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The giant ionospheric depletion on 15 January 2022 around the Hunga Tonga-Hunga Ha'apai volcanic eruption

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Key points:

- The strong (i.e., ~80-95%) and long-lasting (i.e., ~16 hours) ionospheric depletion occurred after the 15 January 2022 Tonga eruption
- The volcanic explosion is responsible for ~60-75% depletion and horizontal extension of ~1500 km
- The depletion was reinforced by the moderate geomagnetic storm, and its extreme duration is due to local night hours

Abstract

The 15 January 2022 Tonga eruption seemed to have caused a strong depletion in the ionospheric electron density. However, the eruption occurred during a moderate geomagnetic storm, so that the depletion could be a local negative effect of the storm. In this work, for the first time, we analyze this depletion and discuss relative contributions of the eruption and the storm through measurements of GNSS-derived vertical total electron content (VTEC), O/N2 ratio by TIMED/GUVI, ion density and temperature by ICON/IVM, and simulations by Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM). We show that shortly after the eruption onset the VTEC in the vicinity of the volcano dropped by ~80-95% below the quiet-time values. The depletion extended up to 4000 km away from the volcano and lasted for ~16 hours, i.e., until local morning hours. Our results suggest that the depletion

38 was initially caused by the eruption (60-75% negative deviation) and was further reinforced by
39 the storm, by at least 20%. Spatially, only ~1500 km could be attributed to the eruption. This
40 study provides a good illustration of understanding the contributions of forcings from above
41 and below to the ionosphere.

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43

44 **1 Introduction**

45

46 Ionospheric disturbances driven by natural geological disasters have been extensively
47 discussed by previous studies (Yuen et al., 1969; Tanaka et al., 1984; Heki & Ping, 2005; Heki,
48 2006; Rolland et al., 2013; Shults et al., 2016; Astafyeva, 2019). Earthquakes, tsunamis or
49 volcanic eruptions generate gravity, gravito-acoustic or shock acoustic waves that propagate
50 upward into the atmosphere and ionosphere. Due to the near-exponential decrease in
51 atmospheric neutral particles with altitude, the corresponding waves can attain rather large
52 amplitudes. Different atmospheric wave modes can be excited and cause ionospheric
53 oscillations in the form of traveling ionospheric disturbances (TIDs) with periodicities in the
54 characteristic frequency domains of infrasonic, acoustic, tsunami-induced gravity waves. These
55 types of waves were observed in the ionosphere by a comprehensive set of satellite and ground-
56 based observations.

57 On 15 January 2022, one of the most explosive submarine volcanic eruptions in recent years
58 occurred at ~0415 universal time (UT) at the Hunga Tonga-Hunga Ha’apai island (20.54°S,
59 175.38°W, hereafter “Tonga”). This eruption lasted 11 hours (Witze, 2022) and generated
60 atmospheric shock waves, and also triggered a tsunami that was felt across the Pacific. The
61 eruption also generated numerous disturbances in the ionosphere, i.e., TIDs, that were detected
62 in the vicinity of the volcano and up to 6,000 km away from it (Themens et al., 2022; Zhang et
63 al., 2022; Lin et al., 2022; Maletckii & Astafyeva, 2022).

64 In addition to the TIDs, the Tonga eruption seemed to cause a huge depletion in the
65 ionospheric total electron content (TEC) in the vicinity of the volcano. Aa et al. (2022) used
66 detrended TEC data and reported a significant local depletion of 5-10 TECU that comprised
67 several cascading TEC decreases. Astafyeva et al. (2022) used unfiltered TEC data and
68 observed the decrease of ~13-18 TECU which represented ~80-90% deviation with respect to
69 the quiet-time reference level. Astafyeva et al. (2022) also reported that the depletion lasted
70 about 1.5-2 hours. They attributed the depletion to the giant shock wave, that was generated by
71 the eruption. Similar ionospheric depletion (also referred to as “ionospheric hole”) was

72 previously observed after large earthquakes (Kakinami et al., 2012; Astafyeva et al., 2013a;
73 Kamogawa et al., 2015) and was explained by strong nonlinear acoustic waves and their
74 impacts (Astafyeva et al., 2011; 2013a; Shinagawa et al., 2013; Zettergren & Snively, 2015).
75 However, the Tonga-related depletion seemed to be much stronger than the earthquake-
76 generated ionospheric holes. Astafyeva et al. (2022) suggested that the eruption-driven hole
77 was reinforced by a moderate geomagnetic storm that was ongoing during the eruption.
78 However, up to now, no detailed analysis was performed and the depletion was fully attributed
79 to the eruption. In addition, the depletion itself has not yet been investigated in detail. In
80 addition, we note that the datasets that were used previously by Aa et al. (2022) and Astafyeva
81 et al. (2022) do not allow to estimate the true magnitude and duration of the depletion. The use
82 of detrending procedure or band-pass filter removes the depletion from TEC data series and
83 alters its magnitude. While, the use of relative TEC time series can only provide relative
84 amplitude of the depletion, and the duration of the depletion observation is compromised by
85 the limited duration of observations by GNSS receivers.

