Spectral characteristics of ionospheric disturbances over the Southwestern Pacific from the January 15, 2022 Tonga eruption and tsunami

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Abstract

On January 15, 2022, Tonga's Hunga Tonga-Hunga Ha'apai (HTHH) volcano violently erupted, generating a tsunami that killed three people. Acoustic-gravity waves propagated by the eruption and tsunami caused global complex ionospheric disturbances. In this paper, we study the nature of these perturbations from Global Navigation Satellite System observables over the southwestern Pacific. After processing data from 818 ground stations, we detect supersonic acoustic waves, Lamb waves, and tsunamis, with filtered magnitudes between 1 and 7 Total Electron Content units. Phase arrivals appear superpositioned up to ~1000 km from HTHH and are distinct by ~2200 km. Within ~2200 km, signals have an initial low-frequency pulse that transitions to higher frequencies. We note the presence of a faster perturbation generated one hour post-eruption which crosses the tsunami disturbance ~3000 km from HTHH, potentially contributing to premature land arrivals. Lastly, the arrival of tsunami-generated disturbances coincides with deep-ocean observations.

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Key Points

- **We see distinct phase arrivals in the ionosphere for a supersonic wave, Lamb wave, and tsunami (the latter is validated by ocean sensors)**
- **Phase arrivals begin to separate at ~1000 km from Tonga and are fully separated by ~2200 km**
- **We highlight a faster disturbance that propagates one hour post-eruption and meets the tsunami perturbation ~3000 km from the volcano**

Abstract

On January 15, 2022, Tonga's Hunga Tonga-Hunga Ha'apai (HTHH) volcano violently erupted, generating a tsunami that killed three people. Acoustic-gravity waves propagated by the eruption and tsunami caused global complex ionospheric disturbances. In this paper, we study the nature of these perturbations from Global Navigation Satellite System observables over the southwestern Pacific. After processing data from 818 ground stations, we detect supersonic acoustic waves, Lamb waves, and tsunamis, with filtered magnitudes between 1 and 7 Total Electron Content units. Phase arrivals appear superpositioned up to ~1000 km from HTHH and are distinct by ~2200 km. Within ~2200 km, signals have an initial low-frequency pulse that transitions to higher frequencies. We note the presence of a faster perturbation generated one hour post-eruption which crosses the tsunami disturbance ~3000 km from HTHH, potentially contributing to premature land arrivals. Lastly, the arrival of tsunami-generated disturbances coincides with deep-ocean observations.

Plain Language Summary

The January 15, 2022 volcanic eruption of Hunga Tonga-Hunga Ha'apai and subsequent tsunamis sent powerful energy waves into the ionosphere (a layer

of Earth's atmosphere that is deformed by energy emitted from events like volcanic eruptions, tsunamis, earthquakes, tornadoes, hurricanes, and large man-made explosions). These waves can provide valuable information about different phases of the event, such as the powerful explosion, sound wave, and tsunami. Using Global Positioning Systems data, we measure these ionospheric signals over the southwestern Pacific Ocean to examine which phases of the event contributed to each ionospheric disturbance. We successfully detect all three event phases in the ionosphere and determine the distance at which these signals separate from one another. Furthermore, we validate our data by comparing tsunami signals in the ionosphere against direct ocean-based observations of tsunami activity. Of particular note is our observation of a faster ionospheric signal that forms an hour after the eruption and catches up to the tsunami's disturbance. Our work supports the hypothesis that others have proposed in which high-energy waves from the eruption escalated tsunami speeds and wave heights. This, in turn, supports the observation of early tsunami arrivals that were reported along many Pacific coastlines.

