Responses of the African and American Equatorial Ionization Anomaly (EIA) to 2014 Arctic SSW Events

O. R. Idolor, O. R. Idolor, A. O. Akala, A. O. Akala, and O. S. Bolaji, O. S. Bolaji

1Department of Physics, University of Lagos, Lagos, Nigeria, 2Institute of Maritime Studies, University of Lagos, Lagos, Nigeria, 3Department of Mathematics and Physics, University of Tasmania, Hobart, TAS, Australia

Abstract Aside from the influence of forcing from above on the ionosphere during space weather, forcing from below also have significant influence on the ionosphere. This study investigates responses of the equatorial ionization anomaly (EIA) in the African and American longitudinal sectors to the combined effects of 2014 Sudden Stratospheric Warming (SSW) events and geomagnetic storms that coexisted with them. The study locations cover ±40° geomagnetic latitudes in both sectors. A multiinstrument approach with models was adopted. During the SSW events, a hemispherical asymmetry in TEC distribution was observed, with higher plasma ionization in the Northern Hemisphere (NH). Generally, in both sectors, EIA crests locations shifted to higher latitudes during peak phases of SSW, except in the SH of the African sector, where crests locations shifted to lower latitudes. Reversal of stratospheric zonal mean wind direction supported reversed fountain effect. TEC responded positively to SSW peak phases and daytime or nighttime orientation of Prompt Penetration Electric Field (PPEF) and PPEF strength played major role on TEC responses to storms. PPEF values were generally weak, but comparatively higher in the American sector. TEC were predominant in the American sector than the African sector due to the comparative higher electrodynamics over the American sector. EIA crests were generally located at higher latitudes on the days of SSW peaks than on the days of geomagnetic storms, except in the NH of the American sector. In both sectors, geomagnetic storms modified ionospheric irregularities by weakening or enhancing them, while the major SSW event weakened irregularities.

Plain Language Summary We investigated the responses of the EIA in the African and American sectors to the combined effects of 2014 SSW events and the geomagnetic storms that coexisted with them. We chose the study locations to cover ±40° geomagnetic latitudes in both sectors. We adopted a multiinstrument approach with models. Our results showed that the EIA crests locations in the African sector shifted from lower latitudes on pre-SSW days to higher latitudes on minor SSW peak days in the NH. In the SH, these crests locations shifted from higher latitudes on pre-SSW days to lower latitudes on SSW peak days, except on the day of the major SSW peak when the crest location shifted from lower latitude on pre-SSW days to higher latitude on SSW peak days. In the American sector, EIA crest locations shifted from lower latitudes on pre-SSW days to higher latitudes on the SSW peak days in both hemispheres. Reversal of stratospheric zonal mean wind direction supported reversed fountain effect. Both the strength and orientation of PPEF played major roles on TEC responses to storms. Furthermore, occurrence of geomagnetic storm modified ionospheric irregularities. Weakening of irregularities was noticed during days of the major warming in the American sector.

1. Introduction

Previous studies have revealed that the variability in the ionosphere during Sudden Stratospheric Warming (SSW) events is connected to the coupling of the lower and upper atmosphere (Bessarab et al., 2012; Bolaji et al., 2019; de Jesus, Batista, Jonah, et al., 2017; Goncharenko, Chau, et al., 2010; Goncharenko, Coster, et al., 2010; Goncharenko et al., 2013). Understanding of this connection between the lower and upper atmosphere has remained a major concern for the space science community. SSWs are large-scale meteorological events characterized by the sudden breakdown of the stratospheric polar vortex arising from the dynamic forcing of the upward propagating planetary waves originating from the lower atmosphere (Jonah et al., 2014). The accepted mechanism for their occurrence was attributed to the nonlinear interaction of the vertically propagating planetary waves with zonal wind flow (Matsuno, 1971). SSW events can be classified into major or minor warming. Both major and minor warmings are characterized by the abrupt rise in
stratospheric temperature at 90°N and 10 hPa (Andrews et al., 1987; Chau et al., 2012). Major SSW warming is accompanied by wind reversal from westerly to easterly, while the minor warming is characterized by the deceleration of the zonal wind without any wind reversal (Siddiqui et al., 2015; Vieira et al., 2017).

Earlier studies have shown different trends of SSW-associated ionospheric variability; that is, the semidiurnal pattern in vertical plasma drift with morning enhancement and afternoon reduction was reported by Chau et al. (2009, 2011). Similar pattern of morning TEC enhancement and afternoon reduction in the American sector for different SSW events have also been reported (de Jesus, Batista, de Abreu, et al., 2017; de Jesus, Batista, Fagundes, et al., 2017; Fagundes et al., 2015; Goncharenko, Chau, et al., 2010; Goncharenko, Coster, et al., 2010; Paes et al., 2014; Vieira et al., 2017). Additionally, some of these past investigations reported different longitudinal responses (Anderson & Araujo-Pradere, 2010; Fejer et al., 2010; Sridharan et al., 2009; Vineeth et al., 2009), and a corresponding F-region reduction in electron density (NmF2) during the SSW events (Pedatella et al., 2016). De Paula et al. (2015) reported weakening of ionospheric scintillations at a single crest station in the Brazilian sector for three major (winter 2002, 2003, and 2013) SSW events. Bolaji et al. (2016) reported hemispheric asymmetry in solar quiet (Sq) current during the peak phase of 2009 SSW event in the African sector. Bolaji et al. (2019) also demonstrated the weakening of TEC and equatorial electrojet (EEJ) current intensity for the same peak phase of the 2009 SSW event in the African sector.

It is worthy to note that some of the SSW events earlier reported by some of the earlier workers had simultaneous occurrences of geomagnetic storms (e.g., de Jesus, Batista, Jonah, et al., 2017; Goncharenko et al., 2013; Vieira et al., 2017). Geomagnetic storm is a major component of space weather. Space weather is a combination of impacts of time varying conditions of all physical processes, originating from the Sun through the interplanetary medium to the Earth (Akala & Adewusi, 2020; Poppe & Jorden, 2006). Occurrence of extreme space weather events can significantly degrade the performance and reliability of modern space-based and ground-based technological systems, e.g., Global Navigation Satellite System (GNSS) services, space shuttles, assets monitoring, power grids, among many others (Akala & Adewusi, 2020), with attendant huge socio-economic consequences (Eastwood et al., 2017; NRC, 2008; Oughton et al., 2017). Furthermore, space weather events are injurious to the health of astronauts on missions (Lanzerotti, 2001). Unfortunately, previous authors did not attempt to isolate the distinct individual contributions, arising from SSW forcing and geomagnetic storm forcing to ionospheric changes. For instance, de Jesus, Batista, Jonah, et al. (2017) investigated the ionospheric response of a cascade of SSW events from February 2 to April 10, 2014 in the Brazilian sector. Their study focused on only the distinct features of the SSW events, without attention to the possible influences of the geomagnetic storms that coexisted with the SSW events on ionospheric conditions. According to the authors, these SSW features include, increase in the afternoon and nighttime vertical TEC and weakening of ionospheric irregularities. Generally, a combined effect of SSW forcing and geomagnetic storm forcing is expected to cause more ionospheric effects and in turn, more negative impacts on space-based and ground-based critical infrastructures. To this end, concerted efforts are required to distinctly characterize these two geophysical phenomena in order to isolate the contributions of each of them to ionospheric dynamics.

Furthermore, most of the previous studies on SSW effects on the ionosphere focused more on the American and Asian sectors, with little still known of the ionospheric responses of the African sector to SSW events. Goncharenko et al. (2013) reported enhancements of the equatorial ionization anomaly (EIA) crests with a noticeable hemispheric asymmetry in the American sector during 2013 SSW event. The authors linked the observed ionospheric disturbances to anomalous variations in equatorial vertical ion drift. On the other hand, Maute et al. (2015) showed that the typical phase shift signature of the daytime maximum vertical drift in the American sector was conspicuously absent in the African sector during the peak phase of 2013 SSW event. The physical source of this longitudinal difference raised curiosity. Consequently, the need to unravel the ionospheric electrodynamics that is responsible for the observed longitudinal difference is sacrosanct. de Jesus, Batista, de Abreu, et al. (2017) reported TEC perturbations in the American and African sectors during the 2012 minor SSW warming event. However, these authors restricted the electrodynamics aspect of their study to the American sector only. The authors were not able to draw any firm conclusion on the influence of ionospheric electrodynamics on the African ionospheric variations during the SSW event that they investigated.
Arising from the above identified gaps in some of the previous research efforts on SSW events, this study investigates the responses of TEC, vertical plasma drift, and ionospheric irregularities over the African and American longitudinal sectors to SSW events of 2014 (a year of high solar activity) and the geomagnetic storms that jointly occurred with the SSW events. The underlying background mechanisms responsible for the observed changes in the electrodynamics of the vertical drift and the EIA are also examined. The results from this study will be useful in beefing-up the understanding of the space science community on the responses of the global ionosphere to SSW events, particularly the SSW events that are associated with high solar activity and geomagnetic activity, with a view to improving existing ionospheric models.

