Significant Ionospheric Plasma Depletions and Enhancements after the 2022 Tonga Volcano Eruption

IRRI-9

Tien-Chi Liu[1], Po-Han Liao[2], Jann-Yenq Liu[1,2], Po-Han Lee[3], Cissi Y. Lin[1,2], Tsung-Yu Wu[2], Chi-Yen Lin[1,2]

[1] Department of Space Science and Engineering, National Central University, Taoyuan, Taiwan; [2] Center for Astronautical Physics and Engineering, National Central University, Taoyuan, Taiwan; [3] Weather Administration, Taipei, Taiwan

Abstract

This study examines the local ionospheric response to the January 15, 2022, Tonga volcanic eruption using the Global Ionosphere Map (GIM), FORMOSAT-7/COSMIC-2 (F7C2), and FORMOSAT-5 (F5). Results show that the total electron content (TEC) decreased by 5–10 TECu (50%) for 12 hours (0500–1600 UT) and subsequently increased by 2–18 TECu (50%) between 17 and 23 hours post-eruption (2100–0300 UT) within approximately 1650 km of the Tonga volcano. The electron density profiles from F7C2 indicate that the F2-layer peak density decreased by 8×10^5 #/cm³ (74%) at nighttime, and the maximum enhancement is approximately 1×10^6 #/cm³ (84%) at daytime over the volcano. During the nighttime on the event day, vertical ion motion at 720 km observed by F5's Advanced Ionospheric Probe (AIP) and at 550 km by F7C2's Ion Velocity Meter (IVM) showed upward and downward directions, respectively, within the depletion region—consistent with southern hemisphere plasma dynamics.

Motivation

The 2022 Tonga Volcano Eruption

- **Jan 15, 2022, 04:00–04:10 UT**: One of the most energetic submarine volcano eruptions in a century occurred at **Hunga Tonga–Hunga Ha'apai** (175.38°W, 20.57°S)
- The volcanic cloud reaches an altitude of **57 km (35 mi)**, into the mesosphere [1] (Fig. 1)
- An umbrella cloud centered on the volcano with a radius of 200–250 km [2]

To investigate whether the eruption triggered umbellar-shaped signatures in the ionospheric plasma, we analyze total electron content (TEC) from the global ionosphere maps (GIMs) and radio occultation (RO) electron density profiles, alongside in-situ plasma parameters observed by F7C2 and in-situ plasma quantities measured by F5 between 01:00 UT January 15 and 06:00 UT January 16, 2022 (Fig. 2).

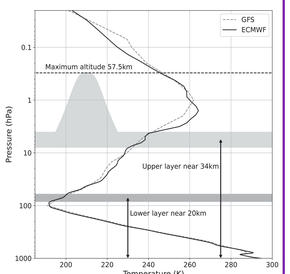


Fig. 1 Vertical structure of the volcanic plume [1]

Data and Methods

GIM TEC
Derived from GNSS data; 1-hr temporal resolution
Global coverage: ±87.5° latitude, ±180° longitude, with 2.5°×5° spatial resolution
Reference: Monthly median of TEC in January 2022

F7C2 RO Electron Density Profiles
Reference: Profiles within ~1000 km at the same LT over a 7-day window

F7C2 IVM
Height: 550 km; low Earth orbit (LEO)
Measures ion temperature, velocity, and density at a 1 Hz sampling rate

F5 AIP
Height: 720 km; sun-synchronous orbit passes at approximately 22:30 LT
Measures ion density and velocities (downward/eastward) at a 1 Hz sampling rate

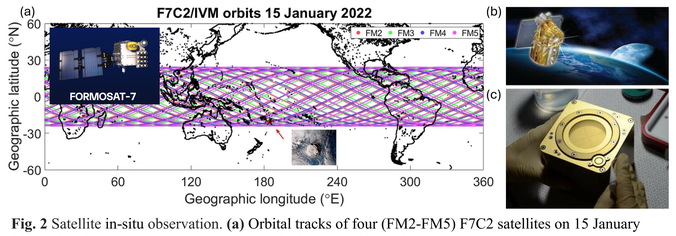


Fig. 2 Satellite in-situ observation. **(a)** Orbital tracks of four (FM2-FM5) F7C2 satellites on 15 January 2022 [3]. **(b)** Image of a flying simulation of F5 and **(c)** F5/AIP [4]

Results: TEC Variations

Prominent reductions of ΔTEC = -5~-10 TECu (TEC unit, 10^{16} #/m²) appear during 05:00–16:00 UT (17:00 – 04:00 LT, nighttime).

Significant enhancements of ΔTEC = 2~18 TECu occur during 21:00 – 03:00 UT (09:00 – 15:00 LT, daytime).