Keywords

Ionosphere

Volcanic eruption

Tsunami

GNSS

1. Introduction

On January 15, 2022, a violent eruption occurred at Hunga Tonga-Hunga Ha'apai (HTHH), a small marine volcano in the Tonga archipelago approximately 65 km north of the main island of Tongatapu. Previously existing as two distinct landmasses, the islands Hunga Tonga and Hunga Ha'apai merged in a 2014-2015 eruption sequence that connected both sides of the volcano subaerially. Volcanic activity renewed in December 2021 and escalated on January 13, 2022 with an eruption that once again separated the two islands and brought the crater below the ocean's surface. Two days later, the climactic eruption occurred at 04:14 UTC (United States Geological Survey origin time of main eruption) and continued in a complex sequence of at least five explosions for the next 20 minutes, concluding with a final large explosion at ~08:31 UTC (Astafyeva et al., 2022; Matoza et al., 2022; Wright et al., 2022).

This event generated incredibly powerful acoustic-gravity (AG) waves, the largest of which was a Lamb wave, which travels in the direction of wave propagation along Earth's surface and in the normal plane near the speed of sound in the lower atmosphere (Lamb, 1911). The Lamb wave produced by HTHH crossed the globe numerous times over the next three days, something which has not been observed since the 1883 eruption of Krakatau (Matoza et al., 2022; Zhang et al., 2022). Furthermore, the eruption generated a tsunami that reached coastlines around the Pacific basin; elevated sea levels were also observed in the Mediterranean and Caribbean seas as well as in the Indian and Atlantic oceans (Carvajal et al., 2022). Lamb waves, typically seen only in extremely powerful explosions and volcanic eruptions, are capable of influencing tsunami activity (Harkrider & Press, 1967) and are thought to have enhanced HTHH's tsunamis. AG waves produced by the eruption and tsunamis propagated into the ionosphere, resulting in traveling ionospheric disturbances (TIDs) that were witnessed on a global scale (Astafyeva et al., 2022; Themens et al., 2022; Zhang et al., 2022).

The ionosphere, a mid- to upper-atmospheric layer containing ions and free electrons, is disturbed by natural events such as volcanic eruptions and tsunamis that propel AG waves along and upward from Earth's surface (Hines, 1972). These perturbations can be tracked in the ionosphere to detect remote events, determine the magnitude of events, and quantify metrics such as propagation velocities and arrival times (Astafyeva, 2019; Huang et al., 2019, and references therein; Manta et al., 2021). In the past two decades, many advancements have been made in ionospheric analysis of natural hazards. The development of the Variometric Approach for Real-Time Ionosphere Observation (VARION) algorithm by Savastano et al. (2017) demonstrated the potential for real-time ionospheric tracking of tsunamis. Additional studies have shown that ionospheric signals can be separated into frequency peaks attributed to distinct phases of a volcanic eruption (Dautermann et al., 2009) or to distinct seismic waves during an earthquake (Astafyeva et al., 2009; Jin et al., 2017; Liu et al., 2011).

In this manuscript, we analyze ionospheric disturbances from the HTHH eruption and ensuing tsunamis recorded by Global Navigation Satellite System (GNSS) observations of total electron content (TEC) throughout the southwestern Pacific basin. The dispersive nature of the ionosphere to radio frequency signals allows for the extraction of this signal with dual-frequency GNSS observations. We look at the moveout of disturbances to isolate key phases in the eruption and tsunamis. We investigate the spectral characteristics of the signal to validate the timing and occurrence of separation between the Lamb wave and initial tsunami arrivals. Finally, we look at arrival times of the first peak at DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys around New Zealand to show the correspondence between the tsunami arrival and the high-frequency phase arrival in the ionosphere.

2. Data and Methods

We focus our analysis on stations in the southwestern Pacific Ocean within 5000 km from the volcano. Within this region, there are three ultra-dense GNSS networks: Australia, New Zealand, and Hawaii. Though the region within ~2000 km is not densely instrumented due to minimal available land, observations in Samoa, Tonga, and other outlying islands provide excellent observations on many satellites. We obtained raw GNSS data in RINEX2 format from UNAVCO, the International GNSS Service (IGS), GNS New Zealand, and Geoscience Australia at either 15- or 30-second sample rates. The orientation of the New Zealand network is particularly advantageous since stations are oriented roughly along the back-azimuth to Tonga, which allows for better tracking of the moveout from the volcano; the networks in Australia and Hawaii are oriented orthogonal to this and have phase arrivals at similar times. In total, we processed data from 818 stations, with most either in Australia (563) or New Zealand (195).

