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EDITORIAL

Overview of the Hunga Tonga-Hunga Ha'apai Volcanic Eruption and Tsunami

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INTRODUCTION

Over the past two decades, tsunamis around the world have caused more casualties than any other natural hazard. The highest number of casualties were caused by the Indian Ocean tsunami of December 2004, spanning 14 countries. Indonesia, Sri Lanka, India, and Thailand were massively hit and reported extensive damage to lives and properties. The great tsunamigenic earthquakes usually occur at subduction zones. The surface of the earth is broken into large tectonic plates. The dense oceanic plate is forced to move under the less dense continental plate or another ocean plate to form a subduction zone at convergent plate boundaries. Around ~80% of tsunamis are caused by undersea earthquakes at megathrust faults of subduction zones. The other causes that can trigger tsunamis are coastal or submarine landslides, flank collapse due to volcanic eruption and meteorite impact. Though only ~ 5% of tsunamis are caused by volcanic eruptions, the limitations of current warning systems in detecting tsunamis triggered by such non-seismic sources called "Atypical Sources" make them more threatening.

The movement at the connecting surfaces of two tectonic plates provides an escaping pathway to hot molten rock, from deep down to reach the surface, to form volcanoes. Usually, "the island arc" type of volcanoes is formed at the subduction zone where both tectonic plates are of the ocean, and "the continental-margin" type of volcanoes at the junction of the ocean and the continental plates, creating mountain belts. These volcanic chains form an arcuate belt across the Earth's surface, such as the "Ring of Fire" of the Pacific Ocean.

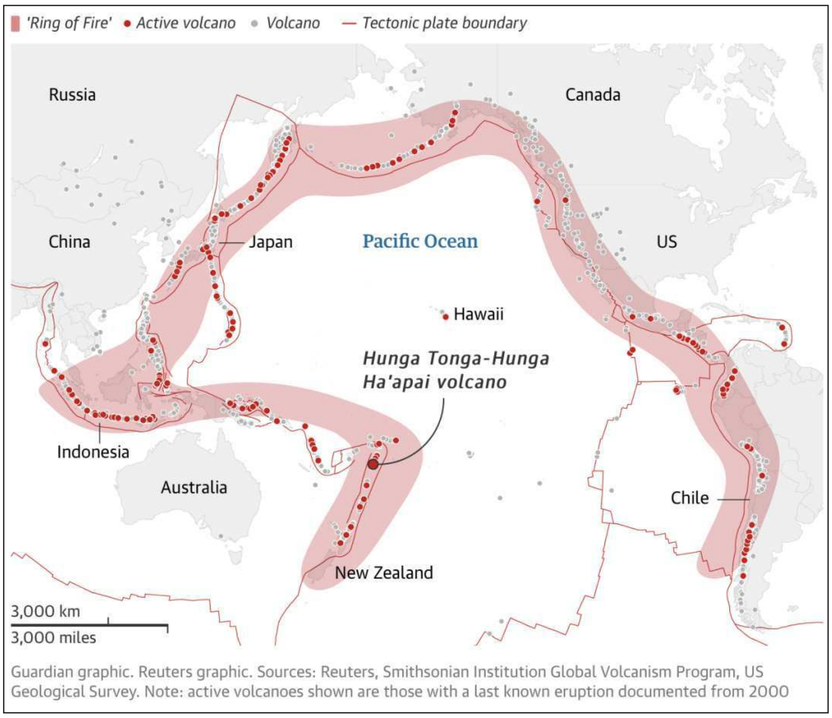

Fig.1. Arcuate belt of volcanoes across "Pacific Ring of Fire" (source: The Guardian)

On 15th January 2022, a large eruption of the undersea volcano of the Kingdom of Tonga, a part of the arc of volcanoes of the "Ring of Fire", generated a tsunami triggering evacuations at local and regional scales in the Pacific Ocean (Fig.1). Tsunami waves of more than one meter were recorded at several coastal gauges of the surrounding countries, and the damage to lives and properties is still being assessed.

