Anatomy of the tsunami and Lamb waves-induced ionospheric signatures generated by the 2022 Hunga Tonga volcanic eruption

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Abstract

As tsunamis propagate across open oceans, they remain largely unseen due to the lack of adequate sensors, hence limiting the scope of existing tsunami warnings. A potential alternative method relies on the Global Navigation Satellites Systems to monitor the ionosphere for Traveling Ionospheric Disturbances created by tsunami-induced internal gravity waves (IGWs). The approach has been applied to tsunamis generated by earthquakes but rarely by undersea volcanic eruptions injecting energy into both the ocean and the atmosphere. The large 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption tsunami is thus a challenge for tsunami ionospheric imprint detection. Here, we show that in near-field regions (<1500km), despite the complex wavefield, we can isolate the tsunami imprint. We also highlight that the eruption-generated Lamb wave's ionospheric imprints show an arrival time and an amplitude spatial pattern consistent with internal gravity wave origin.

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Key points:

- The tsunami of the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption triggered ionospheric imprints across the Pacific Ocean
- The eruption produces high ionospheric noise, especially in the near field, making its tsunami ionospheric imprints harder to identify
- The ionospheric imprints of the eruption-triggered Lamb wave are consistent with internal gravity waves origin

Abstract

As tsunamis propagate across open oceans, they remain largely unseen due to the lack of adequate sensors, hence limiting the scope of existing tsunami warnings. A potential alternative method relies on the Global Navigation Satellites Systems to monitor the ionosphere for Traveling Ionospheric Disturbances created by tsunami-induced internal gravity waves (IGWs). The approach has been applied to tsunamis generated by earthquakes but rarely by undersea volcanic eruptions injecting energy into both the ocean and the atmosphere. The large 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption tsunami is thus a challenge for tsunami ionospheric imprint detection. Here, we show that in near-field regions (<1500km), despite the complex wavefield, we can isolate the tsunami imprint. We also highlight that the eruption-generated Lamb wave's ionospheric imprints show an arrival time and an amplitude spatial pattern consistent with internal gravity wave origin.

Plain Language Summary

To complement conventional tsunami warning systems, it is possible to rely on the imprint of the tsunami in the ionosphere, a high-altitude layer of the atmosphere. This imprint can be tracked using the Global Navigation Satellites Systems to measure the Total Electron Content (TEC) of the ionosphere. On Jan. 15, 2022, the submarine volcano of Hunga Tonga-Hunga Ha'apai erupted, providing a unique opportunity to test the approach on a tsunami generated by a volcanic eruption. Here, we study the tsunami's ionosphere response, the pressure pulse the eruption generated, and the underlying physical mechanisms. We find that the eruption caused a particularly high ionosphere activity in the near-field region, making the tsunami signature assessment and use for early-warning more challenging but still possible.

1. Introduction

Tsunamis are natural hazards that have already claimed the lives of more than 250000 civilians globally (Mizutori & Guha-Sapir, 2018). Tsunamis are commonly monitored on shores by coastal tide gauges or in deep oceans by tsunami buoys. These instruments provide direct measurements of the tsunami but can be insufficient for early warnings because (1) tide gauges are located on the coasts, giving little to no time for a warning, and (2) tsunami buoys are expensive to deploy and maintain, resulting in a limited sampling of the oceans, not sufficient for near-field warning. An alternative but indirect method centers around the computation of the ionospheric total electron content (TEC) to track tsunami propagation. The first tsunami-induced ionospheric (TEC) signature was presented by Artru et al. (2005), and since, this technique has been used to identify and characterize the TEC signatures of a variety of tsunamis, all initiated by submarine earthquakes (Liu et al., 2006; Rolland et al.,2010; Galvan et al., 2011; Grawe & Makela, 2015, 2017). Underwater volcanic eruptions and landslides can also trigger tsunamis, except that there haven't been many large instances in the last decades to study them in the light of modern instrumentation. The 2022 explosion of the Hunga Tonga-Hunga Ha'apai (HTHH) submarine volcano provides a unique opportunity to fill this gap and characterize the generated ionospheric perturbations.

According to the US Geological Survey (USGS), the HTHH volcano (20.546°S 175.39°W; Fig. 1a) violently erupted on Jan. 15, 2022, at 4:14:45 UTC (17:14:45 LT). The eruption released a massive ash plume that reached an altitude of ∼55 km (Smart 2022). It also generated a highly-energetic atmospheric Lamb wave observed globally (for a few days after the eruption) in different types of measurements (e.g., barometers, infrasound sensors, satellites images, ionospheric measurements) (Matoza et al.,2022; Wright et al., 2022). According to Themens et al. (2022), large and medium-scale traveling ionospheric disturbances (TIDs) appeared in global TEC measurements following the eruption, with travel speeds ranging from 200 to 1000 m/s. They attributed the two TIDs types to the initial acoustic response of the explosive eruption and the energetic Lamb wave, respectively. The same findings were reported by Lin et al. (2022). In addition, Astafyeva et al. (2022) used the nearfield TEC measurements to identify the presence of several volcanic explosions during the event timeline. Moreover, the eruption triggered air-sea (tsunami-like) waves induced by the Lamb-wave-sea coupling and observed worldwide (Kubota et al., 2022; Omira et al., 2022). According to Matoza et al. (2022), the Lamb wave signature appears to be consistent (arrival time, waveform) in both the ionospheric and sea-level observations.

