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Research Article

Longitudinal Response of the Low-latitude Ionosphere to 2017 Sudden Stratospheric Warming Event

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Abstract

The Earth's ionosphere, a crucial region for communication and navigation systems, is susceptible to disturbances driven by both external (solar and geomagnetic activity) and internal (atmospheric waves) forces. These internal forces are known to be amplified during SSW events, creating significant ionospheric perturbations. This study investigates the longitudinal response of the low-latitude ionosphere, specifically focusing on the EIA, to the 2017 SSW event. Addressing a gap in current understanding, this research analyzes the longitudinal variations in TEC within the African and Asian sectors during the February 2017 SSW, aiming to provide a more comprehensive global perspective on SSW-ionosphere coupling. Previous findings have suggested longitudinal variations in EIA behavior, and this study seeks to provide concrete evidence of the SSW's longitudinal impact on the ionosphere through TEC data analysis. Using TEC data obtained from GPS observations, this study reveals a strong ionospheric response to the 2017 SSW event, characterized by irregular perturbations with large amplitudes, particularly in the African sector. During the peak phase of the SSW, ionospheric TEC perturbations begin just a day after the peak in stratospheric temperature and manifest as a suppression of the EIA for approximately 72 hours (3 days), indicative of a downward vertical drift. This suppression suggests a modulation of the fountain effect, which is further supported by the observed response of the mean zonal wind. The observed longitudinal differences in TEC perturbations, with stronger effects over the African sector compared to the Indian sector, highlight the influence of local effects on the ionospheric response to SSWs. These local effects could encompass variations in the geomagnetic field configuration, differences in the background ionospheric density and composition, and regional differences in atmospheric wave propagation and dissipation. Regional variations in tropospheric weather patterns and land-sea distribution can further affect the generation and propagation of atmospheric waves that couple the lower and upper atmosphere. The day to day TEC variations are discussed in the context of upward/downward $E\times B$ drift. Therefore, the observed longitudinal discrepancies underscore the importance of considering these local factors when assessing the impact of SSWs on the ionosphere and related technological systems. This study contributes to a more complete understanding of the complex interactions between the stratosphere and the ionosphere during SSW events and their implications for global communication and navigation infrastructure.

Keywords

Sudden Stratospheric Warming (SSW), Ionosphere, Total Electron Content (TEC), Stratosphere-Ionosphere Coupling

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1. Introduction

The Earth's ionosphere, a complex electrodynamic region of the upper atmosphere situated between approximately 90 km and 1000 km in altitude [28], plays a crucial role in communication and navigation systems. This region experiences increased ionization due to solar ionizing flux [6, 9]. However, disturbances within the ionosphere, driven by both external forces (solar flux and geomagnetic activity) and internal forces (planetary waves, gravity waves, and tides) [29], can negatively impact these systems [7]. Notably, these internal forces are amplified during sudden stratospheric warming (SSW) events. This study aims to address the gap in understanding the longitudinal response of the EIA during these events by investigating the longitudinal response of the EIA during the 2016/2017 SSW event. specifically focusing on the Total Electron Content (TEC) variations in the African and Asian sectors during the February 2017 SSW. This longitudinal analysis aims to address a critical gap in current knowledge, providing a more comprehensive global understanding of how SSWs influence the ionosphere across different longitudes and building upon previous findings that suggest longitudinal variations in EIA behavior. By analyzing TEC data, this research seeks to provide concrete evidence of the SSW's longitudinal impact on the ionosphere.

2. Literature Review

Previous research has demonstrated the influence of SSW on ionospheric dynamics. For instance, [11, 4] observed strong semidiurnal modulation of the ionosphere during the prolonged 2008 SSW, attributing these perturbations to enhanced planetary wave activity associated with SSW. This connection was later corroborated by [23].

SSW, first identified by has been the subject of numerous studies [13, 14, 21, 22, 3, 19]. This meteorological phenomenon involves a rapid temperature increase in the polar stratosphere, often accompanied by a slowdown (minor SSW) or reversal (major SSW) of the eastward zonal mean wind, leading to a breakdown of the polar vortex [19].

