

1 **Ionospheric response at conjugate locations during the**
2 **7-8 September 2017 geomagnetic storm over the**
3 **Europe-African longitude sector**

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14 **Key Points:**

- 15 • The storm led to TEC enhancement in the southern hemisphere mid-latitude re-
16 gion that was at least twice that in the northern hemisphere on 08 September 2017.
- 17 • Physical processes related to low latitude origin, thermospheric composition changes
18 and large scale TIDs all had an influence on the observed profound positive iono-
19 spheric storm effects
- 20 • Ionospheric bottomside and topside/plasmasphere contributions to TEC were dif-
21 ferent in both hemispheres during the storm main phase.

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22 Abstract

23 This paper focuses on unique aspects of the ionospheric response at conjugate locations
24 over Europe and South Africa during the 07-08 September 2017 geomagnetic storm in-
25 cluding the role of the bottomside and topside ionosphere and plasmasphere in influenc-
26 ing electron density changes. Analysis of total electron content (TEC) on 07 Septem-
27 ber 2017 shows that for a pair of geomagnetically conjugate locations, positive storm ef-
28 fect was observed reaching about 65% when benchmarked on the monthly median TEC
29 variability in the northern hemisphere, while the southern hemisphere remained within
30 the quiet time variability threshold of $\pm 40\%$. Over the investigated locations, the south-
31 ern hemisphere mid-latitudes showed positive TEC deviations that were in most cases
32 twice the comparative response level in the northern hemisphere on the 08 September
33 2017. During the storm main phase on 08 September 2017, we have obtained an inter-
34 esting result of ionosonde maximum electron density of the F2 layer and TEC derived
35 from Global Navigation Satellite System (GNSS) observations showing different iono-
36 spheric responses over the same mid-latitude location in the northern hemisphere. In situ
37 electron density measurements from SWARM satellite aided by bottomside ionosonde
38 derived TEC up to the maximum height of the F2 layer (hmF2) revealed that the bot-
39 tomside and topside ionosphere as well as plasmasphere electron content contributions
40 to overall GNSS derived TEC were different in both hemispheres especially for 08 Septem-
41 ber 2017 during the storm main phase. The differences in hemispheric response at con-
42 jugate locations and on a regional scale have been explained in terms of seasonal influ-
43 ence on the background electron density coupled with the presence of large scale trav-
44 eling ionospheric disturbances and low latitude associated processes. **The major high-**
45 **light of this study is the simultaneous confirmation of most of the previously**
46 **observed features and their underlying physical mechanisms during geomag-**
47 **netic storms through a multi-dataset examination of hemispheric differences.**

48 1 Introduction

49 It is well established that dynamic and electrodynamic processes associated with
50 interactions between the solar wind, magnetosphere and ionosphere primarily control the
51 ionospheric behavior during geomagnetic storms [e.g., *Kelley et al.*, 1979; *Prölss*, 1993;
52 *Scherliess and Fejer*, 1997; *Buonsanto*, 1999; *Danilov*, 2001; *Prölss*, 2004; *Huang*, 2008,
53 and references therein]. Additionally and over many decades, studies have shown that

54 global and regional ionospheric responses to occurrence of geomagnetic storms signifi-
55 cantly vary with a number of factors such as local time at storm onset, location, seasons
56 and sometimes the intensity as well as the duration of the geomagnetic disturbances [e.g.,
57 *Prölss, 1993; Buonsanto, 1999; Danilov, 2001; Buresova et al., 2014*]. The commonly ob-
58 served responses due to geomagnetic storms are enhancement and depletion in electron
59 density or total electron content of the ionosphere, which are usually referred to as pos-
60 itive and negative ionospheric storm effects, respectively [e.g., *Prölss, 1993; Mendillo,*
61 *2006; Buresova et al., 2014; Vijaya Lekshmi et al., 2011; Matamba et al., 2015*]. Irrespec-
62 tive of the ionospheric parameterization used, there are cases where no significant de-
63 viation (from the background electron density) is observed to ‘qualify’ as negative or pos-
64 itive ionospheric storm effects during storm conditions [e.g., *Vijaya Lekshmi et al., 2011;*
65 *Matamba et al., 2015*]. Thus, there are varying physical mechanisms used to explain dif-
66 ferent observations [e.g., *Prölss, 1993, 1995; Buonsanto, 1999*]. It is now accepted that
67 the composition changes within the thermosphere are largely responsible for negative storm
68 effects [e.g., *Prölss, 1993; Buonsanto, 1999; Danilov, 2001*], while the interpretation of
69 positive storm effects involves various mechanisms such as increased or enhanced ver-
70 tical $\mathbf{E} \times \mathbf{B}$ drift, occurrence of atmospheric gravity waves and prompt penetrating elec-
71 tric fields [e.g., *Prölss, 1993; Tsurutani et al., 2004; Vijaya Lekshmi et al., 2011; Ding*
72 *et al., 2007; Ngwira et al., 2019*, and references therein]. Inevitably, similar latitude re-
73 gions in different hemispheres could present different responses due to the physical mech-
74 anisms that may be dominant in each hemisphere. Consequently, each storm period may
75 have its particular characteristics and influence on the ionospheric electron density re-
76 sponse in high, low and mid latitude regions [e.g., *Yizengaw et al., 2005*]. Recently, the
77 solar and geophysical conditions during/around 05-14 September 2017 have received con-
78 siderable attention for a number of reasons including (but not limited to) the period be-
79 ing associated with: producing most of the solar flares in solar cycles 24 [e.g., *Curto et al.,*
80 *2018; Mosna et al., 2020*] with some flare activity leading to significant ionospheric elec-
81 tron density and TEC increase [*Yasyukevich et al., 2018; Li et al., 2018; Mosna et al.,*
82 *2020*] in the sun-lit longitude regions, geomagnetic storm that led to occurrence of plasma
83 bubbles that were observed over mid latitudes [*Aa et al., 2019*], existence of long dura-
84 tion positive storm effects in some longitudes such as the Asian-Australian sector [*Lei*
85 *et al., 2018*], and the different response in nature of the Earth’s magnetosphere and iono-
86 sphere to the development and occurrence of the two consecutive storms [e.g., *Jimoh et al.,*

2019; *Blagoveshchensky et al.*, 2019]. The interesting nature of this storm period led to a dedicated Special Section Issue in AGU’s Journal of Space Weather under the theme “Space Weather Events of 4-10 September 2017”. This storm period has therefore been studied extensively. Nevertheless, there are some ionospheric storm related features and peculiarities that have not yet been reported. This paper focuses on unique aspects of the ionospheric response at the conjugate locations over Europe and South Africa during the 07-08 September 2017 geomagnetic storm including the role of the bottomside and topside ionosphere and plasmasphere in influencing electron density changes. On 07 September 2017, analyzed TEC over selected locations in the mid-latitude northern hemisphere indicated a positive storm effect while their conjugate counterparts in South Africa did not show significant deviations from monthly median TEC, which is considered as the representation of the background ionospheric conditions. While both mid-latitudes showed positive storm effect during the storm main phase on 08 September 2017, the response (in terms of magnitude) in the southern hemisphere was at-least twice that of the northern hemisphere and for an extended period of time (over 8 hours compared to less than 2 hours for northern hemisphere). We have used ionosonde, GNSS (specifically GPS) and SWARM satellite data to study the evolution, nature of the response, and physical mechanisms that played dominant roles in influencing mid latitude ionospheric density and TEC changes during the storm period of 07-08 September 2017 in the two hemispheres.

2 Data sources

We have utilized both ground-based and satellite observations to describe the temporal, spatial and altitudinal response of the ionosphere during the selected storm period of 07-08 September 2017. The data sources used are:

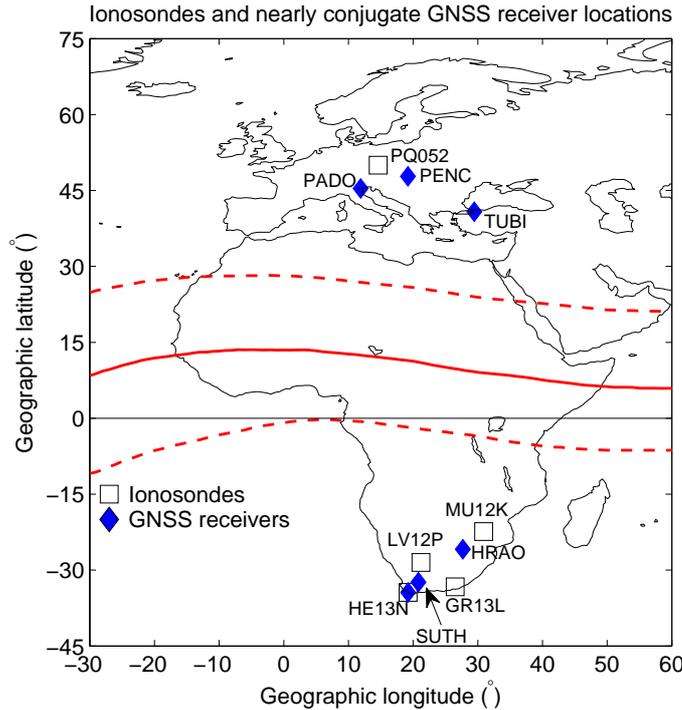
1. Ionosonde data: This provides the bottomside ionospheric parameters. **In this study, the ionosonde was the source of the critical frequency of the F2 layer (foF2) which reveals the F2 region response to the occurrence of the geomagnetic storm. This data also provided the electron density values at different altitudes, which** were used to derive the bottomside contribution of TEC up to the peak height of the F2 layer (hmF2) to analyze the storm-time response of the ionosphere at conjugate locations. Data from the South African **ionosonde** network for locations Grahamstown, GR13L (33.3°S, 26.5°E), Her-

