

1 **Conjugate ionospheric perturbation during the 2017**
2 **solar eclipse**

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7 **Key Points:**

- 8 • Persistent ionospheric density depletion in conjugate lower latitudes was identi-
9 fied during 21 August 2017 Solar Eclipse
10 • Conjugate depletion moved equatorward with eclipse progression and was coin-
11 cident with weakening conjugate/southern equatorial ionization anomaly
12 • Plasma pressure reduction in flux tubes shadowed by the Moon, along with dis-
13 turbed northward trans-equator winds, prohibits fountain plasma southward dif-
14 fusion

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15 **Abstract**

16 We report new findings of total electron content (TEC) perturbations in the southern
 17 hemisphere at conjugate locations to the northern eclipse on 21 August 2017. We iden-
 18 tified a persistent conjugate TEC depletion by 10-15% during the eclipse time, elongat-
 19 ing along magnetic latitudes with at least $\sim 5^\circ$ latitudinal width. As the Moon's shadow
 20 swept southward, this conjugate depletion moved northward and became most pronounced
 21 at lower magnetic latitudes ($> -20^\circ\text{N}$). This depletion was coincident with a weakening
 22 of the southern crest of the equatorial ionization anomaly (EIA), while the northern EIA
 23 crest stayed almost undisturbed or was slightly enhanced. We suggest these conjugate
 24 perturbations were associated with dramatic eclipse initiated plasma pressure reductions
 25 in the flux tubes, with a large portion of shorter tubes located at low latitudes under-
 26 neath the Moon's shadow. These short L-shell tubes intersect with the F region iono-
 27 sphere at low and equatorial latitudes. The plasma pressure gradient was markedly skewed
 28 northward in the flux tubes at low and equatorial latitudes, as was the neutral pressure.
 29 These effects caused a general northward motion tendency for plasma within the flux tubes,
 30 and inhibited normal southward diffusion of equatorial fountain plasma into the south-
 31 ern EIA region. We also identified post-eclipse ionospheric disturbances likely associated
 32 with the global propagation of eclipse-induced traveling atmospheric disturbances in align-
 33 ment with the Moon's shadow moving direction.

34 **Plain Language Summary**

35 A solar eclipse casts a supersonic moving shadow on Earth's atmosphere and im-
 36 pacts the upper atmosphere by masking solar irradiation. For a given location, this re-
 37 sults in local reduction and recovery of photo-ionization and photo-absorption within ~ 2
 38 hours. However, on a much larger scale, the moving, eclipse induced EUV screening last-
 39 ing for multiple hours drives dynamical ionospheric variations. A global perspective on
 40 the eclipse induced ionospheric perturbation is now possible due primarily to the avail-
 41 ability of total electron content (TEC) worldwide data from Global Navigation Satel-
 42 lite System (GNSS) receiver coverage. This paper reports new findings on total electron
 43 content perturbations in the southern hemisphere conjugate to the northern eclipse on
 44 21 August 2017. While the moving Moon shadow was expected to yield traveling atmo-
 45 spheric disturbances, observational signatures of post-eclipse traveling ionospheric dis-
 46 turbances propagating into the southern hemisphere were identified. Significantly, a per-
 47 sistent TEC depletion zone conjugate to the eclipse region occurred, elongated along mag-
 48 netic latitudes with $\sim 5^\circ$ latitudinal width, moving equatorward and most pronounced
 49 at lower magnetic latitudes ($\sim -20^\circ\text{N}$ and equatorward). This depletion was coincident
 50 with a weakening southern equatorial ionization anomaly (EIA) while the northern EIA
 51 remained unaffected or was slightly enhanced. We suggest that both conjugate density
 52 depletion and disappearance of the southern EIA were associated with dramatic plasma
 53 pressure reduction in the magnetic field flux tubes, which are short in length at low lat-
 54 itudes and traverse the ionospheric F region when being shadowed by the Moon for a
 55 significant time. The plasma pressure gradient was skewed northward at low and equa-
 56 torial latitudes, and neutral pressure gradients followed suit. Ultimately, these effects drove
 57 an overall northward motion of plasma in the flux tubes, inhibiting the normal south-
 58 ward diffusion of equatorial fountain plasma into the southern EIA region.

59 **1 Introduction**

60 A solar eclipse impacts the ionosphere due to a sudden reduction in solar irradi-
 61 ation (and therefore in photo-ionization and photo-absorption rates) as the Moon shadow
 62 sweeps through the Earth's atmosphere at a supersonic speed. This reduction results in
 63 ionospheric perturbations, both altitude and geophysical location dependent. Most eclipse
 64 induced local ionospheric perturbations have been explained by various coexisting pho-

65 tochemical and dynamic processes under the direct influence of solar irradiation reduc-
 66 tion (Rishbeth, 1968), including ion production reduction, ionospheric and thermospheric
 67 cooling (thermal contraction), ambipolar plasma diffusion and topside ion flow (MacPherson
 68 et al., 2000; Yau et al., 2018; Hairston et al., 2018; Goncharenko et al., 2018), as well as
 69 disturbances in neutral winds, composition (Harding et al., 2018; Wang et al., 2019; Lei
 70 et al., 2018; Wu et al., 2018; Müller-Wodarg et al., 1998), and electric field perturbations
 71 (Maurice et al., 2011; Huba & Drob, 2017; Dang, Lei, Wang, Burns, et al., 2018; Chen
 72 et al., 2019). By contrast, regional eclipse induced variations have become better known
 73 only recently with the wide availability of ionospheric measurements, especially total elec-
 74 tron content (TEC) from GNSS receiver networks (A. J. Coster et al., 2017; He et al.,
 75 2018; Cherniak & Zakharenkova, 2018). Examples of particularly notable regional effects
 76 include bow-shaped ionospheric waves (Zhang et al., 2017; Liu et al., 2011) and other
 77 atmospheric wave induced fluctuations (Sun et al., 2018; Nayak & Yiğit, 2018; Perry et
 78 al., 2019; Eisenbeis et al., 2019), ionospheric features arising from radiation inhomogene-
 79 ity on the solar disk (Mrak et al., 2018), and the polar region impact (Dang, Lei, Wang,
 80 Burns, et al., 2018). Global scale eclipse effects, however, have to date been largely based
 81 on theoretical estimates and need to be validated with solid observational evidence.

82 Two important aspects are relevant for eclipse global effects and in particular con-
 83 jugate hemispheric effects. The first aspect is associated with excitation of large scale
 84 traveling atmospheric disturbances (TADs) and their subsequent global propagation. TADs
 85 can be launched due to sudden cooling that is sweeping rapidly through the upper at-
 86 mosphere. Key effects here are neutral temperature reduction, spatial homogeneity of
 87 pressure gradient, and wind convergence (Lei et al., 2018; Dang, Lei, Wang, Zhang, et
 88 al., 2018; Lin et al., 2018; Cnossen et al., 2019; Wu et al., 2018; Harding et al., 2018; Wang
 89 et al., 2019; Müller-Wodarg et al., 1998). TADs travel globally even across the equator,
 90 depending on the exact eclipse path and, particularly, the history of that path due to
 91 the changing direction of the associated atmospheric pressure gradient. Many of these
 92 simulations indicate that post-eclipse TADs are essentially a continuation of the global
 93 propagation of the eclipse-induced TADs. While neutral wind observations have confirmed
 94 this post-eclipse TAD effect (Harding et al., 2018), substantial evidence for the post-eclipse
 95 TIDs has not been well established, although highly anticipated due to the close TAD/TID
 96 relationship. The second aspect is a remote effect occurring at eclipse conjugate loca-
 97 tions. At mid- and low latitudes, magnetic field lines provide strong electrodynamic cou-
 98 pling that connects the ionospheres underneath the Moon shadow and in the conjugate
 99 hemisphere through several hypothesized processes. Possibilities include:

100 (1) Photoelectron flux from the sunlit ionosphere loads into the conjugate eclipse
 101 hemisphere, where the ionosphere is cooled down and collapses very much like an accel-
 102 erated version of a sunset. The impact of photoelectrons from the conjugate sunlit iono-
 103 sphere on the hemisphere in darkness has been observed and well explained in earlier work
 104 (Carlson Jr., 1966; Evans & Gastman, 1970). During an eclipse, these conjugate pho-
 105 toelectrons can compensate for primary, local EUV reduction, and this effect becomes
 106 increasingly significant with altitude due to photoelectron loss in the eclipsed (local) iono-
 107 sphere from photo-ionization reduction (MacPherson et al., 2000). This compensation
 108 process could potentially provide a causal connection that would explain a weaker elec-
 109 tron temperature (T_e) reduction shown in the August 2017 eclipse Goncharenko et al.
 110 (2018) compared to model simulations by Cnossen et al. (2019) where conjugate pho-
 111 toelectron effects were not included. However, separate modeling by Le et al. (2009); Huba
 112 and Drob (2017) demonstrated electron cooling in the entire flux tube that thermally
 113 connects both hemispheres through rapid field-aligned thermal conduction. Such con-
 114 jugate hemisphere cooling can potentially alter thermodynamics and eventually electron
 115 density (N_e) by several processes. However, due to the strong dependence of T_e on N_e ,
 116 excessive N_e reduction (increase) normally tends to increase (decrease) T_e , with this trend
 117 depending significantly on the absence of external energy input. For these reasons, it is

118 therefore important to examine T_e and N_e simultaneously to understand T_e ionospheric
 119 variations.

