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Hard Lessons of the 2018 Indonesian Tsunamis

Vasily V. Titov[1]

Abstract—Within 4 months of 2018, two fatal tsunamis struck islands of Indonesia with ferocity that astonished local population, tsunami warning systems and scientists. For both of these events, the September 28 Palu Bay tsunami in Sulawesi and the 22 December Anak Krakatau tsunami in Sunda Strait, the initial tsunami source data was either non-suggestive or simply non-existent to imply such a devastating wave impact. International teams of scientists, members of the International Tsunami Survey Team, descended to Indonesia to help local scientists collecting all possible data from these two events, investigating the origins of these tsunamis to explain the unexpected tsunami strength. The analysis of the observation data presented in this collection of papers mostly explains the unexpectedly devastating impact from these two unusual tsunami events. The lessons learned from the response to these two events coupled with the new scientific understanding of tsunami genesis will provide improved guidance for more effective tsunami warning operations for Indonesia and the coastlines around the World.

Keywords: Tsunami, forecast, tsunami sources, hazard assessment, warning systems.

1. Introduction

Two Indonesian tsunamis of 2018, the September 28 Palu Bay in Sulawesi and the 22 December Anak Krakatau in Sunda Strait created havoc on islands of Sumatra, Java and Sulawesi, misled tsunami warning operations and puzzled scientists with waves of unexpected ferocity inundating nearest coastlines only minutes after generation. The science community was initially perplexed by the unexpected intensity of both tsunamis. The tsunami warning operations and the local community struggled with responses during the events, making decisions based on uncertain, incomplete or even non-existent data and very limited time before the waves started to inundate populated coasts. To avoid or reduce impact from similar events in the future, the tsunami scientific community has mobilized scientists around the world for obtaining all possible data from these two tsunamis and passing the analyses to practitioners of tsunami warning and mitigation operations for improved performance.

As the Global Tsunami Warning Systems (TWSs) expanded after the December 26, 2004 Indian Ocean tragedy, tsunami warnings became available to most of the world's tsunami-prone coastlines (Bernard & Titov, 2015). The March 11, 2011 Tohoku tsunami reinforced the emphasis on effective tsunami detection and warning as an important part of the strategy to reduce tsunami risk in general and tsunami fatalities in particular. Nevertheless, many tsunamis that followed during the last decade, those that affected populated coastlines, resulted in casualties, even in areas where newly established tsunami warning services were implemented. Over 30 significant tsunamis have occurred around World Oceans since the last catastrophic event of March 11, 2011 in Tohoku, Japan (NCEI/WDS, 2020). These events of the last ten years claimed over 5000 victims, confirming that many gaps still exist in tsunami warning and hazard mitigation strategies.

The combined death toll from the two Indonesian tsunamis of 2018 is astounding. While the exact number of tsunami victims will probably never be known (as is often the case for large-scale natural disasters with combined effects of tsunamis, earthquakes and other factors), the two tsunamis killed at least 2000 and possibly as many as 5000 people (GFDRR, 2020; OCHA, 2018; Sangadji, 2019). Such a devastating loss of life from just two tsunamis in Indonesia in 2018, where the new Indonesian Tsunami Early Warning System (InaTEWS) has been

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[1] NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, USA. E-mail: vasily.titov@noaa.gov

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operational since 2008 (Lauterjung & Letz, 2017), demonstrated that much remains to be done to make the TWSs robust and effective. The warning services and hazard mitigation measures rely on tsunami science as the foundation for practical solutions. The operational tsunami warning community is waiting for new, more effective science-based guidance to address the existing gaps and to reduce the staggering tsunami death toll. The Palu Bay and the Anak Krakatau events of 2018 brought the most tragic losses of life and destruction to Indonesian coasts since the 2004 Sumatra catastrophe. The two tsunamis also provided a wealth of new information that the science needs to distill into new improved methods for better tsunami warnings and much more effective hazard mitigation procedures for all coastal communities, especially for the Indonesian coasts.

2. *Tsunamis in Indonesia*

Indonesia has suffered tremendously from tsunamis over its history. More than 200 tsunamis have been documented in Indonesia since the first known event from 416AD (NCEI/WDC, 2020). Among these documented tsunamis (almost certainly very incomplete list, especially for early records before the twentieth century) at least 50 events have been fatal and in total claimed over 280,000 lives in Indonesia, more than in any country in the world (Fig. 1).