Similarly, in the Indian Ocean, on 22nd December 2018, a tsunami was triggered in Indonesia due to the collapse of the Anak-Krakatau volcano, causing at least 430 casualties and massive damage to the surrounding coastal regions (Zengaffinen et al., 2020, Grilli et al. 2019). In the same year, on 28th September, a crustal earthquake of magnitude 7.5 triggered submarine landslides generating a tsunami in the Palu Bay of Sulawesi, Indonesia, that killed at least 2100 people (Widiyanto et al. 2019, Omira et al., 2019). These two events brought to the spotlight the importance of monitoring tsunamis triggered by "Atypical sources", and when warning systems around the world are still working on a monitoring mechanism, the Tonga tsunami accentuated the urgency.

THE HUNGA TONGA-HUNGA HA'APAI VOLCANIC ERUPTION

The Tonga archipelago consists of around 170 islands, of which only 36 islands are inhabited. Located in the South Pacific Ocean, about 2,000 km to the northeast of New Zealand, the neighbouring countries of the Kingdom of Tonga include Samoa to the north, the Cook Islands to the east and Fiji to the west. The country's total surface area is about 750 km² and is divided into three main groups, namely Vava'u, Ha'apai, and Tongatapu. The Hunga-Tonga-Hunga-Ha'apai volcano of the Tonga archipelago consists of two small uninhabited islands, Hunga-Tonga and Hunga-Ha'apai, which were about 2 km apart. The undersea volcano is located approximately 65 km from the capital of Tonga, Nuku'alofa. Though the island looks very small, about 100 m, the bathymetry reveals the actual massive volcano of around 1800 m high and 20 km wide with 150 m caldera hiding below (Fig.2).

The Hunga-Tonga-Hunga-Ha'apai volcano has erupted several times in the past. The first historical observation was made in 1912; later eruptions were in 1937 and 1988. On 18 March 2009 Tonga eruption was captured by NASA's Terra satellite. After the eruption, it was observed that a small part of the land was added to Hunga-Ha'apai and the two islands were about 2 km long. An eruption during December 2014-January 2015 was centred between the islands and combined

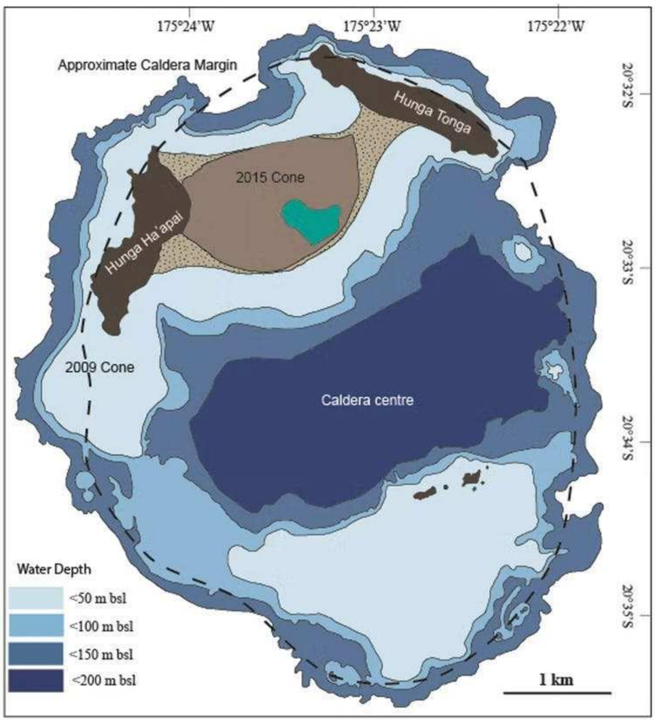

Fig.2. Seafloor mapping of the undersea volcano (source: Cronin, 2022)