119 manus, HE13N (34.4°S, 19.2°E), Louisvale, LV12P (28.5°S, 21.2°E) and Madimbo,
120 MU12K (22.4°S, 30.9°E) represented the southern hemisphere, while Pruhonice,
121 PQ052 (50.0°N, 14.6°E) ionosonde was used to study the northern hemispheric
122 mid-latitude response. These are the ionosonde locations where we had access to
123 all data records to allow us to check the ionograms for the correctness in the au-
124 toscaling software. Manually scaling of some ionograms was performed where nec-
125 essary as autoscaling confidence levels are sometimes degraded during geomagnet-
126 ically disturbed conditions. **This manifests in terms of the autoscaling soft-
127 ware “failing” to follow the ionogram traces which can result into in-
128 correct values of the ionospheric parameters [e.g., *Huang and Reinisch,*
129 *1996; Habarulema and Carelse, 2016*].**

130 2. SWARM satellite data: The SWARM satellite mission consists of three identical
131 satellites with an inclination of 87.75° at altitudes of ~ 460 km (A and C) and
132 500 km (B), and are thus well positioned for topside ionosphere studies. They pro-
133 vide among others, in situ electron density and total electron content at these al-
134 titudes as a function of latitude, and therefore give simultaneous information about
135 the topside behavior (and by proxy, the plasmasphere contribution to TEC) and
136 the extent of the equatorial ionization anomaly (EIA) development or absence dur-
137 ing investigated periods. In this study, SWARM data were used to compare its
138 electron density with bottomside electron content and GPS TEC at nearly con-
139 jugate locations in southern and northern hemisphere mid-latitudes.

140 3. GPS TEC data: This is the basis for providing continuous ionospheric TEC re-
141 sponse with respect to latitude and diurnally during the entire period of study and
142 hence revealing different observations peculiar to each latitude region in both hemi-
143 spheres. **Vertical** TEC was derived from GPS observations using an algorithm
144 that assumes an ionospheric thin shell height at 350 km. To minimize errors re-
145 lated to multipaths while retaining significant data coverage (as our investigation
146 also covered regions with little or no ground-based GNSS receivers), an elevation
147 threshold of 15 degrees was used. Within the longitude sector covering 20°E-40°E,
148 and latitude range of 40°S-70°N, 2-dimensional diurnal **vertical** TEC maps are
149 produced for the 6-9 September 2017. Furthermore, within the same spatial res-
150 olutions, TEC data were detrended using a fourth order polynomial function based
151 on individual GPS satellite’s observations and TEC perturbation (referred to as

152 Δ TEC) plots as a function of latitude and time were generated during 6-9 September
 153 2017. For both TEC and Δ TEC plots, data were binned within 3 minutes by
 154 2° (time/latitude) and average TEC or Δ TEC plotted for each bin. This reveals
 155 regions and times of TEC enhancements and/or depletions on a spatial scale within
 156 the considered longitude sector during the analyzed period.



157 **Figure 1.** Map showing locations of ionosondes and some GNSS receivers which were used in
 158 conjugacy analysis. Over Hermanus (34.42°S , 19.22°E), ionosonde (HE13N) and GNSS receiver
 159 (HNUS) are co-located. The red solid line indicates the geomagnetic equator. Additional details
 160 about the locations can be found in Table 1.

161 Figure 1 is the map showing the location of ionosondes and nearly geomagnetically con-
 162 jugate GNSS receivers used in Europe and South Africa. For clarity, not all GNSS re-
 163 ceivers used in the study for generating 2-dimensional TEC and Δ TEC maps are indi-
 164 cated on this map. While some of the receivers have the capability of providing obser-
 165 vations from more than one GNSS constellation, we have specifically used the Global Po-
 166 sitioning System (GPS) data in this study.

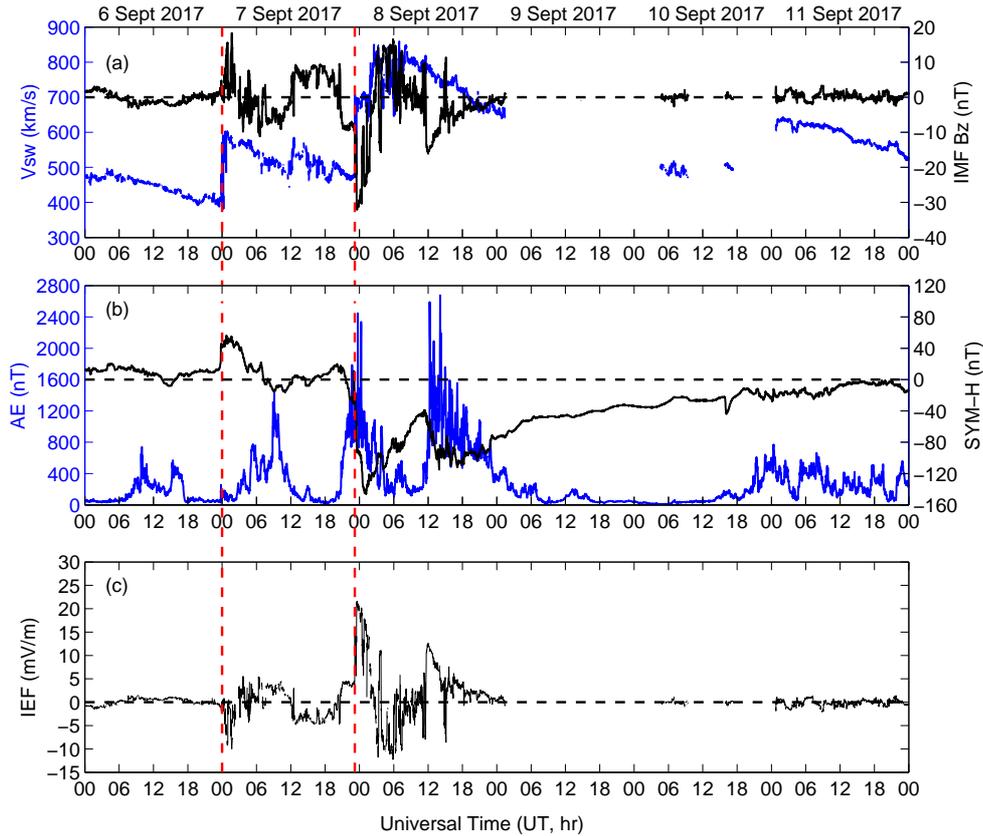
167 2.1 Solar wind and geomagnetic activity conditions

168 In general, the solar and geomagnetic activity conditions for 04-11 September 2017
 169 have been described as complex largely due to the occurrence of multiple solar flares of
 170 different classes [e.g., *Curto et al.*, 2018; *Yasyukevich et al.*, 2018; *Mosna et al.*, 2020] and
 171 storm related activity that led to two consecutive Dst minima separated by about 13 hours
 172 on the same day [e.g., *Lei et al.*, 2018; *Aa et al.*, 2019; *Blagoveshchensky et al.*, 2019].
 173 Figure 2 shows changes in (a) solar wind velocity, V_{sw} (m/s) and B_z component of the
 174 interplanetary magnetic field, IMF B_z (nT), (b) Auroral electrojet, AE (nT) index and
 175 SYM-H (nT) index equivalent to high resolution Dst index [*Wanliss and Showalter*, 2006],
 176 and (c) the interplanetary electric field, IEF = $-V_x \times B_z$ (mV/m); during 06-11 Septem-
 177 ber 2017. Two X-class solar flares occurred on 06 September 2017. The X2.2 and X9.3
 178 solar flares peaked at 0910 UT and 1202 UT respectively. The accompanying coronal mass
 179 ejection (CME) led to the geomagnetic storm conditions of 07-08 September 2017 with
 180 SYM-H minima values of -146 nT and -115 nT at about 0108 UT and 1356 UT on 08
 181 September 2017. The vertical dashed red lines indicate the shocks' arrival times on the
 182 Earth's magnetosphere at about 2343 UT and 2300 UT on 06 and 07 September 2017
 183 respectively. The V_{sw} showed two instances of sudden increase from about 400 km/s to
 184 600 km/s (at 2343 UT on 06 September) and at 2300 UT on 07 September 2017, V_{sw}
 185 reached just over 700 km/s before continuing a steady increase attaining a value of \sim
 186 800 km/s at 0200 UT on 08 September 2017. Before the end of the first storm, an ad-
 187 ditional CME led to another onset of the main-phase at 1135 UT on 08 September 2017
 188 reaching a minimum SYM-H of -115 nT (1356 UT) and thereafter, the geomagnetic storm
 189 conditions began a gradual recovery.

