Traveling Ionospheric Disturbances of the 2022 Tonga Volcano Eruption Observed by Ground-based GNSS Receivers in Taiwan and Japan

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Abstract

The 15 January 2022 Tonga volcanic eruption triggered prominent traveling ionospheric disturbances (TIDs) which propagate worldwide. The total electron content (TEC) and its tie rate of changes (rTEC) derived by local ground-based GNSS receiving stations as well as Doppler frequency shifts (DFSs) recorded by CW-HF (continuous wave-high frequency) Doppler sounding systems are employed to observe the TIDs in Taiwan and Japan. DFSs show that upon the thermospheric and tropospheric lamb wavefront arrivals, the ionosphere has been abruptly uplifted of about 69-114 km and 38-57 km, respectively. The uplifted ionosphere further seeds plasma irregularities and significantly fluctuates rTECs.

Introduction & Motivation

On January 15, 2022, at 04:05 UTC, the Tonga volcanic eruptions triggered traveling atmospheric and ionospheric disturbances (TADs and TIDs) propagating all over the world. Scientists observed that the TADs of tropospheric Lamb waves travel with the horizontal speed of about 315 m/s in Himawari-8 satellite images, while the TIDs related to the tropospheric Lamb waves and thermospheric lamb waves with the horizontal speeds of 315 m/s and 487m/s have been observed in ground-based GNSS total electron contents (TECs), magnetograms, ionograms, and in situ ion densities measured by FORMOSAT-7/COSMIC-2 satellites (Astafyeva et al., 2022; Lin et al., 2022; Liu et al., 2023, 2024). Here, the TEC and its time rate of change (rTEC) derived by local ground-based GNSS receiving stations are used to study the horizontal speed of TIDs in Taiwan and Japan. Doppler frequency shifts (DFSs) recorded by HF (high frequency) Doppler sounding systems, consisting of 5 sounding frequencies and 9 receiving stations, in Taiwan are employed to find response of the vertical motion of the ionosphere to the TIDs in Taiwan.

Methodology

GPS-TEC

- For elevation angle greater than 60, the rate of total electron content (rTEC) is derived from the change in vertical total electron content (VTEC) over time,

$$rTEC = \frac{\partial VTEC}{\partial t}$$

- The rTEC is obtained by various satellites and ground-based stations in Taiwan and Japan.

HF Doppler Sounding Systems

- Ionospheric Doppler frequency shifts recorded by multiple sounding frequencies at various stations in Taiwan.

Ionosonde

- Reference of ionosphere uplift in 4 stations in Japan and 1 station in Taiwan.