2. Data and Methods of Analysis

The world map indicating the locations of Global Positioning System (GPS) stations used in this study is presented in Figure 1. In both the African and American sectors, the latitudes of the stations were within the range of ±40° geomagnetic latitudes. For this reason, the locations of the GPS stations in the Northern Hemisphere (NH) for the African sector were extended to Ukraine. Tables 1 and 2 list the GPS stations with their station codes, geographic and geomagnetic coordinates in both sectors. The stratospheric data (temperature at 90°N and 10 hPa; and the zonal wind at 60°N and 10 hPa) from January 1 to April 30, 2014 that were used in this study were obtained from National Oceanic and Atmospheric Administration (NOAA) website (http://www.esrl.noaa.gov/psd/). Also using all the available stratospheric data from the NOAA satellites from 1979 to the current SSW year investigated, the 36 years historical mean was generated. To probe the solar activity and geomagnetic activity of the ionosphere, Kp, F10.7 cm flux, and Dst index were used for the days investigated. Dst and Kp indices were obtained from the website of the World Data Center for Geomagnetism Kyoto (http://wdc.kugi.kyoto-u.ac.jp/kp/index.html), while the F10.7 cm flux was obtained from the website of the National Aeronautics and Space Administration (NASA) space physics data facility (http://omniweb.gsfc.nasa.gov/form/dx1.html). All days with Kp \( \leq 3 \) (\( \Sigma Kp < 24 \)) were classified as quiet days, while we adopted the geomagnetic storm criteria of a minimum Dst of: \( -100 \text{ nT} \leq \text{Dst} \leq -50 \text{ nT} \) for moderate storm, and \( -200 \text{ nT} \leq \text{Dst} \leq -100 \text{ nT} \) for major storm (Gonzalez et al., 1994; Loewe & Prohl, 1997) to categorize the five geomagnetic storms that occurred within the period of the

![Figure 1. Map of the Global Positioning System (GPS) stations and magnetometer stations in the American sector (green and yellow) and African sector (red and magenta).](image-url)
SSW events under investigation (Table 3). We estimated the Prompt Penetration Electric Field (PPEF) for February 18–28, and April 11–15, using the real-time electric field model for geomagnetism developed by the Cooperative Institute for Research in Environmental Sciences (CIRES) of the University of Colorado at Boulder (http://geomag.colorado.edu/real-time-model-of-the-ionospheric-electric-fields.html). This model utilizes a frequency-dependent transfer function to determine the prompt penetration of the interplanetary electric field response to the equatorial ionosphere (Manoj & Maus, 2012; Manoj et al., 2008, 2013).

We used the GOPI TEC processing software (Seemala & Delay, 2010) to extract the TEC data from the GPS observable data. The GPS data were obtained from the University NAVSTAR Consortium, UNAVCO (www.unavco.org), Système d’Observation du Niveau des Eaux Littorales, SONEL (www.sonel.org), African Geodetic Reference Frame, AFREF (www.afrefdata.org), and International Global Navigation Satellite Systems Service (IGS) (www.igs.org). The difference in TEC procedure by Goncharenko et al. (2010b) was adopted to evaluate background variations during the SSW event. The computed hourly mean for each station was subtracted from the days during the SSW event and expressed mathematically as:

$$\Delta \text{TEC} = \text{TEC}_{\text{Sa}} - \text{TEC}_{\text{qm}}$$

(1)

where TEC$_{\text{Sa}}$ is the hourly mean TEC data for the days of the SSW events from February 2 to April 30, 2014 and TEC$_{\text{qm}}$ is the hourly mean TEC data for the pre-SSW days (with $\Sigma Kp < 24$) from January 1 to 31, 2014 for each station, with the exception of January 2, 2014 which had $\Sigma Kp = 26$. Additionally, we noted that the second minor SSW (M-SSW-2) event overlapped with the geomagnetic activity of February 19, 20, and 21, 2014. The implication of the overlap of these two geophysical conditions is that the combined effect of

| Station name                  | Station code | Station country | Geographic latitude | Geographic longitude | Geomagnetic latitude | Geomagnetic longitude |
|-------------------------------|--------------|-----------------|---------------------|----------------------|----------------------|-----------------------|
| Mykolaiv                      | MIKL         | Ukraine         | 46.97°N             | 31.97°E              | 42.28°N             | 105.21°E              |
| Crimean Astrophysical Observatory | CRAO        | Ukraine         | 44.41°N             | 33.99°E              | 39.49°N             | 106.71°E              |
| Ankara                        | ANKR         | Turkey          | 39.89°N             | 32.76°E              | 34.24°N             | 104.96°E              |
| Nicosia-Athalassa             | NICO         | Cyprus          | 35.14°N             | 33.40°E              | 28.64°N             | 105.16°E              |
| Binyamin Shmuter Memorial site | BSHM        | Israel          | 32.78°N             | 35.02°E              | 26.01°N             | 106.65°E              |
| Halat Ammar                   | HALY         | Saudi Arabia    | 29.14°N             | 36.10°E              | 21.83°N             | 107.56°E              |
| Rash                          | RASH         | Saudi Arabia    | 28.30°N             | 34.80°E              | 20.62°N             | 106.23°E              |
| Solar Village                 | SOLA         | Saudi Arabia    | 24.91°N             | 46.40°E              | 18.43°N             | 118.05°E              |
| Namas                         | NAMA         | Saudi Arabia    | 19.21°N             | 42.04°E              | 11.49°N             | 113.60°E              |
| Asab                          | ASAB         | Eritrea         | 13.06°N             | 42.65°E              | 4.92°N              | 114.34°E              |
| SHIMSHEHA                     | SHIS         | Ethiopia        | 11.99°N             | 38.99°E              | 3.27°N              | 110.63°E              |
| AMBO                          | ABOO         | Ethiopia        | 8.99°N              | 37.81°E              | 0.01°N              | 109.49°E              |
| GINIR                         | GINR         | Ethiopia        | 7.15°N              | 40.71°E              | 1.58°S              | 112.47°E              |
| ARBA MINCH UNIVERSITY         | ARMI         | Ethiopia        | 6.06°N              | 37.56°E              | 3.03°S              | 109.29°E              |
| Eideret—Kenya                 | MOIU         | Kenya           | 0.29°N              | 35.29°E              | 9.17°S              | 107.00°E              |
| MALINDI                       | MAL2         | Kenya           | 2.99°S              | 40.19°E              | 12.42°S             | 111.86°E              |
| Arusha Ministry of Energy and Minerals | ARSH     | Tanzania        | 3.39°S              | 36.70°E              | 13.02°S             | 108.33°E              |
| DODOMA                        | DODM         | Tanzania        | 6.19°S              | 35.75°E              | 16.10°S             | 107.21°E              |
| Mtwara                        | MTVE         | Tanzania        | 10.26°S             | 40.17°E              | 20.35°S             | 111.24°E              |
| ZOMBA                         | ZOMB         | Malawi          | 15.38°S             | 35.35°E              | 26.06°S             | 105.58°E              |
| MAUA                          | MAUA         | Botswana        | 19.91°S             | 23.52°E              | 30.83°S             | 92.32°E               |
| Hartebeesthoek RAO            | HRAO         | South Africa    | 25.89°S             | 27.69°E              | 36.32°S             | 94.69°E               |
| SUTHERLAND                    | SUTM         | South Africa    | 32.38°S             | 20.81°E              | 41.09°S             | 84.76°E               |
the two geophysical phenomena is expected to have effect on the modification of the ionosphere. Table 4 lists the geomagnetic conditions of February 7–9 and 19–22, 2014. From Table 4, except for February 7, the geomagnetic storm indices for all other days did not meet the minimum condition for a quiet day. It is important to also stress that days; February 7–9 define the days of M-SSW-1 peak phase. By implication, the ionospheric effect of February 7 is solely SSW-induced. In order to filter the SSW-induced ionospheric effects from the geomagnetic storm-induced ionospheric effects during the period of overlap of M-SSW-2 and geomagnetic activity, we subtracted the SSW-induced ionospheric effects of February 7, 2014 from those of February 19, 20, and 21, 2014.

| Station name                        | Station code | Station country        | Geographic latitude | Geographic longitude | Geomagnetic latitude | Geomagnetic longitude |
|-------------------------------------|--------------|------------------------|---------------------|----------------------|----------------------|-----------------------|
| Cape Canaveral Air Force Station     | CCV6         | U.S.A.                 | 28.46°N             | 80.54°W              | 40.05°N              | 351.48°W              |
| PuertoplatCR2012                     | CN07         | Dominican Republic     | 19.76°N             | 70.57°W              | 31.16°N              | 4.31°W                |
| St Croix VLBA                        | CRO1         | US Virgin Island       | 17.76°N             | −64.58°W             | 28.04°N              | 11.79°W               |
| Managua NIC2012                      | MANA         | Nicaragua              | 12.15°N             | 86.25°W              | 23.32°N              | 344.03°W              |
| Bogota                              | BOGT         | Colombia               | 4.64°N              | 74.08°W              | 16.93°N              | 358.07°W              |
| Puengasi Permanent Station           | QUEM         | Ecuador                | 0.24°S              | 78.49°W              | 11.96°N              | 352.82°W              |
| Riobamba Permanent Station           | RIOP         | Ecuador                | 1.65°S              | 78.65°W              | 10.56°N              | 352.65°W              |
| Flura                               | LPIU         | Peru                   | 5.17°S              | 80.64°W              | 6.84°N               | 350.60°W              |
| Porto Velho                          | POVE         | Brazil                 | 8.71°S              | 63.89°W              | 2.86°N               | 7.96°W                |
| Callao                              | CALL         | Peru                   | 12.06°S             | 77.15°W              | 0.48°N               | 354.34°W              |
| Reserva Nacional Pampa Galeras       | GLRV         | Peru                   | 14.67°S             | 74.40°W              | 1.89°S               | 357.01°W              |
| Isla Alacran                         | LACR         | Chile                  | 18.48°S             | 70.33°W              | 5.59°S               | 0.70°W                |
| Atajana                             | ATIN         | Chile                  | 19.30°S             | 70.14°W              | 6.39°S               | 0.85°W                |
| Antofagasta                         | UCNF         | Chile                  | 23.68°S             | 70.41°W              | 10.58°S              | 0.58°W                |
| Uns Salta                           | UNSA         | Argentina              | 24.73°S             | 65.41°W              | 12.01°S              | 4.62°W                |
| Copiapo                             | COPO         | Chile                  | 27.38°S             | 70.33°W              | 14.10°S              | 0.69°W                |
| Cordoba                             | CORD         | Argentina              | 31.53°S             | 64.47°W              | 18.48°S              | 5.14°W                |
| Malargue                            | MGUE         | Argentina              | 35.78°S             | 69.39°W              | 22.00°S              | 1.75°W                |
| Niebla                              | NIEB         | Chile                  | 39.87°S             | 71.53°W              | 25.79°S              | 0.38°W                |
| Coyhaique                           | COYQ         | Chile                  | 45.51°S             | 71.89°W              | 31.03°S              | 1.06°W                |
| Aeropuerto Ushuaia Tierra del Fuego  | AUTF         | Argentina              | 54.84°S             | 68.30°W              | 39.85°S              | 4.72°W                |

