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Ionospheric Responses at Low Latitudes to the Annular Solar Eclipse on 21 June 2020

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Abstract In this study, we utilized both ground-based and space-borne observations including total electron content (TEC) from Beidou geostationary satellites, two-dimensional TEC maps from the worldwide dense Global Navigation Satellite System receivers, ionosondes, and in situ electron density (Ne) and electron temperature (Te) from both Swarm and China Seismo-Electromagnetic Satellite satellites, to investigate the low-latitude ionospheric responses to the annular solar eclipse on 21 June 2020. The decrease in TEC during the eclipse at low latitudes showed a local time dependence with the largest depletions in the noon and afternoon sectors. It was also found that the TEC depletions at different latitudes in the equatorial ionization anomaly (EIA) region over the East Asian sector cannot solely be explained by the solar flux changes associated with the obscuration rate. The differences in TEC reduction between stations can be more than a factor of 2 at latitudes with the same obscuration rate of over 90%. Compared with TEC variations in the Northern Hemisphere, the TEC also underwent a considerable decrease in the EIA region in the conjugate hemisphere without eclipse shadow. Meanwhile, the $h_mF_2$ near the magnetic equator increased around the onset of the eclipse, indicating an enhancement of the eastward equatorial electric field. Furthermore, the TEC decrease during the eclipse in the EIA region in both hemispheres lasted for a long period of more than 7 hr after the eclipse, with a TEC depletion of 2–6 TEC units. The Ne from Swarm and China Seismo-Electromagnetic Satellite satellites showed a complicated variation after the eclipse, whereas no visible change was observed in Te. The enhanced equatorial electric field, neutral wind changes, and the associated plasma transport act together to generate the observed ionospheric effects at low latitudes during the eclipse. Our results also suggest that the eclipse-induced perturbations of dynamic processes can continue to impact the ionosphere after the eclipse.

1. Introduction

Solar eclipses are celestial phenomena where the Moon moves between the Sun and Earth and causes a shadow on parts of the Earth. As the sunlight is partially blocked, a solar eclipse provides a natural experiment to study the ionospheric variations associated with dynamic, electrodynamic, and photochemical processes. The ionospheric responses to solar eclipses have been extensively studied for the past decades (e.g., Afraimovich et al., 1998; Cheng et al., 1992; Cherniak & Zakharenkova, 2018; Cnossen et al., 2019; Dang, Lei, Wang, Burns, et al., 2018, Dang, Lei, Wang, Zhang, et al., 2018; Dang et al., 2020; Ding et al., 2010; Huang et al., 1999; Jakowski et al., 2008; Le et al., 2008a; Lei et al., 2018; MacPherson et al., 2000; Rishbeth, 1968; Salah et al., 1986; St-Maurice et al., 2011; Wang et al., 2019; Wu et al., 2018; Zhang et al., 2017). At low altitudes in the ionospheric $E$ and $F_1$ layers, the ionospheric electron density usually had a synchronous and prompt response to the solar eclipse, since the plasma at these altitudes is dominated by the photochemistry (Le et al., 2008a).
Compared with the lower-altitude ionosphere, the responses in the $F_2$ region and topside ionosphere are different during a solar eclipse. Previous studies suggested that there is a time lag in the $F_2$ region ionospheric responses to the solar eclipse (e.g., Adeniyi et al., 2007; Ding et al., 2010; Korte et al., 2001). Especially, the responses are more complex at low latitudes and in the equatorial ionization anomaly (EIA) region where dynamic and electrodynamic processes are dominant. Cheng et al. (1992) suggested that the electron density of the $F_2$ layer in the EIA crest region during the solar eclipse on 23 September 1987 was controlled by the ions produced by the radiation at the magnetic equator through the fountain effect (Duncan, 1960) rather than by the ions produced locally by solar radiation. During another solar eclipse on 15 January 2010, Chen et al. (2011) revealed a new characteristic that the time lag of ionospheric responses at low latitudes to the solar eclipse decreased with increasing latitude. However, the time lag would increase with increasing latitude if the low-latitude ionospheric responses were controlled by the eclipse occultation at the magnetic equator. These results indicated that the low-latitude ionospheric responses to the solar eclipse were not simply dominated by the eclipse occultation at the magnetic equator through the fountain effect. Moreover, the $F$ layer peak electron density underwent a large-amplitude vertical oscillation (St-Maurice et al., 2011). The electron density was even enhanced at low latitudes, due to the changes of the equatorial electric field associated with the solar eclipse (Madhav et al., 2012). Hence, the ionospheric responses at low latitudes to the solar eclipses and the underlying physical mechanisms are still an open question.

