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Introduction to "Sixty Years of Modern Tsunami Science, Volume 2: Challenges"

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Abstract—Fifteen papers are included in this PAGEOPH topical issue "Sixty Years of Modern Tsunami Science, Volume 2: Challenges." The issue starts with a general introduction, and then briefly summarizes all contributions, first papers addressing general topics, and then articles grouped on a regional basis: Northern Pacific, Southeast Pacific, Southwest Pacific and Indonesia, and Mediterranean regions.

Keywords: Tsunami observations, tsunami modelling, tsunami forecasting, tsunami hazard assessment.

1. Introduction

The present topical issue "Sixty Years of Modern Tsunami Science, Volume 2: Challenges", regroups 15 contributions sampling modern aspects of tsunami science. We elect to start this introductory article with a direct quote from the concluding remarks of the previous volume (Kânoğlu et al., 2021)

> "Yet, and despite [...] substantial developments [...] across many disciplines of tsunami science and engineering, we are unfortunately still faced with many unanswered questions",

among which the authors earmarked the problem of the so-called "tsunami earthquakes", a concept introduced half a century ago by Kanamori (1972) and critically affecting the warning and hence the mitigation of powerful tsunamis. In addition, they lamented the high death toll (totaling more than 2500) during the destructive tsunamis at Palu and Anak Krakatau, which took place in Indonesia in September and December 2018, respectively, pointing out in both cases a failure to provide an adequate warning to the populations at risk. Those two events, which both involved underwater landslides, featured waves of unexpected ferocity in the near field, and puzzled the research and warning communities (Titov, 2021). Scores of scientific papers were recently published on these events, including a special collection of 23 PAGEOPH papers, regrouped as a separate book (Rabinovich, 2022). Finally, Kânoğlu et al. (2021) reflected that

> "progress [in tsunami science] is and will remain a never-ending story, reminiscent of the paradox of Zeno of Elea (Okal, 2015, 2019)",

and anticipated that future events would always feature new, unexpected properties nurturing further scientific advances.

Indeed, while the present issue was in progress, a spectacular event took place on 15 January 2022 at the Hunga Tonga—Hunga Ha'apai volcano (Lynett et al., 2022). The eruption generated a Pacific-wide

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tsunami which attacked the nearby Tongan islands with waves locally reaching 15 m, and wrought significant damage in the far field, with run-up in excess of 1 m in Japan, Peru and California. While the death toll from the tsunami (six fatalities) was remarkably contained, it included two swimmers who drowned in Lambayeque Province, Peru, the first such instance in the far field since the two fatalities during the 2011 Tohoku tsunami. However, the most remarkable aspect of the 2022 Tonga volcanic explosion was the generation of atmospheric air waves which circled the Earth several times and became coupled with oceanic basins world-wide, resulting in sea-level fluctuations even in water bodies such as the Eastern Mediterranean Sea, reached after long overland paths across continents. This exceptional event featured complex coupling between the solid, liquid and gaseous shells of the Earth.

In this respect, the 2022 Tonga eruption is remarkably similar to the Krakatau explosion on 27 August 1883, whose sea-coupled air waves were described and modeled by Harkrider and Press (1967), based on a handful of maregraphic records in the far field, and following their theoretical investigations by Press and Harkrider (1962) and Harkrider (1964). However, for the first time, the 2022 Tonga event provided a trove of high-quality data recorded by state-of-the-art instrumentation, such as barographs, maregraphs, seismometers, ocean bottom pressure sensors, and even GNSS sensors, as discussed by Munaibari et al., (2023; see Sect. 4 below). In addition to that paper, eight contributions on the 2022 Tonga eruption have already been published in PAGEOPH (Ajith et al., 2022; Borrero et al., 2023; Gusman et al., 2022; Imamura et al., 2022; Kulichkov et al., 2022; Ortíz-Huerta & Ortíz, 2022; Ramírez-Herrera et al., 2022; Tsukanova & Medvedev, 2022).

Although not studied in the present special issue, two more events are worth a special mention. First, on 12 August 2021, a very complex earthquake took place in the South Sandwich Islands. As discussed in detail by Jia et al. (2022) and Metz et al. (2022), the rupture started around 45 km depth, and propagated upwards into a mainshock featuring a very slow rupture velocity (1.2 km/s), suggesting that the sequence may qualify as a tsunami earthquake. This event is remarkable for its total moment release of 3.4×10^{28} dyn*cm ($M_w = 8.3$), in an area where no interplate thrust earthquakes with $M \geq 7.1$ had been known, thus confirming a new violation to Ruff and Kanamori's (1980) now abandoned model for the maximum magnitude of interplate thrust earthquakes at subduction zones. The tsunami was observed at decimetric levels at a number of Atlantic locations, including in Ghana (a rare occurrence for the Gulf of Guinea), and at sporadic locations in the Indian Ocean, all the way to Cocos Islands, where it was recorded on seismometers. Unfortunately, because of the extremely remote nature of the epicentral area, and under the COVID-19 travel restrictions, no field study could be conducted in the near field, and thus the exact extent of the tsunami remains unknown. It is clear that further study of this exceptional event is warranted.

