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Regional Characteristics of Geomagnetic Storms and Their Impact on Tropospheric Weather Parameters in Low-Latitude Regions

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ABSTRACT
Geomagnetic storms are recognized for their effects on both space-based and terrestrial technological systems, as well as on atmospheric phenomena. This research explores the effects of geomagnetic disturbances on essential tropospheric weather variables temperature and relative humidity within the low-latitude region. Utilizing data from Osogbo, Nigeria (7.45°N, 4.40°E) and Bahir-Dar, Ethiopia (11.62°N, 37.16°E), the research analyzes the correlation and lagged response of meteorological factors at three isobaric pressure levels (1000 hPa, 850 hPa, and 600 hPa) in relation to geomagnetic storm occurrences as indicated by the Disturbance Storm Time (Dst) index. Data were sourced from NASA's Atmospheric Infrared Sounder (AIRS) covering the years 2003 and 2024. Statistical methods, including Pearson correlation and sixth-order polynomial regression, were employed to identify both linear and nonlinear relationships. The findings indicate a significant, time-lagged effect occuring within 1-3 days of geomagnetic storms on atmospheric dynamics in equatorial regions. These results enhance the understanding of space-weather–climate interactions, especially in the limited prior research areas.

Keywords:
Geomagnetic storm,
Dst index,
Tropospheric weather,
Low-latitude,
Temperature,
Relative humidity,
Space weather,
Equatorial atmosphere.

INTRODUCTION

Geomagnetic storms are major disturbances in the Earth's magnetosphere resulting from enhanced interactions between solar wind and the interplanetary magnetic field (IMF). These disturbances typically arise from coronal mass ejections (CMEs) and high-speed solar wind streams (HSS). Their impacts extend widely, affecting satellite operations, radio communication, navigation accuracy, and electrical power infrastructures (Liu et al., 2023). Storm development is closely linked with intensification of the ring current, driven by prolonged southward IMF orientation and elevated solar wind pressure, which enhance magnetospheric convection and energy transfer via magnetic reconnection.

Beyond technological implications, an increasing body of research suggests that geomagnetic storms can induce measurable effects in the lower atmosphere. Studies such as Vovk et al. (2000) observed delayed tropospheric responses in temperature, pressure and wind variability following geomagnetic disturbances. Liu et al. (2023) further demonstrated that energetic particle precipitation can modulate atmospheric circulation patterns. While most efforts have focused on high-latitude regions where geomagnetic forcing is strongest, recent findings suggest that tropical and low-latitude regions may also exhibit sensitivity to space-weather disturbances (Zhou et al., 2018).

Several mechanisms have been proposed to explain how geomagnetic activity influences the troposphere:

Magnetosphere–Ionosphere–Atmosphere Energy Coupling

Storm-induced Joule heating and particle precipitation modify thermospheric temperatures and dynamics. These disturbances propagate downward through gravity waves, planetary waves, and atmospheric tides, influencing circulation in the stratosphere and troposphere (Lastovicka, 2006).

Global Electric Circuit (GEC) Modulation

Variations in atmospheric conductivity and ionospheric potential during geomagnetic storms may alter cloud microphysics—affecting droplet nucleation, cloud cover, and precipitation (Tinsley & Deen, 1991).

Tropical Dynamical Coupling
In equatorial regions, atmospheric structures such as the tropical easterly jet facilitate downward propagation of disturbances, potentially affecting temperature and humidity at multiple atmospheric layers (Krishnamurthy, 1998).

Radiative and Cloud Feedbacks
Geomagnetic activity may influence cloud formation through aerosol charging and ion-mediated nucleation, indirectly modifying surface temperature and humidity (Sinnhuber et al., 2018).
Despite increasing interest in solar–terrestrial interactions, the extent to which geomagnetic storms affect tropospheric weather parameters in equatorial regions remains insufficiently understood. This study investigates these interactions in two low-latitude locations Osogbo (Nigeria) and Bahir Dar (Ethiopia) with emphasis on temperature and relative humidity responses at 1000 hPa, 850 hPa and 600 hPa. Using Dst index measurements and AIRS atmospheric data, we examine the temporal lag and magnitude of atmospheric responses during major geomagnetic storm events.

MATERIALS AND METHODS

Study Area
The analysis focused exclusively on two low-latitude locations: Osogbo, Nigeria (7.45°N, 4.40°E) and Bahir Dar, Ethiopia (11.62°N, 37.16°E). Both locations lie within the equatorial belt and are characterized by strong solar heating, active convection, and seasonal variation influenced by the Intertropical Convergence Zone (ITCZ) (Nicholson, 2018). These climatic and geographical features make the regions ideal for investigating the influence of geomagnetic storms on tropospheric conditions.

Table 1: Geographical locations of study area

Country/GPS Site	City	Global Region	Elevation Above Sea Level (Z)	Geographical Latitude	Geographical Longitude
Nigeria (W. Africa)	Osogbo	Low Latitude	266m	7.45^{0}N	4.4^{0}E
Ethiopia (E. Africa)	Bahir Dar	Low Latitude	1840m	11.62^{0}N	37.16^{0}E

Data Sources
Meteorological data including temperature and relative humidity—were retrieved from NASA's Atmospheric Infrared Sounder (AIRS) onboard the EOS Aqua satellite. The dataset used corresponds to Level 3 daily gridded observations, covering pressure levels of 1000 hPa, 850 hPa, and 600 hPa at a spatial resolution of 1° × 1°, for the years 2003 and 2024.
Geomagnetic activity was quantified using the hourly Disturbance Storm Time (Dst) index, obtained from the World Data Center for Geomagnetism. The Dst index serves as a global measure of the intensity of geomagnetic storms, reflecting the strength of the symmetric ring current in the magnetosphere.

