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Research Article

Impact of space weather on ionospheric dynamics in Bangladesh: Insights from 2022–2023 TEC analysis

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ABSTRACT

Our study, which investigates the impact of space weather on ionospheric variability over Bangladesh, a region near the Equatorial Ionization Anomaly (EIA), using Total Electron Content (TEC) measurements derived from Global Positioning System (GPS) observations, is of significant importance. The analysis, covering 2022 and 2023, characterized by heightened solar activity, reveals a pronounced spatial gradient in TEC values, primarily modulated by proximity to the EIA and geomagnetic disturbances. Seasonal and diurnal patterns further highlight the influence of solar radiation and geomagnetic activity on ionospheric behavior. Notably, severe geomagnetic storms in March and September 2022 and in March and April 2023 induced substantial TEC perturbations, amplifying ionospheric variability. These findings provide critical insights into the complex interactions between solar-terrestrial processes and geomagnetic dynamics, with significant implications for navigation, communication systems, and space weather forecasting in low-latitude regions such as Bangladesh.

Introduction

Space weather, a field that encompasses the dynamic and interconnected processes from the Sun that influence Earth's space environment, has profound effects on technological systems and human activities. This interdisciplinary field primarily involves solar wind, geomagnetic field disturbances, ionospheric variability, and other related phenomena, extending across multiple disciplines, including solar physics, magnetospheric physics, and atmospheric science (Mostofa et al., 2023).

The solar wind is at the core of space weather, a continuous outflow of charged particles (plasma) from the Sun. This stream carries the interplanetary magnetic field (IMF), a component of the Sun's magnetic field that propagates through the solar system. When the IMF interacts with Earth's geomagnetic field, it can lead to reconnection events, allowing energy and particles to enter the magnetosphere. Such interactions often result in geomagnetic storms—periods of intense magnetic activity that can disrupt satellite operations, power grids, and communication systems (Demyanov et al., 2022).

The ionosphere extends from approximately 50 km to over 1,000 km in altitude, with its structure divided into distinct regions based on altitude, electron density, and ionization sources. Fig. 1

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illustrates the differences between the dayside and nightside ionosphere, highlighting key areas and their respective characteristics. The D region is the lowest part of the ionosphere and is present only during the daytime. It is primarily ionized by high-energy solar X-rays and cosmic rays, resulting in low electron density due to rapid recombination (Jee, 2023). This region significantly absorbs low-frequency (LF) and very-low-frequency (VLF) radio waves, causing daytime signal attenuation. The figure shows this region's location and interaction with aircraft and balloons. Above the D region lies the E region, where ionization is driven by solar ultraviolet (UV) radiation. Electron density peaks at around 110 km during the day, enabling the reflection of medium-frequency (MF) radio waves (Némethová and Zýka, 2024). The presence of sporadic E layers, as depicted in the figure, is caused by localized ionization and wind shear effects. This region plays a critical role in supporting shortwave radio communications. The F region is the most important part of the ionosphere for radio communications and satellite operations (Demyanov et al., 2022). It is divided into two sub-layers during the daytime:

F1 Layer (150–250 km): This layer appears only during the day and supports moderate ionization.

F2 Layer (250–500 km): Present both day and night, it has the highest electron density, as shown in the figure. The F2 layer is crucial for high-frequency (HF) radio wave propagation and global communication systems.

At night, the F1 layer disappears, and the F2 layer dominates, as shown on the left side of the figure. The ionization levels are lower during the night due to reduced solar radiation, but sufficient to maintain some electron density (Ishii et al., 2024).

The topside ionosphere, not explicitly labeled in the figure but implied above the F region, extends upward into the plasmasphere. Electron density decreases with altitude, and lighter ions like H^+ and He^+dominate due to gravitational separation.