193 Between \sim 0400-1200 UT, the IMF B_z was mostly southward on 07 September 2017
 194 with some noticeable periods of northward turning. The IMF B_z reached the minimum
 195 value of -32.1 nT and corresponding increase in IEF of 21.6 mV/m at 2335 UT on 07
 196 September 2017. The last substantial IMF B_z negative excursion reaching -16 nT was
 197 recorded at 1200 UT on 08 September 2017.

198 3 Results and discussions

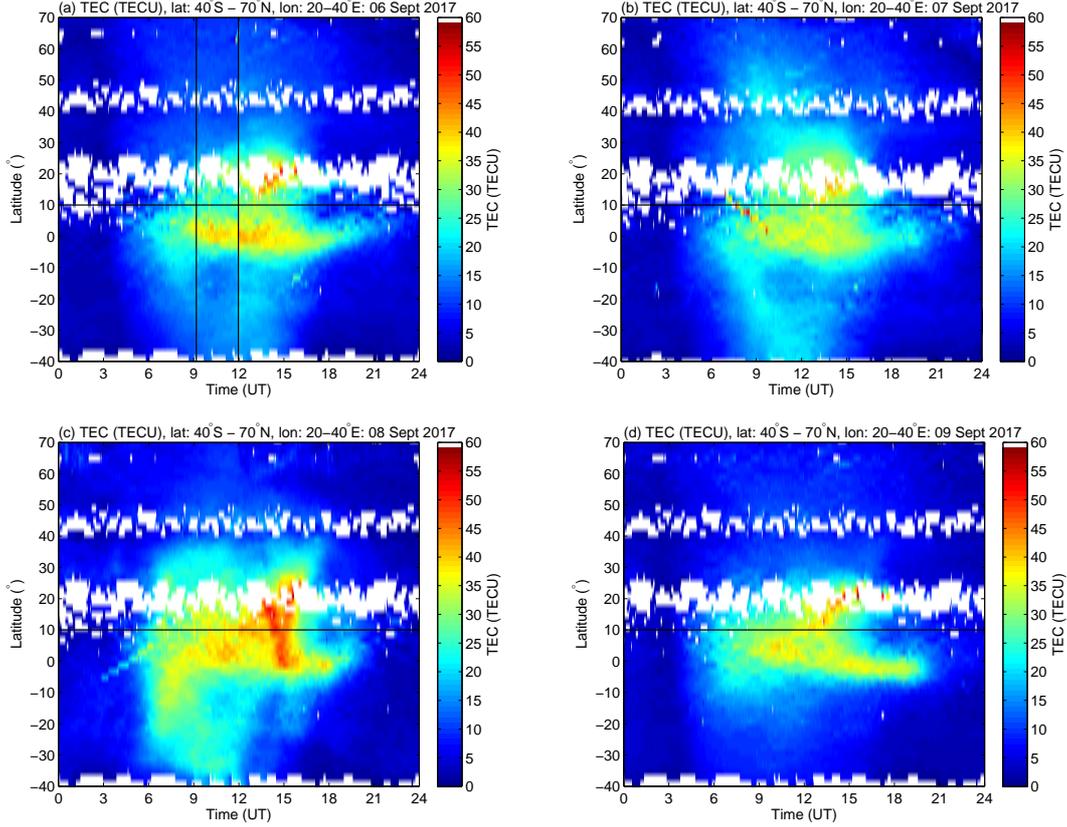
199 Figure 3 shows TEC changes for the period of 06-09 September 2017 within 40°S-
 200 70°N and 20 – 40°E geographic latitude/longitude coverage. The solid black horizon-



190 **Figure 2.** Geomagnetic and interplanetary conditions during 6-11 September 2017. The verti-
 191 cal red dashed lines show the arrival times of CME shocks on the Earth’s magnetosphere at 2343
 192 UT and 2300 UT on 06 and 07 September respectively.

201 tal line at 10°N geographic latitude approximates the geomagnetic equator. Figure 3 is
 202 generated by considering TEC for satellites above 15° elevation and binning data into
 203 2° latitude by 3 minutes.

208 The black vertical straight lines on Figure 3(a) show the occurrence time of the two
 209 solar flares X2.2 and X9.3 at 0910 UT and 1158 UT respectively on the 06 September
 210 2017 [e.g., *Curto et al.*, 2018; *Yasyukevich et al.*, 2018; *Li et al.*, 2018; *Mosna et al.*, 2020].
 211 As indicated in Figure 2, the first sudden storm commencement occurred on 06 Septem-
 212 ber 2017 at 2343 UT, while both main and recovery phases were on 08 September 2017.
 213 In response to the storm activity, Figure 3(c) shows increased TEC in both hemispheres
 214 on 08 September 2017 compared to the rest of the days during this storm period. The



204 **Figure 3.** TEC (TECU) for the period 06-09 September 2017 within 40°S - 70°N and 20 – 40°E
 205 geographic latitude/longitude coverage. The black solid line at 10°N geographic latitude approx-
 206 imates the location of the geomagnetic equator. The white spaces in the northern hemisphere
 207 indicates data gaps.

215 TEC enhancement with an extended latitude coverage can be seen to be more strong in
 216 the southern hemisphere.

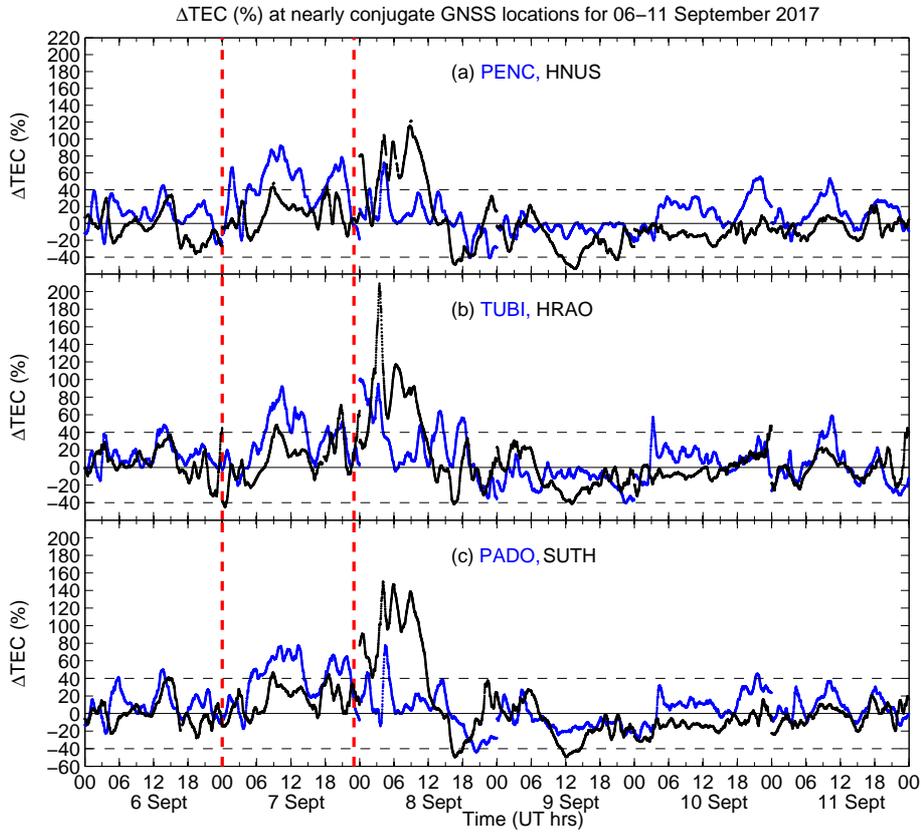
217 3.1 TEC response at conjugate locations

218 For a detailed and quantitative measure of the ionospheric response, Figure 4 shows
 219 the TEC deviations from monthly medians (expressed in percentages) for the three pairs
 220 of nearly geomagnetically conjugate GNSS locations. The conjugacy information was de-
 221 termined based on the altitude-adjusted corrected geomagnetic coordinates system [*Baker*
 222 *and Wing, 1989; Shepherd, 2014*]. The geographic and geomagnetic information of the
 223 respective conjugate receiver pairs are provided in Table 1. With a latitudinal difference
 224 of atmost 1° between the locations within all GNSS receiver pairs, the geomagnetic lat-

225 itudes are close enough to be considered conjugate. The percentage deviations are com-
 226 puted using

$$227 \quad \Delta Y = \left(\frac{Y - Y_m}{Y_m} \right) \times 100, \quad (1)$$

231 where Y and Y_m represents daily TEC and the corresponding monthly median values
 232 respectively. The horizontal black dashed lines in Figure 4 show the quiet time thresh-
 233 old of $\pm 40\%$ [e.g., *Matamba et al.*, 2015], implying that within this range, normal back-
 234 ground ionospheric TEC behavior is expected. This simple procedure is used to iden-
 235 tify the observed ionospheric storm effects during geomagnetically disturbed conditions.



228 **Figure 4.** Percentage deviations of TEC from monthly median values over GNSS conjugate
 229 locations in the Euro-African region. Geographic and geomagnetic coordinates of the GNSS
 230 locations are shown in Table 1.

236

237 **Table 1.** Geographic and geomagnetic coordinates of conjugate GNSS locations used in this
 238 study. NGI and IGS represent National Geospatial Information and International GNSS Service
 239 respectively.

