Introduction to “Tsunamis in the World Ocean: Past, Present, and Future. Volume II”

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Abstract—Fifteen papers are included in Volume 2 of a PAGEOPH topical issue *Tsunamis in the World Ocean: Past, Present, and Future*. These papers are briefly introduced. They are grouped into three categories: reports and studies of recent tsunamis, studies on tsunami statistics and application to tsunami warning, and modeling studies of tsunami runup and inundation. Most of the papers were presented at the 24th International Tsunami Symposium held 14–16 July 2009 in Novosibirsk, Russia, and reflect the current state of tsunami science.

Key words: Tsunami, tsunamigenic earthquake, field survey, tsunami numerical modeling, forecast and warning system, mitigation, tsunami runup, energy decay.

1. Introduction

This volume contains fifteen papers, in addition to the eighteen papers included in Volume I (*Pure and Applied Geophysics*, vol. 168, No. 6/7) of this topical issue. Most of them were presented at the 24th International Tsunami Symposium held 14–16 July 2009 in Novosibirsk, Russia. Background and details of this symposium and the IUGG Tsunami Commission are described in the Introduction to Volume I (SATAKE *et al.*, 2011). During the symposium, on 15 July 2009, an earthquake near New Zealand

generated a tsunami. More recently, on 27 February 2010, the Chilean earthquake also generated a damaging tsunami. Reports on these two tsunamis are also included in this volume. The papers are grouped into three categories: reports and studies of recent tsunamis, studies on tsunami statistics and application to tsunami warning, and modeling studies of tsunami runup and inundation. In the subsequent sections, each paper is briefly introduced.

2. Recent Tsunamis

This volume starts with a paper by RABINOVICH *et al.* (2011) that examines records of the catastrophic Indian Ocean tsunami generated by a giant earthquake (M 9.3) off the coast of Sumatra on 26 December 2004. The tsunami was recorded by a large number of tide gauges throughout the entire World Ocean (TITOV *et al.*, 2005). This study uses tide gauge records from 173 sites to analyze the characteristics and energy decay of the tsunami waves from this event in the Indian, Atlantic and Pacific oceans. Findings reveal that the decay (e -folding) time of the tsunami wave energy within a given oceanic basin is not uniform, as previously reported, but depends on the absorption characteristics of the shelf adjacent to the coastal observation site and the time for the waves to reach the site from the source region.

On 17 July 2006, an earthquake (M 7.7) occurred off the south coast of Java Island, Indonesia, and caused tsunami damage including 730 fatalities on the southern coast. This tsunami inundated nearly 1 km from the coast and left sediment deposits, and provided an opportunity to examine the sedimentary characteristics of modern tsunami deposits. MOORE *et al.* (2011) made a detailed survey and analysis of

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the tsunami deposit near Cilacap along a 750 m transect from the coast. They report landward but discontinuous change in thickness, from 20 cm to 1 mm, and generally fining grain size. The vertical change in grain size indicates two pulses of tsunami waves, and coarsening upward features, or “traction carpet,” made by the overlying suspension-dominated tsunami flows. They also estimate flow depth and speed of the tsunami from the grain size data.

On 15 July 2009, incidentally during the Novosibirsk meeting, a large earthquake (M 7.8) occurred off the west coast of South Island, New Zealand. While some personnel from the tsunami warning centres of Australia, Europe, New Zealand, and the United States were attending the meeting, those agencies issued tsunami information and warnings. USLU *et al.* (2011) report the real-time assessment of tsunami, made remotely during the meeting. Tsunami waveforms based on two scenario models, T1 of Joint Australian Warning Centre and Short-term Inundation Forecasting for Tsunamis (SIFT) of NOAA’s Pacific Marine Environmental Laboratory of the US are compared with the observed waveforms recorded at nearby Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys. This paper demonstrates recent developments of tsunami warning systems and the capability of real-time assessment for regional tsunamis. Another paper on the New Zealand tsunami is presented by PRASETYA *et al.* (2011). The authors undertook detailed near-field numerical modeling of this tsunami for the southwestern part of New Zealand. A combination of Global Positioning System (GPS), satellite radar and seismology data is used to constrain the seafloor deformation for the initial conditions of tsunami simulation. The model is verified based on the data from DART buoy 55015. The model results in the study region show maximum tsunami amplitudes in the range of 0.5–2.0 m inside nearby sounds and inlets with maximum flow speeds up to 3.0 m/s.

