Solar Origins of August 26, 2018 Geomagnetic Storm: Responses of the Interplanetary Medium and Equatorial/Low-Latitude Ionosphere to the Storm

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Abstract

This study investigates the solar origins of August 26, 2018 geomagnetic storm and the responses of the interplanetary medium and equatorial/low-altitude ionosphere to it. We used a multiinstrument approach, with observations right from the solar surface to the Earth. Our results showed that the G3 geomagnetic storm of August 26, 2018 was initiated by a solar filament eruption of August 20, 2018. The storm was driven by an aggregation of weak Coronal Mass Ejection (CME) transients and Corotating Interaction Regions/High Speed Streams (CIR/HSSs). The solar wind energy which got transferred into the magnetosphere drove electrical currents, that penetrated down into the ionosphere to produce weak Prompt Penetration Electric Field (PPEF) (0.3 mV/m). For this reason, during the storm, at daytime, plasma densities of the Equatorial Ionization Anomaly (EIA) crests were localized within the inner flank of ±15° magnetic latitude strip. We attributed this to the extreme quietness of year 2018. There was a clear hemispherical asymmetry, with higher Total Electron Content (TEC) in the northern hemisphere. The major determining factors of the ionospheric responses during the various phases of this storm were the local time of the storm’s onset, local time of storm’s minimum SYM-H, and changes in thermospheric O/N2.

Plain Language Summary

This geomagnetic storm was initiated by a solar filament eruption of August 20, 2018, and driven by an aggregation of weak CME transients and CIR/HSSs. The weak PPEF during the storm, which is associated with the extreme quietness of year 2018 caused plasma densities to localize at locations that are not up to the EIA crests. A clear hemispherical asymmetry, with higher TEC in the northern hemisphere was observed. The determining factors for ionospheric responses to this storm are: local time of the storm’s onset, local time of storm’s minimum SYM-H, and changes in thermospheric O/N2. Furthermore, one major factor that is hindering our progress in developing robust prediction capabilities for geomagnetic storm is the characteristic peculiarity of each storm. August 26, 2018 geomagnetic storm is peculiar due to the intertwined physical processes that led to its occurrence. To develop future forecasting capabilities for this type of a complex storm, a comprehensive understanding of the intertwined physical processes is required, which this study provided.

1. Introduction

Perturbations in the solar atmosphere are the major origins of geomagnetic storms. Reconfiguration of magnetic fields in the solar atmosphere causes uplift of materials from the solar chromosphere into the corona. These relatively cool, but dense materials are suspended against gravity at greater heights by magnetic tension in the dips of the field lines, appearing by absorption against the hotter and brighter background (Carlyle, 2016). These materials could be elongated in structures, to the order of thousands of kilometers in length to form filaments, which could, in turn erupt from the solar coronal surface as Coronal Mass Ejection (CME). CMEs, particularly the Earth-directed ones are the sources of space weather events (e.g., geomagnetic storms) on the Earth. High Speed Streams (HSSs) from the Sun's coronal holes are the sources of the Corotating Interaction Regions (CIRs) which also known to cause geomagnetic storms (Burlaga & Lepping, 1977; Gosling, 1993). The occurrences of geomagnetic storms do influence the electrodynamics of...
the Earth’s ionosphere. This often leads to drastic changes in ionospheric density structures with resultant overbearing negative impacts on space-based and ground-based systems (Akala et al., 2020; NRC, 2008). Sharp and rapid variations in TEC are the essential conditions for occurrences of ionospheric plasma-density irregularities (Valladases et al., 1996), which cause scintillations of radio waves (Kintner et al., 2007). Severe scintillations have been reported to cause loss of signal and cycle slips to transionospheric radio systems (Akala et al., 2012, 2017). Fuller-Rowell et al. (1996) also used thermospheric circulation model to establish that changes in thermospheric circulation are related to the phases of ionospheric responses to geomagnetic storms.

The daytime eastward electric fields cause a vertical uplift of $E \times B$ plasma at the magnetic equator, and its subsequent diffusion in a forward-fountain-like manner along the magnetic field lines due to pressure gradient and gravity forces to form two peaks of plasma density known as the EIA crests at about $\pm 15^\circ$ of the magnetic equator, and a reduced plasma density at the magnetic equator (trough); the so-called Equatorial Ionization Anomaly (EIA; Appleton, 1946). On the other hand, at night, the zonal electric fields become westward directed resulting in a downward orientation of $E \times B$ drift and prevent further upward movement of plasma. Consequently, at night, the distribution of plasma at the EIA region shows a gradual equator-ward movement of the crests (Naranayan et al., 2013). Furthermore, during geomagnetic storms, electric fields of solar wind origin penetrate promptly into the magnetosphere and the dayside equatorial ionosphere (Tsurutani et al., 2008). Consequently, these storm time electric fields are referred to as Prompt Penetration Electric Fields (PPEFs). The net sum of PPEFs and conventional quiet time daytime ionospheric electric fields leads to storm time superfountain effect (Arowolo et al., 2021; Balan et al., 2009).

A combination of PPEF (Vasyliunas 1970, 1972) and Disturbance Dynamo Electric Field (DDEF) (Blanc & Richmond, 1980) drives the storm time ionospheric electrodynamics. PPEF occurs during periods of southward Interplanetary Magnetic Field (IMF) Bz (Senior & Blanc, 1984). Its magnetic signature, known as Disturbance Polar number 2 (DP2) (Nishida, 1968) is caused by electric current systems related to magnetospheric convection electric field. DDEF results from the dynamo action of storm time winds generated by Joule heating (Blanc & Richmond, 1980). Its magnetic signature is referred to as the ionospheric Disturbance dynamo (Ddyn) (Le Huy & Amory-Mazaudier, 2005). Depending on its orientation, either eastward or westward, PPEF can affect $E \times B$ drift, resulting in significant increase or decrease in TEC, as well as affecting the lifting of the postsunset F-layer to higher altitudes. PPEF can penetrate into the low-latitude for several hours during rapid southward turning of IMF Bz (Huang et al., 2007), while DDEF reaches the equator few hours after the beginning of the disturbance, due to the time propagation of the storm wind disturbance generated by Joule heating in the auroral zone, and might last for a day, and even several days during the recovery phase (Nava et al., 2016). At the equatorial/low-latitude region, during geomagnetic storms, when IMF Bz is southward, PPEFs are eastward during the local daytime. The eastward orientation of the PPEFs intensifies ionospheric forward plasma fountain (Fagundes et al., 2016; Huang et al., 2005; Kikuchi et al., 2008), while the westward orientation of the PPEF drives a reverse fountain (Akala et al., 2020), causing reduction in ionospheric plasma density around the EIA crest and subsequent equator-ward movement of the EIA crests (Narayanan et al., 2013). In the dayside equatorial ionosphere, $E \times B$ drift due to strong eastward PPEF drives plasma upward so fast that it cannot recombine (Balan et al., 2018). This leads to superplasma fountain, causing EIA crests to shift to higher latitudes (Balan et al., 2009).