120 (2) Electric fields are induced by the eclipse due to ionospheric dynamo modifica-
 121 tion by substantial conductivity and/or neutral wind changes in the E and F regions.
 122 These effects can be mapped into the conjugate ionosphere as long as conjugate current
 123 short-circuiting in the E region is not present (Huba & Drob, 2017; Dang, Lei, Wang,
 124 Burns, et al., 2018). If the eclipse falls into magnetic low and equatorial latitudes, such
 125 additional electric fields could potentially modify the regular equatorial ionization anomaly
 126 (EIA) (Maurice et al., 2011; Chen et al., 2019).

127 The 21 August 2017 solar eclipse presented an unprecedented modern observational
 128 opportunity to examine some of these hypotheses on conjugate ionospheric variations,
 129 thanks to the excellent available spatial coverage of GNSS TEC observations over the
 130 continental US (CONUS) as well as reasonable coverage in South America. Previous at-
 131 tempts (He et al., 2018; Chen et al., 2019) have been able to hint at eclipse-induced con-
 132 jugate changes, for example, He et al. (2018) showed the southern hemispheric TEC de-
 133 pletion from several GNSS individual receivers. But explicit substantial evidence, espe-
 134 cially the spatial context with the eclipse in the northern hemisphere, was still not pos-
 135 sible in those studies. In this work, we will provide GNSS TEC-based observational evi-
 136 dence of ionospheric eclipse time disturbances occurring in the conjugate ionosphere,
 137 and will characterize these disturbances in the context of the solar eclipse induced iono-
 138 spheric dynamics. We conclude with two main findings: (1) Electron density (N_e) was
 139 depleted over eclipse conjugate ionospheric locations, coincident with weakening of the
 140 conjugate EIA; and (2) substantial large scale TIDs occurred, propagating southward
 141 and arriving at the conjugate hemisphere during the post-eclipse time period.

142 **2 Method: Solar eclipse mapped to the conjugate ionosphere and GNSS** 143 **TEC analysis technique**

144 The 2017 Great America Solar Eclipse on 21 August, optically visible in the CONUS,
 145 started with a partial eclipse at 1604 UT (First Contact, C_1) over Oregon and traversed
 146 southeastward across the central part of CONUS, arriving at $(-90^\circ\text{E}, 36.5^\circ\text{N})$ at 18:20
 147 UT (12:20 SLT) when totality occurred. The totality ended at 20:02 UT (Fourth Con-
 148 tact, C_4) near $(-27^\circ\text{E}, 11^\circ\text{N})$ and the partial eclipse ended at 21:04 UT (P_4) near the ge-
 149 ographic equator. Of particular note, the eclipse progression toward southeast is an es-
 150 sential fact for our study as it determines to a large degree the TAD/TID propagation
 151 direction and the the conjugate ionospheric response pattern. Figure 1 shows the total-
 152 ity path over CONUS and its conjugate locations over the South America, as well as the
 153 Moon shadow area at the 300 km ionospheric height and the region of 25% solar obscu-
 154 ration magnitude at 19:00 UT in the northern hemisphere and its corresponding con-
 155 jugate locations in the southern hemisphere. The obscuration magnitude (ratio) is cal-
 156 culated based on the fraction of the visible solar disk area screened by the Moon. The
 157 magnetic latitude mapping for conjugate latitudes is performed using Altitude Adjust-
 158 ment Corrected GeoMagnetic (AACGM) coordinates (Shepherd, 2014) at 300 km alti-
 159 tude. This 300 km was used to represent the conjugacy of the ionosphere at the F re-
 160 gion height, and is close to the assumed 350 km altitude of the GNSS TEC ionospheric
 161 pierce point used for GNSS TEC data processing. This small altitude difference will have
 162 no visible effects on our eclipse effect analysis. The totality path spanned a range of mid-
 163 and low magnetic latitudes, and was ideally suited for examining latitude dependence
 164 of potential conjugate ionospheric variations. The best availability of GNSS TEC data
 165 in the conjugate South America ionosphere, as shown in the map, started at 19:00 UT
 166 (approximately in the early afternoon).

167 We analyzed ionospheric TEC data obtained around 21 August 2017. The GNSS
 168 processing algorithms that were used to produce TEC were developed at MIT Haystack

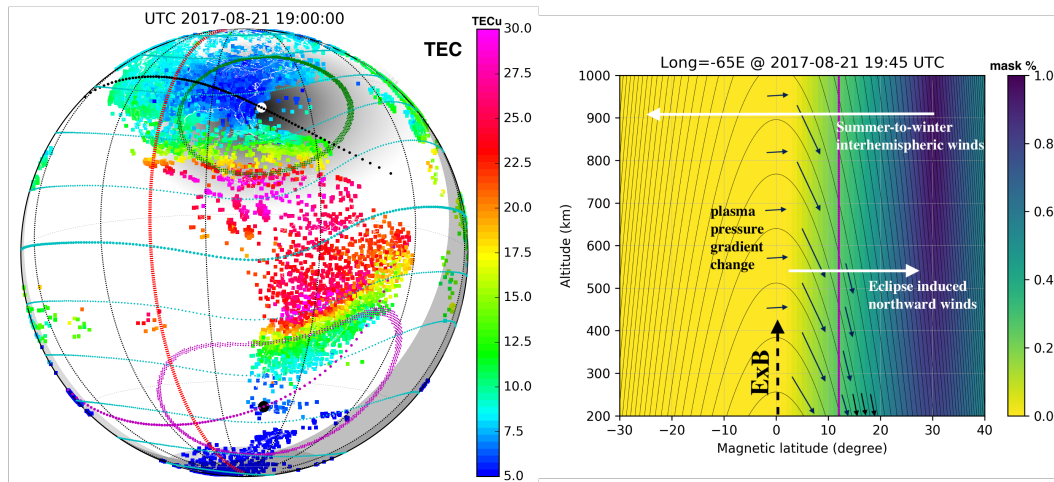


Figure 1: The 21 August 2017 solar eclipse as viewed globally. (left) The totality path (black dotted line) and the corresponding conjugate locations (magenta dotted line) are shown for the entire eclipse period. Shown also are the eclipse magnitude (calculated based on the fraction of the visible solar disk area screened by the Moon) for 19:00 UT represented by the shaded darkness, the 300-km eclipse magnitude contour at $\sim 25\%$ (green dotted curve) and the corresponding conjugate locations (magenta dotted curve), as well as the approximate totality location (white dot) and its conjugate point (black dot) at this time. Magnetic latitude contours are provided at a 15° interval (cyan dotted curve) with magnetic equator marked as heavier cyan dotted curve. Local noon (on the ground) is the red line. GNSS TEC data with minimum elevation of line-of-sight 25° is provided for this time. Solar terminator (on the ground) and the nightside are also marked as the shaded area near the right side of the map. (right) Latitudinal and altitudinal variations at the -65°E cut in the eclipse magnitude (shaded) and L-shell curves. The 25% eclipse magnitude is marked as magenta lines. The schematic representation of the direction of plasma pressure gradient changes in the flux tubes underneath the Moon shadow is also provided as solid arrows. The $\mathbf{E} \times \mathbf{B}$ plasma drift that drives the plasma fountain at the magnetic equator is shown as a dashed arrow. The directions of neutral pressure gradient change and trans-equatorial winds are white arrows. The length of the arrows is not proportional and does not carry physical meaning.

169 Observatory (Rideout & Coster, 2006; Vierinen et al., 2016). This is the same data source
 170 used previously in Zhang et al. (2017); A. J. Coster et al. (2017), except that here a large
 171 amount of GLONASS data, in addition to GPS data, was added to increase coverage in
 172 South America. Overall, the newly added GLONASS data increased the amount of data
 173 by $\sim 30\%$ over the nominal (baseline) 6000+ global receivers used for standard process-
 174 ing.

175 In order to detect ionospheric responses associated with the solar eclipse, we calcu-
 176 lated differential TEC using an approach that effectively removes the background iono-
 177 spheric “trend”, as demonstrated in previous TID studies (Zhang et al., 2017; Zhang,
 178 Coster, et al., 2019; Zhang, Erickson, et al., 2019; Lyons et al., 2019; Sheng et al., 2020).
 179 Zhang, Coster, et al. (2019) provided more detailed discussions of this method. The es-
 180 sential approach is to work with individual receiver-satellite TEC data segments, and
 181 to subtract a background TEC variation determined by a low-pass filtering procedure
 182 using the Savitzky-Golay low-pass filter (Savitzky & Golay, 1964). The filter, implemented
 183 with a linear basis function, is similar to the procedure of calculating averages over slid-
 184 ing windows, where the size of the window (in time) can be conventionally controlled in

185 order to maintain different levels of smoothness in the background TEC. This approach
 186 allows study of fluctuations with different characteristics.

