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Implementation of tsunami warning procedures in the Caribbean in case of a volcano crisis : use of a Volcano Notice for tsUnami Threat (VONUT)

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Abstract

While 80% of tsunamis are related to earthquakes, recent examples of the Hunga Tonga Hunga Ha'apai (2022) tsunami as well as others from the Kick'em Jenny (2015), Saint Vincent (2021) and La Palma (2021) eruptions have sparked renewed reflection on how a tsunami warning system could also handle non-seismic tsunami events. A warning system is usually based on intrinsic and automatic detection by an instrumental network. In the case of tsunamis generated by earthquakes, it is the data from seismic stations, and pre-established location and magnitude criteria that trigger actions from the Tsunami Service Providers (TSP, ie, regional centers for threat information). Realtime sea level data then help constrain forecasts and determine the end of the threat. However, tsunamis generated by volcanic events are different from those induced by earthquakes in terms of source, detection, messaging and modeling. In the Caribbean and Adjacent Regions, the UNESCO/IOC Intergovernmental Coordination Group for Tsunami and other Coastal Hazards Warning Systems created a Task Team to develop tsunami procedures in the case of a volcano crisis. We present here recent progress of the Task Team. A bulletin is proposed to be issued by volcano observatories to the Tsunami Service Providers in the case of a potentially tsunamigenic volcano event. Derived from a Volcano Observatory Notice for Aviation (VONA) bulletin, this proposed VONUT bulletin, (Volcano Observatory Notice for tsunami Threat), is under construction in collaboration with Caribbean volcano observatories and the Pacific Tsunami Warning Center, the TSP for the Caribbean. It was tested during the annual tsunami exercise CARIBE WAVE 2023, which includes testing the communications between the Tsunami Service Provider and nationally designated tsunami authorities. However, much more work is required to get a full operating warning system, as volcano scenarios and subsequent tsunami waves remain highly challenging to model and scale.

Keywords

Caribbean, tsunami, volcano, Volcano Observatory, VONUT, CARIBE-EWS

Statements and Declarations

Competing interests The authors declare that they have no known competing financial interests.

Introduction

Following the 2004 Indian Ocean tsunami, the Intergovernmental Oceanographic Commission (IOC) of UNESCO established in 2005 the Intergovernmental Coordination Groups for Tsunami and Other Coastal Hazard Warning System for the Caribbean and Adjacent Region (ICG/CARIBE-EWS) as well as two other systems in the Indian Ocean, the Mediterranean, and Northeastern Atlantic. These systems were based on the model of the Pacific Tsunami Warning System established in 1965 after the 1960 Chilean earthquake. ICG/CARIBE-EWS (UNESCO, 2005; von Hillebrandt-Andrade, 2013) currently comprises 32 Member States and 16 Territories (which we will be referred to as Member States in the rest of the text) in the Caribbean and is structured around 4 Working Groups (WG): WG1 Risk Knowledge, WG2 Tsunami Detection, Analysis and Forecasting, WG3 Tsunami Warning Dissemination and Communication; WG4 Preparedness and Response Capabilities), and specific Task Teams, such as the Task Team on Tsunami Procedures in Case of Volcano Crisis (2016-2023).

The existing Early Warning System (EWS) in the Caribbean was designed for earthquake-generated tsunamis and is based on two components, the upstream alert (detection and decision making) and the downstream alert (authority and public response) (e.g., Wächter et al., 2012), taking place after the occurrence of a tsunamigenic event, its detection and analysis, issuance of information or warning messages, and the evacuation of people located in a coastal area at risk. However, the full operating EWS (Fig 1) also depends on hazard mapping based on the knowledge of tsunami sources, on the acquisition of high resolution bathymetric and topographic data, on procedures of dissemination of information to all stakeholders and populations, and finally on evacuation plans. This implies achievement of evacuation maps, signage deployment, and over all these prerequisites, the indispensable public awareness and preparedness.

In the case of a tsunami generated by an earthquake, the EWS is activated automatically by strong seismic waves detected by seismic instrumentation transmitting in real time. The Tsunami Service Provider (TSP) analyzes the earthquake data and calculates the event parameters (location, depth and magnitude) using the data contributed to the CARIBE-EWS seismic network (McNamara et al., 2016). Depending on pre-established criteria, it issues and disseminates pre-formatted messages to each Member States including an estimation of the tsunami arrival time for various locations. After the initial message, the TSP issues messages with an initial estimation of expected sea level height above current tide level, which is complemented in following messages by observations from sea level stations. It is important to note that the data from sea level stations are not used for the initial message but are used to recalibrate models, confirm a tsunami generation (and its end), arrival times and wave heights. Another important point to mention in the case of a tsunami generated by an earthquake is that for any real event, a composite scenario can be constructed as a linear combination of existing pre-computed scenarios, because wave heights at forecast points can be obtained directly using the linearity of wave dynamics (Titov et al, 2005). Once the messages from the TSP have arrived in each Member States at the Tsunami Warning Focal Point (TWPF), a national 24/7 institution, then for national sovereignty reasons it is a National Tsunami Warning Center (NTWC) that is in charge of interpreting the TSP messages and other available data, and deciding whether or not to issue information or alert and evacuation messages within its territory. In many cases, the NTWC is also the disaster management organization.