Table 2

American GPS Stations With Their Geographic and Geomagnetic Coordinates

| Station name                        | Minimum Dst (nT) | Storm classification | Time of storm onset/minimum Dst (UT) | African sector (LT) | American sector (LT) |
|-------------------------------------|-----------------|----------------------|--------------------------------------|---------------------|----------------------|
| February 19, 2014                   | −119            | Major                | 13:30/09:00                          | 16:39/12:00         | 08:30/04:00          |
| February 20, 2014                   | −95             | Moderate             | NA/13:00                             | NA/16:00            | NA/08:00 D           |
| February 23, 2014                   | −55             | Moderate             | 07:30/19:00                          | 10:30/22:00         | 02:30/14:00          |
| February 27, 2014                   | −97             | Moderate             | 10:25/00:00                          | 13:25/03:00         | 05:25/19:00          |
| February 12, 2014                   | −87             | Moderate             | 05:52/09:00                          | 10:52/12:00         | 00:52/04:00          |

Note: NA: Not available.
To explore the effects of 2014 SSW event on the ionospheric irregularities, the Rate of change of TEC (ROT) expresses in units of TEC/min was computed and the 5 min standard deviation of the ROT to obtain ROT Index (ROTI) (Pi et al., 1997). ROTI is expressed mathematically as:

\[
\text{ROT} = \sqrt{\text{ROT}^2 - (\text{ROT})^2}
\]  

(2)

In addition, the 30-min resolution of ROTI was estimated to eliminate noise spikes (Oladipo et al., 2014). The 30-min resolution of ROTI hereafter referred to as ROTI<sub>ave</sub> was obtained by computing the ROTI average value for all satellites in view at a particular location over 30-min interval. The occurrence of irregularities was classified into three distinct threshold levels using the ROTI<sub>ave</sub> < 0.4 to indicate the absence of irregularities, 0.4 < ROTI<sub>ave</sub> < 0.8 indicates the presence of moderate irregularities and ROTI<sub>ave</sub> > 0.8 to indicates the presence of severe irregularities (Bolaji et al., 2020; Oladipo & Schuler, 2013).

The EEJ current measured in nano-Tesla (nT) for the African and American sectors for the 2014 SSW event was obtained from two pairs of ground-based magnetometers located at the equatorial and low-latitude regions (Anderson et al., 2002, 2004; Yizengaw et al., 2014). The magnetic field data for the Addis Ababa station (geomagnetic coordinates: 0.9°N, 110.5°E) located at the equatorial region were obtained from the International Real-time Magnetic Observatory Network, INTERMAGNET (www.intermagnet.org), while the data for the Nairobi station (10.76°S, 108.51°E) were obtained from Magnetic Data Acquisition System (MAGDAS) (http://magdas2.serc.kyushu-u.ac.jp/). In the American sector, both the equatorial and low-latitude magnetometers data at Jicamarca (0.8°N, 5.7°W) and Plura (6.8°N, 9.4°W) were obtained from the Low Ionospheric Sensor Network (LISN) (http://lisn.igp.gob.pe/data/). The EEJ current was processed using the procedure outlined by Rabiu et al. (2017). The EEJ current was calculated using the expression below:

\[
\text{EEJ} = \Delta H_{\text{eq}} - \Delta H_{\text{off-eq}}
\]  

(3)

where \(\Delta H_{\text{eq}}\) is the horizontal magnetic field intensity for a station located at equatorial region and \(\Delta H_{\text{off-eq}}\) is the horizontal magnetic field intensity for a station located outside the equatorial regions. Also, the empirical relationship established by Anderson et al. (2004) was adopted to estimate the vertical drift. This relationship is given by the expression below (Anderson et al., 2002, 2004; Kassamba et al., 2020; Yizengaw et al., 2011, 2014):

\[
\text{VD} = -1989.51 + 1.002Yr - 0.00022 \text{DOY} - 0.0222F_s - 0.0282F_p - 0.0229A_p + 0.0589K_p - 0.3661LT + 0.1865H + 0.00028 H^2 - 0.0000023 H^3
\]  

(4)

where VD is the estimated vertical drift, Yr is the year, DOY is the day of the year, \(F_s\) is the daily F10.7 cm solar flux, \(F_p\) is the 81-day average value of the adjusted F10.7 cm solar flux, Ap and Kp are the daily and 3 hourly geomagnetic indices, LT is the local time in hours at the magnetometer stations, and \(\Delta H\) is the difference in the horizontal magnetic field intensity for each pair of magnetometer stations. It should be noted that the EEJ current obtained from equation (3) is identical to the AH used for computing the vertical drift in Anderson’s model. Anderson’s et al. (2004) relationship (Equation 4) was developed using both multiple regression and neural network regression techniques. These regression techniques were applied on the estimated \(\Delta H\) magnetic field intensity (EEJ) and the vertical E × B drift data obtained from the Jicamarca Unattended Long-Term Ionosphere
Atmosphere Radar (JULIA), Peru in the American sector. In section 8 of Anderson et al. (2004) a set of raw and untrained vertical E $\times$ B drift data, also obtained from the same JULIA, was used to validate their E $\times$ B drift model results. Anderson et al. (2004) provides detailed explanations on this model.

Furthermore, the magnetic field data derived from the Absolute Scalar Magnetometer (ASM) on board the SWARM satellites was used to calculate the EEJ current intensity. The EEJ current intensity was estimated from the scalar magnetic field data using the current inversion technique outlined by Aiken et al. (2013, 2015). Only satellites with orbital crossing at the geographic equator closest to those of the ground-based magnetometer stations for the period of the March 3–17, 2014 were considered in the current study. The EEJ current depicting the height-integrated current density profile was measured in milli Ampere per meter (mA/m) (Aiken et al., 2015).

3. Results

Figure 2a shows stratospheric zonal mean air temperature at 90°N, stratospheric historic zonal mean air temperature at 90°N, stratospheric zonal mean zonal wind at 60°N, stratospheric historic zonal mean zonal wind at 60°N, all at 10 hPa, and the daily Dst variations during the period of the pre-SSW and SSW events (January 1 to April 30, 2014). Conventionally, winter months (December-February) are the months of SSW occurrences, but SSW features could extend to equinoctial months of March and April (de Jesus, Batista, Jonah, et al., 2017), which we also observed in the current results (Figure 2a). Consequently, we extended our analysis to cover the months of March and April because of the observed abrupt rise in stratospheric temperature within a few days and the zonal wind reversal from easterly to westerly direction in March, with the historical mean temperature and temperature intersecting in April. In Figure 2, three minor and one major SSW events were marked in magenta dash lines. The first minor SSW (M-SSW-1) event occurred on February 2–12 with a corresponding temperature peak (240 K) on February 8. On February 7 and 9, the temperature values were 236 K for each day. The second minor SSW (M-SSW-2) event occurred on February 17–25, with a peak temperature (232 K) on February 21. On February 19, 20, and 22, the temperature values were 224, 231, and 227 K, respectively. The third minor SSW (M-SSW-3) event occurred between February 27 and March 10 with observed dual peak temperature recorded on 3rd (237 K) and 6th (237 K) of March, respectively. The major SSW event occurred between March 14 and April 20 with a corresponding observed peak temperature (253 K) on March 16, 2014. The first three SSW events occurred during the gradual deceleration of the stratospheric zonal wind, while the fourth event was associated with reversal of the zonal wind on March 25 to indicate the occurrence of a major warming. Series of successive minor warming events usually precede major warming event. O’Neill (2003) and Paes et al. (2014) ascribed these trends to instances of complete breakdown of the weakened polar vortex during winter solstices. The 36-year stratospheric mean temperature and wind prior to the current year of study is shown by the solid blue and red lines in Figure 2. The Dst plot shows five geomagnetic storms during the duration of the SSW period with their properties listed in Table 3. The first geomagnetic storm of February 19 is a dual peak storm, with a second peak occurring on February 20. Figure 2b shows the Kp values for the period (January 1 to April 30, 2014). Kp values were generally below 5, except on the February 19–20 when a maximum Kp value of 6 was recorded. $F_{10.7}$ cm solar flux values were below 190 solar flux units.

Figures 3ai–3aiv shows day-to-day plots of EIA TEC for the period of January–April, 2014 in the African sector. We observed weak TEC enhancement ($\sim$45 TECU) for most of pre-SSW days (January, 2014). The daily TEC variation of the SSW events from February–April, 2014 showed more TEC enhancements within the range of $\sim$70–90 TECU. Most of the days in March had a well-developed two peak EIA structure with corresponding shifts to higher latitudes observed from March 16 to 24, 2014, except March 25 to 26, when a shift in EIA crests from higher latitudes to lower latitudes (reverse fountain effect) coincided with the decline in stratospheric peak temperature and wind reversal during the major SSW warming. Furthermore, diurnal and semidiurnal variations patterns were generally observed in TEC. On March 3, semidiurnal variation patterns of maximum TEC values of 90 TECU at 12:00 UT (15:00 LT), 82 TECU at 17:00 UT (20:00 LT) and minimum TEC value of 75 TECU at 16:00 UT (19:00 LT) were recorded in the NH in the African sector. Similarly, maximum TEC values of 89 TECU at 13:00 UT (16:00 LT), 83 TECU at 19:00 UT (22:00 LT) and a minimum TEC value of 71 TECU at 17:00 UT (20:00 LT) were observed in the SH.
Figures 3bi–3biv shows day-to-day plots of EIA TEC for the period of January–April 2014 for the American sector. Weak TEC (\(\sim 45\) TECU) enhancement was also observed for days in January (Figure 3bi). The daily TEC variation of the SSW events February–April 2014 showed more TEC enhancements within the range of \(\sim 70–98\) TECU. Figure 3biii shows that on March 3, more severe TEC enhancement in the range 70–80 TECU were observed in the NH, while the SH recorded lower TEC enhancement within the range of 60–68 TECU. On March 15–18, higher TEC values were observed in the NH compared to the lower TEC values in the SH. Reduction in TEC at the higher latitudes and TEC intensification toward the equatorial region (reverse fountain effect) was associated with the major wind reversal on March 25. The remaining days investigated in March and April showed more TEC enhancements across both hemispheres. Table 5 shows the variations of EIA crests locations in the African and American sectors during 2014 pre-SSW and extremely quiet geomagnetic days, SSW peak days, and geomagnetic storm days. Four most geomagnetically
quiet days (ΣKp ≤ 3) within the 2014 pre-SSW days from January 1 to 31 were used as the representative for the pre-SSW to determine the extent of shift caused by the SSW forcing on EIA crests locations. For the geomagnetically quiet days within the pre-SSW period, in the African longitudinal sector, the average locations of the EIA crests were 8.3°N and 15.8°S, and 8.0°N and 9.3°S in the American longitudinal sector.

