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IMPACT AND RESPONSE IN CENTRAL AND SOUTH AMERICA DUE TO THE TSUNAMI GENERATED BY THE SUBMARINE ERUPTION OF HUNGA TONGA-HUNGA HA'APAI VOLCANO

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ABSTRACT

The Hunga Tonga-Hunga Ha'apai submarine volcano erupted on Saturday 15, 2022 leading to a VEI 5 eruption at 17.27 local time, shaking the earth with a M5.8. As result of this explosion a tsunami was triggered. The reasons of the tsunami may have been by a complex magma-water interaction or by repeated submarine mass movements. However, this tsunami impacted most of the Pacific during the following couple of hours, reaching also Central and South America. There, local monitoring organizations handled differently this information provided by the PTWC, and so did authorities and local mass media in the transmission of information and consequences for the public. We report the events as occurred in the countries between Costa Rica, Panama, Colombia, Ecuador, Peru and Chile and the respective degree of reaction of the public.

Keywords: *Hunga Tonga-Hunga Ha'apai, volcanic tsunami, early alert, transmission of information, response, public preparedness*

1. INTRODUCTION

Historically, the Pacific side of Central and South America have been impacted by numerous tsunamis from local and distant earthquakes generated along subduction zones of active continental margins (Pararas-Carayannis, 1974; Lockridge, 1988; Gusiakov, 2005; Kowalik et al., 2005; Orfanogiannaki & Papadopoulos, 2007; Medina et al., 2021). The South American continent is subducted by the Nazca Oceanic Plate, while Central America is subducted also by the Cocos Oceanic Plate (Wadge & Burke, 1983; Protti et al., 1994; Trenkamp et al., 2002; Mann, 2007). Most of the tsunamis that impact the coasts of Central and South America are of such local tectonic origin earthquakes and strike shorelines within very short times after generation (Annaka et al., 2007; Løvholt et al., 2012; Carvajal et al., 2019). Nonetheless, there are also tsunamis generated from far-distant generating sources, like the 2011 Sanriku tsunami in Japan, which have impacted Central and South America some 20 hours or more after their generation (Pararas-Carayannis, 2011; Ide et al., 2011; Grilli et al., 2013; Kajitani et al., 2013; Murray et al., 2015; Chian et al., 2019). Once a tsunami is generated by a tectonic earthquake or some other source somewhere in the Pacific Ocean, the Pacific Tsunami Warning Center (PTWC) in Honolulu Hawaii, disseminates initial alerts and subsequent warnings about the arrival time of tsunami waves at various ports or other important sites along the coasts (Fukao, 1979; Bernard et al., 2006; Jiménez et al., 2018). Government institutions or centers receiving such information pass it on to Civil Defense authorities in each country, which in turn assess the potential risks and disseminate notifications to local authorities, followed by alerts or warnings by sirens to the public, so that evacuation to safer higher ground sites can be rapidly initiated (Park et al., 2005; Sahal & Morin, 2012; Itibita & Chen, 2017).

The procedures of evaluating earthquake events and tsunami generation in the Pacific Ocean Basin have been successfully implemented for various decades by PTWC (Bernard et al., 2006; Tkalich et al., 2007; Davis & Izadkhah, 2008; Lauterjung et al., 2010; Okal, 2015; Neußner, 2021). Countries receiving watch or warning information proceed with further transmission of evacuation plans, to ensure the safety of people living in coastal areas (Moe & Pathranarakul, 2006; Yahav & Salamon, 2022). However, if the earthquake source area is close, the arrival time of the tsunami waves may be too short, and authorities lack needed time to transmit information or warnings to the public (Anderson, 1969; Nakamura et al., 2011; Angove et al., 2019). Also, there are cases when authorities fail to adequately interpret or understand the risks of an incoming tsunami, thus taking a wrong decision which may lead to a disaster (Gregg et al., 2006; Igarashi et al., 2011; Farías, 2014). On the other hand, even when all procedures are handled correctly by the authorities and associated scientists, the public may react incorrectly and risk their lives (Allen & Melgar, 2019; Mileti & Sorensen, 1990). The success of any type of tsunami evacuation depends on the degree of preparedness, and of public education, repeated drilling exercises and corresponding signals, as well as on the infrastructure of tsunami-resistant buildings among others (Paton et al., 2008; Nandi & Havwina, 2018; Esteban et al., 2014; Johnston et al., 2005; Esteban et al., 2015; Edler et al., 2020; Suárez-Acosta et al., 2021; Del Pino et al., 2021; Toulkeridis et al., 2021).

For the above-stated timing, geographical, and disaster preparedness limitations, some of the tsunami warnings issued by PTWC and by National authorities - even for earthquake-generated events - fail occasionally to reach on time the public of threatened coastal areas. The problem of timely dissemination of warnings to the public becomes even more difficult to handle by national and international authorities, when a different and difficult to measure tsunami triggering mechanism is involved, which precludes rapid assessment of potential risk (Gardner-Stephen et al., 2019; Lane et al., 2020; Mikami et al., 2020; Selva et al., 2021; Rafliana et al., 2022).

Since tsunamis can be generated also by numerous other sources, such as flank failures of coastal or oceanic volcanoes, underwater slides, submarine Surtsean (phreatomagmatic) eruptions, sub air Plinian eruptions, Ultra-Plinian explosions, landslides, flank failures, subsidences and multiphase massive caldera collapses of a volcano, such events can generate destructive tsunamis – as for example that generated during the paroxysmal phase of the 1883 Krakatoa volcanic eruption (Pararas-Carayannis, 2004, 2006). Furthermore, tsunami-like waves can be generated by atmospheric air pressure pertrubations, and such was the case for the meteo-tsunami of 29 August 1916 at Santo Domingo, in the Dominican Republic (Pararas-Carayannis, 2019).

Large magnitude earthquakes involving significant vertical crustal dispacements such as those of the 1964 Alaskan earthquake, generated atmospheric pressure waves which propagated faster then tsunami waves and were recorded by micro-barographs. The use of such microbarographs was proposed subsequently to serve also as precursory method of forecasting tsunami generation (Pararas-Carayannis, 1967). Furthermore, tsunami waves can be also generated by a rapid, significant and progressive drop in atmospheric pressure which may be caused by a storm, in which case it would be localized and directional, as was the case with the meteo-tsunami of 29 August 1916 at Santo Domingo, in the Dominican Republic (Pararas-Carayannis, 2019).

However, violent eruptions and blast episodes such as that of 1883 Krakatau volcano, can also trigger rapidly moving atmospheric pressure pertrubations which, in turn, as they move over a shallow sea, can couple with the sea surface and generate tsunami-like waves affecting the surface of the sea – often with sizeable waves. Specifically, the atmospheric pressure shock waves from the 1883 explosions of Anak Krakatau volcano circled the earth and were recorded by barographs throughout the world (Pararas-Carayannis, 2004). Apparently, the Hunga Tonga-Hunga Ha'apai submarine volcano's violent explosive index VEI 5 eruption also generated strong atmospheric pressure waves and tsunami-like waves recorded at great distances. (See: http://www.drgeorgepc.com/Tsunami1883Krakatau.html)

In fact, similarly to the explosive 1883 volcanic eruption/explosion of Anak Krakatau reported above (Pararas-Carayannis, 2004), and according to a study pending final publication in EOS (Lin et al., Febr. 2022), the Hunga Tonga Hunga Ha'apai volcanic eruption of 15 January 2022, also created an impulsive giant Ionospheric Lamb Wave in the Northern Hemisphere which, traveling at the speed of sound (about 340 m/sec), reached Japan in six hours.