This study investigates the solar-magnetospheric-ionospheric coupling processes that are associated with August 26, 2018 geomagnetic storm, particularly the storm time responses of the equatorial/low-latitude magnetospheric electric fields, ionospheric TEC, and irregularities. Aside from the quest of the space science community to understand the aforementioned coupling processes, interests in the impacts of solar-magnetospheric-ionospheric coupling processes on technological systems are now in the front burner of the civil society campaigns. In fact, occurrences of space weather events, e.g., geomagnetic storms are now matters of major concerns. More so, recent works, like Al-Shakarchi and Morgan (2018), on the likely interactions between CME transients and CIR transients have laid further credence on the need for the space weather community to explore deeply, all the coupling processes from the Sun to the Earth. As earlier reported, geomagnetic storms have the potential to damage ground-based and space-based infrastructures (Eastwood et al., 2017; NRC, 2008), as well as being injurious to human health (Lanzerotti, 2001; Pulkkinen et al., 2017).
2. Data and Method of Analysis

This study generally adopted a multiinstrument approach for the data analyses. We analyzed solar events dated back to August 20, 2018 prior to the occurrence of August 26, 2018 geomagnetic storm. The solar events were obtained from the Solar Dynamics Observatory: Atmospheric Imaging Assembly (SDO AIA), Solar Terrestrial Relations Observatory-A: Coronagraph-2 (STEREO-A COR2). The Interplanetary Magnetic Field (IMF) and solar wind plasma data were measured by the Advanced Composition Explorer (ACE) satellite. ACE data were obtained at https://omniweb.gsfc.nasa.gov/hw/html. In our recent paper; Akala et al. (2020), we provided detailed explanations on ACE data. Furthermore, we used ground-based magnetometers’ data obtained at the global equatorial/low-latitude region locations to investigate storm time ionospheric current variations. Figure 1 shows the GNSS and magnetometer stations’ locations. The SYMmetric Horizontal magnetic field (SYM-H) index data were used to compute ionospheric electric current disturbance (Diono). Detailed methodology for determining Diono is thoroughly presented by Akala et al. (2020). Over the middle-latitude and low-latitude regions, Diono is the sum of DP2 and Ddyn (Le Huy & Amory-Mazaudier, 2005). We used band-pass filter with bandwidth of 18–28 h to extract Ddyn from Diono, while a high-pass filter with a maximum pass period of about 6 h was used to extract DP2 from Diono. We compared our results with the Cooperative Institute for Research in Environmental Sciences (Cires), University of Colorado’s PPEF model (http://geomag.colorado.edu/real-time-model-of-the-ionospheric-electric-fields.html).

We obtained GNSS observables data from the University NAVSTAR Consortium (UNAVCO) website (http://www.unavco.org/data/data.html). The data were in Receiver Independent Exchange (RINEX) format and they were processed by Gopi TEC processing software (Seemala, 2010). The TEC obtained based on carrier phase was leveled to TEC obtained based on pseudorange. This further entailed detecting and correcting cycle slips (Blewitt, 1990) and calibrating STEC using satellite and estimated receiver biases (Ciraolo et al., 2007). The calibrated STEC was converted to VTEC using mapping function at ionospheric pierce point of 350 km (Ma & Maruyama, 2003; Mannucci et al., 1993). The ionosphere was assumed to be a thin shell located around the maximum F2 height (~350 km), where TEC is maximum. Multipath effects were eliminated by adopting an elevation cut-off angle of 30°. VTEC is hereafter referred to as TEC. The deviations in TEC (ΔTEC) were determined from the difference between the storm time GNSS-TEC and the quiet.
time GNSS-TEC. We selected the quiet days by considering all the days of the month of August, 2018 with Kp < 3 (15 quiet days: August 1, 4–6, 8–10, 12–14, 22–23, and 29–31, 2018). The ground-based GNSS-TEC data were complemented with JASON-TEC data at ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason3/ogdr/ogdr/. JASON-2 is a joint U.S./European Ocean Surface Tomography Mission flying at 1,336 km altitude.

We used the Rate Of change of TEC Index (ROTI) as proxy for ionospheric irregularities using GNSS-TEC data (Amaechi, Oyeyemi, & Akala, 2018; Pi et al., 1997).

\[
\text{ROTI} = \sqrt{\langle \text{ROT}^2 \rangle} - \langle \text{ROT} \rangle^2, \tag{1}
\]

where ROT in Equation 1 is the rate of change of TEC in TECU per minute.

We further computed the mean of all ROTI values available every 30 min. Only ROTI values for satellites with elevation above 40° were employed in the computation (Amaechi, Oyeyemi, Akala & Amory-Mazaudier, 2018; Jacobsen & Dähnn, 2014).

3. Results

Figures 2a and 2b show the images of the filaments, coronal holes, and the CMEs that caused the August 26, 2018 geomagnetic storm. The filament erupted on August 20, 2018 at \( t_0 = 0817 \) UT from the solar surface. The CME associated with this filament eruption left the Sun at 04:39 UT on August 21, 2018 (Figure 2b).

The CME was quite slow in speed (221 km/s) (https://cdaw.gsfc.nasa.gov/CME_list). CME has two subsets, namely, magnetic cloud (Burlaga et al., 1981; Lepping et al., 1991, 2015) and sheath fields; i.e., the turbulent magnetic field regions (Guo et al., 2011) that are often sandwiched in-between a shock and the leading edge of a CME (Colburn & Sonett, 1966). Sheaths are the fields behind a shock at the instant when Bz turns southward with a simultaneous increase in all IMF and solar wind parameters to create a forward shock, or a decrease in all IMF and solar wind parameters, except an increase in the solar wind speed to create a reverse shock. On the other hand, magnetic cloud fields are characterized by smooth rotation of the average magnetic field at angle 180° with low solar plasma wind temperature, preceded by a shock and sheath fields (Burlaga et al., 1981), and intense magnetic field (Echer et al., 2008). CIRs are diagnosed by sharp increase in the IMF and solar wind parameters, except solar wind speed and solar wind temperature which also increase but not simultaneously with the IMF and other solar wind parameters, in addition to southward turning of Bz (Gosling, 1993; Gosling & Pizzo, 1999).

Figures 3a–3d show the IMF data, solar wind plasma data, SYM-H, and Kp indices. The red dash-line F1 at 0645 UT on August 24 is the first forward shock. The shock was weak and could not lead to a geomagnetic storm. A weak shock is characterized by not too drastic changes in solar wind plasma velocity at the shock boundary. The occurrence of a second forward shock, F2 at 08:00 UT on August 25, though also weak, heralded the occurrence of the geomagnetic storm. At this point Bz slightly turned negative, while the average magnitude of IMF (IMF B) and solar wind plasma parameters increased moderately. The observed low solar plasma temperature with high magnetic field strength and southward turning of Bz (Gosling, 1993) and magnetic field regions (Guo et al., 2011) indicated that was a magnetic cloud. The CME was characterized by a magnetic cloud (Burlaga et al., 1981), observed on the Earth between 13:15 UT on August 25 and 10:00 UT on August 26. This time span (∼21 h) also indicates the main phase of the storm with SYM-H minimum value of −201 nT around 07:00 UT on August 26, 2018 (Figure 3d). As shown in Figure 3, at the start of the storm’s main phase, the sharp spike plasma temperature of \( 9 \times 10^4 \) K decreased sharply to \( 2 \times 10^4 \) K, although the value of the plasma temperature consistently maintained low values of less than \( 1 \times 10^4 \) K prior to and all through the storm’s main phase. The solar wind plasma speed fluctuated between 450 and 400 km/s, while the interplanetary electric field increased to 7 mV/m. On August 26, 2018 around 06:00 UT, average magnetic field increased to 18 nT, while IMF Bz recorded ∼17 nT.