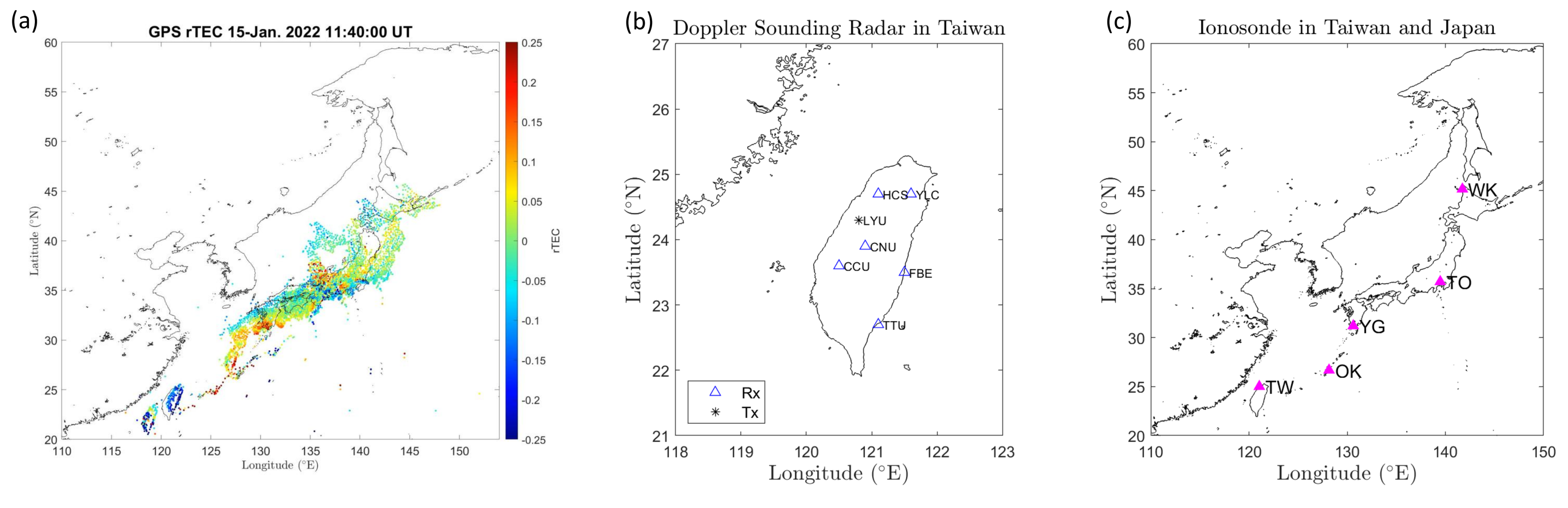

Fig 1. Multiple observation instruments.(a) rTEC observed in Taiwan and Japan. (b) Tx and Rx of Doppler sounding systems. (c) Ionosonde stations in Taiwan and Japan

Result 1: rTEC Disturbances

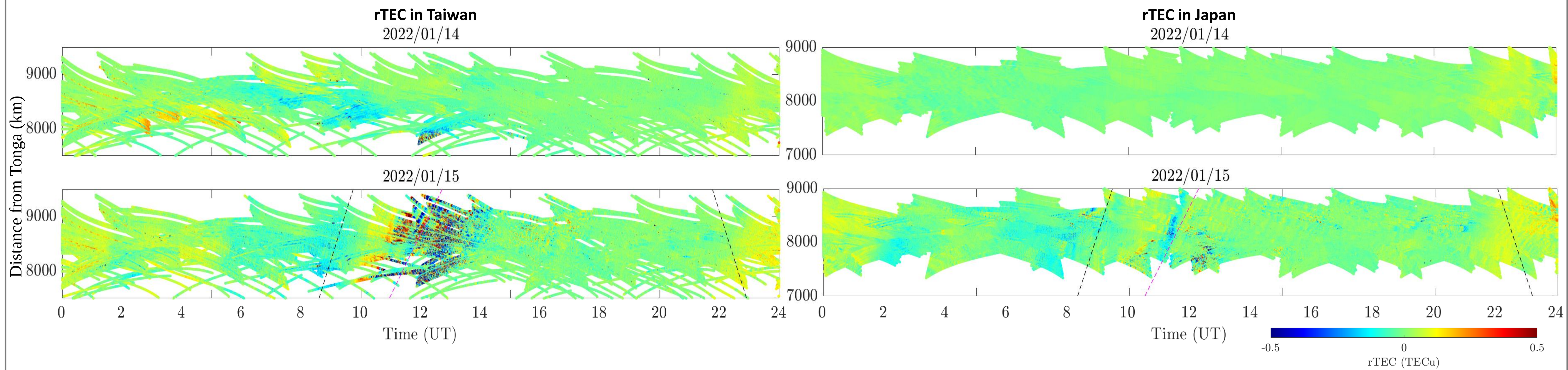

Fig 2. rTEC observed in Taiwan and Japan on Jan14 and Jan15. The ionospheric uplifts enhanced the growth rate of Rayleigh-Taylor instability processes, resulting in occurrences of ionospheric spread-F over Taiwan and Japan during the nighttime on January 15, 2022.(The black/magenta lines indicate the expected passing times of the thermospheric Lamb wave and tropospheric Lamb wave.)