187 Differential TEC calculation of this nature is widely used for GNSS TEC based large
 188 and medium scale TID and ionospheric disturbance studies Saito et al. (1998); Tsugawa
 189 et al. (2007); Ding et al. (2007); Azeem et al. (2015); Chou et al. (2018); Astafyeva (2019).
 190 As our goal here is to examine large scale ionospheric perturbations associated with the
 191 eclipse and at a given location, the eclipse duration is normally contained within 2 hours,
 192 we primarily used a 2-hour sliding window for the differential TEC calculations. We also
 193 examined 1 hour window results for comparison. To be completely free from impacts of
 194 the data edge associated with the use of fixed length windows, we removed data for the
 195 first and the last 1-hour (0.5-hour) of each data segment when a 2-hour (1-hour) slid-
 196 ing window was used. This has the caveat that the 2-hour sliding window results in dou-
 197 bling the loss of data when compared with the 1-hour sliding window. Finally, our anal-
 198 ysis disregarded the portion of data segment with satellite elevation $< 25^\circ$. Final accu-
 199 racy of this method derives from the accuracy of the GNSS phase measurement. Assum-
 200 ing that there is no loss of phase lock in the receiver, the error in differential TEC is less
 201 than 0.03 TEC units (A. Coster et al., 2012), as all satellite and receiver bias terms cancel
 202 out in a differential sense.

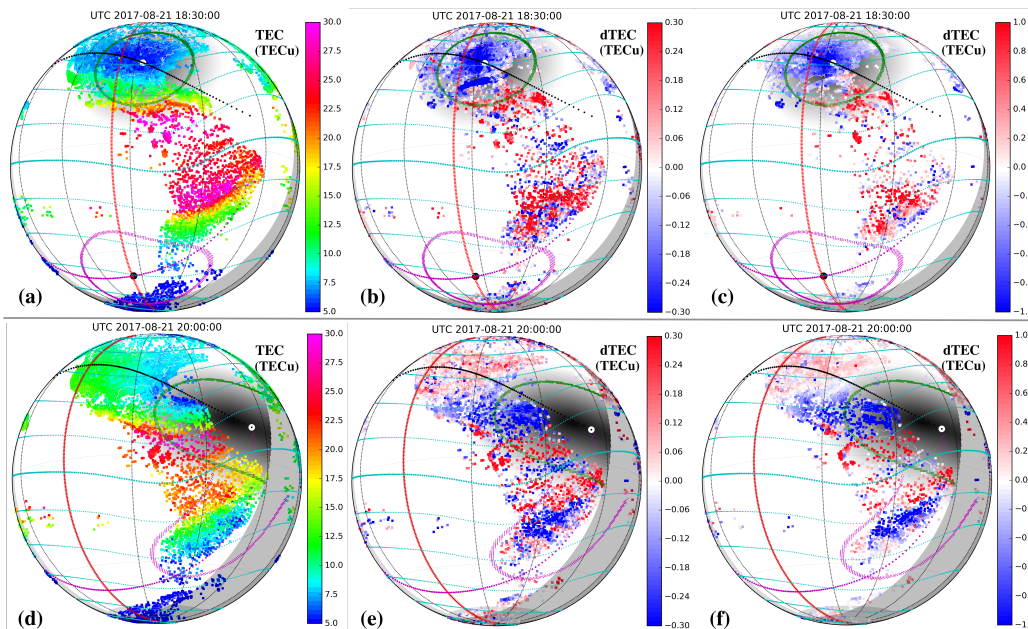


Figure 2: Detecting ionospheric changes during the presence of solar eclipse. Two groups, (a)-(c) as well as (d)-(f), of global maps are shown for 18:30 UT and 20:00 UT respectively at different stages of the eclipse. GNSS TEC maps are in (a) and (d), differential TEC (dTEC) maps after de-trending background variations using the low-pass filter with 60-min sliding windows are in (b) and (e), and with 120-min sliding windows in (c) and (f). Notice the different color scales for dTEC results with different sliding window filters. Similar eclipse and other information as in Figure 1 is also provided.

203 To examine the validity of this de-trending method, Figure 2 plots the original TEC
 204 and differential TEC calculated with 1-hour and 2-hour window sizes at two instances.
 205 Within the eclipse zone in the northern hemisphere, the differential TEC from both win-
 206 dows shows that TEC reduction was largest near totality but lagged behind it, consis-
 207 tent morphologically with results from TEC deviation relative to a reference, e.g., A. J. Coster

208 et al. (2017); Cherniak and Zakharenkova (2018). We emphasize that examining the de-
 209 viation from a reference day would be inappropriate for the present study due to con-
 210 cerns arising from substantial day-to-day and other variability at low latitudes. Specif-
 211 ically, the 20 August was geomagnetically quiet and 22 August was more active, so 20
 212 August could have been used as a reasonable reference. However, there was a significant
 213 morphology change at low and equatorial latitudes between 20 and 21 August, with EIAs
 214 on the eclipse day and without EIAs on the 20th (see Supplement figure S2). TEC dif-
 215 ferences between the two days would therefore reflect, to a large degree, the dominat-
 216 ing EIA physics but would potentially wash out or distort variations with small ampli-
 217 tudes.

218 Owing to the nature of the de-trending technique, for a disturbance signature of
 219 2 TECu peak-to-valley change, a 1 TECu deviation from the background trend will be
 220 identified in our procedure. Although the selection of the window length between 1 hour
 221 or 2 hours is somewhat arbitrary, the large-scale feature of the depletion shown in the
 222 2-hour window was consistent with that in the 1-hour window despite an expectation
 223 of smaller amplitudes and fine structures in the 1-hour data. More generally, coherent
 224 depletion features in the conjugate hemisphere of the eclipse were very pronounced in
 225 both 1-hour and 2-hour differential TEC data, as well as in the original TEC data, and
 226 these features will be further discussed in the next section. A weaker depletion at equa-
 227 torial latitudes was also found consistently from both data analysis methods, further sug-
 228 gesting a small reduction in the EIA plasma source region.

229 **3 Conjugate ionospheric density depletions**

230 **3.1 General features**

231 We first examined ionospheric perturbations from individual global maps of dif-
 232 ferential TEC (dTEC) during the eclipse period. Figure 3 plots dTEC from 19:15 - 21:00
 233 UT on a 15 min cadence (except for 20:00 UT, contained in Figure 2(f)). The dTEC de-
 234 pletion area in the southern hemisphere was not identifiable until $\sim 19:00$ UT (see 18:30
 235 UT in Figure 2(c) and 19:15 UT in Figure 3(a)). At that time, low density developed
 236 near the northeast leading edge of the area conjugate to the 0.25 (25%) eclipse iso-magnitude
 237 curve (hereafter referred as “0.25-curve”), and thereafter became well organized within
 238 the conjugate 0.25-curve. The depletion was observed predominantly near the equator-
 239 ward side of the 0.25-curve (the poleward side had no data). The depletion structure par-
 240 tially visible with available data was elongated along the magnetic latitude with at least
 241 a $\sim 5^\circ$ latitudinal span and a northern edge at $\sim -15^\circ\text{N}$ and higher magnetic latitudes.
 242 As the Moon shadow moved southeastward in the northern hemisphere and the conju-
 243 gate 0.25-curve moved northeastward accordingly, the depletion was extended further
 244 northeastward toward the magnetic equator and the terminator. After 20:15 UT, a pe-
 245 riod when only a partial eclipse was visible in the northern hemisphere and when the con-
 246 jugate 0.25-curve was significantly smaller in coverage area, the eclipse-induced deple-
 247 tion became narrower in the meridional direction with its equatorward edge at $\sim -15^\circ\text{N}$
 248 magnetic latitude. However, this depletion feature survived even in the *wake of TIDs*
 249 (to be discussed later) which almost masked the depletion at $\sim 21:00$ UT, and by 22:00
 250 UT we note that it was still identifiable.

251 Post-eclipse (after 22:00 UT) ionospheric variations also exhibited obvious distur-
 252 bances in the southern hemisphere. Figure 4 are dTEC maps between 22:00–00:30 UT.
 253 By 23:00 UT, the aforementioned depletion at low latitudes in the southern hemisphere
 254 has gradually faded away near -15°N magnetic latitudes. At 23:00 and 23:30 UT, neg-
 255 ative dTEC was found in the latitudes where the eclipse was terminated (i.e., $\sim 15^\circ\text{N}$ mag-
 256 netic latitudes between $-60 - -30^\circ\text{E}$ in Figure 4(c)), to the immediate south of these lat-
 257 itudes (near the magnetic equator, Figure 4(c)), and further south ($\sim -15^\circ\text{N}$ magnetic
 258 latitude) in the conjugate hemisphere. This post-eclipse depletion in the eastern longi-