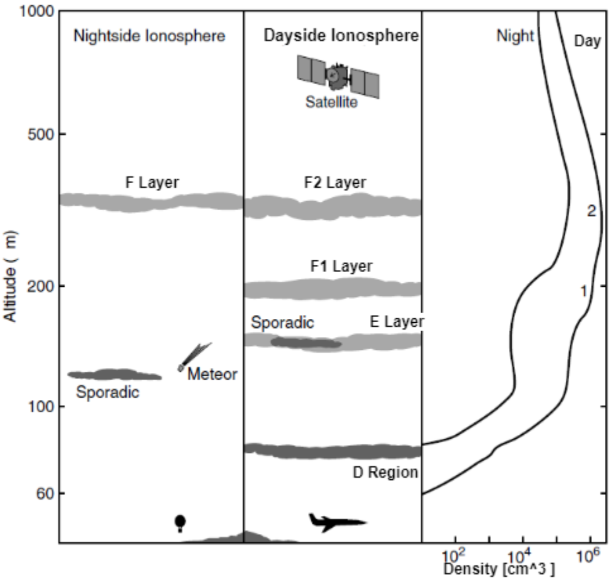

Fig. 1. Vertical structure of the earth's ionosphere: Dayside and nightside characteristics (Moldwin, 2008).

This region interacts with satellites, as depicted in the figure, and is critical for understanding space weather impacts on satellite communication and navigation systems. The attached figure highlights the differences in electron density between the day and night. During the day, solar radiation enhances ionization, leading to higher electron density across all regions. At night, the lack of solar radiation causes recombination, reducing electron density in the D and E regions, while the F2 layer persists due to slower recombination processes. The figure also shows phenomena like meteors interacting with the E region and sporadic ionization events in both the E and F regions (Ishii et al., 2024).

The ionosphere, a highly dynamic region of Earth's upper atmosphere, is central to the study of space weather. This region, populated by free electrons and ions, responds to solar and geomagnetic activity variations. Disturbances in the ionosphere, such as those caused by solar flares or coronal mass ejections (CMEs), can alter the propagation of radio waves, degrade GPS accuracy, and affect ground- and space-based communication networks. Key parameters like Total Electron Content (TEC), which measures the number of electrons along a column between a satellite and a ground receiver, are essential for monitoring these disturbances (Mostofa et al., 2022a). Geomagnetic indices, such as the Dst index (which measures ring current intensity) and the Kp index (which quantifies global geomagnetic activity), provide additional insight into space weather conditions (Singh et al., 2024).

The behavior of the ionosphere is shaped by a complex interplay of factors, including solar radiation, solar wind, interactions with the Earth's magnetosphere, and atmospheric weather patterns (Rodriguez-Solano et al., 2013). These influences result in variations in ionospheric conditions that can be broadly classified into two distinct categories:

1. Predictable Variations (Quiet Ionosphere): These changes occur in well-defined cycles, such as the diurnal (daily) and seasonal variations, which follow established patterns and can be forecasted accurately. Regular solar radiation inputs and atmospheric tides largely govern the quiet ionosphere.
2. Unpredictable Variations (Disturbed Ionosphere): These fluctuations arise primarily due to the Sun’s dynamic and often erratic behavior, particularly during heightened solar activity. Space weather phenomena, including geomagnetic storms and solar flares, introduce significant irregularities in the ionosphere, leading to disruptions in radio communications, navigation systems, and other space-based technologies (Mostofa et al., 2022b).

This study utilizes high-resolution GPS-based data collected from Bangladesh during the high solar activity years of 2022 and 2023, a period associated with the rising phase of Solar Cycle 25. Total Electron Content (TEC) data was acquired from UNAVCO satellites through the GAGE data server and processed using advanced algorithms to account for geometric and receiver biases. By analyzing seasonal, diurnal, and spatial variations in TEC, this research investigates how geomagnetic disturbances and solar activity impact ionospheric behavior over Bangladesh, a region lying near the northern crest of the EIA.

The novelty of this study lies in its region-specific focus on Bangladesh, which is uniquely situated to experience the compounded effects of geomagnetic disturbances and equatorial ionospheric anomalies. Unlike global ionospheric models, which often overlook localized variations, this study provides detailed insights into the dynamics of TEC within this low-latitude region. Furthermore, developing a regional ionospheric disturbance index tailored to Bangladesh’s geomagnetic conditions represents a significant advancement in space weather monitoring.