GNSS data was processed using SNIVEL_ION, a revised version of Satellite Navigation-derived Instantaneous VELocities, or SNIVEL (Crowell, 2021). SNIVEL_ION utilizes the time-differenced geometry-free combination of L1 and L2 phase observables on the GPS constellation. The raw output from SNIVEL_ION is in variometric (i.e., differential) TEC units (vTEC; TEC/unit time) along the slant from satellite to receiver. We processed each station from 03:00 UTC to the end of the day; however, most of our analysis is within 12 hours of the eruption at 04:14 UTC. After we obtained our vTEC observations for each station-satellite pair, we first removed an 8th degree polynomial fit to get rid of large-scale drifts in the time series before numerically integrating to absolute TEC (aTEC) values. This process was originally performed in Savastano et al. (2017) and subsequently revised in Savastano & Ravanelli (2019); similar methods were also performed in Maletckii & Astafyeva (2021). We then applied a bandpass, 4-pole, zero-phase, Butterworth filter between 0.5 and 10 mHz, which corresponds to periods between 100 and 2000 s. We required a minimum of 240 continuous data points for each station-satellite pair to include it in our dataset. This value was arbitrarily chosen and represents two continuous hours of data for 30-second sample rate data. We also excluded observations below an elevation mask of 18 degrees. While some low elevation effects will be observed with this elevation mask, it provides more continuous data points which allows for more stable filtering. Since SNIVEL_ION does not include an outlier filter, we manually inspected all of the waveforms with a filtered aTEC value greater than 5 to remove gross outliers from our analysis; note that many non-outlier observations with aTEC values greater than 5 were present. After removing outlier satellite-receiver pairs, we were left with 9.7 million time series points. Of the total satellite-receiver time series points, 5.6% are within 2000 km of the volcano, 21.2% between 2000-3000 km, 31.9% between 3000-4000 km, and 41.7% greater than 4000 km. To investigate the frequency dependence of the aTEC perturbations for key station-satellite pairs, we performed a wavelet transform using a Morlet wavelet. We only looked at the wavelet transform in the period range between 100 and 2000 s to correspond with the bandpass filter we applied to the aTEC time series. In processing this TEC data, we determined the ionospheric piercing point (IPP) using the Klobuchar model and an assumed thin layer height of 350 km (Klobuchar, 1987). The sub-ionospheric distance used throughout is the distance from the volcano to the surface projection of the IPP. The standard error assumption for variometric TEC is less than 0.03 TECu (Coster et al., 2012; Zhang et al., 2022); however, as the errors are complex and frequency-dependent, we use this value as an approximate uncertainty. Further analysis is required to establish more precise uncertainty estimates of the colored noise structure. All TEC files created in this study are available from Ghent & Crowell (2022).

In addition to the TEC data, we also used data from several DART buoys owned and operated by GNS New Zealand to compare tsunami arrival times with phase arrivals in the ionosphere. For this analysis, we downloaded 15-second sample rate data and bandpassed the data similarly to the TEC data to primarily remove long-period tidal signals.

3. Results and Discussion

Figure 1 shows dense TID arrivals over New Zealand and Australia, while also highlighting the sparsity of data over most of the southwestern Pacific.

Figure 1. Mapview of ionospheric disturbance arrivals over southwestern Pacific for satellites G10 and G23. The general direction of satellite motion is from southwest to northeast between the time of eruption, 04:14 UTC, and 12:00 UTC on January 15, 2022. Yellow boxes represent the positions of DART buoys for which a first peak arrival is available. The red triangle denotes the location of HTHH. Green circles indicate the locations of GNSS stations that are discussed herein. TECu is saturated beyond +/- 0.4 to emphasize the locations of the strongest signals.

