Introduction to “Global Tsunami Science: Past and Future, Volume II”

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Abstract—Twenty-two papers on the study of tsunamis are included in Volume II of the PAGEOPH topical issue “Global Tsunami Science: Past and Future”. Volume I of this topical issue was published as PAGEOPH, vol. 173, No. 12, 2016 (Eds., E. L. Geist, H. M. Fritz, A. B. Rabinovich, and Y. Tanioka). Three papers in Volume II focus on details of the 2011 and 2016 tsunami-generating earthquakes offshore of Tohoku, Japan. The next six papers describe important case studies and observations of recent and historical events. Four papers related to tsunami hazard assessment are followed by three papers on tsunami hydrodynamics and numerical modelling. Three papers discuss problems of tsunami warning and real-time forecasting. The final set of three papers importantly investigates tsunamis generated by non-seismic sources: volcanic explosions, landslides, and meteorological disturbances. Collectively, this volume highlights contemporary trends in global tsunami research, both fundamental and applied toward hazard assessment and mitigation.

Key words: Tsunami observations, detection, tsunami recording, tsunami modelling, 2011 Tohoku earthquake, Pacific Ocean, spectral analysis, tsunami probability, landslide tsunami, volcanic 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.

Whereas one of the main themes in Volume I of “Global Tsunami Science: Past and Future” was on recent advances in tsunami warning and assessment, this Volume II of the Topical Issue returns, as a dominant theme, to the foundation of tsunami science: observations. For the 2011 Tohoku earthquake, for example, a diverse range of observations presented in this volume include wave height measurements, seismic waveforms, and changes in potential fields. In addition, novel observations, such as high-frequency radar measurements, can yield new insights on the tsunami phenomenon. Tsunami observations, followed by the thorough analysis of the respective data, play the key role in explaining the generation, propagation, and runup in historical case studies. These case studies, in turn, form the basis of the various tsunami hazard assessments, uncertainty analyses, and warning systems. Tsunami observations are also crucial in benchmarking analytic and numerical models of tsunami runup and inundation. In the future, tsunamis will remain a major threat to

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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 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 in the entire 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 (ITS) 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 strong events which occurred around this time, attracted so much attention and brought so much new information and data, that an extra, inter-session volume was collected and published (Rabinovich et al. 2014). Moreover, high interest regarding the Chilean (Illaapel) earthquake and tsunami of 16 September 2015 resulted in a Topical Collection of regular PAGEOPH papers “Chile-2015” that were later published as a book (Braitenberg and Rabinovich 2017). However, even these two additional volumes could not accommodate the great number of new tsunami publications prompted by numerous observational data and substantial recent progress in numerical modelling of tsunami waves. From this point of view, “Global Tsunami Science: Past and Future” 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 topical issue “Global Tsunami Science: Past and Future” is mainly based on papers presented at

the 26th IUGG General Assembly and sponsored by the Joint Tsunami Commission held from 22 June to 2 July 2015 in Prague, Czech Republic. Altogether, about 100 presentations comprised the 27th International Tsunami Symposium (ITS-2015) that was a part of the assembly. 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 of this issue (Geist et al. 2016) comprises 25 papers, which were published December 2016 (PAGEOPH, vol. 173, No 12, 2016). Volume II of this issue comprises 22 papers, which became ready for publication by August 2017. Papers in Volume II are separated into similar categories as in Volume I, although a new category is introduced (Tsunami Sources of the 2011 and 2016 Tohoku Earthquakes) and some of the other categories from Volume I have been topically expanded. In addition to the ITS-2015 papers, it also includes several recent papers on various aspects of the tsunami research.

2. *Tsunami Sources of the 2011 and 2016 Tohoku Earthquakes*

The Tohoku earthquake (M_w 9.0) and catastrophic tsunami of 11 March 2011 still attract much attention. The source process of the 2011 Tohoku earthquake is clearly anomalous in the context to other historic $M9$ earthquakes and is the subject intense research, owing to the devastating tsunami that resulted from this earthquake. Two papers of the present volume explore specific properties of the 2011 Tohoku earthquake. Petukhin et al. (2017) examine an important problem: could the same source modelling technique be used for predictions of both tsunami waves and strong ground motions? The authors estimated two slip models and showed that the first slip model reproduced the short-period (~ 3 min) tsunami waves induced in the northern part of the source area, while the second model reproduced the long-period (~ 15 min) waves generated in the southern part of the source region.

Pavlenko (2017) suggested mechanisms that could explain anomalously high peak ground accelerations (PGA) exceeding 1 g recorded during the

2011 Tohoku earthquake. The author assumes that this effect (high PGAs at the surface) can result from the combination of the overlapping of seismic waves at the bottoms of soil layers and their increased amplification by the pre-compressed soils.

