Ionospheric TEC Variations Across Latitudes During the May 2024 Geomagnetic Superstorm

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Abstract: ***Between May 8 and 13, 2024, Earth experienced an intense geomagnetic storm—one of the most powerful in recent decades—initiated by multiple X-class solar flares and rapid coronal mass ejections. This study investigates how the storm influenced ionospheric Total Electron Content (TEC) across low, mid, and high latitudes using data from GNSS-based ionosondes and solar-geophysical indices such as Dst, Kp, and IMF Bz. Findings indicate extreme TEC enhancements, especially in equatorial regions where values exceeded 48 TECU, far surpassing past storm benchmarks. The TEC fluctuations were largely attributed to prompt penetration electric fields, disturbance dynamo processes, and large-scale plasma redistribution. At mid- and high latitudes, different ionospheric dynamics emerged, including the influence of thermospheric winds and auroral precipitation. This analysis reinforces the need for coordinated global monitoring systems to better understand and mitigate space weather threats to navigation, communication, and infrastructure systems.***

Keywords: TEC variations, geomagnetic storm, ionospheric response, latitude dependence, space weather

1. Introduction: Geomagnetic storm

Geomagnetic storms, characterised by significant disturbances in the Earth's magnetosphere, primarily result from the interaction between the solar wind and the interplanetary magnetic field (IMF) with the Earth's magnetic field, often triggered by coronal mass ejections (CMEs) or high-velocity solar wind streams (Gonzalez et al., 1994; Pulkkinen, 2024). The Disturbance Storm Time (Dst) index exhibits greater negative values for stronger ring current disruptions, making it the best measure of geomagnetic storm strength (Love & Gannon, 2022). Figure 1, depicts the Dst patterns for three notable storms: 1989, 2003, and 2024. Each storm intensifies, recedes, and progresses at a distinct pace. The black line, representing the storm of 1989, indicates a rapid decline in Dst below -500 nT, signifying a significant event. Researchers have extensively examined this storm due to its significant effects on technology, notably the failure of the Hydro-Québec power grid (Bolduc, 2002; Boteler, 2019). Prominent research published in Nature and Science has shown that superstorms can produce geomagnetically induced currents (GICs) that threaten energy infrastructure on both continental and regional levels (Kappenman, 2005; Pulkkinen et al., 2012; Cliver & Dietrich, 2013). The 1989 storm has been used as a baseline for testing space weather models and has helped people around the world predict and cope with the effects of space weather better (Boteler, 2019; Hapgood, 2019). This study aims to examine the variations in Total Electron Content (TEC) across different latitudes in response to the May 2024 geomagnetic storm, using geophysical indices and satellite data to characterize ionospheric behaviour and assess space weather implications. The orange line shows the 2003 event. Its Dst profile is convoluted with two core minima at -400 nT. This indicates that Earth was struck by multiple coronal mass ejections in rapid succession. Significant research published in Science and Geophysical Research Letters has elucidated the intricate effects of "Halloween Storms", including heightened auroral activity at unusually low latitudes, satellite anomalies, and high-frequency radio disruptions (Lakhina et al., 2022; Gopalswamy et al., 2005).

