E	4	278 (2)	(+) 08:16	7hr 17min
13	Lamu	Kenya	02.27°S; 40.90°E	4	100 (3)	(+) 09:52	8hr 53min
14	Zanzibar	Tanzania	06.15°S; 39.18°E	4	72 (4)	(+) 10:40	9hr 41min

Comments: (1) The tide gauge at Colombo was damaged by the first tsunami wave and did not operate for 5 hr 40 min; eyewitnesses reported that the second wave was the highest.

(2) The "La Réunion" record was digitized from a float-type analog tide gauge (an analysis of this record is presented in Section 5).

(3) The sign in brackets indicates the sign of the first semi-wave: crest (+) or trough (−).

(4) The tide gauge at Port Louis ceased to operate for one hour; the sign of the first wave remains unknown.

(5) The tide gauge at Rodriguez Island was destroyed by the first arriving tsunami wave.

2.1. Statistical Characteristics

Figure 2 presents de-tided records for the ten GLOSS and the two Australian stations. Due to technical problems, there were gaps in the Colombo, Hanimaadhoo, Gan and Port Louis records. These gaps prevented us from estimating exact statistical parameters for tsunami waves at these sites (Table 1). However, the general structure of the waves measured at each of these stations is well defined. MERRIFIELD *et al.* (2005) estimated the tsunami arrival times as the time of the first measured increase (or decrease) before the wave crest (or trough). In the present study, if there is a significant increase or decrease in water level between two successive observational samples, we have assumed that the actual arrival time is the time midway between the times of these samples; if the change is gradual, we take the first increase/decrease data point as the arrival time. This accounts for the small

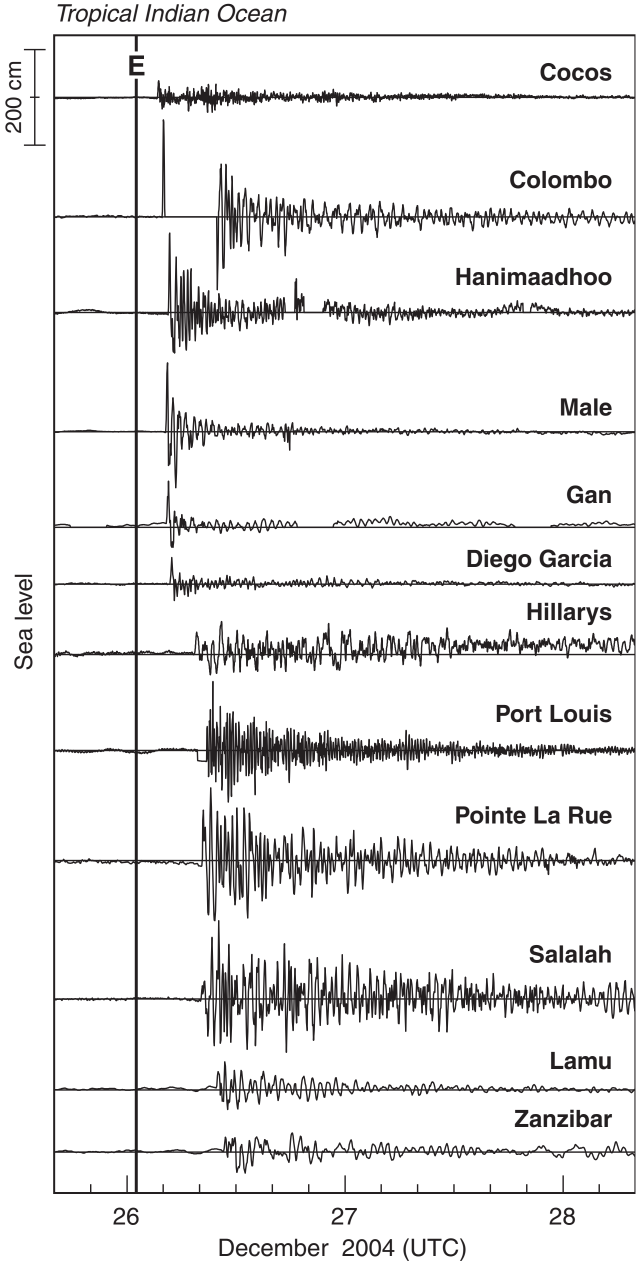

Figure 2
Tsunami records in the Indian Ocean for the 2004 Sumatra tsunami for 10 GLOSS and 2 Australian (Cocos and Hillarys) stations. Solid vertical line labelled "E" denotes the time of the main earthquake shock.