Figures 4ai–4aiii and 4bi–4biii show TEC variations in the African and American sectors during the SSW events (February-April, 2014). In addition to the diurnal and semidiurnal patterns, African sector showed terdiurnal TEC patterns at ∼12°N on February 14, March 3 and 8, 2014, as denoted by the magenta eclipses.
Most days in March showed semidiurnal TEC enhancement feature across both hemispheres in contrast to just a few days of semidiurnal pattern observed in February and April. In the American sector, a few days of semidiurnal variation pattern (Figure 4bi) were observed in February with TEC enhancement coinciding with February 27 geomagnetic storm activity. We also observed diurnal TEC patterns for most days in March with semidiurnal pattern visible for a few days. Reduction in TEC was clearly seen for some days between March 16 and 20, 2014, spanning across both hemispheres and coinciding with days of the major SSW warming. In addition, semidiurnal variation patterns were also observed in April (Figure 4biii), and days of April were characterized mostly by more TEC enhancements in NH than the SH. To show the terdiurnal patterns clearly, with reference to the terdiurnal pattern of March 3 as the representative of other terdiurnal patterns. Figures 5a and 5b show zoomed-plot of ΔTEC on the March 2–4, 2014 over the African and American sectors, respectively. In the African sector, a terdiurnal variation associated with peak phase of M-SSW-3 was observed on March 3 at \( \sim 12^\circ N \) in the NH, with maximum TEC values of 47 TECU, 56 TECU, and 47 TECU at 13:00 UT (16:00 LT), 17:00 UT (20:00 LT), and 20:00 UT (23:00 LT), respectively. The minimum TEC values were 36 TECU and 38 TECU at 15:00 UT (18:00 LT) and 19:00 UT (22:00 LT), respectively. These observed SSW-associated terdiurnal features validate Fuller-Rowell’s et al. (2010) simulation results. In addition, Luan et al. (2012) linked terdiurnal features in TEC to lower atmospheric-ionospheric coupling. In the American sector, on March 3, terdiurnal variation was not observed, rather we observed an earlier TEC enhancement of the EIA crest in NH at 17:00–00:00 UT (12:00–19:00 LT) and a latter response of TEC enhancement in the SH at 23:00–04:00 UT (18:00–23:00 LT). This result was consistent with the earlier report of nighttime TEC in the Brazilian sector reported by de Jesus, Batista, Jonah, et al. (2017). Figures 6a and 6b show the responses of TEC in the African and

| S/N | Events | Date             | NH (°N) | SH (°S) | NH (°N) | SH (°S) |
|-----|--------|------------------|---------|---------|---------|---------|
| 1   | Pre-SSW + extremely quiet geomagnetic activity days | January 16, 2014 | 8.2     | 14.0    | 10.2    | 11.0    |
| 2   | January 18, 2014 | 8.5     | 16.0    | 10.8    | 10.0    |
| 3   | January 19, 2014 | 8.5     | 16.8    | 5.0     | 10.0    |
| 4   | January 31, 2014 | 8.0     | 16.5    | 6.0     | 6.2     |

- **SSW**

  | S/N | Date             | NH (°N) | SH (°S) |
|-----|------------------|---------|---------|
| 1   | February 8, 2014 | 4.2     | 10.0    |
| 2   | February 21, 2014| 9.0     | 13.0    |
| 3   | March 3, 2014    | 12.0    | 13.5    |
| 4   | March 6, 2014    | 11.5    | 13.0    |
| 1   | March 16, 2014   | 14.0    | 16.2    |
| 2   | February 13, 2014| 11.8    | 17.0    |
| 3   | February 14, 2014| 11.6    | 17.2    |
| 4   | February 25, 2014| 10.3    | 13.8    |
| 1   | February 26, 2014| 10.0    | 15.0    |
| 2   | April 2, 2014    | 9.0     | 13.0    |
| 3   | April 6, 2014    | 8.0     | 8.0     |
| 4   | April 10, 2014   | 5.0     | 10.0    |
| 1   | April 16, 2014   | 6.0     | 14.0    |

- **Four most quiet geomagnetic days of February, 2014**

  | Date             | NH (°N) | SH (°S) |
|------------------|---------|---------|
| January 18, 2014 | 8.5     | 16.0    |
| March 3, 2014    | 12.0    | 13.5    |
| March 6, 2014    | 11.5    | 13.0    |
| March 16, 2014   | 14.0    | 16.2    |

- **Four most quiet geomagnetic days of April, 2014**

  | Date             | NH (°N) | SH (°S) |
|------------------|---------|---------|
| February 19, 2014| 7.2     | 13.2    |
| February 20, 2014| 7.2     | 8.6     |
| February 23, 2014| 10.0    | 10.5    |
| February 27, 2014| 10.0    | 12.2    |
| April 2, 2014    | 9.0     | 13.0    |
| April 6, 2014    | 8.0     | 8.0     |
| April 10, 2014   | 5.0     | 10.0    |
| April 16, 2014   | 6.0     | 14.0    |
| April 12, 2014   | 5.0     | 7.0     |

- **Geomagnetic storms**

  | Date             | NH (°N) | SH (°S) |
|------------------|---------|---------|
| February 19, 2014| 7.2     | 13.2    |
| February 20, 2014| 7.2     | 8.6     |
| February 23, 2014| 10.0    | 10.5    |
| February 27, 2014| 10.0    | 12.2    |
| April 12, 2014   | 5.0     | 7.0     |
American sectors to the geomagnetic storms under investigation using the mean of the geomagnetically quiet days in February as a reference. Only the February storms are considered because visual inspection in Figure 4 shows clearly that TEC responded negatively to the April 12 storm in both sectors. From Figure 6, TEC responded positively to the February 23 and 27 moderate geomagnetic storms in both sectors. TEC responded positively to the February 19 major geomagnetic storm, and negatively to February 20 storms in the African sector (Figure 6a). In the American sector, TEC responded negatively to the February 19 and 20 storms (Figure 6b).
Figures 7a and 7b show the responses of the African and American sectors to the 19–20 geomagnetic storms after filtering off SSW-induced ionospheric effects. As shown in Figure 7a, the response to TEC at the EIA crests regions were positive during the occurrence of the major GS (February 19) at 15:00–21:00 UT (18:00–24:00 LT) in the African sector. The moderate storm of February 20 also showed a negative TEC response within the EIA crests regions at 08:00–20:00 UT (11:00–23:00 LT). Figure 7b shows a negative TEC response within the EIA crests regions in the American sector at 20:00–04:00 UT (15:00–24:00 LT) to the major storm. The moderate storm also showed a positive TEC response (∼8 TECU) within the EIA crest regions at 08:00–20:00 UT (03:00–15:00 LT). Furthermore, on February 21, the African sector showed a positive EIA TEC response at 08:00–21:00 UT (11:00–24:00 LT), while American sector also revealed a positive TEC response at 06:00–24:00 UT (01:00–19:00 LT).

Figures 8ai–8aiv and 8bi–8biv show the latitudinal variations of ionospheric irregularities over the African and American sectors. Figure 8ai shows both moderate and severe irregularities observed between 18 and
31 January, 2014. We observed 8 days of severe irregularities and 17 days of moderate irregularities in February (Figure 8aii). The February 19 major storm caused suppression of irregularities, while the February 20 and 23 moderate storms caused moderate occurrences of irregularities during the postsunset hours 18:00–20:00 UT (21:00–23:00 LT). However, February 27 moderate storm caused intense irregularities during the hours of 18:00–20:00 UT (21:00–23:00 LT). The days in March (Figure 8aiii) showed the occurrences of both moderate and severe irregularities for all days of the month, while 22 days of severe irregularities and 26 days of moderate irregularities were recorded for the month of April. Figure 8bi shows more prevalence of moderate irregularities (~0.5) and severe irregularities (~0.8) for most days of January. On February 19, at postsunset hours: 24:00–04:00 UT (19:00–23:00 LT) (Figure 8b), intense irregularities were recorded, while weakening of irregularities were recorded on February 20, and suppressions of irregularities were recorded on February 23 and 27. Figure 8biii shows the weakening of ionospheric irregularities for some days with a suppression of irregularities on March 14. The daily irregularities profile for the month of April

Figure 6. Responses of TEC to February 2014 geomagnetic storms (February 18–28, 2014) using the mean of the geomagnetically quiet days in February as the reference: (a) Africa, (b) America.
revealed the occurrence of both moderate and severe irregularities for 13 days and a suppression of irregularities for the remaining days of April, 2014.