On 21 June 2020, an annular solar eclipse traveled across the low-latitude ionosphere from Africa to Southeast Asia between 03:51 and 09:30 UT, with a unique trajectory where the maximum geographic latitude of the totality was around 30°N. It provides an excellent opportunity to investigate the eclipse effects on the low-latitude ionosphere (especially in the EIA regions), which is shaped by the dynamic processes including the fountain effect and neutral winds. The simulation study of this solar eclipse in Dang et al. (2020) predicted that the total electron content (TEC) variations at low latitudes are strongly affected by the perturbations of neutral wind dynamics induced by the eclipse, even causing a TEC enhancement in the EIA region during the eclipse. In this study, we utilized multiple observations over Africa and Asian longitudes to explore the low-latitude ionospheric responses to this eclipse. Data used include the TEC from Beidou geostationary (GEO) satellites, two-dimensional (2-D) TEC maps from dense networks of worldwide Global Navigation Satellite System (GNSS) receivers, ionosondes, and in situ measurements from both Swarm and China Seismo-Electromagnetic Satellite (CSES) satellites. The underlying physical mechanisms of the observed responses to the eclipse are also discussed.

### 2. Data Description

In this study, Beidou GEO TEC data with a time resolution of 30 s from 15 GNSS receiver stations were used. The Beidou GEO TEC can provide ionospheric observations along fixed paths since ionospheric pierce points (IPPs) almost do not move (Huang et al., 2017, 2018, 2019). Thus, it gives a high-fidelity observation to detect the ionospheric variations, for instance, the changes induced by the eclipse. As shown in Figure 1, about two thirds of the stations are approximately located in the longitude sector around 110°E at low latitudes over the Asian-Australian sector; the rest are situated in different longitudes around the path of the eclipse. The distribution of these stations is suitable for investigating the longitudinal and latitudinal variations of the ionospheric responses at low latitudes to the eclipse. Note that the Beidou system includes five GEO satellites that provide similar TEC observations for each receiver. Therefore, the TEC from only one GEO satellite was used in this study for each receiver. The detailed information of these stations and their selected GEO satellite with its IPP are given in Table 1. It is noted that in this study we also used the IPP to represent the coordinate information of GNSS radio wave rays through the ionosphere to better reflect the location of the observed ionospheric fluctuations.

Meanwhile, the 2-D TEC maps in the Eastern Hemisphere derived from dense networks of GNSS receivers provided by the Massachusetts Institute of Technology’s Haystack Observatory were also used here to explore the variations of the ionosphere due to the eclipse. The 2-D TEC maps have a spatial resolution of 1° in both latitude and longitude and a time resolution of 5 min. In addition, two ionosondes located at Sanya (18.3°N, 109.6°E, magnetic latitude (MLAT) 11.1°N) and Guam (13.6°N, 144.9°E, MLAT 5.9°N) were also employed to explore the ionospheric dynamic processes during the eclipse in the EIA region by examining variations in the critical frequency in the $F_2$ layer ($f_{o}F_2$) and the $F_2$ layer peak height ($h_mF_2$).
Further, in order to examine the ionospheric responses in the topside ionosphere to the solar eclipse, in situ observations of electron density ($N_e$) and electron temperature ($T_e$) from Swarm-B, Swarm-C, and CSES satellites were used. The Swarm mission is a three-satellite constellation of the European Space Agency (ESA) to monitor the Earth's magnetic field and upper atmosphere. The CSES mission monitors the electromagnetic field and waves and the plasma state of the ionosphere. Both Swarm and CSES missions are equipped with a Langmuir probe, providing $N_e$ and $T_e$ measurements along the satellite trajectories (Yan et al., 2020). During the 21 June 2020 solar eclipse, the orbital altitudes of Swarm-B, Swarm-C, and CSES were about 513, 445, and 511 km, and their orbital equator-crossing on the dayside were around 12:34, 14:37, and 14:00 local times (LTs), respectively.