The findings of this study are crucial for mitigating the adverse effects of space weather on communication and navigation technologies. Understanding the ionosphere's response to space weather events will help improve GNSS-based systems, ensuring greater resilience and reliability for applications ranging from aviation and maritime navigation to agricultural monitoring. This work contributes to the global effort to enhance space weather preparedness in vulnerable regions by addressing a critical gap in localized ionospheric research.

Methodology

GPS signals through the ionosphere provide an established method for ionospheric remote sensing (Bojilova and Mukhtarov, 2023). A widely used GPS network offers a powerful tool and cost-effective means for computing the TEC and scintillation characteristics of the ionosphere.

The research methodology integrates data acquisition, processing, and analysis to investigate space weather impacts. Data for 2022 and 2023 (https://gage-data.earthscope.org/archive/gnss/rinex3/obs/2022/) (https://gage-data.earthscope.org/archive/gnss/rinex3/obs/2023/) was sourced from the GAGE data server, using UNAVCO satellite observations in Receiver

Independent Exchange Format, version 3 (RINEX3), known for its Receiver Independent Exchange structure. Compressed into Hatanaka format for efficiency, these files were processed using Gopi Seemala software (Seemala, 2023). The software calculates Total Electron Content (TEC) by deriving Slant TEC (STEC) from the phase difference of dual-frequency GNSS signals – $STEC = \frac{\Delta\emptyset . f_1^2 . f_2^2}{(f_1^2 - f_2^2)}$ (1)

Where, $\Delta\emptyset$ is the phase difference between two frequencies (f_1 and f_2)

f_1, f_2 are the frequencies of the GNSS signals and converting it to Vertical TEC (VTEC) using -

$$VTEC = STEC . Cos\ (E)$$
(2)

Where, E is the satellite's elevation angle, it accounts for the geometric path difference.

GPS data acquisition points in Bangladesh, which were used in this study, are shown in Fig. 2.

The ionosphere exhibits variations based on Earth's geographical position, particularly concerning latitude, owing to the orientation of the geomagnetic field lines in different latitude regions. Notably, the behavior of the ionosphere in mid-latitudes differs from that in low- and high-latitude regions. In the mid-latitude F2 region ionosphere, reaction rates are notably sensitive to temperature and chemical composition changes. The alterations in composition are linked to the global circulation pattern within the thermosphere. The primary influencing mechanism in the mid-latitude ionosphere is the global thermospheric winds, as detailed by. This mid-latitude region is recognized as the transitional zone between low and high latitudes (Radicella, 2023).

Certain regions, specifically low-latitude areas, exhibit elevated electron concentrations around geomagnetic latitudes of approximately ±20°. At the magnetic equator, where Earth's magnetic field lines lie horizontally, solar heating and tidal oscillations in the lower ionosphere induce the movement of plasma upward and across the magnetic field lines. This process establishes a sheet of electric current in the E region, which propels ionization upward into the F layer in conjunction with the horizontal magnetic field. This phenomenon is called the fountain effect or the Equatorial Ionization Anomaly (EIA) (Laštovička et al., 2012). The geographic latitude analyzed in this study starts from 22.291640˚N to 25.088773˚N, and the geographic longitude starts from 88.928156˚E to 91.492842˚E. The geomagnetic coordinates are shown in Fig. 3.

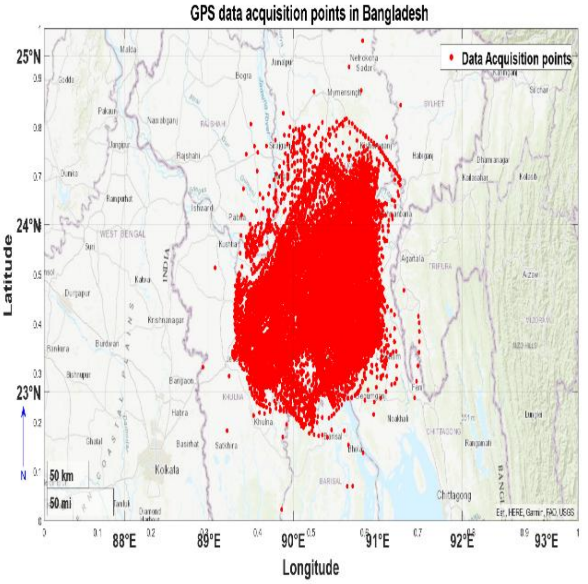

Fig. 2. GPS Data acquisition points across Bangladesh: Latitude 22.291640˚N to 25.088773˚N and Longitude 88.928156˚E to 91.492842˚E.