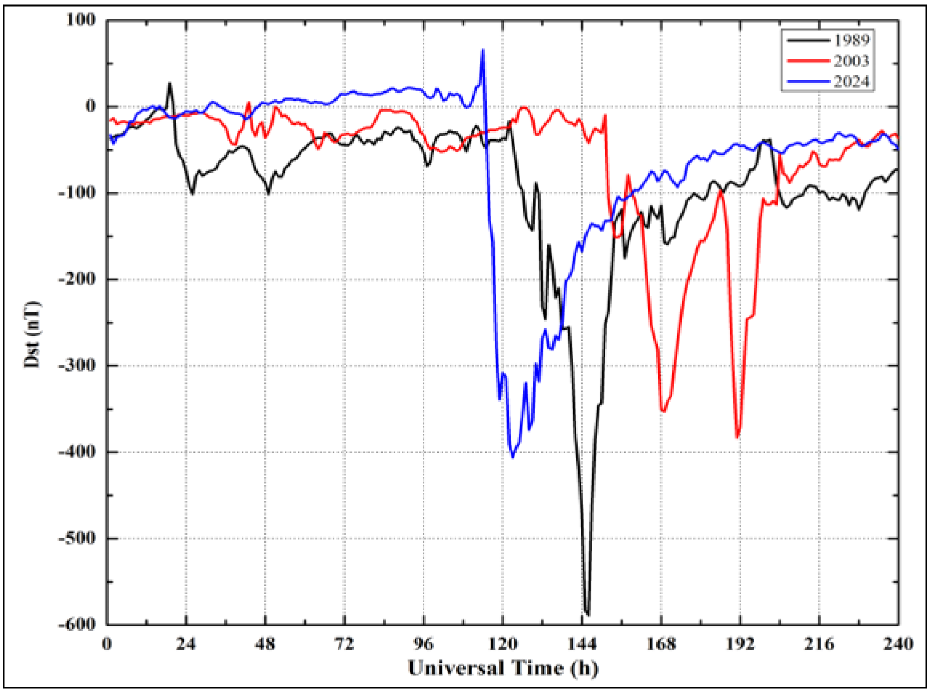

Figure 1: Dst patterns for three notable storms: 1989, 2003, and 2024

The storms of 2003 coincided with the most substantial solar energetic particle fluxes recorded in decades (Gopalswamy et al., 2005; Cliver & Svalgaard, 2004). The double-dip pattern in the Dst curve shows how different interplanetary shocks can mount up, and it has been regarded as a key challenge in predicting space weather (Pulkkinen, 2024). Recent high-impact studies have demonstrated that the 2003 superstorm exerted a greater influence on the world, negatively affecting satellite operations and aircraft. The blue line denotes a Dst of –300 nT for the 2024 storm, which was comparable in intensity to those in 1989 and 2003. This information supports the statement that moderate and strong geomagnetic activity may also be observed in the future (Gopalswamy et al., 2024). Dst index is essential for operations, real-time assessments, and global space weather risk reduction (Love & Gannon, 2022; Pulkkinen et al., 2012).

The paper is structured in the following way. Section 1 presents a background and importance of geomagnetic storms with referencing to some of the notable events in history and the effect on technology. Section 2 describes the sources of data, the preprocessing of TEC and space weather measurements and the approach of correlating ionospheric reaction with geomagnetic indices and Dst, Kp and IMF Bz. The results are presented in section 3 and they reveal the nature of the May 2024 geomagnetic storm including its impact on TEC at low, mid and high latitude, and the temporal and spatial patterns that were observed. These findings are discussed in the context of the existing literature on the technology implications and potential of multi-instrument observations in section 4. The last part provides the concluding remarks and summarizes the key findings and future perspectives of space weather monitoring and ionospheric investigations.

2. Data set

The primary source of information in the research was the GIRO Digital Ionosonde Database (DIDbase) (https://giro.uml.edu/didbase/scaled.php) that provided the vertical Total Electron Content (TEC) measurements of the selected low-, mid-, and high-latitude stations at the time interval 8-13 May 2024. This was done by using only those stations that contained continuous and good-quality data in the geomagnetic storm in the effort to achieve good spatial and temporal coverage. For low latitude WA619 (19.29^0 N, 166.64^0 E), mid latitude MHJ45 (42.6^0 N, 288.5^0 E), high latitude THJ76 (76.54^0 N, 291.56^0 E). The TEC values were standardised into TEC units (TECU), averaged hourly, and then filtered statistically to remove any outliers and to achieve data reliability. In order to contextualize these ionospheric measurements with respect to the activity of space weather, hourly Disturbance Storm Time (Dst) and Kp indices were acquired at the World Data Centre of Geomagnetism in Kyoto and the NOAA SWPC, and the interplanetary magnetic field (IMF) Bz component has been acquired in the NASA OMNI database. These geomagnetic and solar wind parameters were put in synchronised time series and utilised in order to subdivide the storm into pre-storm, main and recovery phases, as well as to enable direct quantitative comparison of TEC changes. In determining the dependence between TEC variations and the geomagnetic indices and IMF Bz, statistical correlation analysis was carried out, and special attention was given to the periods of intense southward Bz that is known to enhance the energy input to the magnetosphere and instrumental ionospheric perturbation. All data were processed, analysed and formatted in Microsoft Excel so as to allow reproducibility of the results as well as to provide a clear picture of the relationship between space weather drivers and the ionospheric response.

