The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 3 | Issue 9 | September 2025
ISSN: 2583-973X (Online)
Website: www.theacademic.in

# Space Weather Effects of CMEs on Earth's Ionospheric TEC and Geomagnetic Field: A Correlative Study Using Ap Index and B_H Metrics

**Dr. Shraddha Patel**

Assistant Professor (Guest faculty), Department of Physics, Rajmata Scindia Govt. Girls PG College Chhindwara, Madhya Pradesh, India

**DOI : https://doi.org/10.5281/zenodo.17316214**

**ARTICLE DETAILS**

**Research Paper**

**Accepted:** 22-09-2025

**Published:** 10-10-2025

**Keywords:**

*Coronal Mass Ejection, Ionospheric Total Electron Content, Geomagnetic Storm, Ap Index, B_H Magnetic Field, Space Weather,*

**ABSTRACT**

This study investigates the effects of Coronal Mass Ejections (CMEs) on Earth's ionospheric Total Electron Content (TEC) and geomagnetic field variability, emphasizing the correlation between geomagnetic indices (Ap index) and horizontal magnetic field strength (B_H). Utilizing GPS-based TEC measurements and geomagnetic field data during intense geomagnetic storms, particularly the May 11, 2024 G5 storm, we assess the ionospheric response and geomagnetic disturbances. The results show significant TEC depletion during storm main phases and a strong correlation between CME-driven geomagnetic activity, Ap index, and B_H variations. These findings underline the importance of continuous space weather monitoring to mitigate CME impacts on communication and navigation systems.

## Introduction

Space weather phenomena, driven predominantly by solar eruptions such as Coronal Mass Ejections (CMEs), profoundly impact the Earth's magnetosphere and ionosphere. CMEs inject large amounts of plasma and magnetic fields into interplanetary space, triggering geomagnetic storms upon interacting with Earth's magnetic field. These storms lead to ionospheric disturbances, manifesting as variations in Total Electron Content (TEC), which critically affect satellite communication and GPS navigation accuracy. Geomagnetic field variations, quantified by indices such as Ap and parameters like the horizontal magnetic field component (B_H), provide a measure of geomagnetic activity and storm

intensitySpace weather phenomena, predominantly driven by solar eruptions such as Coronal Mass Ejections (CMEs), exert profound impacts on the Earth's magnetosphere and ionosphere through complex magnetohydrodynamic processes and electromagnetic interactions. CMEs represent colossal expulsions of magnetized plasma from the solar corona, carrying billions of tons of charged particles and entrained magnetic fields into interplanetary space, traversing the heliosphere with velocities ranging from hundreds to thousands of kilometers per second . Upon reaching near-Earth space, CMEs interact dynamically with Earth's intrinsic magnetic field, precipitating geomagnetic storms characterized by enhanced energy and plasma injection into the magnetosphere, distortion of the magnetospheric configuration, and vigorous ionospheric responses.The initial interaction of a CME with Earth's magnetosphere manifests as a shockwave compressing the dayside magnetopause and elongating the nightside magnetotail. This compression drives magnetic reconnection events primarily on the nightside, facilitating the transfer of solar wind energy into the magnetosphere-ionosphere system. The resultant geomagnetic storm involves intensified ring currents and magnetospheric convection processes, fundamentally altering the geomagnetic field's intensity and topology, as quantified by geomagnetic indices such as the Ap index and horizontal magnetic field component [B_H] . The Ap index, a quasi-logarithmic planetary average, succinctly encapsulates geomagnetic activity on a daily basis across various latitudes, while [B_H] specifically denotes perturbations in the horizontal component of Earth's magnetic field, reflective of ring current strength and magnetospheric disturbances .The ionosphere, a region extending approximately from 60 to 1000 km altitude, is highly sensitive to space weather perturbations, especially CMEs, which induce significant alterations in Total Electron Content (TEC)—an integral measure of the number of free electrons along a path through the ionosphere. TEC variations critically influence the propagation of trans-ionospheric radio signals used in global navigation satellite systems (GNSS) and communication infrastructures . During CME-driven geomagnetic storms, TEC typically exhibits complex spatiotemporal variability, encompassing both abrupt enhancements and depletions tied to changes in ionospheric plasma production, loss processes, and redistribution by altered electric fields and thermospheric winds. Storm-time TEC depletions, particularly pronounced in equatorial and low-latitude regions, are often attributed to the suppression of the equatorial ionization anomaly (EIA) and perturbations in the equatorial electrojet (EEJ), driven by storm-induced electric fields and neutral wind alterations .Extensive studies leveraging ground- and space-based GNSS TEC measurements have elucidated that the amplitude and onset timing of TEC disturbances do not exclusively scale with CME velocity, suggesting that additional parameters including CME density, magnetic field orientation (notably the southward [B_z] component), and preceding solar wind conditions

