Secondary gravity waves generated after the Tonga volcano explosion and its effect on the ionosphere

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Introduction

On **January 15, 2022, between 4:00 and 4:16 UT** a major volcanic eruption occurred on the island of Hunga Tonga-Hunga Ha'apai (20.6° S; 175.4° W) in the South Pacific. The explosion reached the magnitude of 9-37 Mtons of TNT (Astafayeva et al. 2022). The water in contact with the magma quickly turned into gas that expanded rapidly reaching 55 km(Carr et al., 2022). **In this work we present traveling ionospheric disturbances (TIDs) generated by Tonga's eruption over New Zealand (NZ), Australia (AUS), and South America (SA) using detrended total electron content (dTEC) maps.** Next we discuss how these waves propagated in the atmosphere using ray tracing (RT) and The High Altitude Mechanistic general Circulation Model (HIAMCM).

dTEC Methodology

We calculated the vertical TEC (VTEC) from >1000 receivers from GPS and GLONASS constellations every 30 s without including satellite and instrumental bias. Next, we detrended TEC (dTEC) by subtracting a 1-hour running average (centered at ±30 min.) from the original VTEC time series .

$$\text{dTEC}= VTEC(t) - \langle VTEC(t \pm 30\, min)\rangle.$$

2D dTEC maps and keograms were made with 0.2° bin and smoothed by 1°. The ionospheric pierce point was set at 300 km and elevation angle greater than 30°.

NZ and AUS dTEC maps

QR1: Link to the Figure 1 movie.

Figure 1 shows 3 snapshots of dTEC maps with TIDs signatures associated with the Tonga's eruption on January 15, 2022 . The first TID arrived over NZ with $\lambda_H = 1300 \pm 36$ km, $C_H = 551 \pm 38$ m/s, $\tau = 39 \pm 3$ min, and $\alpha = 210$ °. The AUS TID arrived about 2 hours after NZ TID with $\lambda_H = 922 \pm 61$ km, $C_H = 375 \pm 37$ m/s, $\tau = 41 \pm 3$ min, and $\alpha = 266$ °.