3. Observation Results
3.1. Beidou GEO TEC Observations

Figure 2 shows the variations of Beidou GEO TEC at different longitudes at low latitudes from 19 to 22 June 2020. The red lines represent the TEC variations on the eclipse day of 21 June 2020. The average TEC during
16–20 June 2020 is also provided (the gray line) to serve as the reference. These TEC observations were along the path of the eclipse with a maximum eclipse obscuration of over 80% from west to east, except the station at IISC with an eclipse obscuration of about 33%. The TEC did not show substantial changes during the eclipse at NKLG. One possible reason could be that the eclipse just occurred around sunrise (5:00–7:00 LT) at this station, which resulted in a minor effect on the ionospheric TEC. In contrast, at DJIG, LHAZ, HKWS, and GUAM, the TEC showed obvious responses to the eclipse. It dropped at the beginning of the eclipse and recovered near the end of the eclipse. The reduction in TEC varied from about 2 to 10 TEC units (TECu) with respect to the TEC reference. The TEC reduction was most evident at the stations of LHAZ and HKWS where the recovery time was longer than that at other stations. Le et al. (2008a) suggested that the drop of TEC associated with the eclipse is significantly larger when it occurs around the noontime (10:00–15:00 LT) compared to that during other local times. The eclipse at LHAZ and HKWS was right around the noontime. At the station IISC, no obvious decrease in TEC during the eclipse was seen, probably due to the small eclipse obscuration of about 33%.

Figure 3 shows the latitudinal variations of Beidou GEO TEC during the eclipse at low latitudes in the Northern Hemisphere. It is clear that the TEC underwent an obvious reduction of about 4–10 TECu with respect to the reference (the average TEC during 16–20 June 2020) during the eclipse at the stations of MCKD, HSKD, KMMN, HKWS, and PIMO with larger eclipse obscuration (>60%). However, the TEC depletion was not proportional to the magnitude of eclipse obscuration. A decrease of TEC with respect to the reference by about ~5 TECu at the HSKD station (27.3°N, 114.6°E, MLAT 20.6°N) with a maximum eclipse obscuration of 93% was evidently smaller than that (~10 TECu) at KMMN (22.6°N, 115.1°E, MLAT 15.6°N) where the eclipse obscuration was 89%. The background TEC was quite similar (~14–15 TECu) at both stations, and they are located at a similar longitude in the region of the EIA crest (about ±15° MLAT) (Anderson, 1973), with about 5° difference in latitude. However, the eclipse-induced TEC reduction observed at KMMN was at least twice as large as that at the HSKD station. Dynamic processes are more effective in the EIA region where a manifestation of the dynamical processes is the well-known fountain effect, which could be responsible for the different ionospheric responses to the eclipse, as will be discussed later.

From Figure 3, the TEC did not show a remarkable decrease during the eclipse at the magnetic equator stations (CUSV and CPNM), where the eclipse obscuration rates were 45% and 29%, respectively. Instead, there was a fluctuation of TEC during the eclipse at both stations. At NTUS (1.2°N, 107.2°E, MLAT 7.4°S), the eclipse obscuration was about 11%. One would expect that the eclipse-induced TEC variations might be very small due to this low obscuration compared to that at other stations. However, at this station, the TEC underwent an obvious decrease of about 3–4 TECu relative to the reference during the eclipse. It is unclear to us whether this TEC decrease was related to the eclipse, as similar variation was also seen on the posteclipse day of 22 June.

