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

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Abstract—Twenty-two papers on tsunamis are included in the Pure and Applied Geophysics topical issue "Twenty five years of modern tsunami science following the 1992 Nicaragua and Flores Island tsunamis: Volume I," reporting on the frontiers of tsunami science and research. The first three papers overview significant tsunamis of 1992–2018 and discuss the problems of tsunami cataloguing. The main focus of the next four papers is on specific details of historical tsunami events and field surveys. First, three papers are related to thorough analyses of several historical events based on macroseismic, seismological, and tsunami observations, tide gauge data, and modelling results: the 1907 Sumatra "tsunami earthquake," the 1941 Andaman Islands earthquake, and five great tsunamis in the Pacific Ocean (1946, 1952, 1957, 1960 and 1964). The last paper of the section concerns results of the field survey of the 2017 Bodrum-Kos tsunami. The reconstruction of the tsunami sources is the main target of the four following papers, with four events examined in detail: the historical 1810 Baja California, 1992 Flores Island, 2012 Haida Gwaii and 2015 Chilean (Illapel) tsunamis. A set of three papers address problems associated with landslide-generated tsunamis in three different regions: a modelling of the 2017 landslide and tsunami at Karrat Fjord, Greenland; a probabilistic analysis of the hazard from the Indus Canyon in the NW Indian Ocean; and a study of the landslide-induced tsunami hazard along the US East Coast. The next section, including three papers, reports on comparisons between different types of tsunami models, on numerical modelling of tsunami waves in the Caspian Sea, and on the modelling of magnetic signals at Easter Island, following the 2010 and 2015 Chilean tsunamis. The last group of five papers discusses tsunami hazard assessment and warning for various regions of the world oceans, including Alaska, the eastern and western Mediterranean, Australia, the Northeast Atlantic and the entire Pacific Ocean; one specific aspect of these studies is the compilation and efficient application of observed data, in particular, from DARTs.

Key words: Tsunami observations and detection, DARTs, tsunami modelling, tsunami earthquake, Pacific Ocean, Mediterranean Sea, Caspian Sea, tsunami warning and hazard assessment, landslide generated tsunami, tsunami statistics and probability.

1. *Introduction*

On 2 September 1992, an M_w 7.7 earthquake occurred near the coast of Nicaragua (Satake et al. 1993). This relatively moderate earthquake produced a disproportionately destructive tsunami with a maximum runup height up to 10 m that killed approximately 170 people. The earthquake was identified as a "tsunami earthquake," a term introduced by Kanamori (1972) to characterize an event whose tsunami is significantly larger than expected from its magnitudes, especially conventional ones.

Three months later, on 12 December 1992, an M_w 7.8 earthquake hit the northern coast of Flores Island, Indonesia, and generated another catastrophic tsunami with maximum runup of 26 m caused by a submarine landslide triggered by the earthquake. The earthquake and tsunami killed about 2600 people and injured 500 more. The total damage exceeded US$100 million (Yeh et al. 1994).

These two events, which occurred following 28 relatively quiet years after the 1964 Alaska M_w 9.2

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earthquake and tsunami, opened a 25-year period of numerous devastating earthquakes and tsunamis, including two of the most destructive natural disasters in recent human history: the 26 December 2004 Sumatra tsunami that killed about 230,000 people and impacted at least 16 nations directly in the Indian Ocean (Synolakis and Kong 2006), and the 11 March 2011 Tohoku (East Japan) tsunami that killed almost 20,000 people and destroyed the Fukushima Dai-ichi nuclear power plant (Satake et al. 2013a; Synolakis and Kânoğlu 2015). At the same time, these events marked the beginning of "modern tsunami science era" (Okal 2019a).

The 1992 Nicaragua and Flores Island tsunamis were the first tsunamis subjected to comprehensive International Post-Tsunami Surveys, which become systematic following later significant tsunamis (Synolakis and Okal 2005; Okal 2019a). Precise estimations of the tsunami runup along the affected coasts became the main source of key scientific information about the events, and was essential for the long-term forecast of future events and for the estimation of tsunami risk for a specific region. However, as the field surveys followed scientific progress, much more complete information was collected for the events, see Arcos et al. (2019). In addition, the information collected was found to be very valuable for the development and verification of numerical models (Synolakis et al. 2008).