The eruption also produced a classical tsunami, i.e., from direct water mass displacement, detected across the Pacific Ocean (Carvajal et al., 2022), causing four casualties in Tonga (Latu, 2022) and two in Peru (Parra, 2022). The exact mechanism triggering the tsunami is not well-understood yet, but preliminary analysis suggests a combination of submarine explosion and caldera collapse (Hu et al., 2022 and reference therein). An ionospheric imprint of this tsunami was reported by Matoza et al. (2022) at near-field. Here, we strengthen the study with a spatial pattern analysis and expand the investigated dataset more globally (Pacific-wide). We seek to isolate the ionospheric signature of the tsunami from the acoustic and Lamb signals. Because of these multiple, partially overlapping signals, we don't expect the discrimination to be straightforward, yet, it is a necessary step to assess the potential of TEC data for tsunami early-warning even in the case of a volcanic eruption.

To support our TEC signal analysis, we first analyze the ionospheric imprint of a tsunami initiated by the Mw 8.1 Kermadec earthquake, which occurred a year before, on March 4th, 2021 about 1000 km South of Tonga (29.723°S 177.279°W, based on the USGS report) (Fig. 1a). Both events occurred in the Eastern region of Polynesia islands sparsely equipped with GNSS stations installed onland. The size of the tsunami triggered by the Kermadec earthquake was smaller than the one triggered by the HTHH event by less than one order of magnitude (respectively 3 and 20 cm in the near-field after Romano et al., 2021 and Lynett et al., 2022). We thus use the Kermadec ionospheric imprints as a test case to help decipher the HTHH imprints in the ionosphere with a sparse multi-GNSS network.

In addition to presenting the ionospheric imprints of the two tsunamis, we investigate how the tsunami generation mechanism (earthquake vs. volcano) affects the detection of such imprints. We compare the tsunami sea-level variations to the ionosphere imprints to confirm the tsunami origin of the detected ionospheric imprints. Finally, we examine the ionospheric response of the Lamb wave the HTHH eruption produced and compare it to that of the tsunami.

2. Data and methods

The previous detections of tsunami-induced ionospheric imprints in the literature are based on the use of dense networks of GNSS receivers (Grawe & Makela, 2017 and references therein). Here, the sparsity of GNSS receivers in the south Pacific area requires a single receiver approach to identify the tsunami's ionospheric response and study its evolution at various distances and directions. To test the single receiver technique, we examine the Kermadec tsunami through the GNSS receiver located in Niue Island (NIUM; Fig. 1a), ~1400 km from the epicenter. Such distance favors the detection of both the earthquake and the tsunami ionospheric signatures (Fig. 1a). While the coseismic acoustic gravity wave (AGW) can be observed next to the source, the ionospheric imprint of the IGW triggered by the tsunami cannot appear closer than 500 km from the source and sooner than 1h after the initiation because the atmospheric wave also needs to propagate vertically at a speed below 100 m/s (Occhipinti et al., 2013). For tsunami early-warning, these properties make the AGW measurements more suited in the near-field (Zedek et al., 2021) and the tsunami-induced IGW measurements more suited in the medium and far-field (this study).

From the NIUM GNSS observation data, we compute the raw slant total electron content (sTEC) and apply a sequence of filters (polynomial detrend, apodization, and band-pass filter; see S1 & S2 in SM for a detailed description). The bottom panel of Figure 2a depicts the raw sTEC observed by the satellite-receiver pair G12-NIUM. The top x-axis in the panel indicates the satellite elevation where we applied a mask removing data below 20° elevation (unlike the 10° mask adopted for the rest of this work) to minimize the possible artifacts enhanced by the low elevation (see G12 in Figure 3a). After that, we use the theoretical tsunami travel times (TTT) to estimate the expected tsunami arrival time at a particular location (e.g., sTEC data IPPs location: the intersection of the line of sight with the ionosphere shell at a certain altitude [Davies & Hartmann, 1997], 300km in this study), knowing that the associated TEC signature should appear approximately around the same time (Rolland et al., 2010). These processing steps allow us to observe two distinct signatures: the earthquake acoustic response (A1) appearing ~10 min after the initiation time (IT) and the tsunami (T1) emerging within the expected arrival time. This pattern is consistent over the different satellites seen by the receiver (Fig. 3a). The spatial pattern of the imprints' maximum TEC amplitude around the receiver further assesses the detection. According to Grawe & Makela (2015), the TEC amplitude of tsunami-induced IGWs increases from upstream to downstream the receiver (Fig. 3c). The technique's applicability is made possible thanks to multi-GNSS observations with an efficient azimuthal coverage that increases the reliability of the detection.

