

Statistical Analysis of the Relationship Between Traveling Ionospheric Disturbances and Equatorial Ionospheric Irregularities Over Addis Ababa, Ethiopia, During the 2023–2024 Equinox Seasons

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STATISTICAL ANALYSIS OF THE RELATIONSHIP BETWEEN TRAVELING IONOSPHERIC DISTURBANCES AND EQUATORIAL IONOSPHERIC IRREGULARITIES OVER ADDIS ABABA, ETHIOPIA, DURING THE 2023–2024 EQUINOX SEASONS

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ABSTRACT

Traveling ionospheric disturbances (TIDs) and small-scale ionospheric irregularities are important forms of ionospheric variability that can affect transionospheric radio signals. However, their statistical relationship over the East African low-latitude region remains insufficiently characterized. This study investigates the statistical relationship between TID amplitude and ionospheric irregularity activity over Addis Ababa, Ethiopia, during the 2023–2024 equinox seasons. Thirty-second GNSS observations from the Addis Ababa (ADIS) station were used to derive vertical total electron content (VTEC), TID perturbations, and the Rate of TEC Index (ROTI). Observations with satellite elevation angles $\geq 50^\circ$ were used. TID amplitude was obtained from detrended VTEC using a 60-min background interval, while ROTI was calculated over 5-min intervals. Pearson correlation and linear regression were used to quantify the relationship between TID amplitude and ROTI, and cross-correlation analysis was applied to investigate their temporal association. The results show a consistently positive relationship between TID amplitude and ROTI during the investigated equinox seasons, with monthly Pearson correlation coefficients ranging from 0.416 to 0.534 and corresponding R^2 values of approximately 0.17–0.29. Cross-correlation analysis revealed positive optimal lags, predominantly around +5 min, with a longer optimal lag of +35 min observed during April 2024. These results indicate that TID amplitude variations generally preceded subsequent ROTI variations, while the moderate correlation strengths demonstrate that TID amplitude alone does not account for the observed variability in ionospheric irregularities. Solar activity, geomagnetic forcing, atmospheric dynamics, and local electrodynamic processes may also contribute to the observed variability. Overall, the study provides quantitative evidence of a statistical and temporal association between traveling ionospheric disturbances and small-scale ionospheric irregularities over Addis Ababa, without implying a direct causal relationship.

Keywords: Traveling ionospheric disturbances (TIDs); Ionospheric irregularities; Rate of TEC Index (ROTI); GNSS; Total electron content (TEC); Addis Ababa; Equatorial ionosphere

1. INTRODUCTION

The ionosphere is a highly dynamic region of the near-Earth environment in which electron density varies over a broad range of spatial and temporal scales. Its variability is controlled by solar radiation, geomagnetic activity, thermospheric winds, electrodynamic processes, and coupling between the neutral atmosphere and ionized plasma. These variations can significantly affect the propagation of trans-ionospheric radio signals and consequently influence satellite navigation and communication systems. Ground-based Global Navigation Satellite System (GNSS) observations provide an effective technique for monitoring ionospheric variability through measurements of total electron content (TEC) and its temporal fluctuations (Kintner et al., 2007; Hunsucker, 1982; Hernández-Pajares et al., 2009).

Traveling ionospheric disturbances (TIDs) are propagating perturbations of ionospheric electron density that occur over a wide range of spatial and temporal scales. They are commonly associated with atmospheric gravity waves and can be generated by processes originating in the lower atmosphere, as well as by energy and momentum deposited in the upper atmosphere during geomagnetic disturbances (Hunsucker, 1982; Hocke and Schlegel, 1996; Ding et al., 2007). Because TIDs produce propagating perturbations in electron density, they can be detected from wave-like variations in GNSS-derived TEC. GNSS observations have therefore been widely used to characterize TIDs in terms of their amplitude, period, propagation velocity, direction, and occurrence under different geophysical conditions (Hunsucker, 1982; Afraimovich et al., 2008; Astafyeva et al., 2009).

At equatorial and low latitudes, ionospheric variability is also characterized by the development of plasma irregularities over a broad range of spatial scales. These irregularities are strongly influenced by equatorial electrodynamic processes, including the equatorial plasma fountain, vertical image drift, the post-sunset pre-reversal enhancement, thermospheric winds, and plasma instability processes (Olowendo et al., 2018; Sultan, 1996; Kelley, 2009). In particular, the generalized Rayleigh–Taylor instability is considered an important mechanism in the development of equatorial F-region plasma irregularities, while the occurrence and evolution of these structures can also be influenced by background ionospheric conditions and perturbations that provide initial or seeding disturbances (Sultan, 1996; Kelley, 2009; Krall et al., 2011).