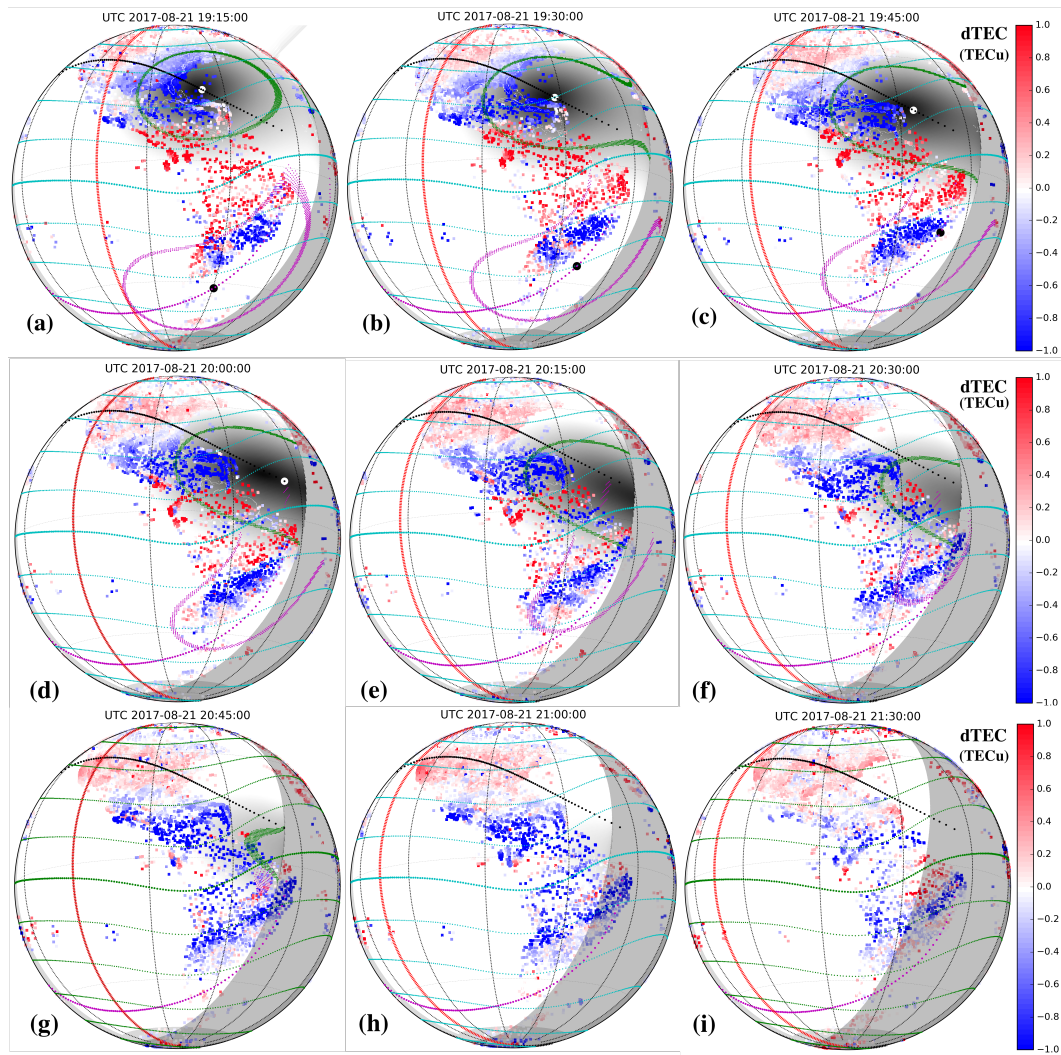


Figure 3: Global dTEC maps derived using the 120-min sliding window de-trending from 19:15 - 21:00 UT at a 15-min interval and at 21:30 UT.

259 tudes ($\sim -60 - -30^\circ\text{E}$, Figure 4(d)) was then extended to the west ($\sim -60^\circ\text{E}$ and west-
 260 ward, Figures 4(e) and 4(f)) at later times. In these western longitudes, the distance to
 261 the northern eclipse zone is longer than that in the eastern longitudes and therefore the
 262 southward propagating thermospheric/ionospheric disturbances took a longer lag time
 263 to arrive. The negative dTEC zone was also found as south as -30°N magnetic latitude,
 264 with reduced amplitudes of dTEC.

265 3.2 Longitudinal and latitudinal variations

266 Next, we characterized the depletion evolution with time and latitude/longitude
 267 using keograms. The longitude - UT variation in dTEC at 4 geomagnetic latitude bands
 268 in the southern hemisphere is given in Figure 5 where the corresponding 0.25-curve (green
 269 dots) is used to guide identification of the eclipse influence. Latitudinal variations at $-$
 270 $70 - -60^\circ\text{E}$ and $-60 - -40^\circ\text{E}$ longitudes are presented as dTEC in percentage (relative to
 271 the background TEC) in Figure 6. Two distinct features which were essentially very con-
 272 sistent in the longitude range between $-75 - -35^\circ\text{E}$ are noted:

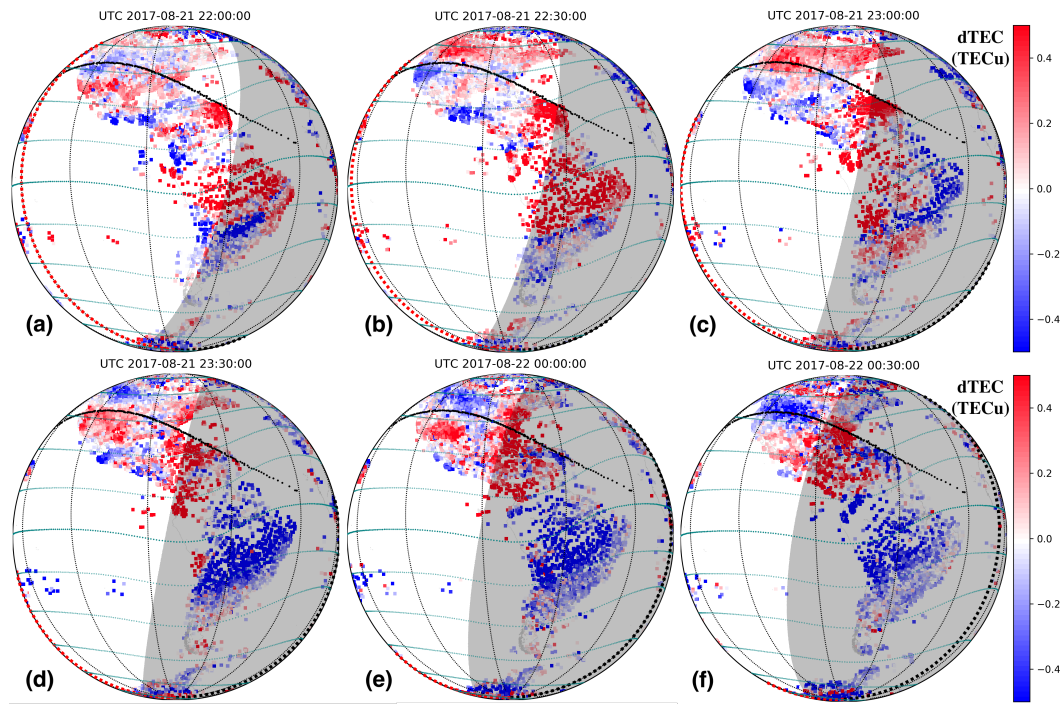


Figure 4: Same as Figure 3 but for the post-eclipse period between 22:00-00:30 UT with a 30 min interval. Notice the color scale changes from Figure 4.

273 (1) **Post-eclipse southward-propagating disturbance fronts**, shown in the
 274 depletion zone, change with latitude and time in Figure 5 panels (a)-(d). Specifically,
 275 the most pronounced depletion with negative dTEC appeared near but before 24 UT of
 276 21 August at $\sim -10^\circ\text{N}$ [in (a)] and similarly at $\sim -15^\circ\text{N}$ latitudes [in (b)], then predom-
 277 inately at or immediately after 24 UT at a higher latitude $\sim -25^\circ\text{N}$ [in (c-d)]. The am-
 278 plitudes of these dTEC absolute values decreased southward as the disturbance prop-
 279 agated away from the northern eclipse region into the region of lower TEC background
 280 in the south. The positive dTEC disturbance fronts (areas between the two solid lines)
 281 arrived earlier, between 22-23 UT at $\sim -10^\circ\text{N}$ and at 23 UT at $\sim -25^\circ\text{N}$. Note that the
 282 propagation of these disturbance fronts as shown in the keograms did not appear to be
 283 consistently correlated with the sunset terminator, and therefore we did not identify them
 284 as a sunset effect. Further ahead of (prior to) these positive dTEC fronts, clear indica-
 285 tions of negative dTEC zones existed. However, these zones were much more complicated,
 286 resulting from the spatially overlapping between these disturbance fronts and the afore-
 287 mentioned northeast extension/progression of the conjugate density depletion (the green
 288 arrow line). The latitudinal variation of percentage dTEC in Figure 6 indicates that the
 289 dTEC negative zone initially in the northern hemisphere eclipse zone moved southward
 290 along with the eclipse shadow, and continued propagating beyond where the eclipse was
 291 terminated into the southern hemisphere. At 23:00 UT, the negative zone reached at least
 292 -40°N geographic latitude (see the left dark arrow); a positive disturbance front occurred
 293 at a later time (see the right dark arrow), and finally a negative disturbance front by $\sim 24:00$
 294 UT.

295 Figures 5 and 6 both indicate enhancement zones prior to the northern eclipse on-
 296 set, which was after 18:00 UT at low latitudes for $\sim -70^\circ\text{E}$ longitudes. These structures
 297 were clearly northward TIDs at low latitudes in both hemispheres (Figure 6), which had
 298 started in the southern hemisphere at $\sim 16:00$ UT, well before the eclipse onset at those

299 longitudes. These TID features were consistent with Figures 7 and 8 which will be dis-
 300 cussed next. Therefore, on top of these northward-propagating TIDs, the eclipse induced
 301 TEC depletion originally in the northern hemisphere propagated through in the oppo-
 302 site direction, and clearly modified the amplitudes of these regional TIDs.