A CIR followed on August 26 (transparent yellow bar), signifying the storm’s recovery phase. At the boundary of magnetic cloud and CIR, solar wind plasma speed was ∼400 km/s, while solar wind plasma temperature experienced sharp increase from \( 5 \times 10^4 \) to \( 2.5 \times 10^5 \) K. Within the CIR patch, solar wind plasma speed increased sharply to ∼500 km/s, while solar wind plasma temperature increased to ∼4.5 × 10^5 K. The solar wind plasma density decreased from ∼34 n/cc at the magnetic cloud-CIR boundary to ∼5 n/cc at ∼11:00 UT within the CIR patch, before rising to ∼24 n/cc at ∼13:00 UT, and then dropped significantly. The
solar wind plasma pressure followed the same pattern as the solar plasma density. Within the CIR patch, the fluctuations of the interplanetary electric field, average magnetic field, and IMF Bz were significantly high (Alfenic waves). After the CIR, for the last 3 days, HSSs with solar plasma speed of over 600 km/s emanated from coronal holes. These HSSs from coronal holes must have over-run the slower CME streams to establish the CIR (Gopalswamy et al., 2001). Three major coronal holes; SPoCA 28,306, 28,526, and 28,544 on the coronal surface subsisted from August 20 to 24, 2018 (https://helioviewer.org/). On the SYM-H data, the regions of CIR and HSS represent the storm's recovery phase, although, the storm did not completely recover within the 3 days after its main phase (Figure 3d).

Figures 4a–4d show the storm time magnetic disturbances and the PPEF model results. DP2 and PPEF variations are more in the Pacific Ocean East sector, and least in the South America sector. On the other hand, Ddyn variations are least in Pacific Ocean East sector and highest in the Africa sector. The magnitudes of the amplitudes of all the parameters, Diono, Ddyn, DP2, and PPEF were the highest during the main and
Figure 3. Variations of (a) average Interplanetary Magnetic Field (IMF) B, IMF Bz, and electric field, Ey, (b) solar wind plasma speed, Vs, and solar wind plasma temperature, Ts, (c) solar wind proton density, Ds, and solar wind plasma flow pressure, Ps, and (d) SYM-H and Kp-index during August 23–26, 2018. Transparent magenta bar represents a magnetic cloud region, transparent yellow bar represents a CIR region, and high-speed stream region covers the recovery phase of the storm.

Figure 4. Variations of (a) Diono, (b) DP2, (c) Ddyn, and (d) PPEF during August 23–26, 2018. The black, blue, and red lines represent Kourou (KOUR), Yaounde (YAOU), and Guam (GUUG), respectively.
recovery phases of the storm. Specifically, all the parameters sustained their high amplitudes up to August 27. It is important to mention that at the three magnetometers stations, the signatures of the DP2 parameters maintained rapid oscillations, while the Ddyn signatures were characterized with longer-hours periods (in the order of days). Generally, the oscillations of the four parameters almost damped off on August 29. In addition, short-term oscillations of Diono with a period around 30 min to roughly less than 3 h, during southward turning of IMF Bz were very evident in DP2. DP2 are signatures of DDEF (Amory-Mazaudier et al., 2017; Nishida et al., 1966), resulting from disturbance wind driven by auroral heating (Blanc & Richmond, 1980). For clarity, a supplementary figure is provided for Figure 4 (see Figure S4).

Figures 5a–5e show temporal variations of ground-based TEC data at different longitude sectors for the 7 days that are associated with the geomagnetic storm. Generally, at the Pacific Ocean West sector, the highest TEC values were recorded at Mauna Kea (MKEA) in the northern hemisphere, and the least at Rikitea (GAMB) and Tahiti-Faaa (FAA1) in the southern hemisphere. At the South American sector, the highest TEC value was recorded at Sco Luis (SALU) and least at Santiago (SANT). The values of TEC for stations in the eastern region of the South American sector were higher than those for stations in the western region. At the African sector, highest TEC values were observed in Addis Ababa (ADIS) and Dakar (DAKR) and the least values at Binyamin Shmuter Memorial (BSHM) and Zomba (ZOMB) which are conjugate stations in the opposite hemispheres. At the Indian Ocean sector, these values were recorded at the National Geophysical Research Institute (HYDE) with the least values at Diego Garcia and Christmas Island. At the Pacific Ocean East sector, highest TEC values were recorded at Guam (GUUG) and Namria General Santos (PGEN) and least values at Chichijima-A (CCJ2).

Figures 6a–6e show the mean of TEC data on the quiet days in the month of August, 2018. The mean TEC data is replotted for the 7 days. We examined the variation of mean quiet TEC (quiet TEC) with reference to its variation presented in Figure 5. At the Pacific Ocean West longitude during the main phase, the values of quiet TEC were lower than the corresponding ones during the main phase of the storm (Figure 5). However, they were higher during the recovery at MKEA (Figure 5). At the South American sector, quiet TEC values were generally lower than those obtained during the main and recovery phases except for LMMF. Over Africa, the values were also lower but during the main phase except in ADDIS. Quiet TEC values were found to be higher than the TEC during the beginning of the recovery phase in ADDIS, MAS1, and DAKR at the beginning of the recovery phase. They remained lower for the rest of the recovery. Over the Indian and Pacific Eastern longitudes, the values of the quiet TEC were essentially lower than those presented during the main and recovery phases of the storm.

The mean TEC in Figure 6 was subtracted from the observed TEC in Figure 5 to obtain the difference TEC (ΔTEC) shown in Figure 7. The ΔTEC shows the relative variation of TEC on the disturbed days with respect to the quiet days. Tables 1 and 2 list the GNSS stations’ parameters, quiet time maximum TEC values. The Tables summarizes the observations of Figures 5 and 6. From Figure 7, over the Pacific Ocean West sector, the maximum TEC variations in response to the main phase of the storm were; 18 TECU at FAA1, 17 TECU at MKEA, and 13 TECU at GAMB. Over the South American sector, the values were; 4 TECU at SALU, 3 TECU at SANT, 1 TECU at SAVO, and 6 TECU at LMMF. Over the African sector, the values were; 5 TECU at BSHM, 2 TECU at ASCG, 4 TECU at DAKR, 1 TECU at ADIS, and 8 TECU at MAS1. Over the Indian Ocean sector, the values were; 20 TECU at HYDE, 20 TECU at XMIS, 17 TECU at SGOC, and 18 TECU at DGAR. Over the Pacific Ocean East sector, the maximum TEC variations in response to the main phase of the storm were; 18 TECU at GUUG, 14 TECU at PGEN, and 12 TECU at CCJ2. For the storm’s recovery phase, in comparison with the main phase of the storm, responses of TEC generally decreased over the Pacific Ocean West, Indian Ocean, and Pacific Ocean East sectors but contrary over the South American and African sectors.