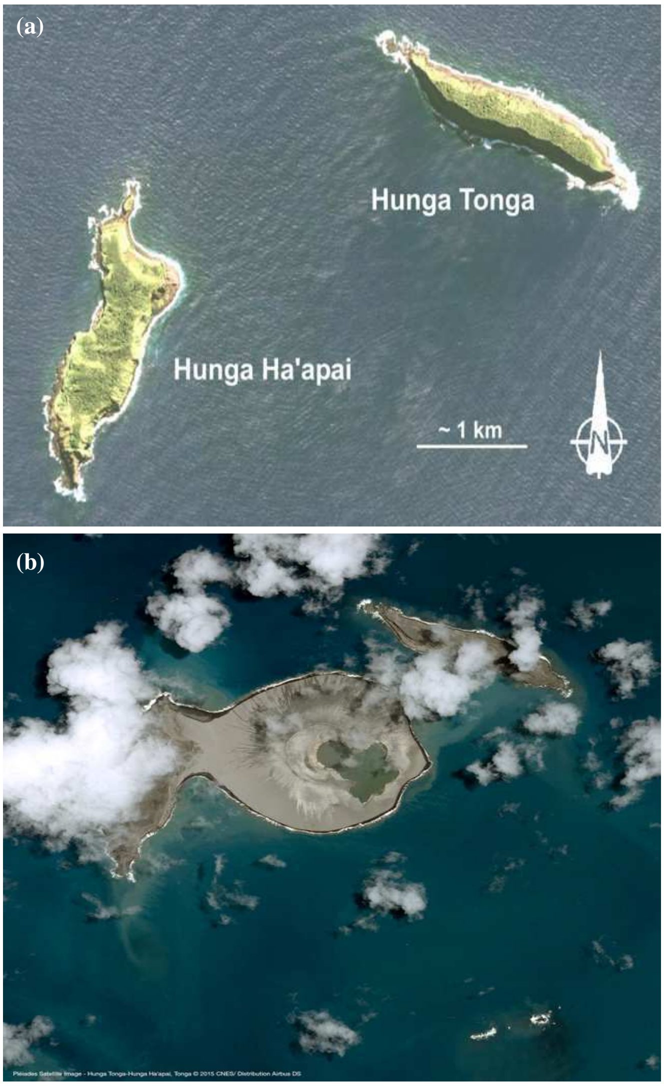

Fig.3. (a) Hunga Tonga (left) and Hunga Ha'apai (right) before the eruption. Courtesy of Brad Scott, GNS Science. **(b)** CNES Pléiades satellite image showing the new crater connecting both islands (source: Global Volcanism Program, 2022).

them into one larger structure (Fig.3) (Source: Global Volcanism Program, 2022).

After the 2015 eruptions, the undersea volcano was inactive for a while and resumed explosive eruption on 20th December 2021. The steam-rich gas and ash plume rose to 12 km, and eruption continued intermittently until 4th January 2022. Steam and gas plumes visible in satellite data occasionally, and ash eruption ceased significantly. However, on 13th January 2022, the more explosive eruption was observed, producing mushroom-shaped ash, steam, and gas plumes that rose as high as 20 km. The eruption triggered Tonga Meteorological Services (TMS) to issue tsunami marine warnings for surrounding areas instructing residents to stay away from low-lying coastal areas, reefs, and beaches. At 2000 Hrs on 14th January (local time) a minor tsunami of 20 cm was observed by Tonga Meteorological Services at the Nuku'alofa tide gauge, which is located at the north coast of Tongatapu island.

Significant explosive eruptions in late 2021 initially reshaped the central part of the combined island before stronger activity

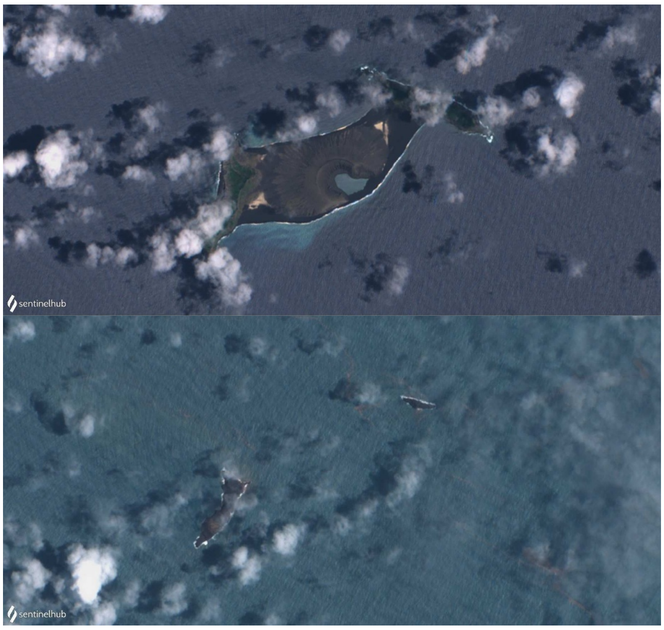

Fig.4. Images obtained by the SENTINEL-2 satellite on December 18, 2021 (top) and January 17, 2022 (bottom) of the Hunga Tonga-Hunga-Ha'apai. The volcanic cone no longer exists, it was destroyed on January 13. The great explosion of January 15 destroyed much of the two islands. (source: Twitter @HungaTongaInfo)