### Table 1

<table>
<thead>
<tr>
<th>Site</th>
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<th>Geomagnetic latitude</th>
<th>Geographic longitude</th>
<th>PRN</th>
<th>Geographic latitude</th>
<th>Geomagnetic latitude</th>
<th>Geographic longitude</th>
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<td>19.38°S</td>
<td>109.09°E</td>
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</table>

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In order to examine the TEC responses at low latitudes to the eclipse in the conjugate hemisphere, we compared the variations of Beidou GEO TEC at two pairs of stations approximately located at the conjugate magnetic latitudes, as shown in Figure 4. The two stations in the Northern Hemisphere are KMNM and HSKD, which are located in the EIA crest region with a large eclipse obscuration of about 90%. The Southern Hemisphere stations are XMIS (9.7°S, 109.1°E, MLAT 19.4°S) and CIBG (6.0°S, 112.5°E, MLAT 15.2°S), which were not in the eclipse shadow. The TEC during the eclipse also underwent a remarkable reduction of about 3–4 TECu with respect to the reference at the approximate Southern Hemisphere conjugate stations that were not covered by the shadow of the eclipse. The occurrence time of the maximum depletion in TEC was very close at the two pairs of approximately conjugate stations, although their magnitudes were different. These results indicate that the decrease in TEC in the conjugate hemisphere (even without the Moon shadow) was correlated with the eclipse. However, it should be noted that the day-to-day variations of the
Figure 3. Temporal variations of Beidou GEO TEC at low latitudes in the Northern Hemisphere between 19 and 22 June 2020. The gray lines represent the average TEC during 16–20 June 2020 as the reference. The gray error areas denote the standard deviations from the average. The yellow shadings denote the duration of the solar eclipse over the observation position.
The ionosphere are very complicated, and their effects cannot be easily ruled out from the TEC depletion. In addition, a decrease in electron densities near the noontime is frequently observed in the EIA region, which is usually known as the ionospheric “bite-out” (e.g., Zhang et al., 2000). This “bite-out” phenomenon could be potentially responsible for the observed TEC depletion. From Figure 4, it can be seen that the ionospheric “bite-out” occurred on days with (5:00 UT, 21 June) and without (22 June) the eclipse. Finally, the low atmospheric forcing also plays an important role in the equatorial TEC variations, which can sometimes result in an obvious depletion in electron densities (de La Beaujardière et al., 2009). Although our observations indicate the simultaneous TEC reduction at low latitudes in the conjugate hemispheres with the eclipse presence, it is not clear whether this reduction was uniquely caused by the eclipse and what would be the physical drivers. Further investigations with both observations and theoretical studies are needed to address these issues.

3.2. Observation of the 2-D TEC Maps

To further explore the evolution of TEC during the eclipse, we examined the differential TEC (DTEC) 2-D maps over the Eastern Hemisphere between 04:30 and 11:30 UT on 21 June, as shown in Figure 5. The DTEC was obtained by subtracting a reference defined as the average TEC over 16–20 June from the TEC on 21 June (the eclipse day) for 0.5 h bins during the considered UTC period (from 4:30 to 11:30 UT). The geophysical conditions showed almost no changes during 16–20 June and the eclipse day of 21 June, when
the solar flux proxy $F_{10.7}$ was around 70 solar flux units and the geomagnetic index $Kp$ was nearly quiescent at about 2. From Figure 5, the TEC exhibited an obvious and complicated response to the eclipse. Although the TEC had day-to-day variations, the TEC within the eclipse obscuration zones showed remarkable decreases and the areas of TEC depletion moved eastward with the movement of the eclipse.