To complement the GNSS-TEC data, we analyzed the spatial variations of JASON satellite’s TEC in response to the geomagnetic storm over the oceanic regions for August 23–29, 2018 (Figure 8). Information on the time of satellite track is given in Figure 9 and Table 3. In Table 3, we listed 26 satellite’s pass-numbers, identified by their serial numbers (S/N) (Figure 9). We compared TEC profile on the storm day (August 26) with corresponding TEC profile on a quiet day before the storm (August 23). On both days, we consider satellite passes over the same location at approximately the same time. For instance, for tracks serial number 25.
on August 23 and 26, JASON satellite covered the Pacific Ocean East sector (∼150°–180°E) during passes 01:60 and 02:38 at 23:16:20–23:55:16 and 22:28:08–23:07:29 UT, respectively (see Figure 9). This period corresponded to 08:16–08:55 LT and 07:28–08:07 LT on the respective days. The time difference between both passes is just about 48 min. We do not expect the daily variability of TEC to have a significant effect on the quiet time ionosphere within this time period. We therefore conclude that the enhancement in TEC captured by the JASON satellite on August 26 over this sector was storm-induced. Overall, at daytime, more enhancements in TEC over the Indian Ocean (S/N 5 (∼9–10 a.m.) and 7 (∼11–12 noon)) and Pacific Ocean

Figure 5. Diurnal variations of TEC for August 23–29, 2018 for stations in the: (a) Pacific Ocean West sector, (b) South American sector, (c) African sector, (d) Indian Ocean sector, and (e) Pacific Ocean East.
Figure 6. Diurnal variations of mean quiet days TEC (TECU) over August, 2018 for stations in: (a) Pacific Ocean West sector, (b) South American sector, (c) African sector, (d) Indian Ocean sector, and (e) Pacific Ocean East. These variations are shown for only days associated with the storm (August 23–29).
Figure 7. Deviations of mean quiet time TEC from the storm time TEC for August 23–29, 2018 for stations in the: (a) Pacific Ocean West sector, (b) South American sector, (c) African sector, (d) Indian Ocean sector, and (e) Pacific Ocean East.

East (S/N 22 (~7–8 a.m.) and 1 (~9–10 a.m.)) sectors were recorded than over other longitudinal sectors, even for passes at almost the same local time. Moderate enhancements in TEC were also recorded at the Pacific Ocean West (S/N 18 (~8–9 a.m.) and 20 (~10–11 a.m.)) and African sectors (western part) (S/N 9 (~7–8 a.m.) and 11 (~9–10 a.m.)) and least TEC variations at the South American Sector. JASON satellite passes during nighttime generally recorded low TEC variations.
Table 1

**GNSS Stations Parameters, Quiet Time Maximum TEC Values, Storm Time Maximum TEC Values, and ROTI Responses to the Storm**

| Station name                      | Station Code/Hemisphere or mag. Eq. | Latitude (°) | Longitude (°) | MLat (°) | Longitude sector | Storm-time TEC Max (TECU) | Quiet time TEC Max (TECU) | ROTI level | Local time (h) storm onset time (time of min. SYM-H) |
|-----------------------------------|------------------------------------|--------------|---------------|----------|-----------------|--------------------------|--------------------------|------------|-------------------------------------------------|
| Haleakala                         | HAL1 (NH)                          | 20.71        | −156.26       | 21.30    | Pacific West    | −, −, −                  | −, −                     | −          | UT-10 (21:00)                                  |
| Mauna Kea                         | MKEA (NH)                          | 19.80        | −155.46       | 20.54    | Pacific West    | 37, 17, 22               | 21, Moderate             | UT-10      | 22:00 (21:00)                                  |
| Tahiti-Faaa                       | FAA1 (SH)                          | −17.56       | −149.61       | −16.42   | Pacific West    | 26, 14, 23               | 13, Mild                 | UT-10      | 22:00 (21:00)                                  |
| Rikitea                           | GAMB (SH)                          | −23.23       | −134.97       | −19.93   | Pacific West    | 21, 14, 21               | 9, Moderate              | UT-9       | 23:00 (22:00)                                  |
| Bogota                            | BOGT (NH)                          | 4.64         | −74.08        | 16.93    | S/Americ (W)    | −, −, −                  | 22, −         | UT-5       | 03:00 (02:00)                                  |
| Santiago                          | SANT (SH)                          | −33.15       | −70.67        | −19.52   | S/Americ (W)    | 10, 17, 19               | 10, None                 | UT-3       | 05:00 (04:00)                                  |
| Lamentin Meteo Fra                | LMMF (NH)                          | 14.60        | −61.00        | 23.78    | S/Americ (E)    | 21, 14, 26,              | 18, None                 | UT-4       | 04:00 (03:00)                                  |
| Sco Luis                          | SALU (EQ)                          | −2.59        | −44.21        | −0.25    | S/Americ (E)    | 25, 29, 30               | 23, None                 | UT-3       | 05:00 (04:00)                                  |
| Salvador                          | SAVO (SH)                          | −12.94       | −38.43        | −10.56   | S/Americ (E)    | 18, 24, 27               | 19, None                 | UT-3       | 05:00 (04:00)                                  |
| Maspalomas                        | MASI1 (NH)                         | 27.76        | −15.63        | 15.75    | Africa (W)      | 16, 10, 27               | 15, None                 | UT         | 08:00 (07:00)                                  |
| Dakar                             | DAKR (EQ)                          | 14.72        | −17.44        | 2.34     | Africa (W)      | 22, 17, 30               | 20, None                 | UT         | 08:00 (07:00)                                  |
| Ascension Island                 | ASCG (SH)                          | −7.92        | −14.33        | −16.34   | Africa (W)      | 14, 23, 28               | 11, None                 | UT         | 08:00 (07:00)                                  |
| Binynim Shmuter Memorial site     | BSHM (NH)                          | 32.78        | 35.02         | 26.01    | Africa (E)      | 14, 15, 15               | 10, None                 | UT+2       | 10:00 (09:00)                                  |
| Addis Ababa                       | ADIS (EQ)                          | 9.04         | 38.77         | 0.18     | Africa (E)      | −, 37, 31                | 24, None                 | UT+3       | 11:00 (10:00)                                  |
| Zomba                            | ZOMB (SH)                          | −15.38       | 35.33         | −26.06   | Africa (E)      | 21, 12, 10               | 9, None                  | UT+2       | 10:00 (09:00)                                  |
| National Geophysical Research Institute | HYDE (NH)                      | 17.42        | 78.55         | 10.18    | Indian Ocean    | 44, 44, 34               | 24, None                 | UT+5.5     | 13:30 (12:30)                                  |
| Surveyor General's Office Colombo | SGOC (EQ)                          | 6.89         | 79.87         | −1.57    | Indian Ocean    | 37, 38, 28               | 20, None                 | UT+5.5     | 13:30 (12:30)                                  |
| Diego Garcia                     | DGAR (SH)                          | −7.27        | 72.37         | −16.89   | Indian Ocean    | 35, 34, 33               | 18, None                 | UT+6       | 14:00 (13:00)                                  |
| Christmas Island                 | XMIS (SH)                          | −10.45       | 105.69        | −20.57   | Indian Ocean    | 36, 34, 35               | 17, None                 | UT+7       | 15:00 (14:00)                                  |
| Chichijima-A                     | CCJ2 (NH)                          | 27.07        | 142.20        | 19.57    | Pacific East    | 23, 19, 15               | 12, None                 | UT+9       | 17:00 (16:00)                                  |
| Guam                             | GUUG (EQ)                          | 13.43        | 144.80        | 5.67     | Pacific East    | 37, 22, 25               | 19, None                 | UT+10      | 18:00 (17:00)                                  |
| Namria General Santos            | PGEN (EQ)                          | 6.07         | 125.13        | −2.00    | Pacific East    | 33, 30, 26               | 20, None                 | UT+8       | 16:00 (15:00)                                  |

**Note.** NH: Northern Hemisphere; SH: Southern Hemisphere; EQ: Magnetic Equator; E: East; W: West.

*Storm time maximum TEC values within the MC, CIR, and HSS patches, respectively.

