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Introduction to "Global Tsunami Science: Past and Future, Volume I"

Eric L. Geist,[1] Hermann M. Fritz,[2] Alexander B. Rabinovich,[3,4] and Yuichiro Tanioka[5]

Abstract—Twenty-five papers on the study of tsunamis are included in Volume I of the PAGEOPH topical issue "Global Tsunami Science: Past and Future". Six papers examine various aspects of tsunami probability and uncertainty analysis related to hazard assessment. Three papers relate to deterministic hazard and risk assessment. Five more papers present new methods for tsunami warning and detection. Six papers describe new methods for modeling tsunami hydrodynamics. Two papers investigate tsunamis generated by non-seismic sources: landslides and meteorological disturbances. The final three papers describe important case studies of recent and historical events. Collectively, this volume highlights contemporary trends in global tsunami research, both fundamental and applied toward hazard assessment and mitigation.

Key words: Tsunami investigation, Tsunami Warning System, Tsunami detection, Tsunami records, Tsunami modeling, Pacific Ocean, Spectral analysis, Tsunami probability, Landslide tsunami, Meteotsunami.

1. Introduction

Tsunami science has evolved significantly since two of the most destructive natural disasters that have occurred in this century: the 26 December 2004 tsunami that killed about 230,000 people along the coasts of 14 countries in the Indian Ocean and the 11 March 2011 Tohoku (Great East Japan) tsunami that killed almost 20,000 people and destroyed the Fukushima Daiichi nuclear power plant (Satake et al. 2013a). There have also been many other devastating tsunamis over the past decade that have guided tsunami science, including the 2006 Java, 2007 Solomon Islands, 2009 Samoa, 2010, 2014, and 2015 Chile, 2010 Mentawai (Indonesia), 2012 Haida Gwaii, and 2013 Santa Cruz Islands events. Not only from countries affected by these events, but scientists from around the world have come together to engage in tsunami research. The global community of researchers has also expanded by discipline, adapting advances in other sciences to study all aspects of tsunami hydrodynamics, detection, generation, and probability of occurrence.

One of the most important outcomes of this research is advancement of tsunami hazard assessment and mitigation. Tsunami warning systems are at the forefront of this effort. When tsunami warning systems were first developed, only the arrival time of the first wave (often not the wave with the largest amplitude) could be accurately forecasted. Now, precomputed tsunami models enable refined real-time forecasts of tsunami runup and inundation for cities and communities at risk from tsunamis. Tsunami hazard assessments continue to improve as well, by analyzing currents during inundation (an important tsunami factor that relates to severe damage in ports and harbors), dynamic interactions with tides and rivers, incorporating landslide and meteorological tsunami generation, and the development of the tsunami hazard curve that yields probability of wave height exceedance. In the future, tsunamis will remain a major threat to coastal infrastructure and human life; so it is of utmost importance to advance our understanding of all aspects of tsunami research and apply our knowledge so that early tsunami

[1] U.S. Geological Survey, 345 Middlefield Rd., MS 999, Menlo Park, CA 94025, USA. E-mail: egeist@usgs.gov
[2] School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA. E-mail: fritz@gatech.edu
[3] Department of Fisheries and Oceans, Institute of Ocean Sciences, 9860 West Saanich Rd., Sidney, BC V8L 4B2, Canada. E-mail: Alexander.Rabinovich@dfo-mpo.gc.ca; a.b.rabinovich@gmail.com
[4] P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr., Moscow 117997, Russia.
[5] Institute of Seismology and Volcanology, Hokkaido University, N10W8 Kita-ku, Sapporo 060-0810, Japan. E-mail: tanioka@mail.sci.hokudai.ac.jp

warning, hazard assessment and mitigation tools continue to be developed and refined.