86 In this work, for the first time, we provide a detailed study of the Tonga ionospheric
87 depletion. We use global maps of the absolute vertical TEC along with O/N₂ data from the
88 Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics/Global Ultraviolet Imager
89 (TIMED/GUVI), and ion density and temperature from the Ionospheric Connection Explorer
90 (ICON) Ion Velocity Meter, to illustrate the ionosphere and thermosphere disturbance during
91 this period. In addition, the model simulation results from the National Center for Atmospheric
92 Research (NCAR) Thermosphere Ionosphere Electrodynamics General Circulation Model
93 (TIEGCM) are further used to determine thermospheric/ionospheric variations during the
94 geomagnetic storm.

95

96 **2 Data and Methods**

97

98 The two-dimensional vertical total electron content (VTEC) observations are provided by
99 the Massachusetts Institute of Technology's (MIT) Haystack Observatory with a 1° by 1° bin
100 in latitude and longitude and a 5-min time resolution (Rideout & Coster, 2006). To investigate
101 spatio-temporal variations, here we analyse VTEC maps for three days, from 14 to 16 January
102 2022. To retrieve the depletion, we subtract the reference values from the event data. The
103 reference is calculated by averaging data over 4 quiet days: 10, 11, 12 and 13 January 2022.

104 The thermospheric O/N₂ ratio measurements are provided by the Thermosphere,
105 Ionosphere, Mesosphere Energetics and Dynamics/Global Ultraviolet Imager (TIMED/GUVI)

106 with 74.1° inclination and a 97.8 min period (Stephan et al., 2008). This ratio is widely used in
107 the ionospheric storm analysis as an indicator of a neutral composition disturbance (Christensen
108 et al., 2003; Meier et al., 2005; Crowley et al., 2006).

109 The ionosphere ion density and temperature measurements are provided by the Ionospheric
110 Connection Explorer Ion Velocity Meter (ICON/IVM) with 27° inclination and 575 km height
111 (Immel et al., 2018). These datasets provide a unique opportunity to analyze the spatio-temporal
112 ionosphere disturbance in the vicinity of Tonga.

113 The model simulation results of storm-related ionosphere and thermosphere effects are from
114 the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamic
115 General Circulation Model (TIEGCM). In this study, we used the high-resolution model version
116 with 1.25°x1.25° in geographic latitude and longitude, and a vertical resolution of 1/4 scale
117 height (Dang et al., 2018). The Weimer empirical model (Weimer, 2005), driven by the realistic
118 interplanetary and solar/magnetic indices, including the daily and 81-day average F10.7 cm
119 solar flux, solar wind velocity and proton number density, and interplanetary magnetic field Bx,
120 By and Bz components, was used to specify the high-latitude ion convection pattern. These
121 space weather indices are provided in Figure S1 in Supplementary Information. At the model
122 lower boundary, atmospheric migrating tides are specified by the Global Scale Wave Model
123 (GSWM) (Hagan & Forbes, 2003). Note that no volcano-related effects are included in this
124 model. The simulation results used in this paper include the TEC and O/N2 ratio.

125

126 **3 Results and Discussions**

127

128 Figure 1 (a) shows the time evolution of the two-dimensional differential VTEC maps from
129 0417 to 2317 UT on 15 January 2022 in the vicinity of the Tonga volcano. The full world
130 coverage for 14-16 January can be found in Animation S1 in Supplementary Information.
131 Figure 1 (a) clearly shows negative deviation of the VTEC around the volcano starting from
132 0437 UT, i.e., ~20 minutes after the beginning of the eruption. The depletion further seemed to
133 propagate away from the volcano to as far as 3000 km distance at around 0637 UT, and ~4000
134 km at around 0717 UT. We also note that the depletion seemed to be stronger on the south-
135 western side from the volcano. However, only a few observation points are available eastward
136 from the volcano to better confirm this asymmetry. The maximum depletion of -24 TECU (i.e.,
137 95% as compared to the before-eruption value of 26 TECU, Figure S2) can be observed at
138 ~0617-0637 UT on the south-west from the volcano, near -30°S.

139 From 1217 UT, the depletion decreased in value and in spatial coverage, and it ended at
140 around 2017 UT, i.e. during local morning hours. Therefore, this great depletion lasted for ~16
141 hours. Similar conclusions about the depletion's duration and magnitude can be done from the
142 time series of the absolute VTEC (Figure S2).

143 To further prove the spatial and temporal of the observed depletion with the volcanic
144 eruption, Figure 2 shows VTEC keograms for the volcano longitude (175.38°W) and latitude
145 (20.55°S) for the period 14-16 January 2022. From Figures 2a and 2b, it follows that no
146 depletion occurred on 14 January. On 15 January, we first see a small -2 TECU deviation
147 between 0200 and 0400UT. However, starting from ~0430 UT the TEC strongly depleted at
148 the volcano latitude, and it further moved away from the volcano with time in both northern
149 and southern directions (Figure 2a). The depletion seems to have an asymmetric pattern after
150 ~0600 UT, as it extends in southern (poleward) direction. From 1300 UT, the TEC comes closer
151 to the reference values, but a smaller -4 TECU depletion persists until ~2000 UT.

152 Along the volcano latitude, very pronounced TEC depletion occurred at the volcano
153 longitude starting from ~0430 UT (Figure 2b). Further, from ~0430 to ~0600 UT, the depletion
154 clearly propagates in both western and eastern directions even though very few data points were
155 available in the eastern direction. The maximum depletion of -21 TECU (i.e., ~80% of the
156 before-eruption level) occurred around 0600 UT. These depleted percentage changes can also
157 be confirmed in Figure S2. After that, the depletion only can be seen eastward from the volcano.
158 The largest longitude extension was near 160°E. Finally, it became less visible at 2000 UT.