303 (2) **An negative dTEC structure in the conjugate hemisphere** was evident
 304 inside the conjugate 0.25-curve, particularly in Figure 5 at $\sim -25^\circ\text{N}$ and $\sim -20^\circ\text{N}$ mag-
 305 netic latitude bands, but was less evident northward into lower latitudes at $\sim -15^\circ\text{N}$ and
 306 $\sim -10^\circ\text{N}$ magnetic latitude bands (see the green arrow line). The negative dTEC was
 307 largest at $\sim -20^\circ\text{N}$ but did not reach $\sim -10^\circ\text{N}$. Figure 6 further reveals that in general,
 308 the conjugate depletion zone moved northward toward the magnetic equator as the north-
 309 ern eclipse mask swept southward. At the eastern longitudes ($-60 - -40^\circ\text{E}$) where the eclipse
 310 zone and its conjugate zone are closer to the magnetic equator, the location of the con-
 311 jugate depletion zone was more at the center of the 0.25-curve than that for the west-
 312 ern longitudes.

313 These two distinct features can be represented by a smoothed version of observa-
 314 tions that are shown in Figures 5 and 6. This version is given in Figure 7 where running
 315 averages within 7.5 min and 10° latitude are calculated. This shows clearly the south-
 316 ward propagating disturbance (the green arrow) in the north hemisphere under the di-
 317 rect influences of the Moon mask, the post-eclipse southward propagation disturbance
 318 in the conjugate hemisphere (the gray arrow), and the northward progression of nega-
 319 tive dTEC (the red arrow) in the conjugate hemisphere during the northern eclipse.

320 Finally, we used latitude-UT keograms to further delineate and summarize latitu-
 321 dinal variations of characteristic eclipse induced TIDs and conjugate TEC depletion in
 322 the longitude sector $-75 - -60^\circ\text{E}$ (Figure 8). Note here differential TEC is shown in per-
 323 centage, and is in magnetic latitude. Results show dTEC variations by up to 10% re-
 324 lative to the smoothed (2-hour average) background trend, corresponding to roughly 20%
 325 deviation from the onset of eclipse effect. Region (1) was located underneath the Moon
 326 shadow as indicated by the 0.25-curve. The dTEC calculation effectively reveals direct
 327 eclipse influences and their latitudinal progression. Note that in these observations the
 328 slope of the depletion as a function of latitude and UT was initially larger: the green dashed
 329 line on the left (tracing the depletion inside the 0.25-curve) has an estimated slope of
 330 ~ 650 m/s; the slope became slightly smaller toward the end of the eclipse before 21:00
 331 UT. This changing slope is likely related to the latitudinal dependence of the eclipse penum-
 332 bra moving speed. Region (2) was in latitudes with less than 25% eclipse obscuration
 333 as well as beyond the immediate end of the eclipse path at 21:04 UT (P4) when the eclipse
 334 was just terminated. The continuous extension of TEC depletion between 21-22 UT, be-
 335 yond the eclipse termination, was identified as the initial sign of the post-eclipse TID.
 336 For a few hours (4-5 hours) since the eclipse termination, post-eclipse perturbations con-
 337 tinued to be present in Region (3) that extended deep in the southern hemisphere. In
 338 Region (3) there was also a positive disturbance front. It appears reasonable to attribute
 339 these post-eclipse ionospheric disturbances in dTEC to large scale TIDs that were driven
 340 by post-eclipse TADs. As discussed in Introduction, TADs excited in situ in the ther-
 341 mosphere by a solar eclipse have been well-known in simulations. Their global propa-
 342 gation in the direction associated with the eclipse path will continue after the eclipse has
 343 terminated, and then become attenuated (Müller-Wodarg et al., 1998; Lei et al., 2018;
 344 Dang, Lei, Wang, Zhang, et al., 2018). These TADs are expected to drive TIDs through
 345 effects of the disturbance winds, temperature, and composition, and therefore post-eclipse
 346 TIDs are quite likely; in fact, Lei et al. (2018); Dang, Lei, Wang, Zhang, et al. (2018)
 347 were able to demonstrate the simulated post-eclipse electron density disturbances (pos-
 348 itive and negative) in the southern hemisphere. Our post-eclipse dTEC observations were
 349 consistent with the southward propagation of the post-eclipse TADs through the south-
 350 ern hemisphere in some of these simulations.

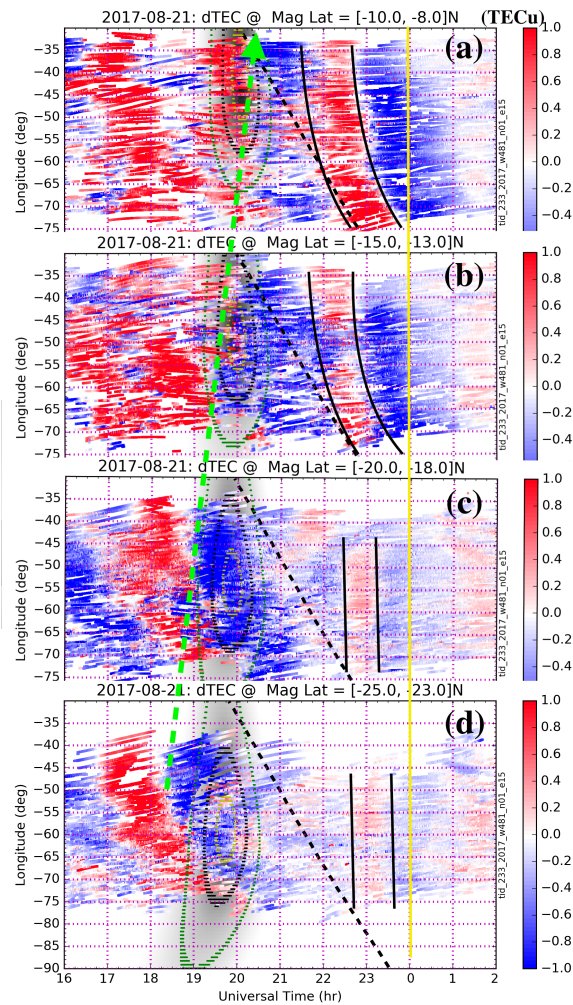


Figure 5: Longitudinal disturbances in dTEC (TECu) as a function of UT at magnetic southern latitudes (a) $-8 - 10^{\circ}\text{N}$, (b) $-13 - 15^{\circ}\text{N}$, (c) $-18 - 20^{\circ}\text{N}$, and (d) $-23 - 25^{\circ}\text{N}$. Green dots are conjugate locations of the 25% magnitude of eclipse in the northern hemisphere, and black dots are the same as the green except for the 50% magnitude. Dashed line represents the sunset times. Solid black lines mark the regions between positive and negative wave fronts of post-eclipse TIDs near 22–24 UT. Dashed green line highlights the equatorward progression of the depletion region. Yellow vertical line is 24 UT.

351 Region (4) is the TEC depletion (negative dTEC) zone in the southern hemisphere
 352 which remained within the conjugate 0.25-curve. It corresponds roughly to the south-
 353 ern depletion in Figure 3. The depletion initially developed near -40°N magnetic lati-
 354 tudes near 19 UT when the eclipse totality occurred in the north, and the depletion in-
 355 tensified at later times when the Moon shadow moved to lower latitudes. By 21 UT, the
 356 eclipse had terminated, post-eclipse TIDs became highly visible in Region (3), and the
 357 conjugate depletion zone remained in Region (4). Therefore these TIDs and the conju-
 358 gate depletion partially overlapped.

359 To summarize these observational results, the eclipse induced ionospheric effect in
 360 the southern hemisphere was characterized by a TEC depletion zone located predom-
 361 inantly in a **triangle region** on the magnetic latitude - UT keogram as shown in Fig-

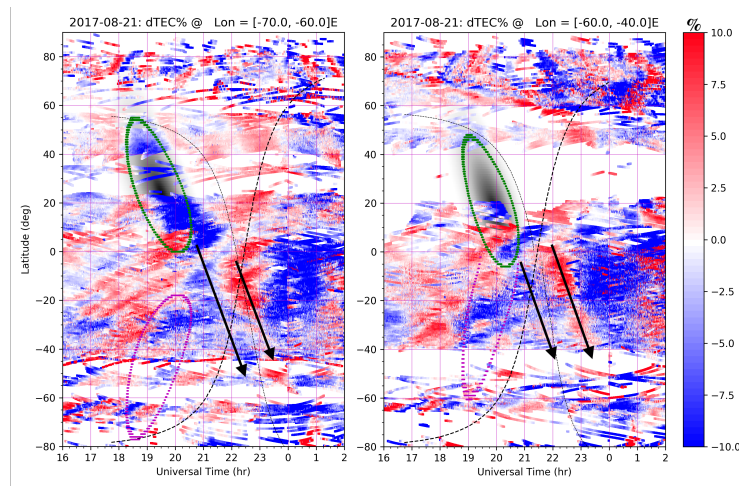


Figure 6: UT vs latitude variations of dTEC (in percentage) derived using the 120-min sliding window de-trending for longitudinal sectors (left) $-70 - -60^{\circ}\text{E}$ and (right) $-60 - -40^{\circ}\text{E}$. The 0.25 eclipse magnitude is marked by the green line and its conjugate location is marked by the purple line. The dark arrows represent the eclipse-induced ionospheric disturbance propagation. Thick dashed line represents the sunset times, and the thin dashed line is the sunset times for corresponding conjugate locations.

