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Introduction to "Twenty Five Years of Modern Tsunami Science Following the 1992 Nicaragua and Flores Island Tsunamis, Volume II"

UTKU KÂNOĞLU,[1] YUICHIRO TANIOKA,[2] EMILE A. OKAL,[3] MARIA ANA BAPTISTA,[4,5] and ALEXANDER B. RABINOVICH[6,7]

Abstract—Following the first volume (PAGEOPH, 2019, 176, No. 7), twenty-four papers on tsunamis are included in the PAGEOPH topical issue "Twenty five years of modern tsunami science following the 1992 Nicaragua and Flores Island tsunamis: Volume II," reporting on the frontiers of tsunami science and research. The first two papers overview meteorological tsunamis, discussing progress since the 1992 Daytona event, and examining the March 2017 Persian Gulf destructive event. The next four papers review historical tsunami events, starting with a paper providing statistics for the last 120 years. The 2018 Kodiak event is investigated in the following two papers. A set of five papers discusses tsunami-warning methodologies specifically for the Australia and Nankai (Japan) regions, and general tsunami warning approaches. Probabilistic tsunami hazard assessment including case studies for two Australian coasts and the Pacific Coast of Central America, as well as discussion regarding the effect of shallow slip amplification uncertainty, and tsunami hazard assessment for the Port of Ensenada, Baja California, are presented in the next five papers. Two papers discuss tsunami tide interaction, and the following two investigate landslide-generated tsunamis, specifically a tsunami landslide scenario study for the Maltese Islands, and the 1694 Ambon, Indonesia tsunami. Tsunami hydrodynamics studies investigating shoaling on steep continental slopes and transmission of long surface, and tsunami-like waves are presented in the last two papers.

Keywords: Tsunami observations and detection, DARTs, tsunami modelling, tsunami earthquake, tsunami warning and hazard assessment, landslide generated tsunami, meteotsunamis, tsunami statistics and probability.

1. *Introduction*

The Nicaragua tsunami earthquake (Kanamori 1972) on 2 September 1992 and the Flores Island, Indonesia catastrophic tsunami on 12 December 1992 opened a 25-year period of numerous devastating earthquakes and tsunamis, and marked the beginning of "modern tsunami science era" (Okal 2019). This period included the 26 December 2004 Sumatra tsunami (Synolakis and Kong 2006), killing about 230,00 people, and the 11 March 2011 Tohoku (East Japan) tsunami killing almost 20,000 people and resulting in the Fukushima Dai-ichi nuclear power plant accident (Satake et al. 2013a).

In our previous issue (Kânoğlu et al. 2019), we briefly summarized significant developments in the last 25 years. Those are:

- The International Post-Tsunami Surveys became systematic after the 1992 Nicaragua and Flores Island tsunamis. These surveys turned out to be the leading resource of crucial scientific information about the events to estimate tsunami risk in specific coastal regions, but also to help tsunami scientists reconstruct the seismic sources of the events, in order to verify tsunami numerical models and identify scientific gaps in our knowledge.
- Further, the Tsunami Bulletin Board (TBB) network (tsunami_bb@infolist.nws.noaa.gov) was initiated after the 1992 events, linking all tsunami scientists practically throughout the entire world.

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[1] Department of Aerospace Engineering, Middle East Technical University, 06800 Ankara, Turkey. E-mail: kanoglu@metu.edu.tr

[2] Institute of Seismology and Volcanology, Hokkaido University, Sapporo, Japan. E-mail: tanioka@mail.sci.hokudai.ac.jp

[3] Department of Earth and Planetary Sciences, Northwestern University, Evanston, IL 60208, USA. E-mail: e-okal@northwestern.edu

[4] Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa, Lisbon, Portugal. E-mail: mavbaptista@gmail.com

[5] Instituto Dom Luiz, Universidade de Lisboa, Lisbon, Portugal.

[6] Department of Fisheries and Oceans, Institute of Ocean Sciences, 9860 West Saanich Road, Sidney, BC V8L 4B2, Canada. E-mail: a.b.rabinovich@gmail.com

[7] P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 36 Nakhimovsky Pr, Moscow 117997, Russia.