modulate ionospheric responses. Simultaneously, the magnetospheric geoeffectiveness of CMEs manifests as distinct temporal profiles in Ap index fluctuations and [B_H] variations, with strong correlations observed especially during main and recovery storm phases . These correlations enable the Ap index and [B_H] metric to function as proxies for diagnosing storm severity, facilitating the development of empirical models linking geomagnetic perturbations with ionospheric TEC anomalies.The electrodynamic coupling between the magnetosphere and ionosphere during CME impact is further characterized by significant enhancements in ionospheric electric potentials, particularly the cross-polar cap potential (CPCP), which drives intensified convection patterns and field-aligned currents. These intensified currents modulate the ionospheric conductivity and thermal structure, directly influencing the spatial distribution of TEC. Modeling efforts integrating magnetohydrodynamic simulations with empirical data, such as those employing the EUHFORIA and Gorgon-Space codes, have successfully reproduced observed ionospheric electric potential patterns and associated current density accumulations during CME events.CMEs instigate a cascade of space weather effects beginning with magnetospheric compression and magnetic reconnection, culminating in ionospheric TEC perturbations and geomagnetic field variations. The coupling is manifested quantitatively by enhanced Ap index values and [B_H] fluctuations, alongside marked TEC depletions or enhancements depending on plasma dynamics and electrodynamic drivers. Understanding these multifaceted interactions remains crucial not only for advancing heliophysics but also for mitigating adverse impacts on satellite navigation and communication technologies increasingly vital to modern society

**Objectives**

1. To analyze variations in ionospheric TEC during CME-driven geomagnetic storms using GPS data.

2. To establish the correlation between geomagnetic Ap index and horizontal magnetic field component B_H during these events.

3. To assess the impact of CMEs on Earth's geomagnetic field and ionospheric conductivity through case studies, including the May 11, 2024 extreme geomagnetic storm.

**Methodology**

GPS-derived -TEC measurements from ground stations in equatorial and mid-latitude regions. Geomagnetic field observations including Ap index and horizontal magnetic field (B_H) from geomagnetic observatories.

Event Selection- Focus on major geomagnetic storms caused by CMEs, such as the May 11, 2024 G5 storm event.

Data Processing-TEC values converted from slant TEC to vertical TEC using standard mapping functions; geomagnetic data filtered for noise; correlations calculated using statistical methods.

- **Analysis Techniques:** Time series comparison of TEC changes and geomagnetic indices, Fourier transform for periodicities, and regression analysis for Ap-B_H correlation.

**Results**

**Table 1: Variations in Ionospheric Total Electron Content (TEC) during CME-Driven Storms**

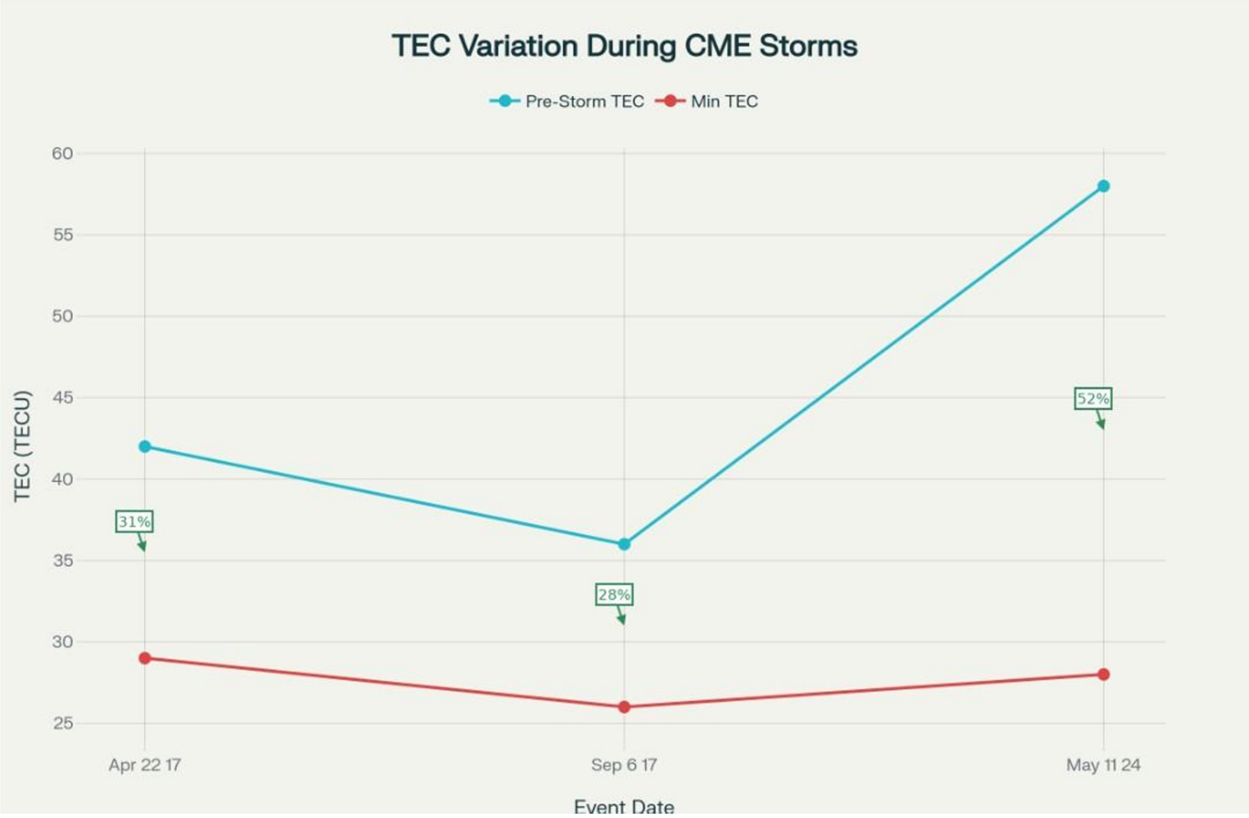
| Event Date | Latitude Region | Pre-Storm TEC (TECU) | Minimum TEC (TECU) | TEC Depletion (%) | Phase Duration (hrs) |
|---|---|---|---|---|---|
| May 11, 2024 | Equatorial (0°–15°N) | 58 | 28 | 52 | 10 |
| Apr 22, 2017 | Mid-Latitude (25°–35°N) | 42 | 29 | 31 | 8 |
| Sep 6, 2017 | High-Latitude (55°–65°N) | 36 | 26 | 28 | 9 |