362 ure 8. During the presence of the northern eclipse, the conjugate ionosphere experienced
 363 the density depletion that developed into lower latitudes at later times. Furthermore,
 364 during the post-eclipse period, both this conjugate ionospheric depletion and large scale
 365 TID influences were concurrent in both space (especially at lower latitudes) and time.

366 3.3 Southern EIA crest weakening

367 The largest depletion of conjugate ionospheric density disturbance (negative dTEC)
 368 during the northern eclipse was observed in the aforementioned triangle area at $\sim 30^{\circ}\text{S}$
 369 geographic latitude ($\sim -20^{\circ}\text{N}$ geomagnetic latitude) and equatorward as shown in Fig-
 370 ures 6, 7 and 8, with a particularly large effect immediately adjacent to the southern EIA
 371 zone. The EIA crests in TEC were nearly symmetric in their location and intensity with
 372 respect to the magnetic equator before the eclipse onset in the northern hemisphere; then
 373 with the eclipse onset, the southern EIA crest weakened gradually. At the end of the eclipse,
 374 the southern EIA crest almost vanished (Figure 9). At the eastern longitudes where the
 375 distance between the northern eclipse zone and its conjugate region is shorter than that
 376 in the eastern longitudes, the weakening southern EIA crest fell into the 0.25-curve and
 377 its TEC intensity reduction (contrast), relative to the northern EIA crest, was larger as
 378 compared to that in the western longitudes. The northern EIA appeared to be slightly
 379 enhanced in the local afternoon during the eclipse time period.

380 Variations in this southern EIA crest were significant and they were accompanied
 381 by the development of eclipse-induced conjugate depletion in dTEC, extending equator-
 382 ward into the polarward vicinity of the crest, and therefore their direct impacts on the
 383 ionosphere adjacent to the conjugate depletion can be important. These EIA variations
 384 will be discussed further in the next Section.

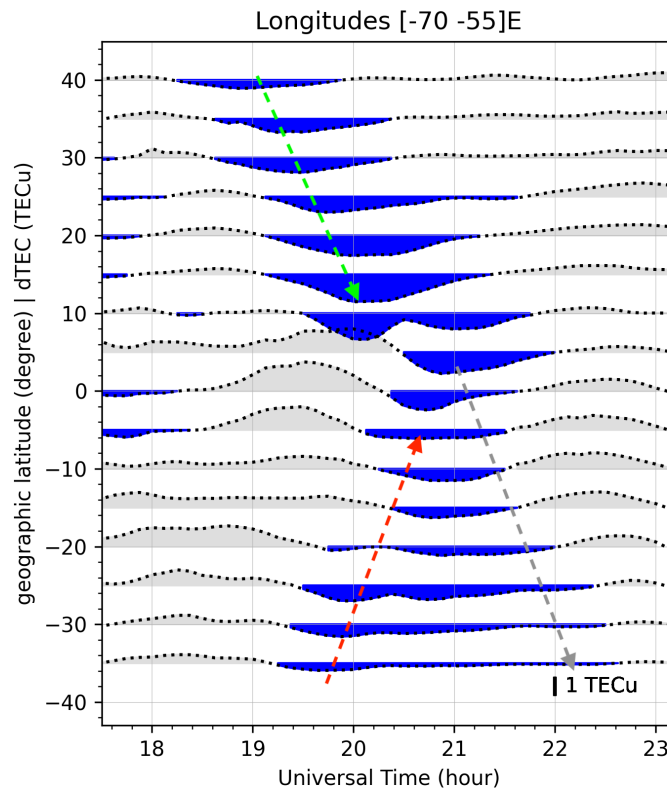


Figure 7: UT time variation of dTEC (in TECu) derived using the 120-min sliding window de-trending at geographic latitudes between $-35 - 40^{\circ}\text{N}$ for longitudinal sectors $-70 - -55^{\circ}\text{E}$. These dTEC values are running averages over ± 3.75 min and $\pm 5^{\circ}$ to represent characteristic dTEC variations shown in Figure 6. Negative dTEC values are marked as blue shadows. The green arrow represents the disturbance propagation under direct influences of the Moon mask, the green arrow represents equatorward progression of ionospheric disturbances in the conjugate hemisphere during the eclipse time period, and the gray arrow is post-eclipse ionospheric disturbance propagation into the conjugate hemisphere.

385 **4 Discussion**

386 Results presented in the prior section reveal a strong correlation between the solar
 387 eclipse and ionospheric response in the southern hemisphere. In particular, the south-
 388 ern hemisphere TEC depletion occurred in a region that was conjugate to the eclipse re-
 389 gion at the correct time although the conjugate properties vary with latitude, and ef-
 390 fects also evolved equatorward as the Moon shadow moved equatorward. We now dis-
 391 cuss sever factors that may cause this conjugate ionospheric depletion effect.

392 **4.1 Conjugate electric field and electron temperature**

393 Eclipse effects simulations shown in Huba and Drob (2017) indicated a TEC de-
 394 pletion band at 18:30 UT located at -30°N and also equatorward in the South Pacific
 395 Ocean, to the west of South America (Figure 6 in Huba and Drob (2017)). At this time,

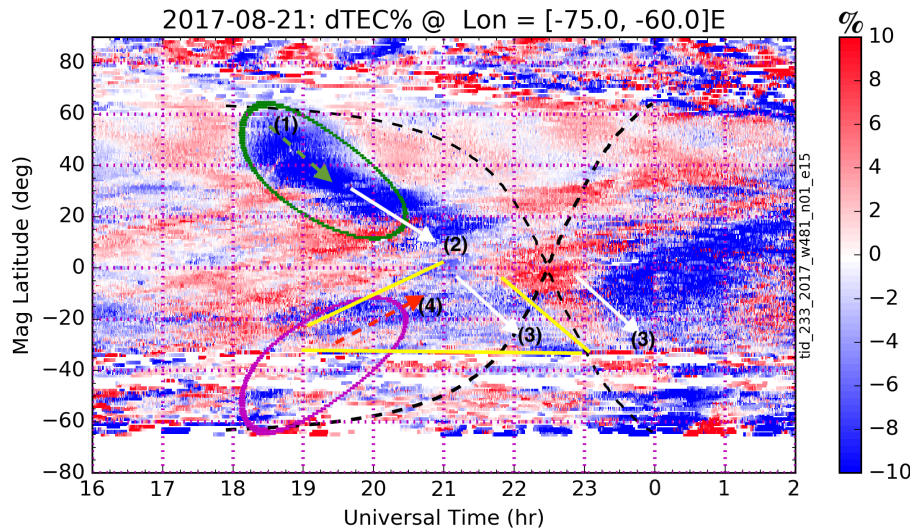


Figure 8: UT vs magnetic latitude variations of dTEC derived using the 120-min sliding window de-trending for longitudinal sectors -75 – -60°E. The southern hemisphere ionospheric effects are identified primarily in a triangle region formed by the three two yellow lines (top). The 0.25 eclipse magnitude is marked by the green line and its conjugate location is marked by the purple line. The green arrow represents the progression direction of density depletion in the eclipse zone, and the white arrow is the eclipse-induced ionospheric wave propagation. Thick dashed line represents the sunset times, and the thin dashed line is the sunset times for corresponding conjugate locations

396 the conjugate latitudes of the 25% eclipse iso-magnitude circle occurred further in the
 397 south, completely beyond this -30°N latitude. Comparison indicates therefore that the
 398 predicted depletion reported by Huba and Drob (2017) is not likely to be the same de-
 399 pletion we report here. Instead, modeling results showed an **enhancement** zone, south-
 400 ward of the -30°N depletion and likely conjugate to the northern eclipse. For Huba and
 401 Drob (2017), the conjugate electron density enhancement was explained in terms of an
 402 enhanced electrostatic field due to reduced conductivity in the eclipse zone (and the sim-
 403 ulated density depletion in the non-conjugate region was explained in terms of electric
 404 field modification). In particular, enhanced electric field in the conjugate hemisphere would
 405 increase the vertically upward component of $\mathbf{E} \times \mathbf{B}$ drift, raising the altitude of the F2-
 406 layer and subsequently enhancing TEC through reduced chemical loss by charged ex-
 407 change and recombination reactions. This mechanism, however, is not applicable to the
 408 TEC depletion in our observation.

409 In the Huba and Drob (2017) simulation, changes in neutral winds, temperature,
 410 and composition were not considered. Dang, Lei, Wang, Zhang, et al. (2018)'s separate
 411 study provides self-consistent thermosphere-ionosphere coupling during the 2017 eclipse
 412 with electrodynamics (but without interhemispheric coupling for mass and thermal ex-
 413 changes especially at low and mid- latitudes) using the TIEGCM model. In that study,
 414 the largest upward vertical component of $\mathbf{E} \times \mathbf{B}$ drift in this simulation appeared to the
 415 south of the eclipse conjugate area. However, within the conjugate area, this simulated
 416 vertical component remained fairly small and would therefore presumably had little over-
 417 all effect.