Also, using new technology, there were recordings of subsequent concentric wave shape traveling ionospheric disturbances (TIDs oscillations) from the Hunga-Tonga volcanic eruptions – which were observed simultaneously in both the northern and southern hemispheres. Thus, the main source mechanism for the 2022 tsunami generation and its observed far-field impacts, were not due to crustal movements related to the relatively shallow underwater eruption of the volcano in the Tonga archipelago, but to Lamb Wave atmospheric pressure turbulence and ionosphere/atmosphere interaction, which forced non-dispersive, horizontally traveling oscillations, similarly to those of Anak Krakatau volcano (Pararas-Carayannis, 2004).

Therefore, high amplitude tsunami waves can be generated not only by earthquakes, but also from less frequently-occurring events, such as impacts of falling asteroids, massive coastal and submarine landslides, and volcanic activity which may include flank and caldera collapses, or violent explosive eruptions that result in significant crustal and water displacements and atmospheric pressure shock waves (Latter, 1981; Bardet et al., 2003; Cita & Aloisi, 2000; Synolakis et al., 2002; Tappin, 2002; Pararas-Carayannis, 2002, 2004, 2011, 2014).

Although tsunami generation from falling space bodies is an extremely rare phenomenon, there is documentation that during the Cretaceous-Tertiary geological period, asteroids struck the earth and generated huge tsunami waves. For example, about 66 million years ago, a large asteroid of about 10 kilometers in diameter struck the earth and created the Chicxulub crater near the coastal area of Yukatan Peninsula of Mexico, and most probably generated a mega tsunami. In fact a study proposing a simulation of asteroid tsunami model validation – characterized as the P-C model - was used to calibrate, verify and validate theoretical modeling studies of asteroid tsunami generation, conducted at the Los Alamos National Laboratory (Pararas-Carayannis, 1999).

More frequent past events generating tsunamis resulted from crustal movements involving severe volcanic activity, as determined by studies of paleo-tsunami deposits (Pararas-Carayannis, 1973, 1974a, 1992; Watkins et al. 1978; Sharpton et al., 1992; Bourgeois, 1994; Dunbar & McCullough, 2012; Paris et al., 2020). Prominent examples may be the Coquimbo event in Chile in the Middle Pleistocene period, the Alika event in Hawaii some 120 thousand years ago, and the Storegga event of Norway some 7,000 years ago (Lipman et al., 1988; Paskoff, 1991; Bondevik et al., 1998; McMurtry et al., 2004; Goff et al., 2014).

Nonetheless, the oldest known tsunami in recent historical time scale was that generated by the 1638 B.C. explosion, caldera collapse, and flank failures of the volcano of Santorini in the Aegean Sea in Greece – which caused the destruction of the Minoan civilization on the Island of Crete, as well as destruction elsewhere in the Aegean Archipelago (Pararas-Carayannis, 1973, 1974a, 1992; Minoura et al., 2000: Manning et al., 2006; Nomikou et al., 2016; Driessen, 2019).

In more recent times, a very destructive tsunami was generated by the 1883 eruption of the Anak Krakatau (Krakatoa) volcano in the Sunda Straits, between the islands of Java and Sumatra in Indonesia (Latter, 1981; Paras-Carayannis, 1983; Tanguy et al., 1998; Choi et al., 2003). Within an hour after the fourth explosion/caldera collapse of the Anak Krakatau, waves reaching heights of up to 37 m (120 feet) destroyed 295 towns and villages and drowned a total of 36,417 people (Pararas-Carayannnis, 1983, 1999). As with the recent eruption/explosion of the Hunga Tonga-Hunga Ha'apai submarine volcano on 15 January 2022 near the Tonga Islands, the far field effects of the tsunami generated by the 1883 eruption of Anak Krakatau were noticeable around the world, but to a much greater extent.

Small sea level oscillations from the 1883 tsunami were recorded by tide gauges at Port

Blair in the Andaman Sea, at Port Elizabeth in South Africa, and as far away as Australia, New Zealand, Japan, Hawaii, Alaska, the North-American West Coast, South America, and even as far away as the English Channel (Pararas-Carayannnis, 1983, 1999). The unusual flooding, which occurred at the Bay of Cardiff, in the U.K. in 1883 was caused by atmospheric coupling of the pressure wave from the major Krakatau eruption.

A more recent eruption of the Anak Krakatau in 2018 caused a partial flank collapse of the volcano, and generated a local tsunami which killed some 437 people (Borrero et al., 2020; Zengaffinen et al., 2020; Heidarzadeh et al., 2020). While the 1883 eruption of the Anak Krakatau volcano occurred when no communication systems were in existence, the 2018 eruption occurred in contemporaneous times, and yet it was not possible to warn surrounding sites of its devastating potential (Sakurai & Murayama, 2019; Ye et al., 2020).

Finally, in the evening of 15 January 2022, the Hunga Tonga-Hunga Ha'apai submarine volcano near the Islands of Tonga, erupted violently and generated a destructive tsunami with local as well as far-field impacts in coastal areas of the Pacific Ocean. This was the strongest volcanic eruption/explosion in the 21st century.

The authors anticipate that further analysis of this event will be needed in order to evaluate the effectiveness of Civil Defense procedures for Latin-American countries between Costa Rica and Chile, in transmitting timely advisories and warnings for the protection of the public in coastal areas, from such volcanically-generated tsunamis.

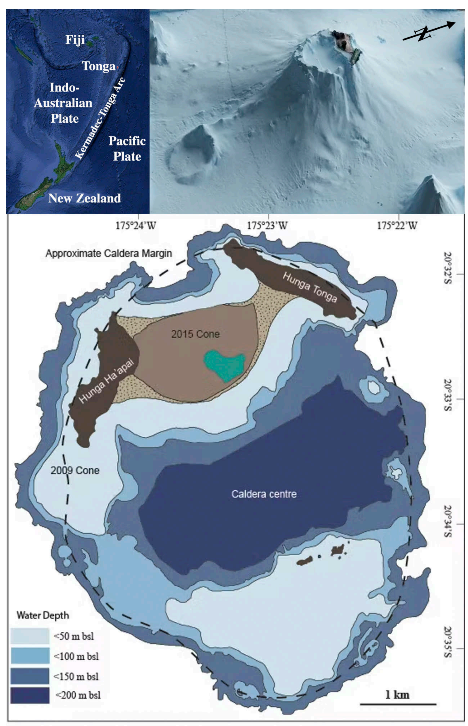

Figure 1. Upper left: Geodynamic setting of Tonga. Credit GoogleEarth™ (2022). Upper right: A rendering of the volcano shows the part of the peak that is known as the two Tongan islands Hunga-Tonga and Hunga-Ha'apai. Credit Frederik Ruys; Below: Volcanic structure of Hunga Tonga-Hunga Ha'apai based on elevation and bathymetric map of this underwater volcano. Credit Shane Cronin / The Conversation, 2022.

2. GEODYNAMIC SETTING AND PRESENT TSUNAMI-TRIGGERING VOLCANIC ACTIVITY

The Hunga Tonga-Hunga Ha'apai volcano is located near to the islands of the Kingdom of Tonga, a group of 169 islands in the SW part of the Pacific Ocean, just north of New Zealand (Fig. 1). Volcanoes in this region developed by the interaction between the Indo-Australian and the Pacific Plate (Timm et al., 2014). Hereby, the descending oceanic Pacific Plate which subducts below the Tonga-Kermadec intra-oceanic arc, is the reason for the region's strong earthquakes and active volcanism (Fig. 1a; Hall & Spakman, 2002; Stern, 2004; Smith & Price, 2006).