in mid-January 2022 removed most of the 2014-15 material; an even larger eruption the next day sent an eruption plume high into the stratosphere, triggered shock waves through the atmo-sphere and tsunami across the Pacific Ocean, and left only small remnants of the islands above the ocean surface (Fig. 4). Though the Hunga Tonga-Hunga-Ha'apai volcano had erupted in 2009 and 2014-15 and changed the landscape of the volcanic island over the past few years, the scale of eruptions was very small compared with the 15^{th} January 2022 eruption with ash plume plunging into the sky about 30 km high.

The massive eruption of the Hunga Tonga-Hunga Ha'apai occurred on 15^{th} January 2022 around 0415 UTC with numerous sonic booms and a powerful shock wave. According to Wellington Volcanic Ash Advisory Centre (VACC) and other satellite data analysis, the plume may have risen to 30 km, and the top of the diameter was at least 600 km. The significant amount of ash obscured the sky and rained down, covering most of the surrounding islands. The loud boom due to violent explosion was heard in the capital city of Nuku'alofa, which is 65 km away from the undersea volcano, and it was heard clearly in other nearby countries Samoa, Fiji, Niue and Vanuatu. The sonic boom was heard as far away as in New Zealand, Alaska and Canada and low-frequency noise was recorded at infrasound stations. The massive shockwaves that followed the eruption travelled around the globe, and the propagation was captured very clearly by satellites such as GOES-17 (Adam, 2022). The pressure wave blasted through air travelled more than 1000 km per hour and was observed across half of the world by weather stations including New Zealand (Fig.5), the United Kingdom, Europe, Japan and India. The measurements from Japan and Utah reported the shockwave as it circled the earth as many as four times (source: Twitter @cataclasite).

The massive explosion sent ripples through the atmosphere and was described as a once-in-a-thousand-year event for the Hunga Caldera, with earlier evidence occurring in AD200 and AD1100 (Cronin et al., 2017). The United States Geological Survey (USGS) calculated the preliminary magnitude of the events as 5.8 using techniques calibrated for earthquakes (source: USGS). Around 105 earthquakes of magnitude, more than 4 mb were recorded within the radius of 250 km of the event during the period of 20 December 2021 to 07 January 2022, signifying the active seismicity in the region.

TSUNAMI OBSERVATIONS

The Hunga Tonga-Hunga Ha'apai volcanic eruption generated a tsunami that caused damage across the Pacific Ocean. Although infrequent, there are several different reasons that volcanic eruptions can generate tsunamis, such as the sudden collapse of the caldera of the volcanic island, massive submarine landslides or the force of pyroclastic flows generated by the eruption. However, the reason for the huge tsunami in the Tonga region, its regional expansion and impacts are yet to be analysed. Also, it is interesting to note that the atmospheric disturbances during the massive eruption were coupled with shallow ocean surface and created small tsunami waves as far away as in the Caribbean Sea, Azores and Madeira in the Atlantic and Mauritius in the Indian Ocean.

Several tsunami wave measurements were reported from 26 countries from the Tonga event. The maximum wave heights were reported in Tonga, Chile, New Caledonia and Vanuatu, with waves reaching greater than 1 meter in amplitude. Many other countries reported tsunami waves of more than 30 cm triggering tsunami advisories to the coastal communities with instructions to stay away from beaches and low-lying coastal areas. The tsunami travel times map of the Tonga event, considering source as earthquake is plotted using TsuDig software (Fig.6).