From the onset of the eclipse (04:30 UT) to 06:00 UT during which the solar eclipse was in the prenoon sector, the decrease in TEC mainly occurred in the eclipse shadow region, and its magnitude was relatively small, about ~2–3 TECu. Then, the eclipse moved into the noon and afternoon sectors where the TEC displayed complex responses between 06:00 UT and the end of the eclipse (09:30 UT). Compared with the TEC variations in the prenoon sector, the TEC was considerably reduced over more or less the entire shadow region of the eclipse. The depletion in TEC reached ~10 TECu (note that the color bar just shows the range from ~6 to 6 TECu), but it was not proportional to the eclipse obscuration rate. The maximum of the TEC decrease was not in the totality region during 06:30–07:30 UT. Additionally, the decrease of TEC was also observed at low and middle latitudes in the conjugate hemisphere (the Southern Hemisphere) during the eclipse, although its magnitude was smaller than that in the Northern Hemisphere directly under the Moon shadow. After the eclipse (09:30 UT), a large TEC decrease of about 2–6 TECu was observed to last for over 7 hr until 16:00 UT (maps after 12:00 UT not shown) at low and middle latitudes in the Northern Hemisphere in the Asian-Australian sector. Meanwhile, the TEC also underwent a decrease at low and middle latitudes in the conjugate hemisphere in the Asian-Australian sector. The TEC depletion in the Southern Hemisphere was smaller than that in the Northern Hemisphere, with the depletion magnitude of about 1–3 TECu. The TEC decreases at low and middle latitudes in the Northern Hemisphere under the eclipse shadow and in the Southern Hemisphere not under the eclipse shadow appeared to be synchronous over the
Asian-Australian sector, although their magnitudes were different. It should be noted that there was an interesting TEC enhancement during the eclipse at middle latitudes in the Indian Ocean without the eclipse obscuration. It was about 2–4 TECu and happened during the eclipse and gradually disappeared after the eclipse.

3.3. In Situ Observations From Swarm and CSES

Figure 6 shows the variations of \( \text{Ne} \) and \( \text{Te} \) from the Swarm-B satellite. Before the onset of the solar eclipse (Figure 6a), the \( \text{Ne} \) at 10–25° MLAT in both hemispheres was generally lower than that before and after the eclipse day as well as the multiday reference (the average \( \text{Ne} \) during 16–20 June). The equator \( \text{Te} \) trough was also narrower. Right after the solar eclipse (Figure 6b), \( \text{Ne} \) almost did not change at low latitudes as compared with the values before and after the eclipse day and the reference, but \( \text{Ne} \) at middle latitudes in the Northern Hemisphere was slightly lower. The corresponding \( \text{Te} \) also did not show obvious changes at low latitudes.

Figure 6. Comparison of the geomagnetic latitudinal profiles of (left column) electron density and (middle column) electron temperature at a similar longitude during 19–22 June (the solar eclipse day in red line) for Swarm-B. The gray lines denote the average \( \text{Ne} \) and \( \text{Te} \) during 16–20 June 2020 as the reference. The standard deviations are also marked with the gray error areas. (right column) The orbital positions are shown with the title of the equator-crossing UT for the solar eclipse day, and the full solar eclipse path and the Sun-shading ratio at the equator-crossing UT are also presented.

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latitudes and had a minor decrease, about 100–200 K, with respect to the values before and after the eclipse day as well as the reference at middle latitudes in the Northern Hemisphere. However, the slightly lower Ne and Te could not be directly associated with the solar eclipse. Ne varied within the standard deviations of the Ne during 16–20 June. The day-to-day variability cannot be ignored in this case. A reduced Te reached more than 700 K that was simulated during an eclipse (Le et al., 2008b), while the Swarm measurements indicated that there was only a minor change, about 100–200 K, in Te, or it recovered fast after the eclipse disappeared. At around 09:00 UT (Figure 6c), Ne had an enhancement in the EIA region with respect to the values before and after the eclipse day as well as the reference at ~50° longitude, especially in the Southern Hemisphere, and the Te in the EIA region was also lower. However, the variations of Ne and Te were within their standard deviations during 16–20 June. The Ne of the last two satellite passes (a couple of hours after the eclipse) did not show obvious differences as compared with the ones before and after the eclipse day and the reference.