2 A. Volcanic Evolution Along the Tonga-Kermadec Intra-Oceanic Arc

Along the central segment of the arc, rise some twenty volcanic edifices from the sea floor up to close or shortly above sea level (a.s.l.) (Worthington et al., 1999; Peate et al., 2001; De Ronde et al., 2007; Lupton et al., 2008). Two of these oceanic volcanic islands form the mainly submarine Hunga Tonga and Hunga Ha'apai volcanoes, which rise to some 114 meters above sea level (Fig. 1b; 1c; Colombier et al., 2018; Garvin et al., 2018; Brenna et al., 2022). These islands are remnants of a previously destroyed cone of the Hunga volcano, due to at least two caldera-forming processes some 840 to 980 years ago (Brenna et al., 2022). Historic and observed volcanic activity above and below the sea surface occurred in 1912, 1937, 1988, 2009 and 2014-15 (Global Volcanism Program, 2009; 2014; 2015; Brenna et al., 2022). The latter activity has been responsible for the creation of a single volcanic cone, when the two aforementioned islands got connected forming the 5 km long Hunga Tonga-Hunga Ha'apai and 1800 meters high submarine volcano (Brenna et al., 2022).

2 B. Recent Volcanic Activity Near the Islands of Tonga

The most recent volcanic activity initiated since the end of 2021, when the Hunga Tonga-Hunga Ha'apai underwater volcano erupted on December 20, 2021, continuing up to January 4 and later on to 13 January 2022 (Global Volcanism Program, 2021a; 2021b; 2021c; 2022). These eruptions are indicating smaller eruptions occurring at the edge of the caldera, while the subsequent stronger events were generated within the caldera when the upper part of the erupting magma collapsed inward, which resulted to a potentially massive deepening of the caldera (Brenna et al., 2022). The two precursor events produced slightly more land to the island, while the ash and gas clouds reached a height of up to 17 km (Fig. 2; Global Volcanism Program, 2021b; 2021c).

Figure 2. Images of the eruption of January 15, 2022. Credit Left: Digicel Tonga. Credit right: Tonga Geological Services / ZUMA Press / IMAGO

Following the new intense explosive phase on Thursday 13 January 2022 some 48 hours later. this volcanic activity continued until Saturday the 15th of January, leading to a VEI 5 eruption at 4.27 UTC (17:27 local time), and a magnitude M5.8 earthquake, as registered by the USGS (Fig. 3; 4; USGS, 2022). The blast of the shock wave from the major eruption travelling at the speed of 300 m /sec, was registered on many sites on the planet, including the other side of the Atlantic region (New York Times, 2022; Science.org, 2022). The eruption destroyed most of the island above sea level, generated an ash plume of some 19.2 km in height, and was followed by massive ashfall which reached the surrounding islands (BBC, 2022).

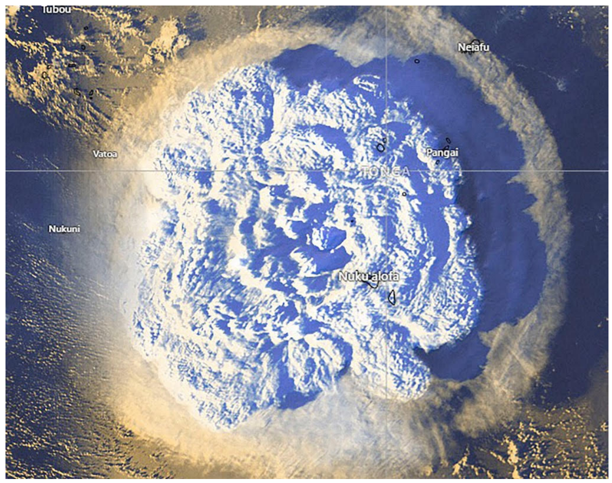

Figure 3. The enormous explosion as seen from the satellite. Credit US Geological Survey and Tonga Meteorological Services. Width of image is of about 600 km

Figure 4. Upper left: Hunga Tonga-Hunga Ha'apai prior eruption. Credit GoogleEarth™ in 2021; Upper right: The apparent volcanic activity as it appeared on January 7 2022. Credit: Planet Labs PBC/EYEPRESS/Shutterstock; Lower left: A Planet SkySat image shows Hunga Tonga-Hunga Ha'apai two hours before its eruption on January 15, 2022. Credit:Planet Labs PBC/via REUTERS; Lower right: Remains of the island as seen on January 17, 2022. Credit: Maxar Technologies

2 C. Tsunami Generated by the Paroxysmal Eruption of the Hunga Tonga-Hunga Ha'apai Volcano

This huge volcanic event triggered a tsunami, which impacted first the kingdom of Tonga affecting almost its entire population, and compromised many strategic infrastructures such as the submarine Internet cable, thus interrupting communication for weeks for many shorelines along the Pacific Ocean. The nearby islands of Tonga were impacted by the tsunami in less than one hour, New Zealand and Australia in four hours, Japan in eight hours, Russia and United States in more than ten hours, and finally South and Central America in more than twelve hours (Fig. 5).

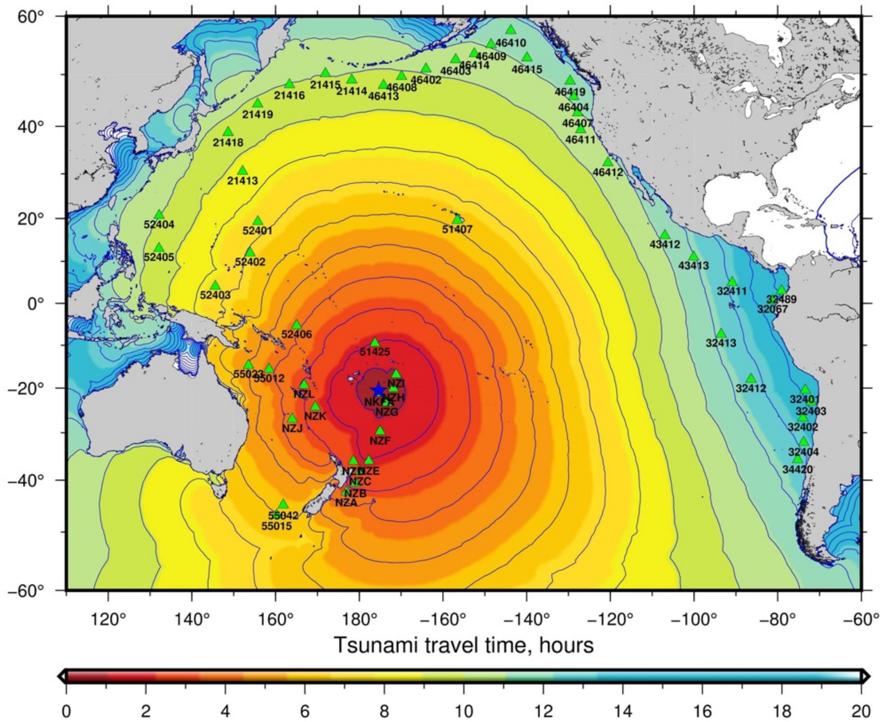

Figure 5. Tsunami travel time based on NOAA (NOAA, 2022a)

The origin of the tsunami generating area remained unclear initially, as the explosion of the Hunga Tonga-Hunga Ha'apai underwater volcano may have included three different possible mechanisms of tsunami generation. The first - and less possible - was that the tsunami was generated by the associated with the eruption magnitude M 5.8 earthquake, which however was too low to trigger a tsunami wave that could reach the shores of Asia and the Americas. The second mechanism for tsunami generation is based on the complex hydrothermal, high temperature molten magma-water interaction and the explosive blasting of both molten magma and gas reacting violently with the ocean´s water. If such interactive processes had occurred deeper in the sea, the hydrostatic pressure of the overlying sea water would have suppressed this process, but in the instant case the volcanic explosion occurred a little below the sea surface at a depth of about 150 to 200 meters below sea level (The Conversation, 2022).