3. Result

3.1. Extreme Geomagnetic Disturbances of May 2024: Insights from Bz, Dst, and Kp.

From May 8 to 13, 2024, one of the largest geomagnetic storms of the 21st century impacted Earth's geomagnetic environment. This space weather event was caused by a rapidly evolving and highly active sunspot region, which resulted in a series of significant solar eruptions, including at least three fast, interacting coronal mass ejections (CMEs) and multiple X-class solar flares (NOAA SWPC, 2024; NASA Heliophysics, 2024). These solar eruptions were detected as they departed the Sun and were closely monitored as they traversed the interplanetary medium by space observatories such as SOHO and DSCOVR. Each CME inflicted shocks and compressions on the solar wind, which subsequently coalesced to form a highly turbulent sheath region (Wang et al., 2021). Between May 7 and May 9, the eruptions occurred. The first shock arrived at Earth in the early hours of May 9 UTC, as indicated by a sudden increase in solar wind speed (exceeding 800 km/s), proton density, and a sharp southward turn of the interplanetary magnetic field Bz component (figure 2), which dropped rapidly from near zero to less than –15 nT and remained negative for 36 hours (Gonzalez et al., 1994; Wang et al., 2021). This southward Bz orientation is recognised as the primary trigger for strong geomagnetic activity because it maximises magnetic reconnection at the dayside magnetopause, allowing solar wind energy to couple directly into the magnetosphere (Gonzalez et al., 1994). As Bz dropped and solar wind dynamic pressure surged, the Disturbance Storm Time (Dst) index began a precipitous decline: from quiet values near 0 nT at 00:00 UTC on May 9, Dst dropped below –100 nT by 10:00 UTC, signalling the commencement of a major geomagnetic storm according to NOAA SWPC and WDC Kyoto standards (NOAA SWPC, 2024). As CME-driven shocks hit one after the other over the next 24 hours, Dst kept going down, reaching –200 nT by the evening of May 9, –350 nT by the early hours of May 10, and finally bottoming out between –400 and –450 nT by midday on May 10.