GNSS-derived indices provide useful methods for quantifying ionospheric irregularity activity. The Rate of TEC Index (ROTI), calculated from the variability of the rate of change of TEC (ROT), is widely used as an indicator of short-term ionospheric variability and irregularity activity (Pi et al., 1997; Liu et al., 2019). Enhanced ROTI values indicate increased fluctuations in TEC along the satellite-receiver ray path and have been used extensively to investigate equatorial and low-latitude irregularities. Although ROTI does not uniquely identify the physical origin or spatial scale of an irregularity, it provides a practical statistical measure of ionospheric variability that is particularly useful for long-term GNSS observations (Pi et al., 1997; Liu et al., 2019; Jacobsen and Dähnn, 2014).

The simultaneous presence of TIDs and ionospheric irregularities raises an important question concerning the relationship between disturbances occurring at different temporal and spatial scales. A TID represents a propagating perturbation of the background ionosphere, whereas enhanced ROTI reflects rapid variability in the TEC signal associated with ionospheric irregularity activity. A propagating TID may modify the background electron-density distribution and gradients and could therefore be associated with subsequent changes in smaller-scale plasma structures. However, the occurrence of a TID and enhanced irregularity activity does not by itself demonstrate a causal relationship. Their statistical association may also depend on local time, season, background electron density, electrodynamic conditions, geomagnetic activity, and the characteristics of the propagating disturbance (Sultan, 1996; Krall et al., 2011; Tsugawa et al., 2004). Quantitative analysis is therefore required to determine whether variations in TID amplitude are systematically associated with variations in ionospheric irregularity intensity.

Observations from the African low-latitude sector provide evidence that TIDs and ionospheric irregularities can occur simultaneously. Moges et al. (2022) reported storm-time TID signatures together with variations in ROT and ROTI over East Africa, demonstrating the presence of wave-like ionospheric perturbations and enhanced small-scale variability during disturbed conditions. Similarly, a subsequent investigation over the East African low-latitude region reported simultaneous post-sunset occurrence of TID-like TEC oscillations and ionospheric irregularities, suggesting that large-scale wave perturbations may be associated with the development of smaller-scale irregular structures (Olwendo and Cilliers, 2024). These studies provide important observational evidence for a relationship between TIDs and ionospheric irregularities over East

Africa. Nevertheless, the quantitative relationship between the magnitude of TID perturbations and the intensity of ionospheric irregularities remains insufficiently characterized.

This question is particularly important during equinox seasons because equatorial ionospheric irregularities exhibit strong seasonal and local-time variability. Previous GNSS investigations over the African sector have reported pronounced seasonal differences in irregularity occurrence, with substantial activity during equinoctial periods (Olwendo et al., 2018; Bolaji et al., 2020; Ikani et al., 2023). The response of the low-latitude ionosphere during these periods reflects the combined influence of equatorial electrodynamics, neutral-atmospheric forcing, solar and geomagnetic conditions, and atmospheric wave activity. Consequently, the equinox seasons provide an appropriate period for examining whether TID variability is statistically associated with changes in ionospheric irregularity activity.

Addis Ababa is an important location for such an investigation because it lies within the East African low-latitude region, where ground-based ionospheric observations remain comparatively sparse. GNSS observations from Addis Ababa can provide continuous measurements of TEC from which both TID perturbations and ROTI can be derived. Previous studies using GNSS observations in the East African sector have demonstrated significant ionospheric variability and irregularity activity, including observations relevant to the Addis Ababa region (Moges et al., 2022; Olwendo and Cilliers, 2024; Bolaji et al., 2020; Ikani et al., 2023). However, a systematic statistical assessment of the relationship between TID amplitude and ROTI over Addis Ababa during the equinox seasons has not been sufficiently addressed.

In this study, we investigate the statistical relationship between traveling ionospheric disturbances and equatorial ionospheric irregularities over Addis Ababa, Ethiopia, during the 2023–2024 **equinox seasons** using GNSS observations. TID activity is quantified from perturbations of vertical TEC relative to the corresponding background TEC, while ionospheric irregularity activity is characterized using ROTI. The study evaluates the relationship between TID amplitude and ROTI through statistical correlation and regression analyses and further examines their temporal association using cross-correlation analysis. Particular attention is given to the strength of the relationship and the time lag at which the maximum association occurs. By combining these approaches, the study aims to determine whether enhanced TID amplitudes are systematically associated with increased ionospheric irregularity activity and to characterize the temporal

relationship between the two phenomena over Addis Ababa. The results provide a quantitative assessment of TID–irregularity relationships in the East African low-latitude ionosphere and contribute to improved understanding of ionospheric variability during the equinox seasons.