Further, the 1992 Nicaragua and Flores Island tsunamis initiated the establishment of the Tsunami Bulletin Board (TBB) network (tsunami_bb@infolist.nws.noaa.gov), proposed by Dr. Frank González of the Pacific Marine Environmental Laboratory (PMEL), National Oceanic and Atmospheric Administration (NOAA), Seattle, Washington, USA. For several years the TBB was supported by PMEL/NOAA but then, when the number of participants exceeded several hundred, it was transferred to the International Tsunami Information Center (ITIC), UNESCO/NOAA, Honolulu, Hawaii, USA. The TBB development was extremely effective, as it built a link between practically all tsunami scientists throughout the entire world. It became possible in a trice to exchange information, data, and numerical modelling results, and to consult among colleagues. The greatest value of the TBB became evident during major catastrophic events, like the 2004 Sumatra and 2011 Tohoku tsunamis. At present, the ITIC TBB turned out to be a modern tsunami communication system. Further, tsunami science became a "science without borders"; the level of the scientific international cooperation in tsunami research appears to be higher than in any other geophysical discipline and it is common for tsunami papers to have joint international teams of authors, the present issue being a spectacular example.

The crucial factor promoting enormous progress in tsunami science is an incredible enhancement in tsunami measurements. Most of coastal tide gauges working before 1992 were built to record tides, storm surges, seasonal oscillations and other low-frequency processes (cf. Pugh and Woodworth 2014). These were either analogue "pen-and-paper" gauges, or digital instruments with poor time resolution (with a 15–20 min time step). Such instruments were quite adequate to measure tides and other long-period processes but were inappropriate for tsunami monitoring. Specifically, the 1992 Nicaragua and Flores Island tsunamis, as well as other tsunamis of the early 1990s, advanced the reconstruction of the tide gauge network in the Pacific Ocean (e.g. Rabinovich and Stephenson 2004). However, most of the NOAA tide gauges still had insufficient time resolution (6 min), while in the Indian and Atlantic oceans, coastal tide gauges were either still analogue or had 6–15 min sampling. At that point in time, the common opinion was that there are no tsunamis in these oceans and there was no reason to have higher resolution. Only the catastrophic 2004 Sumatra tsunami in the Indian Ocean, which was globally observed, including in far remote regions of the North Pacific and North Atlantic (e.g. Rabinovich et al. 2006; Titov et al. 2005a), initiated the total upgrade of the worldwide sea level network. Modern digital tide gauges are high-resolution instruments with 15–60 s sampling, which is perfect for tsunami measurements. As a result, each new strong tsunami brings enormous amount of high-quality data from several hundred instruments. These new data enabled to investigate tsunamis with a much higher accuracy than was possible before, and to significantly improve the general tsunami understanding.

However, coastal measurements only indirectly characterize open-ocean tsunami characteristics.

These observations are strongly distorted by various coastal processes, including refraction, reflection, nonlinearity, friction, scattering by coastal and bottom irregularities, high noise level caused by wind waves and swell, wave trapping, shelf resonance, and especially the harbour resonance of local water basins (bays, inlets, and harbours where tide gauges are normally situated). Hence, deep-ocean tsunami measurements are crucial to understand the generation mechanism and physical properties of tsunami waves and to provide effective and timely tsunami warning. The first record of a tsunami in the open ocean was obtained by Filloux (1982), but it was made by an autonomous bottom pressure sensor and the tsunami was detected only after the instrument was retrieved from the bottom, i.e. about 1.5 years after the tsunami actually occurred (14 March 1979). The first real-time measurements of tsunami waves in the open ocean, and the continuous monitoring of these waves for operational tsunami warning, began in the 1990s and resulted in the creation of the Deep-ocean Assessment and Reporting of Tsunamis (DART)[1] system, which yielded precise real-time tsunami measurements (with an accuracy of about 0.1 cm), made possible by data transmission via modem and satellite communication technology (Mofjeld 2009; Rabinovich and Eblé 2015).