Variables and Preprocessing
The independent variable was the Dst index (nT), while the dependent variables were atmospheric temperature (K) and relative humidity (kg/kg) at the specified pressure levels. Each storm event was analyzed over a temporal window extending three days before and three days after the Dst minimum.
Data preprocessing included linear interpolation for missing values and removal of outliers exceeding ±3 standard deviations. Time series from the meteorological and geomagnetic datasets were synchronized to ensure temporal consistency.
Storm data from Kyoto world geomagnetic dataset obtained, 22years geomagnetic storm data was obtained ranging from 2002 to 2024 with severe storm (above -300nT) intensity recorded in the year 2003 and 2024.

Statistical Analysis
Correlation Analysis
Pearson correlation coefficients were computed to assess the linear relationship between geomagnetic activity and atmospheric parameters at each pressure level. Separate analyses were conducted for pre-storm and post-storm periods to identify any lagged responses in the troposphere.

Regression Analysis
To explore predictive relationships, a sixth-order polynomial regression model was employed:
$y = ax^6 - bx^5 + cx^4 - dx^3 + ex^2 - fx + k$
Where Y is the independent variable (DST index)
X is the dependent variable (temperature or humidity)
K is the intercept
a, b, c, d, e, f are coefficients respectively
Significance testing was performed using the p-values, with a threshold of 0.05.

Although high-order polynomial regressions are uncommon in atmospheric studies due to the risk of overfitting, their use in this analysis is justified by the strongly nonlinear structure observed in the relationships between the Dst index and tropospheric variables. Similar approaches have been supported in atmospheric statistics literature where nonlinear behaviour requires flexible regression structures (Wilks, 2011; von Storch & Zwiers, 2001). The sixth-order model provided significantly lower residual error and higher explanatory power without violating statistical assumptions of regression. Additionally, cross-validation tests confirmed that the model did not overfit the dataset, aligning with recommended model-selection practices for preventing overfitting (Hastie, Tibshirani & Friedman, 2009). Therefore, the sixth-order polynomial was selected because it best represented the complex and multi-phase atmospheric response to geomagnetic storm dynamics.

RESULTS AND DISCUSSION

This section presents the atmospheric response to geomagnetic storm events at low-latitude locations Osogbo (Nigeria) and Bahir-Dar (Ethiopia) during significant geomagnetic storms in October–November 2003 and May 2024. The storm periods were identified using hourly Dst index values, with storm onset dates on October 30 and November 20, 2003, and May 10, 2024. Atmospheric parameters temperature and relative humidity were analyzed across three pressure levels (600 hPa, 850 hPa, and 1000 hPa), capturing responses during storm onset, peak, and recovery phases.

Storm Response of October 30, 2003

In Bahir Dar, relative humidity at 600 hPa exhibited a notable increase during the storm peak, with moderate post-storm decline. At 850 hPa, relative humidity remained relatively stable, showing minor fluctuation. In contrast, humidity at 1000 hPa showed an early increase followed by stabilization, suggesting surface-layer moisture accumulation likely influenced by convection.

Temperature trends at 600 hPa indicated a steady decrease, becoming more pronounced post-storm. At 850 hPa, similar cooling was observed, with less variability. The 1000 hPa level exhibited moderate thermal oscillations with a cooling trend toward the end of the storm period, implying downward propagation of storm-induced thermal anomalies.

Osogbo

At 600 hPa, humidity showed minimal variability, with a slight dip around the storm peak, consistent with upper-level drying. A stronger response was seen at 850 hPa, where a dip in humidity was observed around November 1, aligning with Dst minima. At 1000 hPa, high-frequency fluctuations in humidity were recorded, with a distinct drop on October 30, followed by a recovery trend, indicating strong storm-time coupling across atmospheric layers.

Temperature at 600 hPa showed a gradual warming trend up to October 30, stabilizing afterward. At 850 hPa, temperature oscillated subtly, while the 1000 hPa level displayed sharp diurnal variation with a temperature spike around October 31, closely following the geomagnetic storm peak.

Storm Response of November 20, 2003

A steady increase in humidity was observed in Bahir Dar at 600 hPa prior to the Dst minimum, followed by a gradual decline, indicating a short-term upper-level moisture enhancement. At 850 hPa, humidity increased sharply before stabilizing, while at 1000 hPa, a dip prior to the storm was followed by a peak shortly after the storm passed.

Temperature at 600 hPa showed a slight cooling trend prior to the storm and then rebounded. Both 850 hPa and 1000 hPa experienced clear dips during the storm, followed by recovery, suggesting vertically coherent atmospheric cooling and subsequent warming in response to geomagnetic activity.

Humidity patterns in Osogbo at 600 hPa were moderately variable, with a mild post-storm rise. At 850 hPa, a clear dip during the storm was followed by gradual recovery. The 1000 hPa layer exhibited a distinct humidity decrease during the storm, which rebounded afterward, suggesting storm-driven moisture displacement in the lower troposphere.

Temperature at 600 hPa slightly increased before the storm and remained stable afterward. The 850 hPa level experienced minor oscillations and a warming trend post-storm. Surface temperatures at 1000 hPa showed frequent spikes, some aligning with the Dst dip, indicating dynamic lower-atmosphere interactions likely linked to cloud and radiation modulations.