The new millennium has been especially devastating for the country's coastlines affected by multiple disastrous tsunamis. The December 26, 2004 Sumatra tsunami was the event that vividly demonstrated the hazard and the power of tsunamis to the terrified world. The tsunami inflicted intolerable damage and loss of live on the big part of the Indian Ocean, but hit Indonesia especially hard claiming the majority of its victims along the Sumatra coast. The 2004 Sumatra tsunami became the watershed event for the tsunami warning systems development in Indonesia and in the World. That tsunami was an unwelcome inaugural event for the Indian Ocean tsunami warning services, just like the 1960 Chilean tsunami prompted the establishment of the Pacific Tsunami Warning System in the last century. Along with Indonesia, most Indian Ocean countries established national warning systems for vulnerable coastlines to contribute to the Indian Ocean Tsunami Warning System, coordinated by the UNESCO Intergovernmental Oceanographic Commission (IOC). The new Indonesian Tsunami Early Warning System had no shortage of events that tested its effectiveness since the very beginning of its development. Over 20 tsunamis with various intensities have occurred in Indonesia since the 2004 Sumatra event. Unfortunately, tsunamis continue claiming victims at a rate that doesn't appear to slow down despite the implementation of warning systems and extensive mitigation measures in Indonesia. Throughout the history of Indonesia, only the Krakatau-generated waves of 1883 and the 2004 Sumatra catastrophe have claimed more tsunami victims than the two tsunami events of 2018 combined.

Historically, major milestone developments of tsunami warning systems have occurred in response to major tsunami disasters (Bernard & Titov, 2015; Shuto & Fujima, 2009). Those warning system improvements have always been based on new scientific insights and improved understanding of the nature of tsunamis hazards based on new data and focused studies of unprecedented events by the scientific community. The new data and thorough analyses presented in this collection of papers provides more of these necessary new insights and this new knowledge brings hope that the lessons from Indonesian tsunamis of 2018 will be converted into warning system improvements that could finally reverse the trend of rising coastal risk and fatalities from tsunamis.

2.1. *2018 Palu Bay and Anak Krakatau Tsunamis Overview*

The Indonesian tsunamis of the 2018 were caused by two very different geological phenomena. The Palu tsunami was associated with an earthquake, while the Anak-Krakatau tsunami was related to a volcanic eruption. Nevertheless, these two tsunami sources are eerily related in their unexpected efficiency in generating destructive waves. Neither of these tsunamis were generated by 'typical' subduction-zone earthquake sources that most tsunami warning systems are designed for. Both tsunamis

