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Introduction to "Tsunami Science Four Years After the 2004 Indian Ocean Tsunami, Part I: Modelling and Hazard Assessment"

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Abstract—In this introduction we briefly summarize the 14 contributions to Part I 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 I, and introduced here, cover topics directly related to tsunami mitigation such as numerical modelling, hazard assessment and databases. Part II of this special issue, Observations and Data Analysis, will be published in a subsequent volume of Pure and Applied Geophysics.

Key words: Tsunami, seiche, harbor resonance, numerical modeling, hazard assessment, inundation, tsunami mitigation, tsunami warning system, runup, tsunami database, rissaga.

1. *Introduction*

Four years after the 2004 Indian Ocean Tsunami, the most lethal tsunami disaster in human history, tsunami science continued to move forward rapidly. The research and disaster management community that supports tsunami mitigation has expanded greatly. Observation platforms, especially in the Indian Ocean, have far surpassed their pre-2004 capacity for detecting and measuring tsunamis and the earthquakes that most frequently cause them. A remarkable crosssection of this research was presented in the session Tsunami Generation and Hazard, at the International Union of Geodesy and Geophysics (IUGG) XXIV General Assembly in Perugia, Italy, held in July of 2007. Over one hundred presentations were made at this session, spanning topics ranging from paleotsunami research, to nonlinear shallow-water theory, to tsunami hazard and risk

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assessment. The IUGG's Tsunami Commission arranged for a selection of this work, along with other papers on similar topics, to be published in detail in the 28 papers of this 2-part special issue of Pure and Applied Geophysics.

In this introductory paper, we briefly discuss the papers in Part I of "Tsunami Science Four Years After the 2004 Indian Ocean Tsunami". In Section 2 we discuss new advances in the fundamental numerical techniques used to model tsunamis and Section 3 reviews several contributions that apply such techniques to improve our understanding of how near-coast processes affect tsunami propagation. Sections 4 and 5 discuss the application of tsunami modeling to tsunami hazard assessment, in a deterministic and a probabilistic sense, respectively. Section 6 describes two database efforts that are supporting researchers and warning system operators to access the most current and accurate information on tsunami events.

2. Advances in Analytical and Numerical Modeling of Tsunamis

The increased focus on tsunami science since the 2004 Sumatra-Andaman Earthquake and subsequent Indian Ocean Tsunami has seen a rapid expansion in the tsunami modeling community. Prior to 2004, this community consisted of a handful of research groups that utilized a few well-tested codes for numerical modeling of tsunamis. Since 2004, many more research groups have taken an interest in tsunami modeling, and these groups have in some cases either developed new codes for tsunami modeling, or adapted hydrodynamic codes that had originally been developed for other purposes. Tsunami forecasting via numerical modeling is also seeing increased use as an operational part of tsunami warning systems.

In response to this recent proliferation of tsunami modeling codes, SYNOLAKIS *et al.* (2008) pointed out the importance of validation and verification of codes used in tsunami hazard assessment or forecasting systems. They reviewed several methods by which this can be accomplished. These included analytical and laboratory validation benchmarks, as well as examples of field observations against which numerical models can be verified. A summary of the theoretical development for formulae used as analytical benchmarks was given, and details of the laboratory experiments and field observations were reviewed. In addition to the use of these benchmarks for inundation modeling in tsunami hazard studies, operational requirements for forecasting tsunamis in real-time were discussed.

ZHANG and BATISTA (2008) presented an example of the adaptation of a multi-purpose baroclinic circulation model (SELFE) to tsunami inundation and propagation. The model has several interesting features that make it a useful addition to the suite of tools already available: Release as open source, facilitating further development by a community of users; use of an unstructured grid, allowing for variable resolution to accommodate complex geometry only where necessary; an implicit time-stepping algorithm that avoids the stringent Courant–Friedrichs–Lewy stability condition, and a simple wetting/drying algorithm that implements inundation. Along the lines suggested by SYNOLAKIS *et al.* (2008), the authors presented validation results against scenarios from the 3rd International Workshop in Long-Wave Runup Models (http://www.cee.cornell.edu/longwave).