We follow the same procedure for the HTHH tsunami, selecting GNSS receivers located in several Pacific islands (Fig. 1a; Table S3 in SM), to extend our analysis with more global coverage. The detection made by each receiver is independent of the others. We selected receivers with multi-GNSS capability. The chosen receivers fall in a distance ranging from 700 km to 10 000 km, and thus from near to far field, with respect to the tsunami source. This allows us to track the fully-developed tsunami in the ionosphere as it travels across the Pacific.

3. Results

1. Tsunami-induced TEC signatures across the Pacific Ocean

We identified the ionospheric imprints of the HTHH tsunami in the TEC data from 12 receivers around the Pacific (Fig. 1b). The tsunami-induced ionospheric imprints are corroborated by observations from other satellites for each receiver (Fig. S5 to S15 in SM). The tsunami TEC amplitude and the local tsunami arrival time of the twelve series are illustrated in Table S3 of the SM. These results agree with the dense-network-based study of Ravanelli et al., in review GRL, 2022 (specifically in the vicinity of New Caledonia and New Zealand).

Applying our detection method with the GNSS receiver located on Lord Howe Island (LORD; Fig. 1a) during the generation and passage of the HTHH tsunami, we successfully identified its ionospheric signatures, as confirmed by the two-step verification procedure (Fig. 3b,d). By comparing the Kermadec and HTHH signatures (Fig. 2a,b), we see how exceptional the HTHH event is; a complex time series with imprints of multiple types of waves, and an amplitude one order of magnitude larger (Table S3 in SM).

2. Ionospheric imprints comparison (earthquake-induced vs. volcanic eruption-induced)

To investigate the impact of the trigger source (earthquake vs. volcanic eruption) on the induced ionospheric signatures of a tsunami, we focus on two TEC measurements with optimal configuration (the orientation of the tsunami aligns with the local geomagnetic field, and the observing geometry is downstream the receivers; Grawe & Makela, 2015): G12-NIUM (Kermadec; Fig. 2a) and C01-TUVA (HTHH; Fig. 2b). Both are located in the medium field (∼1400 km) and are band-pass filtered from 0.7 to 10 mHz.

For the Kermadec event, we observe two remarkable signatures that we link to the event. The first signature is the earthquake acoustic response appearing several minutes after the initiation as an N-shape pulse, as routinely observed after earthquakes. We have strong arguments supporting that the second signature is that of the tsunami: (1) it occurs within the expected arrival time of the tsunami, (2) it has an oscillatory signature with a clear frequency peak at 1.2 mHz, in the range of what is expected for the tsunami waves, (3) it is supported by the different satellites seen by the receiver (Fig. 3a), and (4) the IGWs behavior of the detected signatures' maximum TEC amplitude (Fig. 3c).

Unlike the Kermadec submarine earthquake, the HTHH submarine volcanic eruption ionospheric imprints are more complex and present a richer spectrum. Besides the tsunami response (T1) and the signature of the initial acoustic response (A1), a Lamb wave (L1) is visible in the volcano eruption data. The two types of imprints (excluding the tsunami's) are reported by Wright et al. (2022). The imprint of the tsunami emerges at the expected arrival time with an amplitude of 0.58 TECU. In contrast to the earthquake case, the ionosphere during the eruption experiences higher noise related to the main, massive, explosion of the eruption, and the numerous different types of waves it injected into the Earth's atmosphere (Wright et al., 2022). Such noise can also be seen in some of the sTEC series shown in Figure 1 (see also Fig. 3b), especially those close to the volcano.

3. Ionosphere vs. sea-level measurements

To further assess the tsunami origin of the identified imprints, we compared the sTEC disturbance measured offshore Galapagos Islands with the sea-level anomaly registered by a deep-sea DART buoy #32413 about 800 km southwest of the Islands (Fig. 1a). Both signals have similar waveforms with a peak frequency around 1.2 mHz (Fig. 4a). The emergence of the signal 30 minutes earlier in the ionosphere suggests that the shoaling of the bathymetry around the Galapagos archipelago slowed down the tsunami in the sea surface while allowing its induced IGWs to advance ahead of it. A similar effect was observed for the 2011 Tohoku tsunami when it approached Hawaii (Occhipinti et al., 2011).

We also note the presence of an ionospheric signature having an amplitude and a spectral content similar to the tsunami imprint but 2 hours earlier (Fig. 4a). It appears to travel with a speed of ∼235 m/s and could be the imprint of an IGW triggered by the eruption and traveling all the way in the atmosphere.