UNESCO/IOC CARIBE-EWS

Tsunami Warning System for the Caribbean and Adjacent Regions

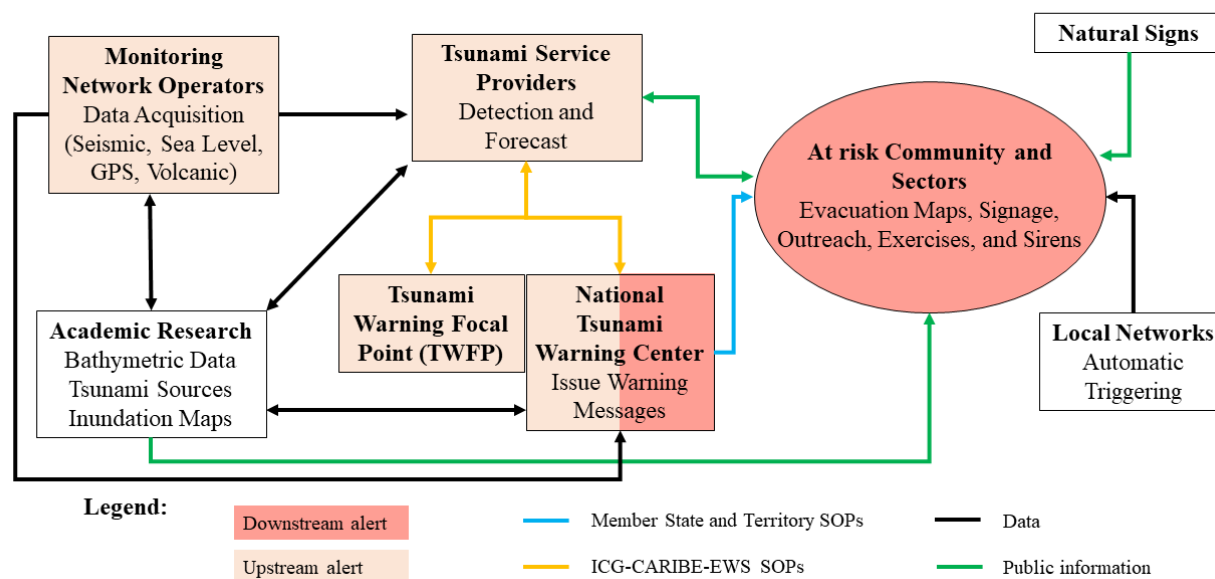


Fig. 1: Schematic representation of the organization of the Caribbean Early Warning System, currently used for earthquake-generated tsunamis. The upstream alert begins with the detection of a tsunamigenic event through seismic networks whose data are processed by the TSP that send messages to each Member States Tsunami Warning Focal Point. Each Member States National Warning Center decides its actions, including the information to the population at risk. Academic research is involved in data acquisition (such as high resolution bathymetry and topography) used to perform tsunami modeling, risk mapping, inundation maps and evacuation maps. Authorities are in charge of the deployment of signage, sirens, preparedness and education, with the support of the Caribbean and the International Tsunami Information Centers (CTIC and ITIC).

In the case of a tsunami generated by non-seismic sources, most of the above procedures are not valid. Non-seismic sources, i.e., volcanic eruptions, pyroclastic density currents (PDC), lahars, aerial or submarine landslides, do produce large seismic signals, but even when it is possible to compute a magnitude, it is well below the M6 threshold used in the case of tectonic earthquakes by the TSP. Thus, strong seismic waves cannot be used to activate the EWS. In this paper, we present a solution that has been tested during the CARIBE WAVE 2023 exercise to address this problem.

Context

13% of historical tsunamis reported in NOAA's National Centers for Environmental Information (NCEI) Global Historical Tsunami database, are generated by non-seismic mechanisms, and 5% by volcanic eruptions (NCEI/WDS 2023; NEIC-ITIC 2022). The tsunami triggered by the Hunga Tonga Hunga Ha'apai eruption of January 15, 2022, was the most recent to be observed worldwide, including in the Caribbean and adjacent regions. This event as well as the recent eruptions of Kick'em Jenny (2015), Saint Vincent (2020) and La Palma (2021) reinforced the need for a tsunami warning system that can handle such non-seismic events.

Historical tsunamis generated by volcano eruption

In the Caribbean, historical records of tsunamis are limited to the last five centuries. Of the 59 tsunamis reported as “probable” or “definite” in the NCEI/WDS database (Dunbar et al. 2008; NOAA, NCEI/WDS 2023), 16 tsunamis of these were generated by volcanoes (Table 1), representing ~27% of the total events. Even if we include the questionable tsunamis in the NCEI/WDS database, the percent of tsunamis generated by volcanoes would be ~18% in the Caribbean, which is higher than the 5% reported worldwide.

To those in the NCEI/WDS database, we added in Table 1 two tsunamis resulting from violent eruptions of Mount Pelée, Martinique, during the 1902-1905 eruption. They are described in detail in Lacroix (1904), one occurring the 6th of June and the other the 9th of July 1902. In both cases, they were generated by pyroclastic density currents (PDC) reaching the western coast, and were recorded in Fort-de-France as 5-minutes period oscillations of the sea, with more than 1-m amplitude. It is important to highlight that Lacroix (p496-502, 1904), when reporting the 6 detailed descriptions of tsunamis associated with 1902 eruption, indicates that all the proximal eruptive phases lead to sea movements, beginning by a sea retreat, followed by 5 to 6 undulations separated by ~5 minutes, and observed all over the western coast of Martinique down to Fort-de-France.

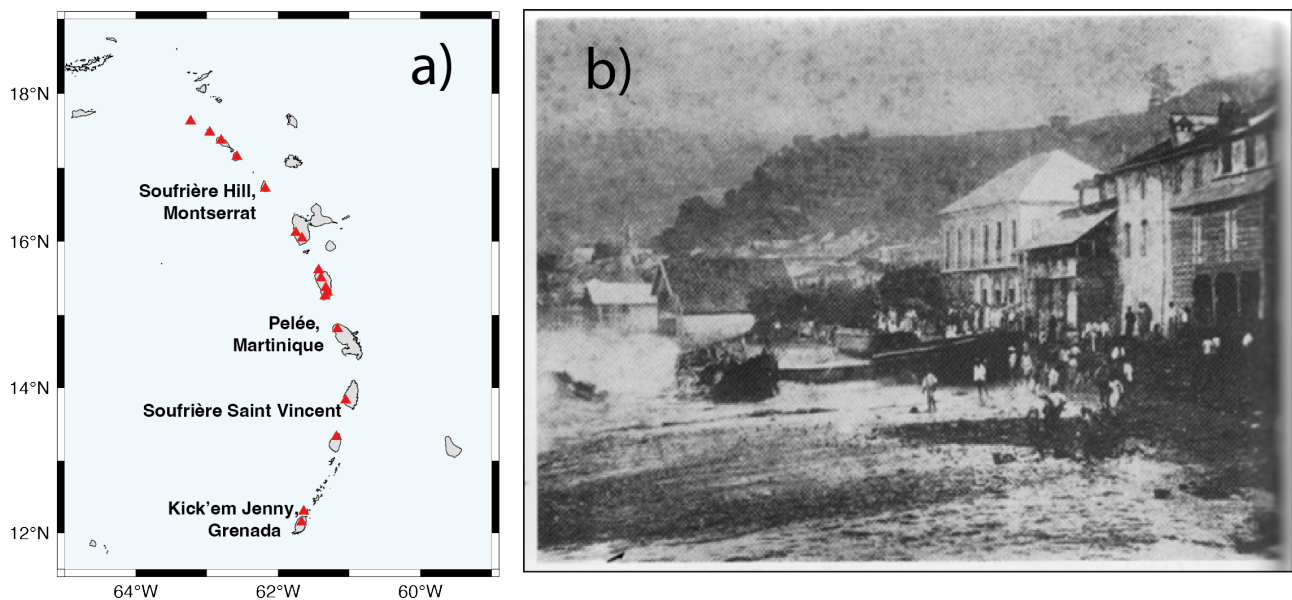


Fig. 2: a) Holocene volcanoes of the Lesser Antilles (red triangles). The names of the 4 volcanoes responsible for historical tsunamis are labeled. b) Picture of the 5 May 1902 tsunami in Saint Pierre, Martinique, following a lahar that came from Mount Pelée volcano. This lahar made the 23 first casualties of the 1902 Pelée eruption (Lacroix 1904). The picture is taken after a retreat of the sea as indicated by the stranded boats.