Result 2: Signatures of Ionospheric Uplifts

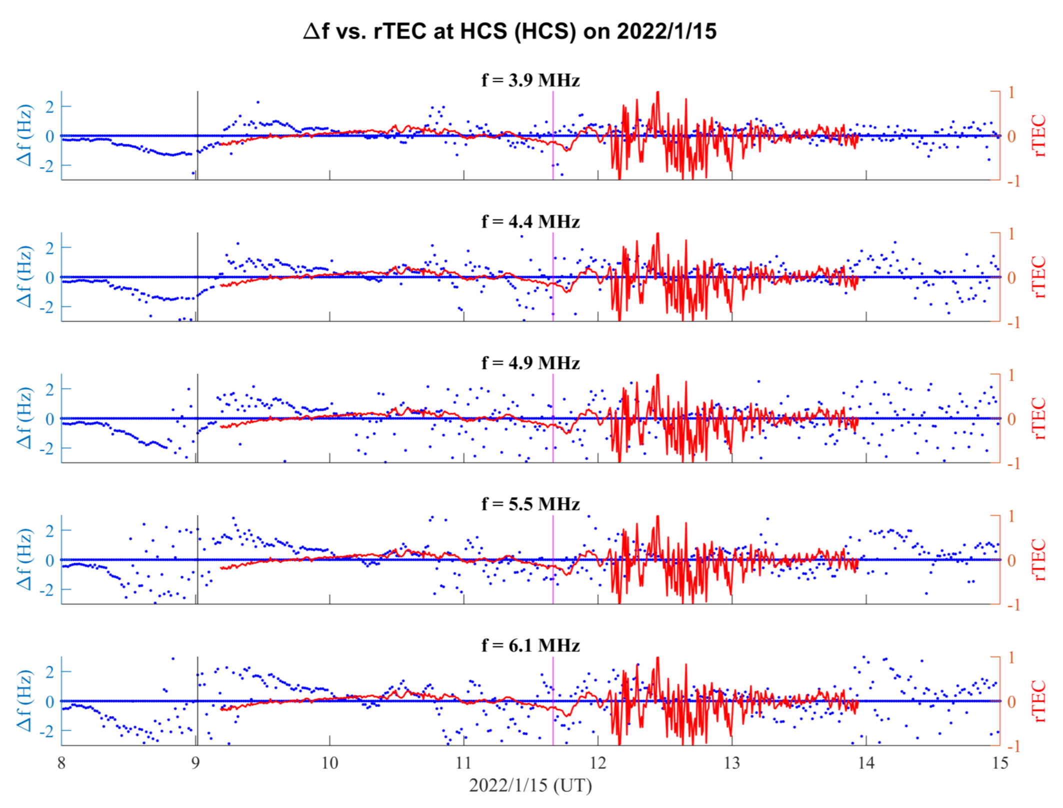

Fig 3. The first thermospheric (tropospheric) Lamb waves start uplifting the ionosphere prior to 0901 (1140) UT, followed by significant fluctuations in rTEC at 1145-1354 UT on January 15. .(The black/magenta lines indicate the expected passing times of the thermospheric Lamb wave and tropospheric Lamb wave.)