4. Ionospheric imprints of the Lamb wave

When examining the ionospheric (TEC) data as we search for the HTHH tsunami imprints, we first notice the peculiar signature of the Lamb wave, whose raw sTEC measurements display massive decreases and increases that resemble a large W-shape (Fig. S16 in SM). The Lamb wave processed imprints exhibit close similarity to the tsunami's. We note that the ionospheric signature of both the Lamb and the tsunami waves peak at a similar frequency of 1.2 mHz (Fig. 2b), with the Lamb wave displaying a more impulsive behavior. Furthermore, Figure 2e shows that the Lamb wave's imprint' maximum sTEC amplitude spatial pattern exhibits IGW behavior (similar to the tsunamis cases in Figures 2c and 2d), where the maximum amplitude is larger downstream of the GNSS receiver. Overall, the Lamb wave signature has a larger amplitude than the tsunami signature.

We also investigated the co-located measurements of a DART buoy's Lamb wave pressure signature and its ionospheric signature in southern New Zealand (Fig. 4b). They both show an impulsive waveform (in the time domain) and a broadband frequency content (Fig. 4b). In addition, when corrected for traveled distances, the imprints show no delay between the arrival at the buoy's location and the ionosphere and are consistent with the Lamb wave constant speed (318m/s). The amplitude pattern and absence of time delay suggest that in the same way as the tsunami, the Lamb wave triggered internal gravity waves (IGW), which traveled upward to ionospheric heights with the same horizontal speed as the Lamb wave.

4. Discussion

The global overview of the ionospheric imprint amplitude shows interesting features (Fig. 1). The tsunami's smallest sTEC amplitude is observed in Hawaii. Three possible reasons could have caused the lower amplitude aside from the tsunami open-ocean size itself (~6 cm zero to crust recorded by the 51407 DART buoy): (1) the local time of the tsunami arrival was around 1 am (Table S3), meaning a low ionization rate (compared to the daytime) and consequently a smaller amplitude of detected signatures (Grawe & Makela, 2015), (2) the inefficient coupling between the tsunami-induced IGWs and the local geomagnetic field, or (3) the destructive interaction between the conjugate Traveling Ionospheric Disturbances (TIDs) and the direct TIDs traveling away from the volcano as suggested by Themens et al. (2022). This later scenario is based on the fact that Hawaii is very close to the volcano's geomagnetic conjugate point. Lin et al. (2022) also reported the presence of conjugate TIDs, lending more support to this explanation.

In contrast, the tsunami ionospheric signature with the largest amplitude in the vicinity of the Galapagos Islands suggests a tsunami with a higher open-ocean wave (~6 cm zero to crust recorded by the 32413 DART buoy), which contradicts the expected wave height decay with increasing distance from the source (~2 cm; model) (Ward 2002). Unlike the other identified imprints, the detection near the Galapagos took place around noon local time (Table S3 in SM), which contributes to the larger amplitude of the detected ionospheric imprints.

The lack of delay between the arrival of the Lamb wave imprints in the ionosphere and on the surface, as illustrated by Figure 4b, suggests that the propagation of the Lamb acts like a moving source (similar to a tsunami), forcing IGWs that travels obliquely upward (Lin et al., 2022). The IGW behavior experienced by the imprints' max sTEC amplitude (depicted in Figure 3e) supports such a hypothesis.

5. Conclusions

The ionospheric imprints of the tsunami generated by Jan. 15, 2022, Hunga Tonga-Hunga Ha'apai volcanic eruption, as it propagates across the Pacific Ocean, are presented and investigated along with that of the Mar. 4, 2021, 8.1 Mw Kermadec Islands earthquake tsunami. Our results indicate that, like the ionospheric imprints of earthquake-initiated tsunamis, the imprints of the tsunami generated by the HTHH eruption can be identified and isolated in the ionospheric data, even with a single station approach. This result was achieved despite a high level of ionospheric noise, especially in near-field, produced by the volcanic eruption. This noise complexifies the detection of tsunami-induced ionospheric imprints, calling for further improvement in the filtering algorithms and differentiation criteria in order to meet the high detection confidence required for early warnings. Yet, the comparison with open-ocean sea-level measurements confirmed that the isolated imprints were those of the tsunami.

Our joint analysis of the ionospheric signatures of the Lamb (pressure) and tsunami waves shows that they both trigger internal gravity waves that can be distinguished thanks to their different traveling speeds. Detecting the HTHH tsunami's ionospheric imprints across the Pacific Ocean demonstrates the potential of our single-receiver approach. Its current implementation requires a visual inspection to validate the identified imprints. This absence of automation presents a limitation that we intend to overcome in future work along with utilizing detected tsunami-induced ionospheric signatures to estimate the open-ocean tsunami's wave height, which is the quantity of interest to tsunami early warning systems.