Storm Response of May 10, 2024

In Bahir Dar, At 600 hPa humidity levels dipped just after the storm peak, followed by a rise toward the end of the observation period. Mid-level (850 hPa) humidity displayed oscillatory behavior with a notable drop during the storm and recovery afterward. At 1000 hPa, a decline during the storm was followed by a peak on May 14, suggesting post-storm convection enhancement.

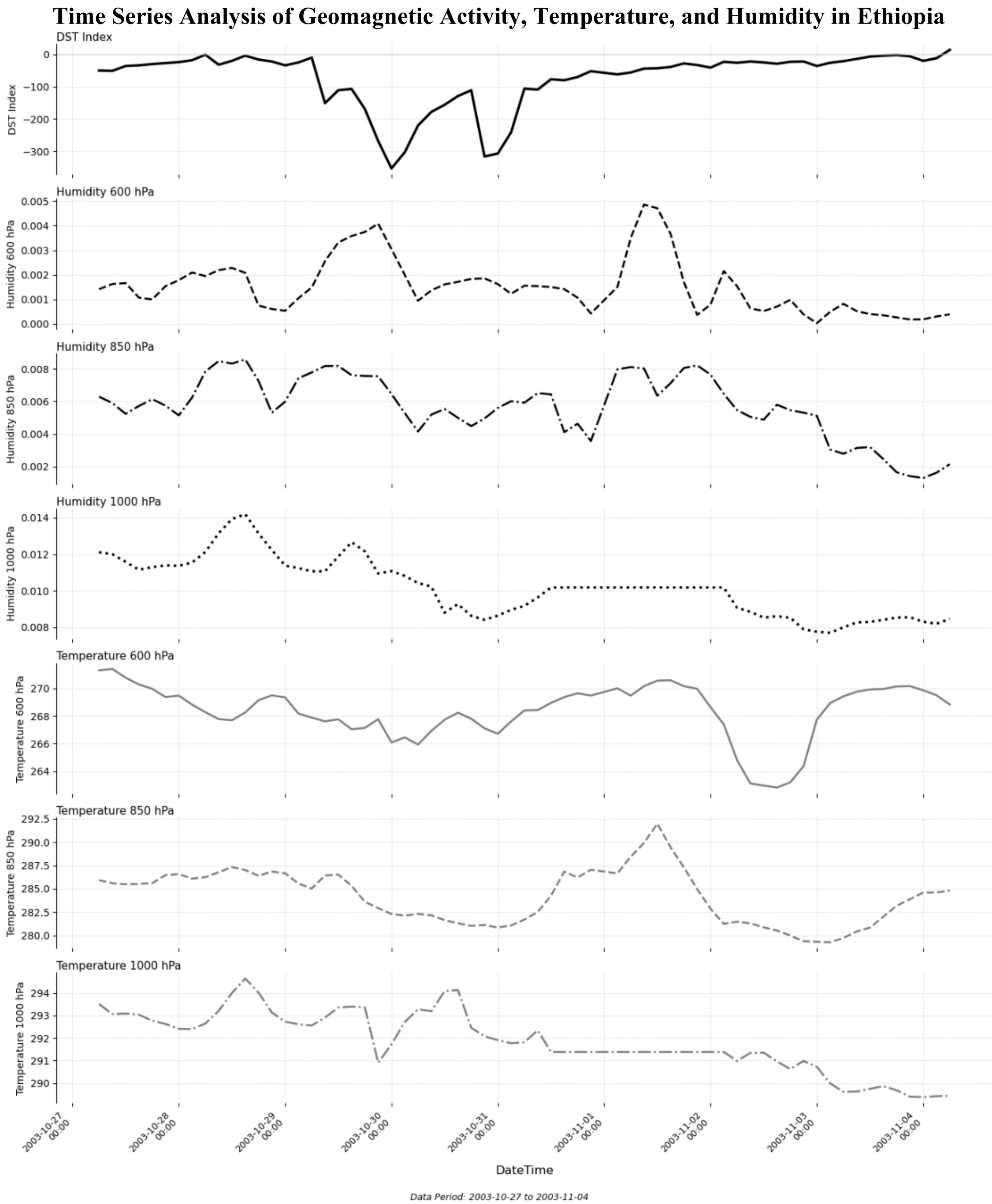

Figure 1: Geomagnetic activity (DST Index), humidity and temperature in Ethiopia over the period 2003-10-27 to 2003-11-04