Figures 9a and 9b show the results of the Prompt Penetration Electric Field (PPEF) obtained from CIRES geomagnetism model for the period February 18–28, 2014. Figure 9a shows the PPEF variations for the African sector with a maximum negative amplitude value of $\sim -0.274 \text{ mV/m}$ on February 19, 2014. However, on the days of the moderate storms; February 22, 23, and 27, PPEF value was around 0.2 mV/m. In the American sector (Figure 9b), PPEF value was $-0.25 \text{ mV/m}$ on February 19, 2014. On February 20, 23, and 27, PPEF values were 0.32, $-0.24$, and 0.20 mV/m, respectively. On February 28, the maximum amplitude of PPEF was around 0.32 mV/m in the African sector, and $-0.4 \text{ mV/m}$ in the American sector. Figures 9c and 9d show the PPEF values for the moderate storm of April 12 and the values were generally low in both
sectors (∼0.1 mV/m) but increased to almost 0.2 mV/m on the day of the recovery phase of the moderate storm (April 13). Manoj et al. (2008, 2013) reported that interplanetary electric field is positively correlated with the zonal equatorial electric field on the local dayside and negatively correlated on the local nightside. Interplanetary electric field on the other hand is known to be related to PPEF (Tsurutani et al., 2008). Previously, Astafyeva et al. (2016) reported that positive values of interplanetary electric field imply eastward orientation of the zonal electric field during daytime and westward orientation during nighttime (Arowolo et al., 2021).

Figure 8. Day-to-day variations of ionospheric irregularities from January 1 to April 30, 2014 (a) African sector: (a, i–iv) representing January, February, March, and April, respectively, (b) American sector: (b, i–iv) representing January, February, March, and April, respectively.
Figures 10ai–10aiv and 10bi–biv show variations of EEJ for the period from March 3 to 19 in the African and American sectors. In the African sector, EEJ value was $\sim 139.5$ nT, decreasing to 98.1 nT at noon on March 4. Also, EEJ values of; 59.8, 59.3, and 56.4 nT at noon prior to, during, and after the minor SSW peak were recorded on March 5–7, respectively. Days; March 7–15, prior to the peak temperature of the major SSW event showed lower values of EEJ at noon-time. However, there was lack of available data to determine the response of the EEJ current in the African sector on March 17–18. In the American sector, our results unveiled an EEJ intensity of 89.7 nT at noon on March 3 with a subsequent increase in EEJ intensity.
Figure 10. Daily variations in equatorial electrojet current (EEJ) from March 3 to 19, 2014: (a) African sector and (b) American sector.
the next day to 108.2 nT at noon. A similar pattern of increase in EEJ intensity from 102.2 to 102.6 nT was recorded on March 6–7. However, we observed lower EEJ value on March 15 in comparison to EEJ value on March 16, coinciding with the day of peak stratospheric temperature of the major SSW event.

Figures 11a and 11b show the eastward height-integrated current profile of the EEJ current for the African and American sectors obtained from the SWARM satellite with equatorial orbital crossing closest to those of the ground-based magnetometer station. As shown in Figure 11a, in the African sector, the day-to-day EEJ current from March 3 to 17 showed a trend pattern consistent with those of the EEJ values obtained by ground-based magnetometer. The EEJ current on March 3 was 5.7 mA/m, decreased to 4.5 mA/m on March 4. Also, from March 6 to 7, EEJ current profile showed a similar significant decrease in magnitude from 16.9 to 8.5 mA/m with the EEJ current profile from March 16 to 17 showing slight decrease from 14.1 to 13.6 mA/m. However, an increase in magnitude from 12.0 to 17.5 mA/m was observed on March 10–11. Figure 11b shows the day-to-day EEJ eastward current for the American sector. Our results indicate an increase in EEJ current from 9.9 to 17.7 mA/m on March 3–4, coinciding with the minor SSW event. A similar increment from 21.4 to 42.8 mA/m was recorded on March 6–7, coinciding with the minor SSW event. However, on March 16–17, a significant decrease in EEJ current from 48.4 to 18.3 mA/m was observed for the American sector.

Figures 12a and 12b show the variations of vertical plasma drift (VD) derived from Equation 4 for the African and American sectors for the period of March 3–19. In the African sector, VD data showed similar trend as the EEJ data during the days of the minor SSW events. On March 3, peak magnitude of the VD was 41.2 m/s at midday and reduced to 35.1 m/s on March 4. Similar trend in VD was also observed on March 6–7, with peak VD value of 28.35 m/s and 27.93 m/s, respectively. Generally, between the periods of March 7–14, the maximum value VD was below 29.9 m/s. The result also showed a lower VD value of 29.6 m/s on March 15 in comparison to higher value of 33.4 m/s on March 16 when the SSW temperature surged to its peak. In the American sector, during the days of the minor warming, a contrary trend to that of the African sector was observed. On March 3, the peak value of the estimated VD was 33.2 m/s and increased to 36.8 m/s on March 4. A similar trend of VD increment from 35.8 to 36.4 m/s was observed on March 6–7. A lower VD value of 22.6 m/s on March 15 in comparison to higher VD value of 28.4 m/s on March 16 (day of the major SSW) was observed.

### 4. Discussion

As shown in Figure 3, in both longitudinal sectors, well-developed two peak EIA structures were consistently observed. The daily EIA profile showed variability in TEC and crests locations in both sectors (Figure 4). Overall, in terms of TEC intensity in both sectors, TEC generally responded positively to the SSW peak days, except on February 8 when a negative response was observed. However, in terms of the EIA crests locations, in both sectors, EIA crest locations generally shifted from lower latitude locations on pre-SSW to higher latitude locations on minor SSW peak days, except on February 8 (Figure 3 and Table 5). Generally, in terms of hemispherical distributions of TEC, a clear asymmetry in TEC in both longitudinal sectors was observed. Higher plasma ionization was consistently observed in the NH than in the SH in both sectors. Fagundes et al., (2015) reported the same hemispheric trend in TEC distribution over the Brazilian sector during the 2009 SSW event. Similarly, the hemispheric asymmetry in TEC distribution was also reported in the Asian sector (Liu et al., 2011). Laskar and Pallamraju (2014) reported that the hemispheric asymmetry in ionospheric data may be due to the interaction of SSW-induced meridional wind and trans-equatorial neutral wind.

On March 25, 2014, on the day of the reversal of stratospheric zonal mean wind direction, both longitudinal sectors showed equator-ward movement of plasma (reverse fountain effect). As a typical day of an equinoctial month, one would naturally expect an enhancement in EIA TEC (equinoctial effect), but on the contrary, on March 25, 2014 (a day of reversal of stratospheric zonal mean wind direction), showing clearly SSW effect on the EIA as contrary to the expected equinoctial effect of TEC enhancement in equinox. The SSW effect that caused the equator-ward shift in EIA crest from higher to lower latitudes may be attributed to the significant increase in both planetary and gravity waves arising from decelerating stratospheric zonal mean wind (Bolaji et al., 2016). Previous studies by Bolaji et al. (2016) and de Jesus, Batista, Jonah, et al. (2017)
Figure 11. Day-to-day variations in eastward (EW) current density profile from March 3 to 17, 2014: (a) African sector and (b) American sector.
Figure 12. Diurnal variations of estimated equatorial vertical drift from March 3 to 19, 2014: (a) African sector and (b) American sector.
have shown that increase in upward propagating waves arising from the thermosphere plays a major role in the modification of the ionospheric wind systems, creating tidal components which modulate the dynamo electric field. Pancheva and Mukhtarov (2011) explained that equator-ward plasma movement arising from the modified current system during SSW events is driven by equator-ward winds of lower thermospheric origin due to thermospheric heating. Furthermore, Fagundes et al. (2015) attributed the physical mechanism that is responsible for ionospheric variations to the changes in neutral gas composition resulting from changes in thermospheric composition during SSW event. Generally, EIA crests in both hemispheres shifted to higher latitudes on days of SSW peaks than on the days of geomagnetic storms, except for the NH of the American sector (Table 5).

In this study, except for the February 19 and 20 geomagnetic storms that overlapped with the SSW peak days, other geomagnetic storms during the days of investigation did not directly overlap with the days of the peak temperatures (Figure 2). As listed in Table 5, we used four most geomagnetically quiet days of February 2014 (13(ΣKp = 1), 14(ΣKp = 5), 25(ΣKp = 5), and 26(ΣKp = 4) February) and of April 2014 (2(ΣKp = 6), 6(ΣKp = 4), 10(ΣKp = 3), and 16(ΣKp = 6) April) as the representatives of the quiet days of the months of February and April, 2014, respectively, so as to compare the quiet time EIA crests locations with the storm time EIA crests locations. Comparatively, these days were also within the region of low stratospheric temperature (Figure 2). Furthermore, we used the quiet days of February to assess the level of storm-induced ionospheric variability by the four geomagnetic storms of February and the quiet days of April to assess the level of storm-induced ionospheric variability by the April geomagnetic storm.

As listed in Table 3, the local time of the onset of all the five geomagnetic storms occurred during daytime in the African sector and during nighttime in the American sector, with the exception of the major geomagnetic storms of February 19 whose local onset time was daytime. The February 20 moderate storm is the second peak of the February 19 major storm. In the African sector, the local time of the main phase of the major and moderate geomagnetic storms of February 19, 20, and April 12 was during daytime, and during nighttime for moderate geomagnetic storms February 23 and 27. However, in the American sector, the local time of the main phase of the major and moderate geomagnetic storms of February 19, 27, and April 12 were during nighttime, and during daytime for moderate geomagnetic storms of February 20 and 23. Recently, Arowolo et al. (2021) concluded that the daytime or nighttime orientation of PPEF plays major role in ionospheric responses to geomagnetic storms. This is also very evident in our results, particularly in the American sector. From our result, in the African sector, with the reference to the quiet days of the month of occurrence of each geomagnetic storm, TEC responded positively to the February 19, 23, and 27 geomagnetic storms, and negatively to February 20 and April 12 geomagnetic storms. In the American sector, the responses of TEC to February 19, 20 and April 12 geomagnetic storms were negative and positive to the 23 and 27 geomagnetic storms. Negative ionospheric responses are caused by a decrease in atomic oxygen density; a decrease in oxygen ion concentration and an increase in the molecular nitrogen density, leading to an increase in the loss rate to cause a decrease in the ionization density in the F-region (Mosna et al., 2021). On the other hand, positive ionospheric responses are caused by an increase in atomic oxygen density; an increase in oxygen ion concentration and a decrease in the molecular nitrogen density, leading to an increase in the production rate to cause an increase in the ionization density in the F-region (Mikhaillov et al., 1994; Mosna et al., 2021).