Data and Resources

All GNSS data are freely available from the Geoscience Australia data archives (ftp://ftp.data.gnss.ga.gov.au/daily/) and the CDDIS data archives (https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/daily_30second_data.html). The ocean bathymetry data ETOPO1 (1-minute global relief model; Amante and Eakins 2009) and the open-ocean sea-level measurements (DART) are from the NOAA data archives (https://www.ngdc.noaa.gov/mgg/bathymetry/relief.html; https://www.ngdc.noaa.gov/hazard/DARTData.shtml). The coastal sea-level measurements (tide gauge) are publicly available via the Intergovernmental Oceanographic Commission of UNESCO (http://www.ioc-sealevelmonitor- ing.org/). To generate the tsunami travel times, we take advantage of Geoware TTT SDK software (Wessel, 2009).

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Figure Captions

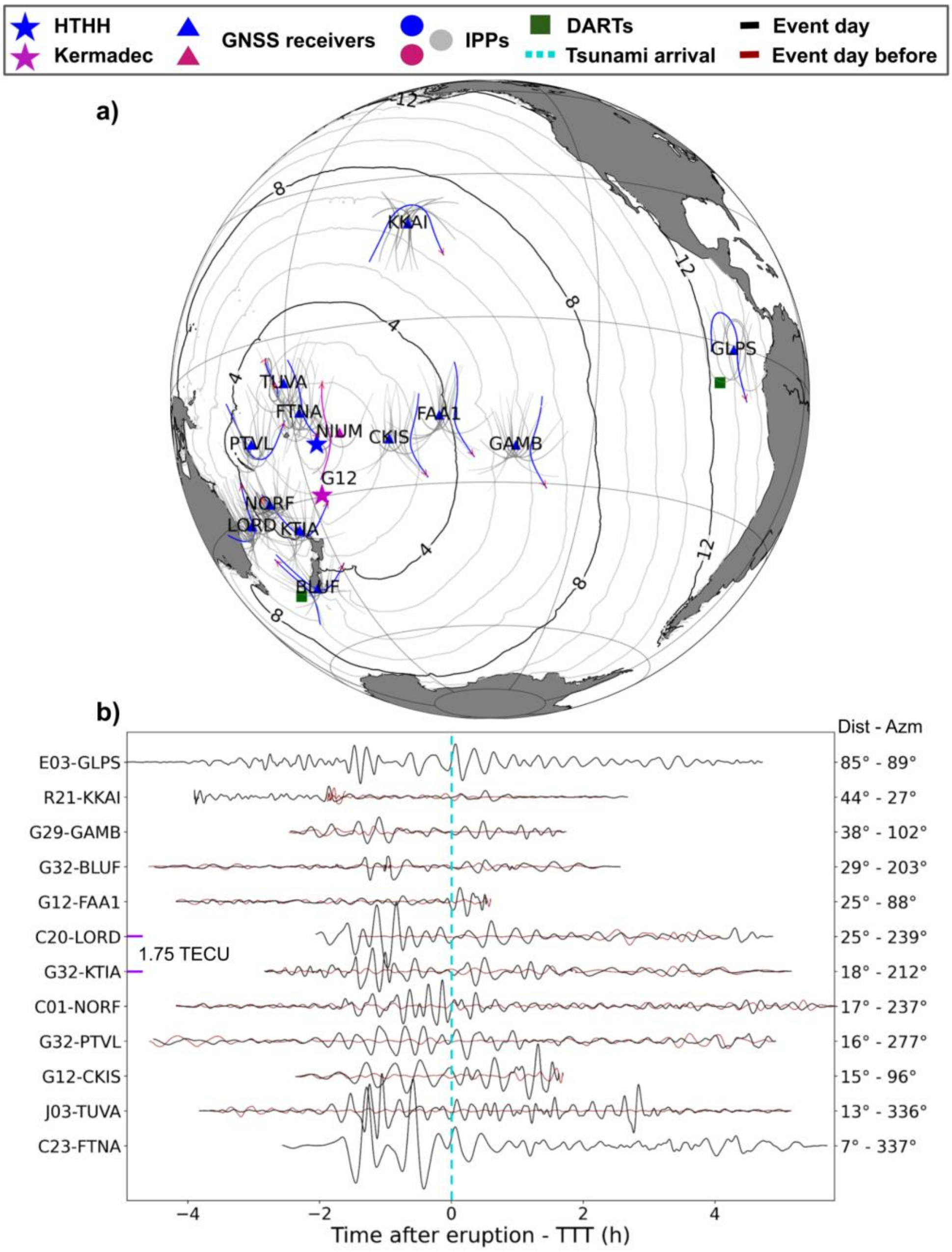

Figure 1. (a) Context map of the study with locations of the tsunami sources and measurements. The Jan. 15, 2022, Hunga Tonga-Hunga Ha'apai volcanic eruption and the Mar. 4, 2021, 8.1 Mw Kermadec Islands earthquake epicenter are marked with a blue and purple star, respectively. GNSS receivers are marked with triangles of the same color. The contours highlight the Hunga theoretical tsunami traveling times (TTT). Ionospheric Pierce Points (IPPs at 300km altitude) are depicted by colored dots for the selected pairs, while gray dots represent that of other pairs. **(b)** A selection of filtered sTEC measurements with tsunami-induced signature. Satellites are marked with a letter: Beidou (C), QZSS (J), GPS (G), GLONASS (R), Galileo (E), and PRN number. To highlight the tsunami signature, the time series are aligned with respect to the tsunami theoretical arrival time (TTT).