2. DATA AND METHODOLOGY

2.1. GNSS Data and Study Region

This study investigates the statistical relationship between traveling ionospheric disturbances (TIDs) and equatorial ionospheric irregularities over Addis Ababa, Ethiopia, during the 2023–2024 equinox seasons. The analysis was conducted using observations from the Addis Ababa International GNSS Service (IGS) station (ADIS), located at approximately 9.03°N geographic latitude and 38.74°E geographic longitude.

Dual-frequency, multi-constellation GNSS observations with a 30-s sampling interval were obtained from the NASA Crustal Dynamics Data Information System (CDDIS). The observations were processed to estimate total electron content (TEC), rate of TEC change (ROT), and the rate-of-TEC index (ROTI). The analysis considered March, April, September, and October of 2023 and 2024, representing the two equinoctial periods.

The equinox seasons were selected because the low-latitude ionosphere experiences substantial variability during these periods as a result of changes in solar illumination, thermospheric winds, ionospheric electrodynamics, and equatorial plasma processes. These conditions provide an appropriate period for examining the relationship between large-scale TEC disturbances and ionospheric irregularities.

To minimize the effects of multipath and increased measurement uncertainty associated with low-elevation observations, only satellite observations with elevation angles of 50° or greater were retained. The processed dataset included satellite elevation and azimuth, slant and vertical TEC, ROT, ROTI, background VTEC, TID, and TID amplitude.

2.2. Estimation of Total Electron Content

The vertical total electron content (VTEC) derived from dual-frequency GNSS observations was used to characterize the temporal variability of the ionosphere over the Addis Ababa GNSS station. The VTEC values were obtained from the frequency-dependent ionospheric delay measured by

the GNSS receiver and converted from slant total electron content (STEC) to VTEC using an ionospheric mapping function.

The geometry-free combination of dual-frequency GNSS carrier-phase observations is expressed as

$$L_4 = \lambda_1 L_1 - \lambda_2 L_2 \quad (1)$$

where L_1 and L_2 are the carrier-phase observations at frequencies f_1 and f_2 , respectively, and λ_1 and λ_2 are the corresponding wavelengths.

The slant total electron content (STEC) was determined from the frequency-dependent ionospheric delay relationship:

$$STEC = \frac{L_4}{40.3(f_1^{-2} - f_2^{-2})} \quad (2)$$

where STEC represents the electron content along the satellite-to-receiver ray path. Appropriate processing corrections and unit conversions were applied during the TEC estimation.

Because GNSS observations measure electron content along a slant path, STEC was converted into vertical total electron content (VTEC) using an ionospheric mapping function:

$$VTEC = STEC \times M(E) \quad (3)$$

where $M(E)$ is the elevation-dependent mapping function and E is the satellite elevation angle.

The mapping function was calculated using

$$M(E) = \left[1 - \left(\frac{R_E \cos E}{R_E + h_I} \right)^2 \right]^{-1/2} \quad (4)$$

where R_E is the mean Earth radius and h_I is the assumed ionospheric thin-shell height.

The resulting VTEC values were used as the primary electron-content parameter in the subsequent analysis. In this study, the processed VTEC data were used directly to characterize temporal ionospheric variability and to derive the perturbation parameters required for the TID analysis.

2.3. Identification and Quantification of TID Perturbations

TIDs appear in GNSS TEC observations as temporal perturbations superimposed on the slowly varying background ionosphere. To isolate these perturbations, the background VTEC component was removed from the measured VTEC. The TID perturbation was therefore defined as

$$TID(t) = VTEC(t) - VTEC_{background}(t) \quad (5)$$

where $VTEC(t)$ is the measured vertical TEC and $VTEC_{background}(t)$ represents the corresponding background TEC.

The absolute TID amplitude was calculated as

$$A_{TID}(t) = |TID(t)| \quad (6)$$

which can equivalently be written as

$$A_{TID}(t) = |VTEC(t) - VTEC_{background}(t)| \quad (7)$$

The relative TID perturbation was additionally expressed as a percentage of the background TEC:

$$TID_{\%}(t) = \frac{VTEC(t) - VTEC_{background}(t)}{VTEC_{background}(t)} \times 100 \quad (8)$$

The absolute TID amplitude, A_{TID} , was used as the principal TID parameter in the statistical analysis because it represents the magnitude of the TEC perturbation independently of whether the disturbance is positive or negative.