159 Based on these keograms, we can roughly estimate that shortly after the eruption onset, the
160 depletion propagated at $\sim 200 \text{ ms}^{-1}$ in meridional direction and $\sim 280 \text{ ms}^{-1}$ in zonal direction.
161 Besides, a travel-time diagram of the north-south differential VTEC from the volcano center
162 position is also represented in Figure S3 in Supplementary Information. The existence of
163 ionospheric holes can be clearly recognized. This confirmed that the observed large-scale
164 depletion was related to the volcanic eruption.

165 However, we note that a keogram for 16 January shows that very similar TEC depletion,
166 although of smaller amplitude, occurs around the same time intervals (e.g., ~0400-2000 UT) as
167 that shown on 15 January southward from the volcano. This phenomenon can also be confirmed
168 in two-dimensional differential VTEC maps for 16 January (Figure S4 in Supplementary
169 Information). Therefore, the 15 January large-scale depletion was, most likely, not fully
170 generated by the volcanic eruption, but, at least partly, was due to a geomagnetic storm that
171 was ongoing during the eruption. The storm commenced at ~1600 UT on 14 January 2022
172 (Figures S1 and 2c). The main phase lasted for about 7 hours from 1600 to 2200 UT. The

173 minimum Dst index dropped to -91 nT, and the maximum Kp index went up to 6 at 2200 UT
174 on 14 January 2022 (Figure S1 in Supplementary Information). Then, a long-lasting recovery
175 phase started on 15 January, i.e., the explosive Tonga volcanic eruption occurred at the early
176 stage of the storm's recovery phase.

177 Geomagnetic storms are known to produce positive and negative variations (often referred
178 to as positive and negative ionospheric storms) in the ionospheric parameters driven by storm-
179 time alterations in the electric field, neutral winds and thermospheric composition. The negative
180 storm effects are often reported during the storm recovery phase due to the occurrence of
181 regions with decreased neutral composition ratio O/N₂. Such regions are originally produced
182 due to heating and upwelling of the lower thermosphere by the magnetospheric energy inputs
183 at auroral latitudes. They are further pushed to lower latitudes by the equatorward
184 thermospheric winds or traveling atmospheric disturbances (Fuller-Rowell et al., 1996). The
185 O/N₂ ratio has a highly positive correlation with ionospheric electron density, with a(n)
186 increase/decrease of the ionosphere electron density as the O/N₂ ratio increases/decreases
187 (Prölss, 1976, 1980; Fuller-Rowell et al., 1994; Strickland et al., 2001; Christensen et al., 2003;
188 Crowley et al., 2006).

189 Figure 3a shows the O/N₂ ratio on 14-16 January 2022 as observed by the TIMED/GUVI
190 satellite (top panel), and as modeled by the TIEGCM and interpolated to the location of the
191 satellite based on the model gridded value (bottom panel). The TIMED satellite passed around
192 the Tonga volcano at ~17.70 UT on 14 January, i.e. before the eruption but during the storm,
193 and at ~17.90 UT on 15 January, i.e. several hours after the eruption stopped, but when the TEC
194 was yet depleted. The decreased O/N₂ bulge first occurred at high latitudes during the main
195 phase of the storm, and it started to extend to middle latitudes at ~2100 UT on 14 January
196 (Figure 3a). On 15 January, the bulge further stretched to low latitudes and covered the Pacific
197 and Australian regions. From these TIMED/GUVI observations we conclude that the
198 composition was depleted around the volcano area during the TEC depletion observation.

199 With regard to the TIEGCM O/N₂ simulations, they differ from the observations in the
200 absolute O/N₂ value and in the O/N₂ disturbance around the volcano area (Figure 3a). While,
201 the relative morphology variations and the O/N₂ disturbance over the Western Australia are
202 correctly simulated. Therefore, we will use them to further investigate the O/N₂ ratio changes
203 during the storm. Figure 3 b shows the differential O/N₂ simulated by the TIEGCM. At 2000
204 UT on 14 January, the O/N₂ depletion occurred in the Australian region, which is consistent
205 with the TIMED/GUVI observations. The O/N₂ depletion further enhanced and was the
206 strongest at 0400UT on 15 January, i.e. during the beginning of the eruption. The composition

207 remained locally decreased until at least 0400UT on 16 January. Besides, Figure 3a and 3b
208 show that a higher O/N2 depletion level occurred on 15 January than that on 16 January, which
209 is in line with VTEC observations depletion on 15-16 January (Figure 2a-b).