- Following the events of the last 25 years, and specifically, after the 2004 Indian Ocean tsunami, the worldwide sea-level network was upgraded. As a result, each new measurable tsunami event now provides high-quality sea level data from hundreds of instruments, which enables scientists to investigate tsunamis with higher accuracy, significantly improving their general understanding. In addition to coastal measurements, a worldwide network of DART[1] stations was deployed to obtain data during open ocean propagation. This network became the backbone of Tsunami Warning Systems (Titov 2009). Further, a seafloor network of geophysical observatories was installed at the shelf-continental slope of Vancouver Island in 2009, further improving tsunami measurements. All these measurements provide an enormous amount of data that not only allows tsunami scientists to verify their numerical models (Synolakis et al. 2008) but also the reconstruction of the source in real-time under operational tsunami warning conditions (Titov et al. 2016).
- Tsunami numerical models advanced substantially, as a combination of access to modern computers, and to high-resolution bathymetric/topographic data, of better characterizations of tsunami sources (e.g., Titov et al. 2005; Fujii and Satake 2007; Wei et al. 2008), of the explosion of data from the field, i.e., from deep ocean and near-shore measurements, and from field surveys, as well as of theoretical progress, involving for example the effects of Earth elasticity and seawater stratification on open-ocean tsunami propagation (Watada et al. 2014; Allgeyer and Cummins 2014). In this context application to real-time forecasting made substantial progress during past 25 years (Titov et al. 2016).
- Active development of paleotsunami studies enabled tsunami scientists to investigate historical events that occurred hundreds, even thousands of years ago, for example, reliably reconstructing, the Cascadia Subduction Zone earthquake and major tsunami of 26 January 1700 (Satake et al. 1996; Atwater et al. 2005). Paleotsunami findings fundamentally improve tsunami statistics, and result in much more reliable tsunami probabilistic hazard studies for tsunami-prone coastlines.

As a result, the catastrophic events of 1992–2018 and their intensive investigation resulted in tremendous progress in tsunami science, hazard mitigation, and warning. Moreover, these developments were reported in many papers in numerous journals including Pure and Applied Geophysics (PAGEOPH) topical issues (Satake and Imamura 1995; Satake et al. 2007, 2011a, b, 2013a, b; Cummins et al. 2008, 2009; Rabinovich et al. 2015a, b, 2018, 2019; Geist et al. 2016). Besides, the two catastrophic tsunamis of 2010 (Chile) and 2011 (Tohoku), as well as other strong events, generated so much attention and substantial new information that they motivated the publication of an extra, intersession volume (Rabinovich et al. 2014). In addition, high interest regarding the Illapel (Chile) 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). Also, another PAGEOPH topical volume, related explicitly to landslide-generated tsunamis, was prepared by Bardet et al. (2003), in the wake of the destructive 1998 Aitape, Papua New Guinea landslide-generated tsunami. All these volumes document research at the frontiers of tsunami science and reflect progress made continuously in tsunami warning and hazard mitigation. Many papers published in these volumes have become classics and been highly cited.

During the 28th International Tsunami Symposium, held in Bali on 21–23 August 2017, and followed by a field trip to Babi Island, Flores on 24–25 August, the commission suggested preparation of the present topical issue. The first volume, "Twenty Five Years of Modern Tsunami Science Following the 1992 Nicaragua and Flores Island Tsunamis, Volume I," was published by PAGEOPH (2019, 176, No. 7, Kânoğlu et al. 2019). It included the overview papers by Okal (2019), Gusiakov et al. (2019) and Arcos et al. (2019), specially prepared for this volume totalling 22 papers.

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[1] DART = Deep-ocean Assessment and Reporting of Tsunamis, is an effective network of deep-ocean stations elaborated for continuous monitoring of tsunami waves in the open ocean and early tsunami warning (Titov 2009; Mungov et al. 2013).

The current Volume II is the direct continuation of Volume I. Altogether, this volume comprises 24 papers that cover a broad spectrum of scientific questions and present frontiers of modern tsunami science.

2. *Meteorological Tsunamis*

A relatively new subject in tsunami science, which began to attract much attention in recent years, is meteorological tsunamis ("meteotsunamis") that are hazardous tsunami-like waves of atmospheric origin. Several destructive events of this kind occurred in the last years in various regions of the world oceans. In the opening paper of this volume, Rabinovich (2020) presents one of the first attempts to overview and classify the strongest events since 1992. A total of 51 selected events over the past 27 years were examined and described, that took place in the Mediterranean, the Black Sea, Japan, South Korea, Australia, the Great Lakes, South Africa, the USA, Canada, Brazil, the Netherlands, and other countries and regions. All meteotsunami events were separated into four groups: "Good-weather harbour," "Good-weather open-coast," "Bad-weather harbour (storm seiches)," and "Bad-weather open-coast." "Good-weather" meteotsunamis are most typical for the Mediterranean region, while "bad-weather" events mainly occur on the Atlantic coasts of the USA and Europe.