Finally, over a window of 9 h on 06 February 2023, two powerful earthquakes struck the southern part of Turkey, along the East Anatolian and associated faults, with a catastrophic death toll of over 50,000, once again in an area where comparable events had not taken place for several centuries. Even though the fault rupture did not reach the Mediterranean Sea, a decimetric tsunami was recorded at several locations in the Eastern part of its basin, suggesting generation by landslides potentially triggered by transient Rayleigh waves (Salaree, 2023). It is clear that the mechanism of its generation will be the subject of further investigations in the future.

In retrospect, all three events (Tonga, South Sandwich and Turkey) constitute vivid illustrations of Kânoğlu et al.'s (2021) reflection on Mother Earth's apparently endless reservoir for future challenges from unsuspected new events. In this context, we present a short scientific review of each of the papers making up this special issue. We start with general studies in tsunami science, with the remaining papers regrouped by geographic region: Northern Pacific, Southeast Pacific, Southwest Pacific and Indonesia, and finally Mediterranean Sea.

2. *General Studies*

We start the topical issue with Reid and Mooney's (2023) study, which provides an overview of global tsunamis from 1900 to 2020. The authors analyze tsunami sources, fatalities, maximum water heights, and observation biases. They find that earthquakes cause 80% of global tsunamis with a median height of only 0.4 m. Landslides, which cause 24% of fatal tsunamis, have a median height of 4 m. Indonesia is used as a case study because it has diverse sources of tsunamis, including subduction zones, crustal faults, landslides, and volcanic events. In this period, Indonesia experienced more tsunamis with heights above 1 m than any other country. Landslides and coastal landforms can cause high local maximum water heights and numerous fatalities. Due to sea level rise and local subsidence, tsunami hazards are increased in this densely populated coastal region, turning to extreme natural hazards.

In the second paper of the section, Bernard (2023) discusses a tsunami preparedness program inspired by Kuroshio Town, Japan, which targets an ultimate goal of zero casualties during a tsunami. The program first requires assessing how many people can be protected using existing evacuation procedures and shelters, *i.e.,* horizontal or vertical evacuation towards existing shelters. The study then uses the concept of "shelter-in-place" for those individuals who cannot or will not use existing protection measures. Immediately accessible customized shelters-in-place could shield such "unprotected" people from drowning, being crushed, being hit by floating objects, suffocation by ingesting silt-laden water, fires, and hypothermia. There is already an example of a patented shelter-in-place, aluminum capsules able to float on a tsunami, and numerical modeling shows a low probability of them being washed out into the sea. In addition to evacuation options, using such shelters-in-place may help reduce the number of casualties.

The last paper in the section, by Tong et al. (2023), presents a method to determine the probability of a tsunami of a certain size reaching the shore, based on earthquake-induced sea floor deformation. They use a sampling-method optimizing fault slips that lead to a sea floor deformation inducing a large tsunami. The resulting tsunamis are modeled using the shallow water-wave equations on a slice, based on a sum of multivariate log-normal distributions that follow the Gutenberg-Richter law. Based on the Tohoku-Oki 2011 earthquake and tsunami, the authors quantify the annual probabilities of tsunamis of different sizes, and identify the most effective tsunami mechanisms, which are found to feature smoothly varying fault slip patches leading to a coherent and expansive bathymetry change. The resulting tsunami waves are compressed and reach the shore as a close-to-vertical leading wave.

3. Northern Pacific Region

In the first paper of this section, Goda and Martínez-Alcala (2023) focus on assessing tsunami hazard along Canada's Pacific coast since the 2012 $M_w = 7.8$ Haida Gwaii earthquake triggered a tsunami that highlighted the importance of tsunami hazard in the region. They use stochastic source modeling, which characterizes earthquake ruptures by accounting for uncertainty in fault geometry and slip heterogeneity. They apply Monte Carlo simulations to generate 1500 stochastic tsunami models, 500 of them reflecting the key features of the 2012 event, in order to assess tsunami hazard and conduct sensitivity analyses of tsunami height variability. The models are constrained by observational data and past source inversion studies, and include both moderate and extreme scenarios. A reasonable agreement is found between 2012 tsunami offshore data and the stochastic tsunami simulations. Goda and Martínez-Alcala (2023) emphasize the importance of the accuracy of bathymetry and elevation data for the improvement of the tsunami simulation. They suggest that such models can be used for future probabilistic tsunami hazard analysis in the region, in order to improve risk management decisions, since the stochastic source models capture both moderate and extreme tsunami hazard scenarios.