differences between our estimates (Table 1) and those of MERRIFIELD *et al.* (2005).[1] As noted above, the Rodriguez Island tide gauge (Mauritius) was destroyed by tsunami waves. In this case, the recording stop time is used to estimate the tsunami arrival and tsunami travel times (Table 1). For comparison, statistical characteristics of an analog record from La Réunion Island, France (a tropical island from the same group of the Mascarene Islands as Mauritius and Rodriguez — see Fig. 1) are also included in Table 1 (analysis of this record is presented in Section 5 together with other French records). Tsunami arrival times (TAT) estimated from direct observations are in good agreement with expected tsunami arrival times (ETA) obtained numerically (Fig. 1).

The main tsunami features evident in the records presented in Figure 2 are:

(a) Arrival times for tsunami waves at each site were abrupt and unambiguous;
(b) The first wave in most records was *positive* (wave crest);
(c) Maximum trough-to-crest wave heights ranged from 59 cm (Cocos Islands) to more than 2.5 m (Colombo, Salalah, and Pointe La Rue);
(d) Maximum waves occurred near the beginning of the first wave train; the first wave was maximum for the Cocos Islands, Hanimaadhoo, Male, Gan, and Diego Garcia; the second wave for Colombo (by eyewitness reports) and Pointe La Rue, the third wave for Salalah and Lamu; and the forth wave for Hillarys and Zanzibar. In general, the greater the distance and wave propagation time for the waves, the higher the sequence number (1st, 2nd, ...) of the maximum wave (Table 1);
(e) The rate of tsunami energy decay was relatively fast for stations close to the source region (Cocos, Hanimaadhoo, Male, Gan and Colombo) and slowed with increasing station distance from the source (Hillarys, Port Louis, Pointe La Rue, Salalah, Lamu and Zanzibar);
(f) In general, the duration of tsunami ringing for distant sites increased with increasing distance from the source region, ranging from a few hours for Male and Gan to more than two days for Salalah and Pointe La Rue.
(g) The recorded oscillations were polychromatic, with different periods for different sites, but with clear dominance of 40–50 min waves at most sites. The exceptions are Port Louis (Mauritius) and the Cocos Islands, where 20-min waves prevailed.

The observational records and numerical simulations (TITOV *et al.*, 2005; KOWALIK *et al.*, 2005) indicate marked anisotropic spreading of tsunami energy from the source area. Most of the energy propagated toward the west and southwest, while only a fraction went toward the south and southeast. This aspect of energy spreading is mainly related to the orientation of the earthquake rupture. Most tsunami energy

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[1] In Table 1 of MERRIFIELD *et al.* (2005), the tsunami arrival time for Diego Garcia was out by 1 hour and the tsunami arrival time for Port Louis was erroneously written as 7:42 instead of 7:46 (Mark Merrifield, Pers. Comm., 2006).

radiates normally (at 90°) to the direction of rupture; little energy radiates outward along the direction of the rupture. For this reason, tsunami waves at the Maldives, Seychelles and Salalah were considerably higher than those at the Cocos Islands, despite the fact that the latter are much closer to the source ($\sim$1650 km versus $\sim$2500–5000 km).

2.2. Spectral Properties

To determine the spectral properties of the tsunami waves at the twelve gauge sites (Table 1; Fig. 2), and to compare these properties with those of the background oscillations at the same sites, we separated the records into pre-tsunami and tsunami parts. The data from roughly 1-day period preceding the tsunami arrivals were selected for determination of the background oscillations. For the "tsunami" periods, we mainly used the leading 21.3 hours of each segment (1280 samples for 1-min data, 640 for 2-min, and 320 for 4-min data); for Diego Garcia, we used 25.6-hour segments (256 samples) for both background and tsunami periods. Our spectral analysis procedure is similar to that described by EMERY and THOMSON (2003). To improve the spectral estimates, we used a Kaiser-Bessel (KB) spectral window with half-window overlaps prior to the Fourier transform. The length of the window was chosen to be 768 min for Diego Garcia and 512 min for the eleven other stations, yielding 6 to 10 degrees of freedom per spectral estimate depending on the length of the data segment.