After the explosion around 0415 UTC, confirmation of

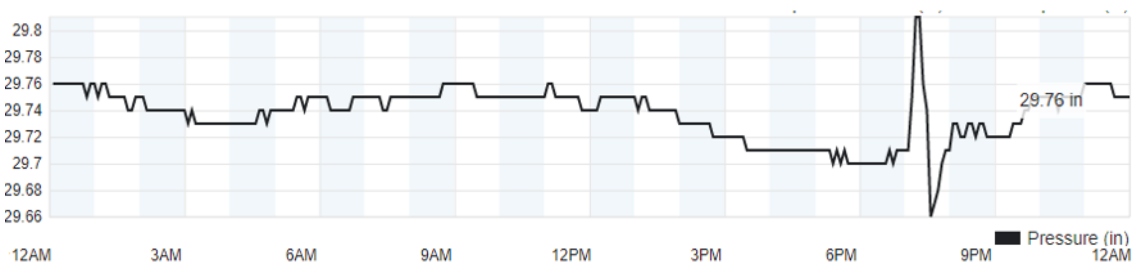

Fig.5. Pressure data of Auckland, New Zealand on 15^{th} January 2022 (Source: Weather Underground)

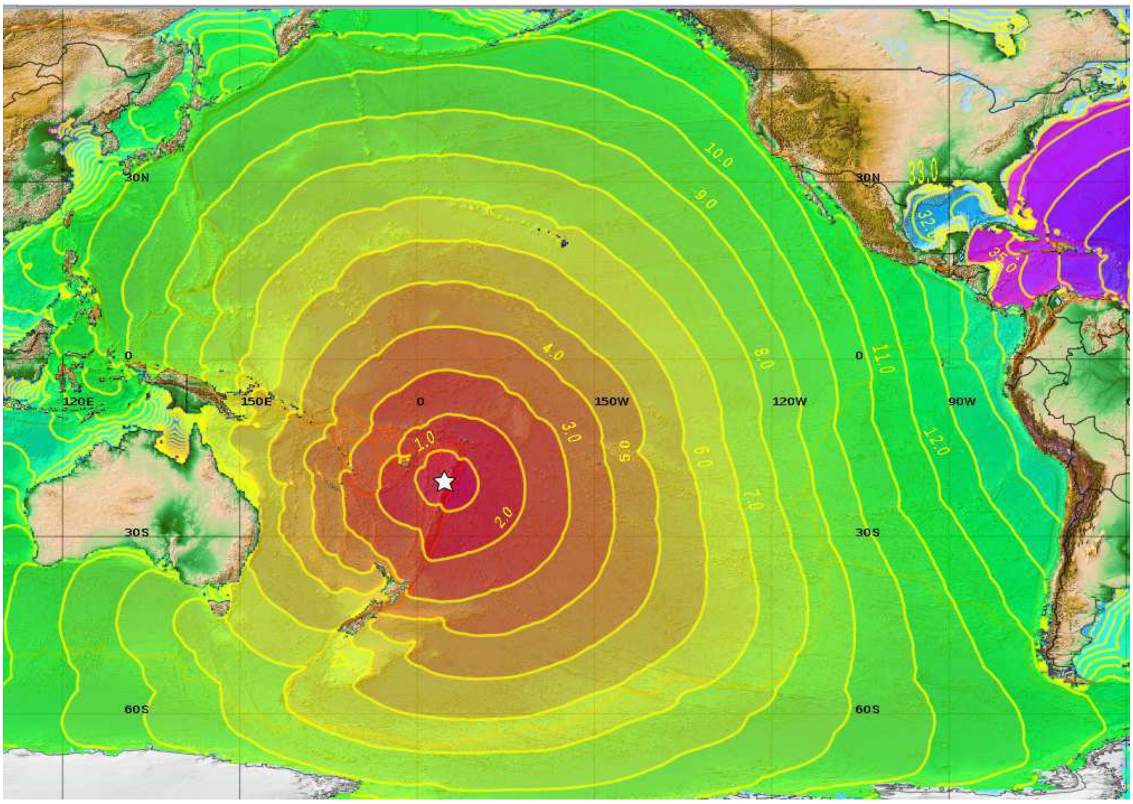

Fig.6. Tsunami Travel Times from source

tsunami generation came from the first observations of Deep-ocean Assessment and Reporting of Tsunamis (DART) followed by tide gauge from the capital city of Nuku'alofa. Later, the surrounding island countries Fiji, American Samoa, Vanuatu, Niue and New Caledonia also started reporting flooding due to tsunami, with waves reaching more than one meter in some regions. On 18 January 2022, the consulate of the Kingdom of Tonga (source: Twitter @ConsulateKoT) confirmed the tsunami wave heights reaching up to 15 m struck the west coast of Tongatapu Islands, 'Eua, and Ha'apai islands.