Location/country	Code	Grouping	Geographic coordinates		Geomagnetic coordinates	
			Latitude	Longitude	Latitude	Longitude
Hermanus (South Africa)	HNUS	NGI	-34.42	19.22	-42.34	82.14
FOMI Satellite Geodetic Observatory (Hungary)	PENC	IGS	47.79	19.28	43.03	93.9
Hartebeesthoek RAO (South Africa)	HRAO	IGS	-25.89	27.69	-36.32	94.69
Tubitak (Turkey)	TUBI	IGS	40.79	29.45	35.07	101.91
Sutherland (South Africa)	SUTH	IGS	-32.38	20.81	-41.09	84.76
University of Padova (Italy)	PADO	IGS	45.41	11.89	40.08	86.94

240 There are two main observations from Figure 4 during the 07-08 September 2017.
 241 On 07 September, we observe a positive ΔTEC deviation of 30-50% from the quiet time
 242 threshold of 40% over the northern hemisphere for a period of about 8 hours (0700-1500
 243 UT). ΔTEC variability for the southern hemisphere locations largely remained within
 244 the normal quiet time range of $\pm 40\%$. This is consistent with thermospheric mass den-
 245 sity results derived from the Gravity Recovery and Climate Experiment (GRACE) ob-
 246 servations at 350 km altitude which showed an increase in the northern hemisphere [*Yuan*
 247 *et al.*, 2019]. However, SWARM-A thermospheric mass density at 450 km altitude showed
 248 a slight enhancement in the southern hemisphere with no corresponding observation in
 249 the northern hemisphere during daytime. In essence, while at different altitudes, GRACE
 250 and SWARM-A thermospheric mass density observations provide contradicting results,
 251 which were partly attributed to the dominant coupling processes between the ionosphere
 252 and thermosphere at GRACE altitudes [*Yuan et al.*, 2019]. In the context of ΔTEC vari-
 253 ability on 07 September 2017, this may point to different contributions at different al-
 254 titudes, an issue that will be investigated further using ionosonde and satellite data. In
 255 the study by *Yuan et al.* [2019], day-time consideration of thermospheric mass density
 256 was centered at about 1000 local solar time (LST) and 0930 LST for SWARM A and GRACE
 257 respectively, while corresponding night time analysis is at 2200 LST (SWARM) and 2130

258 LST (GRACE). Given that the neutral mass is much greater than electrons' mass, de-
 259 crepancies related to response time lag are expected and it is therefore interesting to
 260 note that their respective densities show some similarities.

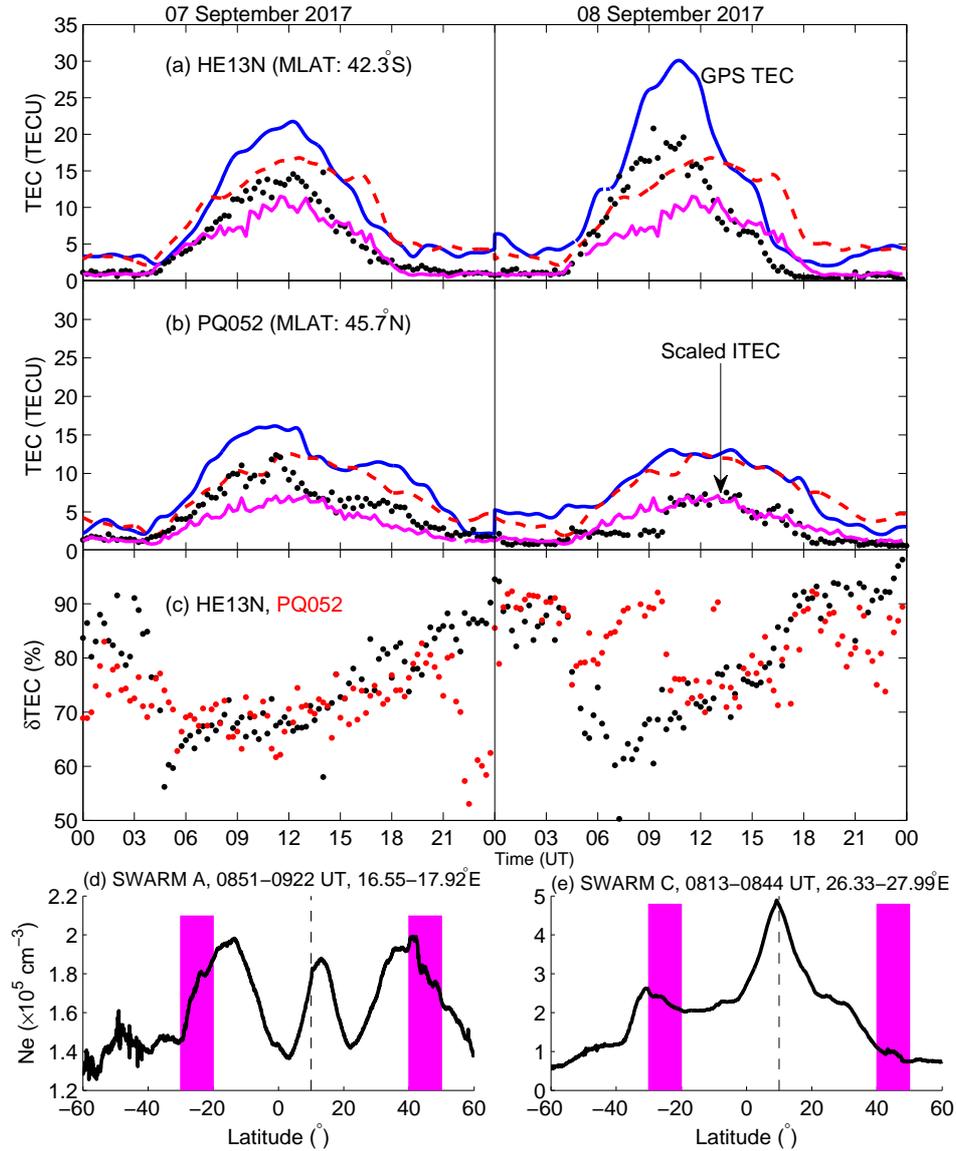
261 The second distinct observation is the positive storm effect observed in both north-
 262 ern and southern hemispheres during the storm main phase on 08 September 2017. How-
 263 ever, the southern hemisphere observations show long-lasting positive storm effect dur-
 264 ing the period of 0300-1200 UT. Within this time interval, northern hemisphere loca-
 265 tions show the positive storm effect not exceeding 1.5 hours compared to 9 hours for the
 266 southern hemisphere. The maximum deviation from monthly median reached just over
 267 200% for HRAO (36°S, magnetic) while its conjugate location TUBI (35°N, magnetic)
 268 had a corresponding deviation of 90%. Maximum deviation (160%) for SUTH (41°S, mag-
 269 netic) is also twice the deviation value for its conjugate location PADO (40°N, magnetic).
 270 The difference in deviation between HNUS and PENC magnetic latitudes of 42°S and
 271 43°N respectively is just over 30% at about 1100 UT. Both GRACE and SWARM-A ther-
 272 mospheric mass densities on 08 September 2017 showed enhancements during day and
 273 night-times in both hemispheres. However SWARM-A results exhibited significantly in-
 274 creased thermospheric mass density in the southern hemisphere from 0000-1200 UT [*Yuan*
 275 *et al.*, 2019] which is exactly the same time duration when Δ TEC values are higher over
 276 South Africa compared to Europe. For GRACE, the response is stronger in the north-
 277 ern hemisphere than southern hemisphere.

278 To establish the relative contribution to **vertical** TEC at varying altitudes, Fig-
 279 ure 5(a)-(b) shows the ionosonde TEC (in black dots) over Hermanus (34.4°S, 19.2°E;
 280 42.3°S geomagnetic) and Pruhonice (50.0°N, 14.6°E; 45.7°N geomagnetic) for 07-08 Septem-
 281 ber 2017. Ionosonde TEC (hereafter referred to as ITEC) is essentially the bottomside
 282 TEC, computed as follows;

$$283 \quad \text{ITEC} = \int_{\sim 90 \text{ km}}^{\text{hmF2}} N_e dx \quad (2)$$

284 where N_e is the electron density per m^3 , and dx is the variable of integration (step size)
 285 along a vertical path between about 90 km and the height of the peak electron density
 286 (hmF2).