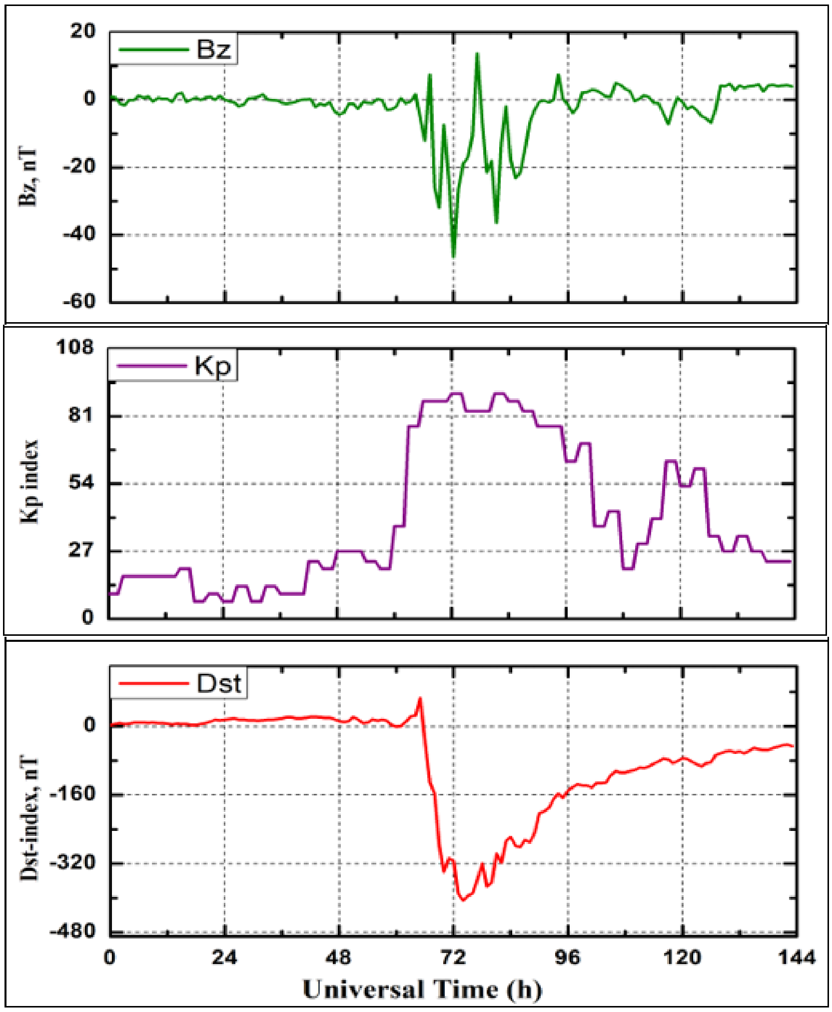

Figure 2: Dst, Kp and Bz index values of the period of May 8 to 13, 2024

This is a level that is rarely seen outside of historic superstorms like the 1989 Quebec and 2003 Halloween events (Gonzalez et al., 1994). This long, deep drop in Dst lasted for more than 30 hours. This means that the ring current, which is a group of energetic ions that circle the Earth, had been greatly increased, which compressed the magnetosphere and caused strong geomagnetic currents at the surface (Pulkkinen, 2017; NOAA SWPC, 2024). In synchrony with the Dst depression, the planetary Kp index, which aggregates 3-hourly geomagnetic activity from a global network of mid-latitude magnetometers, surged from values of Kp=3 in the pre-storm interval to Kp=6 at the time of the storm's main phase onset (about 06:00–09:00 UTC, May 9), then spiked to Kp=8+ between 12:00 and 21:00 UTC on May 10, marking a period of extreme global geomagnetic disturbance (Bartels, 1949; NOAA SWPC, 2024). The auroral oval grew to 30°N according to satellite and ground reports (NASA Heliophysics, 2024; ESA SWE, 2023). This enabled auroras across Texas, California, southern Europe, and northern India. The southward Bz component, often between –20 and –25 nT, facilitated solar wind-magnetosphere interaction, generated PPEFs, and boosted magnetotail substorm activity, affecting the intensity of this event. This caused energy and plasma to be injected into the inner magnetosphere and upper atmosphere (Wang et al., 2021).

Post-event analyses emphasise the crucial need for improved forecasting of IMF Bz (still a major uncertainty in space weather prediction), real-time operational TEC monitoring, and international collaboration in both scientific research and infrastructure resilience (Bilitza et al., 2022; ESA SWE, 2023).

3.2 Effects of the May 8–13, 2024 geomagnetic storm on TEC at low, mid, and high latitudes

During the intense geomagnetic storm occurring from May 8 to 13, 2024, the TEC across different latitudes showed pronounced and dynamic variations, as is evident from the 144-hour time series data (figure 3). For the purposes of this analysis, the time periods are divided as follows: 0–24 hours (May 8), 24–48 hours (May 9), 48–72 hours (May 10), 72–96 hours (May 11), 96–120 hours (May 12), and 120–144 hours (May 13).