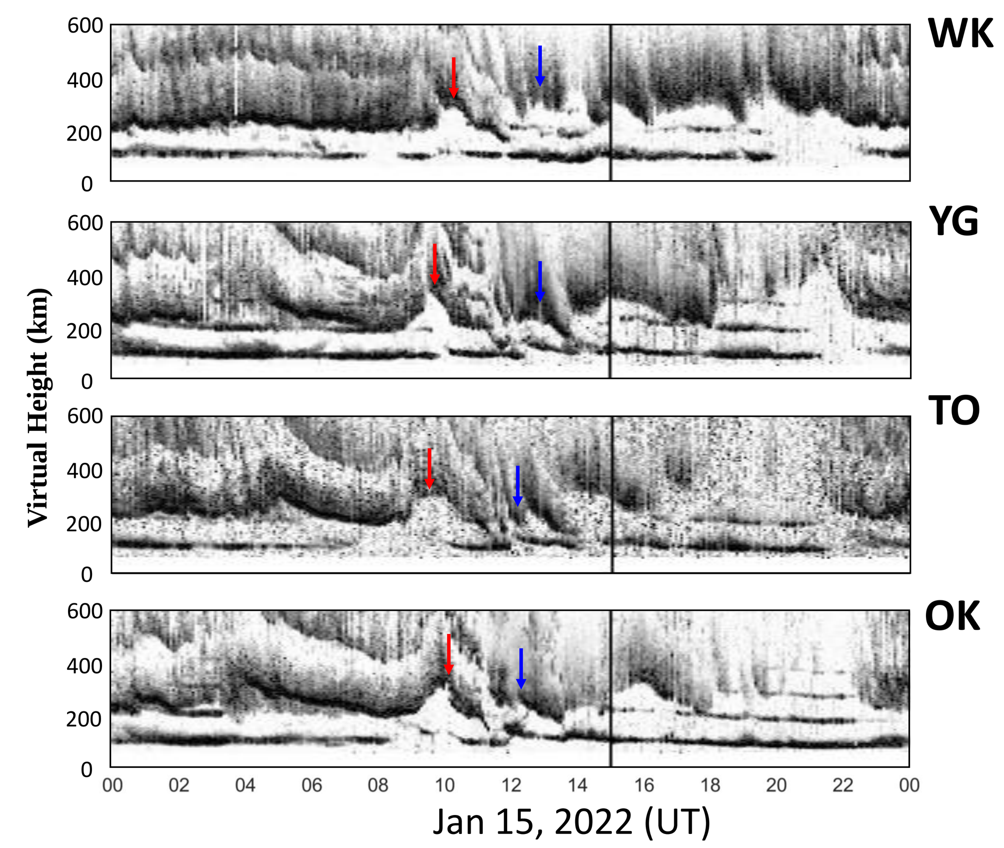

Fig 4. The ionospheric uplift observed by Ionosondes in Japan. Similar uplift signatures associated with thermospheric and tropospheric lamb waves have been observed upon their arrival. (The red/blue arrows indicate the ionospheric uplifts led by the thermospheric Lamb wave and tropospheric Lamb wave)