2.4. Determination of ROT and ROTI

The rate of TEC change was calculated from consecutive VTEC observations. For two consecutive observations, ROT was determined as

$$ROT_i = \frac{VTEC_{i+1} - VTEC_i}{t_{i+1} - t_i} \quad (9)$$

where t_i and t_{i+1} represent the corresponding observation times.

The rate-of-TEC index was subsequently calculated from the statistical variability of ROT:

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \quad (10)$$

where the angle brackets denote the mean over the selected temporal interval.

ROTI provides a measure of short-term TEC variability and is therefore used as an indicator of ionospheric irregularity activity. Larger ROTI values correspond to stronger fluctuations in the ionospheric electron content.

2.5. Data Screening and Quality Control

Several quality-control procedures were applied before the statistical analysis. First, only satellite observations with elevation angles of 50° or greater were retained to reduce multipath effects and uncertainties associated with low-elevation observations.

Second, observations containing missing, invalid, or nonphysical TEC values were removed. Temporal discontinuities were also examined because large data gaps can influence the calculation of ROT and subsequently affect statistical relationships.

The processed observations were organized by month and observation epoch. TID amplitude and ROTI values were paired at corresponding valid epochs so that both quantities represented the same temporal observations.

These procedures were applied to minimize the influence of measurement artifacts, missing data, and inconsistent temporal sampling on the statistical analysis.

2.6. Statistical Relationship Between TID Amplitude and ROTI

The primary objective of this study is to quantify the statistical relationship between TID amplitude and ionospheric irregularity intensity. Pearson's correlation coefficient was therefore calculated between A_{TID} and ROTI:

$$r = \frac{\sum_{i=1}^N (A_{TID,i} - \bar{A}_{TID})(\text{ROTI}_i - \overline{\text{ROTI}})}{\sqrt{\sum_{i=1}^N (A_{TID,i} - \bar{A}_{TID})^2} \sqrt{\sum_{i=1}^N ((\text{ROTI}_i - \overline{\text{ROTI}})^2)}} \quad (11)$$

- where N is the number of paired observations,
- r = Pearson correlation coefficient
- $A_{TID,i}$ = TID amplitude for the i -th observation
- $\bar{A}_{TID}$ = mean TID amplitude
- ROTI_i = ROTI value for the i -th observation
- $\overline{\text{ROTI}}$ = mean ROTI

A positive value of r indicates that larger TID amplitudes tend to be associated with larger ROTI values, whereas a negative value indicates an inverse statistical relationship.

A linear regression was additionally applied to quantify the dependence of ROTI on TID amplitude:

$$\text{ROTI} = a + bA_{TID} \quad (12)$$

where a is the intercept and b is the regression slope.

The coefficient of determination was calculated as

$$R^2 = 1 - \frac{\sum_{i=1}^N (\text{ROTI}_i - \hat{\text{ROTI}}_i)^2}{\sum_{i=1}^N (\text{ROTI}_i - \overline{\text{ROTI}})^2} \quad (13)$$

where $\hat{\text{ROTI}}_i$ is the ROTI value predicted by the linear regression model.

Binned median statistics were also calculated to provide a clearer representation of the central tendency of ROTI as a function of TID amplitude. This approach reduces the visual influence of the large number of individual observations while retaining the overall statistical behavior of the relationship.

2.7. Temporal Cross-Correlation Analysis

Zero-lag correlation provides information about simultaneous variations but does not establish whether one parameter systematically precedes the other. Therefore, temporal cross-correlation analysis was performed to investigate the relative timing of TID amplitude and ROTI variations.

The normalized cross-correlation coefficient was calculated as

$$C(\tau) = \frac{\sum [(A_{TID}(t_i) - \bar{A}_{TID}) (\text{ROTI}(t_i + \tau) - \overline{\text{ROTI}})]}{\sqrt{\sum [A_{TID}(t_i) - \bar{A}_{TID}]^2} \sqrt{\sum [\text{ROTI}(t_i + \tau) - \overline{\text{ROTI}}]^2}} \quad (14)$$

where τ represents the time lag between TID amplitude and ROTI.