Several studies have investigated ionospheric irregularities during SSW events. [16] examined the response of the African and American Equatorial Ionization Anomaly (EIA) to the 2013 SSW, observing significant responses in both sectors during the peak phase, with a strengthening of the EIA due to poleward plasma flow. They also noted uneven plasma distribution, with more irregularities in the American sector. [30] observed a weakening of post-sunset scintillation in the Brazilian sector during various SSW events, highlighting the potential impact on GNSS applications. [20] reviewed ion-neutral coupling effects during low solar activity SSW periods, observing variations in zonal electric field, total electron content (TEC), and electron and neutral densities. [9] found a significant influence of the 2013 SSW on TEC in the American low latitude, suggesting the importance of daytime upward E x B drift [12] also studied the 2013 SSW over the American low-latitude ionosphere, observing TEC perturbations at the EIA crest attributed to anomalous vertical ion drift. [2, 1] using GPS TEC data from Africa and the Middle East, reported a negative TEC response during the 2009 SSW peak phase. [12] also documented diurnal TEC variations (morning enhancement and afternoon suppression), while [3] highlighted semidiurnal variations in vertical drift during SSW days, differing from non-SSW days. Recent work by [15] using TEC data from 1998 to 2022, found that SSW events enhance both semidiurnal and diurnal TEC variations, especially at low and mid-latitudes. Additionally, [5, 17] reported suppression of TEC rate of change (ROT) abnormalities in the Brazilian sector during the 2014 SSW. While existing literature has extensively explored the day-to-day variability of the EIA during SSW events, particularly in the American and Asian sectors, a gap remains in understanding the longitudinal response of the EIA during these events.

3. Materials and Method

3.1. Data Sources

Two different set of data were used for the study, the total electron content (TEC) and sudden stratospheric warming (SSW) events, stratospheric zonal wind (ZW) and temperature data. The SSW meteorological parameters (zonal wind and temperature) reanalysis data are taken from Modern-Era Retrospective analysis for Research and Applications (MERRA-2), which is downloaded-from. *https://acd-ext.gsfc.nasa.gov/Data_services/met/ann_data.html* [26]. It has been developed by NASA’s Global Modeling and Assimilation Office, focusing mainly on the satellite era from 1979 to date [18, 27], Provide an overview of the system and the observations used in the dataset's. Temperature data are taken at 10 hPa and 90 °N, and the ZW data are taken at 10 hPa and 60 °N. The ionospheric parameter (TEC) used in the work was obtained from *https://www.sonel.org/* at Malindi in Kenya, MAL2 (Lat: -2.99 °N and Long: 40.19 °S) in African station and Bangalore in India, IISC (Lat: 13.02 ° N and Long: 77.57 ° S). Gomagnetic index (Ap) and Solar flux (F10.7 cm) data wher obained from https://omniweb.gsfc.nasa.gov/form/dx1.html.

3.2. Methods of Analysis

We have figured out SSW events from temperature and zonal wind data from MERRA-2 reanalysis data obtained. If there is an abrupt increase of temperature at 90 °N and a slow-down of the zonal wind at 60 °N, then the event is consider to be a minor event. The maximum temperature increase is considered to be a major event and the day of maximum temperature is taken as the central date for the event. If the ZW reverses along with the increase in temperature for more than four days continuously, then we consider it as a major event. The first day of wind reversal is considered as the central date of a major event. For the study we have considered major SSW of 2016-2017 winter periods, which has the central date on February 1, 2017. GOPI TEC processing software developed by [31] was used to extract the TEC data from the retrieved GPS observable data. MAT-Lab software application was used to analyze both the ionosphere parameter (TEC), the stratospheric parameters (stratospheric zonal wind and temperature) for the winter period and Gomagnetic index (Ap) and Solar flux (F10.7 cm) data from November to March 2016/2017.