More recently, a small tsunami occurred at Saint Vincent during the 2021 Soufriere eruption on the 19th of April, where a 10-cm high tsunami was recorded on the sea level station located along the southern coast of the island, 13 min after its origin as a PDC entering the sea. Finally, the Hunga Tonga Hunga Ha’apai 2022 tsunami is also added to this list, as it was recorded by Caribbean tide gauges (Carvajal et al. 2022; Sostre-Cortés et al. 2023).

Looking at Table 1, four volcanoes located in the Lesser Antilles volcanic arc (Fig. 2a) are responsible for these tsunamis: Soufriere Saint Vincent in 1902 and 2021, Mount Pelée in

Martinique in 1902 with 5 PDC and a lahar (Fig 2), Soufriere Hills in Montserrat in 1999, 2003 and 2006, and Kick'em Jenny (KeJ) in 1939 and 1965.

Recent tsunami threats due to volcanic eruption

In addition to these observed tsunamis, 3 volcanic eruptions, which have occurred recently must be described, because, while they did not generate a noticeable tsunami, they triggered many false rumors of tsunami in the whole eastern Caribbean basin. These events took place at the same period as the 2018 Anak Krakatau disaster that resulted in 430 fatalities related to the tsunami generated by the flank collapse (Walter et al., 2019) and as the Hunga Tonga Hunga Ha'apai eruption and tsunami (Lynett et al, 2022). This helps explain the high impact they had among the population, recalling in addition that many Caribbean inhabitants are living in low lying areas close to the shore, and that the sea is very present in their daily life.

On 23rd and 24th July, 2015, a high seismic activity level was recorded at Kick'em Jenny Volcano (KeJ), a submarine volcano located to the north of Grenada Island (Fig. 2) and whose summit is located ~200m below sea level. KeJ is one of the most active volcanoes of the Lesser Antilles island arc. This seismic activity was initially interpreted as associated with an eruptive phase (Robertson et al. 2015) and later, with new bathymetric data, to a sequence of submarine landslides (Allen et al. 2018). However, on the 24th of July 2015, correct information about a new submarine eruption at KeJ propagated in a couple of hours through social media networks, and was rapidly followed by erroneous messages, still on the social media networks, predicting, then announcing, a huge tsunami. As KeJ is one of the 4 regional volcanoes that has previously generated a tsunami (see Table 1), the situation turned out to be very challenging for the disaster managers of the neighboring islands and territories. Therefore, this event clearly underlined the need for authoritative tsunami warning procedures, not only in the case of a tsunami generated by a volcano eruption, but more generally in the case of a volcano crisis. It is this eruption that definitively made volcanic tsunamis a priority for the ICG/CARIBE-EWS, which established the Task Team on tsunami procedures for volcanic crisis in 2016 (ICG/CARIBE-EWS 2016). This priority was further reinforced in 2021 when the Saint Vincent and La Palma eruptions occurred.

In December 2020, a new period of high level volcanic activity began at Soufriere Saint Vincent with the growth of a new dome within the crater (GPV 2021) on the southwestern side of the 1979 eruption dome (Cole et al. 2019). The effusive phase turned into an explosive phase in April 2021. On the 19th of April, the Seismic Research Center of the University of West Indies (SRC/UWI), in charge of the volcano monitoring, reported that PDCs descended the western flank of the volcano and reached the Caribbean sea. The Caribbean TSP, once informed by SRC/UWI, observed a 10-cm high tsunami on a tide gauge located to the south coast of St Vincent.

A couple of months later, on September 19, 2021, strong eruptive activity began at Cumbre Vieja Volcano (CVV), on the island of La Palma, in the Canary Islands (Longpré, 2021). During the next 3 months, this eruption generated effusive lava flows, ejection of tephra, and intermittent ash-and-gas plumes (GPV 2022). In the case of the CVV eruption, a tsunami threat could come from a volcano flank collapse resulting from the eruption and that could drop a massive (ie, several km³ to tens of km³) landslide volume into the ocean, causing a tsunami. While the tsunami would be larger

in La Palma and neighboring islands, such a tsunami could propagate across the Atlantic Ocean and arrive in the Eastern Caribbean and Western Atlantic within 8-10 hours. One catastrophic scenario was previously described by Ward and Day (2001), whose models were based on a 500 km³ landslide producing a tsunami of 10 to 25 m height along the Caribbean and the North America eastern coasts. However, subsequent studies have proposed lower far field tsunami heights, based on smaller and probably more realistic landslide volumes of at most 350 km³ and multistage failure mechanisms (e.g., Masson et al 2006; Hunt et al 2013), and better numerical landslide simulations (e.g. Gislér et al 2006, Løvholt et al 2008; Tehranirad et al. 2015; Abadie et al. 2020). While all these studies have proposed lower tsunami heights in the Caribbean, and despite the effort of the scientific community to refute the hypothesis of a giant tsunami (efforts done since 2001 and during the CVV crisis), the rumor of a giant tsunami still persisted when the La Palma eruption occurred. Consequently, during this last crisis, Caribbean disaster managers, local authorities and scientists had to manage the stress of the people scared by a possible giant tsunami threat.

Among these 3 eruptions since 2015 in the Lesser Antilles, only Saint Vincent volcano produced a small (~10 cm) local tsunami. However, all these eruptions and the perceived tsunami threat they represented were widely commented on in the social media networks (Graham et al., 2023). Disaster managers of most of the island territories, even far from the volcanoes, had to respond to this perceived threat, sometimes with very little scientific information available in real time.