On 27 February 2010, a great (M 8.8) earthquake (the fifth largest ever recorded instrumentally) occurred off the coast of Chile and generated a locally catastrophic tsunami. The international tsunami survey team examined about 800 km of the coastline from Quintero to Mehuín and several Pacific islands, including Santa María, Mocha, Juan

Fernández Archipelago, and Rapa Nui (Easter Island). The data collected by the survey team included more than 400 tsunami flow depth, runup and coastal uplift measurements. The maximum tsunami runup of 29 m was found on a coastal bluff at Constitución. The results of the field survey are described in the paper by FRITZ *et al.* (2011). The observations from the 2010 tsunami are also compared with those of the Great 1960 Chile Tsunami.

SHEVCHENKO *et al.* (2011) examine bottom pressure records in bays of Shikotan Island (the South Kuril Islands) from two tsunamis: the Simushir (Kuril Islands) tsunami of 13 January 2007 generated by a local earthquake (M 8.1), and the distant tsunami of 15 August 2007 generated by the Peruvian earthquake (M 8.0). The records are used to investigate the properties of the two events and to estimate the effect of the regional and nearshore topography on arriving tsunami waves. Numerical modeling of resonant oscillations in particular bays enable the authors to examine eigenperiods and spatial structure of various modes in these bays and to compare these results with the observations. Significant amplification of the fundamental (Helmholtz) mode in Malokurilskaya Bay (19 min) and in Krabovaya Inlet (29 min) and of some secondary modes was induced by the Simushir tsunami. The Peruvian tsunami was clearly recorded by the bottom pressure gauge in Tserkovnaya Bay located on the outer (oceanic) coast of the island. Three dominant periods in the tsunami spectrum at this bay were 60, 30 and 19 min; the first two periods appear to be associated with the shelf resonant amplification of tsunami waves arriving in the region of the South Kuril Islands, while oscillations with a period of 19 min are found to be related to the fundamental mode of the bay.

3. Tsunami Statistics and Warning

Four papers report statistical studies on earthquake parameters, tsunami heights, tsunami warnings, and recurrence intervals.

BOLSHAKOVA and NOSOV (2011) examine the relationships between earthquake size and resultant tsunamis by carrying out Monte-Carlo simulations. The parameters they examined are vertical

displacement, displaced volume, and potential energy of seafloor deformation calculated from fault parameters. Based on the simulation, they obtain three empirical relationships between the moment magnitude and the upper limit of the above three parameters. They compare their empirical relations with similar ones previously obtained and the observational data from recent earthquakes. They also confirm that the potential energy for tsunami generation is only about 1% of seismic wave energy.

GUSIAKOV (2011) considers the relationship between the tsunami intensity and earthquake magnitude. At the present time, the operational tsunami warning service is based on two main assumptions: (1) submarine earthquakes can generate dangerous tsunamis when the earthquake magnitude exceeds a certain threshold value; and (2) the height of a resultant tsunami is, in general, proportional to the earthquake magnitude. The author critically considers these assumptions and discusses the degree of agreement of these assumptions to real observations. Tsunami intensity, based on the Soloviev–Imamura scale is used to estimate correlation coefficients with the M_s and M_w magnitudes from the historical seismological data available for the instrumental period of observations (from 1900 to present).

IGARASHI *et al.* (2011) provide an overview of the foundation, development and current status of the Pacific Tsunami Warning System. It was established after the catastrophic 1946 Aleutian Islands tsunami, which caused numerous casualties in the Hawaiian Islands. The ensuing events of 1952, 1957, and 1960 tested the new system, which continued to expand and evolve to an international system in 1965. New analysis techniques, coupled with higher quality data, resulted in a more accurate and reliable warning, but limitations still exist in constraining the source and predicting tsunami wave heights near the coast. The paper reviews historical tsunamis, their warning activities and sea level records to highlight lessons learned from the recent catastrophic events. Faster detection, more accurate evaluations, widespread timely alerts and early warning are the goals and challenges of the updating system.

KAISTRENKO (2011) addresses properties of tsunami distribution functions on general theoretical grounds. The author starts from the assumption that

within a region the recurrence function of tsunamis (that is the expected number of tsunamis exceeding a given runup height value h at a given coastal point in the region) and the spatial distribution along the coast of the observed runup heights for a single tsunami are tied together since they reflect the property of the tsunami's propagation outside the region. Through theoretical considerations the author is able to show interesting properties of the recurrence function, such as (1) that it is the eigenfunction of an integral operator with unitary eigenvalue and (2) that it is a power law of the type Ch^α with a negative exponent. Making reference to physical arguments, the author concludes further that in the range of intermediate-size tsunamis the most acceptable value of α is -1 , while for the largest tsunamis it should be lower than -2 .