4. Results and Discussion

Figures 1 and 2 illustrate the stratospheric parameters during the winter months of November 2016 to March 2017. In Figure 1, the upper panel depicts the stratospheric temperature at 10 N hpa level over the polar region (60 °N to 90 °N) during the 2016-2017 SSW events at Malindi (MAL2) in the African sector. The x-axis represents the period from November 2016 to March 2017. The vertical solid lines indicate the duration of the SSW event. As can be observed in Figure 1 (panel a), all the days before January 29, 2017, the temperature remain relatively calm indication of the absence of SSW effect. Shortly after this period, the temperature rapidly increased on January 27, 2019 during the SSW to reach its peak 2-days later (January 29, 2017). The temperature increased by about 43 K. shortly after the peak, the temperature slightly decrease only to rapidly rise to about 45 K on February 7, 2017. The fluctuation in temperature implies variations in the source mechanism. Associated to the variation of temperature is the reversal of the eastward zonal mean wind at 60 °N to westward indication of major SSW as depicted in Figure 1 (panel b). The westward zonal mean wind reached its minimum value ~40 m/s on February 2, 2017. The zonal mean wind is seen to sluggishly rise for approximately 13 days but unable to return to eastward flow as shown in Figure 1 (panel b). The inability to recover to eastward flow is an indication of the stronger effect of SSW.

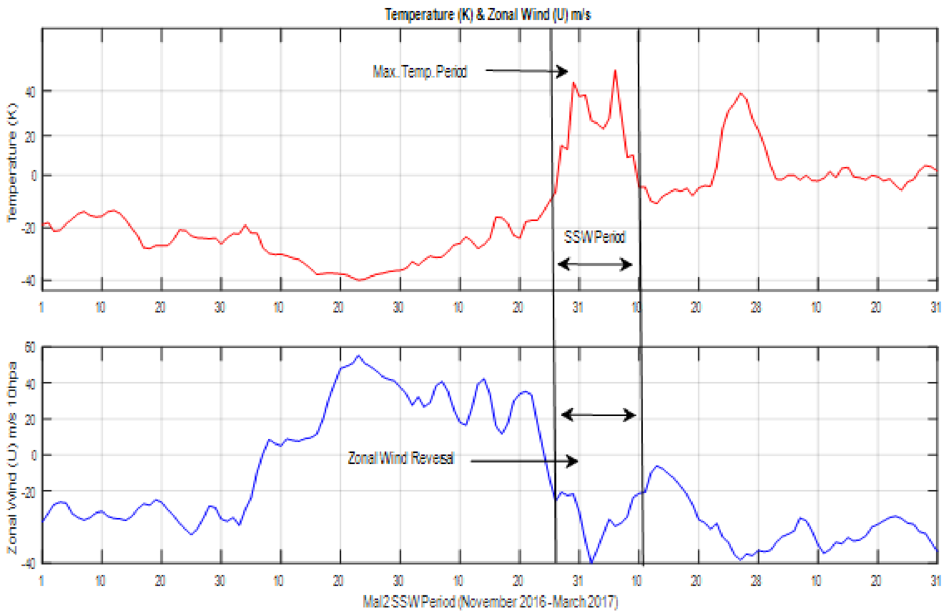

Figure 1. *Temperature Panel and Zonally averaged Zonal wind Panel over the polar region. (60 °N and 90 °N) respectively at 10 hPa during 2016/2017 SSW events. At Malindi (MAL2) Station.*

Figure 2 presents the time series of temperature Panel and zonally averaged zonal wind Panel at the 10 hPa level over the polar region (60 °N to 90 °N) during the 2016-2017 SSW event at the Indian Institute of Science (IISC) Bangalore station. The x-axis represents the period from November 2016 to March 2017. The vertical solid lines indicate the duration of the SSW event.