210 Figure 3c further shows the observed and TIEGCM-simulated differential VTEC
211 comparison for different longitudes and at the volcano latitude for 14-16 January. The global
212 view of the observed and simulated ionosphere negative storm effects in VTEC can be found
213 in Animation S1 in Supplementary Information. From Figure 3c, one can see that the TIEGCM
214 can generally reproduce the negative TEC storm effects due to the storm-time decreased O/N2,
215 especially at 0400-2000 UT on 15 January (the yellow shading). Note that the 85° and 105°
216 longitudes are not shown here due to the absence of observations. The simulated VTEC changes
217 for four longitudes near the volcano have been calculated to estimate the storm's contribution.
218 For 145° longitude, the TEC dropped down to -4.35 TECU around 0800 UT on 15 January,
219 which represents 28% with respect to the background level. We further observe -3.45 TECU
220 (23.6%) at 155°, -2.14 TECU (15.5%) at 165°, and -0.93 TECU (7.6%) at 175°. Note that the
221 simulated O/N2 depletion does not occur over the volcano (shown in Figure 3a), and the model
222 did not correctly simulate the VTEC evolution in this region. While, as indicated above, the
223 relative morphology variations in O/N2 ratio are much better simulated in the Australian region.
224 Therefore, the TEC changes at 155° correctly represent the storm contribution, which is -3.45
225 TECU (23.6%). Considering that the storm-time effects around the volcano area should be
226 similar to those in the Australian region, we estimate the storm contribution to be at least 20%.
227 Consequently, the true contribution of the eruption should be about 60-75%, which remains an
228 impressive number.

229 The true magnitude of the depletion can also be understood from Figure 4 that presents the
230 difference of the Δ VTEC between 15 and 16 January and the ICON/IVM ion density and ion
231 temperature measurements. Note, however, that the storm-driven depletion on 16 January was
232 smaller than that on 15 January, therefore, the differential VTEC between 15 and 16 January
233 still contains a small storm effect in addition to the eruption effect. The differential VTEC maps
234 show the Δ VTEC deviation of -15 to -20 TECU, which represents 60-75% of the background
235 level and is in line with our previous estimations. The true horizontal dimensions can also be
236 seen in Figure 4, as we see the depletion extension up to 1500-2000 km on the west-south-west.
237 While, the depletion ~3000-4000 km south-west from the volcano seen in Figure 1 should be
238 due to the storm.

239 The significant local depletion around the volcano is also seen in the ion density at 575 km
240 as measured by ICON (Figure 4). One can see strong decreases in the ion density (by 1-2 orders

241 of magnitude) and noticeable increases in the ion temperature (by 500-1000 K) at $\pm 15^\circ$ from
242 the volcano. These local effects confirmed that only ~ 1500 km away from the epicenter is
243 attributed to the eruption. We note that the depletion was only seen from 0637 UT to 1657 UT,
244 when the satellite passed close to the volcano. The satellite is away from the epicenter at 1837
245 UT and 2022 UT, but smaller negative deviation is actually well seen in differential VTEC, i.e.
246 until local morning hours.

247 The exact mechanism of the generation of the ionospheric depletion by the eruption is not
248 yet clear. Aa et al. (2022) suggested that the TEC depletion was more likely to be caused by
249 strong expansion and upwelling in the thermosphere along with outward ionospheric plasma
250 flow driven by impulsive nonlinear acoustic wave pulses. Astafyeva et al. (2022) attributed the
251 depletion to the giant shock wave that was generated by the volcanic explosion, however, no
252 detailed investigation was performed. Similar depletions although of much smaller amplitude
253 were previously reported for several large earthquakes (Kakinami et al., 2012; Astafyeva et al.,
254 2013a; Kamogawa et al., 2015). For instance, the 2011 Tohoku earthquake caused a depletion
255 of magnitude -5 - 6 TECU that only lasted 30-50 min (Astafyeva et al., 2011; 2013 a, b;
256 Kakinami et al., 2012). Simulation studies by Shinagawa et al. (2013) and Zettergren et al.
257 (2017) for the 2011 Tohoku-oki earthquake demonstrated that the ionospheric TEC depletion
258 can be formed by large-magnitude earthquakes that generate strong-amplitude, and therefore
259 non-linear acoustic waves. Additionally, Zettergren et al. (2017) showed that such depletions
260 are further reinforced by the uplifted gas that falls back and causes the incoming acoustic waves
261 to slow as they propagate upward (since they are propagating in a falling background medium).
262 As a result, these incoming wave fronts then dissipate more within the F region. For waves with
263 large amplitudes, the slowed incoming wave fronts then may partly or fully merge with the next
264 set of wave fronts that follow. The combined impact of these non-linear acoustic waves and
265 dissipated processes is mostly the strong downward neutral velocity, which generates a
266 downward, field-aligned motion in the ionospheric plasma through ion-neutral drag. The effect
267 of the downward motion will tend to result in enhanced ionospheric O^+ recombination due to
268 the plasma is transported to an altitude where molecular constituents (e.g., N_2) are denser. Then,
269 the effect of this motion is a conversion of O^+ into molecular ions. It is known that molecular
270 ions recombine more readily than O^+ . These net effects result in a TEC depletion that persists
271 longer than the associated thermospheric dynamics.

272 The exceptionally long duration of the Tonga depletion could be explained by very
273 intensive shock wave that was generated by the volcanic explosion as compared to earthquakes,

274 and by the local evening and night hours which should have hindered faster recovery from low
275 ionization.