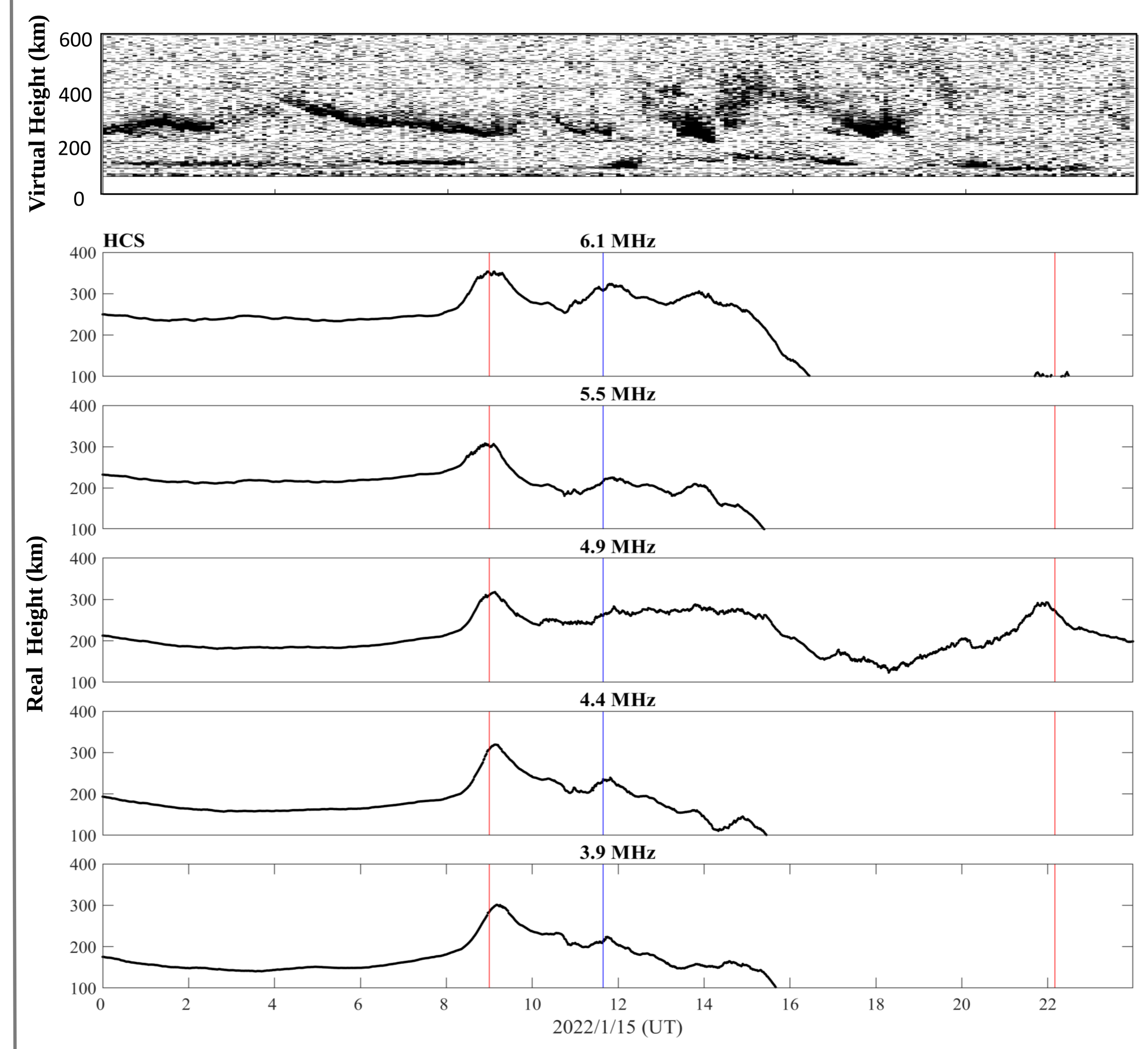

Fig 5. The uplifted signatures observed by the ionogram and the true height of Doppler frequency shifts at the 5 sounding frequencies of 3.9-6.1 MHz in Taiwan. (The red/black lines indicate the expected passing times of the thermospheric Lamb wave and tropospheric Lamb wave)

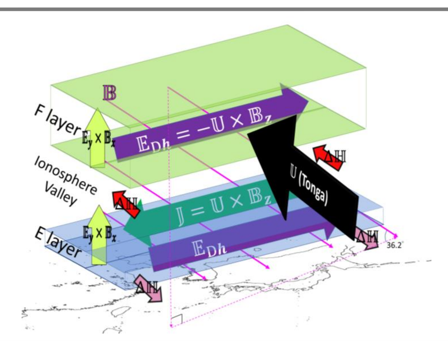

Fig 6. Sketch of the ionospheric uplift induced by eastward dynamo due to Lamb waves. According to $J=q(U\times B)+\sigma E$, when U increases sharply due to the disturbance, the eastward electric field generated by the current enhances. In the E-layer of the ionosphere, collisions are more frequent and tend to cancel each other out, resulting in a current-induced eastward electric field that causes $E\times B$ drift, leading to the uplift of the ionosphere. As the ionosphere uplifts to the F-layer, the TEC increases rapidly. Liu et al. (2023)

Summary & Conclusion

- DFSs (h'F) significantly decreases (increases), which indicates the ionosphere being remarkably uplifted upon the tropospheric and thermospheric Lamb wave arrivals. The uplifted ionosphere can efficiently enhance the Rayleigh-Taylor instability.
- rTEC stands for fluctuations of the GPS carry phase. Prominent rTEC fluctuations and spread-F occurred after the ionosphere had been uplifted by the two Lamb waves.
- Simultaneous uplifts in the reflection height of the five DFSs indicates that the eastward dynamo electric fields play an important role.

Reference

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