293 ITEC is derived up to hmF2 peak to eliminate the topside contribution. Due to
 294 its relatively smaller values, ITEC in Figure 5(a)-(b) has been scaled by a factor of 2 for
 295 easy visibility and comparability with GPS derived TEC. GPS TEC for 07-08 Septem-

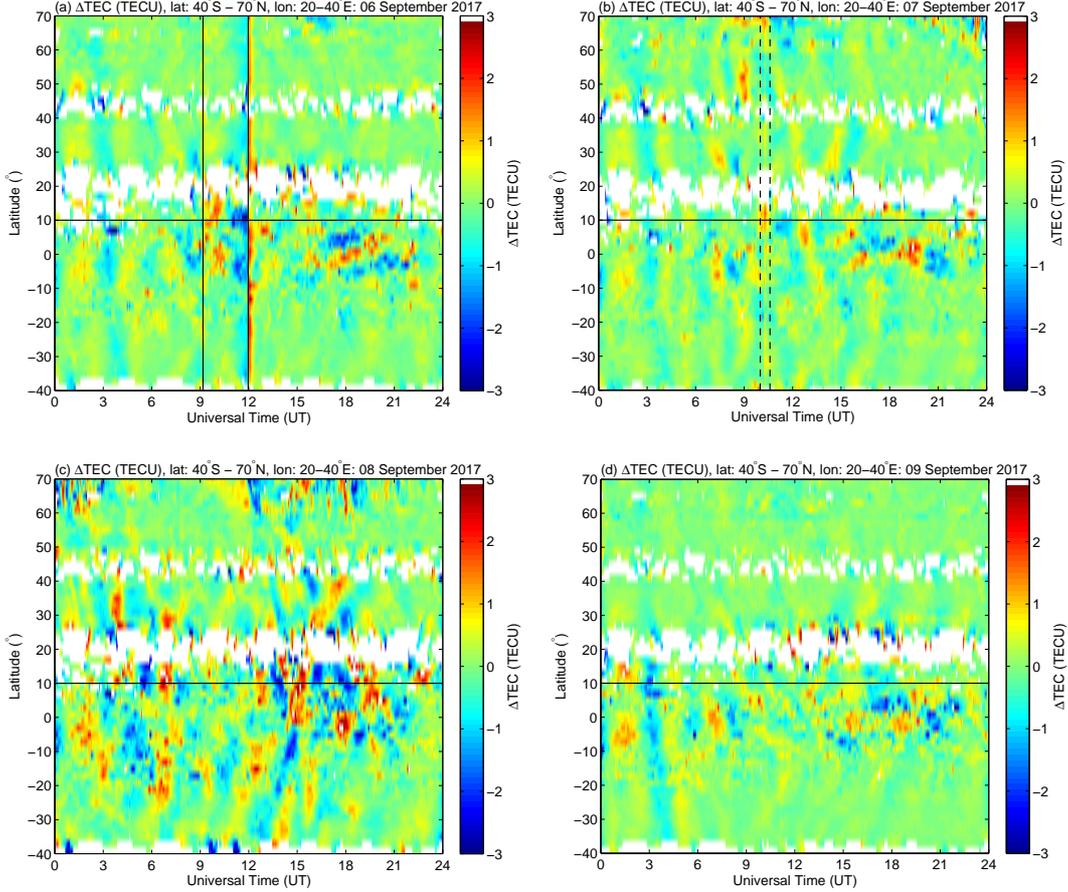


287 **Figure 5.** GPS TEC (blue curve) and scaled ITEC by a factor of two (black dots) for (a)
 288 HE13N, (b) PQ052 on 7-8 September 2017, (c) deviation (%) between GPS TEC and ITEC up
 289 to hmF2 peak. The red dashed and solid magenta lines in (a)-(b) show GPS TEC and scaled
 290 ITEC (by a factor of 2) for the most quiet day of 26 September 2017. SWARM electron density
 291 changes during 0851-0922 UT (17°E) and 0813-0844 UT (27°E) are plotted in (d) and (e) for 07
 292 and 08 September 2017 respectively.

ber 2017 is plotted (solid blue lines) for the two locations for easy reference and direct
comparison. Included in Figure 5(a)-(b) is also TEC for the most quiet day (26 September
2017) of the month plotted in red dashed and solid magenta lines for GPS TEC and
ITEC respectively. In Figure 5(a), there is increased bottomside ITEC (compared to 26
September) on 08 September 2017 until 1300 UT which agrees well with results presented
in Figure 4. However, ITEC appears to be more sensitive to storm induced processes such
as thermospheric composition changes as it shows negative storm behavior (just after
1300 UT) about 2 hours earlier than GPS TEC, a result confirmed later with foF2 anal-
ysis. Basing the analysis on the quiet time reference of 26 September 2017, we can de-
duce different bottomside response for HE13N and PQ052 between 0600-1000 UT on 08
September 2017. Storm-time ITEC is enhanced over HE13N while it reduced over PQ052
during this time interval. While GPS TEC is clearly enhanced (see blue curve) compared
to the quiet-time reference (red dashed line) over HE13N, both disturbed and quiet-time
values for PQ052 are relatively similar during 0600-1000 UT. This is a direct evidence
that bottomside ionosphere contributed differently in the two hemispheres. To quantify
the bottomside contribution, Figure 5(c) shows the relative deviation (δ TEC) between
GPS TEC and ITEC derived up to hmF2 altitude, normalized to GPS TEC and expressed
as a percentage for HE13N (black dots) and PQ052 (red dots). Here, actual ITEC val-
ues (and not scaled ITEC) were used to derive δ TEC. The normalization is important
to have a scale free quantity that provides the realistic behavior of the bottomside re-
sponse/contribution which is location specific. Small percentage deviation values indi-
cate that GPS TEC and ITEC are close to each other and the latter could have made
a significant contribution. Figure 5(c) reveals that the combination of topside and plas-
masphere contributed over 75-90% of the overall TEC on 08 September 2017 over PQ052
compared to 60-70% for HE13N during 0400-0900 UT. Generally, the bottomside con-
tribution is greater during the day-time as opposed to nighttime. This is consistent with
related previous studies. For example, global climatological studies have reported plas-
maspheric contribution reaching 25-45% (daytime) and 50-60% (nighttime) to GPS TEC
on the basis of COSMIC data with integration altitude set at 700 km [Cherniak *et al.*,
2012], and 10% (daytime) and 60% (nighttime) when JASON altimeter data at 1335 km
altitude was used as a reference to GPS TEC [Yizengaw *et al.*, 2008]. Between 0600-1200
UT on 07 September 2017, there are instances where the bottomside contribution is greater
over PQ052 than at HE13N, although other results are comparable. However, Figure 5(c)

329 clearly shows high bottomside ITEC over PQ052 between 1500-1900 UT, a consistent
 330 result with the thermospheric mass density results at GRACE altitude of 350 km in the
 331 northern hemisphere [Yuan *et al.*, 2019]. Plotted in Figure 5(d)-(e) is the in situ elec-
 332 tron density from SWARM A and C satellites when the passes are either close to these
 333 ionosonde locations or within the longitude range of our analysis. SWARM A and C have
 334 data during 0851-0922 UT and 0813-0844 UT along the 17°E and 27°E on 07 and 08 Septem-
 335 ber 2017, respectively. In Figure 5(d)-(e), the magenta shaded regions are equidistant
 336 (30–40°) from the geomagnetic equator (black vertical dashed lines). On the 07 Septem-
 337 ber 2017, SWARM A observations in Figure 5(d) show slightly higher values in the north-
 338 ern hemisphere, while topside electron density values are enhanced in the southern hemi-
 339 sphere on 08 September 2017. A peak in electron density can be seen in Figure 5(e) at
 340 about 40°S magnetic latitude which directly provides evidence of equatorial ionization
 341 anomaly expansion to southern hemisphere mid-latitudes as observed from topside. SWARM
 342 electron density observations are consistent with GPS TEC in both hemispheres. A re-
 343 cent investigation utilizing a number of Low Earth Orbit satellite data (including SWARM)
 344 reported increased topside TEC for the main phase of the storm on 08 September 2017
 345 as well as hemispheric asymmetry during both day and nighttime [Jimoh *et al.*, 2019].

348 In addition to high levels of bottomside contribution to TEC increases in the south-
 349 ern hemisphere on 08 September 2017, there could have been more effective thermosphere-
 350 ionosphere coupling process in the southern hemisphere such as the presence of atmo-
 351 spheric gravity waves which are well known to contribute to electron density or TEC en-
 352 hancement [e.g., Prölss, 1993]. In this regard, Figure 6 shows ΔTEC (TECU) for 06-
 353 09 September 2017 within latitude and longitude ranges of 40°S-70°N and 20 – 40°E
 354 respectively. The solid vertical lines indicate the time occurrence of solar flares on 06 Septem-
 355 ber 2017. The ΔTEC is computed by fitting a fourth order polynomial to each satellite’s
 356 TEC data followed by differencing the TEC and fitted data. Interestingly, Figure 6(a)
 357 reveals insights of the solar flare effects on TEC that were not directly observable from
 358 TEC data in Figure 3(a). This is best illustrated by the black straight line at around
 359 1200 UT (Figure 6(a)) showing ΔTEC enhancement spanning the entire considered lat-
 360 itude range 40°S-70°N within the 20 – 40°E longitude sector. This is due to the X9.3
 361 solar flare which started at 1158 UT on 06 September 2017 [Curto *et al.*, 2018]. The first
 362 X2.2 solar flare at 0910 UT on 06 September 2017 did not generate clearly visible changes
 363 in TEC as seen in Figure 6(a). The global ionospheric response (including using data



346 **Figure 6.** Δ TEC changes for 06-09 September 2017 within latitude and longitude ranges of
 347 40° S- 70° N and $20 - 40^{\circ}$ E respectively.

364 over Europe and South Africa) to solar flares on 06 September 2017 has been reported
 365 in *Li et al.* [2018] highlighting an increase in TEC and foF2 for the X9.3 flare occurrence
 366 which peaked at 1202 UT compared to the less intense X2.2 that had its peak at 0910
 367 UT. Therefore, Figure 6(a) demonstrates the importance of utilizing different param-
 368 eterization when studying different ionospheric phenomena. For example, the quiet time
 369 threshold of $\pm 40\%$ does not reveal the effect of solar flare on TEC while data detrend-
 370 ing shows the clear significant increase on 06 September 2017 at about 1200 UT. While
 371 an increase in TEC is observed starting at 1200 UT in Figure 4, the variability domi-
 372 nantly remained within the quiet-time threshold range of $\pm 40\%$.