276 Besides, the longer depletion could have been additionally reinforced and prolonged by
277 chemical effects due to the eruption. Millán et al. (2022) reported that the Tonga eruption-
278 driven ash plume and water vapor reached as high as 39 to 55 km of altitude, i.e. the mesosphere
279 layer. If this water vapor could further be transported to the ionospheric altitudes, at least partly,
280 it could cause an increase in the recombination rate, leading to a significant decline in
281 ionospheric Ne (e.g., Mendillo & Forbes, 1978). The simultaneous process of the molecule
282 diffusion and the dissociative recombination cause the formation of an “ionospheric hole”.
283 Specifically, the diffusion of molecule density in the exhaust plume at a certain radial distance
284 from a point source can be assumed as a spherical diffusion. The diffusion constant is larger
285 with a higher altitude. The water and hydrogen molecules become positive molecular ions by
286 reacting with ambient oxygen ions. Then, their dissociative recombination with electrons led to
287 the depletion of the ionospheric electron density. This effect has been confirmed by depletion
288 caused by launches of missile and rockets launches (Furuya & Heki, 2008; Ozeki & Heki,
289 2010).

290 Future studies, especially modelling, will help to better explain this observed effect.

291

292 **4 Conclusions**

293 In this work, for the first time, we presented a detailed analysis of the ionospheric depletion
294 that occurred shortly after the 15 January 2022 giant explosive eruption of the Hunga-Tonga
295 volcano. As the eruption began at ~0415 UT on 15 January, the TEC dropped by ~80-95% with
296 respect to quiet-time values. Such negative effect lasted for ~16 hours, i.e., until local morning
297 hours. On VTEC maps, the depletion extended up to ~4000 km away from the epicenter.
298 Additionally, ICON-IVM measurements showed significant decrease in the ion density at 575
299 km of altitude in the vicinity of the volcano.

300 The depletion occurred during the recovery phase of a moderate geomagnetic storm, and
301 storms are known to produce local decreases and increases of ionospheric plasma density.
302 Therefore, we analysed storm-time effects and we found that the decrease in thermospheric
303 neutral compositions ratio O/N₂ was responsible for ionospheric negative storm effects at
304 middle and low latitudes in the Australian and Pacific regions. This storm effect in the
305 ionosphere and thermosphere can also be well reproduced by the TIEGCM simulation.

306 Both observations and simulations suggest that the depletion was initially generated by the

307 volcanic explosion (~60-75% contribution and ~1500 horizontal spatial extent) and was by ~20%
308 reinforced by the thermospheric composition changes due to a moderate geomagnetic storm.

309
310

311 **5 Open Research**

312 The MIT VTEC data are publicly available at the Madrigal Database
313 (<http://cedar.openmadrigal.org/>). The thermospheric O/N₂ composition data are available from:
314 <http://guvitimed.jhuapl.edu/guvi-gallery13on2>. The space weather indices are derived from
315 OMNIWeb database (<http://omniweb.gsfc.nasa.gov/>). The ICON/IVM ion density and
316 temperature data can be accessed at (<https://icon.ssl.berkeley.edu/Data>). The TIEGCM
317 simulations presented in this paper can be accessed from Open Science Framework
318 (<https://doi.org/10.17605/OSF.IO/YAVXN>).
319