Table 2

**Magnetometer Stations’ Parameters**

| Station name             | Station Code | Latitude (°) | Longitude (°) | MLat (°) | Longitude sector | Local time (h) |
|-------------------------|--------------|--------------|---------------|----------|-----------------|---------------|
| Kourou                  | KOUR         | 5.16         | −52.65        | 10.65    | S/Americ (W)    | UT-3          |
| Yaounde                 | YAOU         | 3.84         | 11.50         | −5.31    | Africa (E)      | UT+1          |
| Guam                    | GUUG         | 13.43        | 144.80        | 5.67     | Pacific East    | UT+10         |
Figure 8. Spatial variations of JASON-TEC for August 23–29, 2018. The color bar represents top-side TEC (TECU).
Figure 10 shows the corresponding GUVI data (thermospheric O/N₂). A strong enhancement in thermospheric O/N₂ over the Indian Ocean and the Pacific East sectors was observed during the main and recovery phases of the storm, particularly at the equatorial/low-latitude region. Figure 11 shows the variations of ROTI derived from the GNSS-TEC during the 7 days that are associated with the geomagnetic storm for all the longitudinal sectors. From this Figure, irregularities were observed in the Pacific Ocean West sector with peak ROTI = 0.65 TECU/min recorded Mauna Kea; 0.42 TECU/min at Tahiti-Faaa and 0.22 TECU/min at Rikitea. There was a data gap at Haleakala so we could not record the value of ROTI at that station. For the other longitudinal sectors; South America, Africa, Indian Ocean, and Pacific Ocean East, ionospheric irregularities were absent as ROTI values never exceeded 0.20 TECU/min.

4. Discussion

4.1. Solar Events That Led to the Storm

The G3 geomagnetic storm of August 26, 2018, which is the third largest of solar cycle 24, is smaller only to the geomagnetic storms of March 17, 2015 and June 23, 2015. As shown in Figure 2, the CME that drove the storm was associated with a filament eruption of August 20, 2018. The eruption was later seen in the STEREO-A COR2 images as Earth-directed, diffuse, and slow CME. Previously, Piersanti et al. (2020) provided a sequence of events from the Sun to the Earth during the period of this storm. However, in the aspect of ionospheric response to the storm, these authors provided limited analysis as they only considered SWARM data for August 25–27, 2018 at about 02:00 and 14:00 LT and ionospheric irregularities inferred from only SWARM PRN 17 RODI for only the main phase of the storm. The current work provided a comprehensive analysis of spatial-temporal responses of the global equatorial/low-latitude ionosphere to this storm event for the period of August 23–29, 2018, in relation to the prevailing ionospheric current systems and changes in thermospheric O/N₂. Generally, the current study has taken a deeper step to unravel the physical processes that led to the observed features in the sequence of events during the period of this storm; from the solar corona through the interplanetary medium to the Earth’s ionosphere. Following the lucid explanations provided by Carlyle (2016), reconnection in the lower region of the solar atmosphere produces jets of materials known as filaments. Furthermore, reconnection with low-lying magnetic fields at the foot of a filament injects mass into the magnetic fields arcade (Chae, 2003). It is known that a strongly twisted magnetic field configuration with attendant reservoir of large amount of energy is a progenitor for release of CMEs from the solar surface (Chen, 2011). As these metastable structures got disturbed, they rose, expanded, and released energy during reconnection and reconfiguration (Shibata et al., 1995). Earth-directed CMEs are known with their associated negative space weather impacts on technological systems, e.g., GNSS, satellite communications, power grids, oil and gas pipelines, transportation, assets monitoring, among others, with attendant huge socioeconomic consequences (Arowolo et al., 2021; Eastwood et al., 2017; NRC, 2008; Oughton et al., 2017).
| S/N | Pass no. | Tracking time UT (HH:MM:SS) | Start time | End time |
|-----|----------|----------------------------|------------|---------|
| 1.  | 0138     | 00:48:52                   | 01:27:12   |         |
| 2.  | 0139     | 01:33:38                   | 02:24:59   |         |
| 3.  | 0140     | 02:28:07                   | 03:20:57   |         |
| 4.  |          |                           |           |         |
| 5.  | 0142     | 04:19:29                   | 05:11:33   |         |
| 6.  |          |                           |           |         |
| 7.  | 0144     | 06:11:55                   | 07:07:15   |         |
| 8.  | 0145     | 07:08:09                   | 08:04:20   |         |
| 9.  | 0146     | 08:04:21                   | 08:59:44   |         |
| 10. | 0147     | 09:01:22                   | 09:48:52   |         |
| 11. | 0148     | 09:56:57                   | 10:47:44   |         |
| 12. | 0149     | 10:53:22                   | 11:42:22   |         |
| 13. | 0150     | 11:52:41                   | 12:37:39   |         |
| 14. | 0151     | 12:50:09                   | 13:38:38   |         |
| 15. |          |                           |           |         |
| 16. | 0152     | 14:43:51                   | 15:27:50   |         |
| 17. |          |                           |           |         |
| 18. | 0153     | 16:35:39                   | 17:04:35   |         |
| 19. | 0154     | 17:29:10n                  | 18:19:03   |         |
| 20. | 0155     | 18:30:00                   | 18:59:30   |         |
| 21. | 0156     | 19:24:32                   | 20:13:53   |         |
| 22. | 0157     | 20:22:05                   | 20:58:11   |         |
| 23. | 0158     | 21:17:35                   | 22:04:59   |         |
| 24. | 0159     | 22:09:53                   | 22:52:22   |         |
| 25. | 0160     | 23:16:20                   | 23:55:16   |         |
| 26. | 0163     |                           |           |         |

**August 26, 2015**

| S/N | Pass no. | Tracking time UT (HH:MM:SS) | Start time | End time |
|-----|----------|----------------------------|------------|---------|
| 1.  | 0214     | 00:01:20                   | 00:39:39   |         |
| 2.  | 0215     | 00:46:33                   | 01:36:46   |         |
| 3.  | 0216     | 01:40:02                   | 02:34:18   |         |
| 4.  | 0217     | 02:39:58                   | 03:31:48   |         |
| 5.  | 0218     | 03:31:48                   | 04:23:18   |         |
| 6.  | 0219     | 04:29:29                   | 05:24:13   |         |
| 7.  | 0220     | 05:24:14                   | 06:20:23   |         |
| 8.  | 0221     | 06:22:02                   | 07:16:39   |         |
| 9.  | 0222     | 07:16:40                   | 08:12:28   |         |
4.2. Changes in the Interplanetary Conditions