Close to the source, TIDs arrive in the ionosphere within minutes of the eruption. Filtered disturbances appear to be superpositioned up to a distance of ~1000 km from the volcano (Figure 2). The SAMO station on Samoa (837 km northeast of HTHH; the IPP for satellite G23 is 300 km away at the time of the eruption) recorded a disturbance that peaks at 04:38 UTC at an amplitude of 6.3 TECu (Figure 2a). Our calculated amplitude aligns with others recently published (Astafyeva et al., 2022; Matoza et al., 2022; Themens et al., 2022; Zhang et al., 2022); differences in TEC values are due to individual filtering/processing methods. This amplitude of ionospheric perturbation is significantly larger than observed in previous eruptions (Liu et al., 2017; Shults et al., 2016), demonstrating the immense power of the HTHH eruption. Note that the absolute amplitude of TEC signals depends on many factors outside of the source such as satellite geometry, latitude, geomagnetic variations, and background TEC (Bagiya et al., 2019). Wavelet analysis shows one dominant signal over a broad range of periods that is heavily concentrated in the lower end of the range, with a peak concentration in period at 923 s (Figure 2d) and a mean power peak at 69 (Figure 2g). Note that the mean power absolute units (Figure 2g-i) are dependent on the particular design of the wavelet transform, but all wavelets in Figure 2 have the same design and are in the same units. Both the period and mean power peaks occur at the same time as the maximum TECu.

Figure 2. Comparison of ionospheric disturbances observed from the G23 satellite and SAMO receiver (a, d, g), the G10 satellite and RAUL receiver (b, e, h) and the G10 satellite and 2406 receiver (c, f, i) following the climactic January 15 eruption (red vertical line). Vertical black dashed lines represent the arrival of the tsunami's first peak as recorded by Gusman & Roger (2022). Mean

power in (g-i) is the average power over all periods from the wavelet transform at a given time.

Lamb- and tsunami-induced TIDs begin to show separation on Raoul Island (~1000 km southwest of HTHH), though there appears to be some overlap remaining. Separation of the TIDs is inferred by the arrival of the Lamb wave, which peaks at 05:17 UTC at an amplitude of 3.5 TECu, followed closely by a tsunami signal (inferred from the DART arrival of the actual tsunami) which peaks at 05:41 UTC at an amplitude of 5.0 TECu (Figure 2b). Looking at the wavelet analysis for RAUL, the peak period is 1423 s at 05:30, which drops to 1073 s at 05:42 (Figure 2e); both this shift in period (and thus frequency domain) and the DART arrival support our interpretation that this is the early stage of phase separation. The mean power for each TID peaks at 24 and 36 (Figure 2h). TID separation is even clearer over New Zealand at station 2406 (2175 km southwest of HTHH), with the DART arrival of the actual tsunami dividing each phase across all three metrics (Figure 2c,f,i). The Lamb wave's TID peaks at 06:02 UTC at an amplitude of 0.70 TECu, while the tsunami's TID peaks at 06:43 UTC at a maximum amplitude of 1.1 TECu. In the wavelet analysis for 2406, the two disturbances show peak concentrations in period around ~1800 s and ~800 s (Figure 2f). The mean power for each TID peaks at 1.6 and 2, with a local minimum immediately preceding the tsunami's arrival (Figure 2i). Much of the loss of power between SAMO and 2406 can be explained through geometrical spreading, but some may be due to the spreading out of the Lamb and tsunami disturbances that were previously superimposed at shorter distances.

Moveout of the TIDs is visualized in a distance-time plot of TEC time series across New Zealand (Figure 3a). Here we see TEC time series gathered by individual receivers and projected radially down from IPPs along the ground path of satellite G10. Again, the first disturbance is interpreted to be from the Lamb wave, while the second is inferred to be from a tsunami wave. First peak DART arrivals from Gusman & Roger (2022) placed atop TID moveouts show that the actual tsunami and tsunami-generated TIDs have nearly identical propagation velocities. An abrupt change in wavelength and reduced period of the perturbations are evident on nearly all time series in the dataset; four such time series are featured in Figure 3b-e.