Corrections for receiver hardware biases and elevation mask filtering are applied to ensure high data accuracy. The processed TEC profiles were analyzed to identify ionospheric anomalies, leading to the development of an ionospheric disturbance index. This index facilitates improved monitoring and understanding of space weather effects, particularly for Bangladesh's communication, power, and agricultural systems. The methodology ensures robust and reliable outcomes by combining advanced processing techniques and multiple data sources.

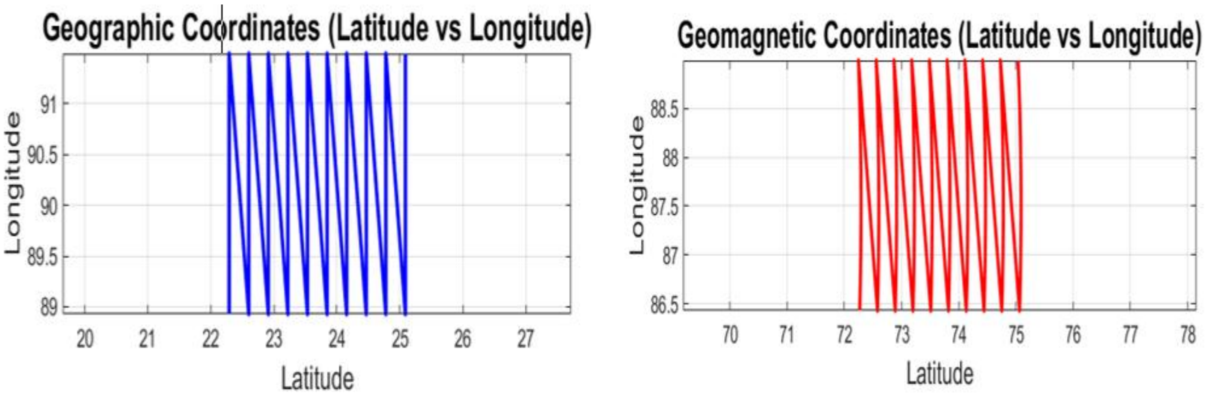

Fig. 3: Conversion of geographic coordinates to geomagnetic coordinates for Bangladesh.

Results and Discussion

Fig. 4 shows the geomagnetic and ionospheric parameters for 2022. The interplanetary magnetic field (IMF_Bz) during 2022 displayed significant fluctuations, with peaks exceeding 20 nT, indicating periods of elevated geomagnetic activity. The Kp index revealed multiple moderate disturbances, with values ranging from 4 to 6, suggesting a frequent occurrence of minor to moderate geomagnetic storms. The Dst index, which measures the intensity of geomagnetic storms, showed several notable storm events with values dropping below -50 nT, particularly in March and September, signaling moderate to severe storm activity. The Vertical Total Electron Content (VTEC) demonstrated seasonal variations, with higher values observed during equinox months, reflecting the increased solar radiation during these periods.