In the following paper, Konovalov et al. (2023) employ logistic regression as a tool to create a binary classifier for identifying tsunamigenic and non-tsunamigenic earthquakes for near-source early warning. A database was created by merging a catalogue of submarine earthquakes and a tsunami database and assigning a binary variable to each seismic event indicating its tsunamigenic class. The training dataset comprised 712 submarine earthquakes with $M \geq 6.0$, which took place from 1960 to 2020 in the northwestern part of the Pacific Ocean, including 80 tsunamigenic and 632 non-tsunamigenic events. The best performance was achieved by using earthquake magnitude, the logarithm of the source depth, and sea-floor depth as predictors. The data-driven logit model showed significant improvements in the performance metrics compared to the threshold magnitude criteria commonly used by tsunami warning agencies. Konovalov et al. (2023) suggest that using a logit-based binary classifier could enhance the efficiency of tsunami alerts in the Northwestern Pacific Ocean.

In the third paper of this section, Medvedeva et al. (2023) use numerical modeling to assess the threat of tsunamis in the Bering and Chukchi Seas caused by trans-oceanic tsunamis traveling through the Aleutian Islands and Bering Strait. They examine eight major far-field and one near-field earthquakes and find that the Bering Sea was most affected by the 1960 Chilean earthquake, with tsunami wave amplitudes up to 294 cm. However, the great 1952 Kamchatka and 1964 Alaska earthquakes produced smaller waves, with maximum amplitudes of 146 cm and a few centimeters, respectively. Their modeling suggests that the straits of the Aleutian Islands have an attenuation coefficient of 0.75 on average, while that of the Bering Strait is approximately 0.29. Based on these estimates, they conclude that tsunamis from remote sources in the Pacific are unlikely to penetrate the Arctic Ocean, although significant wave amplitudes can occur in the Bering Sea due to distant earthquakes.

Tsunamis can cause significant damage and loss of life, especially for nearby communities for which their arrival time is short. Often, warning systems fail to inform these communities promptly. To address this issue, many tsunami early warning (TEW) algorithms have been developed to provide quick and localized warnings. Williamson and Allen (2023) investigate how the warning is disseminated through TEWs. They show that after an initial alert is issued, subsequent ones may follow, emanating from different agencies, leading to further delays and inconsistencies in message content and timing. They propose WaveAlert, a rapid dissemination tool that utilizes pre-existing advances in earthquake early warning systems, and the MyShake EEW phone application to provide timely, clear, and consistent alerts to the public, targeting recipient communities with low message latencies and high spatial resolution. They illustrate the need for such rapid alerting strategies by retrospectively examining the alerting process during the 2022 Tonga tsunami and by modeling a potential near-field Cascadia timeline example affecting the US west coast.

4. Southeast Pacific Region

In the first paper of the section, Jiménez et al. (2023) invert tsunami waveforms from three tidal stations to estimate the slip distribution of the 1966 Huacho Peru earthquake, which caused severe ground shaking and a regional tsunami inundation. They use an inversion procedure, yielding a maximum slip of 5.5 m located offshore Barranca city, and calculate a seismic moment of 2.05×10^{21} Nm, equivalent to a moment magnitude $M_w = 8.1$, and equivalent to Abe's (1972) value derived from long-period surface waves. Despite the occurrence of several earthquakes, including the 1966 Peruvian earthquake, only 20% of the energy accumulated from the 1746 earthquake (M_w estimated at 9.0) has been released, indicating a high potential for future tsunamigenic earthquakes in the central region of Peru.

Large-magnitude earthquakes in the coastal areas of northern Chile and southern Peru occur approximately every 108 years. There have been no similar events since the catastrophic earthquake of May 9, 1877, and only part of the energy accumulated since then was released during the Chilean earthquakes near Tocopilla in 2007 ($M_w = 7.7$) and Pisagua in 2014 ($M_w = 8.1$), and therefore, a significant tsunami hazard exists for all coastal cities in the region. In the second paper of the section, Lobkovsky et al. (2023) simulate the historical earthquake and tsunami of May 9, 1877, considering 23 scenarios and using available historical data. They compute wave fields up to the 5-m isobath, consistent with the historical data.