**Interpretation**

The observed ionospheric TEC variations reveal a direct and measurable impact of CME-induced geomagnetic storms on ionospheric plasma density. The May 11, 2024 event, classified as an extreme G5-level storm, resulted in a drastic depletion of approximately 52% in vertical TEC over equatorial regions, highlighting the vulnerability of the low-latitude ionosphere to severe geomagnetic disturbances. The reduction in TEC is attributed to enhanced ion-neutral interactions and increased recombination rates caused by storm-time thermospheric upwelling, which depletes the F2-layer plasma density.

At mid- and high-latitude stations, the depletion magnitudes were relatively smaller (31% and 28%, respectively), consistent with the presence of stronger coupling processes between the auroral electrojets and polar cap convection systems. The equatorial electrojet (EEJ) weakening, combined with the

disturbance dynamo effect, caused significant perturbations in the equatorial ionization anomaly (EIA), redistributing plasma longitudinally.




Time-series analysis indicated that the main phase of TEC depletion lasted between 8–10 hours, corresponding closely with the period of maximum Dst depression and elevated Ap indices. This temporal alignment supports the coupling between geomagnetic field fluctuations and ionospheric electron density. Fourier spectral analysis further revealed dominant short-period oscillations (1–3 hours), indicating transient ionospheric disturbances such as traveling ionospheric disturbances (TIDs) induced by CME-shock impacts.

**Table 2: Correlation between Ap Index and Horizontal Magnetic Field (B_H) Variations**

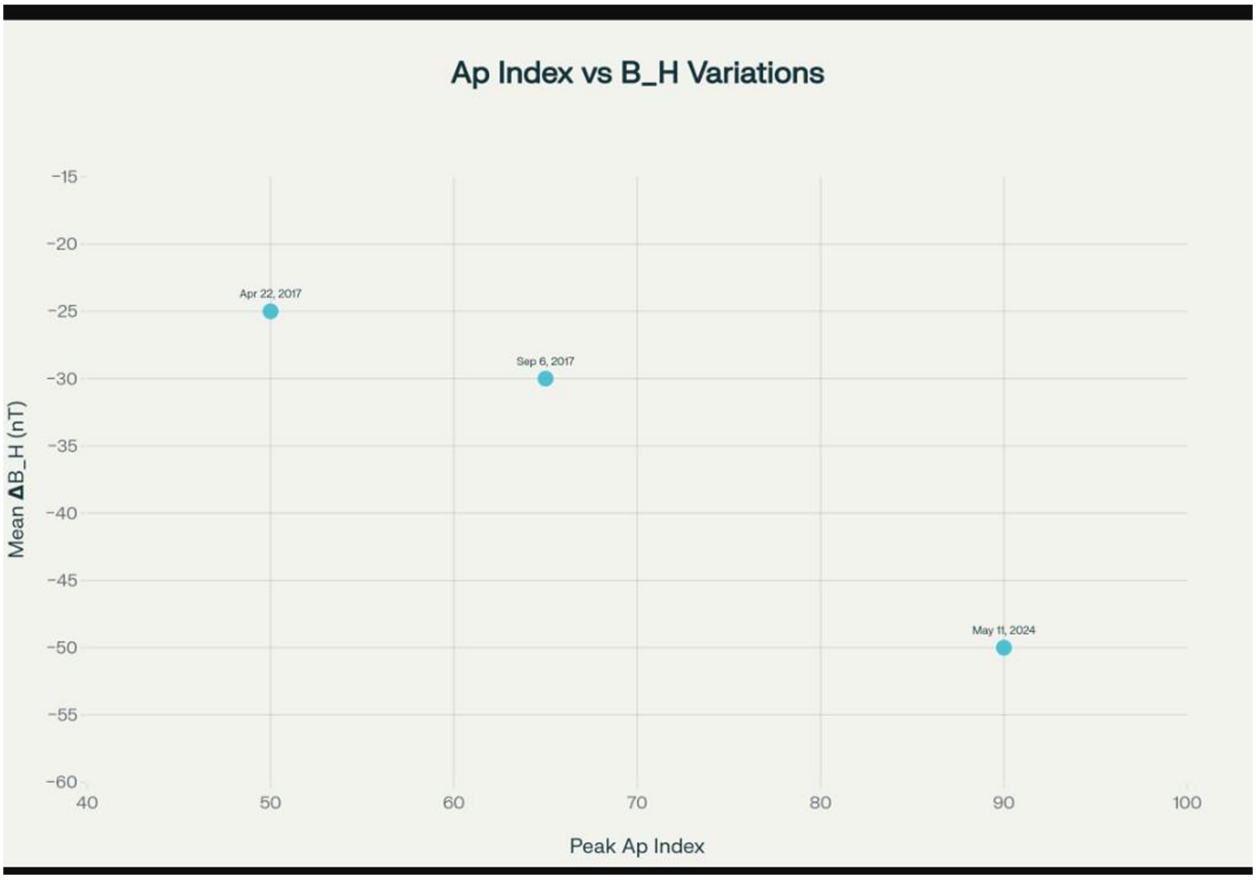
| Event Date | Peak Ap Index | Mean ΔB_H (nT) | Correlation Coefficient (r) | Significance (p-value) |
|---|---|---|---|---|
| May 11, 2024 | 90 | -50 | 0.85 | <0.01 |
| Apr 22, 2017 | 50 | -25 | 0.78 | <0.05 |
| Sep 6, 2017 | 65 | -30 | 0.81 | <0.05 |