In general, the spectra of both tsunami and background (Fig. 3) are "red," with spectral energy decreasing with increasing frequency as roughly ω^{-2}. This is typical for long-wave sea-level spectra (RABINOVICH, 1997). At most stations, tsunami spectra are two to three orders of magnitude greater than background spectra. The background spectra at most stations have a relatively "smooth" profile, probably because the majority of these stations are located on isolated open-ocean islands. On the other hand, background spectra at Port Louis (Mauritius) have prominent peaks at periods of 20 and 7.4 min (Fig. 3b, upper right). Near identical peaks are evident in the corresponding tsunami spectrum indicating that the local topography has a major effect on the longwave oscillations at this site. The dominance of relatively high-frequency oscillations at Port Louis compared to all other sites is clearly evident in the records (Fig. 2). The only other station with dominant high-frequency tsunami oscillations (periods of 21 and 14 min) is the Cocos Islands (the upper record in Fig. 2 and the upper left plot in Fig. 3a). At all other stations, low-frequency tsunami oscillations (with typical periods from 35 to 85 min) prevailed (Fig. 3). The dominance of strong low-frequency oscillations in the 2004 tsunami records is apparently associated with the large extent of the source area (approximately 1300 km according to recent estimates; cf., STEIN and OKAL, 2005; FUJII and SATAKE, 2007). At the same time, the specific tsunami spectral peaks observed at certain sites (73 min at Colombo, 45 min at Salalah, 64 min at Lamu, 51 min at

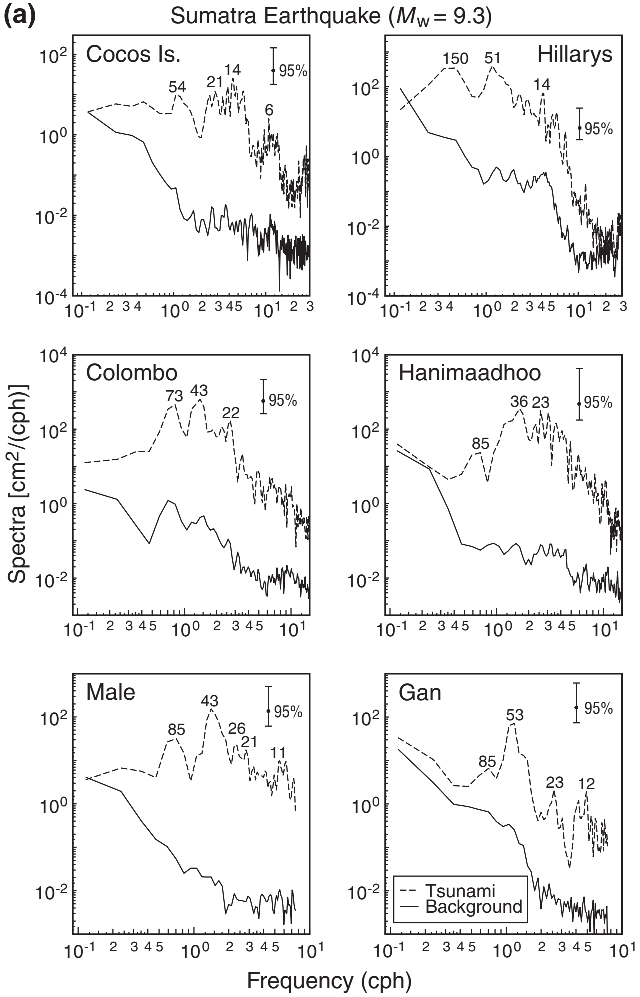

Figure 3

Computed spectra of background (pre-tsunami) and tsunami oscillations for the twelve tide gauge records shown in Figure 2. Periods (in min) of the main spectral peaks are indicated. Note differences in frequency scales for the various stations due to the differences in tide gauge sampling intervals.

Zanzibar) are similar to the background spectral peaks at the corresponding sites, indicating the pronounced influence of local topography.