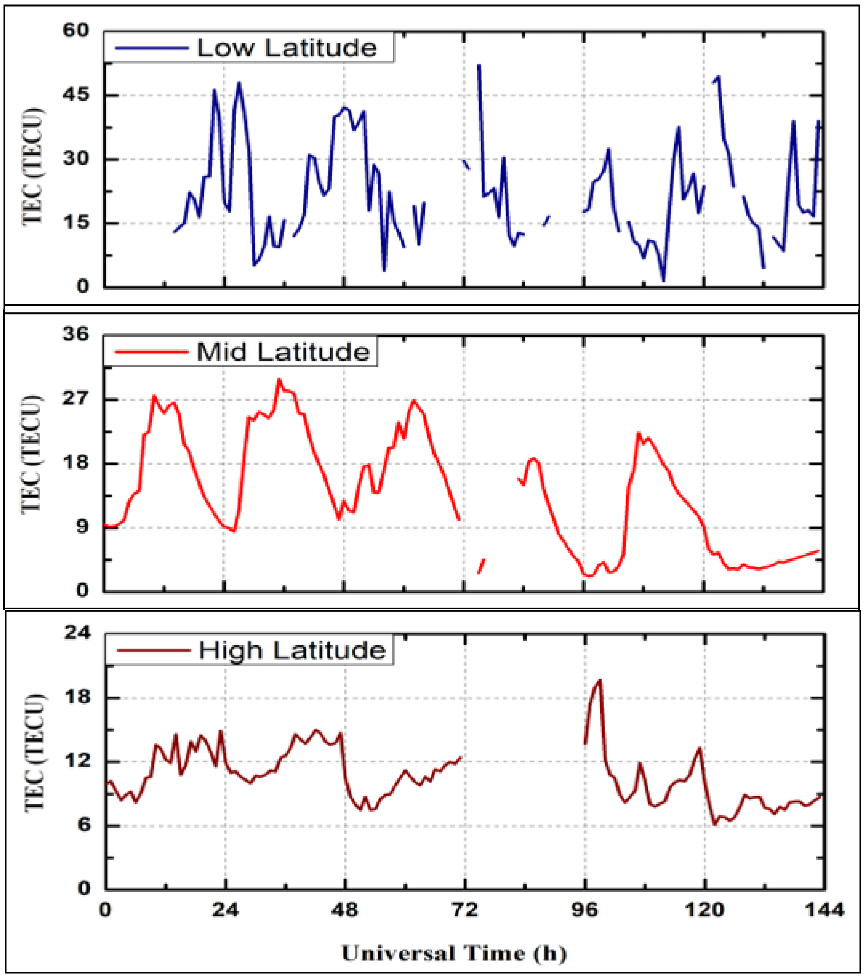

Figure 3: TEC values for low, mid, and high latitude for May 8 to 13, 2024

Low Latitudes: On May 8 (0–24 hours), the TEC at low latitudes experienced a significant surge from approximately 24 TECU to peaks of 36 TECU, with pronounced variations continuing throughout the day. On May 9, TEC fluctuated several times above 48 TECU, interspersed with swift declines down around 12 TECU during a 24–48-hour period. The significant variations are mainly due to the effects of Prompt Penetration Electric Fields (PPEF) and disturbance dynamo processes, which are known to be important in equatorial ionospheric storms (Kelley, 2009; Richmond, 1995; Qian et al., 2021). The TEC measurements decreased on May 10 (48–72 hours), while considerable volatility persisted. On May 11 (72–96 hours), there was a subsequent increase, coinciding with the storm's primary phase. Changes in TEC on May 12 and 13 showed that there was a strong geomagnetic storm that would last for a long time. The unusually high TEC peaks recorded during this storm exceed those from recent events, underlining its severity.