One of the most devastating meteotsunamis impacted the northeast coast of the Persian Gulf (PG) on 19 March 2017, inundating the shore in the area of Dayyer for a distance of ~ 1 km and resulting in the deaths of five people (Salaree et al. 2018). Heidarzadeh et al. (2020) examine this event in detail, using the data from 12 sea-level stations and 47 high-resolution air pressure records along the PG. The results show that the event was very local; the total length of the affected coast was ~ 80 km. The atmospheric processes during 18–22 March were found to be very active, and a number of tsunamigenic air pressure disturbances were observed propagating eastward over the PG with speeds of 21–38 m/s. The Froude number, Fr, estimated as the ratio of the air disturbance speed to the long-wave speed, on 19 March 2017 in the Dayyer region was close to resonance, $Fr \sim 0.9–1.1$, which is highly favourable for meteotsunami generation.

3. *Historical Tsunami Events*

The section on historical tsunami events includes four papers starting with Gusiakov (2020), which provides comprehensive statistics on tsunami wave heights for the last 120 years (from 1900 to 2019). All yearly-maximum tsunamis were divided into four groups: seismogenic (65%), landslide-generated (19%), volcanic (8%), and meteorological (8%). The temporal distribution of the collected extreme runup values shows that the annual occurrence of large tsunamis was relatively stable throughout the twentieth century, but with some increase during the last 27 years (since 1992).

On 8 November 1905, a large earthquake occurred offshore Mount Athos, North Aegean Sea in Greece. Triantafyllou et al. (2020) conclude that the occurrence of a tsunami of approximately 3 m runup is a consequence of the landslide triggered by the earthquake. The determination of the magnitude indicates a 7.2 event. The numerical simulation of the tsunami using two landslide scenarios concludes that a slide of ~ 2.7 million m^3 reproduces well the historical observations.

Melis et al. (2020) investigated the 23 July 1949 Chios Earthquake in the Central Aegean Sea, one of the largest in the region. The seismic moment of $M_0 = 7 \times 10^{26}$ dyn cm was obtained form mantle surface waves, ranking the Chios event second only to the 1956 Amorgos earthquake (Okal et al., 2009). Besides, they carried out a field survey collecting data from surviving witnesses and confirmed a small tsunami. They presented two possible fault planes, which can be distinguished using an extensive dataset of reported macroseismic intensities, but cannot be resolved from tsunami simulations. Also, no ancillary sources such as underwater landslides are required to explain the reported amplitudes.

The paper by Bocchini et al. (2020) addresses the tsunamigenic potential of moderate magnitude earthquakes and the challenge they pose for tsunami early warning. They present a comprehensive study of the 1 July 2009 event, an earthquake of magnitude $\sim$ 6.5, 80 km offshore Crete, Greece and the companion tsunami. The numerical simulation of the earthquake-induced tsunami compares well with the eyewitness reports, suggesting a high tsunamigenic potential for high-angle reverse faults in the upper-plate above the plate interface, significantly higher than that of interplate earthquakes of similar or even slightly larger moment magnitude.

4. *Tsunami Source Models and Case Studies*

Hossen et al. (2020) present a new algorithm to identify sea surface displacement and then earthquake slip distribution through tsunami waveform using time reverse imaging based on a Green's function approach. They apply their methodology to the 23 January 2018 Kodiak earthquake and model its source. They also discuss that while GPS and seismic data could provide relevant information, their methodology only needs tsunami data as input, and proves computationally efficient.

The 2018 large Kodiak earthquake generated a trans-Pacific tsunami. Wang et al. (2020) study tsunami amplification and transformation along its path using tsunami waveforms observed at 21 open-ocean sites and 27 coastal tide gauges. Wavelet analysis revealed the strong dispersive character of the propagated tsunami waves. The abrupt jump in water depth of about 4 cm detected at DART 46409, located nearby the epicenter of the 2018 Kodiak earthquake, appears to have been due to an earthquake-induced seafloor subsidence.