Volcanic tsunami sources

These examples illustrate the wide range of possible tsunami sources from volcanoes. Tsunamis, local or regional, destructive or not significant, may be generated from subaerial and submarine edifices. For subaerial volcanoes, PDC, lahars, and landslides such as those produced by dome or flank destabilization can generate tsunamis when they reach the shore. These phenomena mostly occur during periods of eruptive activity. However, lahars and subaerial landslides can also occur when volcanoes are at rest. For submarine volcanoes, submarine explosions, caldera collapses and submarine landslides have the capacity to generate tsunamis. Finally, major volcanic eruptions can generate atmospheric acoustic-gravity waves as observed during the Hunga Tonga-Hunga Ha'apai 2022 eruption, where air-sea coupling lead to a global tsunami (e.g., Lynett et al., 2022).

Volcano tsunami detection

To create a warning system for these types of events, several problems must first be solved. The first issue is to identify the triggering information that could reach TSPs when a risk of a tsunami coming from a volcano is imminent. A second is, when a volcanic tsunami occurs, to get quantitatively if it is possible, or at least qualitatively, a location of the initial sea level disturbance, an initial time of entry in the sea, and an estimate of parameters such as intensity of the event, volume, and velocity.

Seismic and sea level networks cannot be used to activate the TSP. Seismic signals produced by volcano sources are generally too weak and/or ambiguous. There are ~60 sea level stations in the Caribbean, a small tsunamigenic basin when compared to the Pacific, and the Pacific Tsunami Warning Center (PTWC), the regional TSP for the Caribbean, is also monitoring hundreds of sea level stations across the Pacific. An automatic and reliable alert system based on a threshold on tide gauge data would be difficult for several reasons: data transmission frequency is generally only every 5 minutes, raw data contain many outlier points, and many tide gauges can be out of service

at any one time as can be seen on IOC website for sea level station monitoring (<https://www.ioc-sealevelmonitoring.org/map.php>).

Conversely, many active volcanoes are continuously monitored by a volcano observatory. These observatories can be seen as the primary entities able to determine the potential of a volcano induced tsunami threat. In the Caribbean tsunami basin, the database from the Global Volcanism Program from the Smithsonian Institution indicates 363 volcanoes with eruptions in the last 10,000 years. Assuming that only those that are within 30 km of the ocean could generate a tsunami reduces this list to 21 potentially active volcanoes, mostly in the Lesser Antilles volcanic arc (Fig. 3). In addition, we also have to take into account Northeast Atlantic volcanoes from the Canary, Madeira and Azores archipelagos, yielding a list of 43 potentially threatening volcanoes. These 43 volcanoes are associated with 12 institutions in charge of volcano monitoring. It is with this limited number of volcano observatories that we want to implement a semi-automatic communication procedure with the Caribbean TSP.

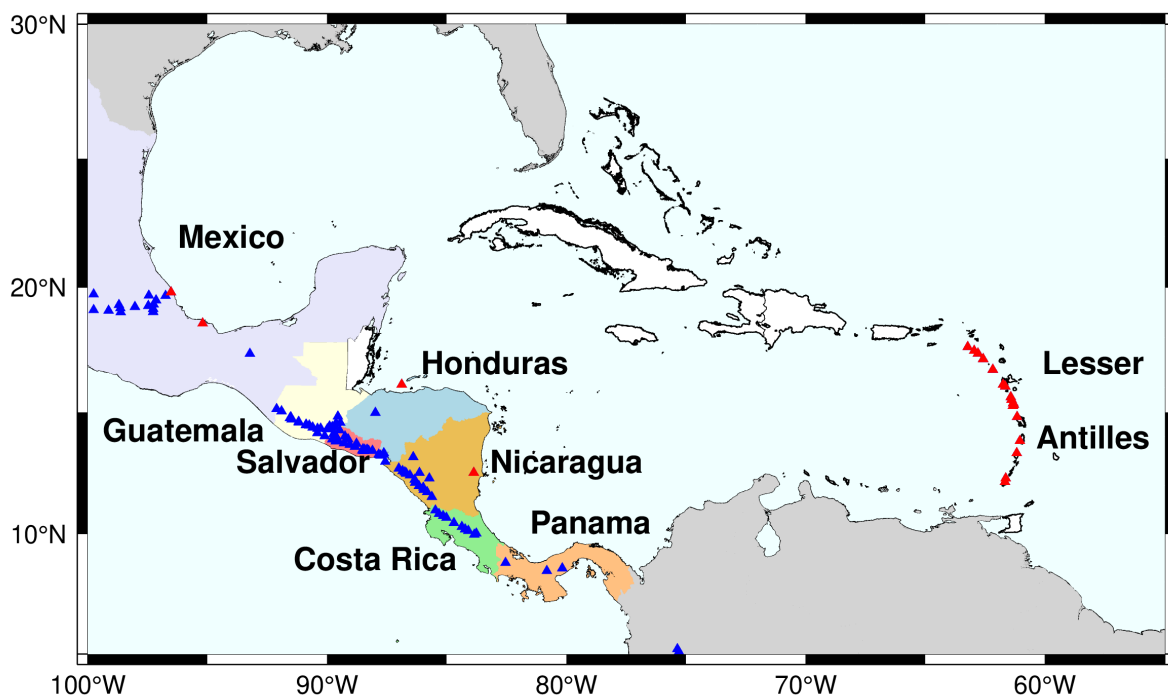


Fig. 3: Regional Holocene volcanoes from the Global Volcanism Program database of the Smithsonian Institution. Red triangles show volcanoes located at less than 30 km from the coastline.

Volcano Observatory Notice for tsUnami Threat: VONUT

Recent volcanic crises in the Caribbean show that there are two different moments when the TSP needs information from a volcano observatory in charge of the monitoring of a volcano showing

unrest. First, in the case of volcanic activity with a possibility of triggering a tsunami, the TSP can implement an alarm system using the closest tide gauges if they know the source area. The TSP needs to be aware if there is an escalation of volcanic activity at a specific volcano to be able to advise Member States. The NTWCs will then get the relevant tsunami information to help their disaster management organizations to inform the public and hopefully stop misinformation from spreading. Secondly, the TSP needs to be informed by the volcano observatory when a volcano erupts and there is a possibility of a tsunami. In either case, this might correspond to a change in the volcano's activity level.