New Zealand and Australia have also reported damages to structures and boats in their respective ports and harbours. Many areas such as Great Barrier Island, Hokianga Harbour and Port Taranaki in New Zealand and Norfolk and Lord Howe Islands of Australia observed high waves of more than 1 m and disturbances lasting several hours (Fig.7).

Tsunami observations of about 0.15 to 0.50 were reported in Russia, Taiwan and South Korea, while some coastal regions in Japan, USA, Peru and Chile reported tsunami waves of more than 1 m. About 0.3 m wave was observed in Nikolski, Alaska region. Chile and Mexico regions also observed more than 1 m tsunami waves and significant damage to ports and harbours was reported in both countries. The maximum wave in Japan was about 1.2 m in Amani city of Kagoshima and in other locations more than 0.5 m.

It is also noteworthy that the tsunami waves reached some of the coastal regions in the Pacific basin earlier than expected travel times. In Japan, the waves were detected 2.5 hours earlier than the predicted time and even in Australia, the initial disturbances were found around 3 hours early. Similar observations were made by a few other agencies which are yet to be analysed. However, as it was already said, the interaction of pressure waves (which travelled much faster than the tsunami wave) with the shallow ocean possibly created tsunami in faraway regions. Hence it may be a reason for earlier detection of tsunami waves on several tide gauges (Titov et al., 2022).

Following the 26th December 2004 tsunami, international initiatives led to the establishment of the Inter-governmental Coordination Group (ICG) for Indian Ocean Tsunami Early Warning and Mitigation System (IOTWMS), North-Eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS), and Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (CARIBE-EWS) under the auspices of UNESCO/IOC, in addition to the already functional Pacific Tsunami Warning and Mitigation System (PTWS). All the regional warning systems operating under ICG operate as "system-of-systems' (IOC-UNESCO). The current warning systems are built on the basis of detection of seismic origin tsunamis, which is characterizing the subduction zone earthquakes and estimating their tsunamigenic potential. Non-seismic sources that trigger tsunamis are yet to be effectively addressed by the warning systems, though Palu and Sunda strait tsunamis of Indonesia in 2018 triggered several actions in this direction. The efforts of early warning centres to develop SOPs to handle tsunamis from non-seismic sources came handy during the Tonga event. Warning services were initiated in the PTWS using sea-level observations. GNS Science (2022) reported the critical nature of data from the DART network in monitoring the Tonga tsunami.