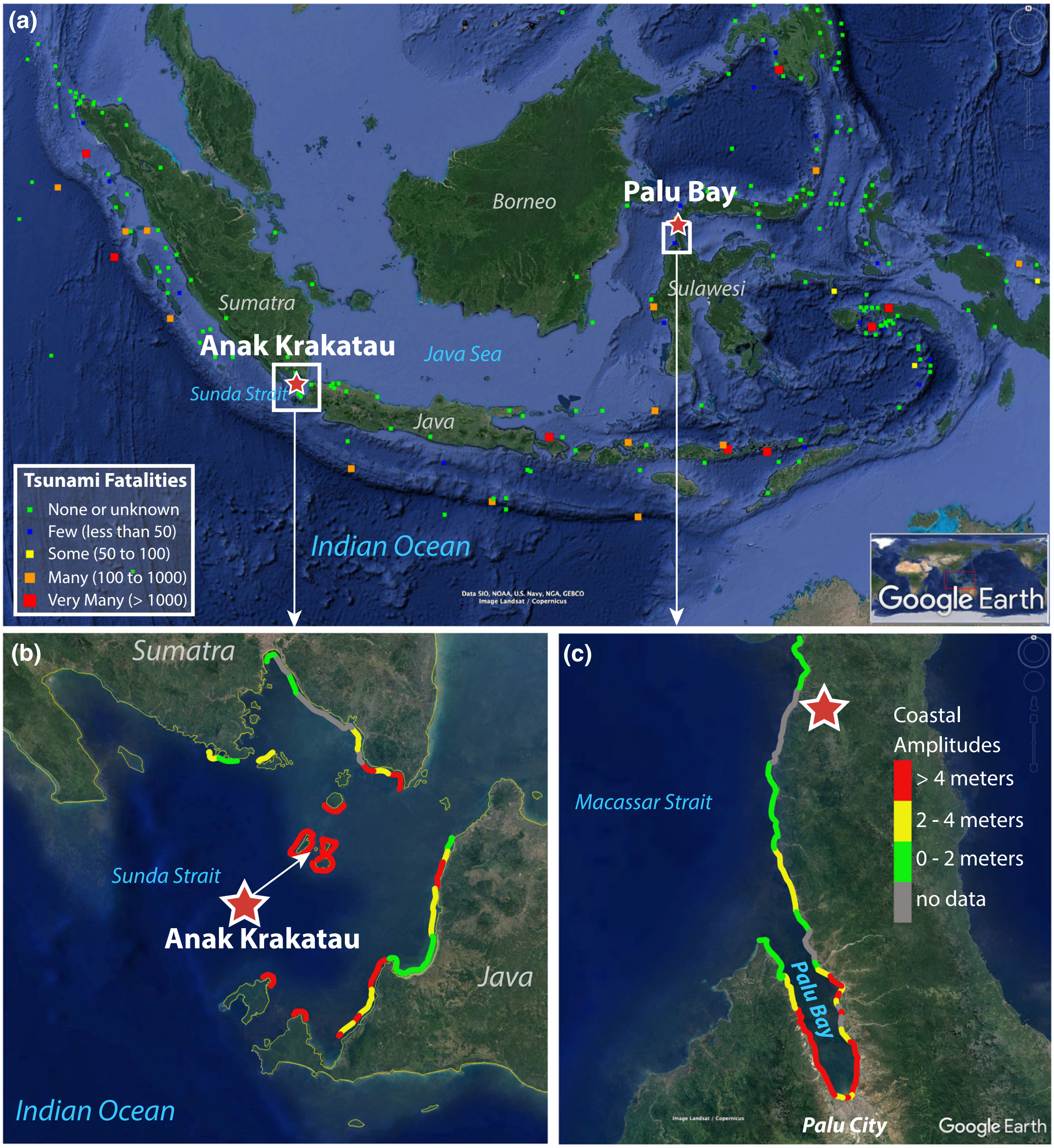

Figure 1

Overview map showing source locations of documented tsunami events that impacted Indonesian coastlines (**a**). *Stars* show the origins of the two Indonesian tsunamis of 2018. Two lower frames illustrate the local geography and ranges of the measured tsunami coastal amplitudes compiled from multiple post-tsunami surveys for the September 28, 2018 Palu Bay tsunami (**b**) and the 22 December, 2018 Anak Krakatau tsunami (**c**)

produced fairly localized impact in semi-enclosed geographic areas (Fig. 1). The Anak-Krakatau tsunami impact was limited to the Sunda Strait coasts within 60-km radius from the source and the effects of the Sulawesi tsunami were largely limited to the shores of 35 km long and narrow Palu Bay (Mas et al., 2020; Paulik et al., 2019; Putra et al., 2020; Sunny, Cheng, & Horrillo, 2019; Williams et al., 2020), with limited impact outside the bay. While the shores of Palu Bay were being flooded by the tsunami almost immediately after the earthquake, waves from Anak-Krakatau reached the nearest coastlines after half an hour of propagation from the source, conceivably leaving time for warning and reaction. However, since the tsunami generating event itself (in this case a volcanic flank collapse and landslide into the sea) went undetected, the waves struck the coasts without any advance notice. Since existing tsunami warning services rely on robust detection of the tsunami-generating events and ample time for analysis and decision-making, the tsunami warning systems were not effective in issuing alerts for vulnerable populations during either of these tsunamis, leading to numerous fatalities in both cases. The two events illustrate the need for changing these TWS paradigms.

2.2. Palu Bay Tsunami

The first of Indonesia's 2018 tsunamis struck Sulawesi Island on 28 September, less than 5 min after a M_w 7.5 earthquake ruptured the Palu-Koro Fault, a known strike-slip fault, part of which runs along a narrow and long Palu Bay. The unexpected tsunami force, almost immediate impact and high population density of the bay shores led to tragically high number of casualties and severe destruction along Palu Bay coasts (Fig. 2). The tsunami landed the main punch on the city of Palu, the densely populated capital of the Central Sulawesi Province at the south corner of the Palu Bay. The data presented in the studies allowed thorough reconstruction of the wave impacts in Palu Bay. The analyses of the tsunami data suggest several possible mechanisms of tsunami generations that explain most of the details of the tsunami event. Many aspects of this tsunami have become reasonably established, while several mysteries and uncertainties remain unresolved. It is evident that at least a substantial part of the tsunami inside the Palu Bay was generated by the fault movement of the strike-slip rupture. Coupled with relatively low magnitude for a tsunamigenic event of M_w 7.5, the strike-slip mechanism of the earthquake was surprisingly efficient in tsunami generation. While the epicenter of the earthquake is located outside of the main tsunami impact area of Palu bay, multiple surveys and observation data analysis (Frederik et al., 2019; Jamelot et al., 2019; Natawidjaja et al., 2020; Ulrich et al., 2019) clearly identified a very active part of the earthquake rupture that was crossing the waters of the Palu Bay and certainly contributed to the tsunami generation. The tsunami observation outside of the Palu Bay show very limited tsunami impact, if at all (Jamelot et al., 2019; Mikami et al., 2019). The local landslides along steep Palu Bay slopes were also evident and their contribution to tsunami generation has become well-established after the field surveys of the Palu Bay shorelines and the multi-beam surveys of the bay bathymetry. (Omira et al., 2019; Pakoksung et al., 2019).