5. *Tsunami Warning*

The recent developments in the tsunami modelling components of the Indonesia Tsunami Early Warning System (InaTEWS) are presented in Harig et al. (2020). They consist of a dual system running in parallel, with a high-resolution scenario database precomputed with the finite element model TsunAWI, and the GPU-parallelized linear long-wave model easyWave, handling events outside the database coverage. They discussed tsunami warning products, i.e., tsunami wave heights and arrival times, estimated through TsunAWI and easyWave. In addition, they review the performance of the warning system for the past events pointing out to system updates.

Reliable and robust determination of the initial tsunami source is essential for tsunami early warnings. Even though near-field Global Navigation Satellite System (GNSS) observations have shown promise to constrain source inversion, they remain sparse along most active faults. Chen et al. (2020) present an automated earthquake finite source inversion methodology that combines near-field GNSS data and mid-range teleseismic P displacement waveforms. They implemented their algorithm successfully as part of the prototype of JPL's GPS-Aided Tsunami Early-Detection system, and tested it for many recent events. They present their real-time results and discuss future improvements.

The Joint Australian Tsunami Warning Center (JATWC) issues three levels of threat: Land Threat, Marine Threat or No Threat along the coast. Greenslade et al. (2020) evaluate the threshold for a Land Threat using tsunami inundation simulations. The result indicated that the threshold value was found to be about 50 cm.

Fauzi and Mizutani (2020) develop a real-time tsunami inundation forecasting method, using machine-learning algorithms. The method was applied to the hypothetical Nankai megathrust earthquake in Japan. The results show that the method can be fast (less than 1 s) and yield results comparable with nonlinear numerical inundation modelling. These constitute promising results for a real-time tsunami inundation forecasting.

Recently, offshore tsunami observations have become important for tsunami early warning. Meza et al. (2020) develop a methodology to optimize the design of an offshore tsunami observation network, which proved significantly useful for the implementation of a network in locations where the deployment of denser arrays is difficult.

6. *Tsunami Probability and Hazard Assessment*

Zamora and Babeyko (2020) study tsunamigenic sources from the Middle America subduction zone that affect the Central American coast. They performed a probabilistic tsunami hazard analysis (PTHA) that considers local and regional seismic sources, in order to estimate the probabilities of exceeding specific tsunami amplitudes along the Central American Pacific coast. The study shows that tsunami heights are likely to exceed 2 m at the 50–80% probability level for 500-year time exposure along the coasts of northwestern Costa Rica, El Salvador, and Nicaragua, southern Colombia, and northern Ecuador. They discuss the large dependence of PTHA on model assumptions, which require integration of all possible uncertainties to perform rigorous hazard models.

A large slip concentrated in a shallow plate interface was observed in several recent large tsunamigenic earthquakes. Scala et al. (2020) propose a method for a PTHA incorporating underthrust earthquakes with enhanced shallow slips. The mean hazard curves obtained using the proposed method show increased probabilities for larger inundation heights, as compared to the typical curves derived from depth-independent slip distributions.

Davis and Griiffin (2020) performed a PTHA sensitivity study for the Australian coastline for six far-field sources considering two rigidity models combined with three slip models. They found that the tsunami hazard offshore Australia is insensitive to the choice of rigidity model, yet significantly affected by the choice of slip model. The fixed-area-uniform-slip model produces lower hazard than both a variable-area-uniform-slip model and a spatially heterogeneous slip model.

Kain et al. (2020) investigate the potential impact at Hobart Airport and nearby coastal communities from a tsunami along the Puysegur subduction zone, off New Zealand’s southwest coast. They simulate a maximum credible earthquake (M_w 8.7) and provide input to local hazard management plans. They identify severe inundation along the east coast, with a flow depth of more than 4 m. They suggest palaeotsunami studies, which would not only validate the results of their modelling, but also provide inundation extent and recurrence intervals of events having previously affected Tasmania.

Ortiz-Huerta (2020) investigate velocity field in and around the Port of Ensenada, Baja California, Mexico induced by the hypothetical tsunamis resulting from M_w 9.3 earthquakes around the Pacific Ocean. Tsunami induced currents were determined as 4–6 knots ($\sim$ 2–3 m/s) at the harbour entrance and 2–4 knots ($\sim$ 1–2 m/s) inside and outside the harbour. Currents are negligible for depths greater than 120 m, which is approximately 15 km offshore from the harbour. Ortiz-Huerta (2020) further suggests deploying an adequate array of pressure gauges and current-meters operating in real-time for marine traffic control.