320

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329

330

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332

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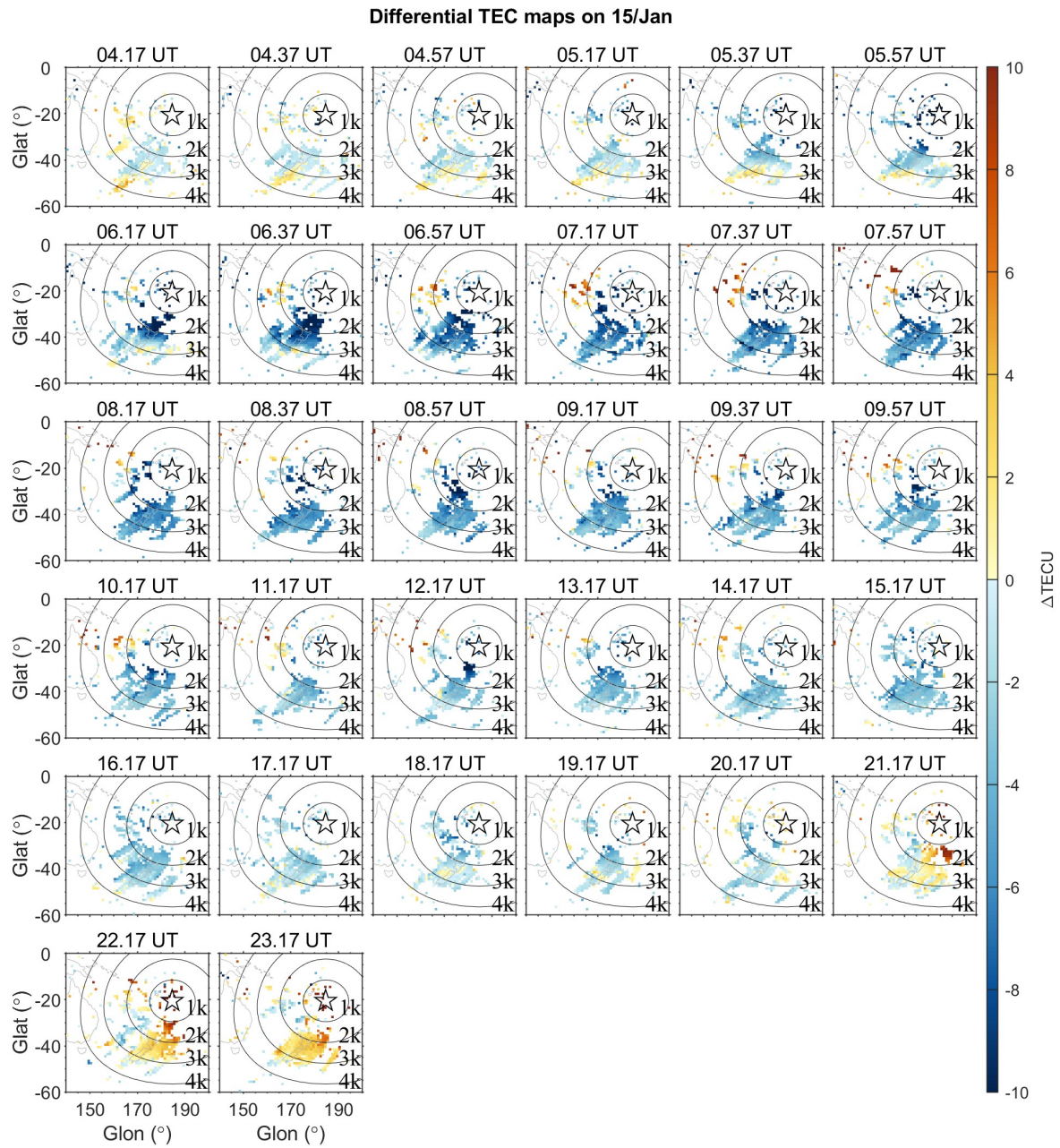
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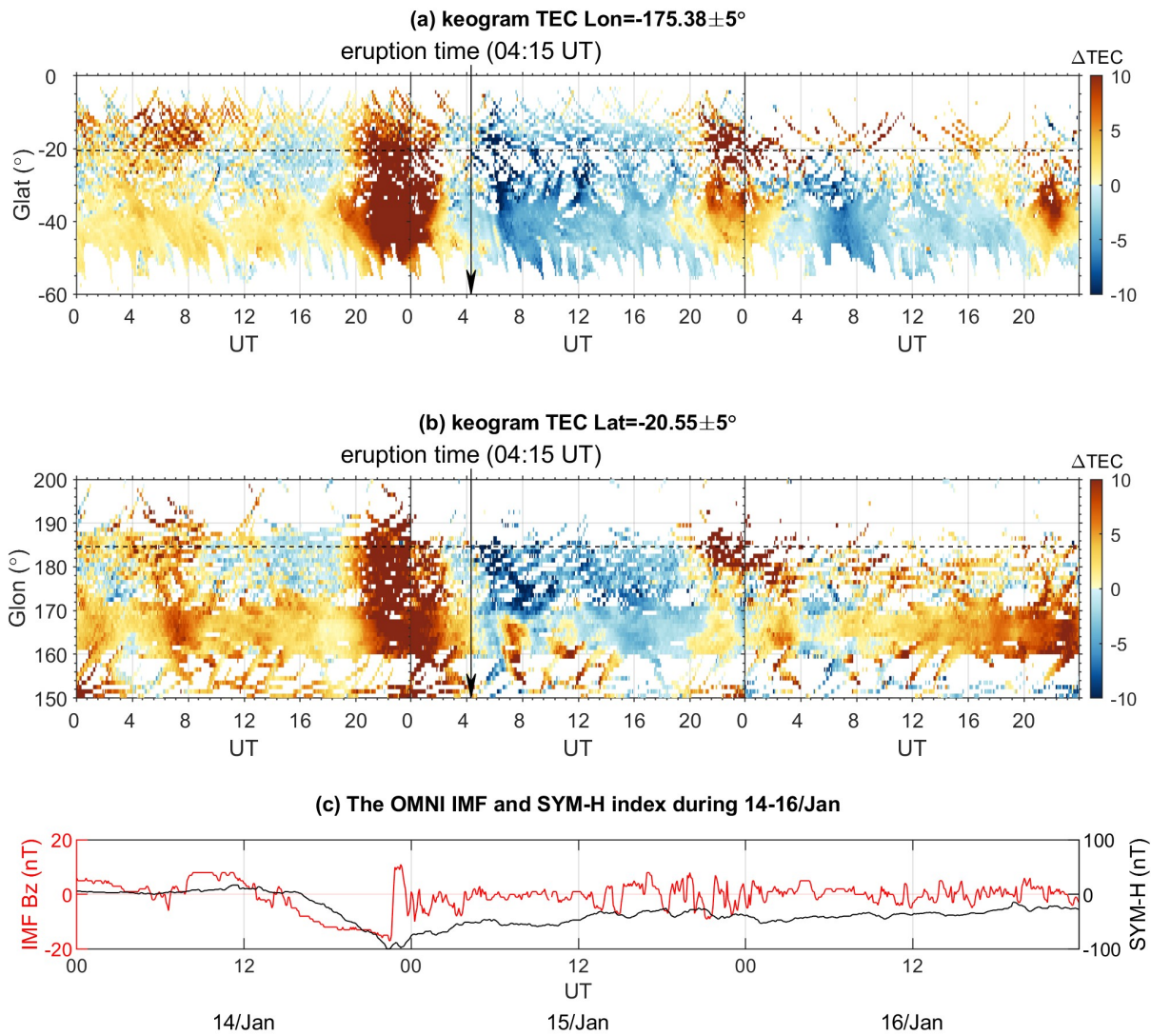
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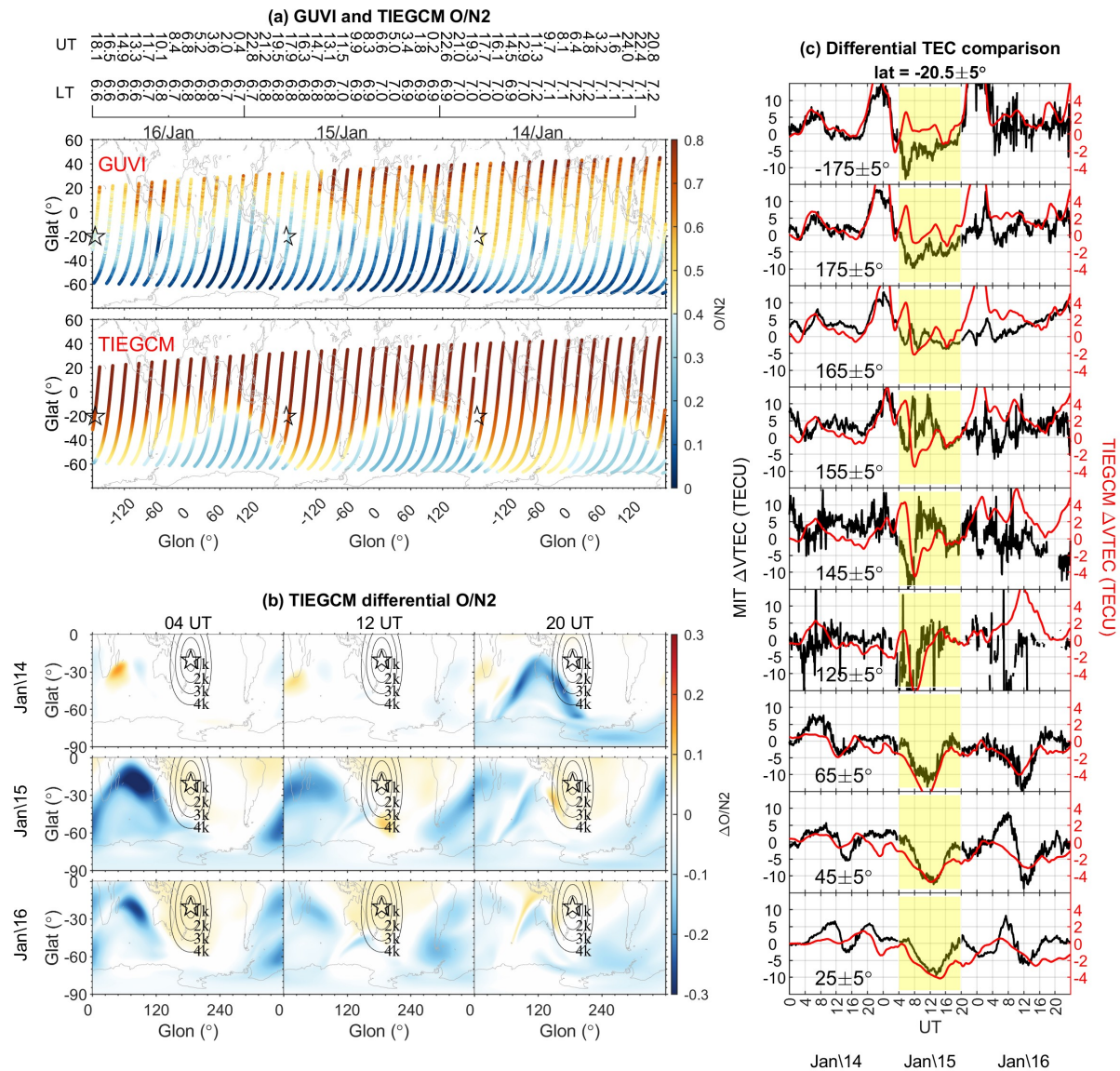
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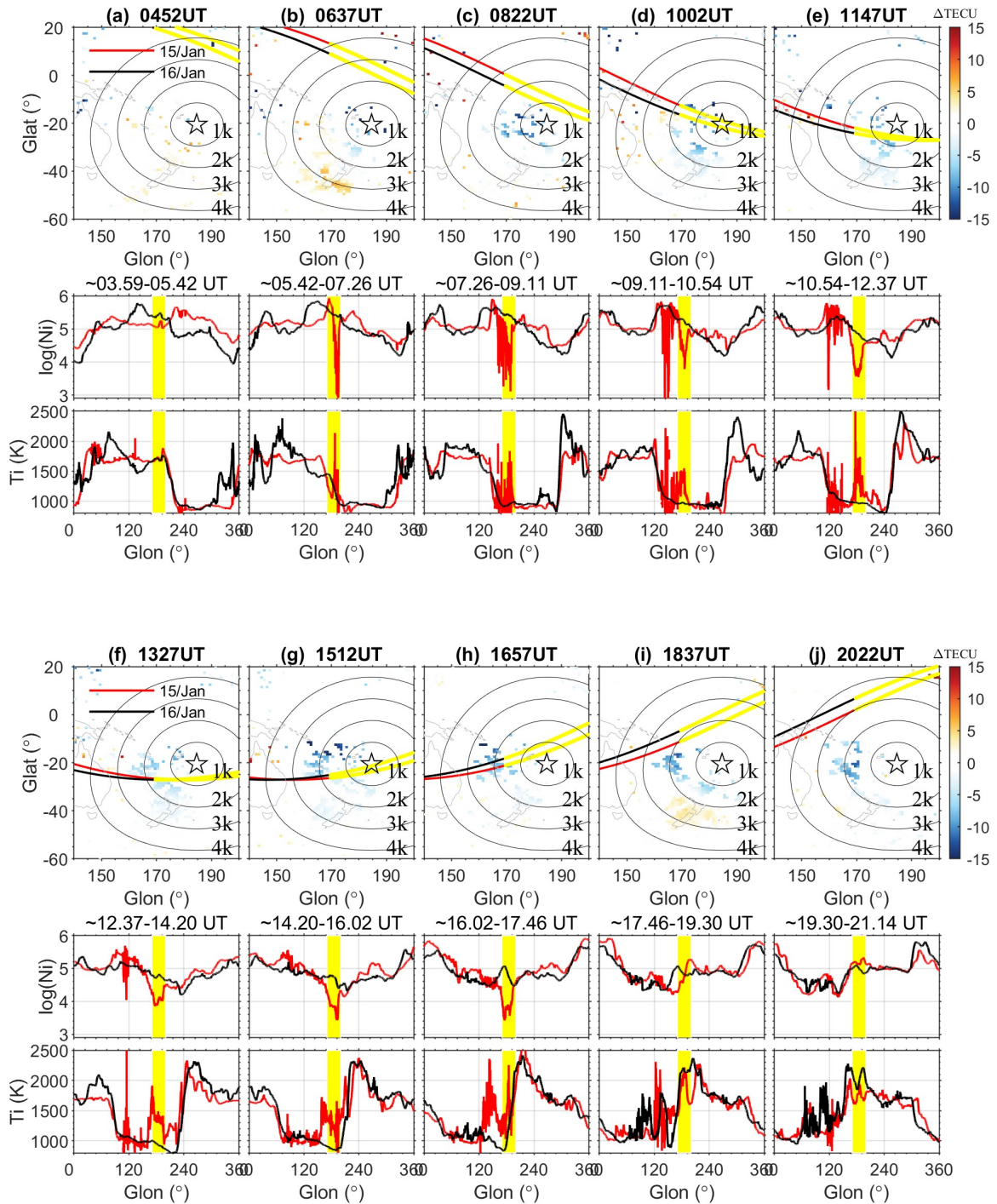
465
 466 **Figure 1** The two-dimensional differential VTEC maps for the near-volcano area at different
 467 universal times on 15 January 2022. The volcano eruption location is marked by the pentagram.
 468 The iso-distance circles from the eruption epicenter are shown in dark solid lines (unit: km).
 469 The differential TEC indicates the deviation of the TEC value on 15 January from the reference
 470 value. The reference value is the averaged data over 4 quiet days: 10, 11, 12 and 13 January
 471 2022.