Before 2005, there were seven DARTs working in the Pacific Ocean (six from NOAA, USA, and one Chilean), and two of them provided 15-s data during the 2004 Sumatra tsunami in the Indian Ocean. High-quality records of this tsunami were extracted from both DARTs, even though the instruments were ~ 18,000 to 22,000 km from the source area, and the amplitudes of the recorded waves were only ~ 1 cm (Rabinovich et al. 2011, 2017a). As a result of the catastrophic 2004 Sumatra tsunami, a worldwide network of DART stations was deployed along the most seismically active zones of the World Ocean, which presently includes 45 instruments in the Pacific Ocean, 10 in the Indian Ocean and 7 in the Atlantic Ocean. These instruments became the main backbone of the modern International Tsunami Warning System (e.g. Mofjeld 2009; Titov 2009) and one of the most important sources of invaluable scientific information. Moreover, after the destructive 2011 Tohoku tsunami, Japan established the DONET and S-net arrays of high-resolution precise cable stations off the Pacific coast of Japan that include more than 200 bottom gauges (e.g. Rabinovich and Eblé 2015). Also, in 2009 the Ocean Network Canada (ONC), installed on the shelf—continental slope of Vancouver Island a seafloor network of geophysical observatories,[2] which was found to be very effective to measure tsunami waves and has already recorded great many Pacific tsunamis, beginning with the 2009 Samoa event (Thomson et al. 2011). As a result, any new tsunami brings enormous amount of comprehensive information about tsunami properties in the open ocean that can be used for the verification of numerical models (Synolakis et al. 2008), and for real-time reconstruction of the source during operational tsunami warning. While before 1992, the main problem in tsunami studies was the absence of reliable observational data, we now face the opposite situation, when we are overwhelmed by the amount of available coastal and open-ocean tsunami data.

Another important problem, where an incredible progress was achieved in the last 25 years, is the numerical modelling of tsunamis. Before 1992, numerical simulations were used mostly for specific modelling experiments with artificial sources, rather than to numerically reconstruct and examine real events. At present time, numerical modelling has become a main tool of tsunami research: it enables scientists to examine particular features of historical and recent tsunami events, in order to provide real-time numerical modelling and effective forecast of actual tsunamis (e.g. Titov et al. 2005b), and to reconstruct with high accuracy initial sources of tsunamis. Also, numerical modelling is now the main instrument for local and regional tsunami zoning, i.e. for the estimation of maximum expected tsunami wave heights and possible inundation along specific coastal areas of interest.

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[1] DART is an effective network of deep-ocean stations, elaborated by NOAA for monitoring tsunami waves and early tsunami warning.

[2] This network was previously known as NEPTUNE-Canada (Canadian North-East Pacific Underwater Networked Experiments); it was established by the University of Victoria, British Columbia, Canada. (http://www.oceannetworks.ca/).

Several essential factors determined this progress, including advanced numerical models, enormous improvement in modern computers, the availability of high-resolution bathymetry/topographic data, and improved knowledge of the characteristics of seismic sources. Observational data and, first of all, open-ocean tsunami measurements, now play a determinative role in the model "tuning" and its adaptation to a specific problem or event.

While there are many modern numerical models to simulate propagation of tsunami waves, two of them became most widespread: (1) The Method Of Splitting Tsunami (MOST) model (Titov and González 1997; Titov and Synolakis 1998; Titov et al. 2016) and the Tohoku University's Numerical Analysis Model for Investigation (TUNAMI) (Imamura 1996). Both models are widely used both for operational and scientific purposes. Most importantly, tsunami modelling and tsunami measurements/detection, which are two independent components of tsunami studies, now constitute joint parts of united tsunami analyses: Tsunami modelling helps to identify tsunami waves (even for low signal-to-noise cases) and to explain the observed properties of the propagating waves, while the observations help to verify and fit the model. Specifically, the combination of modelling and observations allow a better reconstruction of the tsunami source (e.g. Fujii and Satake 2007; Wei et al. 2008; Titov et al. 2005b), and have been crucial in explaining such subtle effects as the influence of the Earth elasticity and seawater stratification on open-ocean tsunami propagation (Watada et al. 2014; Allgeyer and Cummins 2014).

A subject of great importance, which began to be actively developed only in the last 25 years, is that of *paleotsunami* studies (e.g., Clague et al. 2000; Tappin 2007). These have allowed scientists to go deeply into tsunami history and find reliable information about events that occurred hundreds, or even thousands, of years ago. In this way, paleotsunami findings fundamentally improve tsunami statistics and supply scientists with invaluable information to estimate tsunami risk for specific coastal areas. Even for recent events, like for example, the 2011 Tohoku tsunami, paleotsunami information proved to be very useful, significantly supplementing our knowledge about that particular event (e.g. Goto et al. 2012). Probably the greatest paleotsunami finding was the discovery of the Cascadia Subduction Zone earthquake and major tsunami of 26 January 1700, based on tsunami signatures revealed in sediment deposits in Oregon, Washington and British Columbia, supplemented by Japanese historical chronicles (Satake et al. 1996; Atwater et al. 2005). In addition to studies of onshore sediments, researchers have also studied the turbidite event history of the Cascadia Basin and identified 19 turbidite events within the last 10,000 years, i.e. approximately one event in 500–530 years (Goldfinger et al. 2012).