Figure 7 shows the results of Swarm-C. We can also see the lower Ne before the solar eclipse (Figure 7a). Right after the solar eclipse (Figure 7b), Ne also only had a minor decrease at middle latitudes in the Northern Hemisphere in the eclipse shadow. Compared with the TEC that underwent a remarkable decrease in this region (Figure 5), the smaller decrease in Ne could be explained by the fact that the
eclipse-induced photoionization reduction had a relatively small effect on electron densities at the higher altitudes (Le et al., 2008a). In contrast, $T_e$ almost did not change during this period. The next three satellite passes showed the recovery of the ionosphere after the eclipse, but they displayed different responses (Figures 7c–7e). $N_e$ had a slight enhancement in EIA (Figure 7c), obvious depletion (Figure 7d), and great increase at low latitudes (Figure 7e). These different responses might be due to the longitude variations of the dynamic and electrodynamic processes. The results of CSES are shown in Figure 8. As the LTs of CSES orbits are similar to those of Swarm-C, measurements from the two satellites were similar. However, the southern EIA crest was not evident in the CSES, possibly due to its higher-altitude orbit. The CSES results also suggest that there was no significant change in $T_e$ after the solar eclipse.

As Swarm-B and Swarm-C flew at a similar LT with a 2 hr difference, the Swarm-C revisited the path of Swarm-B. Before and right after the eclipse, the $N_e$ from the Swarm-B and Swarm-C shown in Figures 6a
and 7b, as well as in Figures 6b and 7c, respectively, all showed obvious EIA structures. However, after the eclipse, in both Figures 6c and 7d, which have observations at 50° longitude, the Ne at ~09:00 UT had an enhanced EIA structure (Figure 6c), while Ne was depleted at ~11:20 UT (Figure 7d). At 30° longitude, Ne was comparable to that in the reference days near 10:40 UT (Figure 6d), while it turned to be much greater near 12:50 UT (Figure 7e). These contradictory observation results within 2 hr at the similar longitudes indicated complicated ionospheric variations after the eclipse. Simulations by Lei et al. (2018) showed that eclipse-induced remarkable neutral wind perturbations and the associated electric field fluctuations can last for more than a half day after the eclipse. The simulations also revealed that large-scale traveling atmospheric disturbances are excited by the eclipse and exist after the eclipse. These processes could act together to affect the ionosphere, resulting in the long-lasting posteclipse Ne variations.

### 3.4. Ionosonde Observations

Figure 9 shows variations of $f_o F_2$ and $h_m F_2$ at Sanya (18.3°N, 109.6°E, MLAT 11.1°N) and Guam (13.6°N, 144.9°E, MLAT 5.9°N). The gray lines denote the average value during 16–20 June 2020 as the reference. The standard deviations are marked with the gray error areas. The yellow shadings denote the duration of the solar eclipse.
increased from 300 to 350 km around the onset of the eclipse and then decreased rapidly during the eclipse. However, this variations may not be necessarily associated with the eclipse, as differences with respect to the reference were also seen during 00:00–04:00 UT.