2.3. Anak Krakatau Tsunami

The Anak Krakatau tsunami struck the coasts of the Sunda Strait on December 22, 2018 with very little warning. The timing and exact nature of the tsunami source was confidently established days later, only after studying multiple in-situ and remote-sensing data sources along with observations from post-tsunami surveys. However, the prime suspect for the tsunami generation from the very beginning was the ongoing eruption of the Anak Krakatau volcano at the center of the Sunda Strait. The examination of the Anak Krakatau caldera with satellite imagery and aerial surveys immediately after the tsunami revealed significant changes in the topography and shape of Anak Krakatau island, hence a caldera collapse had quickly become the prevailing theory for the tsunami generation (Fig. 3). Despite the deadly volcanic history of Krakatau, the increasingly active eruption of Anak Krakatau for several months prior to the tsunami (or maybe partly because of this, since the continuous eruptions had become a routine daily spectacle), and even prior scientific warnings (albeit unspecified in time by Giachetti et al., 2012), the tsunami came as a complete surprise to the coastal population and tsunami warning operations, ultimately causing 430 deaths along the coasts of the Sunda Strait. The

Figure 2
Illustration of the Palu tsunami impact inside Palu Bay (**a**). The satellite images of North Palu City before (**b**) and after (**c**) the tsunami impact. Photograph from the aerial post-tsunami survey (**d**) showing the destruction of the North Palu City after the September 28, 2018 Palu Bay tsunami. Photograph is courtesy and copyright of Gegar Prasetya, satellite imagery from Google Earth^{TM} are used under license by Google

tsunami traveled about 30 min to the populated shores and produce significant runup along all coasts of Sumatra and Java, reaching over 10 m at places (Heidarzadeh et al., 2020; Muhari et al., 2019; Putra et al., 2020). The waves at uninhabited islands near Anak Krakatau, remnants of the Krakatau volcano