418 Another TIEGCM-based data assimilation study conducted by Chen et al. (2019)
 419 yielded a result of enhanced eastward electric fields at equatorial latitudes. These zonal

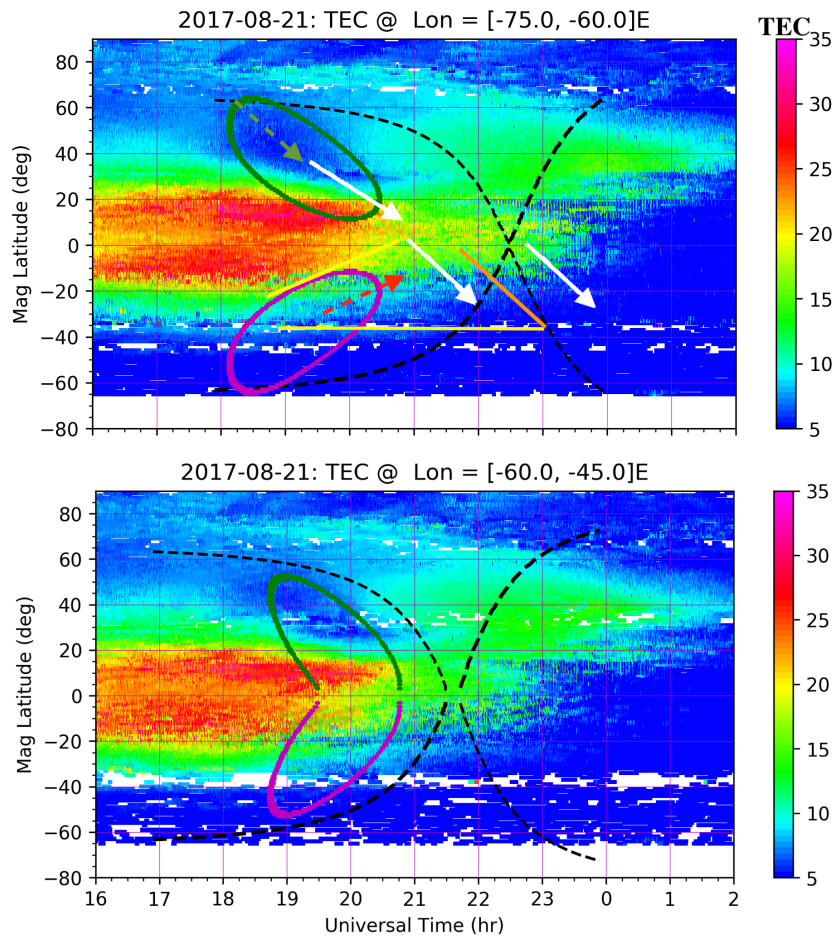


Figure 9: UT vs magnetic latitude variations of TEC for (top) longitudinal sectors -75 – -60°E and (bottom) further west at -60 – -45°E, The arrows and the triangle on the top panel correspond to those in Figure 8.

420 electric field increases subsequently intensified EIAs, with the enhanced westward elec-
 421 tric fields at northern midlatitudes remaining essentially within the Moon shadow due
 422 to the dynamo change. Westward electric fields in this configuration can drive downward
 423 plasma drift and contribute to electron density depletion in the eclipse zone through in-
 424 creased chemical loss. The westward electric fields of Chen et al. (2019) appeared in the
 425 conjugate hemisphere near -20 – -30°N magnetic latitudes, to the south of the southern
 426 EIA region, particularly after 20:00 UT. Such a conjugate westward electric field, cre-
 427 ating a downward ion drift and potentially contributing to electron density depletion,
 428 are indeed qualitatively consistent with our results. However, the magnitude of the west-
 429 ward electric fields was estimated at only ~ 0.1 mV/m translating to a local 2-3 m/s ver-
 430 tical downward drift (i.e., 10 km vertical distance in 1 hour). Furthermore, this electric
 431 field timing is problematic for our observations as it occurred 1-hour behind our observed
 432 density depletion. Overall, therefore, this conjugate electric field mechanism does not
 433 quantitatively fit our depletion observations.

434 Le et al. (2009); Huba and Drob (2017) simulations also noted significant T_e re-
 435 duction in both hemispheres, due to reduced photoelectron heating that is conducted
 436 along the field line. Such a large T_e reduction would decrease the plasma scale height

437 in the topside ionosphere, leading to a reduction in TEC. However, Huba and Drob (2017)
 438 found that the eclipse induced T_e reduction caused only very small predicted TEC changes
 439 (≤ 0.05 TECu). Le et al. (2009)'s simulation, calculated for a different eclipse, showed
 440 similar T_e reductions throughout the two hemispheres, but found N_e enhancement in the
 441 conjugate ionosphere. We note once again here a strong anti-correlation existed between
 442 N_e and T_e . In particular, during a reduction in solar EUV irradiation (and thus N_e), the
 443 associated reduction of photoelectron energy deposition in the upper atmosphere could
 444 result in less efficiency for reductions in T_e due to less available electron density to share
 445 the total energy input available.

446 4.2 EIA relevance

447 The southern EIA crest is usually weaker in the afternoon and is asymmetric to
 448 the northern one in this season (Luan et al., 2015; Huang et al., 2018). This asymmet-
 449 ric behavior was visible also during the eclipse as described earlier, and therefore the eclipse
 450 observation agrees with some of the expected EIA climatology for this season. A ma-
 451 jor difference from the climatology is that on the eclipse day, the crests were initially (be-
 452 fore the eclipse onset) symmetric with similar TEC values (Figure 9), whereas the cli-
 453 matology indicated a consistently weaker southern crest (and an afternoon abatement)
 454 during the day. EIA crests are well known for their large day-to-day and diurnal vari-
 455 ability. For instance, on 20 August, there was no southern EIA crest in TEC; on 22 Au-
 456 gust, the southern EIA crest weakening in TEC took place in the afternoon but less dra-
 457 matically than on 21 August, the eclipse day (Supplement Figure S1). Additionally, dTEC
 458 on the 20th and the 22nd also appeared different from values at eclipse time (Supple-
 459 ment Figure SF2), partially due to geomagnetic activity influences as discussed in the
 460 next section. Other factors potentially driving EIA variability include lower atmospheric
 461 forcing which would modify the equatorial dynamo and thereby affect the EIA fountain
 462 effect. These electrodynamic effects, however, would not introduce a substantial asym-
 463 metry in EIA crests.

464 Absent eclipse effects, summer-to-winter trans-equatorial winds (being strong in
 465 the afternoon hours) would contribute to a larger northern EIA (with winds uplifting
 466 plasma locally) and a weaker southern EIA (with winds pushing down plasma locally).
 467 This wind effect was unlikely to be operating prior to the eclipse onset and up to 19 UT,
 468 when the EIA crests were actually symmetric. During the eclipse time especially after
 469 19 UT, if these background winds happened to be strong, they would enhance the north-
 470 ern crest and also weaken the southern crest. However, the EIA TEC data do not sug-
 471 gest a clear northern enhancement (e.g., between 19-20 UT) that was comparable to the
 472 southern weakening (between 19-20 UT). It is also questionable that the north-to-south
 473 trans-equatorial winds could cause the characteristic southern crest weakening that started
 474 in its southern (poleward) edge and extended northward (equatorward). However, eclipse
 475 presence in the northern hemisphere could create, to the south of the eclipse zone, a per-
 476 turbed south-to-north (winter-to-summer) pressure gradient. This would create a north-
 477 ward wind component due to atmospheric cooling in the shadow, acting counter to the
 478 background trans-equatorial flow. This wind disturbance was observed by (Harding et
 479 al., 2018). This mechanism tends to produce an opposite EIA asymmetry, weakening the
 480 north EIA crest (by providing a downward ion drift) and enhancing the southern crest.
 481 We therefore conclude that the eclipse induced disturbance neutral winds alone were likely
 482 not responsible for the observed weakening of the southern EIA.

483 Electric field disturbances in the local and the conjugate hemispheres at eclipse time
 484 would be expected, as discussed in the previous section, but to date simulation results
 485 are not quite consistent in producing this feature. Nevertheless, it can be stated that while
 486 a westward electric field increase during the Moon shadow passage at mid latitudes ap-
 487 pears promising, this effect is not likely to significantly affect the observed dTEC, since

488 calculated conjugate electric fields are too weak and furthermore the time of their oc-
 489 currence is too late.

490 In conclusion, the EIA southern crest weakening was observed during the north-
 491 ern eclipse period whereas the northern crest was much more stable. Although this EIA
 492 asymmetry pattern was consistent with some of the established EIA climatology, sev-
 493 eral known factors that are normally considered as contributing to the substantial day-
 494 to-day EIA variability cannot be attributed positively in this eclipse event to this weak-
 495 ening and the associated EIA crest asymmetry on the eclipse day. Accordingly, we ar-
 496 gue that other eclipse related processes could have played a role and contributed to EIA
 497 variability.