Figure 3. (a) Distance-time moveout of ionospheric disturbances following the eruption. Each moveout line represents a disturbance time series as recorded by a single receiver and satellite, plotted along the sub-ionospheric distance. Red vertical line is the eruption time, 04:14 UTC. All moveout lines here are observed by satellite G10. Bolded moveout lines correspond to the four time series/period plots (b-e), which emphasize the change in period as the AG wave is compressed. Yellow boxes represent the positions of DART buoys and timing of first tsunami peaks from Gusman & Roger (2022).

We estimate wave propagation velocities using the slope of observed TECu amassed from all available satellites and 818 receivers on a distance-time plot (Figure 4). A faint disturbance arrives earliest propagating toward the volcano.

This disturbance was most likely due to the moderate geomagnetic storm that began on the previous day (e.g., Themens et al., 2022; Astafyeva et al., 2022; Aa et al., Space Weather, 2022), or due to Cyclone 04F near the Cook Islands that was ongoing during the eruption. The supersonic acoustic TID, the first eruption-related perturbation, travels at 833 m/s between 1600 km and ~3000 km from Hunga. This value is in line with typical shock acoustic wave speeds at ionospheric height as reported for volcanic eruptions (Dautermann et al., 2009; Shults et al. 2016) and falls between those recently published (Matoza et al., 2022; Themens et al., 2022; Zhang et al., 2022). One could argue for several different supersonic speeds depending on the specific location of the TID. Between ~3000-3500 km, this pulse decreases in speed before returning to nearly 833 m/s, also observed by Themens et al. (2022) and Zhang et al. (2022). The Lamb wave TID then arrives at 310 m/s, followed at the same speed by a tsunami TID which appears shortly before 06:00 UTC and is validated by the preceding DART arrivals. Shortly before ~08:00 UTC, another set of TIDs arrives at a speed of 463 m/s.

Figure 4. (a) Distance-time plot of total electron content from raw GNSS data. TECu is saturated beyond +/- 2 to emphasize locations of the strongest signals. Between +/- 0.5 TECu is excluded for clarity. For both panels, yellow boxes represent DART arrivals of the first peak in the initial tsunami wave from Gusman & Roger (2022). (b) Distance-time plots of total electron content from interpolated GNSS data. TECu is saturated beyond +/- 0.7 to emphasize locations of the strongest signals. Black dashed lines represent propagation velocities of TIDs. All data is included. An additional speed of 463 m/s is included as a baseline for Figure 5.

We show the interpolated distance-time plot in Figure 4b, which more clearly displays the distinct phase arrivals in the ionosphere. Interpolation was computed with a weighted average using two-dimensional Gaussian distance weighting with decay coefficients of 50 km and 30 s (e.g., Crowell et al., 2013). Within the interpolated data, a TID appears that is more challenging to locate within the raw data shown in Figure 4a. Here, we see a 463 m/s TID emerge just behind the tsunami from ~2000-3000 km. By projecting this 463 m/s line back to a sub-ionospheric distance of zero, we see that this TID would have been generated one hour after the climactic eruption. However, due to the data-poor area immediately surrounding HTHH, we are uncertain whether this TID began above the eruption site or formed between the volcano and where we first observe it here. Additionally, note that the vertical propagation delay between tsunami sources and coupled internal gravity waves in the ionosphere is between 25-60 minutes, but the horizontal propagation delay is on the order of minutes (Occhipinti et al., 2013), which may contribute to the 1-hour time delay between the volcanic eruption and the higher-frequency signal. Interestingly, during this same hour, the tsunami travels ~1100 km (assuming a propagation speed coincident with that of the Lamb wave), which is approximately the distance of the RAUL station at which partial signal separation and a shift toward shorter periods are evident. Figure 4b indicates that the faster TID overtakes the Lamb wave's and tsunami's TIDs at ~3000 km from HTHH; the 310 m/s and 463 m/s TIDS approach each other in Figure 3 as well (starting at ~06:40 UTC just above 2000 km), though it is more challenging to discern in the moveout. Apparent amplification in the TEC signal is visible where the 310 m/s and 463 m/s TIDs cross at ~3000 km and again at ~5000 km; this is potentially due to constructive interference.