As can be observed in Figure 2 The temperature panel exhibit a significant increase during the SSW to reach its peak (~43 K) on January 29, 2017 which is consistent with the peak observed at the Malindi station. In zonal wind panel, the zonal wind undergoes a reversal from eastward to westward during the peak warming phase similar to what was at the Malindi station. The mean zonal wind reached its minimum ~40 m/s seen on February 2, 2017. A slight difference can be seen during the onset (January 24, 2017) of the zonal mean wind between the longitudes. Both the temperature and zonal wind patterns at the IISC Bangalore station show clear signatures of the 2016-2017 SSW events. The timing of the peak temperature increase at Bangalore is similar to that observed at Malindi. The slight differences in the zonal mean wind behavior between the two longitudes could be due to regional variations in the atmospheric dynamics.

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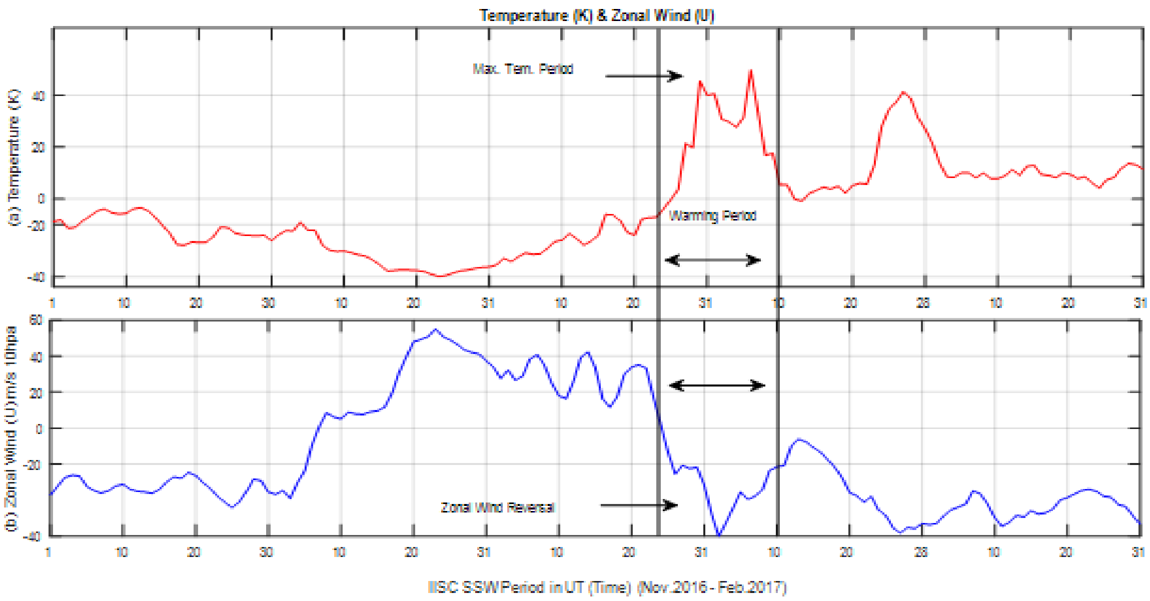

Figure 2. *Temperature Panel and Zonally averaged Zonal wind Panel over the polar region (60 °N and 90 °N) respectively at 10 hPa during 2016/2017 SSWSW events. At Bangalore (IISC) Station.*

Figure 3 TEC panel and Figure 4 TEC panel illustrate the variations of TEC between November 1, 2017 and March 31, 2017 at low-latitudes in Africa and Indian sector respectively. The Figure clearly demonstrates the ionospheric response of TEC before, during and after the SSW event. The variations of TEC remain relatively calm from November 1, 2016 to January 26, 2017 in the Indian sector (see Figure 4 TEC panel), while an irregular variation which seems to be increasing in magnitude and phase is conspicuously seen in the African sector during these periods see Figure 3 TEC panel). In an attempt to investigate the cause of these irregular perturbations we plot in Figure 3 Ap panel and F10.7 panel and Figure 4 Ap index panel and F10.7 panel. The geomagnetic index (Ap) and solar flux (F10.7 cm) was obtained from https://omniweb.gsfc.nasa.gov/form/dx1.html. The variations of Ap index and solar flux indicates that the period of the study is relatively quiet in terms of geomagnetic activity and solar radiation as depicted in Figure 3 and Figure 4. The perturbation of ionospheric TEC in the African sector between November 1, 2016 to January 26, 2017 seems not to be associated to any form of geomagnetic activity but do suggest the influence of local activity. Prior to the main phase of the SSW, the TEC were generally observed to be incredibly enhanced across the two longitudes. This implies that during these periods, the upward plasma at the magnetic equator cause uplift of ionoispheric plasma to altitude of lower recombination rates (minimal loss rate) and the consequence is that more electrons will be deposited at region away from the magnetic equator as seen at MAL2 and IISC located away from the magnetic equator.