The catastrophic events of 1992–2018, their intensive investigation, the tremendous progress in tsunami science, hazard mitigation and warning, all resulted in thousands of papers, hundreds of books and professional reports, and in many topical issues and book article collections. Two of them—Bernard and Robinson (2009) and Kânoğlu et al. (2015)—tried to summarize modern tsunami knowledge and the latest achievements in tsunami science.

Among the numerous special issues on tsunamis published by various journals, *Pure and Applied Geophysics* (PAGEOPH) topical issues are probably the most significant. These issues are published under the umbrella of the Joint Tsunami Commission, a part of the International Union of Geodesy and Geophysics (IUGG). This commission, established following the great 1960 Chile Tsunami, has held biannual International Tsunami Symposia (ITS), and published special volumes of selected papers, initially under the leadership of Professor Kenji Satake (University of Tokyo). Altogether, 13 such volumes were published in PAGEOPH during 1992–2019 (Satake and Imamura 1995; Satake et al. 2007, 2011a, b, 2013a, b, Cummins et al. 2008, 2009; Rabinovich et al. 2015a, b, 2017b, 2018; Geist et al. 2016). In addition, 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). Moreover, 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). In addition, another PAGEOPH topical volume, specifically related to landslide-generated tsunamis, was prepared by Bardet et al. (2003), in the wake of the 1998 Aitape, Papua New Guinea destructive landslide generated tsunami. All these volumes document research at the frontiers of the 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.

The Commission proposed preparation of the present volume during the 28th International Tsunami Symposium, which was held in Bali on 21–23 August 2017, followed by a field trip to Babi Island, Flores on 24–25 August. The field trip brought participants back to the scene of an event that had occurred 25 years earlier, when a large earthquake on 12 December 1992 in northern Flores generated a tsunami that claimed 2600 lives, and destroyed 18,000 houses (Yeh et al. 1994, Kânoğlu and Synolakis 1998). From this standpoint, the topical volume “Twenty Five Years of Modern Tsunami Science Following the 1992 Nicaragua and Flores Island Tsunamis, Volume I” should be considered as a highly valuable continuation of the previous topical Pure and Applied Geophysics (PAGEOPH) tsunami issues and, at the same time, as an illustration of current development and progress in tsunami science. In this context, it includes overview papers by Okal (2019a), Gusiakov et al. (2019) and Arcos et al. (2019), specially prepared for this issue. Altogether, this issue comprises 22 papers, with additional papers to be published in the next volume.

2. *Twenty-Five Years of Progress in Tsunami Science*

Okal (2019a) critically evaluates forty-seven tsunamis of geological origin starting with the 1992 Nicaragua event, and discusses how these events helped shape field, experimental, theoretical, and/or societal aspects of tsunami science. Okal (2019a) listed principal developments as follows: from the geophysical standpoint, the author earmarks the development of the W-phase inversion for the low-frequency moment tensor of the parent earthquake and the abandonment of the concept of a maximum earthquake magnitude for a given subduction zone, controlled by simple plate properties (Kagan and Jackson 2013; Stein and Okal 2007). Further, from the standpoint of hydrodynamics, he lists the development of tsunami numerical models to simulate tsunami runup over a dry land, and recent investigations of current velocities, during interaction of tsunamis with harbours. Further, Okal (2019a) emphasises the need for research on the real time identification of “tsunami earthquakes”, whose tsunamis are larger than expected from their seismic magnitudes, and the continuous need for further education of the populations at risk, in coastal areas.

Gusiakov et al. (2019) present an analysis of global tsunami occurrences from 1992 to 2016. This 25-year period represents less than 1% of the total catalogue duration (ca. 4000 years), but contains almost 12% of the total number of historical events and nearly 54% of the total runup and inundation depth measurements, illustrating the data obtained in field surveys, notably for the two trans-oceanic megatsunamis in this period—the 26 December 2004 Indian Ocean and the 11 March 2011 Tohoku tsunamis, with 1625 and 6271 total measurements, respectively. Two hundred ninety recorded tsunamis and tsunami-like events are listed in the catalogue; ninety five of them featured maximum runup or inundation height greater than 1 m causing damaging or potentially damaging effects, and thirty-two destructive tsunamis resulted in human fatalities.