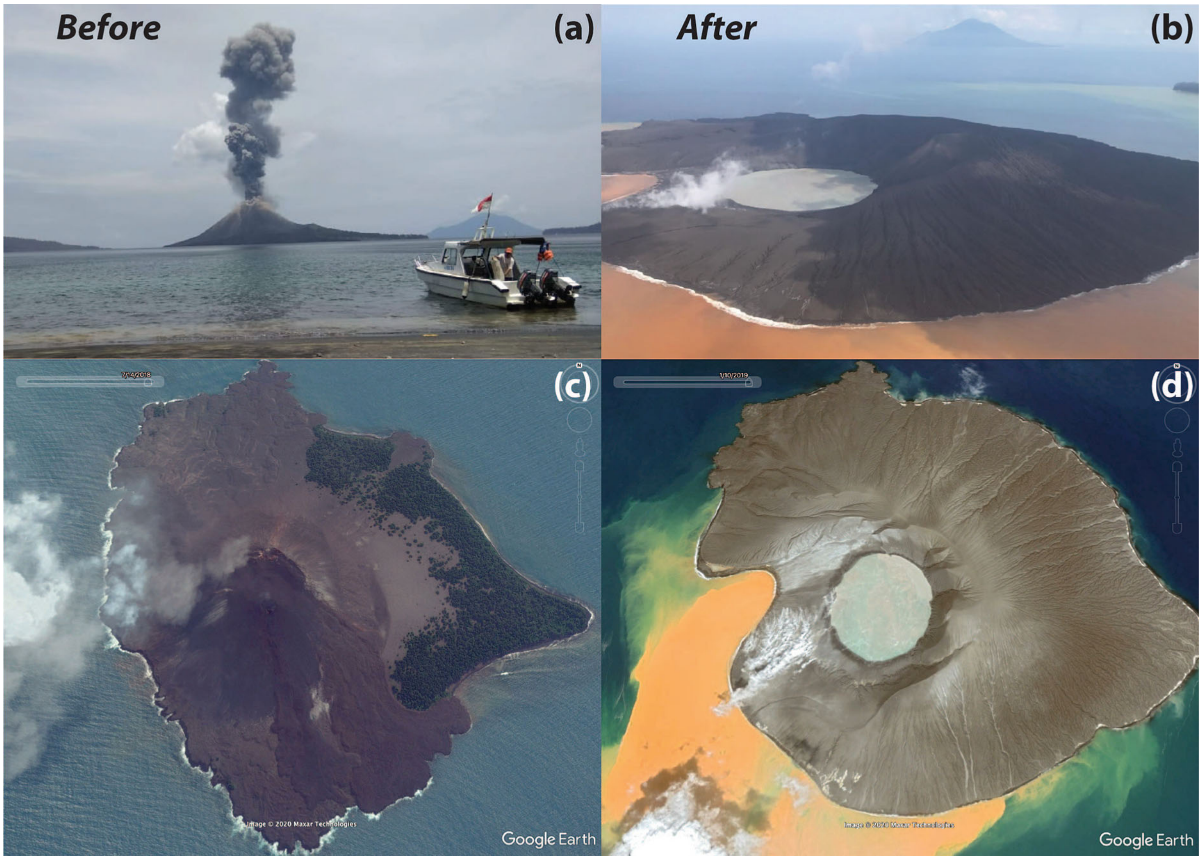

Figure 3
Photographs (**a**, **b**) and satellite imagery (**c**, **d**) of the Anak Krakatau before the 22 December, 2018 Anak Krakatau tsunami (**a**, **c**), and after the event (**b**, **d**). Photographs are courtesy and copyright of Gegar Prasetya, satellite imagery from Google Earth$^{\mathrm{TM}}$ are used under license by Google

caldera, ran up much higher reaching over 80 m (Borrero et al., 2020).

3. *Overview of the New Science*

The evidence collected by international scientific teams for both tsunami events of 2018 are quite comprehensive and overwhelming. The observational data for both tsunamis consist of a multitude of instrumental observations (seismic data, sea-level records, satellite imagery), field measurement data (runup data, eyewitness accounts, multiple videos of the event, including the unique video from a plane depicting the very moment of the Palu Bay tsunami generation), multiple oceanographic surveys providing high-resolution bathymetry, bottom morphology and seismic profiles of ocean floor. The scientific analysis of that data is not yet fully complete, judging from the fact that consensus is still being formed about the exact generation mechanisms of the tsunami waves, especially for the difficult case of the Palu Bay tsunami. However, there are several important scientific outcomes from studies for both of these events that clearly emerge from these concentrated scientific efforts.

Most of the studies of the Palu Bay tsunami agree that the strike-slip fault rupture inside the Palu Bay, as well as the accompanying landslides along the steep shores of the bay contributed to the tsunami generation. The inferred proportions of the contributions of these two sources vary from study to study. Some analyses provide convincing evidence for the major contribution of the co-seismic displacement and associated dynamics of the earthquake rupture to the generation of the waves that produced most of the flooding, leaving only local effects to the landslide-generated waves (Heidarzadeh, Muhari, & Wijanarto, 2019; Jamelot et al., 2019; Ulrich et al., 2019). Other studies explain most of the tsunami observations with the multiple instances of landslide generation as the primary source of the tsunami (Pakoksung et al., 2019; Sunny et al., 2019). Both theories are supported by modeling results that fit reasonably well to runup observations and explain most of the observed tsunami dynamics. The only possible outlier in otherwise good models' reproductions may be the coastal sea-level record in the far-field location of Mamuju, where the early arrival of the first waves cannot be explained by any model with reasonable accuracy. A secondary source, or an error in the tide gage timing have been suggested as explanations (Heidarzadeh et al., 2019), but neither has been confirmed yet. Even with a relative abundance of data and general good fit of models to the observations for the two types of suggested tsunami sources, the uncertainties in defining the exact tsunami generation mechanism are still very high.

For the seismic generation, the exact location of the fault rupture geometry under Palu Bay is still a subject of debate. While the satellite optical image correlations provide fairly certain displacement geometry inland, the rupture under the waters of Palu Bay is a matter of interpretation. The high-resolution bathymetry of Palu Bay from several multi beam surveys helped somewhat, but cannot provide the undisputed fault geometry, therefore several interpretations are still possible allowing a wide spectrum of tsunami scenarios (Frederik et al., 2019; Jamelot et al., 2019; Natawidjaja et al., 2020; Sianipar, 2020; Ulrich et al., 2019; Yolsal-Çevikbilen & Taymaz, 2019).

For the landslide generation, the dynamics, volume and, to a lesser degree, locations of slope failures are also subject to many interpretations and, again, underpin multiple tsunami scenarios. All those uncertainties provide a wide range of the source parameters that can be used for generating models to fit a limited observation set of runup points and just one time series inside Palu Bay. As a result, it is still very difficult to assign a truth value to different generation scenarios, since many of them have reasonable fit to observed tsunami data. More observation and more analysis of this already impressive set of observation data for the event may help to zero on the more precise scenario.