373 Another important observation in Figure 6(b), is the simultaneous TEC enhance-
 374 ment at around 1010 UT (indicated within two dashed vertical black lines) in both hemi-
 375 spheres on 07 September 2017. Conjugacy analysis (Figure 4) shows that this is the ap-

376 proximate time when TEC was slightly enhanced above the background levels in the south-
 377 ern hemisphere while there is a clear TEC increase in the northern hemisphere. In ad-
 378 dition to M7.3 solar flare that peaked at 1015 UT [*Mosna et al.*, 2020], this can also be
 379 linked to the increased auroral activity on 07 September 2017 when we see high AE val-
 380 ues reaching 1430 nT at 0907 UT (Figure 2(b)) and the negative polarity of IMF Bz. These
 381 conditions are favorable for prompt penetrating electric fields which lead to increased
 382 electron density or TEC at all latitudes at the same local time, a consistent feature in
 383 Figure 6(b) at about 1000 UT. Increased TEC has also been reported in high latitudes
 384 on 07 September 2017 [*Blagoveshchensky and Sergeeva*, 2019] and during the nighttime
 385 between 07-08 September 2017. What appears to be an effect of the X1.3 solar flare which
 386 peaked at 1436 UT can faintly be seen in Figure 6(b) on 07 September 2017 at latitudes
 387 10-40°S. The ionospheric electron density on 07 September 2017 was under the influence
 388 of multiple external sources including solar flares and storm induced processes. The ef-
 389 fect of the X1.3 solar flare at 1436 UT on 07 September 2017 was clearly seen in the Very
 390 Low Frequency band using Marion island (46.87°S, 37.87°E) observations [*Lotz and Clil-*
 391 *verd*, 2019].

392 Returning to the possible presence of atmospheric gravity waves (AGWs) during
 393 06-09 September 2017, Figure 6(c) shows traveling ionospheric disturbances (TIDs) which
 394 were predominantly propagating from the southern to the northern hemisphere. The TID
 395 activity is more pronounced in the southern than in the northern hemisphere especially
 396 on the 08 September 2017. Large scale TIDs are known to contribute to positive storm
 397 effects [e.g., *Prölss*, 1993] and their observations during periods of geomagnetic storms
 398 in relation to enhanced ionospheric electron density and/or TEC have been widely re-
 399 ported [e.g., *Ding et al.*, 2007; *Borries et al.*, 2016; *Zakharenkova et al.*, 2016; *Ngwira et al.*,
 400 2019, and references therein].

401 **3.2 Regional Ionospheric response**

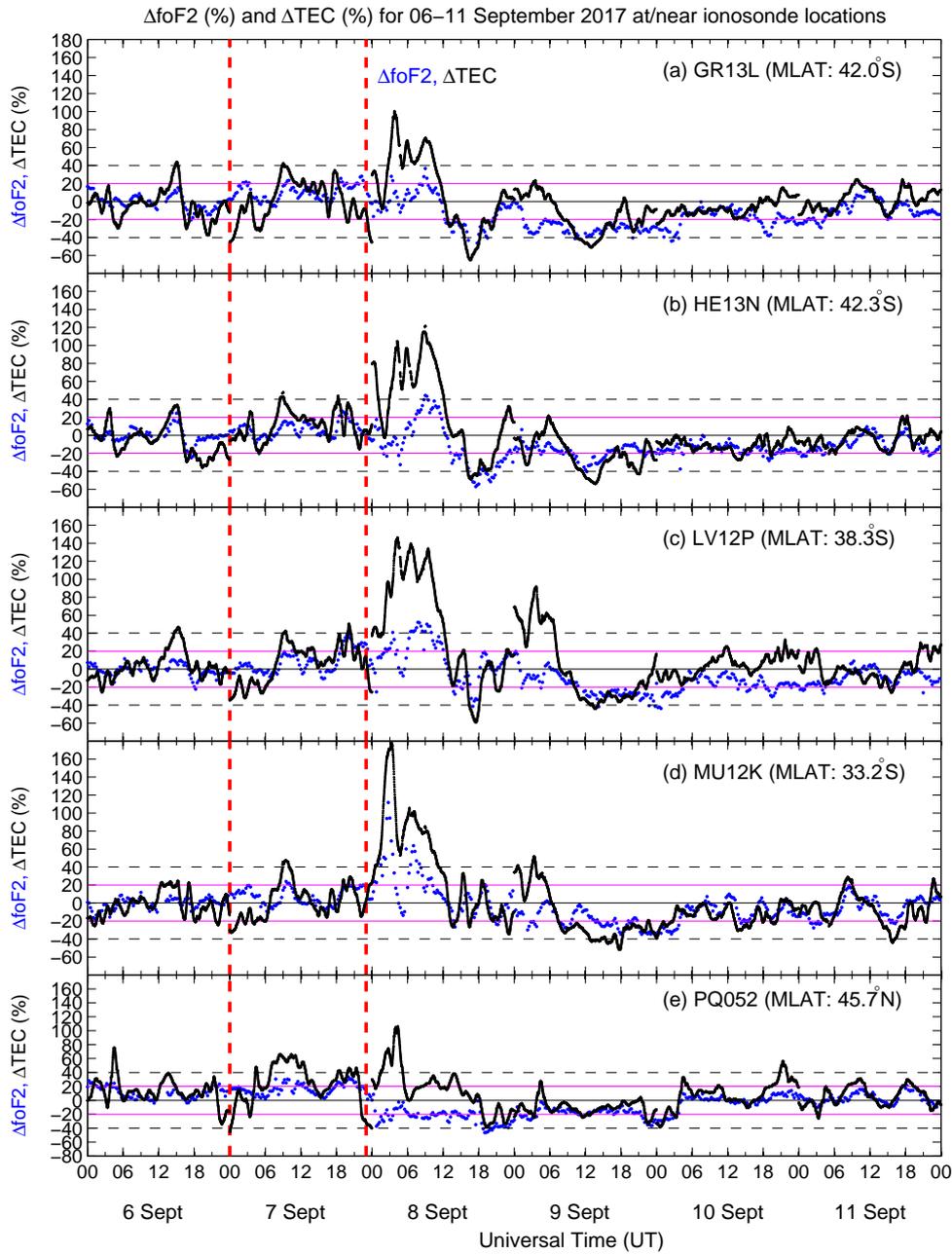
406 Understanding the physical mechanisms for the TEC response during the 07-08 Septem-
 407 ber 2017 storm period requires the use of different independent datasets. Figure 7 shows
 408 the critical frequency of the F2 layer (foF2) and TEC variability expressed as percent-
 409 ages with respect to monthly median values during 06-11 September 2017 over/near South
 410 Africa and Czech Republic ionosonde locations. The percentage deviations were com-
 411 puted using equation (1), where in this case, Y and Y_m represent daily foF2 (TEC) and

412 the corresponding monthly median values respectively. The solid magenta and black dashed
 413 lines in Figure 7 show the quiet time thresholds of $\pm 20\%$ and $\pm 40\%$ for foF2 and TEC
 414 respectively. These threshold ranges of $-20\% \leq \Delta foF2 \leq 20\%$ and $-40\% \leq \Delta TEC \leq$
 415 40% are widely used in literature [e.g., *Danilov, 2001; Buresova et al., 2014; Matamba*
 416 *et al., 2015*] to represent the background variations while studying ionospheric storm ef-
 417 fects in presence of geomagnetic disturbances.

418 **Table 2.** Geographic and geomagnetic coordinates of ionosonde locations used in this study.
 419 SANSА=South African National Space Agency, ASCZ= Academy of Sciences of the Czech Re-
 420 public.