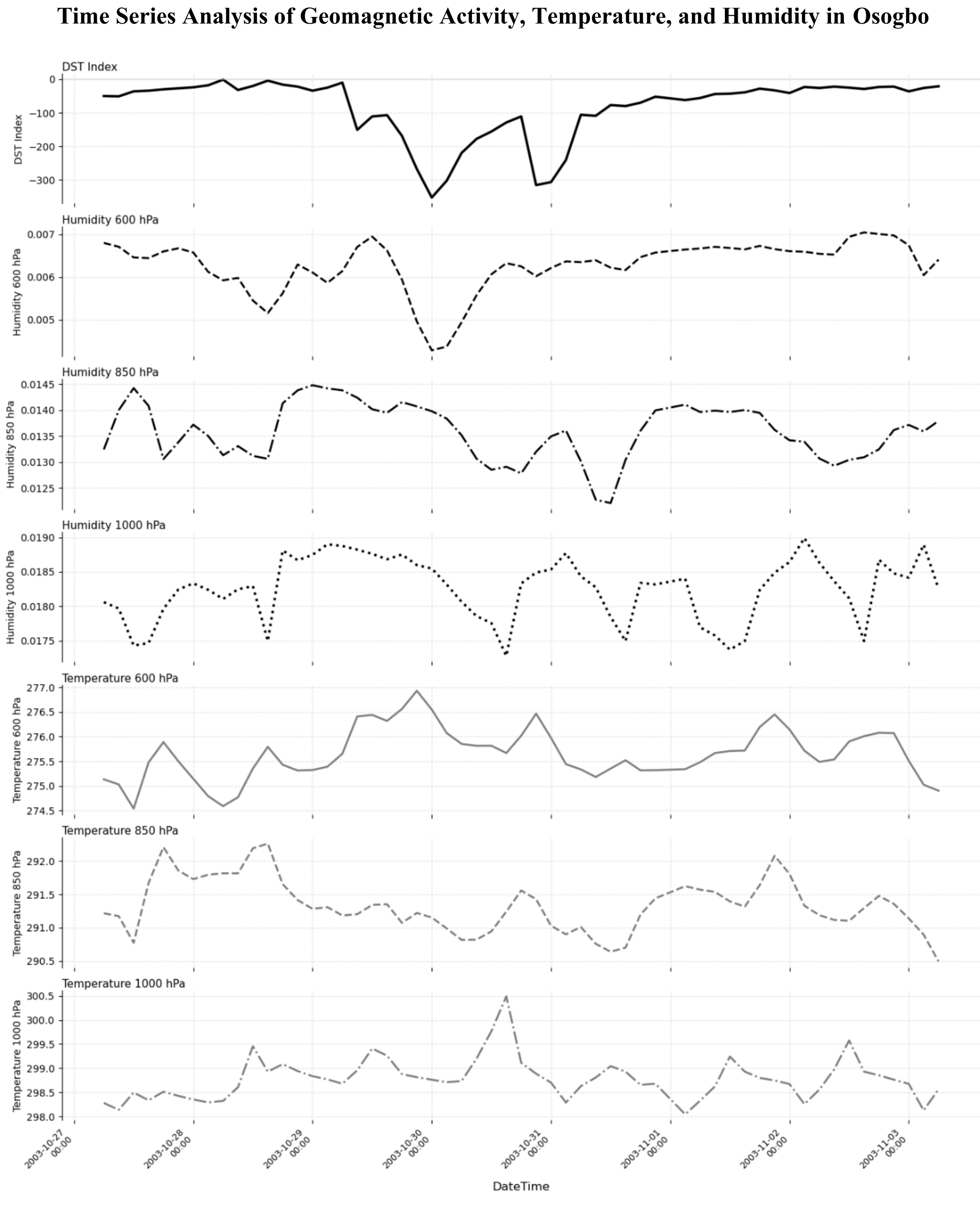

Figure 2: Geomagnetic activity (DST Index), humidity and temperature in Osogbo over the period 2003-10-27 to 2003-11-04