Despite the uncertainties of the exact source details for the Palu Bay tsunami, the science is clearly pointing toward the previously underestimated danger of the strike-slip earthquakes in geographically constrained settings accompanied by multiple landslides for the local tsunami risk. Only few tsunamis have been reported historically with the strike-slip earthquake origin, even smaller fraction of those created similarly distractive coastal impact. The closest case to the Palu strike-slip source was probably the Mindoro tsunami of 1994 (Imamura et al., 1995). The November 15, 1994 M_{w} 7.1 earthquake in the Philippines that generated the Mindoro tsunami, while of substantially smaller magnitude, produced similar co-seismic slip values of up to 5 m on a predominantly strike-slip fault that was documented by direct fault rupture observations near the coastline. The tsunami produced by the Mindoro earthquake killed 62 people within 30 km of the epicenter in the enclosed geographical setting of the Verde Island Passage, which also features steep bathymetric features. Multiple landslides were observed on-land, suggestive of possible slope failures offshore. In general, the Mindoro and Palu Bay tsunamis were very similar strike-slip events with unusually efficient tsunami generation. In both cases, the steep underwater slopes around the strike-slip fault rupture may have contributed to tsunami generation with paddle effects, pushing waters of the semi-enclosed basin during the horizontal displacement (Heidarzade et al., 2018; Jamelot et al., 2019; Tanioka & Satake, 1996; Ulrich et al., 2019). The more recent example of the strike-slip tsunami generation was the M_{w} 7.6 October 19, 2020 Sand Point, Alaska earthquake (NCTR, 2020; USGS, 2020), which did not create any observed coastal damage but recorded significant tsunami amplitudes (over half a meter peak-to-trough) in Hawaii, 5000 km away from the source. Again, unexpectedly efficient tsunami generation. Along with the growing number of historical strike-slip earthquakes that generated substantial tsunamis (including at least one in Indonesia—M_{w} 7.8 March

2, 2016 Southwest of Sumatra in the Indian Ocean), the tragic outcome of the Palu event may be the tipping point for reassessing the tsunami risk of the strike-slip faults, especially in geographically constrained water bodies.

The scientific findings from the Anak Krakatau tsunami are arguably even more significant since that event provided some desperately needed, never before available data from the near- and far-field of a tsunami caused by a volcanic landslide. The observations and measurements collected after this event and preliminary analyses presented in the studies here are just the beginning of the scientific scrutiny of this event and associated data (Borrero et al., 2020; Heidarzadeh et al., 2020; Muhari et al., 2019; Omira & Ramalho, 2020; Paris et al., 2020; Putra et al., 2020; Zengaffinen et al., 2020). The event produced data that can be used to advance modeling capabilities not only for volcano-generated tsunamis, which are a real and present danger for Indonesia coasts, but also for the much more wide-spread risk of landslide-generated tsunamis. After all, landslides are the second most frequent cause of tsunamis following earthquakes, comprise more than 10% of all historically documented events and have generated the highest runup observations among all documented tsunamis.

The Anak Krakatau tsunami may have produced the first real-world data set of a landslide-generated tsunami that includes the near-source amplitude measurement distributed around the flank collapse, dense amplitude measurements in the far-field, several tide-gage records to quantify wave periods, a relatively complete measurements of the sliding mass from bathymetric surveys as well as before and after topography of the collapsed slope. All of these data coupled with the thorough analysis of the pre-tsunami volcano activity monitoring (Walter et al., 2019) may provide a critical information for establishing the robust landslide and volcano tsunami warning capabilities based on real-time data and modeling, similar to the existing seismically-generated TWSs.

The Anak Krakatau data may even provide the final answer to the nature of the 1883 Krakatau tsunami, which still remains largely unresolved due to the lack of reliable quantitative observations. It may be difficult to directly compare the 2018 event to the one in 1883, which was in a class by itself. The 1883 event was a much more complex phenomenon, a combination of several catastrophic processes: an underwater eruption, large-scale slope failures and a catastrophic atmospheric explosion which generated an airwave traveling worldwide and accompanied over the ocean by a surface disturbance that was recorded on tide gages around the Globe. The signals recorded on tidal gauges in 1883 were analyzed by Press and Harkrider (1966) and Harkrider and Press (1967), who used comparisons with nuclear tests (notably Czar' Bomba in 1961) to propose an equivalent yield of 100–150 megatons for 1883 Krakatau explosion, several orders of magnitude more energetic than the 2018 event. Nevertheless, the 2018 Anak Krakatau tsunami provided the science community with the wealth of local observation data to quantify and calibrate models of the volcano-generated tsunamis from the same geographic area, so the verified models may be able to reconstruct one of the most tragic historical tsunamis and in many ways still mysterious event of 1883.

