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Supporting Information for

Extreme poleward expanding super plasma bubbles triggered by Tonga volcano eruption during the recovery phase of geomagnetic storm

P. K. Rajesh[1], C. H. Charles Lin[1], J. T. Lin[1], C. Y. Lin[2,3], J. Y. Liu[2,3], T. Matsuo[4], C. Y. Huang[5], M. Y. Chou[6,7], J. Yue[6,7], M. Nishioka[8], H., Jin[8], J. M. Choi[1], S. P. Chen[1], Marty Chou[1], and H. F. Tsai[1]

[1] Department of Earth Sciences, National Cheng Kung University, Tainan, Taiwan

[2] Center for Astronautical Physics and Engineering, National Central University, Taoyuan, Taiwan

[3] Department of Space Science and Engineering, National Central University, Taoyuan, Taiwan

[4] Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, CO, USA

[5] National Space Organization, Hsinchu, Taiwan

[6] NASA Goddard Space Flight Center, Community Coordinated Modeling Center, Greenbelt,

MD, USA

[7] Physics Department, Catholic University of America, Washington, DC, USA

[8] The National Institute of Information and Communications Technology, Tokyo, Japan

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Additional Supporting Information (Files uploaded separately)

Introduction

Following the explosive eruption of the Tonga volcano, plasma bubbles were observed in total electron content (TEC) measurements of ground based global navigation satellite system (GNSS) at different longitudes across the globe. Figure S1 gives a comparison of the rate of TEC index (ROTI) maps at four different longitude sectors. It can be seen that very intense plasma bubbles are observed over East Asian longitudes, revealing very strong ROTI values (> 0.3) in the GNSS observations over Taiwan, Japan, Australia, and New Zealand, that expand to extreme poleward latitudes, reaching even beyond Tokyo.

These ROTI observations, when projected to corresponding apex altitudes of the magnetic field line over the equatorial plane, offers a unique view of ROTI resembling vertically elongated radar plumes. Such apex projections at different time steps are used to extract the vertical rise velocity of the irregularities. The velocities are estimated separately for both the northern hemisphere and southern hemisphere observations, by noting the variation of uppermost the apex altitudes of the prominent ROTI regions at 140°E and 145°E longitudes seen in Movie S1. The calculated velocities are shown in Figure S2.

Figure S3 shows selected ionograms over Kokubunji in Japan and Townsville in Australia, showing the onset, and progression of spread-F on this day. Over Townsville, the ionograms appear to show the onset of range spread-F at the high-frequency end of the trace around 0914 UT (~1900 local time, LT), which later covers the entire transmitted frequencies in about 2-hours and manifests as complete spread-F by 1134 UT. The intense spread-F echoes that followed lasted the entire night (~0400 LT). The Kokubunji ionograms also reveal a similar progression with diffused high frequency traces from 1910 LT (1010 UT) but turn to complete spread-F by 2020 LT (1120 UT), lasting for several hours. The apex altitudes of the magnetic field lines over Kokubunji and Townsville are ~2000 km.

Prior to the generation of the plasma bubbles, very intense electron density signature of the pre-reversal enhancement (PRE) of upward ExB drift was observed in the GIS electron density profiles. Such PRE is unusual in the solstice period under low solar activity. Figure S4 gives the time variation of the F-region peak altitude (hmF_2) and the peak density (nmF_2) at 140°E longitude on the day of the eruption, in comparison with the selected three reference days. The hmF_2 variation shows strong PRE that lifted the layer by ~200 km for more than 3-hours. The time variation of hmF_2 is used to calculate the vertical rise velocity of F-layer, yielding ~40 m/s, compared to an average ~13 m/s based on the reference day measurements.