GREENSLADE and TITOV (2008), on the other hand, use a tried and tested tsunami code (MOST – see TITOV and GOZAREZ, 1997) to compare two tsunami forecasting systems used by the U.S. National Oceanic and Atmospheric Administration (NOAA), and the Australian Bureau of Meteorology. The tsunamis caused by the 2006 Tonga and 2007 Sumatra earthquakes were used as test cases. Both systems use results of tsunami computations made prior to earthquakes and stored in a database. While the specifications of numerical simulation of tsunami propagation are very similar, the scenario sources distributed around the Pacific Basins are slightly different. The Australian system assumes different faults depending on the earthquake magnitude, while the U.S. system scales the slip amount by assimilation of tsunameter (a.k.a. DART) data. Because different sources are used to approximate the Tonga and Sumatra earthquakes, the forecasted waveforms at offshore tsunameter locations are slightly different. However, the differences in waveforms computed at coastal tide gauges are considerably smaller, indicating insensitivity of coastal tsunamis to the details of the tsunami source.

Despite substantial recent progress in numerical tsunami modeling, the rapid forecast of runup values remains a difficult problem, due to its nonlinearity and sensitivity to input data such as bathymetry and initial waveform. The paper by DIDENKULOVA *et al.* (2008) demonstrated that analytical results still have an important role to play in estimating runup. They discussed results from nonlinear shallow-water wave theory for runup of solitary tsunami waves, and showed that appropriate definitions of significant wave height and length (based on 2/3 of maximum wave height) result in formulae for computing runup characteristics that are relatively independent of incident wave shape (for symmetric incident waves). Such formulae may be used in rapidly estimating potential inundation once the tsunami height, wavelength and period in the open ocean are known.

3. *Modeling of Near-Coast Effects on Tsunami Propagation*

One of the most challenging aspects of tsunami modeling is accurate representation of propagation effects near the coast, including reflection and refraction by shallow bathymetry, and resonances in semi-enclosed bays and inlets. Several papers in this issue address these topics.

BABA *et al.* (2008) examined the effects of Great Barrier Reef, the world's largest coral reef located offshore Australia, on the tsunami generated by the April 1, 2007 Solomon Islands earthquake. They carried out tsunami numerical simulation from a source model based on their seismic waveform inversion. The simulated waveforms show good agreement with tide gauge data in northeast Australia. In order to examine the effect of the coral reef, they also made tsunami simulations with artificial bathymetry data without the coral reef; the reef was replaced with deep ocean in one dataset and shallow ocean in the other. Simulations with these models indicate that the tsunami energy was reduced by direct reflection outside the reef and by refraction when the tsunami passed through the reef. As a result, the tsunami was delayed by 10–15 minutes, the amplitude became about a half or less, and the period became longer.

Semi-enclosed bays and inlets present another challenge to tsunami modeling in the form of potential resonant enhancement of tsunamis. Alberni inlet is a long (~40 km) and narrow (1–2 km) fjord in Vancouver Island, Canada. The tsunami caused by the 1964 Alaskan earthquake had a height of about 8 m above mean sea level at Port Alberni, located at the head of the inlet and about 65 km from the Pacific Ocean. Fine *et al.* (2008) examined resonance characteristics of the Alberni inlet by using numerical calculations. Their results indicated that strong amplification occurred at a period of 112 min with an amplification factor of more than 10.

Vilibić *et al.* (2008) presented a comprehensive analysis of a destructive meteotsunami (*rissaga)* that occurred in the Balearic Islands in 2006. This event was not associated with an earthquake source and excited destructive harbor oscillations of several meters amplitude, resulting in an economic loss estimated at tens of millions of euros. Vilibić *et al.* used a numerical model, verified using a series of measurements made during smaller *rissaga* events in 1997, and microbarograph measurement to show how the 2006 *rissaga* resulted from ocean-atmosphere resonance excited by a travelling atmospheric disturbance, which in turn induced the hazardous harbor oscillations observed. The potential for developing a *rissaga* warning system based on this model was also discussed.

4. *Scenario Modeling for Tsunami Hazard Assessment*

In addition to rapid tsunami forecasts that may form part of a tsunami warning, emergency managers and planners in coastal communities need information about how large tsunamis affecting their communities might be. Such questions can be answered by scenario modeling, which forms the basis of a deterministic hazard assessment. Such assessments are normally designed to encompass the worst credible, as well as the most likely, scenarios.

Tiberti *et al.* (2008) numerically modeled potential tsunamis in the Adriatic Sea. Maximum credible earthquakes were assumed along the six source zones. They classified the computed maximum tsunami heights into three levels: marine, land and severe land for 0.05 m, 0.5 m and 1.0 m, respectively. The results indicate that the largest tsunamis are expected on the Apulia and Gargano coasts of southern Italy. They found that focusing of energy due to bathymetric features enhances the tsunami heights.