A third possible mechanism of the tsunami source mechanism for this volcanic event is a massive and repeated submarine mass movement giving rise to marine landslides as well to flank or caldera collapses (The Conversation, 2022). Due to the enormous explosion only two smaller island fragments remained above sea level, which may favor the magma-water interaction or the flank collapse or even the combination of both triggering mechanisms (see Fig. 4).

3. EARLY ALERT AND RESPONSE BY THE AUTHORITIES AND THE PUBLIC

According to the USGS, the complex paroxysmal eruption of the Hunga Tonga-Hunga Ha'apai volcano occurred 68 km west of the island of Nuku'alofa of Tonga at 04:14:45 (UTC), on January 15, 2022 (USGS, 2022). This report takes this time as being the main tsunami initiation (PTWC, 2022). It is clear, in our understanding, that the source and development of this transoceanic tsunami is still unknown, and is out of the scope of this present report. Our subsequent analysis focuses on the tsunami recording by tide gauges in El Salvador, Costa Rica, Panama, Colombia, Peru, and Chile (Fig. 5, 6 and 7). Some of this information was available from the Flanders Marine Institute (Flanders Marine Institute, 2021). We have chosen the stations shown in Fig. 6 below, and the tide gauge records (Fig. 7), in order to have a panoramic picture of the tsunami impact on the Southeast Pacific coast of part of Central America and on the West of the South American continent.

Figure 6: Tide gauges station of the study area

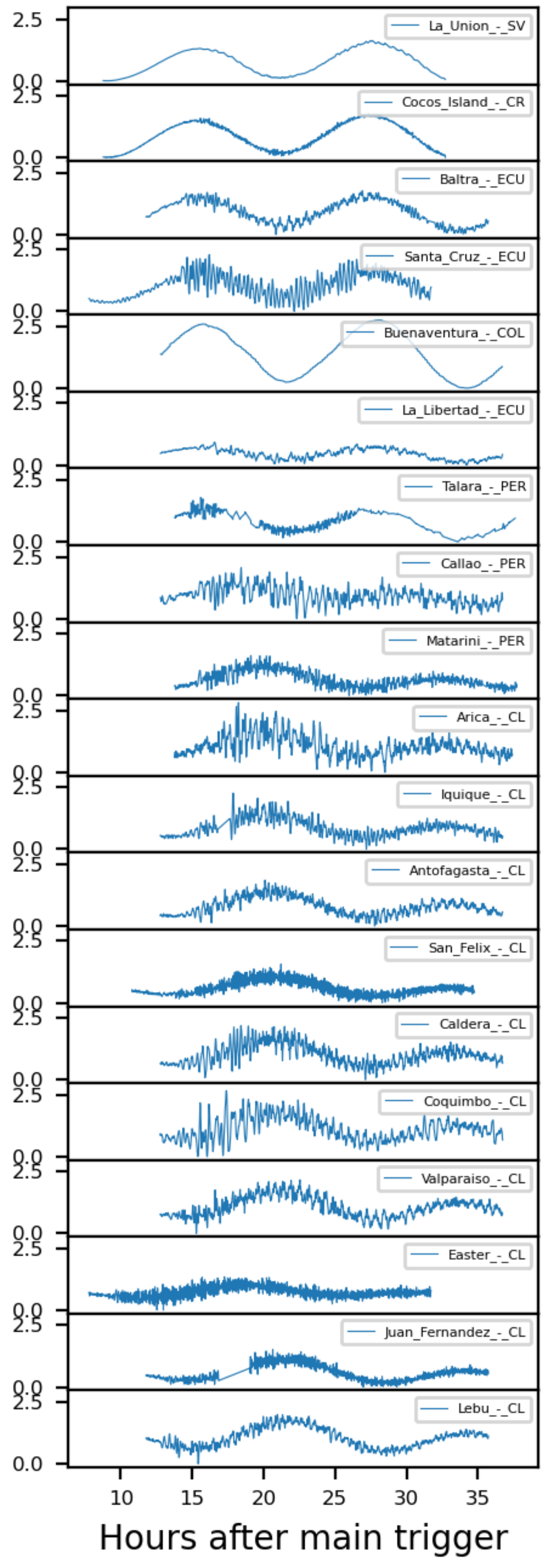

Figure 7. Tsunami wave amplitude registered at tide gauges stations

Analysis of tide gauge records (see Fig. 6 and 7 above) shows that the first tsunami wave arrival at the tide gauge station at Easter Island, Chile, was 9h 45min after the volcano's main eruption, and had a maximum wave amplitude of 0.5 meters. Most of the other stations recorded the tsunami's first arrival between 14-15 hours after the time of the volcano's paroxysmal eruption. The tide station at Eastern Island, located closer to the tsunami source, gives important information for the purpose of an early warning system for these kinds of events. The amplitude of the tsunami registered at the different tide gauges ranged from 0.1 - 1 meter. Maximum wave amplitude registered at the tide gauge in Arica, Chile, where the third tsunami wave reached a wave amplitude of ~ 1m. Regardless of the location, the stations in El Salvador, Costa Rica, Panama and Colombia, registered not important oscilllations. In the case of Buenaventura, Colombia, it is important to remark that this station is located in an estuary, where most of the energy of the tsunami dissipated by shoaling.

Another important issue about the tsunami's height is related to the stage of the tidal level at the time of arrival at each tidal station. In general, the tsunami's arrival occurred at or near high tide level in El Salvador, Costa Rica, Panama, Colombia, Ecuador, and northern Peru. Stations in southern Peru and all stations in Chile recorded the tsunami arrival close to low tide level. This is an important aspect of the tsunami impact since the tide gauges in Chile received the highest wave amplitudes of the tsunami (Fig. 7).

The very first tsunami message of the event in Tonga was issued at 0623 UTC, then at 0720 UTC, and later at 0852 UTC (NOAA, 2022b). In the first three messages, only local and some West Pacific sites were mentioned as potential tsunami impact sites (Vanuatu, New Zealand, Kiribati, Australia etc.), as well as the times of arrival and probable expected tsunami heights. The first advisory/warning of a tsunami impact in Central and South America was sent by the Pacific Tsunami Warning Center (PTWC) in Honolulu, Hawaii at 1246 UTC, on Saturday 15 January 2022 as "Tsunami Message Number 4", referring only to Chile and Mexico, excluding at that time Central and South American countries, which were further away from the tsunami generating source. However, a sixth message at 1645 UTC issued an advisory/warning to all other Central and South American countries (NOAA, 2022b). The last twelfth message was issued at 0246 UTC on Sunday 16 January 2022. Based on these advisories to country-members of the Pacific Tsunami Warning System (PTWS), we begun analyzing responses of authorities, of media and of the public for the countries in the region from Costa Rica and Chile.

3a. Costa Rica

According to historical tsunami catalogs and records, since 1746 Costa Rica has been impacted about 39 times by tsunamis (Fernandez et al., 2000; Chacón-Barrantes, & Protti, 2011; Chacón-Barrantes & Zamora, 2017; Chacon-Barrantes & Arozarena-Llopis, 2021). Most of the observed or recorded tsunamis were generated mainly from local tectonic sources. Even the tsunamis of 1950 and 1992 which had runups of up to 7.3 meters, there were no reported fatalities along the country's Pacific coast. Fortunately in Costa Rica there are regular educational and awareness programs, as well as occasional local drilling of evacuation exercises, for both of the country's Pacific and Caribbean coastal sides.