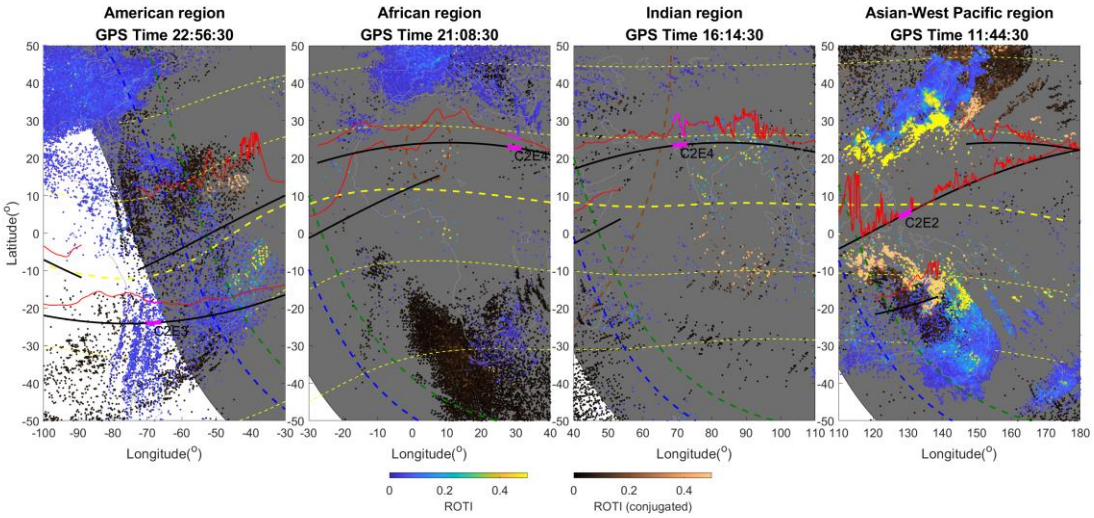

Figure S1. ROTI maps over selected longitude sectors. The selected time in the plot corresponds to the period when the ROTI appeared most prominent over that region. The left colormap indicates the ROTI observed over the given location, while the right colormap denotes the ROTI values projected from corresponding conjugate hemisphere to that location. The red line shows the in-situ ion-density measurements by FORMOSAT-7/COSMIC-2 during a 30-minute interval of the plotted time. The brown dashed line is the simulated ground locations of the barometric Lamb wave. The blue and green dashed lines denote E- and F-region terminators and the gray shaded region represents the regions under the ground-sunset. The yellow lines denote the locations of the geomagnetic equator in quasi-dipole apex coordinates, and the parallels at ±20 and ±40 degrees off the equator.

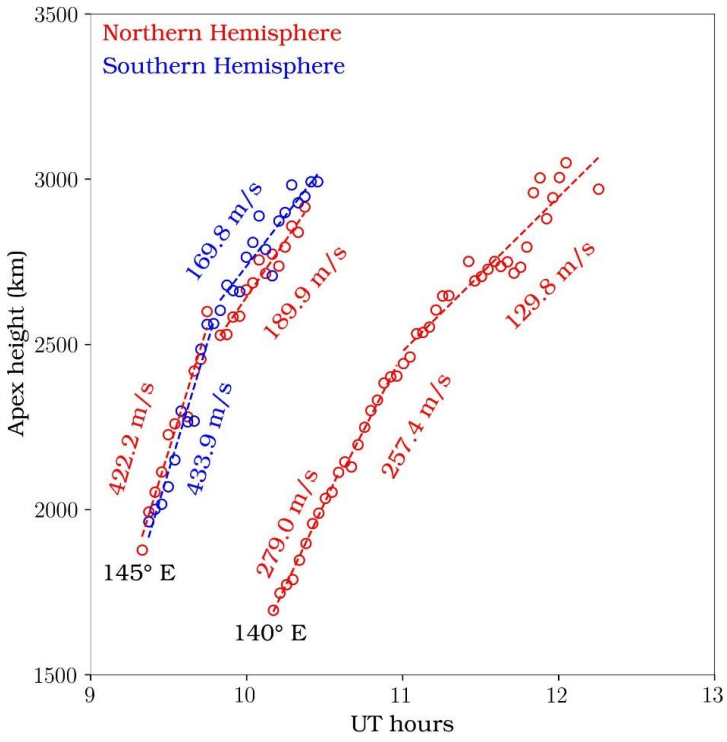

Figure S2. Vertical rise velocity of the plasma bubbles observed at 145° and 140°E, derived from Figure 3. The velocity is extracted by noting the variations of the apex altitudes of the selected ROTI regions at every 5-minute interval.