2.3. *Time-frequency Analysis*

To examine temporal variations in the frequency of the observed tsunami waves, we used a method developed by DZIEWONSKI *et al.* (1969) to study nonstationary

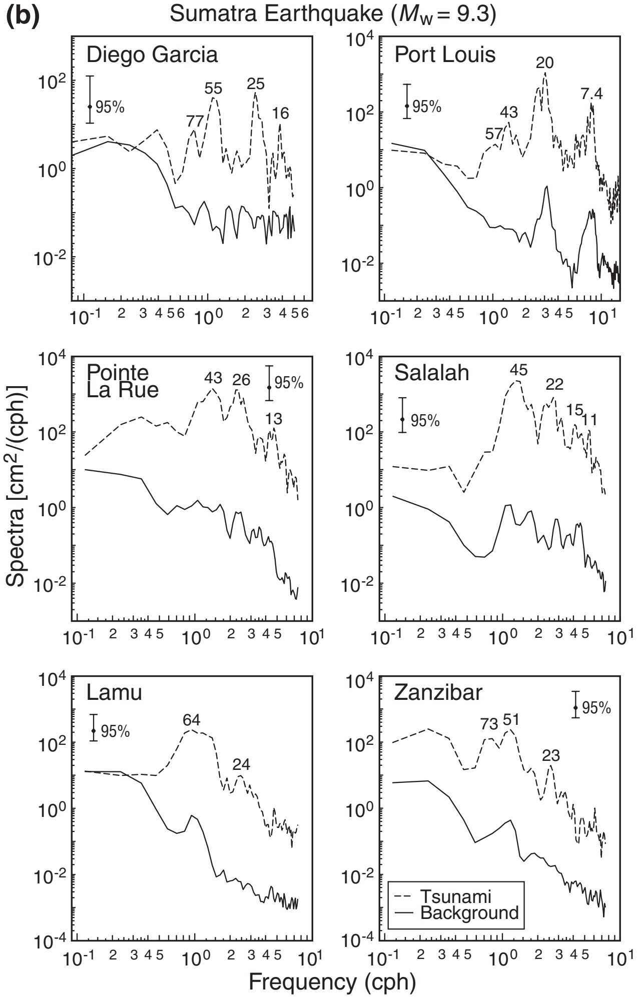

Figure 3
(Contd.)

seismic signals in which the time series displays rapid temporal changes in amplitude and/or phase. The method, which is similar to wavelet analysis (EMERY and THOMSON, 2003), is based on narrow-band filters, $H(\omega)$, with a Gaussian window that isolates a specific center frequency, $\omega_n = 2\pi f_n$:

$$H_n(\omega) = e^{-\alpha\left(\frac{\omega-\omega_n}{\omega}\right)^2}. \tag{1}$$

The frequency resolution is controlled by the parameter α. The higher the value of α, the better the resolution in the frequency domain but the poorer the resolution in the time domain (and *vice versa*.) We used α = 60–80 in our computations.

Demodulation of a sea-level time series, $\zeta(\omega_n; t)$, yields a matrix of amplitudes (phases) of wave motions with columns representing time and rows representing frequency (the so-called *f-t* diagrams). This method can be used effectively to indicate how the tsunami wave energy $E(f, t)$ changes as a function of frequency, f, and time, t (GONZÁLEZ and KULIKOV, 1993; KULIKOV *et al.*, 1996; RABINOVICH *et al.*, 2006).