From Figures 3a to 3d, we noted that the CME transients were wrapped-in with HSSs from the coronal holes. As previously reported by Heinemann et al. (2019), magnetic flux rope is the core structure of major solar eruptions, while magnetic clouds are post-eruption magnetic flux rope in the interplanetary space (Wang et al., 2018). Ideally, a CME-driven geomagnetic storm is often characterized with high solar wind plasma speed. Surprisingly, on August 26, solar wind speed had a nominal value of 463 km s\(^{-1}\) at first, but increased to a maximum of 566 km s\(^{-1}\) later in the day due to the wrapping-in of HSSs from the coronal holes. The solar wind plasma speed is related to the strength of a shock. Strong shocks compress IMF B components, while weak shocks do not have the capability to significantly compress IMF B components (Richardson et al., 2006). A strong shock compression leads to intense fluctuations of IMF B fields in the sheath region (Jurac et al., 2002). The southward turning of the Bz was observed around 15:00 UT on August 25, and the value gradually decreased to a minimum of −17 nT on August 26 with a resultant release of large amounts of energy, which disturbed the Earth’s magnetosphere. In Figure 3, although very weak, the interaction of CME with the interplanetary medium led to the development of two shock waves; FS1 and FS2 recorded on August 24 around 07:00 UT and August 25 around 08:00 UT, respectively. A shock is identified by abrupt changes in IMF and solar wind plasma parameters.

As shown by the magenta bar in Figure 3, the observed low solar plasma temperature, high magnetic field variations, and southward orientation of IMF Bz are features of magnetic cloud (Wei et al., 2003). The southward orientation of IMF Bz caused a compression of magnetospheric ram pressure. The magnetic cloud spans between 12:15 on August 25 and 10:00 UT on August 26, corresponding to the main phase of the geomagnetic storm. This geomagnetic storm was characterized with a gradual Sudden Storm Commencement (SSC) around 08:00 UT on August 25. The magnetic cloud was comparatively slow, with solar wind plasma speed of around 400–450 km/s. The dominating activity of the HSSs within the interplanetary medium and its interaction with the heliospheric current plasma sheet produced the observed CIR high field region (Tsurutani et al., 1995). CIR features manifested on August 26 at about 09:30–21:30 UT. The leading edge of the fast stream compresses the plasma to produce a high-pressure region. Other interesting features observed from Figures 3a–3d are the sharp decrease in proton density and plasma pressure at

| S/N | Pass no. | Tracking time UT (HH:MM:SS) |
|-----|----------|-----------------------------|
|     |          | Start time                  | End time   |
| 10. | 0223     | 08:13:20                    | 09:00:39   |
| 11. | 0224     | 09:09:16                    | 10:05:16   |
| 12. | 0225     | 10:05:19                    | 10:55:19   |
| 13. | 0226     | 11:04:50                    | 11:49:31   |
| 14. | 0227     | 12:02:27                    | 12:51:03   |
| 15. | 0228     | –                           | –          |
| 16. | 0229     | 13:55:57                    | 14:46:22   |
| 17. | 0230     | –                           | –          |
| 18. | 0231     | 15:48:14                    | 16:18:03   |
| 19. | 0232     | –                           | –          |
| 20. | 0233     | 17:42:10                    | 18:11:42   |
| 21. | 0234     | 18:36:49                    | 19:25:20   |
| 22. | 0235     | 19:34:35                    | 20:05:08   |
| 23. | 0236     | 20:29:55                    | 21:16:24   |
| 24. | 0237     | 21:22:43                    | 22:03:09   |
| 25. | 0238     | 22:28:08                    | 23:07:29   |
| 26. | 0239     | 23:15:14                    | 00:07:17   |
Figure 10. Spatial and temporal variations of thermospheric O/N₂ for August 23–29, 2018.
boundary of the magnetic cloud and CIR. Barely 2 h from the magnetic cloud-CIR boundary, sharp increase in proton density and plasma pressure were observed. This is attributable to the preceding magnetic cloud-CIR interaction (Al-Shakarchi & Morgan, 2018). As it could be seen in Figure 3, the recovery phase of the geomagnetic storm covered both CIR and HSS regions.

4.3. PPEF and DDEF Variations During the Storm Event

From Figures 4a–4d, the amplitudes of Diono, Ddyn, DP2, and PPEF were highest during the main and recovery phases of the storm, and damped off after the storm’s recovery phase (August 29). During the storm’s main phase, Diono mainly had positive orientation at YAOU (African sector) and KOUR (South American sector), and negative orientation at GUUG (Pacific Ocean East sector). The PPEF model results agree with our DP2 results except during the period of the magnetic cloud (magenta bar) when DP2 showed varying features than the PPEF model. The reason for these discrepancies is not clear and raises question on the accuracy of the PPEF model during different phases of geomagnetic storms. This however, calls for more studies aimed at assessing the accuracy of the PPEF model using large quantity of data. As shown in Figure 4, variations of DP2 and PPEF were highest in the Pacific Ocean East sector, and least in the South America sector, while Ddyn variations were least in Pacific Ocean East sector and highest in the Africa sector. Conventionally, PPEF and DDEF drive storm time ionospheric electrodynamics (Akala et al., 2020). PPEF occurs during periods of southward IMF Bz, and it can penetrate into the low-latitude for several days.
hours (Huang et al., 2007). On the other hand, DDEF reaches the equator few hours after the beginning of a disturbance, due to the time propagation of the storm wind disturbance generated by Joule heating in the auroral zone, and might last for a day, and even several days during the recovery phase (Nava et al., 2016).

4.4. Storm Time TEC Variations

As listed in Table 1, the storm’s onset time and the corresponding time of the storm’s minimum SYM-H at the Pacific Ocean West sector were during nighttime (postsunset: 21:00–22:00 LT) hours, early morning hours over the South American (03:00–05:00 LT) and West African (07:00–08:00 LT) sectors, prenoon (10:00–11:00) hours at the East African sector, postnoon (12:30–15:00 LT) hours at the Indian Ocean sector, and presunset (16:00–18:00) hours at the Pacific Ocean East sector. Normally, during geomagnetic storm, at daytime in the equatorial/low-latitude regions, the net eastward electric field (ionospheric electric field + PPEF) increases the intensity of the plasma fountain greatly to cause a superfountain effect (Arowolo et al., 2021). Generally eastward electric field causes vertical uplift of ExB drift at the magnetic equator, causing plasma to diffuse along the magnetic field lines to form two peaks of plasma density (crests) at about ±15° of the magnetic equator and a reduced plasma density at the magnetic equator (trough) in a process similar to a fountain (Appleton, 1946). Ideally, at storm time, the combination of solar photoionization and plasma transport enhances EIA plasma densities to values above quiet time levels (±15°; Balan et al., 2009), creating a positive ionospheric response to geomagnetic storm. At night, westward electric field (ExB) may considerably reduce the TEC and cause a contraction of the EIA. Strong nighttime westward electric fields could lead to total coalition of the EIA structure to form a single strip of plasma density around the equator (Arowolo et al., 2021).