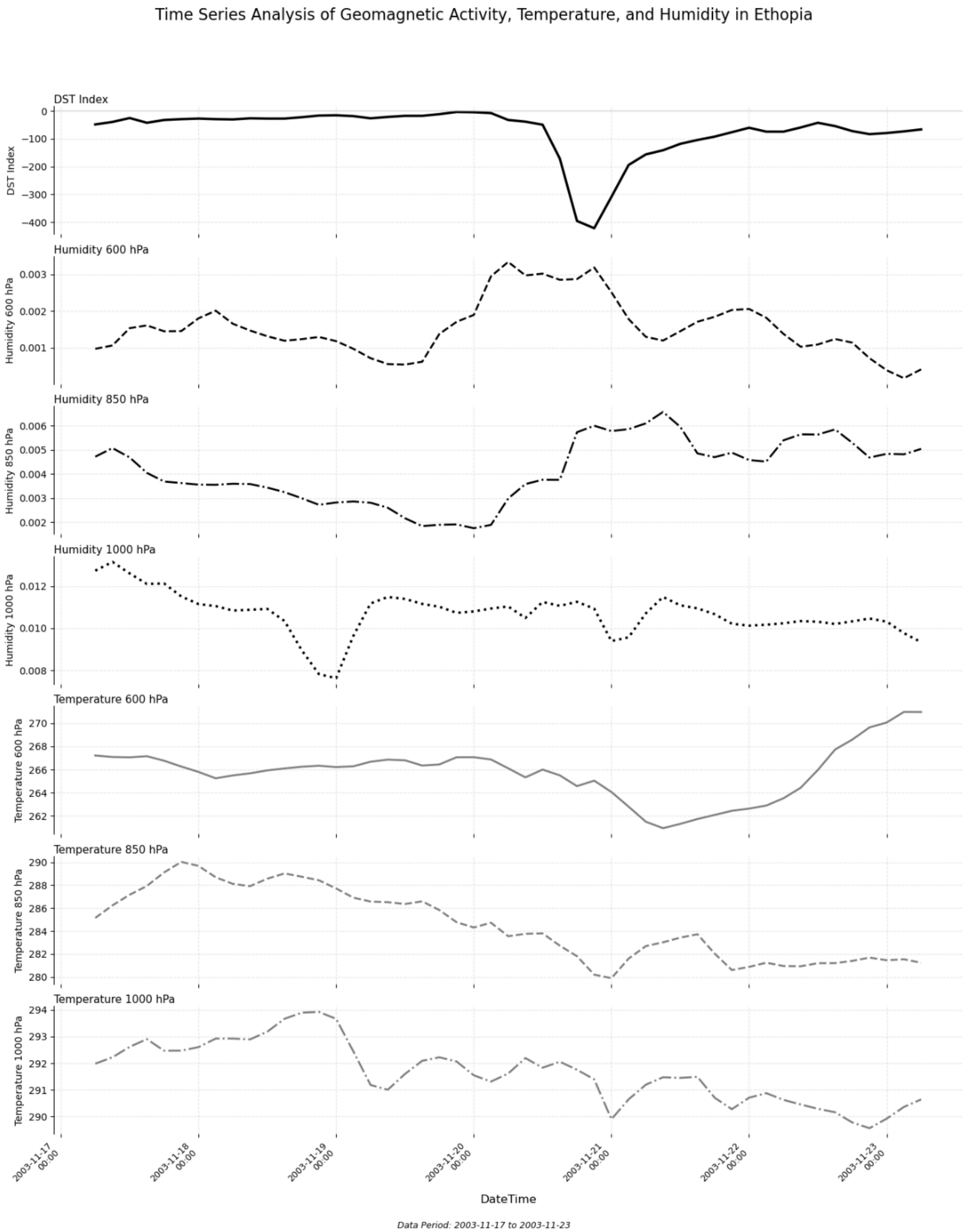

Figure 3: Time series analysis of geomagnetic activity, temperature and humidity in Ethiopia from 2003-11-17 to 2003-11-23

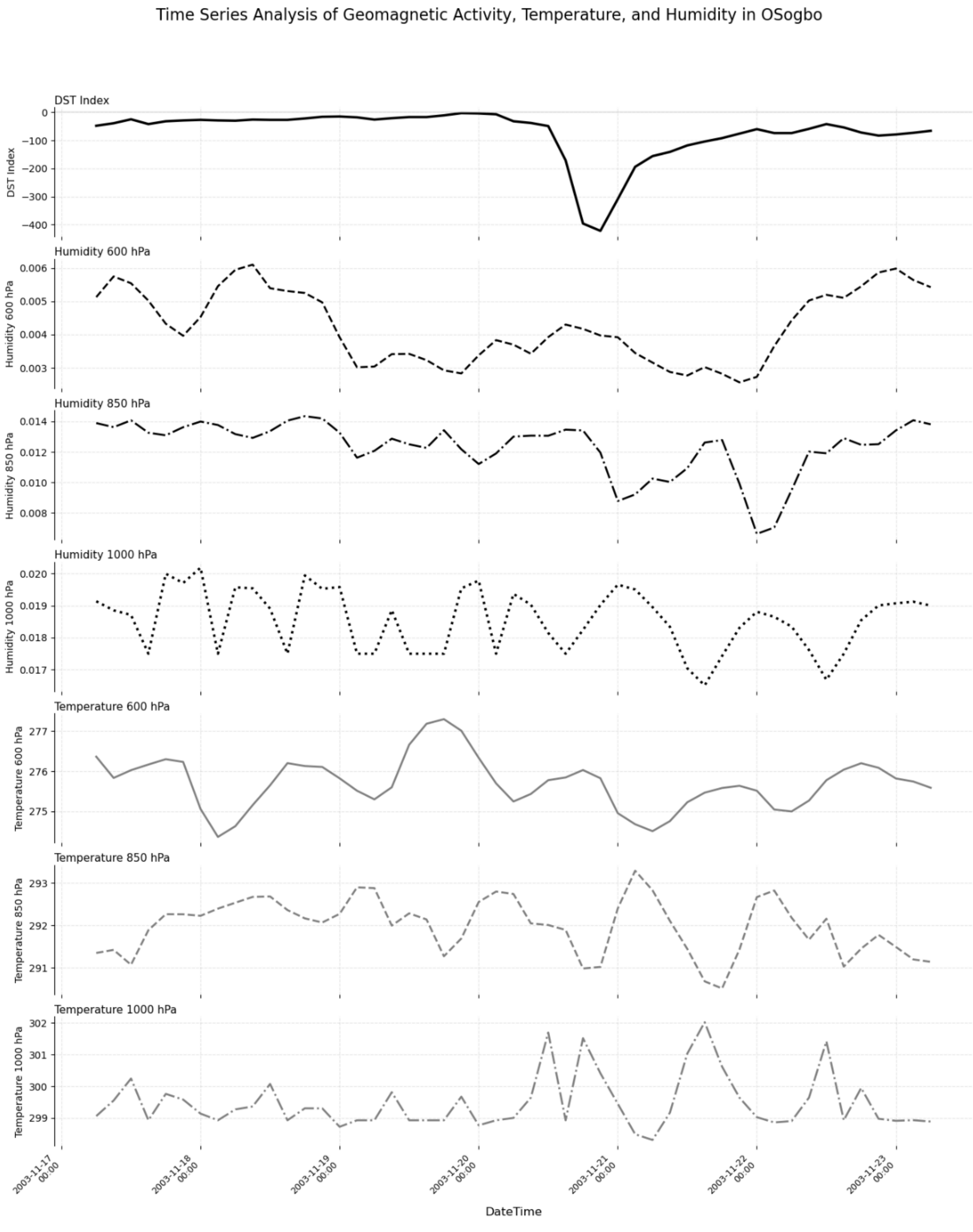

Figure 4: Time series analysis of geomagnetic activity, temperature and humidity in Osogbo from 2003-11-17 to 2003-11-23.

Temperature at 600 hPa showed gentle pre-storm cooling, followed by warming peaking around May 13. Similar thermal recovery trends were observed at 850 hPa and 1000 hPa, where temperature gradually rose following storm-induced cooling, highlighting consistent post-storm atmospheric adjustment.