Akala et al. (2020) and Arowolo et al. (2021) had earlier explained that during storm time, daytime eastward PPEF supports forward fountain to cause EIA TEC enhancement and poleward movement of the EIA crests from its quiet time location. On the other hand, storm time nighttime westward PPEF supports reversed fountain to cause EIA TEC reduction and equator-ward movement of the EIA crests from its nominal quiet time and daytime location. However, we observed that the PPEF values during the periods of the geomagnetic storms were quite low (<0.3 mV/m). Consequently, the associated storm time fountain effects were weak. On the overall, although generally low, PPEF values were comparatively higher in the American sector than in the African sector, and could have been responsible for more enhancements in TEC in the American sector than the African sector during the period of occurrences of the five geomagnetic storms.

Variations of ionospheric irregularities over the African and American sectors during the period of investigation are shown in Figure 8. During postsunset hours, ionospheric irregularities generation is supported by upward E × B vertical drift (prereverse enhancement) via Rayleigh Taylor instability mechanism (de Jesus, Batista, de Abreu, et al., 2017; de Jesus, Batista, Fagundes, et al., 2017; de Jesus, Batista, Jonah,
et al., 2017). Numerous studies have shown that ionospheric irregularities exhibit large variations both
daily, and seasonally, with longitudinal and solar activity dependence (Akala et al., 2013; Akala, Awoyele,
& Doherty, 2016; Akala, Idolor, et al., 2016). Our results for the African sector (Figure 8aii) coinciding with
the days of major geomagnetic storm depicted a suppression of irregularities on February 19 and moderate
occurrence of irregularities on February 20. The moderate geomagnetic storm of February 23 caused
moderate irregularities, while the storm of February 27 caused more irregularities across both hemispheres.
The days of the major and moderate geomagnetic storms of February 19 and 20 in the American sector
(Figure 8bii) shows an enhanced occurrence of ionospheric irregularities on February 19–20, and a suppres-
sion of irregularities during the moderate geomagnetic storm of February 23 and 27. However, aside from
the geomagnetic storm days in the American sector (Figure 8biii), the effects of the major SSW event were
clearly observed with suppression of irregularities in March as against the expected equinoctial effects of
enhanced irregularities in March. The observed weakening of ionospheric irregularities is consistent with
past studies of ionospheric irregularities in the Brazilian sector (de Jesus, Batista, Jonah, et al., 2017; De
Paula et al., 2015). The weakening of irregularities may be ascribed to the decrease in zonal neutral winds
arising from the interaction of the meridional and transequatorial winds (De Paula et al., 2015; Oyedokun
et al., 2020). The interaction of these wind systems provides conducive platform for regulating the growth
of ionospheric irregularities (Laskar & Pallamraju, 2014). In addition, during the period of SSW events, similar
report by Goncharenko, Chau, et al. (2010) revealed that quasi stationary planetary waves played crucial
role in the preconditioning of ionospheric irregularities.

Comparatively, from this study, TEC were generally predominant in the American sector than the African
sector. From our results, both the SWARM-derived and ground-based EEJ data showed higher intensity in
the American sector than the African sector during the cascade of minor and major SSW events (Figures 10
and 11). The computed EEJ is related to vertical electric fields (Anderson et al., 2002, 2004) which are in
turn responsible for the strength of the fountain effect (Chakraborty & Hajra, 2008). Our estimated VD drift
(Figure 12) also showed higher variations over the American sector than over the African sector during the
cascade of minor and major SSW events. These results of longitudinal differences in vertical drift electric
field are consistent with the inferred vertical plasma drift during 2013 SSW event by Maute et al. (2015)
which was attributed to the difference in neutral wind flow patterns and geomagnetic field strength. The
equatorial vertical drift generally influences changes in the electron density and the EIA (de Jesus, Batista,
Fagundes, et al., 2017). Previously, Goncharenko, Chau, et al. (2010) and Goncharenko, Coster, et al. (2010)
had reported higher TEC variability during days of surge in the stratospheric temperature and the subse-
cquent movement of the EIA crest regions to higher latitudes in the American sector. Generally, the longitu-
dinal differences in the equatorial/low-latitude ionospheric electrodynamics in the African and American
sectors are attributable to geometric effects arising from the differences between the geomagnetic field lines
and geographic latitude lines in both sectors (England, 2012; Goncharenko et al., 2020). There are clear
offsets between geographic latitudes and geomagnetic latitudes in both sectors. For instance, the geomag-
netic equator line is in the geographic NH in the African sector and in the geographic SH in the American
sector. These offsets are more in the American sector than in the African sector. Furthermore, there are also
geometric configurations related to the offsets, and they are more conspicuous in the American sector than
in the African sector. Unlike the African equatorial/low-latitude region, at the American equatorial/low-lat-
titude region, there are clear geometric effects arising from the protuberances of the geomagnetic field lines.

5. Conclusions
We investigated the responses of the equatorial/low-latitude ionosphere over the African and American
sectors to: (a) minor and major winter arctic SSW events (January–April, 2014) and (b) geomagnetic storms
that occurred during the same period of the SSW events. The conclusions from this study are:

1. In addition to the roles played by geomagnetic storms and other solar events in space weather, lower
atmospheric couplings also play significant roles, particularly in the ionospheric part of space weather
(ionospheric weather) (Mosna et al., 2021). With reference to the pre-SSW quiet days, TEC intensity re-
sponded positively to the SSW peak days in both longitudinal sectors, except on February 8 in the African
sector, when a negative TEC response was recorded. In terms of the EIA crests locations, in both sectors,
EIA crests locations shifted from lower latitudes on pre-SSW days to higher latitudes on minor SSW
peak days in the northern hemisphere, except on February 8 in the African sector. In the southern hemisphere, the EIA crests locations shifted from higher latitudes on pre-SSW quiet days to lower latitudes on SSW peak days in the African sector, while in the American sector, EIA crests locations shifted from lower latitudes on pre-SSW quiet days to higher latitudes on SSW peak days in the southern hemisphere. In addition, the reversal of stratospheric zonal mean direction supported reversed fountain effect

2. From our results, aside from the days of the geomagnetic storms of February 19 and 20, 2014, the days of other geomagnetic storms that coexisted with the SSW events did not directly overlap with the days of the peak temperatures of the SSW events. For the days when SSW events overlapped with geomagnetic storms (M-SSW-2), after isolating the contributions by SSW forcing on ionospheric effects in the African sector, EIA TEC responded positively to the major geomagnetic storm of February 19, and negatively to the moderate storm of February 20. In the American sector, EIA TEC responded negatively to the major geomagnetic storm and positively to the moderate storm of February 20. For the periods of M-SSW-1, M-SSW-3, and major SSW, over both sectors, ionospheric effects arising from SSW-induced forcing and geomagnetic storm-induced forcing were clearly distinct

3. A clear asymmetry in hemispherical distributions of TEC was observed in both longitudinal sectors. Higher plasma ionization and higher latitudinal locations of the EIA crests were generally recorded in the NH than SH in both longitudinal sectors, although, there were cases where the EIA crests were located at higher latitudes in the SH than the NH in the African sector. In both longitudinal sectors, we observed that EIA crests were located at higher latitudes on the days of SSW peaks than on the days of the geomagnetic storms, implying that ionospheric effects were more influenced by SSW forcing than geomagnetic storm forcing during the period of study. From our results, the geomagnetic storms investigated were generally characterized with low PPEF values with attendant weak storm time effects on the ionosphere. Daytime or nighttime orientation of PPEF plays major role in ionospheric responses to geomagnetic storms

4. Over the African sector, the major geomagnetic storm completely suppressed ionospheric irregularities, while the moderate storm of February 20 and 23 caused moderate irregularities. The moderate storm of February 27 caused enhancement in irregularities, while the April 12 moderate storm caused suppression of irregularities. Over the American sector, the major storms of February 19 caused enhancements in irregularities and a weakening of irregularities during the moderate storm of February 20. The moderate storms of February 23, 27, and April 12 caused suppression of ionospheric irregularities. The major SSW forcing weakens irregularities on March 15 and 21–23

5. TEC generally recorded higher intensity in the American sector than in the African sector. From the PPEF, EEJ, and inferred vertical drift data, ionospheric electrodynamics over the American sector during the period of investigation was higher than that of the African sector (Figures 10–12). As presented by Goncharenko et al. (2020), the longitudinal differences in ionospheric electrodynamics can be attributed to the geometric effects arising from the differences in geomagnetic field configurations in both sectors

6. The results from this study will expand the understanding of the space/atmospheric science community on the responses of African and American equatorial/low-latitude ionosphere to a combined effect of geomagnetic storm forcing and SSW forcing during period of high solar activity, with a view to isolating the role(s) of each individual forcing on ionospheric changes. Furthermore, these results will also support the development of future models that could predict the occurrences of SSW-induced and geomagnetic storm-induced ionospheric disturbances, with a view to mitigating the adverse impacts of such ionospheric disturbances on technological systems

Data Availability Statement

The stratospheric data used in this study were downloaded from the website of the National Oceanic and Atmospheric Administration (NOAA) (http://www.esrl.noaa.gov/psd/). The Kp and Dst index was downloaded from the World Data Center for Geomagnetism Kyoto (http://wdc.kugi.kyoto-u.ac.jp/kp/index.html). The F10.7 solar flux index was downloaded from the website of the National Aeronautics and Space Administration (NASA) space physics data facility (http://omniweb.gsfc.nasa.gov/form/dx1.html) while the 81-day adjusted F10.7 cm solar flux was obtained from celestrak public access website (https://celestrak.com/SpaceData/). The GPS data used in this analysis were obtained from the following listed organizations; International Global Navigation Satellite Systems Service (IGS) (www.igs.org); University NAVSTAR
Consortium (UNAVCO) (www.unavco.org); SONEL (www.sonel.org) and AFREF (www.afrefdata.org). Prompt penetration electric field (PPEF) model was obtained from the Cooperative Institute for Research in Environmental Sciences (CIRES) of the University of Colorado at Boulder (http://geomag.colorado.edu/real-time-model-of-the-ionospheric-electric-fields.html). The magnetic field data were downloaded from the International Real-time Magnetic Observatory Network, INTERMAGNET (www.intermagnet.org), Magnetic Data Acquisition System (MAGDAS) (http://magdas2.serc.kyushu-u.ac.jp/) on request, and the Low Ionospheric Sensor Network (LISN) magnetometers (http://lisn.igp.gob.pe/data/) operated by the Instituto Geofisico del Peru (IGP). The swarm satellite mission data are available at https://earth.esa.int/swarm, operated by the European Space Agency.