Figure 4 presents *f-t* diagrams for tide gauge records for twelve Tropical Indian Ocean stations. Blank bands correspond to data gaps. The tsunami wave arrival times are well defined at all stations and mutually consistent. There were no pronounced background oscillations prior to the tsunami arrival, which is an advantage for tsunami wave detection and estimation of exact arrival time. Overall, the range of periods having high energy concentration (20 to 85 min) with peak values at 35–60 min is roughly the same for the entire Indian Ocean and approximately the same as that observed in the North Pacific and North Atlantic oceans (RABINOVICH *et al.*, 2006). However, the *f-t* diagrams for Port Louis and the Cocos Islands are different from the others in that most of the observed tsunami energy is associated with short wave periods (<22 min), with little energy at periods of 35–60 min (see also Fig. 3). According to the *f-t* diagrams, the tsunami waves at most sites were mainly polychromatic with several dominant energy bands. There is an obvious difference between the *f-t* diagrams for stations located relatively close to the source area (i.e., Colombo, Hanimaadhoo, Male, Gan, and Diego Garcia, which lie within 3–4 hour travel distances from the source) and similar diagrams for far-field stations (Hillarys, Salalah, Pointe La Rue, Port Louis, Lamu, and Zanzibar). The former are characterized by high energy 6–12 hr after the tsunami arrival with negligible energy afterwards; the latter are remarkable for their long ringing times and clear wave-train structure with train durations from 8 to 18 hours. Once again, the Cocos record is different. Located closest to the source (2.3-hr travel time), this station is characterized by a long ringing time ($\sim$1.5 days) and many short-duration wave trains ($\sim$3–5 hr) (Fig. 4, top left). Apparently, the tsunami wave behavior at this site is attributable to the fact that the waves emanating from the source travelled in a parallel direction to the earthquake rupture and to the influence of tsunami waves reflected from the southwestern coasts of the Indonesian Islands and northwestern coast of Australia.

3. Indian Stations

The Survey of India (SOI) agency maintains a network of tide gauges along the coast of India (Fig. 5) that accurately recorded the 2004 Sumatra tsunami (Fig. 6). High-quality de-tided records for this region are available from the National Institute of Oceanography (NIO), Goa, India for seven tide gauges (see the NIO website: http://www.nio.org/jsp/tsunami.jsp): Paradip, Vishakhapatnam,