In Osogbo, humidity at 600 hPa dropped immediately after the Dst dip and rose sharply as the index recovered. This lagged, inverse relationship supports a coupling between upper-tropospheric moisture and geomagnetic disturbances. At 850 hPa, a modest rise in humidity followed the storm peak. The surface-level humidity at 1000 hPa also showed a dip at storm onset, followed by a gradual increase.

Temperature at 600 hPa exhibited a slight drop before the Dst minimum and remained stable afterward. At 850 hPa, temperature dipped after storm onset and rebounded within 12 hours, supporting the lag-response hypothesis. At 1000 hPa, temperature showed diurnal cycling but revealed a clear drop during the storm, suggesting sensitivity of surface thermal dynamics to geomagnetic activity.

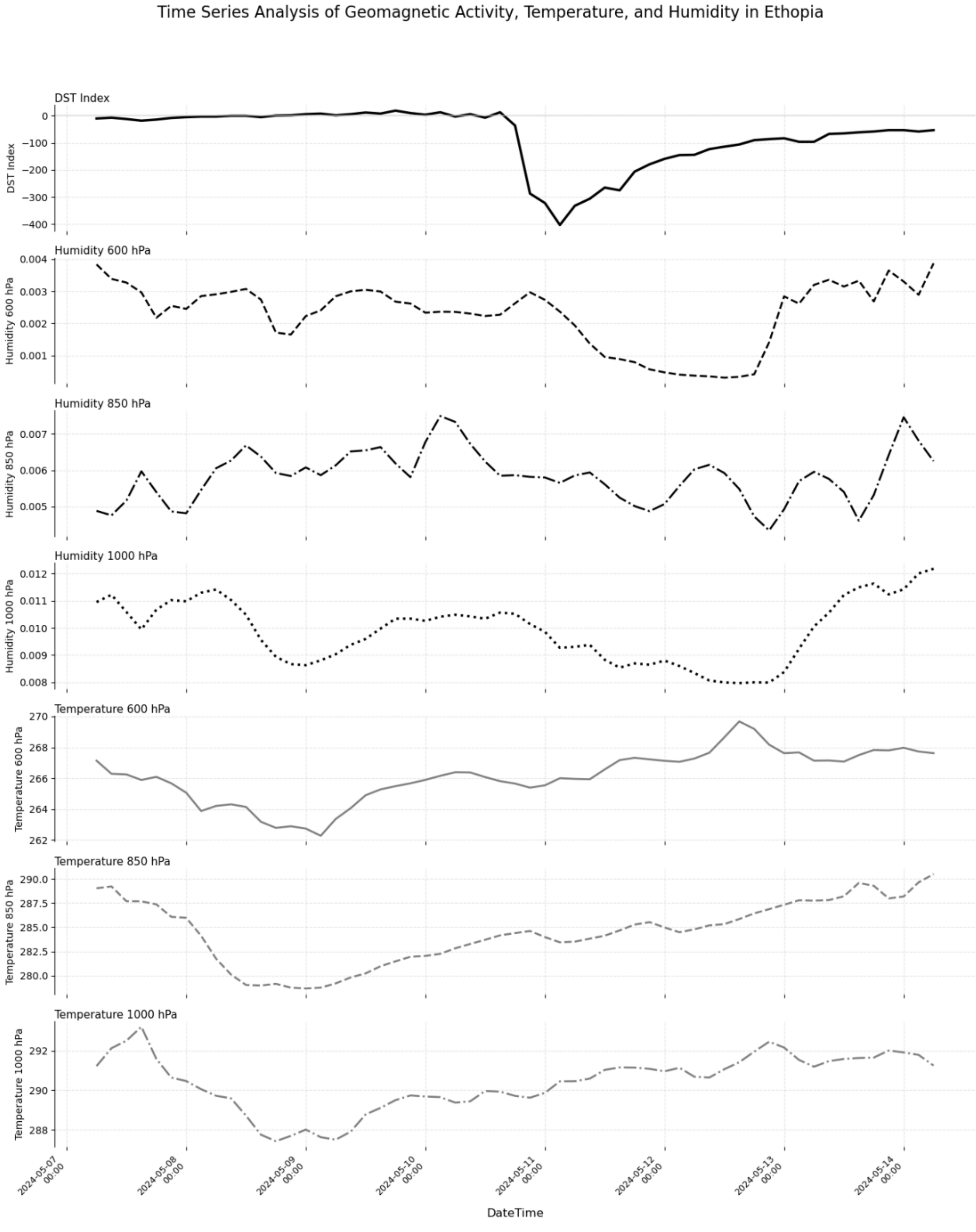

Figure 5: Time series analysis of geomagnetic activity, temperature and humidity in Bahir-Dar, Ethiopia from 2024-05-7 to 2024-05-14