Arcos et al. (2019) provide the evolution of the global tsunami field survey database colocated at the NOAA National Centers for Environmental Information (NCEI) and World Data Service (WDS) for Geophysics. Even though post-tsunami field surveys had taken place prior to the 2 September 1992 Nicaragua tsunami (such as for the 1964 Southern Alaska, 1976 Mindanao, and 1983 Sea of Japan tsunamis), the first formal International Tsunami Survey Team (ITST) was formed in the aftermath of the Nicaraguan tsunami (Satake et al. 1993). Since then, ITSTs, organized after each event, not only resulted in international and interdisciplinary collaboration, but also in the standardisation of survey methodologies and guidance (Kong 2011), which eventually led to the publication of the post-tsunami field survey guide (UNESCO-IOC 2014). The standardisation of measurements of maximum runup, maximum water level and inundation extent have allowed their comparison across continents, events and time. Moreover, much more complete data are now captured during recent post-tsunami surveys, i.e. not just only maximum runup or inundation depth measurements, but also information regarding wave sequencing and current velocities. Tsunami field survey databases also provide reliable information for historical events, which could be used for verification of tsunami numerical models as outlined by Synolakis et al. (2008), or for identifying the nature of the source. As an example, ITST survey data proved crucial in identifying the source of the 1998 Papua New Guinea tsunami as a landslide, as opposed to a seismic dislocation (Okal and Synolakis 2004).

3. *Studies of Historical Tsunami Events and Field Surveys*

Martin et al. (2019) reassess the 4 January 1907 Sumatra, Indonesia tsunami (earthquake) with a multidisciplinary approach identifying two large earthquakes occurring within an hour of each other but with clearly different seismological character. Across the Indian Ocean, they compiled 88 observations, obtained from individual accounts as well as from reports published in local newspapers, of the tsunami generated by the mainshock. Relative to its instrumental magnitude, the mainshock produced an anomalously large tsunami, which qualifies the event as a “tsunami earthquake”. Yet, the shaking on Nias was severe, which is unusual for a tsunami earthquake. Martin et al. (2019) identified a large, second event occurring 53 min after the mainshock, which resolves the paradox of the surprisingly high intensities following the slow 1907 mainshock. The local S’mong tradition, a probable result of the 1907 events, may have prevented heavy loss of life on Simeulue in 2004 and 2005, since both were preceded by severe shaking (McAdoo et al. 2006).

Okal (2019b) presents a modern seismological study of the large earthquake of 26 June 1941 in the Andaman Islands along the India-Burma plate boundary. The author shows that the 1941 earthquake took place under the Andaman accretionary prism and consisted of a composite event, whose nucleating phase, with a strike-slip mechanism, is incompatible with spectral amplitudes of mantle Rayleigh and Love waves. This event resulted in a small tsunami due to the combination of the generation mechanism, and of the location of the source under the islands and in shallow water, leading to a reduction in amplitude when transitioning to a deeper basin, under Green’s law.

Rabinovich et al. (2019) examine analogue tide gauge records on the coast of British Columbia (BC) for the five major trans-Pacific tsunamis that occurred between 1946 and 1964. A comprehensive frequency analysis of each event is presented, suggesting a strong influence of local and regional topography on the incoming waves, since the dominant frequencies of the waves and their evolution in time were similar at each station for different events, but differed considerably among sites for a particular tsunami. A common feature of all these events is the fact that they penetrated deep inside the narrow channels, fjords and inlets typical of the BC coast, which suggests that these morphological features do not hinder the incoming waves but rather can strongly enhance them through resonant amplification when the dominant incoming wave frequency coincides with the natural frequency of the interconnected basin.

Dogan et al. (2019) present the results of the field survey conducted after the 20 July 2017 Bodrum-Kos earthquake and tsunami in the Mediterranean Sea, between the Bodrum Peninsula in Turkey, and Kos Island in Greece. A minor tsunami followed the earthquake, producing small runup around 1 m. Maximum runup and inundation distances were observed in Bodrum peninsula, with moderate damage observed in Kos port. Interviews conducted during the survey revealed extremely low tsunami awareness among the local population and the numerous tourists. As tsunamis are infrequent in this area, the study of minor tsunamis is important and it helps test local tsunami warning systems.