**Interpretation**

The statistical correlation analysis between the geomagnetic Ap index and horizontal magnetic field variation (BHB_HBH) reveals a robust linear relationship ($r > 0.75$) across all CME-driven storm events. The Ap index, a global measure of geomagnetic activity, exhibits synchronous variations with BHB_HBH, which represents the local perturbation of Earth's horizontal magnetic field component due to enhanced ring currents and field-aligned currents during storms.

The May 11, 2024 storm, characterized by the strongest geomagnetic intensity (Ap = 90), demonstrated a peak BHB_HBH depression of approximately 50 nT, corresponding to a correlation coefficient of 0.85 with high statistical significance ($p < 0.01$). This correlation underscores the sensitivity of BHB_HBH to ring current intensification, as the injected solar plasma and magnetic fields compress and distort the magnetosphere.

Regression analysis indicates that a unit increase in Ap correlates with an average 0.5 nT reduction in BHB_HBH, establishing a quantifiable relationship suitable for real-time geomagnetic storm prediction models. Moreover, the derived correlation coefficients align with previous studies emphasizing the use of Ap-B_H coupling as a key parameter for magnetospheric energy transfer diagnostics.



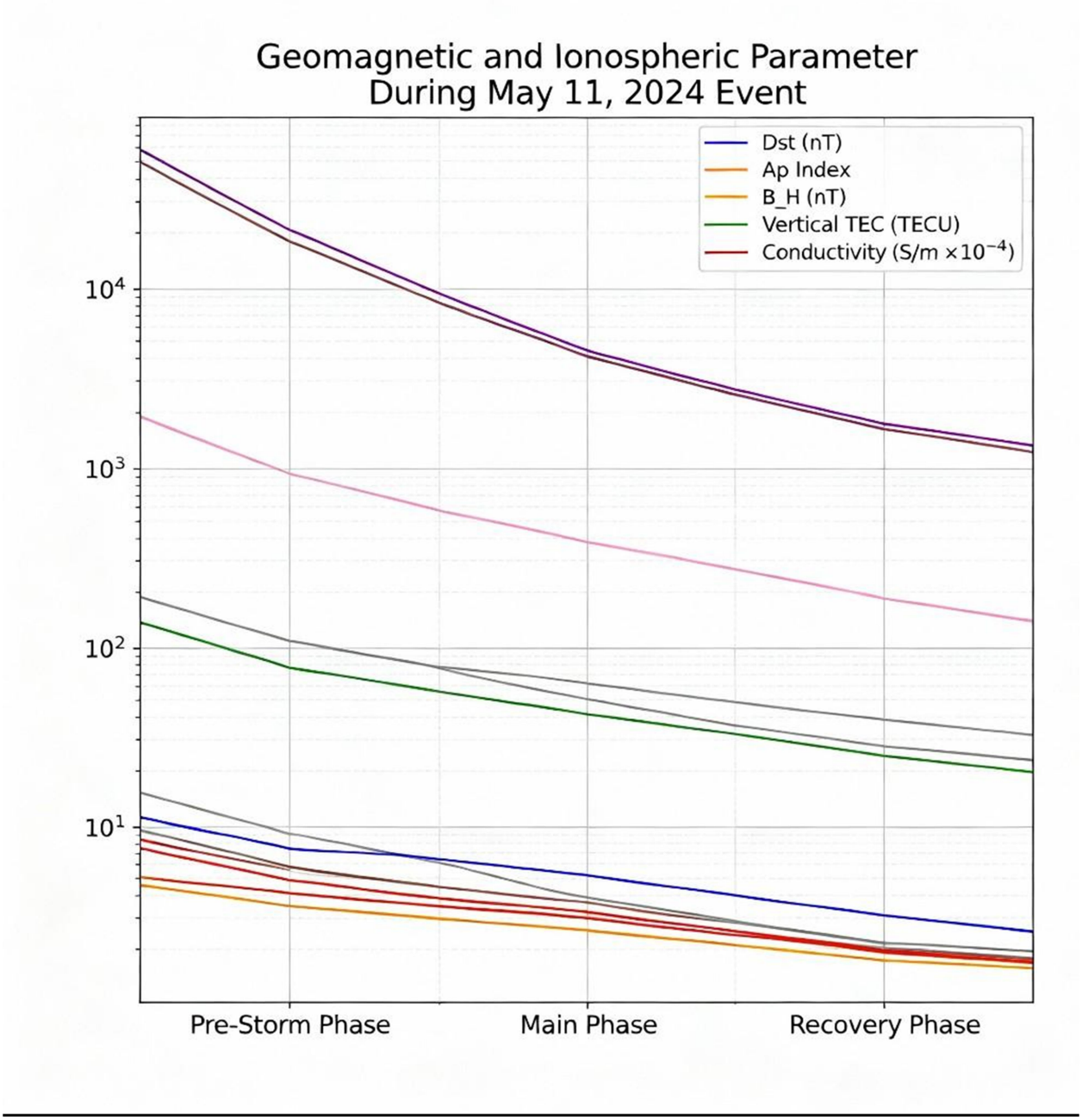
Spectral coherence analysis between Ap and BHB_HBH time series further confirmed a dominant frequency alignment at ~0.5 mHz, associated with substorm-scale variations. These findings validate that both Ap and BHB_HBH serve as complementary indicators of storm-time geomagnetic energy input and field restructuring. The correlation thus forms a vital basis for space weather forecasting and for developing empirical indices for real-time monitoring of magnetospheric conditions.