Following the PTWC advisory about the possible impact of a tsunami from the Hunga Tonga-Hunga Ha'apai volcanic event, the National Tsunami Monitoring System (SINAMOT) of Costa Rica in its Report # 1 at 9:54 local time, announced that the earthquake magnitude associated with the eruption in Tonga should be ignored, but that very strong currents would arrive, classifying them as of low threat (SINAMOT, 2022). Later SINAMOT reported that the impact times were cestimated to be at 12:20 in the Gulf of Nicoy, and at 12:53 in Quepos (Fig. 8).

Figure 8. Potential impact sites (in blue) of tsunami in Costa Rica with low threat (SINAMOT, 2022)

However, based on what was observed and reported elsewhere, it was recommended that all sea-related activities such as swimming, surfing, diving, snorkeling, artisanal fishing, water sports, should be terminated. Furthemore an order was issued to vacate the beaches, and in a general way abstain from such activities until further notice by the official media that there were no-longer existing threat conditions. At 10:16 local time, the national media issued such official notice, recommending evacuation of the Pacific coast for at least a period of one hour (12:30 pm to 1:30 pm). At 1:15 p.m. local time, abnormal behavior of the sea was reported at Potrero (Guanacaste), when the sea level rose and subsequently receded, twice. At 3:30 p.m., there was an announcement that monitoring was completed, and that there were no reports of losses or injured persons anywhere along Costa Rica's Pacific coast.

3b. Panama

Panama, like Costa Rica was impacted by tsunamis of both sides, at the Pacific Coast and on the Caribbean side. Tsunamis in Panama are subduction related, as well as based on volcanic activity and landslides (Fernandez et al., 2000; Lander et al., 2002; O'loughlin & Lander, 2003; Pararas-Carayannis, 2004). Unfortunately, there is a general lack of awareness of these oceanic hazards and there is a lack of implementation of concrete plans and actions at the local, regional and national levels, which leaves the population to be much more vulnerable to the possibility of a disaster caused by tsunamis and associated hazards (Martinez & Toulkeridis, 2020).

In Panama, the organization in charge of receiving, analyzing and disseminating technical-scientific information related to tsunami warnings is the Institute of Geosciences (IGC) of the University of Panama, which is part of the Tsunami Warning System for the Caribbean and the Pacific. It is the national and international organization which provides scientific information in the areas of earth sciences to the Panamanian authorities, the National Civil Protection System (SINAPROC), and the public in general. The IGC, upon receiving the tsunami alert for Panama on January 15, 2022, announced that this phenomenon did not represent a threat to the Panamanian coasts and notified the SINAPROC, which is responsible organization, foe management and communications of specific actions related to the prevention of risks in the country (Gaceta Oficial de Panamá, 2005)

SINAPROC, through its official Twitter account - citing the IGC Panama as an official source - ruled out the tsunami threat to the Panamanian coasts from the eruption of the Hunga-Tonga-Hunga-Ha'apai submarine volcano. But they stressed out that they would remain in constant monitoring and vigilance in the face of any adverse phenomenon presented in the region (Twitter.com/Sinaproc Panama, 2022).

The national press, citing the IGC and SINAPROC as official sources, issued different communiqués informing the general population of the situation in Panama in the face of this possible threat. Newspapers such as La Estrella de Panamá published headlines ruling out the tsunami warning for Panama due to the eruption of an underwater volcano near Tonga Island (La Estrella, 2022). For its part, ECOTV Panama confirmed the same news (ECOTV Panama, 2022). Other media, both written and television, maintained constant communications to the population in the afternoon of January 15, 2022, among which stand out the Sigo de Panamá (El Siglo de Panamá, 2022), TVN-2.com (TVN Canal 2, 2022), critica.com (La Crítica Panamá, 2022) and Telemetro.com (Telemetro Panamá, 2022).

Fortunately, no injuries, fatalities or any damages were reported by any media. However, in the aftermath we may report that most of the people living, working and or staying at the coast, did not realize that there has been any threat by a tsunami, indicating that the official and mass media notices did not reach them at all.

3c. Colombia

A very strong earthquake on January, 31, 1906 along the Colombian-Ecuadorian border generated a tsunami which killed about 1,500 people (Pararas-Carayannis, G. 2012; Yamanaka et al., 2017; Pulido et al., 2020; Yamanaka & Tanioka, 2021). Subsequent tsunamis, as one in 1979 also killed many, especially in the southern part of the country (Herd et al., 1981; Kanamori & McNally, 1982; Adriano et al., 2017). The preparation of the public for such disasters was inadequate because of prevailing structural, political, social and economic conditions and reasons (Harden, 2007; Mas et al., 2017).

Recognizing this insufficiency, the National Tsunami Detection and Warning System – SNDAT, was formed as a subsidiary of the National Disaster Risk Management System, with the responsibility of detecting and evaluating events having tsunamigenic potential, as well as defining and disseminating tsunami warnings for the coasts of Colombia. This system is currently made up of four national institutions, these being the General Maritime

Directorate (DIMAR), the Colombian Geological Service (SGC), the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM), the National Unit for Risk Management of Disasters (UNGRD), with the collaboration of the Seismological and Geophysical Observatory of the Colombian Southwest (OSSO) Corporation.

Furthermore, in July 2018, the General Maritime Directorate, through Decree 1338, was designated by the National Government to fulfill the functions of Tsunami Warning Focal Point - TWFP and of the National Tsunami Warning Center - CNAT, in order to monitor and evaluate the possibility of tsunami generation by seismic events, as well as to receive and transmit relevant technical data to the International Tsunami Warning Centers and to the National Unit for Disaster Risk Management. Since 2012, the General Maritime Directorate - Dimar implemented the Tsunami Warning Center in the city of Bogotá, to act as the main center, given that the location of the CAT in Tumaco would prevent its normal operation in the event of a tsunami event that affects the Pacific coast of Colombia. At the same time, in December 2016, the first version of the National Tsunami Detection and Warning Protocol was signed, which would allow coordinating the actions of the National Tsunami Detection and Warning System - SNDAT, and provide the National Risk Management System of Disasters of an instrument to unify information and issue alerts for events having the potential to generate tsunamis in Colombia. The Protocol was updated in 2018, and again in April 2020 by the SNDAT.

Figure 9. Official tweet issued by the UNGRD in Colombia on the occasion of the tsunami caused by the eruption of the submarine volcano Hunga-Tonga volcano in the Tonga Islands on January 15, 2022 (Source: https://twitter.com/UNGRD)

However, in the case of Colombia, no emergency was declared on January 15, 2022 for a possible tsunami from the Tonga archipelago that would affect the populations located on the western coast of the national territory. Despite of the existence of a National Tsunami Detection and Warning System and the established protocol, the first official communications by DIMAR regarding the tsunami threat to Colombia after the volcanic eruption near the island of Tonga, first appeared at 7:31 p.m. on January 15, 2022. At that time, DIMAR announced the state of observations in the Pacific basin, through several short posts and through its social media accounts, in addition to a press release. Therefore, the only official reaction was presented by the National Unit for Risk Management of Colombia (UNGRD), which on the day of the tsunami at 6:51 p.m. local time, published on Twitter that the General Maritime Directorate (DIMAR) was monitoring possible effects on the Pacific coast of Colombia (Fig. 9 above). In this sense, the newspaper El Colombiano, reported that the Colombian authorities are evaluating whether there is a risk of a tsunami, and that "the eruption of the submarine volcano near Tonga, in the South Pacific, has Latin American countries Chile and Ecuador on alert after generating a tsunami" (DIMAR, 2022).