These notifications must be in a standard format, with basic information on the volcano (name, location, eruptive activity stage), and information on any potential or occurring tsunami (location, time, amplitude, validity of the observation). A good example of such a system is the existing Volcano Observatory Notice for Aviation (VONA) bulletins. VONA (ICAO, 2020) are formatted bulletins issued by volcano observatories to their regional Area Control Centre/Flight Information Center, their regional Meteorological Watch Office and their regional Volcanic Ash Advisory Centre (VAAC) to inform them of changes in volcanic activity that have a potential volcanic ash threat.

We have developed a new bulletin named VONUT (Table 2), which stands for Volcano Observatory Notice for tsUnami Threat, based on the VONA bulletin. Many fields in the VONUT are identical to the ones in the VONA bulletin, and those can be issued according to the volcano activity code as used in the VONA (Fig. 4). Keeping in mind that these notices are sent during a volcano crisis when the volcano observatory staff is busy, it is important for the bulletins for tsunamis to be as simple and as similar as possible to VONA bulletins.

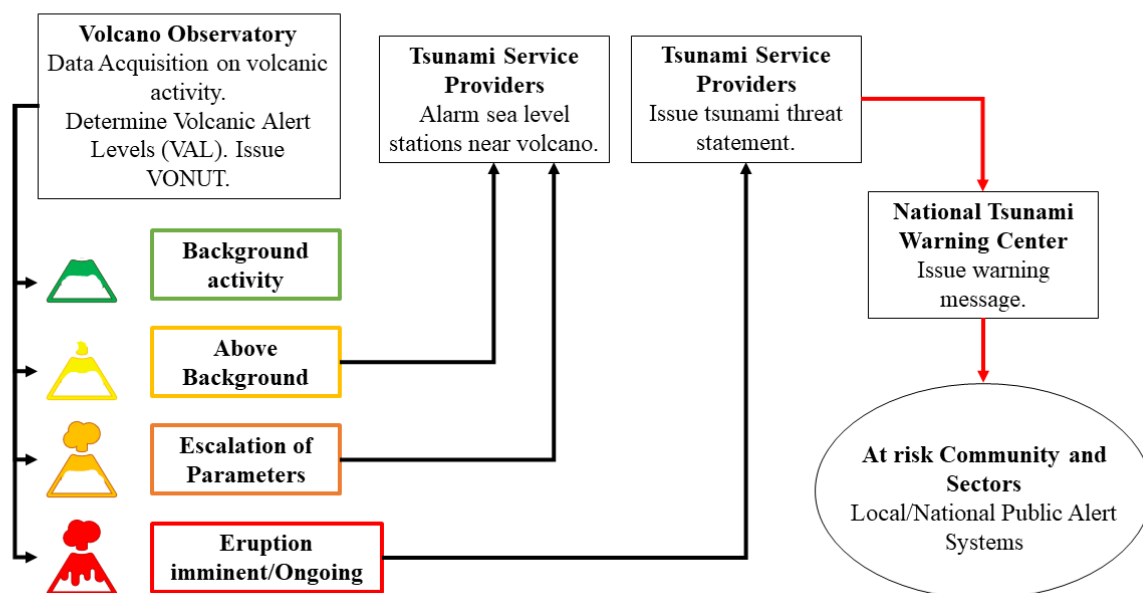


Fig. 4: Proposed system for issuing alerts about tsunamis generated by volcanoes. The color codes of the volcano pictograms are the same as those for volcanic ash warnings to aviation as determined by the volcano observatory.

A VONUT might be sent by volcano observatories due to a change in volcano alert level or within a color alert code in case of an event that could generate a sea level disturbance or any significant change in terms of volcanic behavior. Fields must be filled as shown in Table 2.

TSP volcano tsunami procedures

The PTWC is the only regional TSP for the Caribbean and adjacent regions (UNESCO/IOC 2016), while the Central America Tsunami Advisory Centre (CATAC) is a candidate to be the sub-regional TSP for Central America. TSP volcano tsunami procedures were thus developed by the PTWC. They are based on the reception of the VONUTs and remain as close as possible to tsunami procedures in the case of an earthquake-generated tsunami.

The initial VONUT would be issued by the volcano observatory in the case of volcanic activity with a possibility of triggering a tsunami. This first VONUT simply advises the TSP about heightened volcanic activity indicative of an impending eruption and the potential for tsunami generation. It serves as situational awareness for the TSP and Duty Scientists are alerted to the possibility of a tsunamigenic eruption of a specific volcano. This enables the TSP to anticipate potential scenarios and prepare appropriate actions. Sea-level gauges nearest the volcano are identified and armed to automatically detect any anomalous signals and alert the Duty Scientists. Tsunami travel times from the volcano to nearby coasts are pre-computed. Then, should an eruption occur and the TSP receive another VONUT with that information and observe tsunami waves on the nearest sea-level gauges, then a tsunami threat message would be issued to the Member State NTWCs, advising them about the eruption and tsunami, giving computed estimated times of arrival (ETA) at nearby locations. The subsequent TSP messages would report on the location, time and amplitude of observed tsunami waves.

Currently there is no capability to provide a tsunami forecasts in the VONUT threat messages. However, while the threat remains, the TSP would continue to monitor the tsunami's propagation on sea-level gauges and would issue additional messages with that information. In the future, a forecast may be possible based on information contained in the VONUT and matching pre-run model scenarios with observations on coastal gauges.

This procedure was tested during CARIBE WAVE exercise 2023.

Application during CARIBE WAVE 2023 Tsunami Exercise

Since 2011, ICG/CARIBE-EWS has organized an annual tsunami exercise in the Caribbean (Soto et al. 2022). The main objectives of the CARIBE WAVE exercises are to advance tsunami resilient communities in the region and to evaluate tsunami programs and procedures within the Member States. Specifically, it also enables the evaluation of the communications between the regional TSP, which can test new products, and the Member States and then validate the issuance and receipt of tsunami products. In 2019, a first exercise involving a scenario of a hypothetical volcano tsunami originating at Kick'em Jenny submarine volcano was carried out (UNESCO/IOC 2018). The initial triggering event modeled was a M6.5 earthquake. While such a strong magnitude is not usual

during a volcano crisis, this scenario enabled the TSP to follow its standard procedures based on a tsunami generated by an earthquake and then adapt their messages to this specific volcano source.