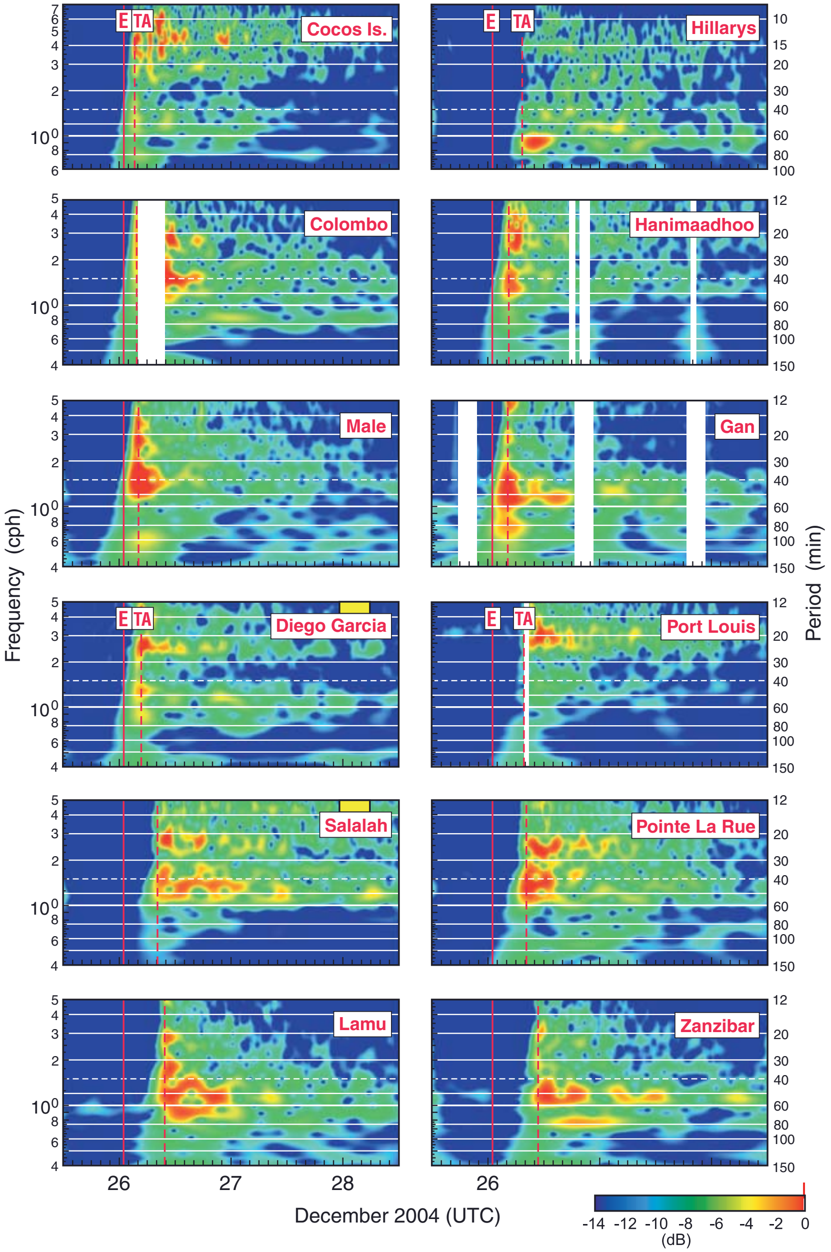

Figure 4

Frequency-time plots (*f-t* diagrams) for the 2004 Sumatra tsunami tide gauge records for twelve records shown in Figure 2 (station locations are shown in Figure 1) Blank bands correspond to the data gaps. The dashed white horizontal line indicates the 40-minute wave period; the solid red vertical line labelled "E" denotes the time of the main earthquake shock and the dashed red vertical line indicates tsunami arrival time ("TA").

Chennai, Tuticorin, Kochi (Cochin), Mormugao, and Okha (Table 2). Unfortunately, the tide gauge for Nagapattinam, located in the most strongly affected sector of the Indian coast (southward from Chennai; Fig. 5), was heavily damaged by the tsunami waves so that the 2004 tsunami record could not be retrieved (Nagarajan *et al.*, 2006).

SOI tide gauges were either mechanical float-type analog gauges or pressure-sensor gauges (Nagarajan *et al.*, 2006). The pressure-sensor gauges (Paradip, Tuticorin and Kochi) had sampling intervals of 6 min; the analog records were digitized by SOI at an interval of 5 min for Vishakhapatnam, Chennai, and Mormugao and at interval of 6 min for Okha (Table 2). We also used the 15-min sampled tsunami record (provided to us by K.A. Abdul Rasheed, NIO, Regional Centre, Kochi, India) from the tide gauge at Neendakara located on the southwestern coast of India southward from Kochi (Fig. 5). Pronounced tsunami oscillations were clearly recorded at this station (Kurian *et al.*, 2006; Rasheed *et al.*, 2006). Figure 6 presents the de-tided records for all eight stations of Group 2. Due to instrumental problems, the Vishakhapatnam record had a gap of approximately two hours that was filled by zeros.

3.1. General Description and Statistical Characteristics

Maximum tsunami wave heights (2.9–3.2 m) were recorded at Paradip, Vishakhapatnam and Chennai on the east coast of India. Tsunami waves arrived at these

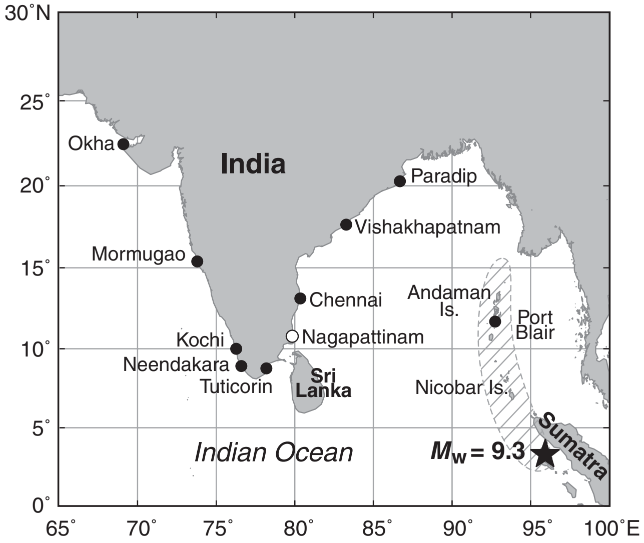

Figure 5

Map of the coast of India showing the location of the $M_w = 9.3$ earthquake epicenter (star), the aftershock zone (shaded area), and positions of Indian tide gauges where the 2004 Sumatra tsunami waves were recorded (solid circles) and the Nagapattinam tide gauge destroyed by the tsunami (empty circle).