Other national media outlets, such as Caracol Radio (AFP), in a news item broadcast on their website on January 16, 2022 at 8:07 p.m. local time, did not report any alert situation for Colombia either. This media mentioned the following: "The Darwin Volcanic Ash Advisory monitoring center, located in Australia, reported this Sunday about a new large volcanic eruption that was detected near the island of Tonga. This occurs three days after another eruption that generated an increase in waves in the Pacific and a moderate tsunami in countries such as the United States, Chile, Peru and Ecuador. The Pacific Tsunami Warning Center (PTWC) also added that it detected large waves in the area and that these could be from another explosion of the Hunga-Tonga volcano".

In general terms, it was established that after the tsunami had been generated in the Pacific Ocean by the eruption of the Hunga-Tonga volcano, there was no damage on the Colombian coast, and there is no report on the community's reaction to possible effects caused for this event. It should be noted that the local tsunami modeling for Colombia, considering seismic scenarios such as those of the 1906 and 1979 earthquakes, and of other seismogenic zones along the Colombian Pacific coast, with maximum recorded seismic events, show flood sheets that do not exceed 5.0 meters in towns such as Buenaventura, Tumaco, Juanchaco, Curay and Salahonda (Caballero y Ortiz, 2002; Cardona *et al*., 2007; Restrepo y Otero, 2007; Dirección General Marítima, 2013; Ministerio de Defensa Nacional *et al*., 2014; Cocuñame y Salcedo-Hurtado, 2017).

Nonetheless, the reactions of citizens on twitter to the DIMAR press release criticized the delay (18 hours) in issuing a communication, and the discrepancy with the measures taken by countries such as Chile and Ecuador that did issue tsunami warnings several hours earlier. The Redacción CV Noticias was the only Colombian national press outlet that made the report that reached the general population, by literally reproducing the DIMAR press release at 7:41 p.m. on January 15, 2022, just ten minutes after the publication of the same (Redacción CV Noticias, 2022).

Later, at 11:32 pm on January 15, 2022, DIMAR announced the tsunami risk reduction by posting the following two messages on its social networks: "According to the monitoring of the tsunami wave generated by the eruption of the volcano in waters near the island of Tonga, we report that no significant changes have been recorded in the sea level stations in Colombia during the last few hours" ….“Reducing the probability of tsunami risk for the Pacific Coast of our country”. These posts again received criticism from several citizens who noted the changes and rises in sea level reported in other countries of the Pacific, and demanded that a tsunami alert should have been declared in Colombia out of institutional responsibility and duty to the population.

The next day, on January 16, 2022, the national press, through the SEMANA medium, published an article reporting the cancellation of tsunami alerts in three countries: Ecuador, Peru and Chile. However, this article did not mention the official communications by the Colombian government agencies in charge of tsunami detection and warning (La Semana, 2022). It should be noted that the UNGRD did not issue any press release on January 15, 2022 regarding the tsunami threat due to the volcanic eruption in Tonga and this, despite the fact that it did issue two separate press releases with the title "There is no tsunami warning for the Colombian Pacific Coast", both on January 6, 2022 after the earthquake of magnitude 6.2 59 km from Corinto, Nicaragua, and on January 28, 2022 after the earthquake of magnitude 6.0, 30 km from Panama.

3d. Ecuador

Ecuador has suffered the impact of a variety of tsunamis during the last recorded two centuries, including the tsunami generated by the 8.8 Mw earthquake of 1906 (Pararas-Carayannis & Zoll, 2017; Ioualalen et al., 2011; 2014; Heidarzadeh et al., 2017; Chunga et al., 2017; 2019; Aviles-Campoverde et al., 2021). Several studies have documented vulnerabilities, damages, and also made proposals for improvements in awareness, education, early warning systems, as well as in the use of seismic and tsunami resistant temporal shelters (Celorio-Saltos et al., 2018; Chunga, K. & Toulkeridis, T. (2014; Del-Pino-de-la-Cruz et al., 2021; Edler et al., 2020; Matheus-Medina et al., 2016; 2018; Mato, F. & Toulkeridis, T. (2017; Rodríguez et al., 2016; 2017; Suárez-Acosta et al., 2021; Toulkeridis et al., 2017a; 2017b; 2018; 2019a; 2019b; Yepez et al., 2020). Since 1972, Ecuador has a monitoring organization named Oceanographic Institute of the Ecuadorian Navy (INOCAR) for oceanic processes and hazards. Also since 2019, the National Risk and Emergency Management Service (SNGRE) was created as an administrative unit at the ministry level to guarantee the protection of people and communities from the negative effects of natural or man-made disasters - which replaced the now extinct National Service of Civil Defense of 2007.

Immediately after the eruption/explosion of the Hunga Tonga-Hunga Ha'apai underwater volcano near Tonga, studies were initiated to review the situation in Ecuador, by studying and analyzing the information provided by the authorities, and anything else related that was published by different media reports or Internet sites. Also, the official information provided by INOCAR was communicated by the SGRE with thirteen consecutive statements beginning at 11:57 local time on the 15th of January 2022. The first statement informed the media (SNGRE, 2022a) that continuous monitoring of the Ecuadorian coast was being carried out.

Previously, there were three other media reports which provided general information regarding the activity of the underwater volcano. At that time there was no information about a possible tsunami. However, people residing or staying near Ecuadorian beaches reported receiving such information via Whatsapp™ or other personal exchange of messages, starting long before midday (around 11.00) local time, prior to official notifications.

At 12:37 local time - 39 minutes later - a second statement was issued, reporting that authorities were still under continuous monitoring of the volcanically-generated tsunami, and recommended the suspension of maritime and recreational activities on the island coastal zone regions until 3:00 p.m., and until 5:00 p.m. on continental Ecuador. At 14:02, - after 1-hour 39 minutes - a third statement was issued suggesting suspension of maritime and recreational activities on the coasts of the island regions. After this early official warning, the media also begun warning and alerting the public. The first response was the evacuation of bathers from the beaches of Crucita, La Boca, Pueto Cayo and elsewhere.

A fourth official statement at 15:04, - after 3 hours and 16 minutes - activated sirens in tsunami warning mode for Puerto Ayora in the Galápagos islands. This statement was communicated by the media at 15:28. Then, a fifth statement at 15:42 informed that the monitoring continued, but the sixth statement at 16:21, after 5 hours and 2 minutes, the tsunami warning for Puerto Ayora was canceled.

A seventh statement at 16:56, 5 hours, 51 minutes later, was of a tsunami warning for the country's mainland coast. At 17:24, after 6 hour 02 minutes, the media issued statements that the tsunami warning was cancelled. Subsequently, at 17:38, after 6 hour 38 minutes, there was also an official announcement of the tsunami warning cancellation. Afterwards the media provided general information about the cancellation of the warning, and provided information that in La Libertad (Santa Elena), Manta (Manabí), Esmeraldas, and Bahía Academia (Galapagos) sea level disturbances of 50 centimeters were evident (SNGRE, 2022b).