5. Southwest Pacific and Indonesia Regions

In the first paper of this section, Salaree et al. (2023) present numerical experiments using ocean bottom pressure and seismic data from a simulated so-called "SMART" cable array off the Sumatra-Java trench. Their simulations of six rupture scenarios show that adding such a system in the Indian Ocean basin could advance tsunami detection by several hours compared to existing DART systems. Additionally, calculated seismic phase arrival times show that adding a SMART array could enhance network parameters for detecting and locating seismic events. The authors also tested 58 submarine landslide scenarios and found that the SMART system could also provide critical information for early warning against landslide tsunamis.

The next paper, by Munaibari et al. (2023), focuses on the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption, which presented a challenge due to the complex wavefield featuring both regular tsunamis and ocean-coupled air waves. The authors focus on the disturbance in Total Electronic Content (TEC) of the ionosphere, expanding the proven detection capabilities of Global Navigation Satellite Systems, in order to isolate the regular tsunami signature even in near-field regions (1000–1500 km), from the TEC signal created by the atmospheric (Lamb) wave generated by the explosion, the latter traveling faster, at a quasi-constant propagation speed of around 315 m/s. Their results indicate that combining GNSS data to track the ionospheric TEC with ocean bottom pressure sensors can help distinguish regular tsunamis from initial air-sea waves in sensor observations.

In the final paper of the section, Pranantyo et al. (2023) investigate the major earthquake and tsunami that occurred on February 23, 1969, in the Majene region of Southwestern Sulawesi Island, Indonesia, which is located in a tectonically active region and experienced tsunamis in the past. The earthquake had a surface-wave magnitude $M_s = 7.0$ generating strong shaking up to VIII on the Modified Mercalli Intensity scale, but a moment magnitude of only $M_w = 6.2$. It was followed by an unusually high tsunami of 4 m that quickly dissipated within 25 km from the highest observation site. Analysis of the earthquake's hypocenter and mechanism revealed that it was an inland earthquake with a thrust mechanism. However, while ground motion modeling can replicate the earthquake's intensity, it fails to explain the tsunami observations. Pranantyo et al. (2023) suggest the combination of an earthquake and a 0.5 km^3 submarine mass failure as a plausible scenario to explain the tsunami observations, and reconcile them with the "snappy" character of the earthquake, *i.e.,* blue-shifted towards high-frequencies.

6. Mediterranean Region

In the first paper of the section, Triantafyllou et al. (2023) introduce a probabilistic model, previously used for earthquake and tsunami hazard assessment, but instead of hazard, they focus on risk metrics, defined as the probability of a tsunami striking a coastline and causing a certain level of damage. As such, the impact metric is determined by tsunami intensity values, *K*, on a 12-degree scale. To assess tsunami risk, the authors consider tsunami history in the region; their model then calculates probabilities of exceedance, and return periods of specific intensity values. Their study focuses on the Mediterranean and connected seas, and shows that the highest risk is in the eastern Mediterranean while the lowest is in the Black Sea. The return period for damaging tsunamis is found to be 22 years for the entire Mediterranean basin.

The 2018 Anak Krakatau volcano collapse reminded us of the need to improve tsunami warning systems for non-seismic events. Landslides associated with volcanoes have generated tsunamis in the past, making it necessary to identify and quantify tsunami hazards and risks due to possible flank instability. Necmioglu et al. (2023) examine three possible landslide scenarios with tsunamigenic potential for Santorini Island. Their results show that these scenarios could generate significant local tsunamis with extreme amplitudes and short arrival times to Greek and Turkish coasts, making warning and mitigation challenging. They discuss the requirements for a local tsunami warning system addressing atypical sources in the context of multi-hazard disaster risk reduction.

In the last paper of this topical issue, Nemer et al. (2023) analyze the seismic hazard of the Lebanese Restraining Bend, a region where destructive earthquakes have occurred historically. They apply a neo-deterministic method to generate synthetic seismograms over the area and produce maps of seismic hazard, featuring ground displacement, velocity, and acceleration throughout the region. Their findings confirm Lebanon as an area of high seismic hazard, and emphasize that authorities should take precautionary measures to mitigate the potential effects of seismic events. The authors recommend further investigations at local scales for specific sites of interest. Some of the sources in this study might help future tsunami studies in the region, and in particular shed insight into the earthquake of 9 July 551 A.D., with magnitudes estimates ranging from 7.2 to 7.8, which wrought catastrophic damage in the Beirut area, including from a positively documented tsunami.

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