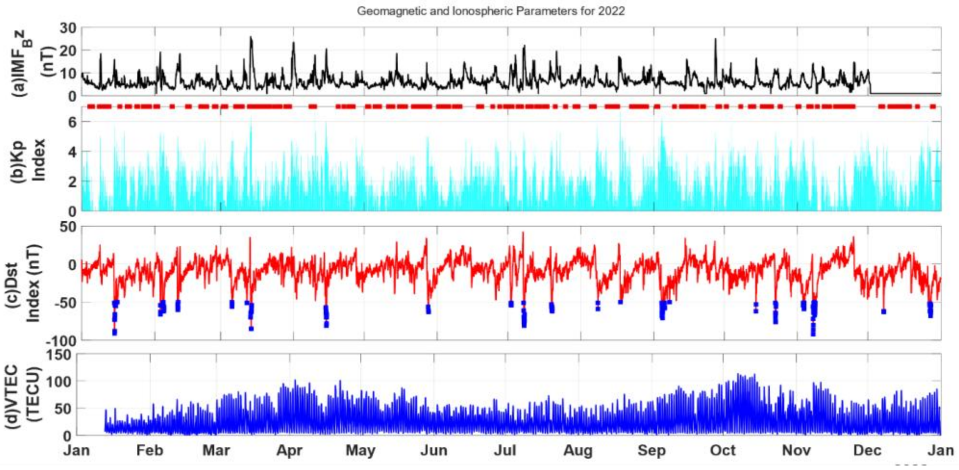

Fig. 4. Geomagnetic and ionospheric parameter for 2022: IMF_Bz, Kp index, Dst index, and VTEC trends.

The geomagnetic activity observed in 2022 can be attributed to solar phenomena such as coronal mass ejections (CMEs) and high-speed solar wind streams (HSS), key drivers of geomagnetic storms. The fluctuations in IMF_Bz and elevated Kp index align with the expected impacts of these solar events during the 25th solar cycle. Seasonal peaks in VTEC are consistent with the equinoctial effect, which enhances ionospheric ionization due to more effective solar radiation during equinoxes (Mostofa et al., 2023). The significant geomagnetic storms in March and September align with historical data showing these months as periods of heightened geomagnetic activity.

Fig. 5 shows the geomagnetic and ionospheric parameters for 2023. In 2023, the IMF_Bz exhibited similar variability to 2022 but with peaks reaching up to 30 nT, indicative of increased geomagnetic activity. The Kp index showed prolonged periods of moderate disturbances, with fewer intervals of quiet geomagnetic conditions compared to 2022. The Dst index highlighted intense geomagnetic storm events, particularly in March and April, with values dropping below -100 nT, marking severe geomagnetic disturbances. VTEC trends were slightly elevated compared to 2022, showing increased ionospheric ionization, likely due to intensified solar activity during this period.

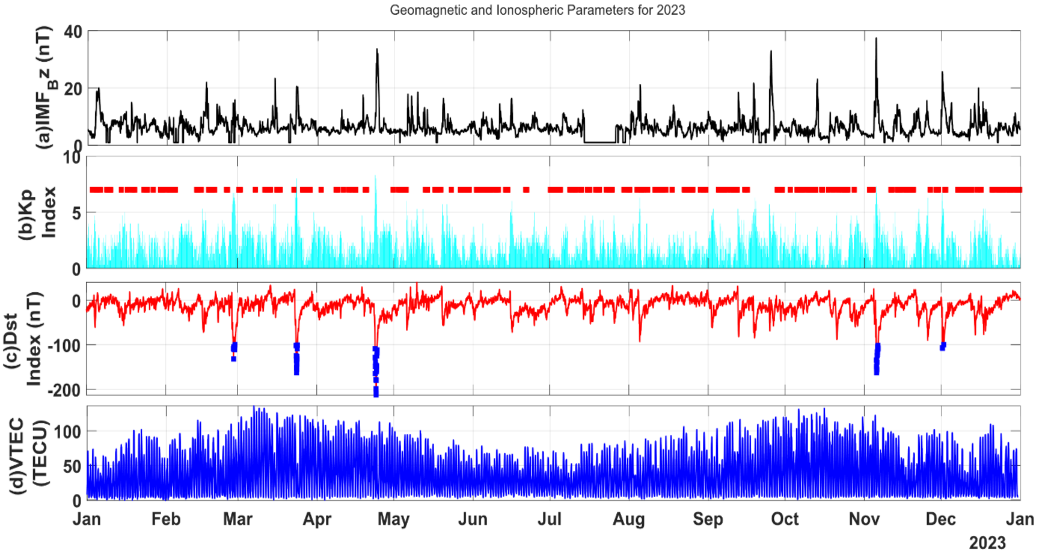

Fig. 5. Geomagnetic and ionospheric parameters for 2023: IMF_Bz, Kp index, Dst index, and VTEC trends.