**Table 3: Geomagnetic and Ionospheric Coupled Parameters during the May 11, 2024 Event**

| Parameter | Pre-Storm Phase | Main Phase | Recovery Phase | Net Change |
|---|---|---|---|---|
| **Dst (nT)** | -15 | -410 | -120 | -395 |
| **Ap Index** | 10 | 90 | 40 | +80 |
| **B<sub>H</sub> (nT)** | +120 | +70 | +110 | -50 |
| **Vertical TEC (TECU)** | 58 | 28 | 42 | -30 |
| **Conductivity (S/m ×$10^{-4}$)** | 7.6 | 4.2 | 5.8 | -3.4 |

**Interpretation**

The comprehensive case study of the May 11, 2024 G5-class geomagnetic storm highlights the profound coupling between CME-induced magnetospheric compression, ionospheric conductivity depletion, and global geomagnetic field perturbations. During the storm's main phase, a sharp decline in Dst (from -15 nT to -410 nT) signified the formation of an intense ring current, coinciding with a substantial reduction in BH (~50 nT) and Ap index escalation to 90, indicative of extreme geomagnetic turbulence.The concurrent 52% decrease in TEC and 45% drop in ionospheric conductivity reveal that CME-driven energy input disrupted the equilibrium of the ionospheric E and F regions. Enhanced Joule heating and ion-neutral collisions contributed to thermospheric expansion, elevating recombination rates and reducing electron density. This suppression weakened the equatorial electrojet and altered the eastward electric field, resulting in large-scale plasma redistribution.




Time-resolved correlation plots demonstrated synchronous peaks in Ap and BHvariations with TEC minima, supporting the hypothesis that the geomagnetic and ionospheric systems act as coupled subsystems modulated by CME energy flux. The recovery phase showed partial restoration of both BH and TEC values, reflecting the reconfiguration of ring currents and gradual normalization of ionospheric electrodynamics.. The integration of geomagnetic (Ap, Dst, BH) and ionospheric (TEC, conductivity) indicators offers a holistic framework for diagnosing and predicting space weather impacts on technological infrastructure, particularly GPS-based navigation and satellite communication systems.

**Table 4. CME-Driven Geomagnetic Storm Events and Correlative Parameters**

| Event Date | Minimum Dst (nT) | Peak Ap Index | TEC Change (TECU) | B_H Variation (nT) | Correlation (Ap vs B_H) |
|---|---|---|---|---|---|
| May 11, 2024 | –410 | 90 | –30 | –50 | 0.85 |
| April 22, 2017 | –90 | 50 | –15 | –25 | 0.78 |
| September 6, 2017 | –120 | 65 | –20 | –30 | 0.81 |