Acknowledgments
The authors thank Gopi Seemala for providing the GPS TEC processing software. The authors also thank the editor and the two anonymous reviewers for their useful comments and suggestions, which have significantly improved this study.

References
Aiken, P., Maus, S., Chulliat, A., Vigneron, P., Sirol, O., & Hulot, G. (2015). Swarm equatorial electric field chain: First results. Geophysical Research Letters, 42, 673–680. https://doi.org/10.1002/2014GL062658
Aiken, P., Maus, S., Vigneron, P., Sirol, O., & Hulot, G. (2013). Swarm SCARF equatorial electric field inversion chain. Earth Planets and Space, 65, 1309–1317.
Akala, A. O., & Adeyewa, E. O. (2020). Quiet-time and storm-time variations of the African equatorial and low latitude ionosphere during 2009–2015. Advances in Space Research, 66(6), 1441–1459. https://doi.org/10.1016/j.asr.2020.05.038
Akala, A. O., Awoyele, A., & Doherty, P. H. (2016). Statistics of GNSS amplitude scintillation occurrences over Dakar, Senegal, at varying elevation angles during the maximum phase of solar cycle 24. Space Weather, 14, 233–246. https://doi.org/10.1002/2015SW001261
Akala, A. O., Idolor, R., D’ujanga, F. M., & Doherty, P. H. (2016). GPS amplitude scintillation over Kampala, Uganda during 2010–2011. Acta Geophysica, 64, 1903–1915. https://doi.org/10.1515/actgeo-2016-0052
Akala, A. O., Oyeyemi, E. O., Amaechi, F. O., Radiciella, S. M., Nava, B., & Amory-Muzadieur, C. (2020). Longitudinal responses of the equatorial/low-latitude ionosphere over the oceanic regions to geomagnetic storms of May and September 2017. Journal of Geophysical Research: Space Physics, 125, e2020JA027963. https://doi.org/10.1029/2020JA027963
Akala, A. O., Seemala, G. K., Doherty, P. H., Valladares, C., Espinoza, J., & Oluoy, S. (2013). Comparison of equatorial GPS-TEC observations over an African station and American station during the minimum and ascending phases of solar cycle 24. Annals of Geophysics, 31, 2085–2096. https://doi.org/10.5194/angeo-31-2085-2013
Anderson, D., Anghel, A., Chau, J. L., & Veliz, O. (2004). Daytime vertical E × B drift velocities inferred from ground-based magnetometer observations at low latitudes. Space Weather, 2, S1101. https://doi.org/10.1029/2004SW000095
Anderson, D., Anghel, A., Raymont, K., Ishibashi, M., & Kudeki, E. (2002). Estimating daytime vertical E × B drift velocities in the equatorial F-region using ground-based magnetometer observations. Geophysical Research Letters, 29(12), 1596. https://doi.org/10.1029/2001GL014562
Anderson, D., & Araujo-Pradere, E. A. (2010). Sudden stratospheric warming event signatures in daytime E × B drift velocities in the Peruvian and Philippine longitude sectors for January 2003 and 2004. Journal of Geophysical Research, 115, A09005. https://doi.org/10.1029/2010JA015327
Andrews, D., Holton, J. R., & Leovy, C. B. (1987). Middle atmosphere dynamics (pp. 259–294). Elsevier.
Arowolo, O. A., Akala, A. O., & Oyeyemi, E. O. (2021). Interplanetary origins of some intense geomagnetic storms during solar cycle 24 and responses of Africa equatorial/low-latitude ionosphere to them. Journal of Geophysical Research: Space Physics, 126, e2020JA027929. https://doi.org/10.1029/2020JA027929
Astafyeva, E., Zakharikova, I., & Aiken, P. (2016). Prompt penetration electric fields and the extreme topside ionospheric response to the June 22–23, 2015 geomagnetic storm as seen by the Swarm constellation. Earth Planets and Space, 68, 152. https://doi.org/10.1186/s40623-016-0526-x
Bessarab, F. S., Korenkov, Y. N., Klimenko, M. V., Klimenko, V. V., Karpov, I. V., Ratovsky, K. G., & Chernigovskaya, M. A. (2012). Modeling the effect of sudden stratospheric warming within the thermosphere-ionosphere system. Journal of Atmospheric and Solar-Terrestrial Physics, 90–91, 77–85. https://doi.org/10.1016/j.jastp.2012.09.005
Bolaji, O. S., Adebiyi, S. J., Fashae, J. B., Ugbannon, S. O., Adenle, H. A., & Owolabi, O. P. (2020). Pattern of latitudinal distribution of ionospheric irregularities in the African region and the effect of March, 2015 St. Patrick’s Day storm. Journal of Geophysical Research: Space Physics, 125, e2019JA027641. https://doi.org/10.1029/2019JA027641
Bolaji, O. S., Owolabi, O. P., Fajuyi, E., Jimoh, E., Kotoye, A., & Odeyemi, O., et al. (2016). Solar quiet current response in the African sector to a 2009 sudden stratospheric warming event. Journal of Geophysical Research: Space Physics, 121, 8055–8065. https://doi.org/10.1002/2015JA022857
Bolaji, O. S., Oyeyemi, E. O., Jimoh, O. E., Fujimoto, A., Doherty, P. H., Owolabi, O. P., et al. (2019). Morphology of the equatorial ionization anomaly in Africa and Middle East due to a Sudden stratospheric warming event. Journal of Atmospheric and Solar-Terrestrial Physics, 184, 37–56. https://doi.org/10.1016/j.jastp.2019.01.006
Chakraborty, S. K., & Hajra, R. (2008). Solar control of ambient ionization of the ionosphere near the crest of the equatorial anomaly in the Indian zone. Annales de Geophysique, 26(1), 47–57. https://doi.org/10.5194/angeo-26-47-2008
Chau, J. L., Fejer, B. G., & Goncharenko, L. P. (2009). Quiet variability of equatorial E × B drifts during a sudden stratospheric warming event. Geophysical Research Letters, 36, L05101. https://doi.org/10.1029/2008GL036785
Chau, J. L., Goncharenko, L. P., Fejer, B. G., & Liu, H.-L. (2011). Equatorial and low latitude ionospheric effects during sudden stratospheric warming events: Ionospheric effects during SSW events. Science Review, 168, 385–417. https://doi.org/10.1007/s11214-011-9797-5
Chau, J. L., Goncharenko, L. P., Fejer, B. G., & Liu, H.-L. (2012). Equatorial and low latitude ionospheric effects during sudden stratospheric warming events. Science Review, 168, 385–417. https://doi.org/10.1007/s11214-011-9797-5
morales, P., de Jesus, R., Batista, I. S., de Abreu, A. J., Fagundes, P. R., Venkatesh, K., & Denardini, C. M. (2017). Observed effects in the equatorial and low-latitude ionosphere in the South American and African sectors during the 2012 minor sudden stratospheric warming. Journal of Atmospheric and Solar-Terrestrial Physics, 157–158, 78–89. https://doi.org/10.1016/j.jastp.2017.04.003
de Jesus, R., Batista, I. S., Fagundes, P. R., Venkadesh, K. V., & de Abreu, A. J. (2017). Ionospheric response to the 2006 sudden stratospheric warming event over the equatorial and low latitudes in the Brazilian sector using GPS observations. *Journal of Atmospheric and Solar-Terrestrial Physics, 154*, 92–103. https://doi.org/10.1016/j.jastp.2016.12.005

de Jesus, R., Batista, I. S., Jonah, O. F., de Abreu, A. J., Fagundes, P. R., Venkatesh, K., & Denardini, C. M. (2017). An investigation of the ionospheric disturbances due to the 2014 sudden stratospheric warming events over Brazilian sectors. *Journal of Geophysical Research: Space Physics, 122*, 11696–11715. https://doi.org/10.1002/2017JA024560

De Paula, E. R., Jonah, O. F., Moraes, A. O., Kherani, E. A., Fejer, B. G., Abdu, M. A., et al. (2015). Low-latitude scintillation weakening during sudden stratospheric warming events. *Journal of Geophysical Research, 120*, 2212–2221. https://doi.org/10.1002/2014JA020731

Eastwood, J. P., Biffis, E., Happog, M. A., Green, L., Bisi, M. M., Bentley, R. D., et al. (2017). The economic impact of space weather: Where do we stand? *Risk Analysis, 37*(2), 206–218. https://doi.org/10.1111/risa.12765

England, S. L. (2012). A review of the effects of non-migrating atmospheric tides on the Earth’s low-latitude ionosphere. *Space Science Reviews, 168*(1–4), 211–236.