During the SSW peak phase, the TEC is generally suppressed seen at the two longitudes sector. This indicates that the EXB drift responsible for transporting ionospheric plasma to a height with minimal recombination rate is inhibited by stronger mechanism. In other words, during the peak phase of the SSW, the additional zonal electric field is westward generating a downward plasma drift in the ionosphere with a higher level of recombination processes [13], which lead to total reduction of TEC magnitude as observed during the peak phase of the SSW event at both longitudes. Different mechanisms have been suggested to alter the ionospheric EXB drift that play significant role in the transport mechanism in the upper region of the atmosphere. For example, [23, 24] demonstrate that the semidiurnal tides in the low-latitude ionosphere is significantly perturbed during SSW event. Similar study by [3] also observed dramatic changes at the low-latitude during and after SSW event. Liu et al. reported that the intensification of semidiurnal wave modulate the EEJ current intensity which play important role in the transport mechanism of the electron density at the low-latitude. [34] observed that the planetary wave (PW) which are usually amplified during SSW event play significant role in altering the equatorial E and F region dynamo mechanism and this in-turn influence the ionization distribution at the low latitude ionosphere. In another study, [8, 10, 23, 32, 33] have explained that changes and alterations in thermospheric tides can lead to severe changes in electric field through the E-region and this can affect the ionospheric response to SSW event.

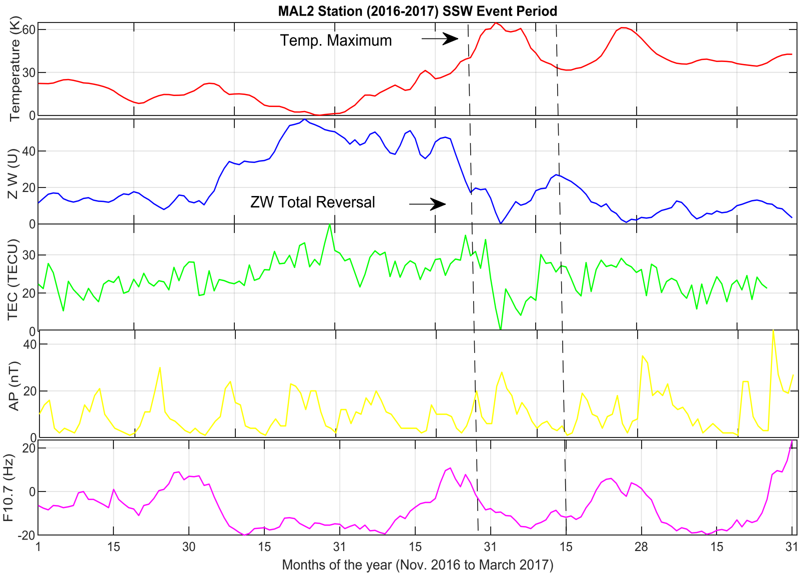

Figure 3. *Zonally averaged vertical distribution of temperature (K) Panel, Zonal wind (ms−1) panel and TEC (TECU) panel at 10 hPa to 1 hPa level over the polar region from (60 °N–90 °N) during 2016/17 SSW events, at MAL2.*

In Figure 4, it is observed that, TEC direction in the ionospheric region was also alter around the period of the SSW events and persists for about 14 days. In general, the vertical TEC in the ionosphere during winter remains calm prior to the occurrence of SSW events in the stratospheric region. But the rapid and substantial increase in temperature within the polar stratosphere associated with a complete reversal of the westerly winds lead to TEC variations in the ionospheric region. This finding supported the work of [5].