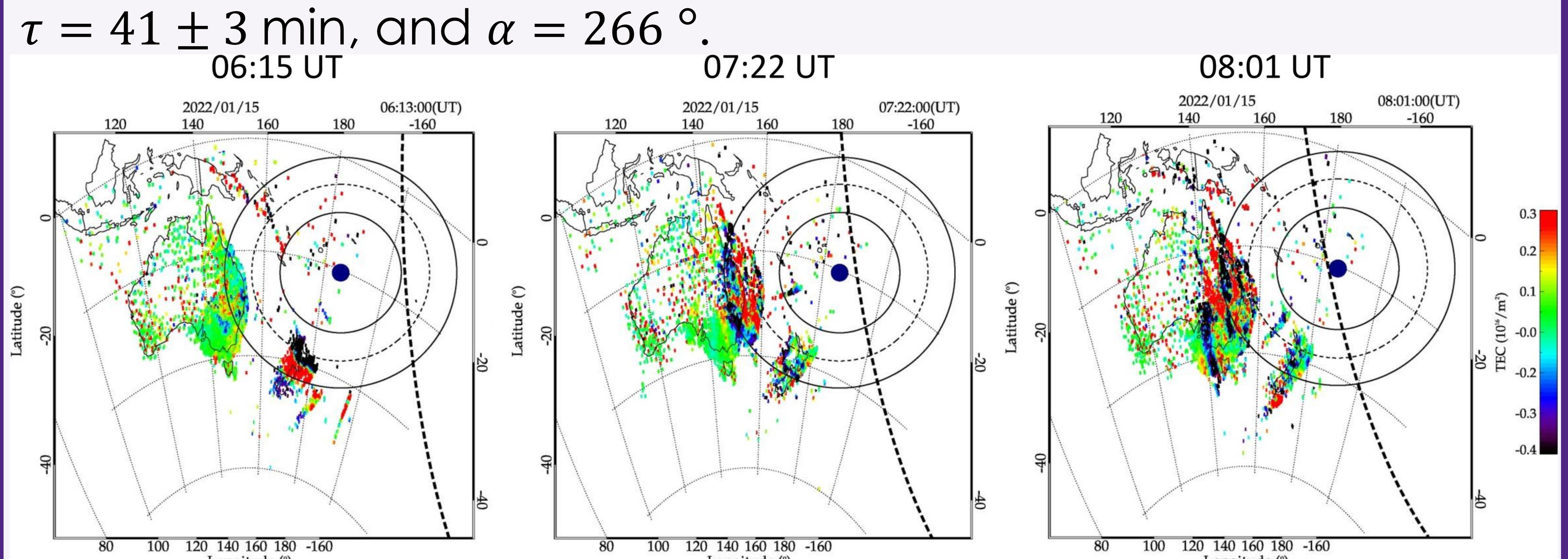

Figure 1: shows a sequence of 3 snapshots of dTEC maps on January 15, 2022 between 06:15 and 09:03 UT. The Tonga Volcano is located at the blue dot. The concentric circles from inner to outer have 2000, 3000, and 4000 km radius. The dashed black lines represent the dusk solar terminator at ~300 km height.

3D Ray Tracing

This RT model solves the gravity wave dispersion relation with thermal diffusivity and kinematic viscosity (Vadas and Fritts, 2005). The input background neutral temperature, wind, and density are from the HIAMCM (Becker et al. 2022) nudged to the Modern-Era Retrospective and analysis for Research and Application-version 2 (MERRA-2) (Gelaro et al., 2017).

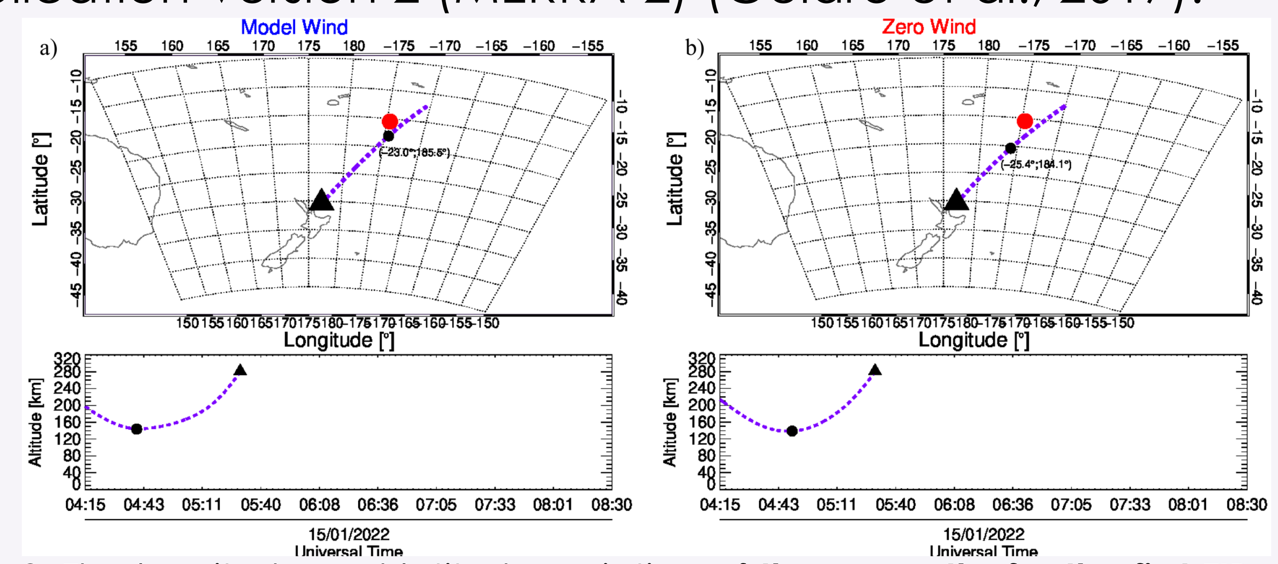

Figure 2: The longitude and latitude variation of **the ray paths for the first TID over NZ** are shown in the upper row, whereas time variation of the tID ray path with altitude is presented in the lower row. a) backward ray tracing with the HIAMCM wind b) backward ray tracing with zero wind. The red dot is the location of the Tonga volcano, and the black triangle shows the starting location of the RTing. The black dot shows lowest altitude the attained by the gravity waves .