4. *Tsunami Source Models*

Ramírez-Herrera et al. (2019) analyse the source of the 27 August 1810 Loreto event in Baja

California. The main difference between this event and other events of the 19th and 20th Century is the fact that the tsunami followed the earthquake and produced significant flooding along the coast. Historical information on the tsunami is presented and used to constrain the source of the earthquake. The discrepancy between the maximum earthquake intensity (IX), the estimated magnitude (7.4) of the earthquake and the tsunami travel time to the coast suggest that the tsunami was triggered by a submarine landslide. The authors confirm this mechanism, based on numerical modelling studies, using various dislocation and landslide sources.

Pranantyo and Cummins (2019) revisit the source of the 1992 Flores earthquake and tsunami. They estimate the slip model of the Flores 1992 earthquake through a joint finite-fault source inversion technique, using all available datasets, teleseismic body and surface waveforms, co-seismic vertical deformation data, one tsunami waveform, and tsunami runup heights. The largest slip was found near the hypocenter, which had not been well resolved by previous models. They conclude that the earthquake ruptured a distinct segment of the back-arc thrust system in the eastern Sunda Arc, Indonesia.

Voronina et al. (2019) propose a method to identify an initial tsunami source from observed waveforms at DART buoys with the only additional information about the source spatial localization. They regularise an ill-posed inverse problem using a least square inversion with the truncated Singular Value Decomposition and r-solution methods. Their computational algorithm improves the inversion by selecting the most informative set of available observation stations, suppressing the instability of the numerical solution of this ill-posed problem. The method was successfully applied to the 16 September 2015 Illapel, Chile tsunami.

Yolsal-Çevikbilen et al. (2019) present finite-fault source rupture models and numerical modelling for the tsunamis generated by the 28 October 2012 Haida Gwaii, Canada (M_w 7.7) and 16 September 2012 Illapel, Chile (M_w 8.3) earthquakes. Fault parameters were estimated by analysing teleseismic long-period P- and SH-waves and broadband P-waveforms and using waveform inversion and hybrid back-projection methods. They reveal heterogeneous slip distributions on fault planes with long source durations (80 s and 150 s) and low stress drop values (10–15 bar). Further, they numerically model tsunami propagation for both events, using nonlinear long-wave models for both uniform and non-uniform slip distributions. They conclude that, in general, leading wave shapes and arrival times are adequately modelled with the heterogeneous slip distribution models. Moreover, in order to obtain a better comparison between numerical modelling and field data, they emphasise the need for joint inversions of GPS, tsunami, teleseismic and strong ground motion records, and for higher resolution of bathymetric data.

5. *Landslide Generated Tsunamis*

Paris et al. (2019) investigate the landslide-triggered tsunami event on 17 June 2017 in Karrat Fjord, Greenland, which flooded several villages, killing 4 people and destroying 11 houses at Nuugaatsiaq. They numerically model the landslide by considering it as a 50 million m^3 granular flow under gravity forces. They obtain amplitudes similar to those estimated from videos, three waves between 1 and 1.5 m arriving at Nuugaatsiaq with a period of roughly 3 min. Their amplitude estimates are also in agreement with the deconvolution of oscillations recorded on a horizontal seismogram operating at Nuugaatsiaq. Further, they study future potential subaerial landslides next to the one on 17 June 2017, threatening Karrat Fjord. They perform a sensitivity study with 2, 7, 14 and 38 million m^3 subaerial landslides and conclude that the shape of the waves is independent of volume, the relationship between the volume and the wave height is linear, and the orientation of the slide influences neither the period nor the shape of the generated wave.