4. Lessons for Tsunami Warning and Hazard Mitigation

The comprehensive scientific analyses of the vast number of observations and model data described in the papers of this volume present several rather convincing answers to the question of *why* the two Indonesian tsunami events generated unexpectedly large tsunamis. While the details may differ from one study to the next, and more science is to be done to pinpoint the exact mechanisms, especially for the Palu tsunami, the general understanding of the tsunami generation and impact has definitely emerged from the studies for both events.

The questions of *what to do* with this new science and *how to apply* the new knowledge to improve the tsunami warning is much more difficult to answer.

While this article is not intended to provide final answers or recommendations to the operational community, the summary of observations and scientific findings from the studies of the two Indonesian events imply some obvious directions for improvement of existing warning systems.

1. Both Indonesian tsunamis of 2018 are highly localized events (i.e., mostly impacting coastlines within 1 h of generation). The problem of warning, forecast and general hazard mitigation for local events is a well-recognized problem for tsunami warning systems (Angove et al., 2019; Bernard & Titov, 2015). The March 11, 2011 Tohoku tsunami experience in Japan is a vivid prior example of the difficult task that tsunami warning systems face in the case of local events. The answer to the local tsunami warning and hazard mitigation problem is a major challenge for tsunami warning systems, which was (re)emphasized by the 2018 Indonesian tsunamis. Solutions for the problem of providing a timely warning for local tsunamis are in the works but additional research, development and implementation efforts are still required (e.g. Tang et al., 2016; Wei et al., 2013). The Palu Bay and Anak Krakatau tsunamis, besides being local event, provided additional specific challenges.
2. Both origins of the 2018 Indonesian tsunamis are unorthodox tsunami sources, ones that would have slipped under the radar of most modern tsunami warning systems, which are based exclusively on the assessment of the tsunami source. The Palu Bay tsunami was generated by an earthquake with a strike-slip mechanism, which have been historically considered as non-tsunamigenic, hence mostly ignored by the tsunami warning system algorithms. There are other types of tsunami-generating earthquakes that are often missed by tsunami warning systems, generally called “tsunami earthquakes”, a mostly generic name for earthquakes that deceive TWS with their unexpectedly strong tsunamis. The explanations of “tsunami earthquakes” generating larger than expected (or entirely unexpected) tsunamis are multiple, including slow ruptures, unusually efficient fault mechanisms, unusual placement of the rupture, or other, often not well-established factors. Non-earthquake sources of tsunamis are even more difficult to quantify in terms of tsunami potential in real-time. Volcanoes, landslides and meteotsunami sources are less frequent origins of destructive tsunamis than earthquakes, as the result, existing TWSs are not typically designed to deal with such threats. At the same time, the risk from non-earthquake tsunamis is steadily increasing. As coastal population and infrastructure grow, the impact from such events can be devastating, if not mitigated against. Those tsunami sources, however, unlike earthquakes, can often be anticipated. The impending danger of the Anak Krakatau tsunami, for example, was previously described and simulated with astonishingly prescient detail by Giachetti et al. (2012). Heinrich et al. (1998) had produced a similarly remarkable prediction of a tsunami due to pyroclastic flow from Montserrat Volcano, just a few weeks before it took place. The science community seems to be well armed to develop very reliable models of such hazards (obviously without the exact timing of their occurrence). Even such information with non-specific timing but robustly defined source details can be used to prepare for and effectively alleviate the tsunami hazard, the luxury that random process of the earthquake-triggered tsunamis usually don’t allow. When the definitive source information is not available during the event, however, as was the case for both 2018 events, a quick tsunami instrumental detection may be the necessary TWS enhancement that is required for any useful immediate response.
3. The fast offshore detection of tsunamis from local events, from sources with non-standard mechanisms or from otherwise unexpected tsunami sources ought to be a required component for an effective warning. As a revealing historical note: the first offshore tsunami detections and measurements by prototype systems that later became DARTs were two tsunamis generated by strike-slip earthquakes in the Gulf of Alaska on 30 November 1987 and 6 March 1988 (Gonzalez et al., 1991). That historical recordings were the proof of concept for an offshore tsunami detection as the method for assessing tsunami hazard from sources with uncertain tsunami potential. That was, in fact, the original objective for developing the DART system, with the overall goal to alleviate the rampant “false alarms” problem in tsunami warning operations at that time (Milburn, Nakamura, & Gonzalez, 1996). The offshore

tsunami measurement capability is now a standard component of warning operations and have proved effective for forecast and warning of far-field tsunamis (Angove et al., 2019; Bernard & Titov, 2015; Tang et al., 2012; Titov, 2009). The use of offshore data in forecasting also shows promise for regional tsunami warning (Tang et al., 2016), but use of tsunami measurements for local events forecast is still a developing concept (Wei et al., 2013). A detection and measurement system for nearby coasts, which is inexpensive and immediately actionable may be the most relevant TWS component for effective tsunami risk reduction not only for Indonesia, but for all World coastlines, since most fatalities in general occur at shores closest to the source. However, even the fastest tsunami detection and warning leaves only minutes for actions in case of the local event. Hence, the need for effective preparedness and education of the population at risk becomes another obvious lesson learned from these events.