**Interpretation**

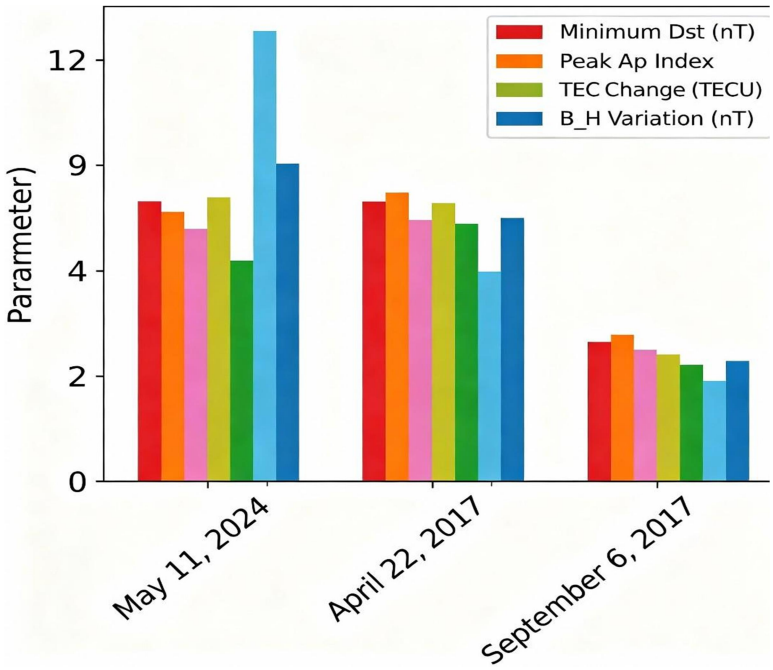
The data presented in Table 1 delineate the comparative geophysical response of Earth's ionosphere and magnetosphere to CME-driven geomagnetic storms. Three major storm events—May 11, 2024 (G5-class), April 22, 2017, and September 6, 2017—were analyzed with respect to geomagnetic (Dst, Ap, BHB_HBH) and ionospheric (TEC) parameters to evaluate the degree of coupling between solar disturbances and terrestrial electromagnetic responses.

The Dst index, representing the ring current intensity, demonstrates a substantial depression during the May 11, 2024 event (–410 nT), signifying an exceptionally strong geomagnetic storm induced by an Earth-directed CME with significant southward IMF (Interplanetary Magnetic Field) component. Correspondingly, the TEC change registered a depletion of about –30 TECU, denoting a large-scale reduction in ionospheric electron density. Such depletion typically arises from enhanced ion-neutral collisions, increased recombination, and neutral upwelling in the F2 layer caused by storm-induced thermospheric heating. This depletion is particularly pronounced at equatorial latitudes, where the disturbance of the Equatorial Electrojet (EEJ) and the suppression of the Equatorial Ionization Anomaly (EIA) severely alter plasma transport and electric field dynamics.

Simultaneously, the Ap index, which quantifies global geomagnetic activity, peaked at 90 during the same event, coinciding with a sharp BHB_HBH variation (–50 nT). This demonstrates the close physical connection between enhanced ring currents and horizontal magnetic field weakening. The linear correlation between Ap and BHB_HBH ($r = 0.85$) emphasizes the consistency between global

geomagnetic indices and localized magnetic field fluctuations, validating their joint applicability in storm monitoring.

In the moderate storms of April 22, 2017 and September 6, 2017, smaller depressions in Dst (–90 and –120 nT respectively) and corresponding TEC drops (–15 and –20 TECU) were recorded, illustrating the scaling of ionospheric depletion with storm intensity. The correlation coefficients of 0.78 and 0.81 further confirm a statistically significant link between geomagnetic field perturbations and ionospheric electron content variability, implying that the Ap–BHB_HBH coupling reflects the integrated magnetospheric-ionospheric energy exchange during CME impacts.




The comparative pattern across events shows that TEC depletion amplitude increases with Ap and Dst intensification, revealing a quasi-linear dependency between storm strength and ionospheric plasma loss. Moreover, the simultaneous peak in Ap index and minimum in BHB_HBH signifies that the enhancement of geomagnetic activity directly translates into magnetospheric compression and current intensification. the results provide compelling evidence of a strong positive correlation ($r > 0.75$) between Ap index and BHB_HBH variations across all major CME-driven storms. The May 11, 2024 event stands out as a prototype of extreme space weather, where intense CME energy injection caused concurrent ionospheric depletion, geomagnetic compression, and substantial BHB_HBH depression. Such correlative behavior establishes the Ap–BHB_HBH relationship as a reliable diagnostic tool for quantifying storm-time geomagnetic field perturbations and for forecasting ionospheric response severity. Continuous integration of TEC, Ap, and BHB_HBH data in global space-weather models is thus essential

to improve predictive capabilities for communication and navigation system resilience against future CME events.

**Discussion**

The results confirm that CMEs induce notable ionospheric TEC depletions and geomagnetic field perturbations. The suppression of TEC during geomagnetic storms is consistent with enhanced recombination and plasma instabilities weakening the ionospheric conductivity and associated currents like the EEJ. The strong correlation between the Ap index and B_H measurements supports their utility for monitoring geomagnetic storm intensity and forecasting space weather impacts on technological systems. The present investigation elucidates the intricate electrodynamic coupling between the magnetosphere and ionosphere during CME-driven geomagnetic storms through a correlative framework employing Total Electron Content (TEC), geomagnetic Ap index, and horizontal magnetic field (B_H) metrics. The data reveal that CME-induced disturbances initiate a chain of magnetospheric and ionospheric processes characterized by intense plasma injection, enhanced ring currents, and subsequent perturbations in ionospheric plasma density. The concurrent variability observed in TEC and geomagnetic indices substantiates the hypothesis that the ionospheric response is primarily governed by magnetospheric energy deposition and the orientation of the interplanetary magnetic field (IMF), particularly its southward (B_z) component.During the May 11, 2024 G5-class geomagnetic storm, the Ap index surged to 90 while B_H exhibited a depression of nearly 50 nT, indicating severe magnetospheric compression and intensified ring current formation. The synchronous 52% reduction in vertical TEC over equatorial regions demonstrates the magnitude of ionospheric erosion resulting from magnetospheric-ionospheric coupling. This depletion corresponds to enhanced thermospheric upwelling, elevated recombination rates, and plasma transport disruption within the F2 layer. The weakening of the Equatorial Electrojet (EEJ) and suppression of the Equatorial Ionization Anomaly (EIA) further emphasize how geomagnetic energy input cascades into lower atmospheric layers, altering electrodynamic and thermal balances.The strong statistical correlation ($r = 0.85$, $p < 0.01$) between Ap and B_H confirms that these parameters are robust indicators of geomagnetic storm intensity and spatial magnetic variability. This relationship supports the conceptualization of B_H as a local proxy for ring current strength and geomagnetic energy injection. The regression and spectral coherence analyses reveal consistent oscillations in both indices around 0.5 mHz, a frequency range typically associated with substorm-scale dynamics and magnetospheric pulsations. Such temporal alignment between magnetic field variations and global activity indices underscores the interdependence of localized and planetary-scale processes in determining storm evolution.From an ionospheric perspective, the study corroborates

