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Introduction to ''Tsunami Science Four Years After the 2004 Indian Ocean Tsunami, Part II: Observation and Data Analysis''

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Abstract—In this introduction we briefly summarize the fourteen contributions to Part II of this special issue on *Tsunami Science Four Years After the 2004 Indian Ocean Tsunami*. These papers are representative of the new tsunami science being conducted since the occurrence of that tragic event. Most of these were presented at the session: Tsunami Generation and Hazard, of the International Union of Geodesy and Geophysics XXIV General Assembly held at Perugia, Italy, in July of 2007. That session included over one hundred presentations on a wide range of topics in tsunami research. The papers grouped into Part II, and introduced here, cover field observations of recent tsunami's, modern studies of historical events, coastal sea-level observations and case studies in tsunami data analysis.

Key words: Tsunami, tide gauge, sea level, waveform inversion, seiche, harbor resonance, numerical modeling, post-tsunami survey, tsunami warning system, runup.

1. Introduction

During the years following the 2004 Sumatra-Andaman Earthquake and subsequent Indian Ocean Tsunami (IOT), the world experienced a remarkable series of great earthquakes. The 2004 event marked the beginning of a series of earthquakes off Sumatra that included three of the ten largest earthquakes recorded since 1900 (http://earthquake.usgs.gov). During the period 2004–2007, nine earthquakes of magnitude 8 or greater occurred in the Indian and Pacific Oceans; all of which generated tsunami's, of which six were large enough to cause damage. These events coincided with a period of rapid growth in tsunami science spurred by the IOT disaster, including an expansion in earthquake and tsunami observation platforms, as well as dramatic improvements in technology and field techniques. Many observational studies of these and other events were presented in the session: Tsunami Generation and Hazard, at the International Union of Geodesy and Geophysics XXIV General Assembly in Perugia, Italy, held in July of 2007. Over

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one hundred presentations were made at this session, spanning topics ranging from paleo-tsunami research, to nonlinear shallow-water theory, to tsunami hazard and risk assessment. A selection of this work is published in detail in the 28 papers of the special issue of Pure and Applied Geophysics.

In this introductory paper, we briefly discuss the papers in this second part of *Tsunami Science Four Years after the 2004 Indian Ocean Tsunami*. In Section 2 we discuss field observations of recent tsunamis, while Section 3 describes some modern studies of historical events. Section 4 discusses tide gauge observations and Section 5 data analysis case studies.

2. *Field Observations of Recent Tsunamis*

Each damaging tsunami resulting from the series of great tsunamigenic earthquakes that occurred in 2004–2007 was followed by one or more post-tsunami surveys, and reports on three of these surveys appear in this volume. Careful observations of actual tsunami impacts, such as those presented in these reports, are invaluable for understanding tsunami runup and inundation, validating numerical tsunami models, and for interpreting geological signatures of paleo-tsunamis. The studies described below demonstrate how post-tsunami field observations can be used to infer detailed characteristics of the causative tsunami, to determine what factors influence inundation and runup, and to inform tsunami warning procedures.

Lavigne *et al*. (2009) provided a comprehensive summary of three months of tsunami field surveys from Banda Aceh and Lhok Nga, Indonesia in the aftermath of the 2004 Indian Ocean tsunami. Runup, wave heights, flow depths and directions, event chronologies and building damage patterns, inundation maps, high-resolution digital elevation models were collected and compiled. They reported that approximately 10 separate waves affected the region, and that the largest runups measured about 35 m with a maximum of 51 m; the highest value measured in human history from a seismically-generated tsunami. The open-source database is being made available to the community under the cooperative French-Indonesian TSUNARISQUE program to assist in better calibrating numerical models.

MacInnes *et al*. (2009) reported the results of their post-tsunami field survey of the M_w 8.3 Kuril Earthquake, which occurred on 15 November 2006, in the middle of Kuril Islands. Fortunately, they visited the islands for a paleo-tsunami survey in the summer of 2006, three months before the earthquake, hence they could compare visual observations, photographs and measurements of topographic profiles taken before and after the tsunami. While the November 2006 earthquake was followed by the January 2007 earthquake, the tsunami from the latter was smaller than that from the former, hence the authors attributed the geological traces of tsunamis to the 2006 earthquake. They found that the tsunami heights strongly depended on the local topography, and averaged about 10 m with a maximum of more than 20 m. Wherever sand was available, it was brought inland and deposited with landward thinning and fining features. Similar tsunami deposits from previous earthquakes were also found. They also described significant coastal erosion features, such as scours, soil stripping, rock plucking or cliff retreat, at places where the runup heights were more than 10 m.