The stronger geomagnetic activity in 2023 corresponds with the rising phase of Solar Cycle 25, which is characterized by increased solar activity and a higher frequency of geomagnetic storms (Rao et al., 2009). Severe geomagnetic storms observed in March and April align with the equinoctial maxima, which historically record enhanced geomagnetic disturbances. The elevated VTEC levels further indicate the impact of intensified solar EUV radiation and geomagnetic activity, supporting findings that correlate ionospheric behavior with solar cycle phases (Rao et al., 2009).

In 2022, the VTEC values for the geographic latitude range of 22.291640˚N to 25.088773˚N and longitude range of 88.928156˚E to 91.492842˚E exhibited clear spatial variability. The region's proximity to the Equatorial Ionization Anomaly (EIA) significantly influenced the distribution of electron content. Areas closer to the EIA crest exhibited higher VTEC values due to the accumulation of ionized plasma caused by the equatorial electrojet and fountain effect (Balan et al., 2018). This latitudinal gradient is a well-known phenomenon in low-latitude regions, as documented by Buhari et al. (2017).

Geomagnetic disturbances in 2022 further contributed to VTEC variations. The year experienced several geomagnetic storms, particularly in March and September, as indicated by drops in the Dst index below -50 nT. These disturbances caused fluctuations in the ionospheric electron content, leading to regional disparities in

VTEC (Hafteh et al., 2024). Like those studied, low-latitude regions are susceptible to geomagnetic activity due to their interaction with equatorial electrojet currents, amplifying storm-induced plasma redistribution (Elmunim et al., 2021).

Table 1. Comparative Summary of Geomagnetic and Ionospheric Parameters for 2022 and 2023.

Parameter	2022 Highlights	2023 Highlights	Observations
IMF Bz (nT)	Peaks around 20–25 nT, frequent smaller fluctuations	Peaks exceed 30 nT, more intense spikes	2023 shows more substantial and more frequent magnetic field variations
Kp Index	Mostly below 5, occasional bursts	Frequent spikes approaching or reaching 8	2023 indicates more geomagnetic disturbances
Dst Index (nT)	Dips frequently to -50 to -100 nT, moderate storms	Dips reach -150 to -200 nT, intense geomagnetic storms	2023 had stronger geomagnetic storms
VTEC (TECU)	Average range 20–90 TECU, lower during mid-year	Average range 30–120 TECU, higher overall, peaks in March, October, Dec	2023 had higher ionospheric electron content
Seasonal Variation	Noticeable VTEC variation in April/Oct, fewer storm events mid-year	Strong seasonal trends, especially March-May and Oct-Dec	More seasonal consistency and peak activity in 2023
Seasonal Variation	Noticeable VTEC variation in April/Oct, fewer storm events mid-year	Strong seasonal trends, especially March–May and Oct–Dec	More seasonal consistency and peak activity in 2023

Solar activity also influenced VTEC trends in 2022. Seasonal variations in solar zenith angle, particularly during equinox months, resulted in higher VTEC values due to increased ionization from enhanced solar radiation (Liu et al., 2013). These patterns align with the equinoctial effect, where solar radiation is more effective in ionizing the ionosphere during equinoxes (Forbes et al., 2000). The combination of geomagnetic and solar influences shaped the observed spatial and temporal differences in VTEC across the region in 2022.

In 2023, the VTEC values showed an overall increase compared to 2022, reflecting the rising phase of Solar Cycle 25, which is associated with higher solar activity and more substantial ionization effects. The EIA influenced the region, with higher VTEC values observed at lower latitudes closer to the anomaly crest. The latitudinal gradient persisted, but the elevated baseline electron content in 2023 amplified the overall values, consistent with previous findings on solar cycle impacts on the ionosphere (Pancheva et al., 2024).

Geomagnetic activity played a more pronounced role in 2023, with severe storms observed in March and April, indicated by Dst index values dropping below -100 nT. These storms caused significant disturbances in the ionosphere, leading to heightened variability in VTEC. The intensified geomagnetic conditions likely increased plasma transport and irregularities, further amplifying spatial VTEC differences (Stankov et al., 2003). The interaction between geomagnetic activity and the equatorial electrojet currents in low-latitude regions was a key factor driving these variations, as noted by (Emmela et al., 2024). The heightened solar activity in 2023 also significantly impacted VTEC values. The year exhibited more substantial seasonal variations, with elevated VTEC levels during equinox months due to increased solar EUV radiation (Huang, 2018). Diurnal variations in the solar zenith angle also modulated the electron content, resulting in localized VTEC anomalies (Picanço et al., 2022). These observations align with studies highlighting the combined effects of solar and geomagnetic activity on low-latitude ionospheric behavior (Bojilova and Mukhtarov, 2023).