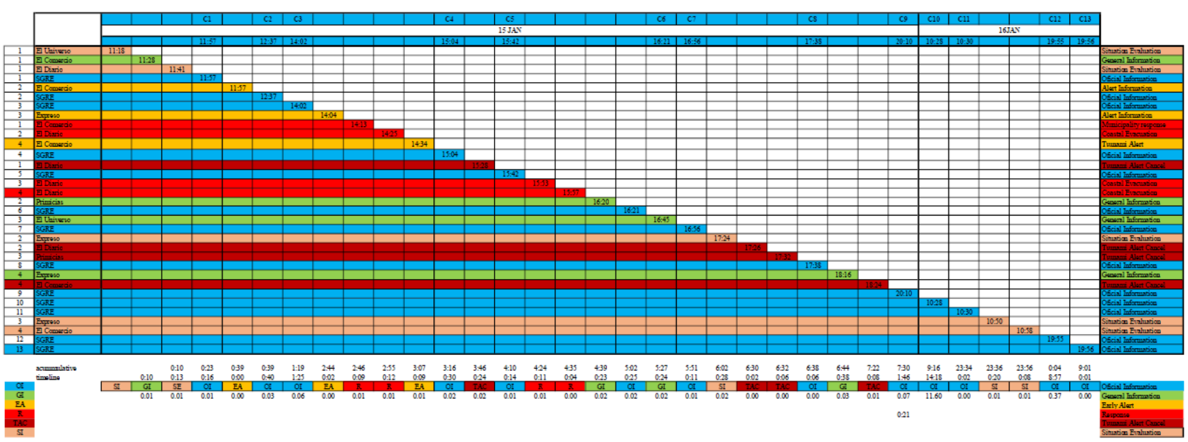

Figure 10. Timeline of transmission of information about the eruption in Tonga and consequences in Ecuador by the official institutions and national mass media.

The ninth official statement at 20:10 - after 7 hours 30 minutes - reported that the authorities were continuing to monitor the impact of the tsunami, while a tenth statement at 10:28, and an eleventh statement - after 9 hours 16 minutes and 23 hours 36 minutes -

recommended maintainance of caution in the execution of productive and recreational activities on the continental and insular coastal zones. Subsequently, the media followed with a commentary and evaluation of the situation.

A twelfth statement issued at 19:55 - after 1 day and 4 minutes - reported that authorities were still monitoring the event. However, a thirteenth statement at 19:56 - after 1 day 5 minutes – reported that the tsunami observation status was cancelled for the country's mainland and island coasts. In conclusion, the official information delivered with the 13 statements, combined with the information provided by the media, was provided every 21 minutes (Fig. 10 above).

In the Galapagos Islands, and as demonstrated by a variety of circulating videos, local fisherman and other boat-owners challenged or ignored the potential tsunami hazard of which they had been warned. Some of the smaller boats collided with each other while other boats tried to withstand with difficulty the power of the tsunami-generated sea currents. Locals in the area reported that there was unusual and repetitive tsunami wave activity that lasted for about two hours. Shown by many other circulating videos from a variety of touristic beaches in continental Ecuador, several vehicles of firefighters and policemen were patrolling along the coastlines warning people of the potential impact of a tsunami, at the expected time of the waves's arrival. However, tourists and locals alike ignored all warnings and stayed as close as possible to the beaches in order to film and photograph the incoming tsunami waves. Later, long after the arrival of the tsunami in many places in Ecuador, it appears that the sirens had scared the public and occasionally had let some to panicking. Such, but more severe reactions of the public in Ecuador, occurred with the earthquake and tsunami of 2016 (Mato and Toulkeridis, 2018; Toulkeridis et al., 2018).

3e. Peru

Peru is a country with a long shoreline, which has been struck frequently by tsunamis (Pelayo & Wiens, 1990; Bourgeois et l., 1999; Kulikov et al., 2005; Okal et al., 2006; Fritz et al., 2008; Omira et al., 2017). Awareness, preparedness, prevention and mitigation studies are advanced for this country, in order to reduce the vulnerability of tsunami impacts (Hébert et al., 2009; Yamazaki, et al., 2010; 2013; Mas et al., 2013; 2015).

The volcanic eruption of the Hunga Tonga-Hunga Ha'apai on 15 January 2022 near the island of Tonga in the Pacific Ocean, generated fear on the coast of Lima, where a false tsunami alarm was disseminated about abnormal waves on the coasts of the country. Initially the Peruvian Navy ruled out that a tsunami would strike, but later municipal officials intervened to evacuate people from coastal areas before the arrival of a possible tsunami. Soon thereafter, a local television station reported that dozens of tourists in the Lima district of Chorrillos evacuated, after receiving an alert from the Control Center of the Metropolitan Municipality of Lima (El Comercio, 2022). Also, the Directorate of Hydrography and Navigation of the Peruvian Navy indicated "a possible arrival of anomalous waves" to the Peruvian coast, generated by the eruption of the volcano near Tonga (El Pais, 2022).

At Pisco, in the southern region of Ica, the RPP News station reported unusual wave inundation, and that 38 stores located at the Chaco beach were affected by seawater entering restaurants and causing material damage (RPP Noticias, 2022). Other social media networks reported alterations in sea level at the Ancón resort north of Lima, and at Punta Negra, in the south of the Peruvian capital. The ASISMED - collectively made up of a team of specialists - indicated that a maximum wave height of 68 centimeters was recorded in the port of Callao, while in Marcona it reached 72 centimeters, and in Paita 65 centimeters. The National Institute of Civil Defense (INDECI) confirmed the presence of abnormal waves near the beaches (Prensa Libre, 2022).

The Navy, through the Directorate of Hydrography and Navigation, reported "constant monitoring" of sea levels after the volcanic eruption in Tonga, first on Twitter, stating that "the volcanic eruption in Nukualofa - Tonga, "DOES NOT GENERATE A TSUNAMI ON THE PERUVIAN COAST", and for all to "remain calm" (Marina de Guerra, 2022). However, during the night of that same date, dozens of national police agents (PNP) and crews of municipal workers from Paracas, began the construction of sand dykes along the Paracas bay, to contain the advance of waves.

The contradictory communications raised questions for the Government of Peru to explain the reason for the delay in issuing a tsunami warning that left two dead, since the Navy's warning of "anomalous waves" as a result of the eruption of the volcano in Tonga came late, unlike the warnings and evacuations in Chile and Ecuador.

Subsequently, the Peruvian Prime Minister, Mirtha Vásquez, requested a report from the Navy on the technical criteria for the issuance of a tsunami alert, after they had notified late on Saturday of "anomalous waves" from the eruption of a volcano in Tonga and hours later, two women drowned inside a van that was swept away by the tsunami waves near the shore of Naylamp beach (El Pais, 2022).

The INDECI indicated that there were also alerts for strong waves in other areas of the country, such as the coast of the Department of Ica, the sout-central part of the nation, although without registering victims. INDECI itself also communicated through its account on the social network Twitter that "in the event of abnormal waves in different areas of the Peruvian coast, sports and recreational activities should be avoided during the wave period, as well as camps near beach areas". They also reported that there was no damage in Paracas, Ica, due to the rise in sea level, however there was evidence of flooding and damage in 38 commercial premises, according to Mayor Juan Mendoza to the Radio Programas del Perú radio station (INDECI, 2022). Meanwhile, the PNP reported on Twitter that its troops "rescued 23 people after the first reports of abnormal waves on the Peruvian coast," without specifying under what circumstances or conditions (Swissinfo, 2022).

On the same day, the Peruvian Government announced that it had closed preventively 22 ports on the north and central Pacific coasts of the country because "anomalous waves" were expected from the eruption of the Hunga Tonga-Hunga Ha'apai volcano in Tonga. Also on the same day, there was a report that exceptional waves, mainly on the southern coast of the country, caused slight flooding in some coastal towns, and that more than 20 people had been rescued and that two women lost their lives at Naylamp beach of the Lambayeque region of the Peruvian north coast, where 2.5 meter high tsunami waves struck. The authorities added that the beach area was already declared "not suitable for bathers." (TelesurTV, 2022).