Mid-Latitudes: On May 8, mid-latitude TEC began at roughly 10 TECU, peaking at 24 to 30 TECU during daylight hours, and subsequently declining overnight. The diurnal cycle continued on May 9, 10, and 11, with the most significant decrease observed on May 11, coinciding with the storm's primary phase, in accordance with established storm-related ionospheric patterns (Prölss, 2004). On May 12 and 13, TEC exhibited a gradual decline, punctuated by intermittent brief surges. These patterns show solar-induced ionisation, interrupted neutral winds, and TIDs (Hunsucker, 1982; Kelley, 2009). Recent and fundamental research has shown positive (enhancement) and negative (depletion) storm-time phases at these latitudes, supporting the data's general trend.

High Latitudes: The TEC at high latitudes exhibited relative stability, often ranging from 6 to 18 TECU. Insignificant increases were noted on May 11 (72–96 hours) and May 13 (120–144 hours); however, these were negligible in comparison to lower latitudes. This aligns with the traditional perspective that, although auroral precipitation and particle influx are pronounced at high latitudes during storms, the cumulative electron content remains comparatively low due to accelerated recombination rates and diminished background densities (Kelley, 2009; Hunsucker, 1982). These findings are consistent with both recent studies and established ionospheric research indicating that high-latitude TEC boosts during storms are generally ephemeral and localised.

4. Discussion

The May 2024 geomagnetic storm provided a unique opportunity to observe the complicated state of ionospheric response during the severe space weather. TEC was observed to dramatically rise and exceed the normal diurnal patterns, especially during the main storm and subsequent to it. The primary reasons behind these enhancements were the large levels of solar EUV and X-ray flux, prompt penetration electric fields and the exaggerated neutral wind motions (Tsurutani et al., 2004).

The link between the input of energy in high latitudes and the reorganisation of the global plasma was also revealed by the fact that persistent high TEC into evening and nighttime hours, as well as the nocturnal sharp variations that were synchronised with the occurrence of substorms (Coster et al., 2023; Wang et al., 2021; Themens et al., 2024). It is also confirmed by the recent observations that both the formation of the large-scale ionospheric disturbances and the long belts of enhanced ionisation are characteristic of the powerful geomagnetic storms not only due to the magnetospheric forcing but also due to the thermospheric physics (Carmo et al., 2024; Danilchuk et al., 2025).

Technologies had a really broad impact; satellites all over the world experienced both the increase in GNSS positioning errors and communication failures (Pulkkinen, 2017; Hapgood, 2019; Gordiyenko et al., 2025). In North America and Europe, geomagnetically induced currents (GICs) occurred and required active mitigation measures to safeguard the infrastructure (NOAA SWPC, 2024; Love et al., 2020).

This experience proved the topicality of the multi-instrument observations (GNSS, ionosondes, magnetometers, and satellites), which are coordinated to present the entire picture of the ionospheric disturbances (Bilitza et al., 2022; Li et al., 2025). Both augmented monitoring and interdisciplinary research should improve space weather predictions and the development of effective mitigating measures in the event of extreme events in the future.

In conclusion, the May 2024 storm proved the need to use the integrated observational networks and further develop the models to understand and manage the threats of extreme geomagnetic disturbances.

The findings are significant, as they provide new insights into latitude-dependent ionospheric responses during extreme geomagnetic storms, thereby contributing to the development of more accurate forecasting models and mitigation strategies for space weather disruptions.

5. Conclusion

The May 2024 geomagnetic storm revealed complex and pronounced ionospheric disturbances across all latitudinal zones, particularly at low latitudes, where TEC values spiked significantly. These findings reaffirm the crucial role of integrated monitoring systems in understanding the spatial and temporal dynamics of ionospheric responses. Given the increasing reliance on GNSS and communication technologies, improving space weather forecasting and preparedness is more urgent than ever. This study contributes a valuable dataset and analytical framework for future modelling efforts and highlights the need for global coordination in space weather mitigation strategies.

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