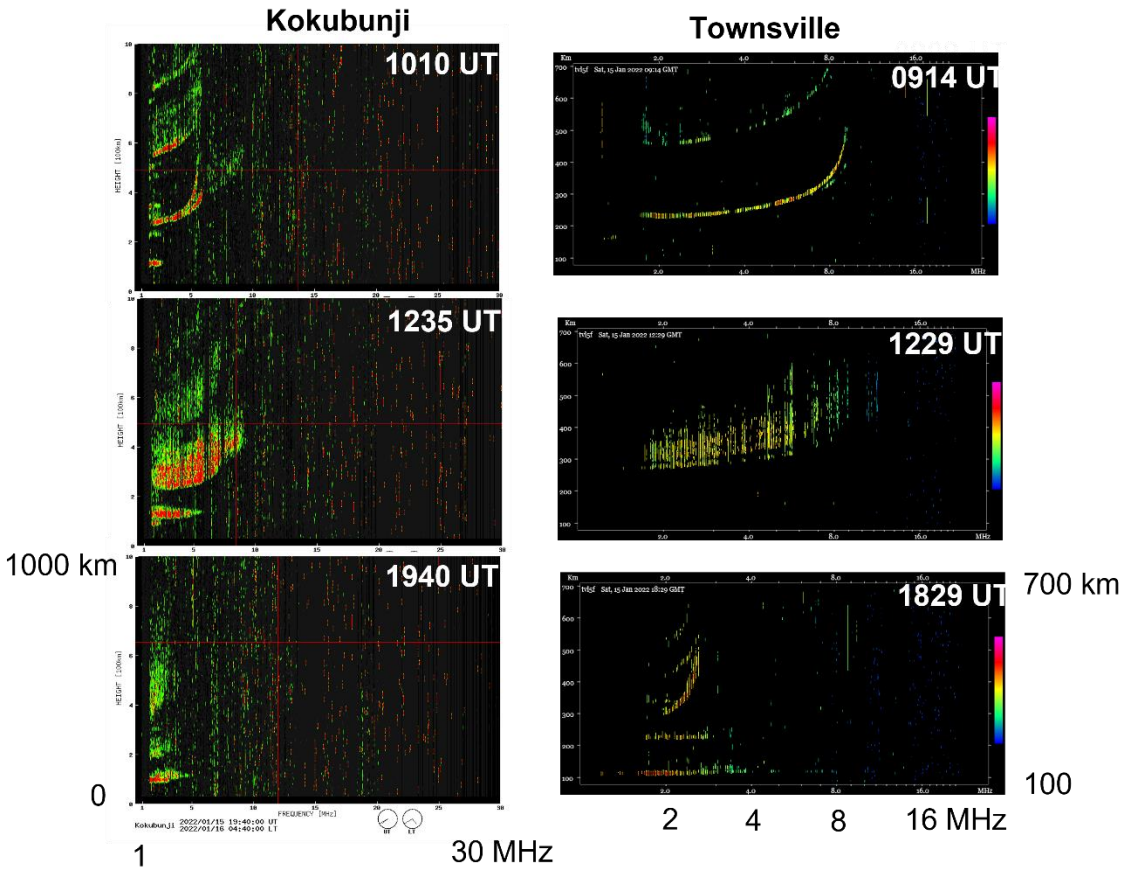

Figure S3. Selected ionograms showing the (top) onset, (middle) peak and (bottom) end stage of spread-F at (left) Kokubunji and (right) Townsville.

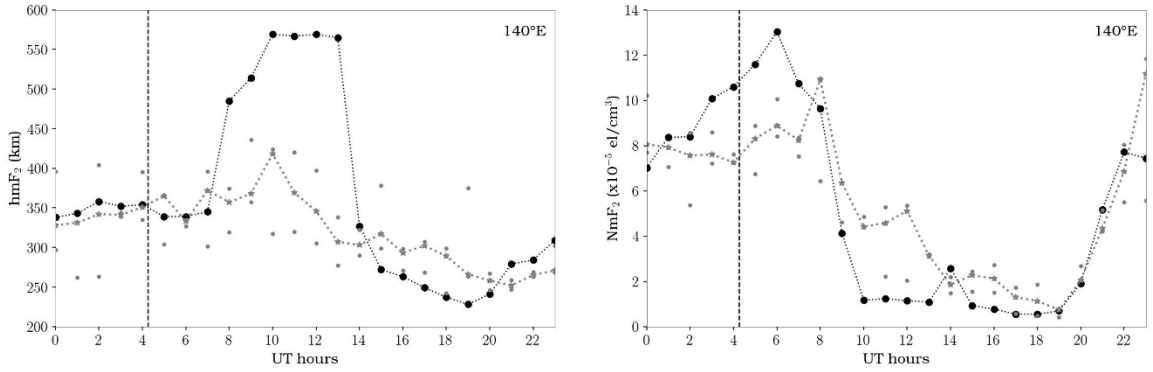

Figure S4. The hmF_2 and NmF_2 (black dots) on the volcano eruption day (15 January 2022) derived from GIS electron density maps. The gray-line shows the median value of the previous quiet 3-day values (gray-dots). The vertical rise velocity estimated from the hmF_2 variation on the eruption day during 0700-1000 UT (1700-2000 LT) is ~40 m/s.

Movie S1. A movie of the TEC, ROTI and filtered TEC values over the East Asian longitudes from 0400 hours to 1400 hours on 15 January 2022, illustrating the poleward expansion and eastward movements of strong ROTI locations. The format of the movie frames is same as that of the rows in Figure 1. The F7/C2 IVM observations at the corresponding time intervals are also overplotted in dark red color, adopting the similar format used in Figure 2.