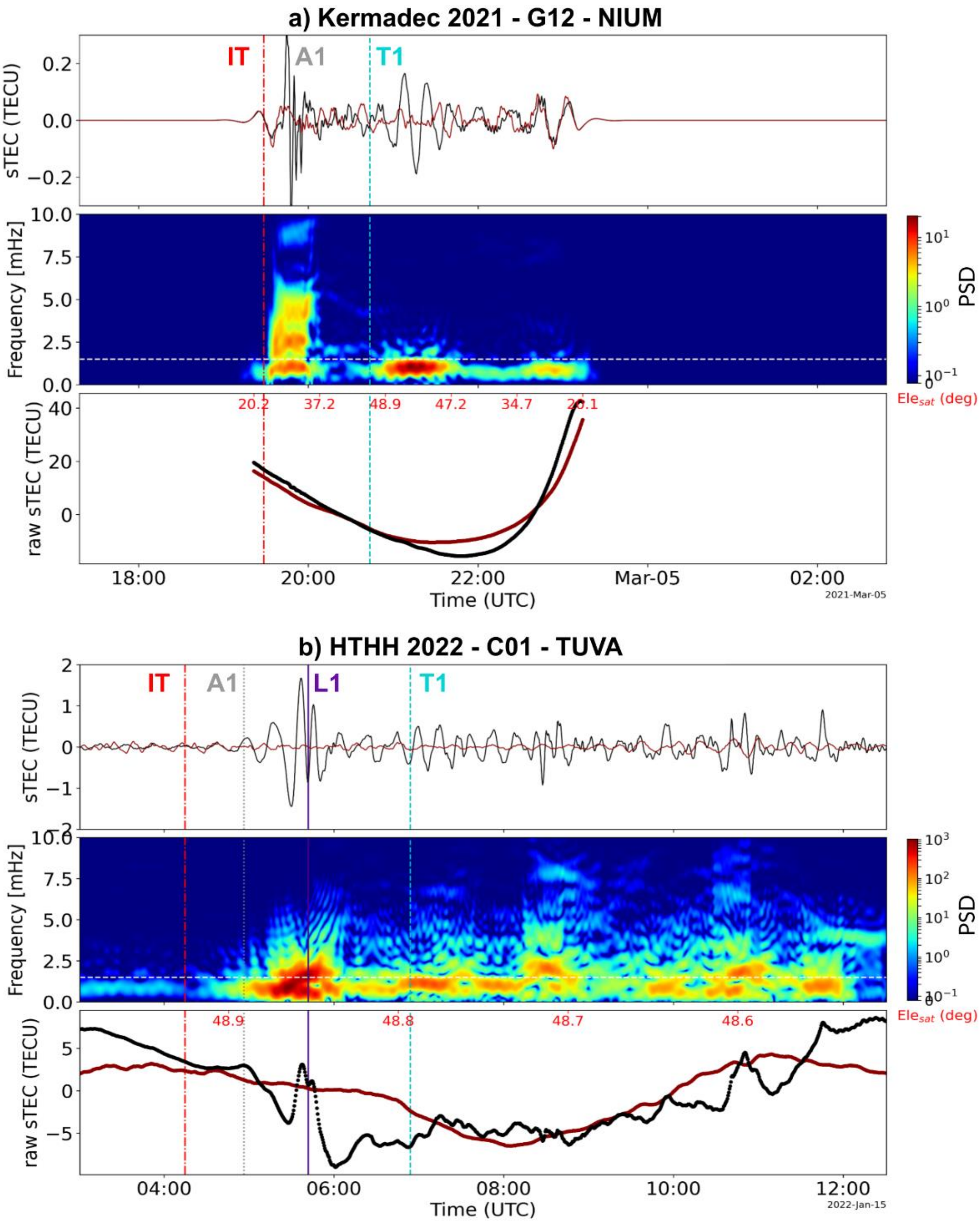

Figure 2. Comparison between the ionospheric TEC imprints obtained by the satellite-receiver pairs G12-NIUM (Kermadec) and C01-TUVA (HTHH). **(a)** TEC measurements during the Kermadec earthquake and the passage of the triggered tsunami. The three panels from bottom to top are: the raw sTEC, the event day filtered sTEC spectrogram, and the filtered sTEC. The filtered sTEC is zero-padded to match the length of C01-TUVA. The vertical red line represents the event initiation time (IT). The top x-axes show the satellite's azimuth and elevation, respectively. The horizontal white line in the spectrogram indicates the expected frequency of tsunami ionospheric signature (i.e., 1.5mHz; 11min). **(b)** TEC measurements during the HTHH volcanic eruption and the produced tsunami passage. The expected arrival times of the acoustic pulse A1; 667m/s, the Lamb wave L1; 318m/s and the tsunami are highlighted.