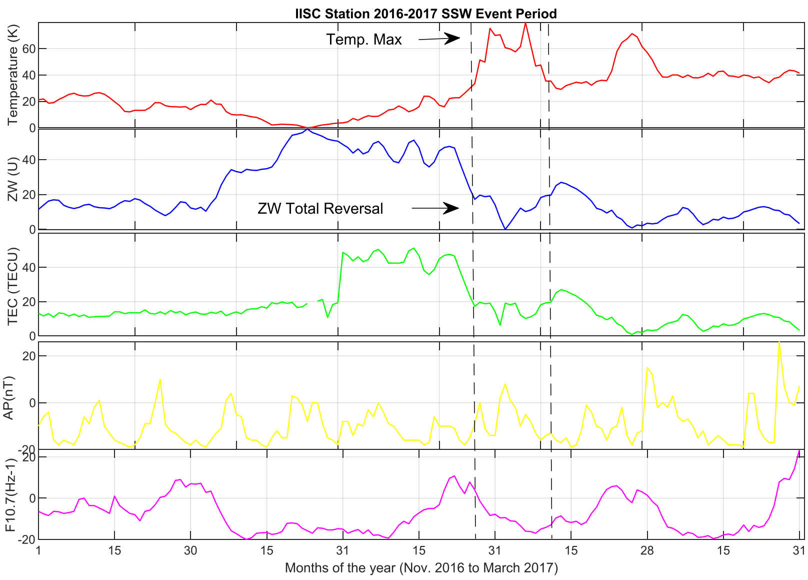

Figure 4. *Zonally averaged vertical distribution of temperature (K) panel, Zonal wind (ms−1) panel and TEC (TECU) panel at 10 hPa to 1 hPa level over the polar region from (60 °N–90 °) during 2016/17, SSW events, at IISCE Station.*

5. Conclusion

This study investigates the coupling between the high-latitude stratosphere and the ionosphere during the 2016-2017 Sudden Stratospheric Warming (SSW) event over the African (Malindi) and Indian (Bangalore) sectors. By analyzing the Total Electron Content (TEC) and stratospheric parameters, we found significant ionospheric perturbations associated with the SSW that are more prominent in the African sector. The result indicates meteorological phenomenon (SSW) can induce significant perturbation to ionospheric TEC. The zonal wind and TEC disturbances persisted for approximately 14 days following the major SSW event. Additionally, temperature profiles at both stations exhibited significant increases during the winter period, particularly during the peak phase of the SSW event.

The observed longitudinal differences in TEC perturbations, with stronger effects over the African sector compared to the Indian sector, highlight the influence of local effects on the ionospheric response to SSWs. These local effects could encompass a variety of factors, including variations in the geomagnetic field configuration, differences in the background ionospheric density and composition, and regional differences in atmospheric wave propagation and dissipation. The geomagnetic field, for instance, plays a crucial role in controlling the transport and distribution of charged particles in the ionosphere, while background ionospheric conditions can influence the efficiency of energy and momentum transfer from the stratosphere. Furthermore, regional variations in tropospheric weather patterns and land-sea distribution can affect the generation and propagation of atmospheric waves that couple the lower and upper atmosphere. Therefore, the observed longitudinal discrepancies underscore the importance of considering these local factors when assessing the impact of SSWs on the ionosphere and related technological systems.

Abbreviations

TEC	Total Electron Content
SSW	Sudden Stratospheric Warming
Ap index	A Planetary Geomagnetic Index
F10.7	Solar Radio Flux

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Author Contributions

Abbas Mustapha: Supervision
Joshua Benjamin Wisdom: Supervision
Mukhtar Ibrahim Furfuri: Conceptualization, Funding acquisition, Project administration, Writing – original draft
Mohammad Bello Kaoje: Supervision

Conflicts of Interest

The authors declare no conflict of interest.

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