4. Modeling Tsunami Runup and Inundation

DIDENKULOVA *et al.* (2011) propose that long ship-induced waves in Tallinn Bay, the Baltic Sea, serve as a physical model for nearshore dynamics and runup of tsunamis caused by landslides. They discuss that in many aspects these ship-generated waves can model nearshore dynamics and runup of tsunamis caused by landslides, including processes of wave refraction, diffraction and sea-bottom interaction in bays and harbors, i.e., nondimensional parameters such as the nonlinearity, dispersion, Reynolds and Ursell numbers, surf similarity parameter, breaking parameter are the same order of magnitude for the largest ship waves and landslide tsunamis. Therefore, they suggest that near-critical ship waves could be used as a natural substitute for tsunamis caused by landslides of moderate size, and can be studied under controlled and safe conditions.

OZER and YALCINER (2011) introduce and analyze a parameter, which they call "hydrodynamic demand." This parameter can be used to estimate the potential for the tsunami drag force to damage structures along coastlines. It depends on the instantaneous values of the flow depth and speed during the tsunami inundation. In their study, the tsunami numerical model for two altered regular-shaped basins with different bottom slopes is used to

examine the effects of a potential tsunami. The simulations are provided for a single sinusoidal wave with particular initial parameters. Two different wave amplitudes are applied to assess the distribution of the square of the Froude number along the coastline.

APOTSOS *et al.* (2011) present comparisons of Delft3D nonlinear shallow-water wave numerical model results with analytical, laboratory benchmark problems such as ones presented in SYNOLAKIS *et al.* (2008). They employ wetting and drying methods for tsunami inundation modeling for breaking and non-breaking waves and a shock-capturing scheme to describe the total decrease in wave height due to breaking. They conclude that their model could be appropriate for modeling propagation and inundation for both breaking and non-breaking earthquake-induced tsunamis but not for modeling highly dispersive tsunamis, such as those generated by landslides or impacts, especially over long distances. Then they compare the modeling results with field observations near Kuala Meurisi, Sumatra, for the 26 December 2004 Indian Ocean tsunami including sediment transport. They can generally reproduce the sediment deposit thickness within a factor of 2. They suggest that a validated tsunami numerical model coupled with sediment transport models and paleo-tsunami deposits could improve tsunami hazards assessments.

The catastrophe of the 2004 Indian Ocean tsunami showed the need for a Tsunami Early Warning System covering the region, which, among others, implies the need for adequate tsunami simulation tools to estimate tsunami propagation and impact that are quick and easy to use. TITOV *et al.* (2011) present one such tool, the Community Modeling Interface for Tsunamis (ComMIT) and demonstrate its potential to forecast tsunami inundation with an application to the 10 August 2009 Andaman tsunami. ComMIT, whose development was supported by UNESCO, USAID and NOAA, uses initial conditions from a pre-computed propagation database, has an easy-to-interpret graphic interface, and requires only portable hardware, which makes it quite convenient for community-oriented operational inundation mapping.

BARBEROPOULOU *et al.* (2011) present an overview of development of tsunami inundation maps in California and new generation maps. New inundation

maps are prepared for 20 coastal counties in California covering previously unmapped regions, making California the largest covered coastal area of any US state, and show an improvement over previous efforts (BORRERO *et al.*, 2003). Additional improvements include usage of the most recent descriptions of potential tsunami sources and recently updated numerical modeling techniques. The authors emphasize that these maps are intended for emergency preparedness and evacuation planning since they are based on deterministic but not probabilistic modeling, such as the one in GONZÁLEZ *et al.* (2009). They also discuss real time response of the State of California to several tsunami events, e.g., the 14 June 2005 nearshore event off Crescent City, the 15 November 2006 Kuril Islands tsunami and the 27 February 2010 Chile tsunami. Even though the release of these maps is both a milestone and improvement in tsunami preparedness, they emphasize that the new maps need to be integrated into a consistent statewide hazard-planning framework.

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REFERENCES

- APOTSOS, A., BUCKLEY, M., GELFENBAUM, G., JAFFE, B., and VATVANI, D. (2011), *Nearshore tsunami inundation model validation: toward sediment transport applications*, Pure Appl. Geophys., 168, This issue.
- BARBEROPOULOU, A., BORRERO, J.C., USLU, B., LEGG, M.R., and SYNOLAKIS, C.E. (2011), *A second generation of tsunami inundation maps for the State of California*, Pure Appl. Geophys., 168, This issue.
- BOLSHAKOVA, A.V., and NOSOV, M.A. (2011), *Parameters of tsunami source versus earthquake magnitude*, Pure Appl. Geophys., 168, This issue.
- BORRERO, J., YALCINER, A.C., KANOĞLU, U., TITOV, V., MCCARTHY, D., and SYNOLAKIS, C.E. (2003), *Producing tsunami inundation maps: The California experience*, in *Submarine Landslides and Tsunamis*, NATO Science Series IV Earth and Environmental Sciences, 21, 315-326, IDS Number: BY68 ISBN: 1-4020-1348-5.