By rotating the interpolated data to explore disturbances relative to the first arrival of the 463 m/s TID (Figure 5a), it is evident that TIDs in the negative time domain have a longer period than those arriving afterward. Slices taken at 2000 km, 2250 km, and 2500 km from HTHH reinforce this observation by showing much higher-frequency signals in the positive time domain of both the TEC and DART time series (Figure 5b-d). The DART data in particular show a low-frequency response to the low-frequency supersonic signal in the negative time domain. Crossing into the positive time domain, the speed of high-frequency waves in the ionosphere appears to be roughly identical and certainly not slower than 463 m/s.

Figure 5. Rotated interpolated distance-time plot of total electron content to correspond with the first tsunami peak in the ionosphere (a), with slices at 2000 km, 2250 km, and 2500 km (b-d). Color scale of (a) is the same as Figure 4b. Arrival times of the first tsunami peak from Gusman & Roger (2022) are shown by the yellow squares. Vertical dashed lines in the sliced time series represent the minimum TECu that precedes initial tsunami arrival for all three slices, with bolded vertical dashed lines representing the minimum for that particular slice.

While we do not have a definitive explanation for the generation of the 463 m/s TID, we speculate that it is a combined signal and acknowledge that local bathymetry (or wave guiding along the Kermadec trench), secondary sources, or excitation from the large atmospheric waves may have influenced this data. Atmospheric influencing is demonstrated elsewhere in our data as an abrupt change in frequency between disturbances. This sudden compression of TIDs likely appears due to the coupling of AG waves with water gravity waves, during which ocean waves are excited by the large atmospheric pressure wave and then build due to resonance from similar phase velocities of the lower atmosphere and ocean surface (Kubota et al., 2022; Press & Harkrider, 1966; Somerville et al, 2022). Given our abnormally high tsunami velocity estimations, this likely explains why many countries across the Pacific basin experienced earlier tsunami arrivals than expected.

4. Conclusions

The HTHH event was highly unique and has prompted many studies in the short time since its occurrence. Recent publications have emphasized its basin-wide tsunami - never before witnessed in the Pacific from a volcanic eruption (Terry et al., 2022) - and have questioned the source of its immense power (Cronin et al., 2022). In our own work, we have highlighted ionospheric disturbances during various phases of the event, from the supersonic acoustic wave to a powerful Lamb wave and subsequent tsunami enhanced by air-sea coupling and resonance. We have validated initial tsunami arrivals with available DART data and have shown that a faster disturbance surpassed the initial tsunami around 3000 km from HTHH. Our work contributes to the ever-growing research surrounding tsunamigenic submarine volcanism and ionospheric propagation. Future work may involve exploring whether we can distinguish the role of crater collapse and individual explosions in each TID, as well as whether additional DART data can be filtered and examined farther from the volcano.

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Data Availability Statement

All raw GNSS data is publicly available at GNS (https://data.geonet.org.nz/gnss/rinex/), UNAVCO (https://data.unavco.org/archive/gnss/), CDDIS (https://cddis.nasa.gov/archive/gnss/data/daily), and Geoscience Australia (https://data.gnss.ga.gov.au/). The SNIVEL_ION code is freely available at https://zenodo.org/record/6885331. DART data from New Zealand was accessed through the GEONET FDSN API (https://www.geonet.org.nz/data/tools/FDSN). NOAA DART data was obtained through their event response page (https://www.ngdc.noaa.gov/hazard/dart/2022tonga.html). All of the ionospheric waveforms used in this study are available on Zenodo (https://doi.org/10.5281/zenodo.6568025).

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