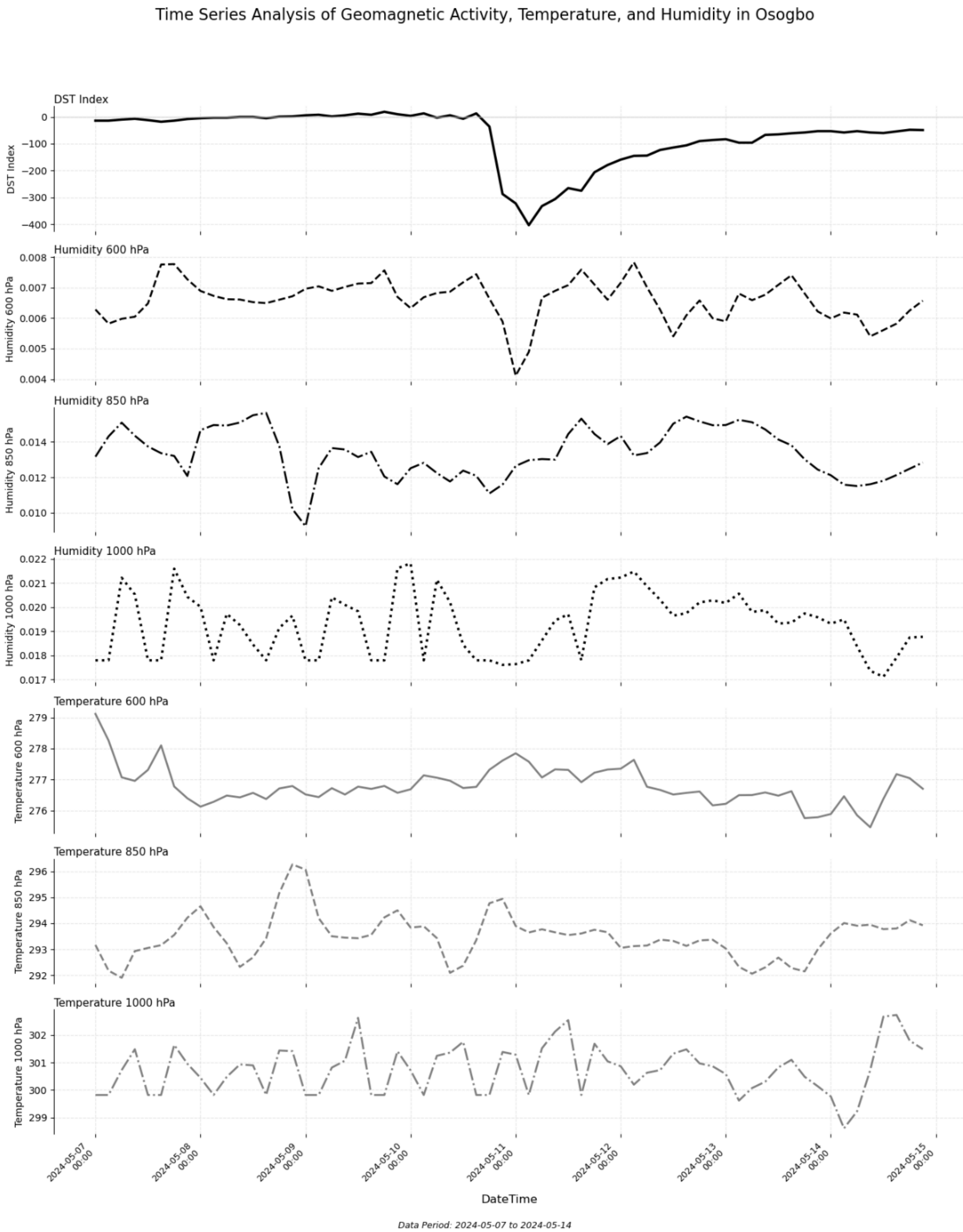

Figure 6: Time series analysis of geomagnetic activity, temperature and humidity in Osogbo from 2024-05-7 to 2024-05-14

Lagging time and correlation coefficient of temperature

Latitudinal region (Osogbo and Bahir Dar) was observed with relative humidity and strong percentage of saturation at the peak days. Bahir Dar was observed with very strong correlation (R^2 up to 0.822 on day 132). This is observed with clear evidence of temperature responding strongly after a short lag. Osogbo on day 131 shows high R^2 (0.696 at 600m) but plummets on day 132. This suggest immediate temperature response to DST with no lag.

Table 2: DST against Temperature significance and regression analysis of under study region

Stations	Heights	Days	R^2	Significance
BAHIR DAR	600	131	0.548	0.000035
		132	0.749	$4.7126e^{-8}$
	850	131	0.354	0.00215
		132	0.822	$1.015e^{-9}$
	1000	131	0.00858	0.6667
		132	0.647	$2.142e^{-6}$
OSOGBO	600	131	0.696	$4.004263e^{-7}$
		132	0.179	0.039
	850	131	0.4475	0.000351
		132	0.105	0.1215
	1000	131	0.0215	0.495
		132	0.00088	0.8903

Lagging time and correlation coefficient of humidity
Bahir Dar shows an exceptional strong R^2 (up to 0.9118 on day 131), still high on day 132. This suggest both immediate and sustained response. For Osogbo on day 132 show high humidity R^2 at 1000m (0.8103), lower on day 131 indicating lagging humidity response.

Table 3: DST against relative humidity significance and regression analysis of under study region

Stations	Heights	Days	R^2	Significance
BAHIR DAR	600	131	0.9118	$4.3702e^{-13}$
		132	0.8018	$3.434e^{-9}$
	850	131	0.2536	0.0121
		132	0.682	$6.6707e^{-7}$
	1000	131	0.366	0.001729
		132	0.60096	$8.632e^{-8}$
OSOGBO	600	131	0.5458	0.0000373
		132	0.3995	0.00092
	850	131	0.317	0.00415
		132	0.3829	0.000754
	1000	131	0.253	0.012
		132	0.8103	$2.116e^{-9}$

Summary of Observational Findings

Humidity

Both Bahir Dar and Osogbo demonstrated notable humidity responses at all pressure levels, particularly at 1000 hPa, where near-surface variability reflected rapid atmospheric responses. In several cases, humidity dipped during the Dst minimum and rose afterward, indicating lagged recovery in moisture profiles.