The first TIDs observed over NZ cannot propagate directly from Tonga's eruption due to the fact that Ch is much larger than the sound speed in the lower atmosphere. Therefore, we must consider the mechanism of secondary gravity wave generation from the thermosphere body forces created by the dissipation of primary GWs from Tonga's volcano

Primary and secondary GWs from Tonga

1) Primary GWs excited by convective plume envelope model adapted to the explosions (Vadas & Fritts, 2009);
2) RT these primary GWs into the thermosphere and calculates the body forces (Vadas & Liu, 2013);
3) Input these body forces into the nudged HIAMCM to calculate the 2nd GWs.

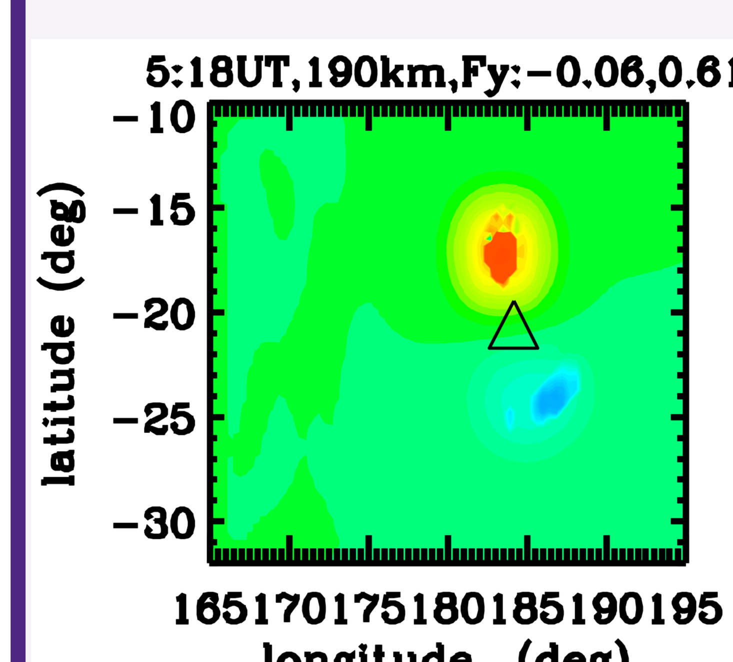

Figure 3: shows dissipation of 1st GW creating body forces at 5:18 UT at 190 km altitude. The color indicates the body forces amplitudes (m/s²).

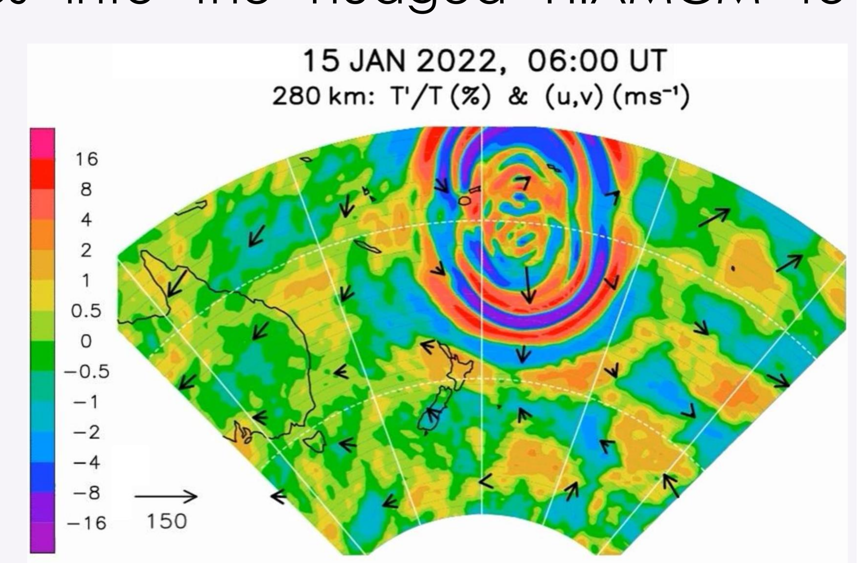

Figure 4: shows 2nd GWs at 6:00 UT propagating toward New Zealand at 280 km altitude with $\lambda_H = \sim 1000$ km. The Arrows indicate the direction and magnitude of the background wind. The colorbar indicates the GWs perturbation in the neutral temperature (%).