From both Figures 5 and 8, and following the summary provided in Table 1, generally, significant TEC enhancements were recorded at Indian Ocean and the Pacific Ocean East sectors: The dayside sectors during the time of the minimum Dst of the storm. Figure 8 shows spatial variations of JASON satellite TEC over the oceanic regions for August 23–29. From the figure, TEC were more prevalent over the Indian Ocean and Pacific Ocean East sectors and less prevalent over the South American sector, thereby showing good agreement with our TEC data derived from stand-alone ground-based GNSS receivers. From Figure 5, at the Indian Ocean sector for instance, highest TEC values were recorded at the National Geophysical Research Institute, India (HYDE) (mag. lat.: 10.18°N), while least values of TEC were recorded at Diego Garcia (mag. lat.: 16.89°S) and Christmas Island (mag. lat.: 20.57°S). At the Pacific Ocean East sector, highest TEC values were recorded at Guam (GUUG) (mag. lat.: 5.67°N) and Namria General Santos (PGEN) (mag. lat.: 2.00°S), and least values at Chichijima-A (CCJ2) (mag. lat.: 19.57°N). Ordinarily, daytime storm time electric fields are expected to cause superfountain effect, whereby EIA crests at the same longitude are shifted poleward to ~±20° and above (Balan et al., 2009). On the contrary, from our results, at the Indian Ocean and Pacific Ocean East sectors, highest values of TEC were recorded at National Geophysical Research Institute, India (mag. lat.: 10.18°N) and Guam (5.67°N), respectively, as against recording such highest values of TEC at Christmas Island (mag. lat.: 20.57°S) and Chichijima-A (mag. lat.: 19.57°N), respectively. For GNSS stations located on the same longitude (~same time zone), but different latitudes, we can infer the variations of the EIA. Consequently, we inferred from our results that at daytime during the geomagnetic storm, the expected combined effect of the ionospheric electric field and PPEF was not strong enough to produce the superfountain effect which was expected to transport plasma above ±15° of the magnetic equator (Balan et al., 2009). EIA crests seem generally localized at locations below ±15° magnetic latitude band. We attribute this to the extreme quietness of the year 2018; a minimum phase of a rather weak solar cycle with its feebler drift and consequent weak fountain effect.

The time of the minimum Dst of the storm corresponds to sunset hour in the African sector. From Figure 5 and Table 1, at the African sector, highest TEC values were recorded at the equatorial stations; Addis Ababa (ADIS; mag. lat.: 0.18°N) and Dakar (DAKR; mag. lat.: 2.34°N), while least values were recorded at Binyamina Shmutter Memorial site (BSHM; mag. lat.: 26.01°N) and Zomba (ZOMB; mag. lat.: 26.07°S). BSHM and ZOMB are conjugate stations in the opposite hemispheres. The disparities in the values of TEC at conjugate stations are attributed to hemispherical asymmetry in TEC distribution driven by change in composition and interhemispheric neutral winds (Oyedokun et al., 2020). On the other hand, the night-side sectors during the time of the minimum Dst of the storm are the Pacific Ocean West and South American sectors.
At the Pacific Ocean West sector, highest TEC values were recorded at MKEA and HAL1 in the northern hemisphere, and the least at GAMB in the southern hemisphere. The above three stations are located above ±15°. At the South American sector, highest TEC value was recorded at Sco Luis (SALU), an equatorial station (mag. lat.: 0.25°S), and least at Santiago (SANT; mag. lat.: 19.52°S). These enhancements in TEC were driven by eastward DDEF. The diurnal oscillations of Ddyn on this day confirmed the presence of DDEF. The configuration of DDEF is a function of the local time and is mainly westward in the daytime and eastward at night (Amaechi et al., 2020; Astafyeva et al., 2018). DDEF are produced through the ionospheric dynamo process associated with the disturbed thermospheric circulation and wind due to the energy at high latitude during the storm (Blanc & Richmond, 1980). Abdu (2012) showed that eastward polarity of DDEF begins at about 22:00 LT and can cause large vertical drift of the F-layer to altitude where recombination rate is significantly reduced.

From Figure 7, TEC variations in response to the main phase of the storm were major over the Indian Ocean (HYDE: 20; XMIS: 20; SGOC: 17; DGAR: 18 TECU), Pacific Ocean East (GUUG: 18; PGEN: 14; CCI2: 12 TECU), and Pacific Ocean West sectors (FAA1: 18; MKEA: 17; GAMB: 13 TECU), with mild responses over the South American (SALU: 4; SANT: 3; SAVO: 1 TECU, and 6 TECU at LMMF) and African sectors (BSHM: 5; ASCG: 2; DAKR: 4; ADIS: 1 TECU, and 8 TECU at MAS1). For the storm's recovery phase, responses of TEC over the Indian Ocean and Pacific Ocean East sectors were generally positive with some mild and negligible negative incursions. Further detailed analyses showed that over the Pacific Ocean West sector, TEC responded positively to the storm's recovery phase, except over Mauna Kea (MKEA) where TEC responded negatively. At the South American sector, TEC responded positively to the storm's recovery phase, but with a few marked negative responses at Lamentin Meteo Fra (LMMF) and Salvador (SAVO). Over the African sector, TEC responses fluctuated between the negative and positive phase, but generally, positive responses of TEC to the storm's recovery phase were prevalent. Also from the JASON satellite TEC data, storm time TEC enhancements were observed (August 26) as compared to a quiet day (August 23, Kp < 3; Figure 9).

### 4.5. Thermospheric Responses to the Storm Event

The positive responses over the Indian Ocean and the Pacific Ocean East sectors during the main and recovery phases of the storm are mainly attributed to the strongly enhanced thermospheric O/N₂ (Figure 10). As shown in Figure 10, an increase in O/N₂ caused enhancements in TEC (Lissa et al., 2020). Variations of thermospheric composition during geomagnetic storms are closely related to both positive and negative storm time responses in the ionosphere (Fuller-Rowell et al., 1994). The thermosphere is diffusively separated, with heavier species dominant at lower altitudes and lighter species dominant at higher altitudes (Fuller-Rowell et al., 1996). During geomagnetic storms, the upwelling transports heavier species from the lower thermosphere to higher altitudes and increases the relative abundance of heavier species, while lighter species are left at the lower thermosphere. With the lighter species, photoionization restores plasma densities at lower altitudes with resultant enhancements in TEC (Tsurutani et al., 2008). During recovery phase of a storm, neutral composition changes play important role in daytime electron density increase (Klimenko et al., 2018). On the other hand, Richmond and Roble (1979) explained how electric currents at the auroral latitudes got enhanced by precipitating particles, field aligned currents, and convection of magnetospheric electric field via Joule heating and momentum transfer by the Ampere force. Joule heating leads to transfer of energy to the neutrals, while Ampere force moves neutral wind by momentum transfer. Both processes drive thermospheric wind (Sharma et al., 2011), which could extend from the high-to-middle-latitude and low-latitude regions (Mazaudier et al., 1985). These winds drag ionization to altitudes where recombination rates are significantly reduced, thereby causing enhancements in TEC. These winds are responsible for global changes in thermospheric composition (Fuller-Rowell et al., 1994) and they are longitudinal dependent (Prößl, 1995).