472
 473 **Figure 2** The time evolution of the differential VTEC at a fixed longitude (a) and latitude (b)
 474 near-volcano location during the whole day of 14-16 January 2022. The dark dashed lines
 475 indicate the latitude and longitude of the Tonga volcano. The arrows indicate the eruption time
 476 at 0415 UT on 15 January 2022. (c) The interplanetary magnetic field (IMF) Bz component
 477 (red line) and SYM-H index (black line) from the OMNI dataset with 5-min resolution for 14-
 478 16 January 2022.



479
 480 **Figure 3** (a) The thermospheric O/N₂ ratio as measured by the TIMED/GUVI satellite (top)
 481 and modeled by TIEGCM (bottom) on 14-16 January 2022 in the local early morning sector
 482 (6.6-7.2 LT). The universal times and local times of the equator crossings for each orbit are
 483 indicated on the top. The pentagram indicates the volcano eruption location. (b) The longitude-
 484 latitude distribution of the TIEGCM differential O/N₂ ratio in southern hemisphere at 0400 UT,
 485 1200 UT and 2000 UT on 14-16 January. The differential O/N₂ ratio indicates the deviation of
 486 the O/N₂ value on 14-16 January from the reference value on 13 January. The iso-distance
 487 circles from the eruption epicenter are shown in dark solid lines (unit: km). (c) The differential
 488 TEC comparison between MIT VTEC (black lines) and TIEGCM (red lines) for different
 489 longitudes at a fixed latitude near-volcano location on 14-16 January 2022. The yellow shading
 490 indicates the period of TEC depletion observation, i.e. 0400 to 2000 UT on 15 January 2022.
 491



493

494 **Figure 4** (a-j) The top panels: The two-dimensional differential VTEC maps between 15 and
 495 16 January on the near-volcano area at different universal times. The ICON-IVM observation
 496 tracks near volcano area are shown in red and dark thick solid lines on 15 and 16 January,
 497 respectively. The volcano eruption location is marked by the pentagram. The iso-distance
 498 circles from the eruption epicenter are shown in dark thin solid lines (unit: km). The middle and

499 bottom panels: The ICON-IVM ion density and ion temperature measurements at different
500 universal times on 15-16 January. The red and black thick solid lines indicate the ion density
501 and ion temperature on 15 and 16 January, respectively. Note that the yellow part of each trace
502 and the yellow shading of each subpanel indicate the volcano location within $\pm 15^\circ$.