Location/country	URSI Code	Grouping	Geographic coordinates		Geomagnetic coordinates	
			Latitude	Longitude	Latitude	Longitude
Hermanus (South Africa)	HE13N	SANSА	-34.4	19.2	-42.34	82.14
Grahamstown (South Africa)	GR13L	SANSА	-33.3	26.5	-41.95	90.17
Louisvale (South Africa)	LV12P	SANSА	-28.5	21.2	-38.31	86.87
Madimbo (South Africa)	MU12K	SANSА	-22.4	30.9	-33.19	99.24
Pruhonice (Czech Republic)	PQ052	ASCZ	50.0	14.6	45.66	90.42

421 For TEC variations, GNSS receivers are colocated with ionosondes at Hermanus,
 422 HE13N (34.42°S, 19.22°E) and Grahamstown, GR13L (33.3°S, 26.5°E). The GNSS re-
 423 ceiver codes for Hermanus and Grahamstown are HNUS and GRHM respectively. For
 424 Louisvale, LV12P (28.50°S, 21.20°E) and Madimbo, MU12K (22.39°S, 30.88°E) ionosonde
 425 stations, the nearest GNSS receivers are located at Upington, UPTA (28.40°S, 21.25°E)
 426 and Thohoyandou, TDOU (23.08°S, 30.38°E) which are approximately 10 and 90 km
 427 away, respectively. For the northern hemisphere mid-latitude region, ionosonde and TEC
 428 data are from Pruhonice, PQ052 (50.0°N, 14.6°E) and the nearby receiver Ondrejov, GOPE
 429 (49.9°N, 14.8°E), respectively, which are about 18 km apart. Table 2 shows the geographic
 430 and geomagnetic coordinates of the ionosonde locations. The underlying idea for the si-
 431 multaneous analysis of ionosonde foF2 and TEC data at co-located sites is to investi-
 432 gate whether these datasets exhibited an identical response to the geomagnetic activ-
 433 ity. Short durations of increased foF2 are observed over GR13L and MU12K at around
 434 1000 UT on 07 September 2017, with clear increased foF2 around 1800-1900 UT for all

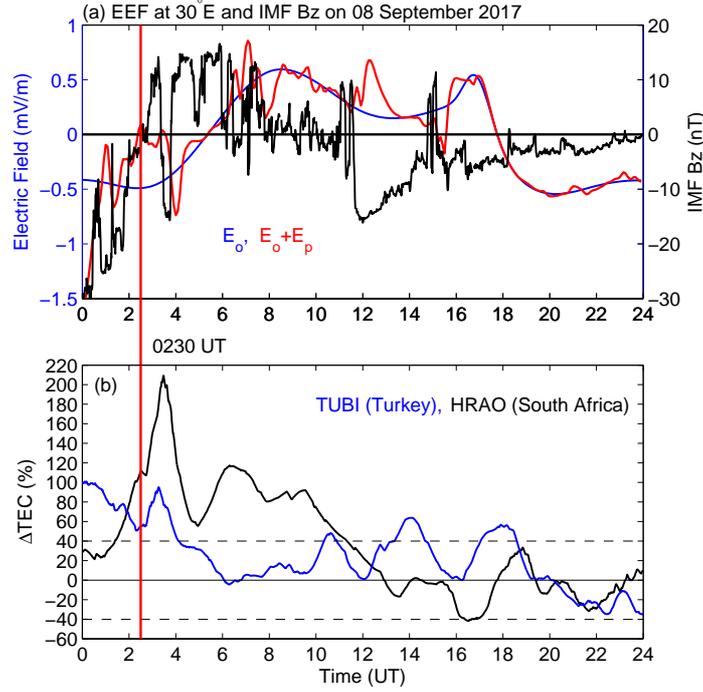


402 **Figure 7.** Variability of foF2 and TEC expressed as a percentage to respectively monthly me-
 403 dian values over South African ionosonde ((a)-(d)) locations and (e) Pruhonice, Czech Republic
 404 during 06-11 September 2017. The red vertical dashed lines show the shocks arrival times at 2343
 405 UT (06 September) and 2300 UT (07 September).

435 South African ionosonde data. On the contrary, PQ052 ionosonde data showed enhanced
436 foF2 for almost the whole of 07 September 2017, a result that was also recently reported
437 by *Mosna et al.* [2020] and confirmed by GOPE TEC data for a large part of the day
438 (0600-1300 UT). Both foF2 and TEC over South Africa show positive storm effect on
439 08 September 2017 from around 0300-0900 UT (with TEC increase extending until 1200
440 UT) which largely coincided with the storm main phase (as shown in Figure 2), followed
441 by a negative storm phase, with exception of MU12K where decreased foF2 is only seen
442 on 09 September during similar times as at the other locations. Considering MU12K's
443 geomagnetic latitude location (33.2°S), we can conclude from Figure 3(c) that it could
444 have been under the influence of the EIA during the whole of 08 September 2017 which
445 will be further investigated later. Increase in foF2 reached 40% for HE13N and GR13L
446 with LV12P's highest value at just over 50% between 0600-1200 UT, while MU12K which
447 is towards the low latitude region registered the highest electron density increase reach-
448 ing 60% during this time period. In addition, an even higher increase in foF2 was reg-
449 istered over MU12K during the pre-dawn hours at around 0300 UT, and this is well cor-
450 roborated with the TEC response as shown in Figure 7(d). On the other hand, positive
451 storm effect from TEC data over GOPE (49.9°N , 14.8°E) is observed during ~ 0300 –
452 0500 UT, while Pruhonice (50.0°N , 14.6°E) shows decreased foF2 below the background
453 for the entire 08 September 2017 reaching maximum negative deviation of 40%. Iono-
454 spheric positive response for HE13N is just over 40% at 1200 UT at the time when PQ052
455 recorded a negative storm effect and yet these locations are nearly geomagnetically con-
456 jugate. The maximum ΔTEC reached over GOPE at ~ 0400 UT is comparable with
457 the corresponding value at HNUS, although the latter indicates higher values before and
458 after this time. The key observation here is the different ionospheric responses over PQ052
459 from two datasets (ionosonde foF2 and GPS TEC), suggesting different physical mech-
460 anisms at different altitudes. One of the possible sources for positive storm effect as shown
461 by GPS TEC is the electron content from the topside and plasmasphere as has been clearly
462 shown in Figure 5(c). During the recovery phase, a negative ionospheric storm effect was
463 largely evident (especially from ionosonde data) on 08 September from 1000 UT and 09
464 September 2017 starting at 0900 UT until 0600 UT on 10 September 2017. Over Europe,
465 results of maximum electron concentration of the ionospheric F2 layer (NmF2) increase
466 and decrease on 07 and 08 September respectively for Ebre (40.8°N , 0.5°E) have been
467 reported [*Cander*, 2018]. Thermospheric O/N₂ ratio results from the Global Ultraviolet

468 let Imager (GUVI) onboard TIMED satellite published in *Imtiaz et al.* [2020] show en-
 469 hanced and depleted values over the analyzed locations in the southern and northern hemi-
 470 spheres respectively on 08 September 2017. Temporal evolution of TEC and electron den-
 471 sity dynamics indicate that the southern hemisphere mid-latitude region was under the
 472 influence of competing/opposing processes arising from the EIA expansion and neutral
 473 composition changes as a result of heated lower parts of the thermosphere in auroral and/or
 474 high latitudes [*Buonsanto, 1999; Yizengaw et al., 2005*]. At the same time, large scale
 475 TIDs are known to contribute to short-lived positive storm effect [*Prölss, 1993*] and can
 476 be seen to be present on 08 September 2017. Therefore EIA expansion and TIDs were
 477 responsible for the positive storm effect until 1200 UT on 08 September 2017, while the
 478 equatorward movement of depleted O/N₂ ratio that is redistributed by neutral winds
 479 led to the decreased TEC and foF2 observed after 1200-1300 UT on 08 September and
 480 09 September 2017. Figure 3(d) shows that all mid-latitude regions experienced depleted
 481 TEC changes, which is well reflected in ΔfoF2 showing negative storm effect on 09 Septem-
 482 ber 2017 (Figure 7). In the summer hemisphere, the combined effect of background ther-
 483 mospheric neutral gas composition and storm-related circulation can lead to short-lived
 484 positive storm effect [*Prölss, 2004*], although the thermospheric composition changes orig-
 485 inating from auroral and high latitudes play a major role leading to negative storm ef-
 486 fects. This is the probable mechanism for the observed depleted TEC in the northern
 487 hemisphere on 08 September 2017 and for the rest of the storm duration. Indeed, the
 488 O/N₂ ratio shows a decrease over the northern hemisphere mid-latitude region on 08 Septem-
 489 ber 2017 [*Imtiaz et al., 2020*].

493 Therefore, from Figure 7, we observe strong TEC enhancement on the 08 Septem-
 494 ber 2017 during night-time, with the southern hemisphere mid-latitude TEC increase
 495 extending to daytime. What could be the causes of this profound night-time electron den-
 496 sity enhancement? To partly answer this question, Figure 8(a) shows the equatorial elec-
 497 tric field (EEF) from the real-time prompt penetration electric field model [*Manoj and*
 498 *Maus, 2012*] at 30°E longitude, along with the IMF Bz for the 08 September 2017. In
 499 Figure 8(b), TEC perturbations for two conjugate locations (HRAO, South Africa and
 500 TUBI, Turkey) are shown to simply demonstrate the response levels in the two mid-latitude
 501 hemispheres. While IMF Bz is characterised by significant fluctuations on 08 Septem-
 502 ber 2017 during the first two hours, it is largely negative. Both the background (E_o , blue
 503 curve) and total electric field ($E_o + E_p$, red curve) are negative, although the contribu-