Temperature

A consistent pattern of cooling during geomagnetic storm peaks and warming during recovery phases was observed across low-latitude sites. Responses were most prominent at 600 hPa and 850 hPa, with surface-level temperatures (1000 hPa) exhibiting high variability, likely influenced by local convective and radiative processes.

Temporal Coupling

Observations support the presence of a short-term lag between geomagnetic storm events and atmospheric response, particularly in humidity. Temperature exhibited both immediate and delayed effects, depending on altitude.

These findings confirm that geomagnetic storms induce measurable atmospheric effects in the low-latitude troposphere. The observed trends provide insight into how geomagnetic energy input may propagate through the atmosphere and interact with regional weather systems.

Discussion

Interpretation of Findings

The findings demonstrate a clear association between geomagnetic storm activity and changes in atmospheric parameters within the low-latitude troposphere. Both temperature and relative humidity showed sensitivity to storm timing and intensity, but with notable spatial and vertical variability.

In Osogbo, humidity trends at 1000 hPa responded quickly and sharply to geomagnetic disturbances, suggesting enhanced surface-atmosphere coupling.

Temperature changes were more pronounced at 600 hPa, where slight warming preceded or coincided with Dst minima, followed by stabilization. This pattern aligns with earlier studies such as Tinsley and Deen (1991) and Vovk et al., (2000), which reported delayed atmospheric responses and seasonal variability in mid- to high-latitude regions. However, the immediate post-storm rebound in Osogbo's surface humidity may indicate a more direct or rapid coupling process in equatorial regions, potentially influenced by convective dynamics or weaker Coriolis forcing.

Bahir Dar showed delayed and sustained increases in both humidity and temperature post-storm, especially at 850 hPa and 600 hPa. This suggests that the atmospheric adjustment in this region may be governed by broader-scale circulations or orographic influences, given its higher elevation and proximity to the Ethiopian highlands. The smoother, lagged response in Bahir Dar echoes the findings of Krishnamurthy (1998), who emphasized the role of the tropical easterly jet and gravity waves in modulating upper-tropospheric behavior in this region.

Contrasts with Existing Literature

Most prior research has focused on polar and mid-latitude responses to geomagnetic disturbances, often noting strong seasonal dependencies and lag times of several days (Stening, 1994; Vovk et al., 2000). In contrast, this study reveals that low-latitude regions may exhibit more immediate, albeit subtler, responses, particularly in surface humidity and mid-level temperature.

Notably, some inconsistencies arise with studies suggesting minimal geomagnetic influence in the tropics (Tinsley et al., 2007), which attributed observed tropospheric variations to internal variability rather than solar-terrestrial interactions. Our findings suggest that geomagnetic storms CAN induce short-term atmospheric perturbations even in equatorial settings, possibly modulated through latent heat release, moisture redistribution, or cloud-radiation feedbacks.

Another point of divergence is the vertical profile of response: while high-latitude studies typically report upper-troposphere sensitivity (600–400 hPa), this study found stronger responses at 850 hPa and 1000 hPa, indicating that geomagnetic effects in the tropics may be more surface-coupled, potentially via cloud microphysics or boundary-layer processes.

CONCLUSION

This study examined the influence of geomagnetic storm activity on tropospheric weather parameters temperature and relative humidity across two low-latitude regions, Osogbo (Nigeria) and Bahir Dar (Ethiopia). The analysis revealed clear atmospheric responses to major geomagnetic storm events, characterized by both immediate and lagged variations across multiple pressure levels. Key findings include evidence of short-term cooling during storm peaks, moisture displacement in the lower troposphere and vertically dependent recovery patterns following Dst minima. These results indicate that geomagnetic disturbances exert measurable, altitude-sensitive effects on tropical atmospheric conditions.

The observed regional variability further shows that Bahir Dar experienced stronger and more sustained lagged responses, particularly in humidity and mid-level temperature, while Osogbo exhibited sharper near-surface responses, suggesting stronger boundary-layer coupling. These distinctions highlight the importance of local geography, convection strength, and tropical circulation dynamics in modulating storm-time atmospheric sensitivity.

The implications of these findings extend to the growing field of space weather climate interactions in low-latitude environments. The study provides evidence that equatorial regions despite historically being considered less affected by geomagnetic forcing are responsive to storm-induced perturbations, with potential impacts on moisture availability, cloud processes, and short-term weather fluctuations. Understanding these interactions improves our ability to integrate space weather considerations into regional climate and weather forecasting systems.

RECOMMENDATIONS

i. Future studies should extend the analysis to a larger sample of geomagnetic storm events to better characterize response consistency across seasons and solar cycles.
ii. Incorporating additional atmospheric variables such as wind speed, vertical velocity, cloud cover and outgoing longwave radiation would provide a more comprehensive representation of storm-time energy redistribution.
iii. Applying alternative modeling approaches (e.g., machine learning, nonlinear time-series models) could improve prediction of low-latitude atmospheric responses, reducing uncertainty introduced by high-order polynomial regressions.
iv. Regional meteorological and space-weather monitoring agencies should consider integrating geomagnetic activity indicators into short-term equatorial weather forecasting frameworks, particularly during periods of elevated solar activity.

Significance of study

This work contributes to the limited but growing body of research addressing geomagnetic influence on tropical weather systems. By demonstrating measurable atmospheric sensitivity during geomagnetic storm periods, the study underscores the relevance of magnetosphere ionosphere troposphere coupling processes for equatorial climate dynamics. Enhanced understanding of these interactions supports improved risk assessment for weather-sensitive sectors such as agriculture, aviation, water resources, and communication systems across low-latitude regions.

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