In 2022 and 2023, VTEC variations were shaped by proximity to the EIA, geomagnetic disturbances, and solar activity. While 2022 highlighted moderate solar and geomagnetic influences, 2023 exhibited heightened activity due to the rising phase of Solar Cycle 25. The observed spatial and temporal differences in VTEC underscore the complex interplay of solar-terrestrial and geomagnetic processes in the low-latitude ionosphere. Future studies using advanced ionospheric models could further elucidate these dynamics and improve space weather forecasting for regions vulnerable to ionospheric disturbances (Pancheva et al., 2024). Table 1 shows the overall summary for all parameter changes in 2022 and 2023.

Conclusion

This study highlights the profound impact of space weather on ionospheric dynamics in Bangladesh's low-latitude region, emphasizing the ionosphere's sensitivity to solar and geomagnetic activity. Data from 2022 and 2023 revealed significant TEC variations influenced by proximity to the Equatorial Ionization Anomaly, geomagnetic disturbances, and solar radiation cycles. Seasonal peaks in TEC during equinoxes, combined with severe geomagnetic storms, underscore the intricate interplay of solar-terrestrial processes. The rising phase of Solar Cycle 25 in 2023 further amplified ionospheric variability, demonstrating the need for robust monitoring and predictive models. These findings are crucial for mitigating space weather impacts on critical technologies, including GNSS-based navigation and communication systems. Future efforts should focus on developing localized ionospheric models and integrating real-time geomagnetic indices for enhanced space weather resilience in Bangladesh and other vulnerable regions.

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Author contribution

Sadia Mostofa: Writing-review & editing, writing–original draft, conceptualization, lead, methodology, formal analysis, software, resources, validation, investigation. Mohammad Badal Ahmmed: Methodology, formal analysis, software, resources, validation, data curation. Mohammad Mahdi Hasan: Writing-review & editing, formal analysis, investigation. jagobandhu some: writing-review & editing, formal analysis, investigation. Muhammad Sharif: Writing-review & editing, conceptualization, formal analysis, investigation.

Declaration of conflicting interest

The authors declare that they have no conflict of interest.

References

Balan N, Liu L and Le H. A brief review of equatorial ionization anomaly and ionospheric irregularities. *Rev. Space Phys. Earth Planet. Phys.* 2018, 2: 257-275.

Bojilova R and Mukhtarov P. Comparative analysis of global and regional ionospheric responses during two geomagnetic storms on 3 and 4 February 2022. *Remote Sens.* 2023, 15(7): 1739.

Buhari SM, Abdullah M, Yokoyama T, Otsuka Y, Nishioka M, Hasbi AM, Bahari SA and Tsugawa T. Climatology of successive equatorial plasma bubbles observed by GPS ROTI over Malaysia. *J. Geophys. Res. Space Phys.* 2017, 122(2): 2174-2184.

Demyanov V, Yasyukevich Y, Sergeeva MA and Vesnin A. *Space Weather Impact on GNSS Performance*. Springer Nature, 2022. p. 368.

Elmunim N, Abdullah M and Bahari S. Evaluating the performance of IRI-2016 using GPS-TEC measurements over the equatorial region. *Atmos.* 2021; 12(10): 1243.

Emmela S, Ratnam DV, Otsuka Y, Shinbori A, Sori T, Nishioka M and Perwitasari S. Statistical analysis of global and regional ionospheric total electron content (TEC) using extreme value distributions. *IEEE Trans. Geosci. Remote Sens.* 2024; 62: 1-8.

Forbes JM, Palo SE and Zhang X. Variability of the ionosphere. *J. Atmos. Sol. Terr. Phys.* 2000; 62(8), 685–693.