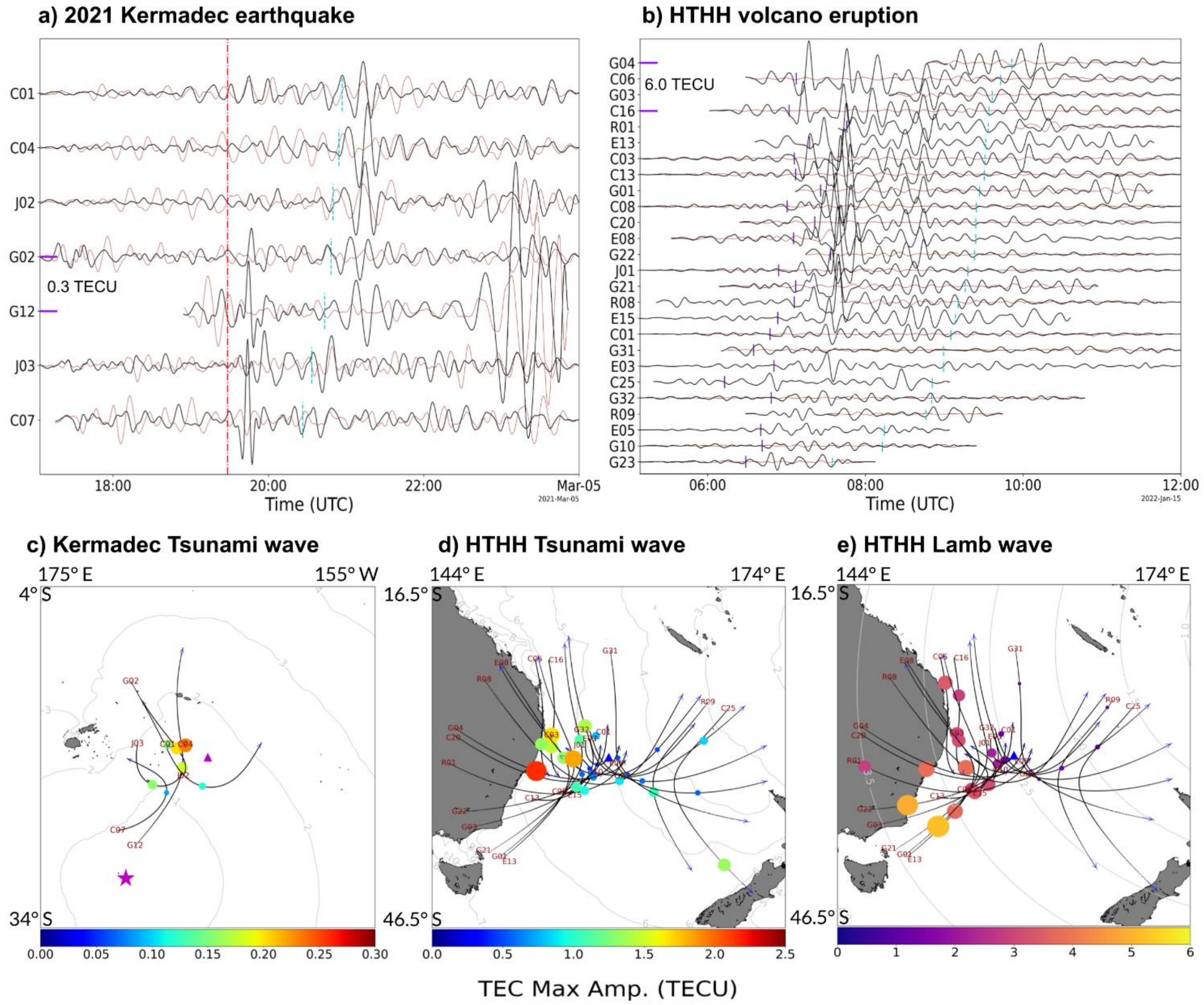

Figure 3. (a) The tsunami-induced ionospheric signatures detected in the vicinity of Niue Island (NIUM) after the 2021 Kermadec earthquake. **(b)** The ionospheric imprints detected in the vicinity of Lord Howe Island (LORD) induced after the HTHH volcanic eruption. **(c)** Geographic view of the earthquake's epicenter, the GNSS receiver, and the ionospheric tracks of the satellites whose sTEC time series are shown in (a). Along the satellites' tracks, the disks indicate the satellites' locations at the tsunami expected arrival time, whose size and color point out the detected maximum sTEC amplitude of the tsunami imprints. The max sTEC amplitude is calculated within a 2-hour observation window starting 15 minutes before TAT as $\frac{max_{obs\_w} - min_{obs\_w}}{2}$. **(d)** Map showing the GNSS receiver and the ionospheric tracks of the satellites whose sTEC time series are shown in (b). **(e)** The disks depicted in the map show the satellites' locations at the Lamb wave arrival, with their size and color representing the wave's maximum sTEC amplitude. The results illustrated by (c), (d), and (e) demonstrate that ionospheric imprints downstream of the receiver display larger max sTEC amp. than upstream, as expected from IGWs.