498 **4.3 Eclipse induced plasma pressure gradient reduction**

499 Factoring in the discussion above, a new mechanism is proposed here with better
 500 consistency with known thermal behavior during eclipses and with observed TEC eclipse
 501 time behavior in both hemispheres. It is clear that, in the eclipse region, plasma den-
 502 sity (to a large degree), electron temperature, and ion temperature (to a less degree) all
 503 drop. For example, Hairston et al. (2018) reported a 500-1000K drop in T_e during this
 504 eclipse in DMSP data. The F region T_e in the direct, partial eclipse zone at the mid lat-
 505 itude Millstone Hill incoherent scatter radar experienced a similar temperature drop al-
 506 though with smaller magnitude (Goncharenko et al., 2018). Given these trends, eclipse
 507 time plasma pressure (proportional to plasma density and plasma temperature ($T_e +$
 508 T_i)) should decrease as well, and this pressure would have a larger reduction amplitude
 509 compared to either of its constituent quantities. This pressure drop would lead to a eclipse-
 510 induced plasma pressure gradient, oriented downward along the flux tubes at mid- and
 511 low latitudes in the eclipse hemisphere, and directed northward at equatorial latitudes
 512 (Figure 1, right panel).

513 The resulting plasma pressure gradient imbalance during the eclipse would facil-
 514 itate enhanced efficiency in field-aligned plasma flow in various flux tubes affected by the
 515 Moon shadow. When the eclipse shadow arrives at lower latitudes where flux tubes have
 516 a shorter length (Figure 1, right panel), this field-aligned transport would operate effi-
 517 ciently for those flux tubes that transverse the F2 region topside ionosphere. For instance,
 518 the flux tube at the L-shell intersects 20° magnetic latitudes at a 700-800 km apex al-
 519 titude. However, plasmasphere flux tubes where the field-aligned thermal conduction is
 520 strong would experience less this effect, as the conduction would act to smooth out plasma
 521 temperature hemispheric differences (Huba & Drob, 2017). As a result, the overall plasma
 522 fountain above the magnetic equator F region would be skewed towards the northern eclipse
 523 hemisphere (unlike under a normal situation, with diffusion equally northward and south-
 524 ward), and the northern EIA could therefore be maintained or even intensified. This re-
 525 sult is inherently asymmetric, since the southern EIA would be weakened due to a lack
 526 of sufficient plasma pressure to drive southward diffusion.

527 It is important to note that this overall eclipse scenario is not analogous to the con-
 528 dition where a long flux tube connects one hemisphere on the dayside to the other one
 529 on the nightside via the plasmasphere. In the eclipse scenario here, the equatorial east-
 530 ward electric field would still create $\mathbf{E} \times \mathbf{B}$ drift that would continuously uplift the foun-
 531 tain plasma, generated by substantial daylight photo-ionization up to high altitudes. The
 532 eclipse induced disturbance in neutral winds would also cause a northward ion flow, but
 533 this flow would be increasingly weaker away from the eclipse region and hence it would
 534 have very limited effects on the southern hemisphere.

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4.4 Magnetic disturbance effect

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Another possibility for generation of the depletion progression we observed lies in whether the effect originated from geomagnetic activity at southern high latitudes. This does not appear likely in the event we studied. In particular, on 20 August, no similar depletion in the aforementioned triangle region nor within the conjugate 0.25-curve region (determined for the eclipse day) was found, although AE indices on both 20 August and 21 August were very similar (Supplement Figure SF2). In fact, the largest disturbances for both days occurred under conditions with AE at $\sim 750+$ nT at ~ 09 UT, with no connection to TEC perturbations after 18 UT. The second largest disturbance occurred very briefly at 18 UT with maximum AE ~ 700 nT, but this AE spike produced dayside poleward TIDs only in the northern polar region (Figure 8, a feature similar to what was reported in Zhang, Erickson, et al. (2019). Furthermore, in the southern hemisphere, the depletion in dTEC in the eclipse conjugate region and the triangle region was predominately located at magnetic -30° N latitudes and equatorward, starting prior to 19 UT. Thus, the depletion progression slope was far too small to be consistent with an auroral disturbance source at -60° N at 18 UT, and we therefore judge the AE spike at 18 UT as largely irrelevant to the conjugate depletion. Finally, examining the Hemispheric Power indices at these times for both northern and southern hemispheres shows consistency in key energy input features as represented by AE.

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We note that 22 August was more geomagnetically disturbed, and in particular AE was above 500 nT for two hours between 12-14 UT. During this period, southern hemispheric TIDs arrived at the latitudes where the conjugate depletion was identified on the eclipse day as well as higher and lower geomagnetic latitudes (Supplement Figure SF2). It is clear that the magnetic disturbance drove TID symmetry between northern and southern hemispheres. It is therefore clear also that the southern EIA weakening cannot be uniquely tied to eclipse conjugate effects or geomagnetic activity effects. However, the latter effects can indeed be uniquely traced back to its auroral source region.

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5 Summary

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This study investigates ionospheric conjugate perturbations during the 21 August 2017 solar eclipse using ground based GNSS TEC observations. Differential TEC was determined by de-trending the smooth background ionospheric variation within 2-hour long sliding windows. Results for 1-hour long time windows were similar but with smaller amplitudes. Observations identified two categories of conjugate ionospheric perturbations.

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The first category was represented by post-eclipse large scale TIDs which traveled into the southern hemisphere approximately in alignment with the Moon-shadow moving direction. These post-eclipse TIDs were consistent with some of the simulated large TADs and the associated electron density disturbances.

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The second category was represented by observations of TEC depletion in the southern hemisphere, conjugate to the northern eclipse zone, with at least 25% eclipse magnitude. The depletion occurred at up to 1 TECu less than a 2-hour window background average, or ~ 2 TECu (10-15%) less than TEC at the onset of this eclipse effect. This depletion started at higher southern latitudes and continued to be present for 2-3 hours as it moved into lower latitudes at a similar pace as the Moon shadow moved equatorward, with intensification located at $\sim -20^\circ$ N. Later in the event, this density depletion and the arriving LSTIDs formed an overlapping zone at lower latitudes. Evolution of this conjugate depletion was coincident with a weakening and eventually disappearing southern EIA, with similar timing and plausible effect as southern EIA evolution during the northern eclipse period.

584 TEC depletion and weakening EIA are features that are not unique to the eclipse
 585 day as compared to other days surrounding the event. However, TEC variations observed
 586 in the eclipse conjugate hemisphere cannot be fully ascribed to magnetic disturbances
 587 nor to other theorized mechanisms previously suggested, including conjugate electric field
 588 driven dynamics due to the eclipse induced dynamo change, and plasma thermal con-
 589 traction presumably throughout both hemispheres due to eclipse induced photoelectron
 590 reduction. In particular, enhanced westward electric fields, originating in the Moon shadow
 591 region at midlatitudes and magnetically mapping to the conjugate hemisphere, appear
 592 initially to be promising drivers of plasma depletion. However, when compared to ob-
 593 servations, the previously simulated electric fields were too weak and occurred too late
 594 for consistency with data. Other factors that normally contribute to the EIA variabil-
 595 ity and climatology cannot. Instead, we suggest a new eclipse time mechanism associated
 596 with a reduced plasma pressure gradient in the flux tube underneath the Moon shadow.
 597 As plasma density and plasma temperature (especially electron temperature) both de-
 598 creased in response to solar irradiation obscuration, an additional plasma pressure gra-
 599 dient was established, directed northward and downward in the northern midlatitudes,
 600 and northward at the magnetic equator. Under these conditions, as fountain plasma was
 601 pumped continuously upward by the nominal eastward electric field toward higher al-
 602 titudes, field-aligned diffusion occurred on flux tubes connected to the lower plasma pres-
 603 sure region in the north, but less likely towards the south. Furthermore, a lower neutral
 604 pressure gradient in the eclipse region would produce northward disturbance neutral winds
 605 predominately in the northern hemisphere low and equatorial latitudes, but not further
 606 south in the conjugate hemisphere where they would have moved up the plasma in com-
 607 pensation for skewing of the equatorial plasma fountain toward the other hemisphere.
 608 Overall, these eclipse-time processes could contribute to weakening of the southern EIA
 609 and ultimately drove the observed conjugate density depletion.

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 621 RAMSAC CORS of Instituto Geográfico Nacional de la República Argentina, Arecibo
 622 Observatory, Low-Latitude Ionospheric Sensor Network (LISN), Topcon Positioning Sys-
 623 tems, Inc., Canadian High Arctic Ionospheric Network, Institute of Geology and Geo-
 624 physics, Chinese Academy of Sciences, China Meteorology Administration, Centro di Ricerche
 625 Sismologiche, Système d’Observation du Niveau des Eaux Littorales (SONEL), RENAG
 626 : REseau NATional GPS permanent, GeoNet - the official source of geological hazard in-
 627 formation for New Zealand, GNSS Reference Networks, Finnish Meteorological Institute,
 628 and SWEPOS - Sweden. Original TEC data from Madrigal database (<http://cedar.openmadrigal.org/openmadrigal/>) can be found here: https://w3id.org/cedar?experiment_list=experiments2/2017/gps/21sep17&file_list=gps170921g.002.hdf5 and the line-of-sight TEC which are used for differential calculation is here https://w3id.org/cedar?experiment_list=experiments2/2017/gps/21sep17&file_list=los_20170921.001.h5

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