Ionospheric depletion and enhancement are observed within a range of 1650 km.

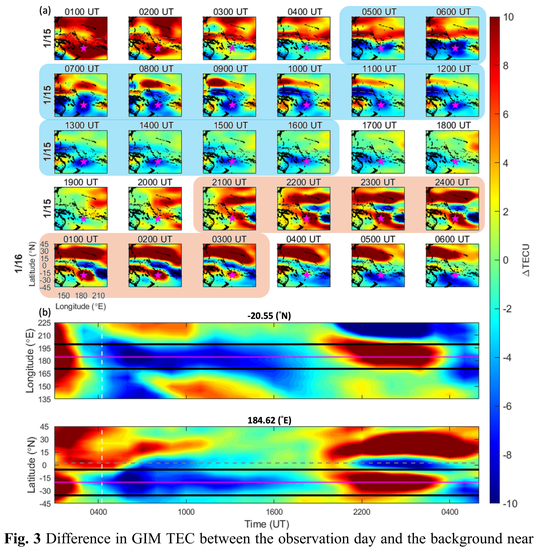
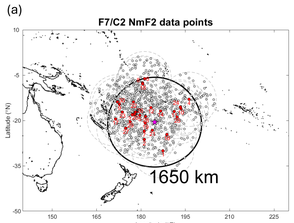


Fig. 3 Difference in GIM TEC between the observation day and the background near the Tonga volcano from 1800 UT on 14 January 2022 to 0600 UT on 16 January 2022. **(a)** Hourly TEC variation within the study region (135°E to 225°E, 45°S to 45°N). **(b)** TEC variation at a longitude of 184.62°E and latitude of -20.55°N.

Results: Hourly Electron Density Profile

Electron Density significantly decreases at altitudes between 200 and 500 km during nighttime, and becomes prominently greater than the reference value, especially above the F2-peak height, during daytime.



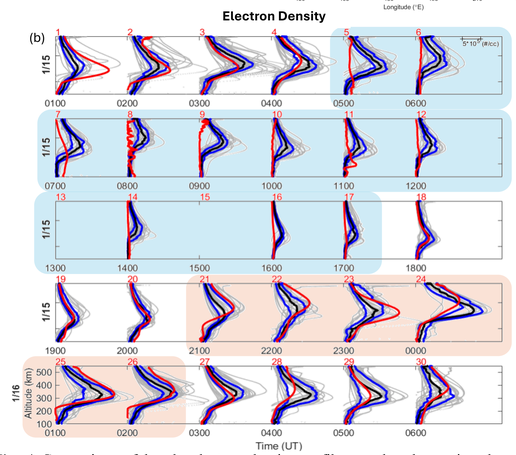


Fig. 4 Comparison of hourly electron density profiles on the observation day with background by F7/C2 from 1800 UT on 14 January 2022 to 0600 UT on 16 January 2022 within the range of 1650 km. **(a)** The NmF2 positions of F7C2 profiles. **(b)** The red line indicates observation day, the gray line indicates background, the black line indicates the background median, and the blue line indicates the interquartile of background.

Results: Ion Density, Temperature, and Velocities Changes at 550 km and 720 km Altitude

Nighttime: Changes of the center from the edge that the ion density (Ni) reduces by about 2.6–4.1x10^5 #/cm³ (72–95%); the ion temperature (Ti) increases from 1000–1500°K to 3200 – 4000°K by a factor of 2.4.
Daytime: Ion density increases by about 3.1–6.8x10^5 #/cm³ (234 – 532%); and the ion temperature tends to slightly decrease by about 319 – 470°K (19 – 27%).

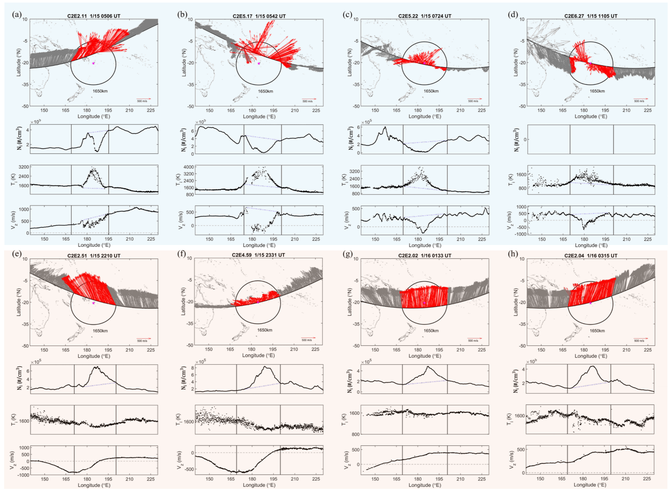


Fig. 5 Post-eruption IVM data along the longitude of the satellite trajectory, including ion density, temperature, eastward velocity, northward velocity, and vertical velocity.