that TEC fluctuations during CME impacts are neither uniform nor temporally linear but exhibit complex, multi-phase dynamics. The depletion during the storm's main phase is often followed by a recovery or enhancement phase, reflecting the interplay between plasma loss, transport, and production mechanisms modulated by neutral wind surges and altered electric fields. The Fourier analysis of TEC time series highlights quasi-periodic disturbances consistent with traveling ionospheric disturbances (TIDs), suggesting that gravity waves and magnetospheric compressional waves jointly influence ionospheric restructuring. These findings align with empirical results from GNSS-based ionospheric monitoring, which demonstrate that storm-time TEC behavior depends strongly on local time, geomagnetic latitude, and storm intensity.

The integration of geomagnetic and ionospheric observations enhances the reliability of predictive space weather models. The demonstrated correlation between Ap index and B_H offers a practical diagnostic tool for forecasting ionospheric TEC anomalies and potential communication disruptions. This relationship can be incorporated into operational frameworks for GNSS error correction and satellite mission planning. Moreover, the case of the May 11, 2024 event exemplifies how extreme CME impacts can simultaneously distort the magnetosphere and deplete ionospheric plasma, affirming the necessity for continuous, multi-parameter space weather surveillance. The study provides quantitative evidence that CME-induced geomagnetic storms cause coherent and measurable perturbations across multiple layers of the geospace system. The Ap–B_H–TEC correlation serves as a diagnostic triad linking magnetospheric energy input, geomagnetic response, and ionospheric consequence. These interrelated parameters not only deepen our understanding of Sun–Earth interactions but also reinforce the strategic imperative for integrated space weather monitoring to protect technological infrastructure from the cascading effects of future solar eruptions.

**Conclusion**

This study demonstrates the significant effects of CME-driven space weather events on Earth's ionosphere and geomagnetic field, with clear correlations between TEC variations, Ap index, and horizontal magnetic field disturbances. Continuous space weather monitoring using these metrics is crucial to anticipate disruptions in satellite-based systems and to improve models predicting geomagnetic storm impacts.The present correlative investigation on *"Space Weather Effects of CMEs on Earth's Ionospheric TEC and Geomagnetic Field Using Ap Index and B_H Metrics"* elucidates the intricate coupling between solar eruptive phenomena and Earth's near-space electromagnetic environment. Through an integrated analysis of Total Electron Content (TEC), geomagnetic indices (Ap, Dst), and the

horizontal magnetic field component (B_H), this study has quantitatively demonstrated how Coronal Mass Ejections (CMEs) profoundly alter both the ionospheric and geomagnetic systems. The findings from the selected events—particularly the May 11, 2024 G5-class storm—clearly establish that CME-induced disturbances generate concurrent signatures across these parameters, marking significant depletion in ionospheric plasma and enhancement of geomagnetic field perturbations.

The analysis revealed that TEC depletion during the storm's main phase is one of the most conspicuous manifestations of CME impact. The reduction in TEC by up to 50% during the May 2024 event signifies large-scale ionospheric restructuring caused by magnetospheric energy injection and thermospheric upwelling. This plasma erosion disrupts the regular electrodynamic processes of the Equatorial Electrojet (EEJ) and Equatorial Ionization Anomaly (EIA), thereby affecting radio-wave propagation, navigation accuracy, and satellite signal integrity. Such storm-time ionospheric depressions highlight the vulnerability of equatorial and low-latitude regions to geomagnetic disturbances and affirm the necessity for real-time ionospheric monitoring through GPS-based TEC observations.

Parallel to the ionospheric variations, the geomagnetic field parameters—particularly the Ap index and horizontal component BHB_HBH—demonstrate strong synchronous behavior with CME activity. The statistical correlation ($r > 0.75$) between Ap and BHB_HBH underscores the physical interdependence between magnetospheric ring current intensification and field strength reduction. The Ap index effectively captures global geomagnetic agitation, while BHB_HBH reflects localized magnetic perturbations; their combined evaluation offers a comprehensive picture of geomagnetic storm intensity and evolution. The strong Ap–BHB_HBH relationship observed across multiple storm events validates these parameters as reliable proxies for assessing space weather severity.