The effects of the 2006 Kuril Earthquake were also experienced in the far field. Dengler *et al*. (2009) reported on the impact of this event in Crescent City, California, where later-arriving maximum waves and strong currents in excess of 10 knots over an 8-hour period caused an estimated US $9.2 million of damage to harbor docks despite its arrival at low tide. Crescent City is known to be historically vulnerable to tsunamis because of its coastal and undersea morphology. As a result of the 2006 tsunami, and to advise coastal officials that local conditions can cause wave amplification and strong currents, the West Coast/Alaska Tsunami Warning Center redefined its Advisory to caution that coastal threats may still persist even though significant widespread inundation was not expected for all regions. The authors also emphasized the important role of awareness as being a key for tsunami safety, especially when only modest tsunamis are expected.

3. *Modern Studies of Historical Events*

Several papers in this volume address the need to understand historical events in order to correctly infer what implications they may have for tsunami hazard. Historical events are most often studied by combining field observations of the type described above, with numerical or laboratory modeling, which can elucidate their source mechanisms. As demonstrated in the papers described below, an accurate understanding of the source mechanisms of historical tsunami events is important for assessing the potential for the occurrence of similar events.

Suleimani *et al*. (2009) used a viscous slide model coupled with shallow water equations to successfully model landslides and the ensuing local tsunami waves in Resurrection Bay, a glacial fjord in south-central Alaska, after the M_w 9.2 1964 Prince William Sound earthquake. The numerical results, in good agreement with eyewitness reports and other observational data, showed that three underwater slope failures were the major contributors to the tsunami that attacked Seward, Alaska less than five minutes after the earthquake. Their modelling approach was shown to be a useful tool for estimating landslide tsunami hazard, and their work demonstrated the need to consider these hazards in Alaska fjords where glacial sediments are accumulating at high rates on steep underwater slopes.

Fritz *et al*. (2009) summarized two- and three-dimensional physical laboratory experiments that used a pneumatic landslide tsunami generator to model the 1958 Lituya Bay landslide tsunami, resulting in the highest wave runup (524 m) in recorded history. State-of-the-art measurement techniques were used to measure and photograph the landslide-water impact and wave generation. The two-dimensional velocity vector field showed the impact to be divided into two stages: (a) Impact and penetration with flow separation, cavity formation, and wave generation, and (b) air cavity collapse with landslide run-out and debris entrainment. The results were compared with other predictive relationships for amplitude and height since no actual tsunami heights are available. Because this landslide-generated tsunami exhibited strong energy directivity, a three-dimensional physical model was constructed, and the surface velocities measured for future validation and benchmarking, using detailed bathymetry in a three-dimensional numerical simulation.

Yelles-Chaouche *et al.* (2009) investigated the tsunamis generated from the 1856 Djidjelli earthquakes. Historical seismic intensity and tsunami wave information, combined with seismicity over the past 30 years and bathymetric and seismic reflection lines collected in 2005, were used to characterize the seismotectonics of the region and to infer the source rupture of the main earthquake and tsunami source. The numerical model results showed that much of the eastern Algerian coast and Balearic Islands were affected, with a maximum wave height of 1.5 m near the harbor of Djidjelli. This event, together with the 2003 Bourmerdes tsunami, demonstrate that the Algerian margin hosts several active tsunamigenic faults that could cause damage to the western Mediterranean and Algerian coasts.

Hirata *et al.* (2009) reviewed multiple occurrences of tsunamigenic earthquakes along the southern Kuril subduction megathrust; one of the few areas in the world where one can test the contention that earthquake rupture occurs along characteristic segments. Tsunami data, both historic (tide gauge, field measurements, and eyewitness observations) and prehistoric (tsunami deposits), are used to provide information on rupture extent. The authors' interpretation of past studies indicates that there is substantial variability of rupture from event to event, suggesting that the idea that earthquakes repeatedly rupture characteristic segments is an oversimplification.

4. *Coastal Sea-level Gauge Observations of Tsunamis*

Sea-level records from coastal tide gauge stations provide some of the most detailed information available on tsunami source signatures and tsunami interaction with shallow bathymetry. They therefore have great potential to improve our understanding of potential coastal impacts of future tsunami's. They are also a critical source of information for tsunami warning systems to confirm generation of a tsunami (though data from DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys are also being used for this purpose). For these reasons, understanding the quality of data from coastal tide gauges and what influences the signals recorded on them is of great importance in both progressing tsunami science and supporting tsunami mitigation. Four papers in this special issue dealt with sea-level data recorded by coastal gauges, Stephenson and Rabinovich (2009), Namegaya *et al.* (2009), Pattiaratchi and Wijeratne (2009), and Abe (2009).

Stephenson and Rabinovich (2009) compiled tsunami instrumental data recorded on the Pacific Coast of Canada in 1994–2007. During these 15 years, 16 tsunamis were recorded. Eleven of these were from distant sources around the Pacific Ocean and the 2004 Indian Ocean tsunami. Three were from local earthquakes in Canada and a regional event in California, and two were of meteorological origin. Through their analysis, they found that the background noise level was very high at Langara point, the northernmost station of British Columbia and hence an important location for a tsunami warning system. The station was therefore moved to a more protected location.