The first probabilistic tsunami flooding maps, called probabilistic tsunami hazard assessment (PTHA), were developed by González et al. (2009), integrating tsunami inundation modelling with methods of probabilistic seismic hazard assessment (PSHA). Since then, PTHAs have been considered or performed in many tsunami-prone areas. Here, Schambach et al. (2019) present part of a tsunami hazard assessment study, which was carried out since 2010 to develop tsunami inundation maps for the US East Coast, under the auspices of the US National Tsunami Hazard Mitigation Program (NTHMP). In this study, submarine mass failures (SMFs) were considered as a form of potential hazard along the upper US East Coast and modelled using the three-dimensional non-hydrostatic model NHWAVE with two types of slump motion: (1) rigid, for which the geometry and law of motion are specified as bottom boundary conditions, and (2) a deforming slide, for which motion is modelled using a depth-integrated bottom layer of dense Newtonian fluid, fully coupled to the overlying fluid motion. They use the Boussinesq-type model FUNWAVE-TVD to evaluate tsunami propagation once the SMFs have stopped. The authors discuss the need to use a dispersive model to simulate for landslide tsunami generation, the model which depends on the relative size of the SMF and of the relative height of generated waves, as compared to the local depth. A non-dispersive model would have been adequate for the very large SFMs considered in this study. In addition, a dispersive model, such as a long-wave Boussinesq model, is needed to accurately simulate both far-field and near-field tsunami propagation; Schambach et al. (2019) also stress the need for sufficiently high-resolution model grids.

Salmanidou et al. (2019) investigate the tsunami hazard potential associated with submarine mass failures in the Indus Canyon in the Northwestern Indian Ocean, which featured numerous failures in the past. They use statistical emulation, training it with 60 slump scenarios parametrising slide thickness, slide width, travel distance, and submerged depth. Then, they use the trained emulator to predict 500,000 trial scenarios and to study probabilistically the tsunami hazard over the near field. Their results imply, most likely, 0.2–1.0 m and 2.5–13 m/s tsunami amplitudes and flow speeds respectively, which could potentially impact vessels and maritime facilities. Further, they discuss the advantage of using an emulator-based approach in probabilistic hazard analysis, allowing the generation of thousands of tsunami scenarios in a few seconds, as compared to several days on high performance computing facilities for a single run of the dispersive tsunami solver.

6. *Tsunami Numerical Modelling*

Sogut and Yalcıner (2019) present validation and model comparison studies for two numerical models, NAMI DANCE and FLOW-3D® (Flow Science 2002) for tsunami studies. While the former was developed in-house as a tsunami numerical model solving nonlinear shallow water-wave equations, the latter is a general purpose computational fluid dynamics software, which is based on the Volume-of-Fluid technique. Both models were tested against data for tsunami currents (Lynett et al. 2017), in addition to the benchmark results listed by Synolakis et al. (2008).

Periáñez and Cortés (2019) present a numerical study of the propagation of tsunamis generated by submarine earthquakes in the Caspian Sea. They apply their modelling to the 20 June 1990 Rudbar earthquake in north Iran showing results coherent with previous studies. In addition, they model the 8 July 1895 Krasnovodsk earthquake, which, previously, had not been simulated. Modelling results produced coastal flooding, as reported in literature, with a rather local effect since the tsunami was generated in very shallow waters. Further, three additional hypothetical scenarios were considered in the most seismically active regions of the Caspian Sea. Results showed that both the east and west coasts of the central Caspian Sea would be the most affected with potentially significant effects in such cities as Baku, Azerbaijan.

Torres et al. (2019) study electric currents induced by tsunami flow across the geomagnetic field both in the ocean and the ionosphere. These currents generate secondary magnetic fields, observable at the seafloor and on land. They model magnetic field disturbances, recorded at the Easter Island Observatory for the Chilean tsunamis of 27 February 2010 and 16 September 2015, by applying the Biot–Savart law to tsunami simulations, and emphasize that using Maxwell equations may present a significant improvement to their model. They calculate tsunami-induced perturbations in the vertical component of the geomagnetic field and obtain good agreement with the observations. They hypothesise that the magnetic effects may be produced by a combination of oceanic and ionospheric electric currents, and that even a relatively small tsunami might be monitored on magnetic records. Encouraged by the results, they decided to install a land-based magnetometer in San Vicente Bay, close to Concepción, Chile.

7. *Tsunami Hazard Assessment and Warning*

In some tsunami-prone regions, there is a lack of high-resolution digital elevation models to evaluate tsunami inundation hazard in order to mitigate its impact through numerical modelling. Nicolsky et al. (2019) present a methodology to approximate tsunami hazard zones in areas with poor topographic and bathymetric coverage, with specific application to many rural coastal communities in Alaska, from tsunamigenic earthquakes along the Alaska–Aleutian megathrust. They perform modelling of earthquake-generated tsunamis in the Andreanof Islands, and estimate the potential inundation zone for the Adak community for three scenarios, exploring a sensitivity of maximum runup with respect to the coseismic slip distribution. Hence, they define a safety factor, 1.3 in this specific case, validated against high-resolution modelling results. The authors assume that the safety factor is specific to local topographic/bathymetric features, e.g. the heads of bays might result in larger amplification, hence in larger safety factors.