INDECI decreed on Monday the 17th the closure of 80 ports on the Peruvian coast, after registering disturbances higher than usual waves, as a consequence of the volcanic eruption of January 15, near Nukualofa, Tonga. Some of the temporarily closed port points were, in the ports of Pizarro, Zorritos, Paita, and Pimentel on the north coast; the ports of Chimbote, Casma, Huarmey, Chicoon along the central coast; and Puerto Viejo, Planchada, Quilca, and El Faro in the south (El Universo, 2022). The Peruvian Navy notified the suspension of fishing, sports and recreational activities near the sea.

The tsunami from Tonga caused an oil spill that affected two natural parks in Peru, for which the Government requested technical support from the United Nations to assess the impact and response measures spilled (NBCNEWS, 2022).

The Civil Defense indicated that the spill was controlled, and there was ongoing cleaning of the coast, in conjunction with the La Pampilla refinery off the Pacific coast of Peru, managed by Repsol, and by the ship "Mare Doricum". Therefore, the authorities closed the recreational facilities near the spill to protect the tourists. The Environmental Prosecutor's Office indicated that a dense oil stain was observed on the beach of Ventanilla, located on the coast of the Peruvian capital (Voz de América, 2022).

3f. Chile

Chile has the longest shoreline of all Pacific countries and represents therefore the most frequented impacted coast by tsunamis in the recorded past (Lomnitz, 2004; Yamazaki & Cheung, 2011; An et al., 2014; Carvajal et al., 2017; DePaolis et al., 2021). The strongest ever-recorded earthquake with Moment magnitude Mw 9.5 occurred in Chile and generated a tsunami, which resulted in many deaths on both sides of the Pacific Ocean (Plafker & Savage, 1970; Liu et al., 1995; Cisternas et al., 2005). Nonetheless, Chile has a very advanced system of preparedness and mitigation (Atwater et al., 1999; Esteban et al., 2013; León & March, 2014; Catalan et al., 2020). Therefore, both the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) and the National Emergency Office of the Ministry of the Interior and Public Security (ONEMI), responded effectively to the tsunami advisory/warning issued by the Pacific Tsunami Warning Center (PTWC) at 01:27 (local time in Chile) on Saturday, on 15 January 2022 of a volcanic eruption of the Hunga Tonga-Hunga Ha'apai volcano 73 kilometers north of Nukuʻalofa, in Tonga

Given this information, and in accordance with the ONEMI – SHOA protocol, a State of Alert was declared in Chile for the regions of Coquimbo, Tarapacá, Atacama, Arica, Parinacota, Los Ríos and Los Lagos, and an Advisory of Precaution for the regions of Maule, Ñuble, Antofagasta, O'Higgins, Biobío Valparaíso and La Araucanía, adding also the Antarctic and the insular territory (ONEMI, 2022a). A forecasted tsunami height was that tsunami waves of one to two meters could be expectedto be above one and below two meters.

For its part, ONEMI declared a Red Alert for the coastal districts of the Arica and Parinacota, Tarapacá, Atacama, Coquimbo, Los Ríos and Los Lagos regions, and issued messages from the platform of the Emergency Alert System (SAE), addressing the communities of the coastline and island territories of the aforementioned regions (ONEMI, 2022a). Additionally, ONEMI quickly disseminated the information through social media networks (such as Twitter https://twitter.com/onemichile/with_replies), at 08:39 on January 15, 2022, reporting on a State of Precaution decreed by SHOA (Fig. 11).

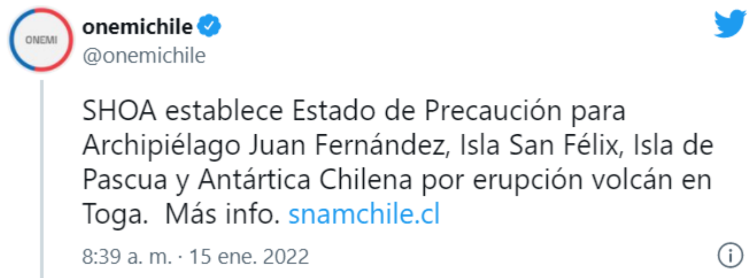

Figure 11. Tweet sent by ONEMI on state of caution.

Figure 12. Recession of the sea on the coast of Coquimbo in Chile (La Cuarta, 2022b).

In turn, throughout the day, the main press media in Chile, reported on the decisions being taken about the event prior to its impact in Chile, and informed the public to evacuate the beaches of Easter Island due to a "minor tsunami" (El Mercurio, 2022a; La Cuarta, 2022a). Furthermore, in its official Twitter account the Geoscientific Network of Chile, indicated that the tsunami had reached Rapa Nui, that the island's tide gauge had registered up to 30 cm in height, and also estimated that waves would reach Easter Island at 10:43, at 08:43 a.m. the continental and insular-western Chile, respectively, the Juan Fernández at 2:12 p.m., the Antarctic Base Prat at 2:26 p.m., San Félix at 2:38 p.m., and the Antarctic Base O'Higgins at 2:56 p.m. (El Mercurio, 3:01 p.m.) (El Mercurio, 2022b). Later in the afternoon, the Chilean Geoscientific Network disseminated the first images of the recession of the sea on Chilean beaches (Fig. 12), and of what was happening in other coastal regions of the country (La Cuarta, 2022b). Finally, on the night of 15 January 2022, ONEMI summarized what was happening and indicated that there were minor flooding in several coastal areas - such as Iquique - and reiterated the advisory for the public to move to safe areas (La Cuarta, 2022c).

In the early hours of January 16, 2022 (00:07 local time), SHOA, through Bulletins No. 26 and 27, reported that the threat levels had decreased for the coastal communities of Arica, Parinacota and Atacama, canceling the tsunami red alert, although a State of Precaution was maintained for coastal regions of Arica, Parinacota, Tarapacá, Antofagasta, Atacama, Coquimbo, Valparaíso, O'Higgins, Maule, Ñuble, Biobío, La Araucanía, Los Ríos and Los Lagos, adding also the insular territory (Fig. 12; ONEMI, 2022b). Already on 17 January, SHOA asserted that this volcanic eruption was an unprecedented event, since it was the first time that such an event generated a tsunami alert in the entire territory of Chile (El Mercurio, 2022c). During the alert period (January 15 and 16, 2022), no victims were registered, since all inhabitants evacuated the threatened areas on time, according to local media reports (La Cuarta, 2022d), and unlike Peru where two people died, and the three f victims in the Tonga region.

4. CONCLUSIONS

Tsunamis generated by volcanic activity are not frequent as by earthquake related events. However, the same amount of attention must be given to volcanically-generated tsunamis in order to forecast potential impacts on shorelines in the Pacific and elsewhere.

The Hunga Tonga-Hunga Ha'apai submarine eruption triggered a tsunami, which had most likely a complex interaction of factors responsible for its development and propagation.

Authorities along the southeastern side of the Pacific Ocean, between Costa Rica and Chile, reacted differently to the announcement of a potential tsunami impact on their shorelines. It is unclear yet, why Colombia and Peru did not issue any warning to the public, although both countries have sophisticated institutional mechanisms and had sufficient time to react and warn.

Therefore, it is certain that alerts and early warning systems need to be re-evaluated and re-adjusted in different degrees per country along the Pacific and Latin America in particular, based on what occurred on 15 January 2022, following the eruption of the Hunga Tonga-Hunga Ha'apai submarine volcano.

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