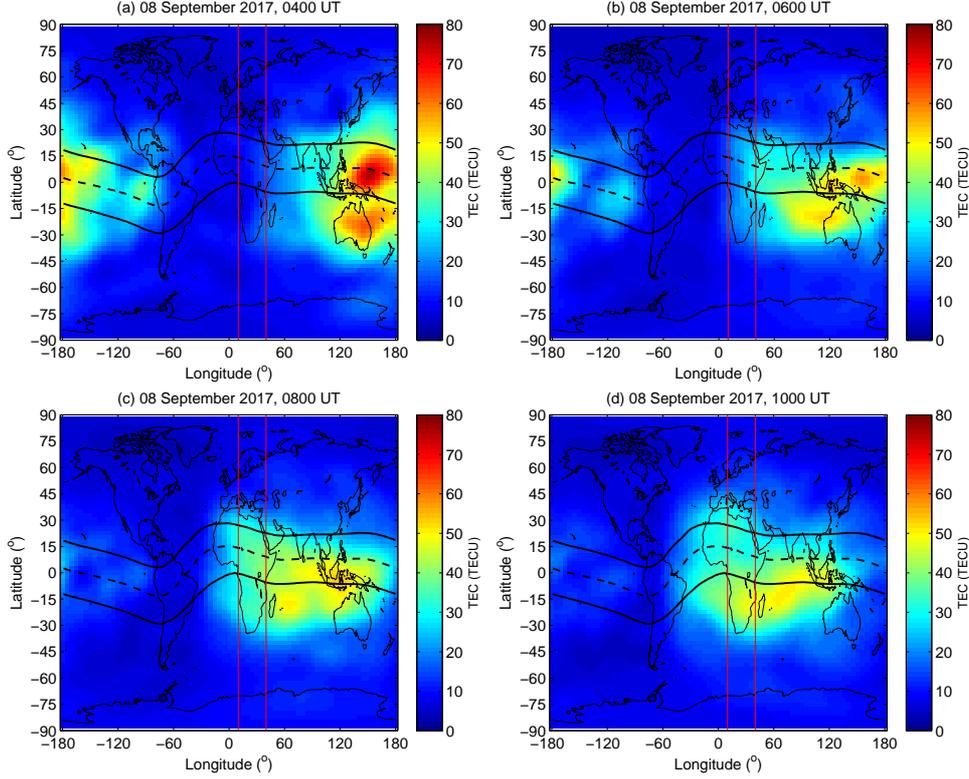


490 **Figure 8.** Equatorial electric field (EEF) at 30°E and IMF Bz; and Δ TEC changes over con-
 491 jugate locations HRAO (South Africa) and TUBI (Turkey) for 08 September 2017. In (a), E_o
 492 and E_p represent background and prompt penetration electric fields respectively.

504 tion of prompt penetrating electric field is evident to have started deviating from west-
 505 ward to eastward peaking at 0230 UT (see red straight line in Figure 8) which coincided
 506 with positive IMF Bz and followed by sharp increase in TEC over TUBI (blue curve)
 507 and HRAO (black curve). Maxima Δ TEC of 210% and 95% are reached at 0328 UT and
 508 0316 UT for HRAO and TUBI respectively. For the short duration of positive IMF Bz
 509 starting from 0230 UT (reaching maximum of 14 nT at 0325 UT), we see sustained in-
 510 crease in TEC in both northern and southern hemispheres. The change of IMF Bz ori-
 511 entation from positive to negative reaching -15.7 nT at 0344 UT is followed by a sud-
 512 den drop in $E_o + E_p$ to -0.74 mV/m (0400 UT) and Δ TEC (from 210% to 55% at 0457
 513 UT) for HRAO. It therefore appears that low/equatorial region processes have some in-
 514 fluence on TEC variability in mid latitudes during the period (0300-0900 UT) of signif-
 515 icant TEC increase on 08 September 2017. Background equatorial electric field is east-
 516 ward (positive) and westward (negative) during local day and night-time respectively.
 517 During storms, southward IMF Bz can lead to penetrating electric field of magnetospheric

518 origin to low/equatorial latitudes which is eastward and westward during day and night-
 519 time respectively [*Kelley et al., 1979; Scherliess and Fejer, 1997; Huang, 2008*]. When
 520 the IMF Bz changes polarity from southward (negative) to northward (positive), the west-
 521 ward electric field reverses to eastward during nighttime. Although we do not have data
 522 to conclusively investigate the ionospheric current system over the region of study, mag-
 523 netometer data showed increased ionospheric currents in the first hours of 08 Septem-
 524 ber 2017 over Mbour (14.39°N, 16.96°W; 2.06°N magnetic) which has local time differ-
 525 ence of about 3 hours from our longitude sector [*Imtiaz et al., 2020*]. The reversal of prompt
 526 penetration electric field from westward to eastward during night time combined with
 527 the already existing eastward disturbance dynamo electric field can lead to strong ver-
 528 tical $\mathbf{E} \times \mathbf{B}$ drift over low latitudes. The consequence of this is that ionospheric plasma
 529 is lifted to higher altitudes with lower recombination processes and could lead to increased
 530 integrated electron content, which seems consistent with observations in Figure 8 start-
 531 ing from 0230-0400 UT. During local day-time, increased eastward electric field (as shown
 532 in Figure 8(a) from 0600-1200 UT with exception of a decrease within 0700-0800 UT)
 533 translates into enhanced vertical drift leading to electron density enhancements that have
 534 significant effects on the formation/expansion of the EIA. The EIA expansion will then
 535 lead to increase in TEC as far as mid-latitude regions. This is one of the possible causes
 536 of the increased TEC on 08 September 2017 during 0600-1200 UT. To confirm the role
 537 of the EIA expansion towards mid-latitudes, Figure 9 shows TEC from Global Ionospheric
 538 Maps (GIM) for 0400, 0600, 0800 and 1000 UT on 08 September 2017. The vertical red
 539 lines show the 10-40°E longitude sector covering data used for conjugate analysis within
 540 latitude ranges of $\sim 20 - 35^\circ\text{S}$ and $\sim 40 - 50^\circ\text{N}$.

545 In Figure 9(a), an increase in TEC is already visible at 0400 UT in southern hemi-
 546 sphere which is absent at similar latitudes in the northern hemisphere. Taking local time
 547 into account, this may not only be attributed to the photoionization effect given that
 548 the local time is the same, and therefore has to do with the storm induced processes. By
 549 1000 UT (Figure 9(d)), the EIA has fully expanded as far as 40°S magnetic latitude and
 550 is prominent in the southern hemisphere. This confirms the higher levels of positive storm
 551 effect observed at MU12K (33.2°S, magnetic latitude) compared to other ionosonde lo-
 552 cations. Corresponding TEC increase is observed in the northern hemisphere, although
 553 with relatively smaller TEC magnitudes. In summary, GIM TEC agrees with and sup-
 554 ports observations of the conjugacy analysis, and consequently highlighting the role of



541 **Figure 9.** Global Ionospheric Maps (GIM) showing TEC for 0400 UT, 0600 UT, 0800 UT and
 542 1000 UT on 08 September 2017. The vertical red lines show the 10-40°E longitude sector cov-
 543 ering data used for conjugate analysis for locations in Table 1. GIM data was downloaded from
 544 <ftp://cdis.gsfc.nasa.gov/pub/gps/products/ionex/>.

555 low latitude processes in influencing TEC in mid-latitudes on 08 September 2017. How-
 556 ever, as earlier mentioned, we observe prolonged positive storm effect over southern hemi-
 557 sphere pointing to the existence of other physical mechanisms during this storm period.
 558 One such additional mechanism has been identified and shown as the existence of atmo-
 559 spheric gravity waves launched from high latitudes leading to the clearly more equator-
 560 ward TID activity which extended from southern hemisphere latitudes into the north-
 561 ern hemisphere as shown in Figure 6(c). Δ TEC fluctuations related to TIDs' presence
 562 are apparent for almost the entire 08 September 2017 with the estimated velocity of 350
 563 m/s. As mentioned earlier, increased O/N₂ ratio has been reported over the Europe-African
 564 mid and low latitudes for the 08 September 2017 compared to the quiet period of 05 Septem-
 565 ber 2017 [Imtiaz *et al.*, 2020], pointing to thermospheric composition changes as an ad-

566 dditional contributor to the observed behavior in electron density or TEC within the 10-
567 40°E longitude sector.

568 4 Conclusions

569 We have presented conjugate and regional analyses of ionospheric response during
570 the geomagnetic storm of 07-08 September 2017 over the Europe-African mid latitude
571 regions. Overall, it was found that electron density was enhanced over the European mid-
572 latitudes on 07 September 2017 while a corresponding feature or behavior was not ob-
573 served in the southern hemisphere. On 08 September 2017, TEC showed a positive storm
574 effect over both hemispheres with long-duration enhancements over Southern Africa last-
575 ing over 8 hours. The magnitude of the response in the southern hemisphere was at-least
576 twice the derived percentage increase in the northern hemisphere when quantified based
577 on the monthly median values. A combination of large scale TIDs, thermospheric com-
578 position changes and expansion of equatorial ionization anomaly were all found to be present
579 during the duration of the positive storm effect in the southern hemisphere. The pos-
580 itive storm effect over PQ052 (northern hemisphere mid latitude) was only revealed by
581 GPS TEC data, and a further analysis of ionosonde derived TEC up to the hmF2 peak
582 and electron density variations from SWARM satellite showed that the topside and plas-
583 masphere electron content was responsible. Consequently, it was shown that bottomside
584 ionosphere contributed more (less) electron concentration on 08 September 2017 to the
585 overall TEC in the southern (northern) hemisphere mid-latitudes, and thus the positive
586 and negative storm effects shown by ionosonde foF2 over the two respective hemispheres.
587 This study has furthered the understanding of relative contributions at varying altitudes
588 to TEC and highlighted the relative roles of competing/opposing mechanisms in mid-
589 latitudes within the two hemispheres. **Thus, through a multi-dataset examination
590 of hemispheric differences, we have simultaneously confirmed some of the pre-
591 viously observed features and associated physical mechanisms during geomag-
592 netic storms.**

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