Gusman et al. (2017) examine the 2016 Fukushima normal fault earthquake (M_{JMA} 7.4) that occurred 40 km off the coast of northeastern Honshu Island, i.e. very close to the source area of the 2011 Tohoku earthquake. The 2016 earthquake generated a moderate tsunami that was recorded by coastal tide gauges and offshore bottom pressure recorders (BPR). The observed tsunami waveforms were compared with computed waveforms for four available focal mechanisms; it was found that a simple fault striking northeast–southwest and dipping southeast (strike = 45° , dip = 41° , rake = -95°) yielded the best agreement with observations. The corresponding fault geometry was then used in a tsunami inversion to estimate the fault slip distribution.

3. Case Studies and Observations

Case studies and the observations therein are an important part of tsunami research that highlight the hazard for specific areas, including important recent and historic events. The largest recorded tsunami along the Caribbean coast of Central America occurred on 22 April, 1991 when an earthquake with magnitude M_w 7.6 ruptured along the thrust faults of the North Panama Deformed Belt (NPDB). Chacón-Barrantes and Zamora (2017) investigated this event in detail. They constructed four models of the seismic source and numerically simulated associated tsunamis. The model results enabled the authors to determine the character of the 1991 tsunami for the affected regions where tsunami records were not preserved and to simulate possible effects of a similar event but with a larger magnitude (M_w 7.9) offshore of southern Costa Rica.

As a companion paper to Zaytsev et al. (2016), who examined recordings from three recent Chilean tsunamis (2010, 2014, and 2015) along the coast of Mexico, Zaytsev et al. (2017) investigates the manifestation of the 2011 Tohoku tsunami on this same

coast. Statistical and spectral analyses of the onshore and offshore tsunami records allowed the authors to estimate the principal parameters of the waves and to compare statistical features of the 2011 tsunami with other tsunamis recorded along this coast. In particular, it was found that about 65% of the total Tohoku tsunami energy was associated with low-frequency waves at frequencies <1.7 cph (periods >35 min).

One of the findings of Zaytsev et al. (2016, 2017) was the identification of “hot spots” along the coast of Mexico (Manzanillo, Zihuatanejo, Acapulco, and Ensenada) corresponding to sites having greater tsunami wave heights compared to other parts of the coast. For the U.S. West Coast, a well-known “hot spot” is Crescent City (California) that typically records the largest wave heights and has suffered more loss than any other North American site in the past century. Crawford et al. (2017) analysed variations in water level and currents at this site caused by several different phenomena: tsunamis, tides, and weather events. The authors demonstrate that during weak 2014 tsunamis, spectral levels increased by roughly an order of magnitude at the 20-min spectral peak with current velocities aligned roughly NE–SW along the channel leading into the inner boat basin, whereas at 5.6-min periods the motions were roughly NW–SE, suggesting a higher-frequency modal response of the harbour.

Grilli et al. (2017) presented the second part of their two-part study of tsunami detection algorithms (TDA) based on analysing tsunami currents inverted from high-frequency (HF) radar Doppler spectra. In Part I of this work (Grilli et al. 2016), the authors proposed a method, referred to as time correlation (TC) TDA that does not require inverting currents, but instead detects changes in correlations between radar signal time series. In Part II (Grilli et al. 2017), the TC-TDA is applied for realistic tsunami case studies for the area West of Vancouver Island, British Columbia. Two case studies are considered, both simulated using long-wave models for (1) a far-field seismic and (2) a near-field landslide, tsunami. Numerical experiments show that the arrival of a tsunami causes a clear change in radar signal correlation patterns.

The study by Fu et al. (2017) is related to examination of independent oceanic and geodetic signatures of major earthquakes that are observed by

different modern geophysical observational networks. The gravity recovery and climate experiment twin satellites detect gravity changes induced by large earthquakes, while altimetry satellites and DART buoys observe resultant tsunamis. A method suggested by the authors to connect oceanic tsunami measurements and geodetic gravity observations is applied for three great events: the 2004 Sumatra (M_w 9.2), the 2010 Maule (M_w 8.8), and the 2011 Tohoku (M_w 9.0) earthquakes. The results indicate consistent agreement between these two independent measurements.

The NOAA National Centers for Environmental Information (NCEI) and co-located World Data Service for Geophysics (WDS) maintain the global tsunami archive consisting of a historical tsunami database, imagery, and raw and processed water level data. Dunbar et al. (2017) describe some problems with incorporating maximum tsunami wave heights into the historical tsunami database. The authors processed tsunami time-series for 57 coastal tide gauges during the 2015 Chilean (Illapel) tsunami and used different definitions to compare maximum wave heights. They found large reported variation in maximum tsunami wave heights from different definitions, owing to possible instrumental clipping.

4. *Tsunami Hazard Assessment and Uncertainty Analysis*

Probabilistic tsunami hazard analysis (PTHA) has become an important tool for hazard assessment in recent years. Continuing from the six papers related to PTHA in Volume I, Smit et al. (2017) provide new methods for empirical hazard assessment of tsunamis, taking into account uncertain and incomplete data that are listed in historical catalogs and databases. PTHA based on numerical simulations is commonly hampered by the amount of computational resources required, a problem addressed by two papers in this Volume. De Risi and Goda (2017) describe a Bayesian fitting methodology using empirical results that greatly reduces the number of numerical simulations required, and therefore the computational effort of a site-specific PTHA. An important component of

PTHA is also quantification of various forms of uncertainty. De Baar and Roberts (2017) tackle the problem of the computational resources required to comprehensively include various sources of uncertainty, termed the “curse of dimensionality”. The authors present a multifidelity approach that combines a small number of accurate, high-fidelity simulations with a larger number of low-fidelity simulations that greatly reduces the computational cost of uncertainty quantification.