In March 2023, a scenario involving a tsunami generated by a large flank collapse of Mount Pelée volcano similar to one of those modeled in Poulain et al. (2023) was carried out. The TSP included in the CARIBE WAVE messages the computed tsunami travel times and amplitudes produced artificially using the RIFT tsunami forecast model (Wang et al., 2012) initialized with a large displacement at the source over a small area. In addition to the usual communication between the TSP and the Member States, the Volcanological and Seismological Observatory of Martinique (OVSM-IPGP) issued two VONUTs to the TSP. The first VONUT was used to focus the attention of the TSP on Pelée volcano and on surrounding tide gauge stations, while the second VONUT was the one that actually activated the TSP. For the purpose of the exercise, the first alert was issued 30 minutes before the beginning of the exercise. It indicated the likelihood of an imminent eruption and that a partial collapse from the south-western flank of the volcano could occur at any time. The second alert was issued five minutes before the beginning of the exercise to report on a major volcano flank collapse and to provide the TSP with the time when it entered the sea. In the VONUT form, the Volcano Observatory is not requested to report the source of the observations transmitted: these can be derived from instrumental monitoring and also from qualitative observations. In the case of Pelée volcano, if we refer to the 1902-1905 eruption, the volcano observatory observed in detail major phenomena, such as PDCs or partial dome collapses, and recorded initiation times and arrival times at sea (Lacroix, 1904). This was possible because of the location of the observatory, which had visual contact with the eruptive activity, from the source down to the sea. The present-day OVSM could do the same. This is why during CARIBE WAVE 23 exercise, the OVSM provided the arrival time at sea. However, we are aware that this kind of observation would not be possible at most of the other volcano observatories. In the Caribbean, there are also examples of qualitative information on tsunami generation, as for the May 5, 1902 Pelée tsunami, observed by people close to the shore (Fig 2b) or as during St Vincent 2021 eruption, where it was a fisherman in a boat that informed the local authorities (and the volcano observatory) of a sea disturbance following the arrival of a PDC into the ocean.

Comparing the messages sent by the TSP to the Member States (UNESCO/IOC, 2023) to those sent in the case of a tsunami generated by an earthquake, the title of the first paragraph is changed from « Preliminary earthquake parameters » to « Tsunami source event parameters » indicating an origin time, the name of the volcano and its coordinates. The next paragraph « Evaluation » is important, as it indicates at the same time that the volcano observatory « reports a flank collapse », that « a tsunami has been observed » and that « widespread hazardous tsunami waves are possible », but also that « it is not possible to forecast tsunami impacts but this center will continue to monitor and report tsunami observations until it appears that the threat has passed ». Consequently, in this message and the following ones, only an ETA (Estimated Time of Arrival) derived from modeled tsunami travel time and observed tsunami wave heights derived from the amplitudes at tide gauges are reported.

Discussion

Implementing tsunami warning procedures for volcano crises is challenging. The first issue is that, so far, no instrumental network is currently able to automatically inform a TSP that a volcano is generating a tsunami. While bottom ocean pressure stations are able to detect tsunami waves (see review in Rabinovitch and Eblé, 2015), to our knowledge, only Stromboli volcano is equipped with

near field shallow water pressure sensors used to trigger sirens (Bonilauri et al., 2021). In the Caribbean, to address this lack of instrumental network, and until such a network can be developed, using the experience of the 2021 Soufriere Saint Vincent eruption, it is proposed that the volcano observatory responsible for monitoring the unrest at a volcano would be the « device » that informs the TSP of any imminent risk of eruption that could generate a tsunami. As described above, this information would be transmitted through a formatted document that we have named a VONUT. We modeled the VONUT format on the existing VONA bulletin, with many fields in common. We adopted the same synthetic syntax, which is easier to read by non-specialists, since TSP staff may not be volcano specialists and volcano observatory staff may not be specialists in tsunamis. In general, we anticipate that VONUT bulletins should be issued at the same time as VONA bulletins, reducing the work load of the staff of the volcano observatory at the initiation of a new volcano crisis, and thus increasing the probability that the VONUT is issued in a timely manner.