At Stromboli volcano, southern Italy, on December 30, 2002, a moderate-sized landslide (with a volume of 0.02–0.03 km^3) generated a tsunami, with a maximum runup height of about 10 m. Because it occurred in the winter, there was no loss of human life, nonetheless damage was caused on the coast. This slide occurred at Sciara del Fuoco (SdF), a steep scar of the island which can potentially produce a landslide with a volume of 1 km^3. TINTI *et al.* (2008) numerically simulated tsunamis from three other potential sources of landslides around the island. The expected landslide volume is similar to that of the 2002 slide. They showed that a landslide at Punta Lena, south of the island, can produce a tsunami even larger than the 2002 tsunami.

The paper by HEIDARZADEH *et al.* (2008) presented a deterministic assessment of tsunami hazard in the northwestern Indian Ocean by considering a series of six large (M_w 8.3) tsunamigenic earthquake scenarios along the Makran subduction zone. They used the tsunami model TUNAMI-2 (GOTO *et al.*, 1997), along with the GEBCO bathymetry grid, to calculate tsunami heights at the coastline for these scenarios. The calculated tsunami heights and arrival times were verified against observations of the tsunami caused by a Makran subduction zone earthquake that occurred in 1945. The scenario modeling demonstrated that earthquakes along the Makran subduction zone pose a substantial tsunami threat to the Arabian Sea coasts of Iran, Pakistan, Oman and India.

5. *Probabilistic Tsunami Hazard Assessment*

A further level of refinement in tsunami hazard assessment considers not only how large a tsunami affecting a particular community may be, but also how likely is the occurrence of a tsunami of a given magnitude. This is known as probabilistic tsunami hazard assessment, and its implementation is similar in concept to that of Probabilistic Seismic Hazard Assessment (CORNELL, 1968).

The paper by PARSONS and GEIST (2008) presents a probabilistic tsunami hazard assessment for the Caribbean region. This assessment involves consideration of both historical events, based on the impressive 500-year-long catalog of Caribbean tsunami observations, and also earthquake sources based on numerically-modelled seismic moment release along the convergent margins of the Caribbean plate. While the former potentially accounts for non-earthquake tsunami sources (e.g., submarine landslides), the latter accounts for earthquakes with long return periods that may not be represented in the catalog. The authors developed a Bayesian method for combining these to produce a tsunami hazard map that made optimal use of the information available from both the catalog and modeling results.

BURBIDGE *et al.* (2008) calculated probabilistic tsunami hazard for the coast of western Australia. Tsunamis from great earthquakes along the Sumbawa, Java and Sunda trenches have affected the western coasts of Australia. Probabilistic tsunami hazard was used to estimate offshore wave heights as a function of return period. While the tsunami heights along the Australian coasts from a magnitude 8 earthquake with the return period of about 100 years were not very high, those from a magnitude 9 earthquake, similar to the 2004 Sumatra-Andaman earthquake, with a return period of about 1,000 years, would be very large and potentially cause damage.

6. *Tsunami Databases*

Databases are essential for the support of tsunami hazard and risk assessments and warning systems. The task of collating information of varying quality from many different sources is a formidable one, and unless validated information about tsunami observations and observation platforms is made available in a consistent form, this information cannot be used effectively. Two papers in this issue discuss databases that are designed to provide effective support to hazard/risk assessment and warning systems.

Marra *et al.* (2008) introduce readers to the concept of web services as a means to efficiently describe, collect, integrate, and publish sea-level station metadata that are contributed by many countries and organizations, and used by station operators, tsunami and other coastal hazard warning systems, disaster management officials, and coastal inundation researchers. The service incorporates an agreed-upon sea-level station XML schema for automatic and continuous station reporting, thus facilitating the implementation of always up-to-date data mining client applications. One example that is described is Tide Tool, which was developed by the Pacific Tsunami Warning Center to continuously download and decode sea-level data globally and to monitor tsunamis in real-time.

Dunbar *et al.* (2008) describe the enhancements to the National Geophysical Data Center World Data Center for Geophysics and Marine Geology (WDC-GMG) national and international long-term tsunami data archive since 2004. The archive has expanded from the original global historical event databases and damage photo collection, to include tsunami deposits, coastal water-level data, DART buoy data, and high-resolution coastal Digital Elevation Model datasets for supporting model validation, guidance to warning centers, tsunami hazard assessment, and education of the public. The data are available in the public domain, and tools have been provided for interactive on-line and off-line data discovery and download in multiple formats to facilitate further integration and re-use by everyone.

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