An important complement to PTHA is deterministic tsunami hazard assessment. As an example, Allgeyer et al. (2017) assess the tsunami hazard to La Réunion Island located in the western Indian Ocean by performing detailed tsunami simulations for different historical and hypothetical scenario earthquakes. They determine that the Sumatra subduction zone is the most threatening source region for La Réunion Island, despite the closer proximity of other tsunami sources in the Indian Ocean.

5. *Tsunami Hydrodynamics and Modelling*

At the core of tsunami hazard assessment methods is an accurate understanding of tsunami hydrodynamics, from both numerical modelling and analytical perspectives. As a companion paper to Macías et al. (2016) who described in Volume I the Tsunami-HySEA numerical model used in the Caribbean and Atlantic, Macías et al. (2017) present the results from five benchmark problems, required for Tsunami HySEA to be considered for U.S. National Tsunami Hazard Mitigation Program projects. Tsunami propagation and runup modelling in bays present difficult challenges. Anderson et al. (2017) develop an analytical method to calculate the propagation and runup of long waves in U-shaped bays with piecewise linear slopes, using the Carrier-Greenspan transform. Aydin and Kânoğlu (2017) also present new analytical results, in this case for runup on a linear sloping beach under general initial conditions. The new method allows for a solution using eigenfunction expansions, which is computationally more efficient than previous methods.

6. Tsunami Warning and Forecasting

An important application of global tsunami science is improvements in tsunami warning, including the difficult problem of near-field tsunami warning. Many modern tsunami-warning systems are based on a database of pre-computed sources that are able to rapidly assess regions at risk. Setiyono et al. (2017) develop a new pre-computed inundation forecast system, Near-TIF, and demonstrate its application at Pelabuhan Ratu on the southern coast of Java, Indonesia. In order to obtain accurate information of the earthquake source for warning purposes, Tanioka et al. (2017) first perform a W-phase inversion using seismological data and obtain other parameters important for tsunami generation using scaling relationships and depth-dependent rigidity evident in subduction zones. The authors demonstrate this method as part of a conceptual tsunami early warning for Central America.

For far-field tsunami warning, there has been increasing focus in recent years on using valuable deep-sea pressure measurement from tsunameters to estimate tsunami generation parameters and to forecast tsunami amplitudes (cf. Rabinovich and Eblé 2015). Tolkova et al. (2017) describe a pre-compute pulse response function approach for rapidly estimating far-field tsunami amplitudes. The authors demonstrate the performance of this method using data from the 2010 Chile and 2011 Tohoku tsunamis.

7. Volcanic, Landslide, and Meteorological Tsunamis

Tsunami hazard assessments in recent years have increasingly included various non-seismic sources. Tsunamis generated by diverse volcanic processes are especially complex to analyse. Yamanaka and Tanioka (2017) considered three historical volcanic collapses in Japan that caused tsunamis: Komagatake Volcano (1640), Oshima–Oshima Island (1741), and Unzen–Mayuyama Volcano (1792). The primary objective of the study was to estimate the topography before the events, and compare the results with those from inverse numerical modelling and tsunami survey data. The runup heights were found to be especially sensitive to the collapsed volume and

frictional acceleration affecting the collapsed material; however, the observed runup heights could be reproduced with high accuracy using proper conditions of frictional acceleration for the event scenarios.

Although landslide-generated tsunamis are relatively infrequent compared to earthquake tsunamis, they can generate extreme runups. Poupardin et al. (2017) describe a submarine landslide that induced partial submersion of the atolls of Mururoa and Fangataufa in 1979 and produced a considerable tsunami. The Saint–Venant equations were used to numerically compute tsunami propagation in coastal areas, whereas offshore tsunami propagation was simulated by solving the weakly non-linear Boussinesq equations. Several scenarios were tested to reproduce the observed water and runup heights in the near-field and far-field regions.

One type of tsunami that has attracted much attention in recent years is the ‘meteorological tsunami’ (‘meteotsunami’), i.e. tsunami-like ocean waves that have approximately the same temporal and spatial scales as ordinary tsunami waves, but are generated on 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). Carvajal et al. (2017) reported on meteotsunamis that have recently occurred along the Chilean and Peruvian coasts. These tsunami-like oscillations were clearly recorded by coastal tide gauges during an intense storm that affected central Chile on 8 August 2015. The atmospheric origin of the intense sea-level oscillations was researched by further analysing meteorological records of air pressure and wind. The results indicate that intense meteotsunamis along the west coast of South America can cause severe damage, comparable to that resulting from $M_w > 8$ earthquake-generated tsunamis.

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