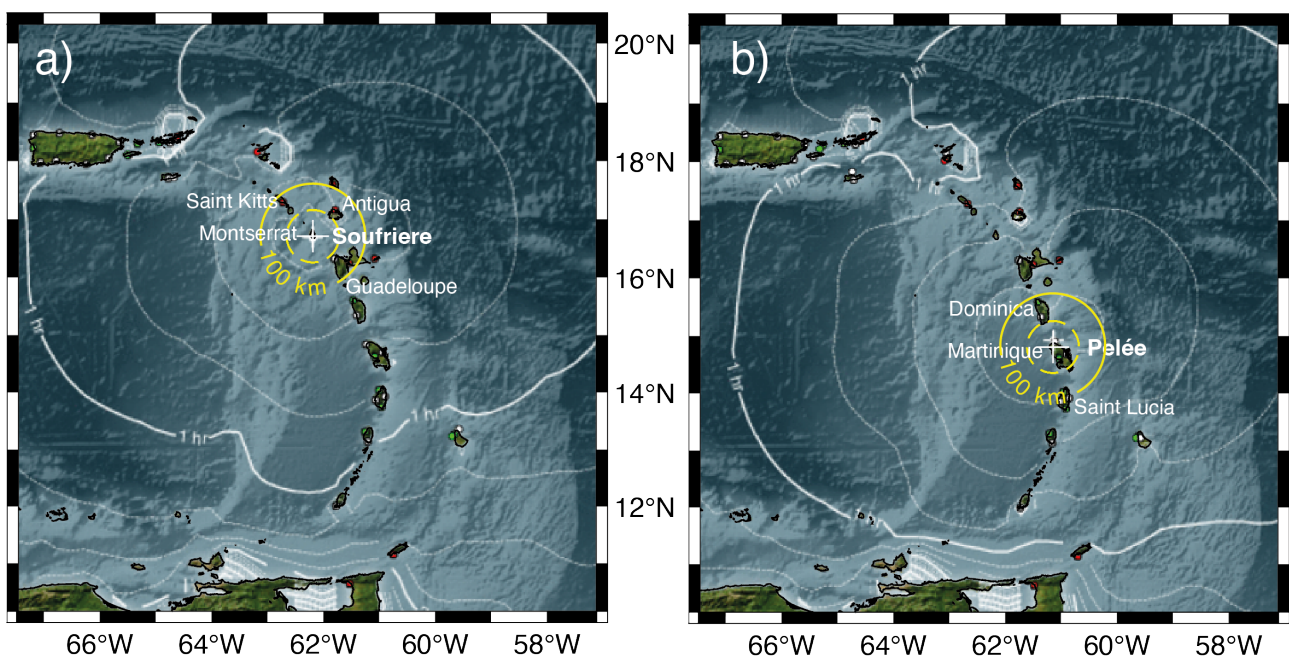


Fig. 5: Tide gauge stations available for real time sea level monitoring in the Caribbean and computed tsunami travel time in the case of two volcano crisis scenarios. Tide gauge locations (colored dots) come from the Unesco/IOC website (<https://www.ioc.sealevelmonitoring.org>, accessed 10 Dec. 2023); white or green dots indicate a station currently sending data, red dots indicate a station not currently working. The thin white lines show tsunami travel times. Isochrons are at a 15-minute intervals. Yellow circles at 50 and 100 km highlight the distance to the eruptive centers relative to where tide gauges are monitored during a volcanic crisis. a) Scenario CARIBE WAVE 2019 (UNESCO/IOC 2018) for Soufriere Hills volcano, Montserrat b) Scenario CARIBE WAVE 2023 (UNESCO/IOC 2023) for Mount Pelée volcano, Martinique.

The receipt of a VONUT by a TSP would trigger monitoring of specific tide gauge stations around the volcano. However, not all volcanoes are surrounded by tide gauge stations. Fig. 5 illustrates the non-uniform distribution of sea level stations in the Caribbean. In the case of Mount Pelée volcano, there are 3 stations located on Martinique at less than 50 km from the top of volcano and 4 more at less than 100 km (Fig. 5b). On the other hand, none exist at Montserrat (Fig. 5a) and only 4 are

present at less than 100 km. Furthermore, most sea-level gauges currently used for tsunami detection and measurement routinely only sample once per minute. This rate is fine for most earthquake-generated tsunamis since their period typically ranges from 10 to 30 minutes. But one-minute sampling is inadequate for the much shorter period tsunami waves generated from a volcano. Higher sample rates will be needed for volcano and other non-seismic source tsunamis that have shorter wave periods and generally have local impacts by nature. For these reasons, we have recommended to the ICG/CARIBE-EWS Working Group (WG) 2, in charge of detection and forecasting, to focus on increasing the density of this tide gauge network, which is essential for detecting non-seismic tsunami, and to explore other means of detection such as GNSS-Reflectometry altimetry (e.g., Roussel et al, 2015).

However, another major issue is that it is currently not possible to model a tsunami generated by a volcano event in real time. It is only possible to provide observed wave amplitudes after they have been measured. So far, no pre-computed models of volcano tsunamis exist, and in general, the tsunami-risk is unknown for most volcanoes. This highlights the difficulty for the TSP to issue warning messages in the case of a volcano crisis. As a first step, a recommendation from ICG/CARIBE-EWS XV in 2021 (UNESCO/IOC 2021) was made to WG1, in charge of tsunami risk knowledge, to compile and provide access to possible non-seismic tsunami sources. Clearly, further work will be necessary to perform volcano tsunami scenario modeling.

Preparedness and awareness actions for volcano tsunamis are another important issue. In the case of a tsunami generated by an earthquake, these actions are robust, in particular for the specific case of the impacts from a local earthquake, where it is explained that no alert system can issue timely alerts for people located close (<10-15 min) to the tsunami source, ie., the epicenter of the earthquake, and that spontaneous evacuation is necessary. Thus, in the case of an earthquake source, preparedness includes a description of natural signs of a tsunami, and flyers recommend to « evacuate from low-lying areas immediately ». In the case of a volcano tsunami, it is plausible that an exclusion zone might already exist around the volcano, as PDCs or huge landslides rarely occur when the volcano is not on a red volcanic alert level. Consequently, few recipients of the tsunami warning messages are expected to be at less than 15 min from the tsunami source (ie, the point where a landslide or a PDC reaches the sea). For these persons, only preparation, education and auto-evacuation might save them. Conversely, alert dissemination will be useful for people that have not seen or felt the eruption. In particular, it is incredibly important for remote parts of the island and for neighboring islands, where people need to receive by their national authorities reliable information derived from the messages of the TSP. To tackle this educational challenge and to test our procedures based on the communication between a volcano observatory and the TSP, the annual tsunami exercise CARIBE WAVE 2023 used a volcano scenario.

Over 420,000 people from 48 Member States participated in the CARIBE WAVE 2023 (<http://tsunamizone.org>). Of the 48 Member States, 31 decided to follow the Martinique scenario. In addition to getting feedback on their status of tsunami preparedness and response activities, the Member States also provided feedback on the experimental products for tsunamis generated by volcanoes. One highlight was that the NTWCs did not mention any difficulties for interpreting these experimental products and it was a step forward if we compare to their reactions to the messages issued during CARIBE WAVE 19 with a KeJ scenario. Consequently, two recommendations were approved at the ICG/CARIBE-EWS XVI meeting held in April 2023: first, it was suggested that TSPs include the VONUT messages in its procedures to activate its alert system; and second, it was recommended to initiate contacts with the identified volcano

observatories and/or institutes responsible for monitoring volcanoes threatening the Caribbean basin, to implement an agreement concerning the use of the VONUT.

We also anticipate that, once these procedures are adopted, messages from the TSP to the NTWCs will contribute to a better dissemination of the scientific and factual information and reduce false alarms. In that sense, TSP initial messages will hopefully play a role in lessening the anxiety of the communities at risk, and the fear caused by unfounded and catastrophist rumors.

Future work that is needed includes tsunami risk estimation for each threatening volcano, continued operation and expansion of the sea level networks for faster detection of any tsunamis generated. While there is some awareness that tsunamis may be generated by volcanic activity, more public awareness about this as well as on the limitations of early tsunami warning for these types of events and the natural warning signs of tsunamis generated by volcanoes is vitally important. Many of these actions have been included in the implementation plan of the UN Decade of Ocean Science for Sustainable Development Tsunami Programme. This Programme that includes the 4 regional tsunami warning systems seeks to reduce the detection time of all tsunamis with a potential human impact to 10 minutes and for 100% of communities at risk to be prepared and resilient to tsunamis by 2030 through efforts like the UNESCO/IOC Tsunami Ready Recognition Programme. Furthermore, recognizing the importance of having procedures to address and warn for tsunamis generated by volcanic activity, the UNESCO/IOC Working Group on Tsunamis and Other Hazards Related to Sea-Level Warning and Mitigation Systems through its task team on Tsunami Operations has made a series of recommendations for Member States that have this threat (UNESCO/IOC, 2023).