QR2: Link to the Figure 4 movie.

SA dTEC Keograms

QR3: Link to the Figure 5 movie. QR4: Link to the 2nd GWs over SA.

Effects of Tonga's eruption were also observed in SA. Figure 5 shows latitudinal (-35° N) and meridional (290°) keograms with TIDs propagating northeastward after 11:30 UT. Besides, few TIDs are propagating southward.

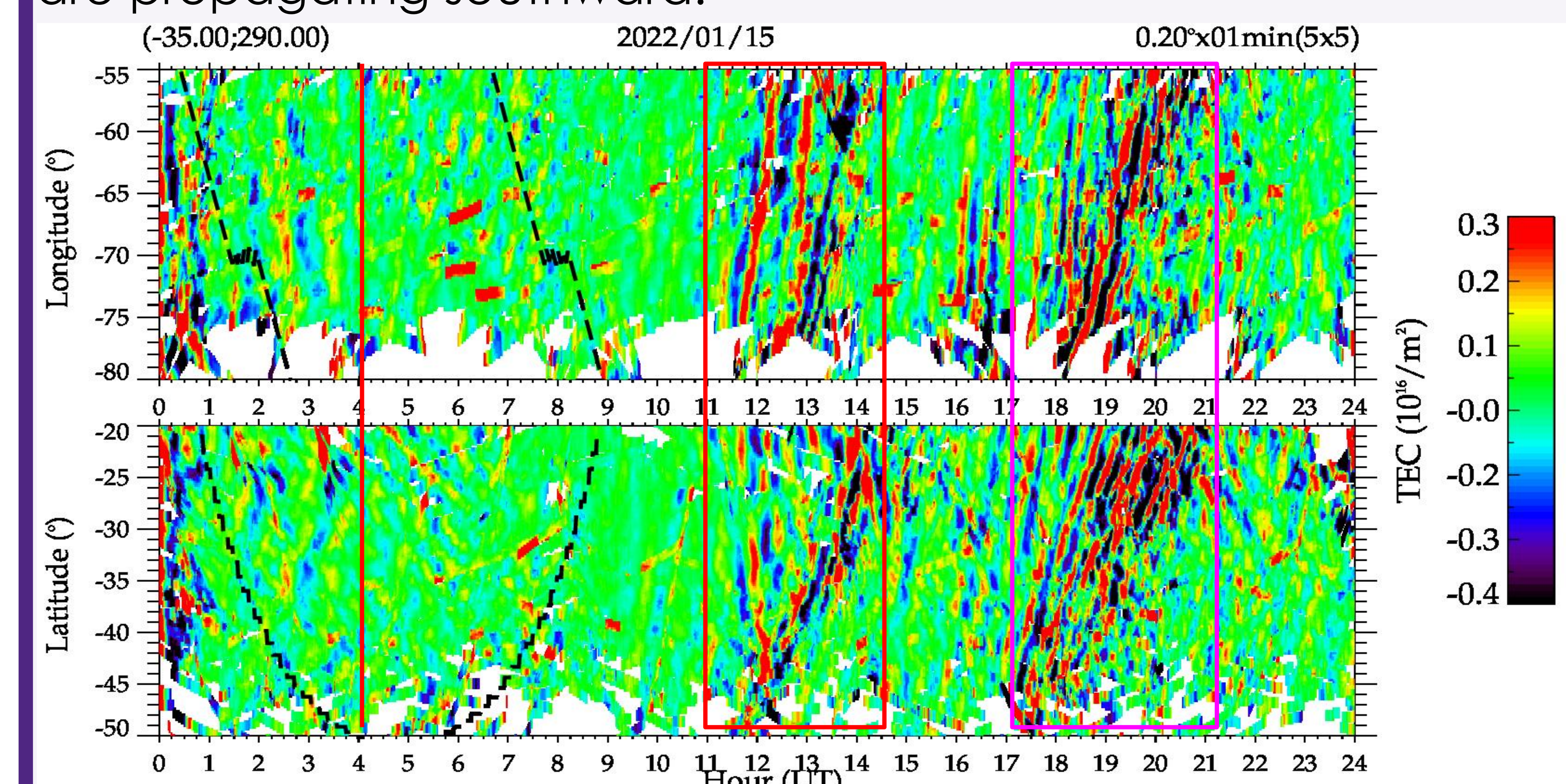

Figure 5: shows dTEC latitudinal and longitudinal keograms on January 15. The Tonga's eruption start in the continuum red line. The dashed black lines represent the terminator at ~300 km height.