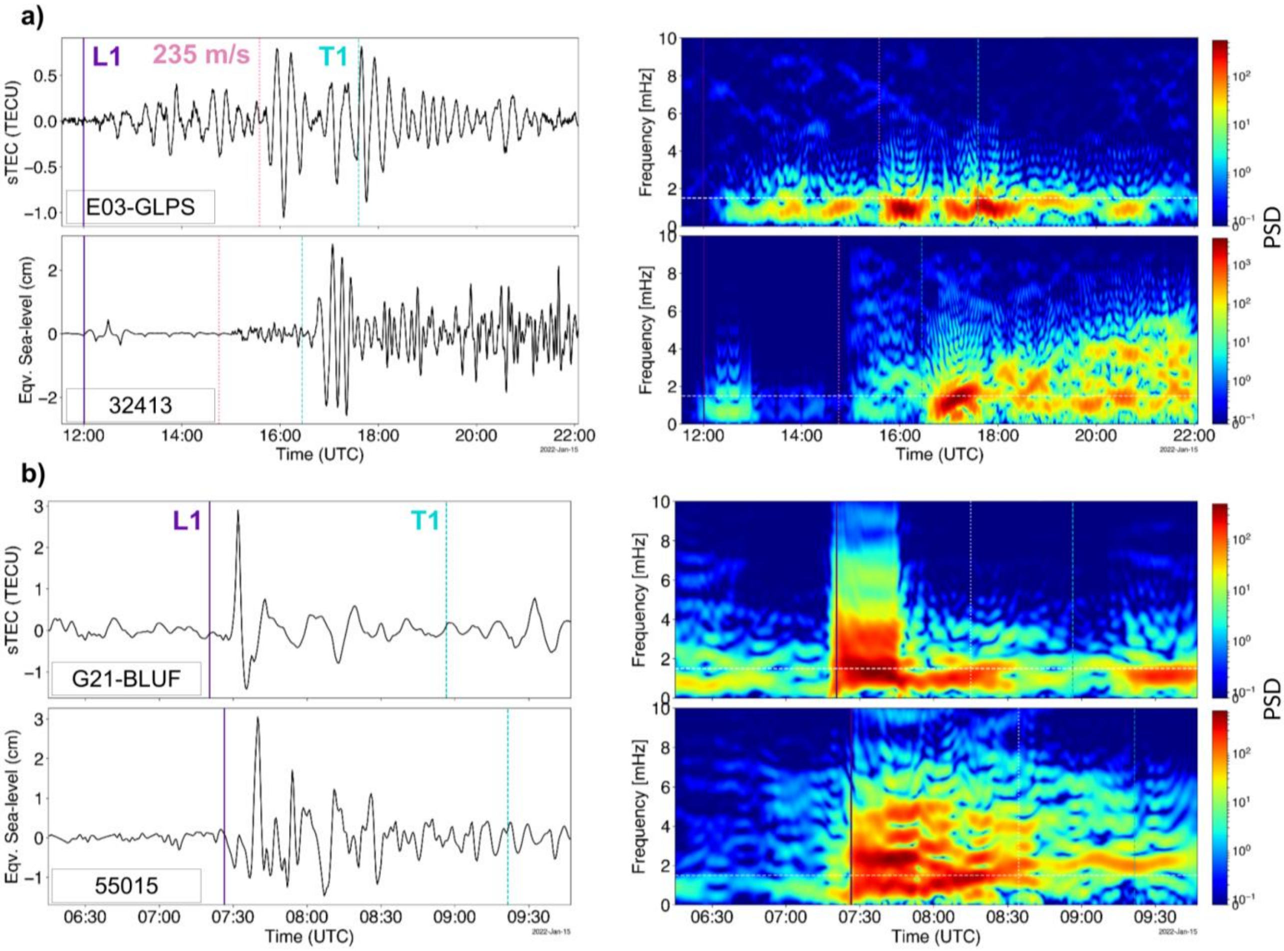

Figure 4. Comparison between open-ocean sea-level anomaly and ionospheric signatures in the vicinity of Galapagos Islands (a) and southern New Zealand (b) on Jan. 15, 2022. Time series are on the left, and spectrograms are on the right. **(a)** The top panel shows the filtered E03-GLPS sTEC measurements. The bottom panel presents the sea-level measurements from the tsunami buoy DART 32413. **(b)** The top panel is the sTEC measurements of G21-BLUF, and the bottom is the sea-level observation of DART 55015. The results show that the Lamb wave is better sensed in the vicinity of southern New Zealand, whereas near the Galapagos Islands, the tsunami is. In addition, the comparison presents a solid confirmation of the origin of each imprint.