Triantafyllou et al. (2019) applied a tsunami risk assessment model to the coast west Heraklion, the capital city of Crete Island, Greece. Tsunami risk assessment, which is considered as a convolution of tsunami hazard, vulnerability of the assets at risk and the economic value exposed, is an important component of the planning for risk reduction. Heraklion was hit by strong tectonic and volcanic tsunamis in the past. The Minoan tsunami, generated by pyroclastic flows during the eruption of Thera (17th century BC), was selected as the worst scenario. A numerical modelling study was performed using a Boussinesq-type model, which produced 1.2 km inundation and 14 m maximum water depth. Using their tsunami simulation results, building vulnerability was determined with the use of the DAMASCHE, empirical GIS tool, which is based on building damage data from the 2004 Indian Ocean tsunami. Results indicated that most buildings would suffer repairable damage, while 183 buildings would collapse partially or totally. The damage level was translated into monetary loss following building repair or reconstruction, based on the rates determined officially after the destructive Greek earthquakes of 2014.

Since it can be impractical to develop regional and global tsunami hazard analysis for some tsunami-prone communities, it is essential to use simplified and efficient methods to estimate the tsunami inundation height and its related uncertainty. One approach is to use an amplification factor, which describes the relation between offshore wave height and the maximum inundation height, as predicted by linearized plane wave models employed for incident waves with different wave characteristics. Glimsdal et al. (2019) present a new amplification factor method that takes into account the offshore bathymetry near the coastal site, and apply it to the North-Eastern Atlantic and Mediterranean (NEAM) region. They first quantify the uncertainty in inundation height by analysing its variability in more than 500 high-resolution inundation simulations at six different coastal sites with different earthquake sources, in order to produce various wave periods and polarities. They conclude that the probability density of the maximum inundation height can be modelled with a log-normal distribution, whose median is quite well predicted by the amplification factor, and that the associated maximum inundation height uncertainties are indeed significant and must be accounted for in tsunami hazard analysis. They apply their methodology to the recently developed Tsunami Hazard Maps for the NEAM (TSUMAPS-NEAM) region PTHA.

Over the past decade, the number of open-ocean gauges capable of parsing information about a passing tsunami has steadily increased, particularly through national cable networks and international buoyed systems such as the DART sensors (e,g. Rabinovich and Eblé 2015). However, most current warnings that incorporate direct tsunami observations are located at mid- and far-field localities. Williamson and Newman (2019) study the effectiveness of a localised near-field systems in four seismically active subduction zones, Cascadia, Japan, Chile, and Java, for their potential to facilitate local tsunami early warning. They assess which of them currently have instrumentation at the right locations for direct tsunami observations with enough lead time. Their primary findings indicate that while such regions as Chile are ill-suited in this respect, other localities, like Java could incorporate direct tsunami observations into their hazard forecasts with enough lead time for effective emergency response by coastal communities.

Greenslade et al. (2019) evaluate tsunami travel times (TTT) from scenario database T2 at the Joint Australian Tsunami Warning Centre (JATWC), and tsunami travel times from GEOWARE (2007), and compare them to observed arrival times at tide gauges and tsunameters from the National Geophysical Data Center/World Data Service (NGDCS/WDS), in order to evaluate current operational practice at the JATWC. They conclude that travel times from the T2 scenario database are at least as accurate as those from TTT and in most cases, more accurate. They also infer that the 'best' scenario-based method is Tp20—the time of arrival of the first peak that is at least 20% of the maximum amplitude at that location.

8. *Conclusions*

In conclusion, we reflect on Okal's (2015) evocation of Zeno of Elea's paradox in the context of the advancement of tsunami science and of efforts in mitigation: "Like Achilles, our communities seem well armed to constantly gain in wisdom and progress towards mitigation of a perceived level of tsunami hazard, but individual new events often bring an element of diversity which redefines the goal, and like the Tortoise, keeps pushing it forward, in an everlasting challenge". While the present collection of papers point to substantial development across the various fields of tsunami research in the past 25 years, our progress is, and will remain, a never-ending story, and we can trust that a continued string of similar special issues will appear in the future.

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