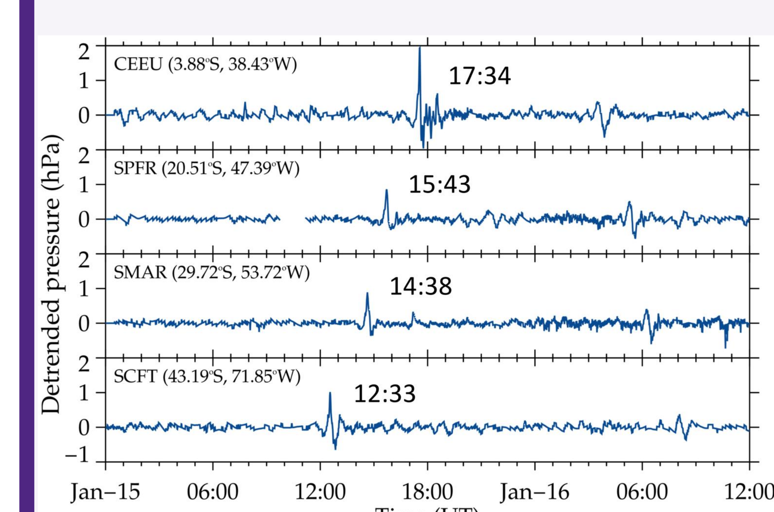

Figure 6: shows Lamb wave signature on detrended tropospheric pressure over SA on January 15 and 16.

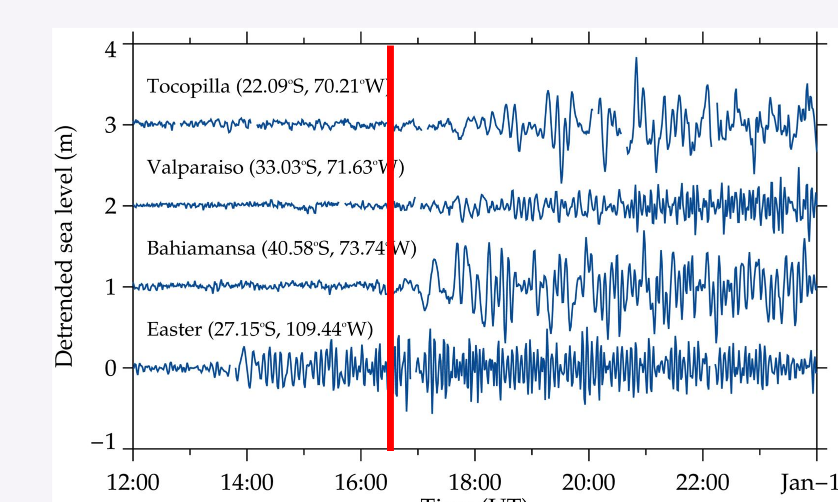

Figure 7: shows tsunami signature from Tonga's eruption in the detrended sea level on Chilean coast at 16:30 UT (red line).

Summary

- We observed different TIDs over NZ, AUS, and SA.
- The first TIDs observed over NZ cannot propagate directly from Tonga.
- It is likely that secondary GWs can explain the early fast TIDs seen over New Zealand but not seen over Australia.
- There is an apparent correlation in time between TIDs and Lamb/tsunami over SA.

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Astafyeva, E., Maletckii, B., Mikesell, T. D., Munaibari, E., Ravanelli, M., Coisson, P., et al. (2022). The 15 January 2022 Hunga Tonga eruption history as inferred from ionospheric observations. *Geophysical Research Letters*, 49, e2022GL098827. https://doi.org/10.1029/2022GL098827
Sharon L. Vadas & Dave C. Fritts (2009). Reconstruction of the gravity wave field excited by convective plumes via ray tracing in real space, Annals. Geophys., 27, 147-177.
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