The Joint Tsunami Commission, part of the International Union of Geodesy and Geophysics (IUGG), conceived the present volume. The Joint Tsunami Commission was established following the 1960 Chile tsunami, which was generated by the largest (M_w 9.5) instrumentally recorded earthquake, propagated throughout the entire Pacific Ocean, and affected many countries throughout the ocean basin. It became obvious that tsunami investigation and effective tsunami warning is impossible without intensive international cooperation. Since 1960, the Joint Tsunami Commission has held biannual International Tsunami Symposia and published special volumes of selected papers. Several such volumes have been published in PAGEOPH during ten years following the 2004 Sumatra tsunami, including, Satake et al. (2007, 2011a, b, 2013a, b), Cummins et al. (2008, 2009), and Rabinovich et al. (2015a, b). Two recent catastrophic tsunamis, the 2010 Chile and 2011 Tohoku, as well as other events which occurred around this time, attracted so much attention and brought so much new information and data, that an extra, intersession volume was collected and published (Rabinovich et al. 2014). From this point of view, these volumes can be considered as the frontiers of the tsunami science and research, as well as a record of continuous progress in tsunami warning and hazard mitigation.

The current volume is mainly based on papers presented at the 27th International Tsunami Symposium sponsored by the Joint Tsunami Commission, as part of the 26th IUGG General Assembly held from 22 June to 2 July 2015 in Prague, Czech Republic. Altogether, about 100 presentations comprised the symposium. At the business meeting of the Joint Tsunami Commission, it was decided to publish selected papers presented at this symposium, as well as other papers on related topics. Volume I comprises the first contribution, 25 papers, which became ready for publication by December 2016. Approximately, the same number of papers is planned for the forthcoming Volume II in 2017.

2. *Tsunami Probability and Uncertainty Analysis*

Probabilistic tsunami hazard analysis (PTHA) has become an important tool for hazard assessment in recent years. Six papers in this volume related to this analysis represent significant advances and refinements in PTHA methodology. One of the principal earthquake source parameters controlling tsunami generation is slip and its variability within the rupture zone. LeVeque et al. (2016) present a new method to stochastically simulate earthquake slip for general fault geometries as part of calculating tsunami hazard curves from numerical models. They demonstrate how this new method incorporates aleatory uncertainty (i.e., natural randomness) associated with rupture complexity into computational PTHA for earthquakes along the Cascadia subduction zone. Carvajal and Gubler (2016) indicate the importance of slip variation on tsunami hazard assessment by directly comparing tsunami results using traditional uniform-slip ruptures to results from different bell-shaped slip patterns.

A different and lesser-known type of PTHA, in contrast to the computational approach, is empirical PTHA where hazard curves are constructed from tide-gauge data directly, without the use of numerical hydrodynamic models. Empirical PTHA often suffers from short catalog durations and saturation of tsunami wave amplitudes for large events. Geist and Parsons (2016) develop a method to bolster empirical PTHA by transforming earthquake catalogue magnitudes to tsunami amplitudes, using station-specific scaling functions.

Three papers show how PTHA is put into practice in developing tsunami hazard curves for specific regions. Two papers are among the first to incorporate landslide tsunami sources into PTHA. Kulkarni et al. (2016) calculate hazard curves for a site on the Bay of Fundy, Canada, considering both local and regional earthquake and landslide sources. Lane et al. (2016) calculate tsunami hazard curves for Wellington, New Zealand specific to tsunamis produced by local landslides in the nearby Cook Strait Canyon. In past PTHA applications, aleatory uncertainty is integrated directly into computation of the hazard curve. As an alternative, Omira et al. (2016) present an event-tree method for incorporating aleatory uncertainty into the hazard calculation and use this procedure for a site on the northeast Atlantic coast of Portugal.

3. Deterministic Hazard and Risk Assessment

An important complement to PTHA is deterministic tsunami hazard assessment. Deterministic assessments are directly amenable to risk analysis as in the case of the paper by Pagnoni and Tinti (2016). The authors considered several inundation scenarios to examine tsunami vulnerability for the area of Siracusa on the eastern coast of Sicily and evaluated possible damage to buildings for various events. Latcharote et al. (2016) evaluate tsunami hazards in the Marmara Sea from possible worst-case tsunami scenarios originating from submarine earthquakes and landslides. The confinement of the Marmara Sea along the North Anatolian Fault has produced deadly historical tsunamis. The tsunami hazards are evaluated from both individual and combined cases of submarine earthquakes and landslides through numerical tsunami simulations for the entire Marmara Sea region. Historical observations from the 1509 and 1894 earthquakes are used to validate tsunami modeling results with a particular focus on the tsunami heights at Istanbul.