### 4.6. Storm Time Ionospheric Irregularities Variations

For the variation of GNSS-ROTI shown in Figure 11, the storm's onset time and the time of appearance of the storm's minimum SYM-H corresponded to the local daytime hours at the African and Indian Ocean sectors and local presunset hours at the Pacific Ocean East sector. At the South American sector, these time periods
corresponded to the early morning hours. All these time periods are outside the time for PRE occurrence. For the reasons of these time periods, this geomagnetic storm did not support irregularities generation in the equatorial/low-latitude regions of the South American, African, Indian Ocean, and Pacific Ocean East sectors. However, at the Pacific Ocean West sector, these time periods corresponded to postsunset hours (Figure 11). At the equatorial/low-latitude regions, during postsunset hours, emergence of PRE-related ExB drift creates conducive environment for irregularities generation over the Pacific Ocean West sector. At sunset, the daytime quiet time eastward ionospheric electric field reverses westward. Prior to this reversal, PRE occurs. During the PRE, the upward ExB drift is enhanced to create a suitable ionospheric F-layer that supports the propagation and growth of irregularities via Rayleigh Taylor (R-T) instability mechanism (Kelley, 1989). As earlier explained, PRE causes a vertical uplift of ExB drift at the magnetic equator thus, to form the EIA crests and trough (Balan & Bailey, 1995). During geomagnetic storm, the above process is enhanced due to the combined effect of eastward PPEF and PRE that further lifts the ionosphere to altitude where irregularities are generated through the R-T instability mechanism.

5. Conclusions

1. The G3 geomagnetic storm of August 26, 2018 (https://www.spaceweather.com/), the third largest geomagnetic storm of solar cycle 24 was initiated by a solar filament eruption of August 20, 2018. This eruption later translated to a diffuse, weak, and slow-moving Earth-directed CME. The CME billowed away from the solar corona on August 21, 2018 and buffeted the Earth's magnetosphere with a weak shock around 06:45 UT on August 24, 2018, and another shock around 08:00 UT on August 25, 2018 with weak sheath fields behind it (Figures 3a–3d). This shock led to the magnetic cloud region indicated by the characteristic low plasma temperature, increased magnetic field strength, and negative turning of IMF Bz. Afterward, HSSs from the solar coronal holes also interacted with the CME transients to cause a CIR (Golpaswamy et al., 2009). Generally, the storm of August 26, 2018 was driven by an aggregation of CME transients and CIR/HSSs. This sequence of solar events is in agreement with the report of Piersanti et al. (2020).

2. The weak solar wind energy got transferred into the magnetosphere to drive electrical currents, which propagated down into the ionosphere to also produce weak PPEF (0.3 mV/m). Consequently, our results showed that at daytime during the geomagnetic storm, the combined effect of the ionospheric electric field and PPEF was not strong enough to transport plasma to both sides of the conventionally known ±15° of the magnetic equator. At daytime, plasma was localized at HYDE (10.18°N) as against DGAR (16.89°S) in the Indian Ocean sector, and GUUG (5.67°N) as against CCJ2 (19.57°N) in the Pacific Ocean East sector (Figures 5a–5e). We attributed this to the deep quietness of year 2018. However, at night, the net westward electric field drove a reverse fountain that caused plasma density loading at the magnetic equator or at locations close to it, which is in agreement with the report of Narayanan et al. (2013).

3. At all the longitudinal sectors, equatorial/low-latitude ionosphere generally responded positively to August 26 storm, with a few cases of negative responses at Salvadore and Ascension Island (Figures 7a–7e). Generally, the responses of TEC over the Indian Ocean, Pacific Ocean East, and Pacific Ocean West sectors were high (∼15 TECU), while mild (∼5 TECU) responses were recorded over the South American and African sectors. TEC also recorded highest values over the Indian Ocean sector, and least over the South American and African sectors. Within the African sector, the western longitude recorded higher values of TEC than the eastern longitude, and on the contrary in the South American sector. Furthermore, a clear hemispherical asymmetry to the advantage of the northern hemisphere at the expense of the southern hemisphere was observed in the distribution of TEC.

4. The positive responses of TEC during the storm are attributed to strongly enhanced-thermospheric O/N₂ (Figure 10). During the geomagnetic storm, vertical upwelling transported heavier species from the lower thermosphere to higher altitudes and increased the relative abundance of heavier species at the higher altitudes, while lighter species were left at the lower thermosphere. With the lighter species, photoionization restored plasma densities at lower altitudes resulting to the observed enhancements in TEC. This result validates the thermospheric circulation model by Fuller-Rowell et al. (1996).

5. The local time of the storm's onset and local time of storm's minimum SYM-H are the major determining factors for irregularities generation. At the equatorial/low-latitude region, during postsunset hours, PRE-related ExB drift creates conducive environment for irregularities generation (Akala et al., 2014).
As shown in Figure 11, irregularities were only prevalent in the Pacific Ocean West sector where the storm's onset and local time of storm's minimum SYM-H correspond to post-sunset hours (21:00–22:00 LT). During the geomagnetic storm, the combined effect of PPEF and PRE intensified post-sunset hours' plasma to support irregularities generation in the Pacific Ocean West sector.

6. One major factor that is still hindering our progress in developing robust capabilities for space weather prediction to avert its impacts on technological systems (GNSS, satellite communications, power grids, oil and gas pipelines, transportation, assets monitoring, among others) and on the safety of astronauts and aircraft passengers and crews is the characteristic peculiarity of each space weather event (NRC, 2008). For instance, August 26, 2018 storm is peculiar due to the intertwined physical processes that led to its occurrence. To develop future forecasting physics-based capabilities for this type of a complex storm, a comprehensive understanding of the intertwined physical processes from multiple studies is required. Consequently, although Piersanti et al. (2020) had earlier reported a whole sequence of events from the Sun to the Earth for this storm, however, new studies that will assist space weather community’s understanding of the physical processes that led to the storm and the subsequent responses of the ionosphere to it (storm), particularly with a view to developing future space weather forecasting capabilities are required.

Data Availability Statement

The solar wind data and the SYM-H index data were obtained at https://omniweb.gsfc.nasa.gov/ow_min.html. We obtained Kp-index data from http://wdc.kugi.kyoto-u.ac.jp/ GUVI O/N data at http://g- vitimed.jhuapl.edu/data_on2_info. TEC data were obtained from https://www.unavco.org/data/data.html. Gopi Seemala provided the TEC processing software (GPS GOPI_V2.9.5). We obtained magnetic data at https://www.intermagnet.org/data-donnee/data-eng.php. PPEF model data were obtained at http://geomag.colorado.edu/real-time-model-of-the-ionospheric-electric-fields.html. JASON-TEC data were obtained at ftp://ftp.nodc.noaa.gov/pub/data.nodc/jason3/ogdr/ogdr/. SDO data were obtained at https://heliовизор.org, STEREO data at https://cdaw.gsfc.nasa.gov/movie/make_javamovie.php?date=20180821&img1=lasc2rdf&img2=sta_cor2rd.

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