- DIDENKULOVA, I., PELINOVSKY, E., and SOOMERE, T. (2011), *Can the waves generated by fast ferries be a physical model of tsunami?* Pure Appl. Geophys., 168, This issue.
- FRITZ, H.M., PETROFF, C.M., CATALÁN, P.A., CIENFUEGOS, R., WINCKLER, P., KALLIGERIS, N., WEISS, R., BARRIENTOS, S.E., MENESES, G., VALDERAS-BERMEJO, C., EBELING, C., PAPADOPOULOS, A., CONTRERAS, M., ALMAR, R., DOMINGUEZ, J.C., and SYNOLAKIS, C.E. (2011), *Field survey of the 27 February 2010 Chile tsunami*, Pure Appl. Geophys., 168, This issue.
- GONZÁLEZ, F. I., GEIST, E. L., JAFFE, B., KÄNOĞLU, U., MOFJELD, H., SYNOLAKIS, C. E., TITOV, V. V., ARCAS, D., BELLOMO, D., CARLTON, D., HORNING, T., JOHNSON, J., NEWMAN, J., PARSONS, T., PETERS, R., PETERSON, C., PRIEST, G., VENTURATO, A., WEBER, J., WONG, F., and YALCINER, A. (2009), *Probabilistic tsunami hazard assessment at Seaside, Oregon for near- and far-field seismic sources*, J. Geophys. Res., 114, C11023. doi:[10.1029/2008JC00513](https://doi.org/10.1029/2008JC00513).
- GUSIAKOV, V. K. (2011), *Relationship of tsunami intensity to source earthquake magnitude as retrieved from historical data*, Pure Appl. Geophys., 168, This issue.
- IGARASHI, Y., KONG, L., YAMAMOTO, M., and MCCREERY, C.S. (2011), *Anatomy of historical tsunamis: lessons learned for tsunami warning*, Pure Appl. Geophys., 168, This issue.
- KAISTRENKO, V. (2011), *Tsunami recurrence versus tsunami height distribution along the coast*, Pure Appl. Geophys., 168, This issue.
- MOORE, A., GOFF, J., MCADOO, B. G., FRITZ, H.M., GUSMAN, A., KALLIGERIS, N., KALSUM, K., SUSANTO, A., SUTEJA, D., and SYNOLAKIS, C.E. (2011), *Sedimentary deposits from the 17 July 2006 Western Java tsunami, Indonesia – use of grain size analyses to assess tsunami flow depth, speed, and traction carpet characteristics*, Pure Appl. Geophys., 168, This issue.
- OZER, C., and YALCINER, A.C. (2011), *Sensitivity study of hydrodynamic parameters during numerical simulation of tsunami inundation*, Pure Appl. Geophys., 168, This issue.
- PRASETYA, G., BEAVAN, J., WANG, X., REYNERS, M., POWER, W., WILSON, K., and LUKOVIĆ, B. (2011), *Evaluation of the 15 July 2009 Fiordland, New Zealand, tsunami in the source region*, Pure Appl. Geophys., 168, This issue.
- RABINOVICH, A.B., CANDELLA, R., and THOMSON, R.E. (2011), *Energy decay of the 2004 Sumatra tsunami in the world ocean*, Pure Appl. Geophys., 168, This issue.
- SATAKE, K., RABINOVICH, A., KÄNOĞLU, U., and TINTI, S. (2011), *Introduction to "Tsunamis in the World Ocean: Past, Present, and Future. Volume I"*, Pure Appl. Geophys., 168, 6–7.
- SHEVCHENKO, G., SHISHKIN, A., BOGDANOV, G., and LOSKUTOV, A. (2011), *Tsunami measurements in bays of Shikotan Island*, Pure Appl. Geophys., 168, This issue.
- SYNOLAKIS, C.E., BERNARD, E.N., TITOV V.V., KÄNOĞLU, U., and GONZÁLEZ, F.I. (2008), *Validation and verification of tsunami numerical models*, Pure Appl. Geophys., 165, 2197–2228.
- TITOV, V.V., MOORE, C.W., GREENSLADE, D.J.M., PATTIARATCHI, C., BADAL, R., SYNOLAKIS, C. E., and KÄNOĞLU, U. (2011), *A new tool for inundation modeling: Community Modeling Interface for Tsunamis (ComMIT)*, Pure Appl. Geophys., 168, This issue.
- TITOV, V.V., RABINOVICH, A.B., MOFJELD, H.O., THOMSON R.E., and GONZÁLEZ, F.I. (2005), *The global reach of the 26 December 2004 Sumatra tsunami*, Science, 309, 2045–2048.
- USLU, A., POWER, W., GREENSLADE, D., EBLÉ, M., and TITOV, V. (2011), *The July 15, 2009 Fiordland, New Zealand tsunami: real-time assessment*, Pure Appl. Geophys., 168, This issue.