The development and improvement of modern tsunami warning systems strongly depend on the exact knowledge of the potential risk to coastal areas from local and distant tsunamis generated in major seismically active fault zones. Gailler et al. (2016) examined possible impacts of Hellenic Arc tsunamis on the coast of Corsica, France. The main result of their study is the establishment of magnitude thresholds that determine the threat of tsunami waves for Corsica.

4. Tsunami Warning and Detection

An important application of global tsunami science is improvement in tsunami warning. Rapid and accurate estimates of tsunami energy are critical for tsunami warning. Titov et al. (2016) developed a new method by combining two independent estimates of tsunami energy from the land-based coastal global positioning system (GPS) and the Deep-ocean Assessment and Reporting for Tsunamis (DART). First, the tsunami energy is estimated from the globally expanding GPS network immediately after a large earthquake for near-field tsunami early warning, and then that estimate is refined using data from nearby DART stations to improve forecast accuracy and provide near real-time updates. The combination of these two real-time networks provides a promising method to further improve tsunami warning systems. Rapid estimation of earthquake magnitude is also a critical component in tsunami warning systems, aided by the development of *W*-phase moment magnitude estimates (Kanamori and Rivera 2008). In this volume, Roch et al. (2016) detail *W*-phase centroid inversion that rapidly estimates other fault parameters, in addition to earthquake magnitude, that are critical toward estimating tsunami severity: fault type (reverse, normal, strike-slip) and focal depth.

One of the problems of existing tsunami warning systems, however, is providing an early alarm for non-seismic events, in particular, meteotsunamis and landslide-generated tsunamis. The tsunami propagation time to the affected coast for these events is too small to effectively use open-ocean or shallow-water recorders. Grilli et al. (2016) for this purpose suggest the use high-frequency (HF) radar remote sensing and introduce new algorithms allowing detection of tsunami waves ranging from nearshore regions to deep water beyond the shelf.

Although it has been theoretically known that tsunamis may induce fluctuations in the Earth's electromagnetic field, it has only been since the 2010 Chile and the 2011 Japan tsunamis that scientists have convincingly established that these fluctuations are measurable. Schnepf et al. (2016) use recordings from highly sensitive seafloor magnetometers to determine the time–frequency characteristics of tsunami signals and to develop methods to isolate tsunami signals from background noise. As more real-time seismic and tsunami data become available and as numerical tsunami models continue to improve, it becomes possible to provide tsunami inundation forecasts as part of a tsunami warning system. Allen and Greenslade (2016) demonstrate the feasibility of a pilot tsunami inundation forecast system for a site in southeast Australia, and evaluate the system based on both accuracy and computational speed.

5. Tsunami Hydrodynamics and Modeling

At the core of tsunami hazard assessment methods and modern tsunami warning systems is an accurate understanding of tsunami hydrodynamics and modeling. For example, the Tsunami-HySEA model is used by Macias et al. (2016) to simulate tsunamis during the Caribbean Large AtlaNtic Tsunami EXercise (LANTEX 2013) with a special emphasis on the coastal areas of Puerto Rico. The results of the Tsunami-HySEA model were compared with those of the MOST model. The domain decomposition techniques used in Tsunami-HySEA allowed high-resolution inundation modeling and decreased computational times.

Tsunami propagation and inundation modeling in riverine and estuarine environments present difficult challenges, especially with regard to dynamic interaction between tides and tsunami waves. Shelby et al. (2016) examine the combined effects of tides and tsunamis in the Hudson River Estuary, by linearly superimposing the two types of waves in deep water, and propagating them into the estuary using a nonlinear, dispersive long-wave model (FUNWAVE-TVD). They indicate that detailed, high-resolution simulations (down to a 39-m grid spacing in their study) are critical when tidal forcing is significant. When a tsunami enters a river, it propagates a long distance as a tsunami bore. The flow velocity estimation of the bore is important for hazard mitigation of various infrastructures along the river. Tolkova and Tanaka (2016) successfully model the flow velocity of the tsunami bore observed at several stations along the Kitakami River during the 2011 Tohoku Tsunami using shock theory.

Davis and LeVeque (2016) develop numerical methods for tsunami modeling that contain solutions with time-varying regions where much higher resolution is required than elsewhere in the domain. Solving the time-dependent adjoint equation and using a suitable inner product with the forward solution allows more precise refinement of the relevant waves. This adjoint method has been integrated into the adaptive mesh refinement strategy of the open source GeoClaw software maintaining the accuracy of the solution, while the computational time required is significantly reduced.