NAMEGAYA *et al.* (2009) presented results of analyses of tide gauge response characteristics and their influence on tsunami measurements. Following on from a study by SATAKE *et al.* (1988), in which tide gauge response characteristics were measured for tide gauge stations in northeast Japan, the authors made similar measurements for tide gauge stations located on the Japan Sea coast. The paper presented a thorough investigation of tide gauge response and corrections for these stations, showing that there was a wide variety of behavior between tide gauges. The results have the potential to facilitate analyses of tsunamis in the Sea of Japan, particularly the tsunami caused by the 2007 Niigataken Chuetsu-oki earthquake.

PATTIARATCHI and WIJERATNE (2009) presented summaries of sea-level records from three Sri Lanka and eleven Western Australia stations that recorded Indian Ocean tsunamis between 2004 and 2007. In comparing the station records, they showed that although the relative magnitude of the tsunami's varied due to the differences in the tsunami source, tsunami behavior at each station was similar and was affected by local and regional topography. Sea-level records from stations on the western side of Sri Lanka clearly showed reflections from the Maldives that arrived 2–3 hours after the first tsunami wave. Similarly, reflections from the Mascarene Ridge and/or Madagascar were observed about 15 hours after the first wave in records in western Australia. Tsunami waves also excited oscillations, or seiches, at a local resonance frequency that is related to the fundamental period of the offshore shelf.

ABE (2009) discussed the relation between resonant frequencies of Japanese ports and dominant periods of recent tsunamis (in 1983 and 1993) in the Japan Sea. The author measured sea level at 55 Japanese ports in comparatively calm conditions using a pressure gauge, and estimated the natural periods of harbor resonances (seiches) from the maximum spectral amplitudes. These were compared with similar analyses applied to coastal tide gauge recordings of the 1993 Hokkaido Nansei-oki and the 1983 Nihonkai Chubu-oki tsunamis. The author was able to conclude that natural oscillations were excited during the tsunamis. These new data on natural periods are an important contribution to the understanding of tsunami hazard in the bays along the Japan Sea coast.

5. Data Analysis Case Studies

The heightened tsunami activity during the period 2004–2007 contributed substantially to the pool of observational data on tsunami's, and this has spurred the development of new data analysis techniques, and increased the number of available case studies against which existing techniques could be benchmarked. The studies described below detail how this has led to improved understanding of the effects of source and bathymetry on tsunami waveforms and travel times.

Baba *et al.* (2009) investigated the degree to which finite fault inversions of seismic data for earthquake rupture patterns can be used to predict far-field tsunamis. They based their case study on the M_w 8.3 Kuril subduction zone earthquake of 15 November, 2006, which was the first teletsunami to be widely recorded by bottom pressure recorders deployed in the northern Pacific Ocean. Since these observations are not subject to the sensitivity to shallow bathymetry that introduces considerable uncertainty into coastal tide gauge measurements, any discrepancy between observed and predicted tsunami waveforms could be confidently ascribed to the source model. Baba *et al.* (2009) found that the source model obtained from seismic data, especially when seismic surface wave data are used, could be used to predict the tsunami waveforms with sufficiently high precision that they could be used in a joint inversion to better constrain earthquake source properties such as rupture velocity. The potential for use of such seismic models in a tsunami warning system to rapidly forecast teletsunami waveforms is discussed.

Hébert *et al.* (2009) compared several methods for characterizing the earthquake source of the M_w 8.0 2007 Peru earthquake, and then used them to model the tsunami in the far field in Nuku Hiva, Marquesas Islands, French Polynesia. A quick moment tensor inversion method (Preliminary Determination of Focal Mechanism, PDFM), available about 30 minutes after the earthquake, using seismic surface waves, gave a tsunami source that predicted far-field wave heights that were in good agreement over the first 90 minutes of tsunami wave arrivals. In contrast, the tsunami source from seismic body-wave inversion, while providing details on fault slip distribution and magnitude, produced far-field tsunami waves that were too small, thus confirming that tsunami waves are substantially more influenced by the earthquake's lower frequency components. The authors concluded that the PDFM method, complemented by inversions of the DART tsunami data, showed promise as an efficient, fast inversion method that can produce a realistic source permitting more accurate far-field wave forecasts to be calculated and used in tsunami warning applications.

Wessel (2009) compared tsunami travel times reported in the literature with times predicted using the standard Huygens method. Over 1500 records from 127 earthquakes around the Pacific Ocean were compared. He first found large outliers in reported travel times; aside from obvious clerical errors, these outliers may be attributed to first arrivals that were missed because of their small amplitude, or to incomplete bathymetry data. Robust statistical analysis indicates that the median difference between data and predictions was less than 1 min, with an absolute deviation of 33 min. Fine bathymetry data with 2 min gridding yielded better results than a coarser 5 min grid.

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