4. Discussion

The solar eclipse on 21 June 2020 provides a unique opportunity to investigate the ionospheric responses to eclipses at low latitudes. Note that the geophysical conditions were nearly quiescent with a $Kp$ value of about 2 on 21 June and over the days 16–20 June, which were selected as the reference. Thus, the geomagnetic activity effect should be small. In addition, atmospheric forcing may drive ionospheric day-to-day variability. Here we used the multiday average as the reference to limit the effects of ionospheric day-to-day variability when deriving the eclipse-induced ionospheric changes. The results in the previous section show that the ionospheric responses to this low-latitude solar eclipse had some interesting characteristics. The decrease in TEC mostly occurred in the areas with large eclipse obscuration. However, its magnitude was not solely controlled by the eclipse obscuration ratio. As shown in Figures 3 and 4, the TEC reduction with respect to the reference was about ~10 TECu at KMNM with an eclipse obscuration of 89%, which was twice as large as that (~5 TECu) at HSKD with an eclipse obscuration of 93%. Dang et al. (2020) predicted the ionospheric variations during this eclipse using model simulations. They suggested that the neutral winds driven by the eclipse play a dominant role in modifying the ionospheric variations. The disturbance neutral winds converged toward the eclipse totality where the atmospheric pressure is the lowest due to the neutral temperature maximum reduction by the solar mask effect. Therefore, there were southward wind perturbations north of the totality path and northward wind perturbations south of the totality path. The IFPs of HSKD and KMNM are located on the north and south sides of the totality, respectively. Thus, there were poleward (northward) wind perturbations at KMNM and equatorward (southward) wind perturbations at HSKD. The poleward wind perturbations tend to weaken the upward pushing of the plasma along the magnetic field lines, and thus, the plasma stays at lower altitudes where the recombination rate is large, and consequently, they result in a decrease in TEC in the south side of the totality and vice versa in the north side of the totality. Therefore, the neutral wind perturbations could enhance the depletion of TEC at KMNM and suppress it at HSKD, resulting in their different responses to the eclipse.

Besides the neutral wind transport, the eclipse-induced ionospheric equatorial electric field perturbations can also possibly affect the ionospheric variation. Previous observations and numerical simulations suggested that solar eclipses can induce a considerable increase in the eastward equatorial electric field, which then modifies the ionospheric variations by the upward $E \times B$ drifts (Chen et al., 2019; Dear et al., 2020; Goncharenko et al., 2018; St-Maurice et al., 2011; Tsai & Liu, 1999). As shown in Figure 9, the $h_mF_2$ at Guam which is close to the magnetic equator evidently increased from 300 to 350 km around the onset of the eclipse and then decreased rapidly during the eclipse, which was different as compared with that before and after the eclipse day and the reference. This indicates that there was an enhanced eastward equatorial electric field near the equator to elevate the ionosphere around the onset of the eclipse. The enhanced equatorial eastward electric field could cause a strong upward $E \times B$ drift, which would push the plasma to the higher altitudes and then shifts the EIA crest locations poleward through the fountain effect. As mentioned above, the TEC depletion during the eclipse had obvious differences at stations around the EIA crest region, such as at the stations of KMNM and HSKD. The depletion of TEC at HSKD was not as evident as that at KMNM, which could be due to KMNM being closer to the EIA crest. However, the enhancement in the equatorial eastward electric field was speculated from the variations of $h_mF_2$ at Guam that were observed only around the onset of the eclipse. More observations of electric fields are needed to address this aspect. Furthermore, previous studies reported that the ionospheric equatorial electrojet can be altered by the solar eclipse, which occurs always at new moon (Choudhary et al., 2011). Therefore, whether there was a change of lunar tides associated with the eclipse and it would impact the ionospheric variations during the eclipse requires further investigations.

We also found a prominent TEC variation in the EIA crest region in the conjugate hemisphere not directly in the eclipse shadow over the Asian-Australian sector (Figures 4 and 5). TEC decreases were observed almost simultaneously in the Northern Hemisphere under the Moon shadow and in the southern conjugate hemisphere not in the eclipse shadow. As simulated by Dang et al. (2020), this can be caused by the
transequatorial transport of plasma due to the northward perturbations of neutral winds induced by the eclipse. At the summer solstice, the transequatorial transport usually moves the plasma from the northern EIA crest region to the southern EIA crest region due to transequatorial southward neutral winds. During this eclipse, the neutral winds had large northward perturbations on the southern side of the totality (Dang et al., 2020). The northward perturbations of the neutral winds would reduce the southern transequatorial neutral winds, weakening the transequatorial transport of plasma from the northern EIA crest to the Southern Hemisphere and thus cause a reduction in TEC in the EIA crest region in the Southern Hemisphere. In addition, the downward plasma motion driven by the southward wind is also weakened in the Southern Hemisphere with the effects of the northward neutral wind perturbations induced by the eclipse, resulting in a relative enhanced TEC because the plasma remains to stay at high altitudes where chemical loss rates are low. The increase of TEC at middle latitudes in the Indian Ocean (Figure 5) and the prominent enhancement in Ne at around 50° longitude in the Southern Hemisphere (Figure 6c) could be explained by this mechanism, which was also predicted by Dang et al. (2020). However, the TEC decrease during the eclipse in the Southern Hemisphere over the Asian-Australian sector extended to the middle latitudes. The effects of the eclipse at the conjugate hemisphere at middle latitudes need further investigation.