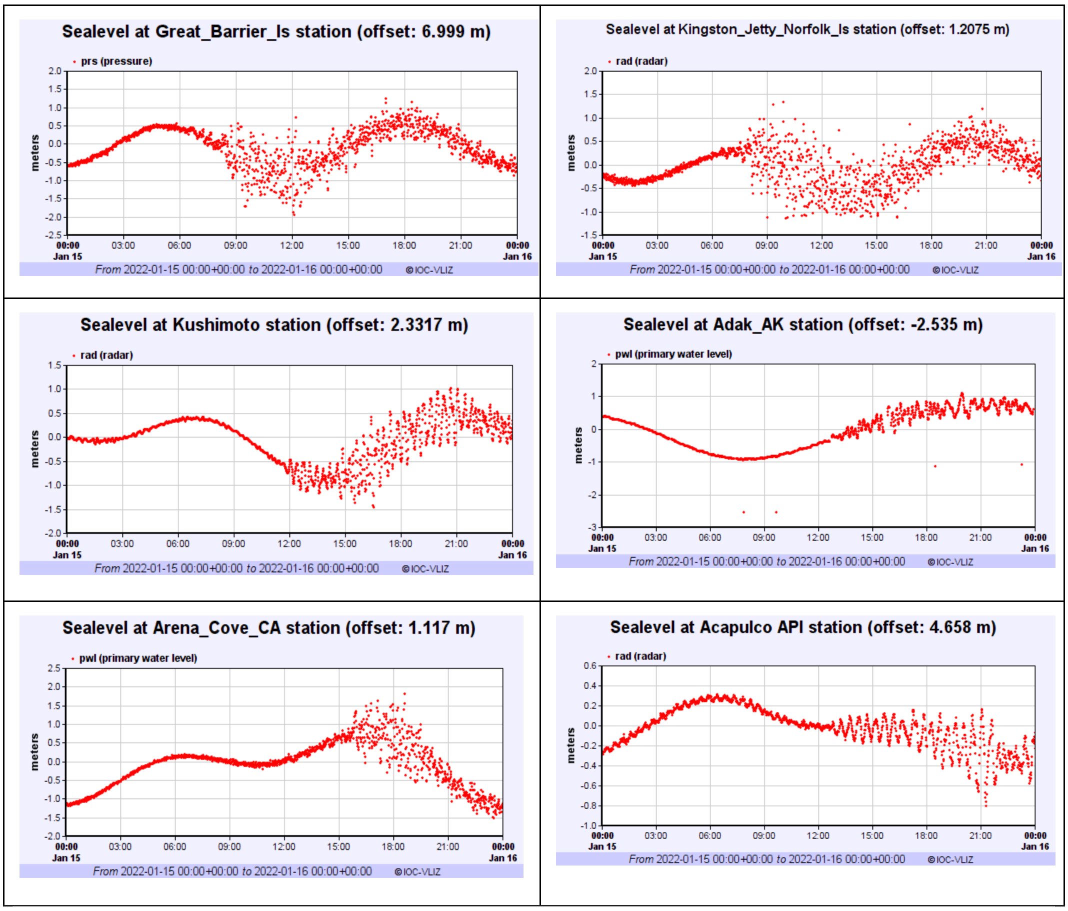

Fig.7. The tsunami observations from IOC sea level station monitoring facility during January 15-16, 2022 around the Pacific basin (Source: http://www.ioc-sealevelmonitoring.org/)

As tsunami warning is a race against time, early detection and warning are very crucial, especially for near-source regions where the response time is only a very few minutes. Due to the complex nature of tsunami sources, uncertainties at the initial stages influence the correctness of warnings. To effectively address uncertainties in tsunami warning, there is a need for enhancing hazard / risk assessments, improving monitoring technologies and strengthening community preparedness (Angove et al., 2019).

CONCLUSION

In the recent past, tsunamis triggered by volcanic eruptions were confined to local damage. Only a very few events such as the 1792 eruption of Mount Unzen in Japan, 1883 eruption of Krakatau in Indonesia and 1980 eruption of Mount St. Helens in the USA, created huge tsunami waves. Evidences of a large tsunami that hit the east coast of Australia and a ~30 m wave inundation signatures in Tongatapu island were found which are dated back to mid-15th century (Lavigne et al., 2021).

The information about previous eruptions lies in geological deposits, in order to understand the complex sequence of caldera formation and explosive eruptions, we need to explore the seafloor with advanced technology and analyse the data with improved procedures. It is important to identify and characterize submarine active and dormant volcanoes that may create huge damage in future. Risk assessment studies need to be carried out to estimate future damage based on past and probable events. Also, we need to develop numerical modelling capability to estimate tsunami travel times and amplitudes by simulating volcanic eruptions.

Observation networks play a crucial role in the early detection of tsunamis. For detection of tsunamis from non-seismic sources, direct measurement of sea level through denser networks of tsunami buoys and tide gauges near the source regions is extremely important. The observation network needs to be densified at least around active volcanic regions for early detection of tsunami generation. Real-time sea-level anomaly detection can act as a critical trigger for early warning centres for monitoring tsunamis generated by non-seismic sources. Community awareness and preparedness activities, such as developing risk knowledge and self-evacuation practices play an important role in saving lives especially for near-source events which need a quick response. The UN Decade of Ocean Science for Sustainable Development (2021-30) is a great opportunity for wide stakeholder collaboration to address critical gaps in global end-to-end tsunami warning capabilities.

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