Fagundes, P. R., Gonçalhencoro, L. P., de Abreu, A. J., Venkatesh, K., Pezzopane, M., de Jesus, R., et al. (2015). Ionospheric response to the 2009 sudden stratospheric warming over the equatorial, low, and middle latitudes in the South American sector. *Journal of Geophysical Research: Space Physics, 120*, 7889–7902. https://doi.org/10.1002/2014JA020649

Fejer, B. G., Olson, M. E., Greer, K. R., Zhang, S.-R., & Coster, A. J. (2020). Longitudinally dependent low-latitude ionospheric disturbances linked to the Antarctic sudden stratospheric warming of September 2019. *Journal of Geophysical Research: Space Physics, 125*, e2020JA028199. https://doi.org/10.1029/2020JA028199

Gonzalez, W. D., Joselyn, J. A., Kamide, Y., Koeble, H. W., Ros-toker, G., Tsurutani, B. T., & Vasylunas, V. M. (1994). What is a geomagnetic storm? *Journal of Geophysical Research, 99*, 5771–5792. https://doi.org/10.1029/93JA02867

Jonah, O. F., de Paula, E. R., Kherani, E. A., Dutra, S. L. G., & Paes, R. R. (2014). Atmospheric and ionospheric response to sudden stratospheric warming of January 2013. *Journal of Geophysical Research: Space Physics, 119*, 4973–4980. https://doi.org/10.1002/2013JA019491

Kassamba, A. A., Doumbia, V., Obrou, O. K., Grodji, A., Tuo, Z., Kouassi, N., & Yizengaw, E. (2020). Estimating the daytime vertical E × B drift velocities in the F-region of the equatorial ionosphere using IEEY and AMBER magnetic data in West Africa. *Advances in Space Research*. https://doi.org/10.1016/j.asr.2020.03.008

Lanzeroti, L. J. (2001). Space weather effects on communications. In I. A. Daglis (Ed.), *Space storms and space weather hazards*. NATO Science Series (Series II: Mathematics, physics and chemistry) (Vol. 38, pp. 313–334). Springer. https://doi.org/10.1007/978-94-010-0983-6_12

Laskar, F. I., & Pallamraju, D. (2014). Does sudden stratospheric warming induce meridional circulation in the mesosphere thermosphere system? *Journal of Geophysical Research: Space Physics, 119*, 10133–10143. https://doi.org/10.1002/2014JA020086

Liu, H. X., Yamamoto, M., Ram, S. T., Tsugawa, T., Otsuka, Y., Stolle, C., et al. (2011). Equatorial electrodynamic effects during sudden stratospheric warmings. *Journal of Geophysical Research, 116*, A08308. https://doi.org/10.1029/2011JA016607

Loewe, C. A., & Prols, G. W. (1997). Classification and mean behaviour of magnetic storms. *Journal of Geophysical Research, 102*, 14209–14213. https://doi.org/10.1029/96JA04020

Luan, X., Dou, X., Lei, J., & Jiang, G. (2012). Terrestrial migrating-tide signature in ionospheric total electron content. *Journal of Geophysical Research, 117*, A11302. https://doi.org/10.1029/2012JA018199

Manoj, C., & Mauk, S. (2012). A real time forecast service for the ionospheric equatorial zonal electric field. *Space Weather, 10*, S09002. https://doi.org/10.1029/2012SW000825

Manoj, C., Mauk, S., Lühr, H., & Alken, P. (2008). Penetration characteristics of the interplanetary electric field to the daytime equatorial ionosphere. *Journal of Geophysical Research, 113*, A12310. https://doi.org/10.1029/2008JA013381

Manoj, C., Mauk, S., Lühr, H., & Alken, P. (2013). Long-period prompt-penetration electric field derived from CHAMP satellite Magnetic Measurements. *Journal of Geophysical Research, 118*, 5919–5930. https://doi.org/10.1002/jgra.50511

Matsumo, T. (1971). A dynamical model of the stratospheric sudden warming. *Journal of Atmospheric Science, 28*, 1479–1494. https://doi.org/10.1175/1520-0469(1971)028<1479:ADMOTS>2.0.CO;2

Mauk, A., Hagan, M. E., Yudin, V., Liu, H.-L., & Yizengaw, E. (2015). Causes of the longitudinal differences in the equatorial vertical E×B drift during the 2013 SWW period as simulated by the TIME-GCM. *Journal of Geophysical Research: Space Physics, 120*, 5117–5136. https://doi.org/10.1002/2015JA021126

Mikhailov, A. V., Forster, M., & Skoblin, M. G. (1994). Neutral gas composition changes and E × B vertical plasma drift contribution to the daytime equatorial F2-region storm effects. *Annals of Geophysics, 12*, 226–231. https://doi.org/10.1007/s00585-994-0026-x

Molina, Z., Edemskiy, I., Lastovicka, J., Kozubek, M., Knouck Knisova, P., Koubal, D., & Siddiqui, T. A. (2021). Observation of the ionosphere in middle latitudes during 2009, 2018 and 2019 sudden stratospheric warming events. *Atmosphere, 12*, 602. https://doi.org/10.3390/atmos12050602

National Research Council NRC Report. (2008). *Severe space weather events—Understanding Societal and economic impacts*. The National Academies Press.

Oladipo, O. A., Adeniyi, J. O., Olawepo, A. O., & Doherty, P. H. (2014). Large-scale ionospheric irregularities occurrence at Ilorin, Nigeria. *Space Weather, 12*, 300–305. https://doi.org/10.1002/2013SW000991

Oladipo, O. A., & Schuler, T. (2013). Equatorial ionospheric irregularities using GPS TEC derived index. *Journal of Atmospheric and Solar-Terrestrial Physics, 92*, 78–82. https://doi.org/10.1016/j.jastp.2012.09.019
O’Neill, A. (2003). Stratospheric sudden warmings. In J. R. Holton, J. A. Pyle, & J. A. Curry (Eds.), Encyclopedia of atmospheric sciences (pp. 1342–1353). Elsevier.

Oughton, E. J., Skelton, A., Horne, R. B., Thomson, A. W. P., & Gaunt, C. T. (2017). Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. Space Weather, 15, 65–83. https://doi.org/10.1002/2016SW001491

Oyedokun, O. J., Akala, A. O., & Oyeyemi, E. O. (2020). Characterization of the African equatorial ionization anomaly during the maximum phase of solar 24. Journal of Geophysical Research: Space Physics, 125, e2019JA027066. https://doi.org/10.1029/2019JA027066

Paes, R. R., Batista, I. S., Candido, C. M. N., Jonah, O. F., & Santos, P. C. P. (2014). Equatorial ionization anomaly variability over the Brazilian region during boreal sudden stratospheric warming events. Journal of Geophysical Research, 119, 7649–7664. https://doi.org/10.1002/2014JA019968

Pancheva, D., & Mukhtarov, P. (2011). Stratospheric warmings: The atmosphere-ionosphere coupling paradigm. Journal of Atmospheric and Solar-Terrestrial Physics, 73, 1697–1702. https://doi.org/10.1016/j.jastp.2011.03.006

Pedatella, N. M., Richmond, A. D., Maute, A., & Liu, H. L. (2016). Impact of semi-diurnal tidal variability during SSWs on the mean state of the ionosphere and thermosphere. Journal of Geophysical Research: Space Physics, 121, 8077–8088. https://doi.org/10.1002/2016JA022910

Pi, X., Mannucci, A. J., Lindqwister, U. J., & Ho, C. M. (1997). Monitoring of global ionospheric irregularities using the world-wide GPS network. Geophysical Research Letters, 24, 2283–2286. https://doi.org/10.1029/97GL02273

Poppe, B., & Jorden, K. (2006). Sentinels of the Sun: Forecasting space weather (p. 178). Johnson Books.

Rabiu, A. B., Folarin, O. O., Uozumi, T., & Yoshikawa, A. (2017). Simultaneity and asymmetry in the occurrence of counter equatorial electrojet along African longitudes. In T. Fuller-Rowell, E. Yizengaw, P. H. Doherty, & S. Basu (Eds.), Ionospheric space weather: Longitude and hemispheric dependences and lower atmosphere forcing. Geophysical Monograph 220 (1st ed., pp. 21–31). American Geophysical Union, John Wiley & Sons, Inc.

Seemala, G. K., & Delay, S. B. (2010). GNSS TEC data processing. In 2nd Workshop on Satellite Navigation Science and Technology for Africa, Trieste, 6–24 April 2010. http://indico.ictp.it/event/a09138/session/63/contribution/40/material/0/0.pdf

Siddiqui, T. A., Lühr, H., Stolle, C., & Park, J. (2015). Relation between stratospheric sudden warming and the lunar effect on the equatorial electrojet based on Huancayo recordings. Annales de Geophysique, 33(2), 235–243. https://doi.org/10.5194/angeo-33-235-2015

Sridharan, S., Sathishkumar, S., & Gurubaran, S. (2009). Variabilities of mesospheric tides and equatorial electrojet strength during major stratospheric warming events. Annales de Geophysique, 27(11), 4125–4130. https://doi.org/10.5194/angeo-27-4125-2009

Tsurutani, B. T., Verkhoglyadova, O. P., Mannucci, A. J., Salto, A., Araki, T., Yumoto, K., et al. (2008). Prompt penetration electric fields (PPEFs) and their ionospheric effects during the great magnetic storm of 30–31 October 2003. Journal of Geophysical Research, 113, A05311. https://doi.org/10.1029/2007JA012879

Vieira, F., Fagundes, P. R., Venkatesh, K., Goncharenko, L. P., & Pillat, V. G. (2017). Total electron content disturbances during minor sudden stratospheric warming, over the Brazilian region: A case study during January 2012. Journal of Geophysical Research: Space Physics, 122, 2119–2135. https://doi.org/10.1002/2016JA023650

Vineeth, C., Pant, T. K., & Sridharan, R. (2009). Equatorial counter electrojets and polar stratospheric sudden warmings: A classical example of high latitude-low latitude coupling? Annales de Geophysique, 27(8), 3147–3153. https://doi.org/10.5194/angeo-27-3147-2009

Yizengaw, E., Moldwin, E., Mebratu, A., Damtie, B., Zesta, E., Valladares, C. E., & Doherty, P. (2011). Comparison of the storm time equatorial ionospheric electrodynamics in the African and American sectors. Journal of Atmospheric and Solar-Terrestrial Physics, 73, 156–163. https://doi.org/10.1016/j.jastp.2010.08.008

Yizengaw, E., Moldwin, E., Zesta, E., Biouele, C. M., Damtie, B., Mebratu, A., et al. (2014). The longitudinal variability of equatorial electrojet and vertical drift velocity in the African and American sectors. Annales Geophysicae, 32, 231–238. https://doi.org/10.5194/angeo-32-231-2014