The in situ Te data from both Swarm and CSES satellites did not show visible changes at low latitudes before and right after the eclipse. Le et al. (2008a, 2008b) and Ding et al. (2010) suggested that Te decreases by more than ~500 K during an eclipse above an altitude of 400 km. Unfortunately, the two satellites used here did not pass the zones which were right in the eclipse shadow. Swarm-C revisited the path of Swarm-B 2 hr later, and their Ne data showed quite different behaviors compared with those at the similar LT observed before and after the eclipse day as well as the reference after the eclipse. In addition, the decrease in TEC during the eclipse at low latitudes was long-lasting over the Asian-Australian sector even though the eclipse disappeared (Figure 5). This further confirms the findings in Lei et al. (2018) that the perturbations of the global dynamic and energetic processes induced by the eclipse can last for more than half a day after the eclipse.

5. Conclusions

This study investigated the low-latitude ionospheric responses to an annular solar eclipse that occurred on 21 June 2020 with a trajectory that was purely at low latitudes by using multiple data sources from the Beidou GEO TEC, 2-D TEC maps, ionosonde data, and in situ Ne and Te measurements from both Swarm and CSES satellites. The observed TEC during the eclipse decreased at low latitudes with a local time dependence showing the largest depletions in the noon and afternoon sectors. The TEC depletions within the eclipse shadow in the EIA region over the East Asian sector were not solely controlled by the obscuration rate, given that the TEC reductions differed by more than a factor of 2 between stations with different latitudes, even though their obscuration rates were both larger than 90%. Additionally, a noticeable TEC decrease in the EIA crest region in the conjugate hemisphere not in the eclipse shadow was observed. The \( h_mF_2 \) near the magnetic equator station Guam increased from 300 to 350 km around the onset of the eclipse, which could be related to an enhancement of the eastward equatorial electric field. Furthermore, TEC and Ne had a long-lasting response over 7 hr after the eclipse, although the Te data from satellite observations did not show visible changes before and after the eclipse. Together with the previous model predictions (Dang et al., 2020), we suggest that the variations in equatorial electric fields and neutral wind changes, and their associated plasma transport, played an important role in producing the observed ionospheric behavior at low latitudes during this eclipse. The dynamic processes associated with the solar eclipse could also last for a long period of more than 7 hr as part of the posteclipse recovery of the ionosphere after the eclipse.

Data Availability Statement

The Beidou GEO TEC data are provided by the University of Science and Technology of China, NASA CDDIS (https://cddis.nasa.gov/), and the data resources are from the National Space Science Data Center, National Science and Technology Infrastructure of China (http://www.nssdc.ac.cn/eng/); 2-D TEC map data access is through the Madrigal distributed data system (http://cedar.openmadrigal.org/) from the Massachusetts Institute of Technology (MIT); the ionosonde data at Sanya and Guam are provided by the Data Center for Geophysics, National Earth System Science Data Sharing Infrastructure, at BNOSE, IGGCAS (http://wdc.geophys.ac.cn/), and the University of Massachusetts Lowell DIDBase.
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References


(http://umlcar.uml.edu/DIDBase/); the Swarm data are obtained from the ESA Earth Online service (http://earth.esa.int/swarm/); and the data of the Chinese Meridian Project are accessed from https://data.meridianproject.ac.cn/.