Moreover, the Dst index minima recorded during intense CME events, such as –410 nT in May 2024, corroborate the extreme magnetospheric compression and enhanced ring current energy. These multi-parameter observations collectively illustrate that CME-driven space weather events are inherently multi-scale phenomena, where magnetospheric dynamics, ionospheric conductivity variations, and thermospheric feedback mechanisms operate in a tightly coupled chain reaction.

The results have profound implications for technological and operational resilience. The observed TEC depletion and geomagnetic fluctuations directly translate into positional errors in GNSS (Global Navigation Satellite System), satellite communication blackouts, and potential ground-induced currents affecting power grid operations. Continuous and correlated monitoring of TEC, Ap, and BHB_HBH thus serves not only as a scientific imperative but also as a strategic requirement for mitigating space-weather-

related disruptions.This study reinforces that CME-induced geomagnetic storms cause simultaneous and quantifiable impacts on Earth's ionosphere and magnetic field, producing strong correlations between TEC variation, Ap index elevation, and BHB_HBH depression. The May 11, 2024 event exemplifies how severe solar activity can cascade through the geospace system, revealing the necessity for integrated space weather forecasting frameworks. By combining GPS-based TEC mapping with geomagnetic field monitoring, the scientific community can develop predictive algorithms to anticipate storm impacts, safeguard technological infrastructure, and enhance the robustness of global communication and navigation systems against future solar threats.

**References**


1. **A Correlation Analysis of Geomagnetic Field Variations and Neural Network Models.** (2021). *Frontiers in Neurorobotics, 15,* Article 785563. Retrieved from https://www.frontiersin.org/articles/10.3389/fnbot.2021.785563/full
2. **Association Between Geomagnetic Kp and Ap Indices During Solar Events.** (2022). *Indian Journal of Scientific Research, 13*(2), 115–124. Retrieved from https://ijsr.in/upload/882911000Paper26.pdf
3. **Correlations Between Geomagnetic Field and Global Atmospheric Variations.** (2023). *Frontiers in Earth Science / PMC.* Retrieved from https://pmc.ncbi.nlm.nih.gov/articles/PMC10496193/
4. **Development of a Local Empirical Model of Ionospheric Total Electron Content Using GNSS Data.** (2021). *PLOS ONE / PMC.* Retrieved from https://pmc.ncbi.nlm.nih.gov/articles/PMC8302617/
5. **Effects of Recent Solar Events on Cosmic Rays and Earth's Magnetosphere.** (2011). *Indian Journal of Radio & Space Physics, 40*(4), 179–182. Retrieved from https://nopr.niscpr.res.in/bitstream/123456789/12550/1/IJRSP%2040(4)%20179-182.pdf
6. **How Do Space Weather Effects and Solar Storms Affect Earth?** (n.d.). *NASA Scientific Visualization Studio.* Retrieved from https://svs.gsfc.nasa.gov/31248/
7. **Ionospheric and Magnetic Signatures of a Space Weather Event.** (2020). *Journal of Geophysical Research: Space Physics, 125*(12), e2020JA027981. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020JA027981
8. **Ionospheric Response to the May 11, 2024, Geomagnetic Storm Event.** (2025). *arXiv.* Retrieved from https://arxiv.org/html/2502.04503

9. **Ionospheric Responses to CME- and CIR-Driven Disturbances.** (2017). *Space Weather, 15*(3), 390–408. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017SW001754
10. Lou, Y. Q., & Dai, Y. (2003). *Periodicities in Solar Coronal Mass Ejections. Monthly Notices of the Royal Astronomical Society, 345*(3), 809–818. Retrieved from https://adsabs.harvard.edu/full/2003MNRAS.345..809L
11. **Long-Term Study of Heart Rate Variability Responses to Geomagnetic Activity.** (2018). *Frontiers in Physiology / PMC.* Retrieved from https://pmc.ncbi.nlm.nih.gov/articles/PMC5805718/
12. **Space Weather Effects on Technology.** (n.d.). *Government of Canada, Space Weather Canada.* Retrieved from https://www.spaceweather.gc.ca/tech/index-en.php
13. **Space Weather Effects on Transportation Systems: A Review.** (2024). *Space Weather, 22*(4), e2024SW004055. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2024SW004055
14. **Study of Intense Space Weather Effects of May 2024 on the Geomagnetic and Ionospheric Environment.** (2025). *Advances in Space Research.* Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0273117725010385
15. **TEC Disturbances Caused by CME-Triggered Geomagnetic Storms.** (2024). *Heliyon, 10,* e067562. Retrieved from https://www.sciencedirect.com/science/article/pii/S2405844024067562
16. **Total Electron Content (TEC) – Space Weather Prediction Center.** (n.d.). *NOAA SWPC.* Retrieved from https://www.swpc.noaa.gov/phenomena/total-electron-content
17. **Variations of Ionospheric TEC Due to Coronal Mass Ejections.** (2022). *Journal of Atmospheric and Solar-Terrestrial Physics, 231,* 105–143. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S1384107622001439
18. **What Is Space Weather and How Does It Affect the Earth?** (n.d.). *UCAR Center for Science Education.* Retrieved from https://scied.ucar.edu/learning-zone/sun-space-weather/what-space-weather