Zhang et al. (2016) present model results derived from a tsunami current benchmarking workshop held by the U.S. National Tsunami Hazard Mitigation Program (NTHMP) in 2015. Modeling was undertaken with a 3D unstructured-grid model that has been previously certified by the NTHMP for tsunami inundation. Results are presented for two benchmark tests including a vortex structure in the wake of a submerged shoal and the impact of tsunami waves on Hilo Harbour from the 2011 Tohoku event. The modeled current velocities are compared with available lab and field data. Voroninna and Romanenko (2016) develop a new tsunami inversion method that uses a least-square inversion with a truncated Singular Value Decomposition method to find the best solution for the source. They apply this method to the 2013 Solomon tsunami and validate the usefulness of their method.

6. Landslide and Meteorological Tsunamis

Tsunami hazard assessments have increasingly included non-seismic sources in recent years. Landslide-generated tsunamis are relatively infrequent, compared to earthquake tsunamis, but can potentially generate extreme run-ups. Although much of the North American continental margin seafloor has been mapped in detail, one area where little had been known with regard to past submarine landslides is the Yucatán Shelf and Campeche Escarpment, offshore Mexico. Chaytor et al. (2016) presents newly acquired, high-resolution bathymetric data from this margin and indicates that several large submarine landslides have occurred along this margin in the past. Results from preliminary tsunami modeling compare deep-water amplitude distributions from the different landslides and indicate complex basin-wide propagation patterns caused by the near-source seafloor physiography.

One type of tsunami that has begun to attract much attention is the *'meteorological tsunami'* (or '*meteotsunami*'), i.e. tsunami-like waves that have approximately the same temporal and spatial scales as ordinary tsunami waves, but are generated above the ocean surface by atmospheric gravity waves or air pressure jumps, rather than by submarine earthquakes or landslides. Several destructive meteotsunamis that have occurred during recent years in various regions of the world demonstrate that this phenomenon is much more frequent and widespread than previously thought (Vilibić et al. 2016). A unique chain of meteotsunami events occurred on 23–27 June 2014 in the Mediterranean/Black Sea region (Šepić et al. 2015). The strongest oscillations (up to 3 m) were observed in the Adriatic Sea; the examination and numerical modeling of these oscillations were performed by Šepić et al. (2016). The authors achieve good agreement between observed and simulated waves and could explain the nature and generation mechanism of extreme meteotsunamis in this particular region.

7. Case Studies

Case studies are an important part of tsunami research that highlight the hazard for specific areas, including great recent and historic events. The three latest major tsunamis generated by the great Chilean earthquakes of 2010 (M_w 8.8), 2014 (M_w 8.2) and 2015 (M_w 8.3) were clearly recorded by a number of tides gauges on the Pacific coast of Mexico and by open-ocean DART stations located nearby. Zaytsev et al. (2016) examined these data and compared the principal features of the three events. The authors used coastal observations to determine the spectrum of tsunami waves in the deep ocean. The "reconstructed" open-ocean tsunami spectra are in close agreement with the actual tsunami spectra evaluated from direct analysis of the DART records offshore of Mexico.

The 1969 and 1975 great Kurile earthquakes occurred at the same plate interface along the Kurile subduction zone. Also, the 1975 event is classified as a "tsunami earthquake" that generates outsized tsunamis relative to the magnitude of the causative earthquake. Understanding the behavior of the plate interface in this region is necessary for tsunami hazard analysis in this region. Ioki and Tanioka (2016) estimate the slip distribution for these two earthquakes using tsunami waveforms observed at tide gauges. They conclude that the 1975 earthquake ruptured the shallowest part of the plate interface in an area where the 1969 earthquake did not rupture. The authors also conclude that the 1975 earthquake was probably triggered by the viscoelastic relaxation or after-slip from the 1969 Kurile earthquake.

In the Alaska-Aleutian subduction zone, the 1946 Aleutian earthquake is often considered as one of the most unusual "tsunami earthquakes". von Huene et al. (2016) reprocesses the seismic survey data and find a splay thrust fault zone that may lead megathrust slip upward to the mid-slope terrace. The slip on this splay fault during the 1946 Aleutian earthquake possibly generated the anomalously large tsunami.

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