Hafteh MV, Mahmoudian A, Yoshikawa A and Girgis K. Mid-Latitude study of ionospheric variation over iran associated with equatorial ionization anomaly (EIA), and artificial neural networks model development. *Space Weather,* 2024; 22(11): e2024SW004032.

Huang C-S. Effects of the postsunset vertical plasma drift on the generation of equatorial spread F. *Prog. Earth Planet. Sci.* 2018; 5 (1): pp. 15.

Ishii M, Berdermann J, Forte B, Hapgood M, Bisi MM. and Romano V. Space weather impact on radio communication and navigation. *Adv. Space Res.* 2024 (in press).

Jee G. Fundamentals of numerical modeling of the mid-latitude ionosphere. *J. Astron. Space Sci.* 2023; 40(1), 11-18.

Laštovička J, Solomon SC and Qian L. Trends in the neutral and ionized upper atmosphere. *Space Sci. Rev.* 2012; 168(1-4): pp. 113-145.

Liu JY, Yang WH, Lin CH, Chen YI and Lee IT. A statistical study on the characteristics of ionospheric storms in the equatorial ionization anomaly region: GPS-TEC observed over Taiwan. *J. Geophy. Res. Space Phys.* 2013; 118(6): 3856-3865.

Moldwin M. *An Introduction to Space Weather*. Cambridge University Press, 2008.

Mostofa S, Abdullah M, Bahari SA and Islam MT. Analysis of the regional ionospheric disturbance index during geomagnetic storm in 2012. *IEEE Access*, 2023; 11: 94742-94752.

Mostofa S, Abdullah M, Islam MT, Bahari SA and Ahmmed MB. A GPS TEC-based Ionospheric-M Index over Malaysia. *2022 IEEE 20th Student Conference on Research and Development* (SCOReD), 2022a: 185-189.

Mostofa S, Abdullah M, Islam MT, Bahari SA and Ahmmed MB. Variations of total electron content during quiet and disturbed geomagnetic conditions over Malaysia. 2022 *IEEE 6th International Symposium on Telecommunication Technologies (ISTT),* 2022b: 97-101.

Némethová H and Zýka J. Overview of the space weather impact on the navigation and communication systems. *Acta Avion. J.* 2024; 26(1): 27-39.

Pancheva D, Mukhtarov P and Bojilova R. Response to geomagnetic storm on 23–24 March 2023 long-lasting longitudinal variations of the global ionospheric TEC. *Adv. Space Res.* 2024; 73(12): 6006-6028.

Picanço GAS, Denardini CM, Nogueira PAB, Resende LCA, Carmo CS, Chen SS, Barbosa-Neto PF and Romero-Hernandez E. Study of the equatorial and low-latitude total electron content response to plasma bubbles during solar cycle 24-25 over the Brazilian region using a disturbance ionosphere index. *Ann. Geophys.* 2022; 40(4): 503-517.

Radicella SM. New ways to modelling and predicting ionosphere variables. *Atmos.* 2023; 14(12): 1788.

Rao PVSR, Gopi Krishna S, Vara Prasad J, Prasad SNVS, Prasad DSVVD and Niranjan K. Geomagnetic storm effects on GPS based navigation. *Ann. Geophys.* 2009; 27(5): 2101-2110.

Rodriguez-Solano CJ, Hugentobler U, Steigenberger, P and Allende-Alba G. Improving the orbits of GPS block IIA satellites during eclipse seasons. *Adv. Space Res.* 2013; 52(8): 1511-1529.

Seemala GK. Estimation of ionospheric total electron content (TEC) from GNSS observations. In: *Atmospheric Remote Sensing*. *Elsevier.* 2023. pp. 63-84.

Singh BKR, Ali AM, Bahari SA and Abdullah M. *A Review on GBAS: Ionospheric Effects at Low-Latitude Regions,* 2024: pp. 337-346.

Stankov SM, Jakowski N, Heise S, Muhtarov P, Kutiev I and Warnant R. A new method for reconstruction of the vertical electron density distribution in the upper ionosphere and plasmasphere. *J. Geophys. Res. Space Phys.* 2003; 108(A5):1-21.