Conclusions

Since 2015, Caribbean territories have faced several regional volcanic crises that have resulted in over-reactions of the population about the perceived tsunami threat. On the other hand, the tsunami threat from volcanic sources is real, shown by the 2018 Anak Krakatau flank collapse and associated tsunami that caused 430 fatalities and the Hunga Tonga Hunga Ha'pai eruption of 2022 and ensuing tsunamis. These events illustrate the need for tsunami warning procedures that can respond effectively to a volcano crisis. However, when compared to a tsunami generated by an earthquake, implementation of warning procedures for a volcano crisis is complicated by the lack of effective detection networks, the absence of pre-calculated models, and therefore it is more difficult to estimate the real threat and the arrival time of tsunami waves in neighboring territories. To tackle this problem, noting that volcano observatories are the primary entities able to determine the potential of a volcano induced tsunami threat, we constructed a VONUT bulletin for volcanic tsunamis modeled on the VONA bulletins that warn of volcanic ash. As for the VONA, VONUT bulletins should be issued by a volcano observatory to the regional TSP due to a change in the volcano activity level or any event that can generate a tsunami. The VONUT model was successfully tested during the exercise CARIBE WAVE 2023 based on a Mount Pelée flank collapse triggering a tsunami. Experimental products issued by the TSP based on getting VONUT bulletins were received positively by the NTWCs. When an agreement between the TSPs and volcano observatories is signed, VONUT should be included in the standard operating procedures of the Caribbean and adjacent regions Member States for use during volcano crises.

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Table 1: Historical tsunamis due to volcanic eruption in the Caribbean. * indicate that hours are in local time. Text in bold italic corresponds to modifications to the NEIC database or new events.

Year	Mo	Dy	Hr	Mn	Val	Country	Location Name	Max Water Height (m)	Nb of runups	Source
1902	5	5			4	MARTINIQUE (FRENCH TERRITORY)	MOUNT PELEE	5	1	NEIC database
1902	5	7			4	SAINT VINCENT AND THE GRENADINES	SOUFRIERE VOLCANO	1	3	NEIC database
1902	5	8	8*	2	2	MARTINIQUE (FRENCH TERRITORY)	MOUNT PELEE	2	3	NEIC database + <i>this paper from Lacroix 1904</i>
1902	5	20	5*	20	4	MARTINIQUE (FRENCH TERRITORY)	MOUNT PELEE	4	3	NEIC database
1902	6	6	10*	0	4	MARTINIQUE (FRENCH TERRITORY)	MOUNT PELEE	1	1	<i>This paper from Lacroix 1904</i>
1902	7	9	20*	20	4	MARTINIQUE (FRENCH TERRITORY)	MOUNT PELEE	0.6	1	<i>This paper from Lacroix 1904</i>
1902	8	30	8°	45	4	MARTINIQUE (FRENCH TERRITORY)	MOUNT PELEE	3	5	NEIC database + <i>this paper from Lacroix 1904</i>
1911	11	3			3	TRINIDAD AND TOBAGO	TRINIDAD		1	NEIC database
1939	7	24			2	GRENADA	KICK 'EM JENNY VOLCANO	2	3	NEIC database
1965	10	24			1	GRENADA	KICK 'EM JENNY VOLCANO	0		NEIC database
1997	12	26	8		4	MONTserrat	WHITE RIVER VALLEY	3	1	NEIC database
1999	1	20			4	MONTserrat	SOUFRIERE HILLS VOLCANO	2	3	NEIC database
2003	7	12			4	MONTserrat	SOUFRIERE HILLS VOLCANO	4	5	NEIC database
2006	5	20	11	20	4	MONTserrat	SOUFRIERE HILLS VOLCANO	1	4	NEIC database
2021	4	19			4	SAINT VINCENT AND THE GRENADINES	SOUFRIERE VOLCANO	0.1		<i>This paper</i>
2022	1	15			4	TONGA	Hunga Tonga Hunga Ha'apai	0.3		Sostre-Cortés et al 2023, Carvajal et al. 2022

Table 2 : Volcano Observatory Notice for tsUnami Threat - VONUT - to be filled by a Volcano Observatory. The present (4) and previous (5) aviation color codes are included on the form, as this is relevant information for the TSP.

(1) VOLCANO OBSERVATORY NOTICE FOR TSUNAMI THREAT-VONUT	
(2) Issued: Universal (Z) date and time (YYYYMMDD/HHMMZ):	
(3) Volcano: Name and number (per Smithsonian database at http://volcano.si.edu/):	Pre-filled
(4) Current Aviation Colour Code: GREEN, YELLOW, ORANGE, OR RED in upper case bold font	
(5) Previous Aviation Colour Code: Lower case font, not bold	
(6) Source: Name of Volcano Observatory (volcanological agency)	Pre-filled
(7) Notice Number: year-VONUT number (e.g. 2010-1)	
(8) Volcano Location: Latitude, longitude in NOTAM format (deg min N or S deg min W or E, e.g. 4701N 0513W)	Pre-filled
(9) Area: Regional descriptor	Pre-filled
(10) Summit Elevation: nnnnn FT (nnnn M)	Pre-filled
(11) Volcanic Activity Summary: Concise statement that describes activity at the volcano. If known, time of onset and duration of eruptive activity are specified (local and UTC).	
(12) Sea sector of the impact (North/South, East, West) "UNKNOWN" if no data available	
(13) Name of the sea (Caribbean, Atlantic, Dominique Channel, etc) "UNKNOWN" if no data available	
(14) Closest tide gauge stations Indicate name and url (from IOC web site: https://www.ioc-sealevelmonitoring.org/station.php?code=) of tide gauges at less than 100 km. A map of tide gauge locations and name is Annex 4.	Pre-filled
(15) Remarks: Optional; brief comments on related topics such as monitoring data, observatory actions, volcano's previous activity, sea level disturbance observed, etc.	
(16) Contacts: Names, phone numbers (voice and fax), email addresses.	Pre-filled

<p>(17) Next Notice: “A new VONUT will be issued if conditions change significantly or the colour code changes.” “Final notice” if final notice for an event. URLs of Websites where the latest volcanic information is posted are included.</p>	
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Table captions

Table 1: Historical tsunamis due to volcanic eruption in the Caribbean. * indicate that hours are in local time. Text in bold italic corresponds to modifications to the NEIC database or new events.

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