4. Many post-tsunami surveys for both 2018 events indicated that the level of population awareness of the tsunami risk and the knowledge of proper response to tsunami warnings was very low for many affected communities. Abandoned evacuation structures, broken tsunami sirens, populations that were mostly unaware of tsunami danger and immediate tsunami response are disturbing observations of post-tsunami survey teams, especially considering the tsunami history of Indonesia and the amount of effort that has been put into development of the Indonesian TEWS. The education of population about tsunami risk, especially from numerous volcanic eruptions appear to be the most obvious missing strategy for the tsunami risk reduction in Indonesia. Unfortunately, volcanic eruptions are a prolonged phenomenon, a full cycle lasting typically weeks or months. And the cataclysmic event rarely occurs at the start of the sequence. Then, local communities have a tendency to be lenient and forget about the looming danger. In addition to the case of 1883, two examples come to mind: Mount Pelée in Martinique in 1902, had been erupting for several weeks when it finally blew up discharging its lethal pyroclastic flows which killed nearly all of St. Pierre's 27,000 inhabitants; Mount St. Helens in 1980 had also been active for a while when the catastrophic explosion took place on 18 May; in that case, however, thanks to the status of the area as a National Park, an efficient evacuation was in place which considerably reduced the death toll. The situation was no different in 2018 during Anak Krakatau: the volcano had been erupting for several months, and there are pictures of it glowing full red on the horizon just a couple of hours before the tragedy. Under the circumstances, it is a matter of common sense that an enclosed hall right on the beach with its back to the water was not the best locale to host a rock concert (Heidarzadeh et al., 2020; Muhari et al., 2019). Of course, it is easy to make such comments *post-factum*, with the wisdom of hindsight, but nevertheless, the message is there. As an anecdote illustrating the potential of educational aspect for risk reduction (Emile Okal, personal communication), at a town meeting in Martinique held a few months later, a local lady asked what to do, since as she put it "she liked to take a swim in the ocean in the morning". It was no trouble convincing her and all the audience that "you just do not go swimming when the volcano glows red on the horizon".
5. Yet another important missing part of the existing tsunami preparedness for local population appears to be actionable tsunami warning products that are developed not only for emergency managers, but for the immediate population at risk. In addition to tsunami risk education gaps, the absence of such products was evident during the Indonesian events when the population was mostly unaware of the tsunami situation while the tsunamis waves were pounding the coastlines. Such products may reduce the reaction time of the tsunami warning system better than many technical improvements of internal decision-making machinery of TWS itself.

5. *Discussion and Conclusions*

This volume documents the vast amount of information collected after the two Indonesian events of 2018, the Sulawesi-Palu and the Anak-Krakatau tsunamis. It includes studies that analyze observations and provide new understanding for these unusual events that deceived tsunami warning and mitigation efforts developed over the past decade. The lessons learned from studying these events ought to be applied to practical measures, with the hope to finally reverse the trend of increasing tsunami risk and reduce tsunami fatalities for not only the Indonesian coastlines but for all World Oceans.

Scientifically, the two Indonesian event of 2018 (re)emphasize the challenges and importance of scientific understanding and analysis of tsunamis that are generated by earthquakes with "non-standard" tsunamigenic earthquake mechanisms, and non-standard tsunami sources in general. A "typical" tsunami source, a large shallow thrust earthquake at the subduction zone interface, have probably generated about 70–80% of all historical tsunamis and about 90% of all earthquake-generated tsunamis (Gusiakov, 2009; NCEI/WDC, 2020)—this is the reason why most TWSs are 'calibrated' for such typical tsunami generation. However, the "non-standard" sources are responsible for the highest measured runup (e.g. the 1958 Lituya Bay tsunami) and some most devastating historical tsunamis (e.g. the 1833 Sanriku and 1883 Krakatau events). The 2018 Indonesian tsunamis, along with growing evidence of increased risk from such events around unprotected coasts around the world (Higman et al., 2018; Paris, 2015; Pattiaratchi & Wijeratne, 2015; Rabinovich, 2020) demonstrated that this risk should be urgently addressed with new scientific methods applied to tsunami warning and mitigation measures.

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