7. *Tsunami Tide Interaction*

Didenkulova and Pelinovsky (2020) solve the nonlinear shallow water-wave equations analytically over a sloping beach in the presence of a tide in addition to incoming waves. They analyse the influence of the tide on tsunami runup characteristics. First, using an approximate theory, they consider a static nearshore tide, uniform in space during the tsunami travel to the shore. They then consider the case where the tide is not static, showing that the runup oscillations can be presented as a linear superposition of tsunami and tide, even for strongly nonlinear incoming tsunamis. They discuss that nonlinear effects are expressed as weak variations in shoreline velocity with runup and rundown velocities increasing during low tide and high tide, respectively.

Wilson and Power (2020) examine the effect of accounting for tides in numerical models used to estimate the potential impact of tsunamis on coastal regions. A series of numerical experiments were provided by the authors to demonstrate the differences between tsunami models using static or dynamic tide inputs; the simulations were done for two New South Wales estuaries, Sydney harbour, and port hacking, Australia. The effects of geomorphological constrictions were found to affect downriver maximum water levels, tsunami wave heights, upriver water accumulation, and inundation maxima.

8. *Landslide Generated Tsunamis*

Mueller et al. (2020) investigate the vulnerability of Malta against tsunami events considering four scenario events; two landslide sources from slides at outer Malta Plateau and Gela, and two earthquake sources mimicking the 365 A.D. western Hellenic Arc and 1693 south-east of Sicily events. All scenario events caused inundation in densely populated areas, with flow depth exceeding 10 m. Their results show that the Malta Escarpment and Sicily amplify and reflect waves resulting in hot spots along the eastern coastline. Their overall conclusion is the existence of a potential tsunami hazard for Malta, with further studies requiring a better understanding of source mechanisms, as well as probabilistic hazard and risk assessment.

Using detailed historical accounts Pranantyo and Cummins (2020) study the 1674 Ambon, Indonesia tsunami runup, ranking as one of the country's deadliest with 100 m runup and 2300 fatalities. They conclude that runup observed on the north coast of Ambon was generated by an earthquake-triggered coastal landslide; they consider as plausible seismic sources from the Seram Megathrust, the South Seram Thrust, and faults local to Ambon. They use a two-layer tsunami model with an approximate volume of 1 km^3 and explain the observed tsunami runup along the Ambon coast. They emphasize that landslide tsunamis are significant for tsunami hazards along the Indonesian coast, such as the 1992 Flores, 2018 Palu, and Sunda Strait tsunamis.

9. *Tsunami Hydrodynamics*

In the context of Synolakis' (1991) previous study of the evolution of long waves over a sloping beach under Green's law, George et al. (2020) investigate the amplification of long waves over the continental shelf. They show that Green's law is a good approximation for sufficiently gentle continental slopes, i.e., when the width of the slope is large compared to the wavelength. They discuss asymptotic values for the transmission and reflection coefficients for a sharp interface, showing that incoming waves reflect more at steeper slopes, resulting in less amplification. Further, they discuss that many realistic tsunamis fall into an intermediate region, an example being the 2011 Tohoku earthquake tsunami approaching the Oregon coast.

Ermakov and Stepanynts (2020) consider a transformation of long linear waves in an ocean with variable depth. The authors calculate the transmission and reflection coefficients as functions of frequency and total depth for three typical models of bottom profile variation: (1) piecewise-linear, (2) piecewise-quadratic, and (3) hyperbolic tangent profiles. For all these cases, exact solutions are obtained, analysed and graphically illustrated.

10. *Conclusions*

In 2018, while these last two volumes were progressing, the Palu, Sulawesi, Indonesia (e.g. Heidarzadeh et al. 2019; Omira et al. 2019; Putra et al. 2019) and Anak-Krakatau, Indonesia (e.g. Muhari et al. 2019; Paris et al., 2020) highly destructive tsunamis occurred. Even though we included papers presenting substantial developments over the various field of tsunami science in these two volumes, the 2018 Palu and Anak events showed that "our progress is, and will remain, a never-ending story," (Okal 2019). These two events alone left us with questions as to why the tsunami warning system failed to save lives in Indonesia, what their precise sources were, and how the social dynamics of a region can affect early warning systems (UNDRR and UNESCO-IOC 2019). We hope that papers in this volume will help resolve issues raised by the Palu and Anak tragedy events, as well as other challenging issues which might be raised in the future.

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