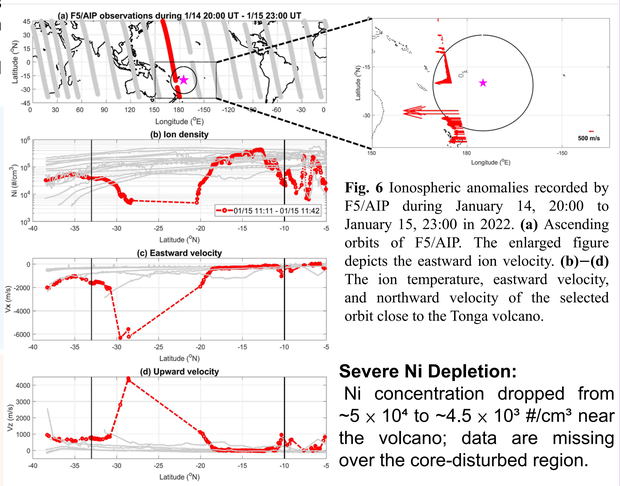


Fig. 6 Ionospheric anomalies recorded by F5/AIP during January 14, 20:00 to January 15, 23:00 in 2022. **(a)** Ascending orbits of F5/AIP. The enlarged figure depicts the eastward ion velocity. **(b)–(d)** The ion temperature, eastward velocity, and northward velocity of the selected orbit close to the Tonga volcano.

Severe Ni Depletion:
Ni concentration dropped from ~5 x 10^4 to ~4.5 x 10^3 #/cm³ near the volcano; data are missing over the core-disturbed region.

Extreme Ion Velocities:
Vx peaked at ~6000 m/s (vs. ~200 m/s background).
Vz peaked at ~4500 m/s before dropping to ~0 m/s at the edge.

Core Disturbance Zone:
Ni and velocity data are unmeasurable between –28° and –20°N

Main Findings

Parameter	Nighttime (05:00–16:00 UT / 17:00–04:00 LT)	Daytime (21:00–03:00 UT / 09:00–15:00 LT)
TEC (GIM)	Decrease of 5–10 TECu (~50%)	Increase of 2–18 TECu (~50%)
Affected Area	~1650 km radius from the volcano	
Electron Density (F7C2 RO)	Max reduction of ~8×10^5 #/cm³ (74%)	Max enhancement of ~1×10^6 #/cm³ (84%)
Ion Density (F7C2/IVM)	Depletion at 550 km altitude	Enhancement at 550 km altitude
Ion Temperature (F7C2/IVM)	Significant increase	No significant change
Vertical Ion Velocity	Downward (F7C2/IVM, 550 km altitude); Upward (F5/AIP, 720 km altitude)	No significant change
Horizontal Ion Velocity	Radially outward from volcano	Not pronounced
Overall Effect	Long-lasting plasma depletion	Long-lasting plasma enhancement

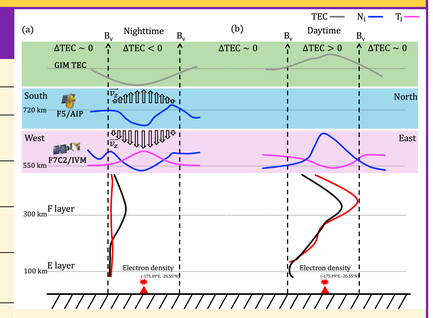


Fig. 7 A summary sketch of the ionospheric response during the (a) nighttime and (b) daytime periods after the Tonga volcano eruption on 15 January 2022

Discussion and Conclusion

Thermal and Hydrostatic Effects:
Elevated neutral temperatures raised N_2, O_2, and O densities while decreasing the O/N_2 ratio. These compositional changes accelerated ion loss processes, further reducing the total electron content (TEC) and plasma density.

Plasma Motion Patterns:
F7C2/IVM horizontal ion drifts (Vx/Vy) are radially outward from the volcano. While the vertical ones (Vz) are upward at 720 km (F5/AIP) and downward at 550 km (F7C2/IVM), respectively.
These motions align with expected southern hemisphere plasma transport: poleward/downward south of Tonga and equatorward/upward to the north.
Strong downward plasma flux during 04:00–08:00 UT increased electron density at 100–200 km altitude.

Daytime Ionospheric Response:
Increased neutral temperature and atomic oxygen enhanced photoionization rates, resulting in enhancements in ion and electron density from 18:00 to 20:00 UT.

Acknowledgements and References

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