The lag corresponding to the maximum correlation was determined from

$$\tau_{max} = \arg \max_{\tau} C(\tau) \quad (15)$$

The cross-correlation analysis was performed over the lag range

$$-120 \text{ min} \leq \tau \leq +120 \text{ min} \quad (16)$$

with a lag increment of

$$\Delta\tau = 5 \text{ min} \quad (17)$$

A positive lag was defined as TID amplitude leading ROTI, whereas a negative lag indicated that ROTI variations preceded TID-amplitude variations. The lag corresponding to the maximum cross-correlation therefore provides an estimate of the temporal offset at which the statistical association between the two parameters is strongest. The cross-correlation results were interpreted as evidence of temporal association and lead-lag behavior rather than direct evidence of causality.

2.8. Solar and Geomagnetic Parameters

To provide the broader solar and geomagnetic context for the observed ionospheric variability, selected parameters from the OMNI database were examined. These included the planetary K_p index, the disturbance storm-time index (Dst), and the solar 10.7-cm radio flux ($F_{10.7}$). The K_p index was used to characterize the level of global geomagnetic activity, while Dst was used to characterize storm-time geomagnetic disturbance. The $F_{10.7}$ index was used as an indicator of solar activity and the background solar radiation influencing the ionosphere.

The selected parameters were examined for March, April, September, and October of 2023 and 2024. Their temporal variations were compared with the GNSS-derived TID amplitude and ROTI parameters to provide an external solar–geomagnetic context for the observed ionospheric variability. These parameters were not used to establish a direct causal relationship with TID or ROTI. Instead, they were used to describe the solar and geomagnetic conditions under which the observed ionospheric variability occurred.

2.9. Seasonal and Monthly Analysis

The observations were analyzed separately for March, April, September, and October in both 2023 and 2024. This monthly separation was used to investigate possible differences in the TID–ROTI relationship among the individual equinoctial periods. For each month, the Pearson correlation coefficient, regression relationship, coefficient of determination, and cross-correlation function were evaluated. The monthly results were subsequently compared with the combined equinoctial results.

The separate monthly analysis is important because ionospheric variability can differ between the March and September equinoxes and between adjacent months. A combined analysis alone could therefore mask important temporal differences in the relationship between TID activity and ionospheric irregularities.

2.10. Interpretation of the Statistical Results

The statistical relationship was interpreted using the correlation coefficient, regression slope, coefficient of determination, and temporal cross-correlation. A positive correlation between TID amplitude and ROTI indicates that enhanced TEC perturbations tend to occur during periods of

enhanced ionospheric irregularity activity. However, correlation alone does not establish that TIDs cause ionospheric irregularities or that irregularities generate TIDs.

The statistical relationship may also reflect the response of both parameters to common external drivers, including changes in ionospheric electrodynamics, thermospheric disturbances, solar-wind forcing, and geomagnetic activity. Similarly, a non-zero maximum cross-correlation lag indicates a temporal association between the two parameters but does not independently establish a physical propagation mechanism or causal relationship.

2.11. Overall Methodological Framework

The analysis followed a sequential processing procedure. First, 30s dual-frequency, multi-constellation GNSS observations from the ADIS station were processed to estimate TEC. Second, elevation-angle filtering and quality-control procedures were applied to remove observations that could introduce significant uncertainty.

Third, VTEC was separated into background and perturbation components, and the resulting perturbations were used to determine TID amplitude. Fourth, ROT and ROTI were calculated from the temporal variations of VTEC to characterize ionospheric irregularity activity.

Fifth, TID amplitude and ROTI were temporally matched and statistically analyzed using Pearson correlation and linear regression. Binned median statistics were used to illustrate the central tendency of the relationship, while R^2 was used to quantify the fraction of ROTI variance statistically associated with TID amplitude.

Sixth, temporal cross-correlation was performed over lags from -120 to $+120$ min at 5min intervals to investigate possible lead-lag behavior. Finally, K_p , Dst , and $F_{10.7}$ were examined to provide the solar and geomagnetic context of the observations.

This methodological framework was designed to quantify the statistical relationship between large-scale TEC perturbations represented by TID amplitude and ionospheric irregularity intensity represented by ROTI over Addis Ababa during the 2023–2024 equinox seasons, while maintaining a clear distinction between statistical association and physical causality.

3. RESULTS AND DISCUSSION

3.1 Overview of the GNSS-Derived Ionospheric Variations

The temporal behavior of the ionosphere over Addis Ababa was investigated using GNSS observations from the ADIS station during the March, April, September, and October equinox months of 2023 and 2024. The analysis focused on the identification of traveling ionospheric disturbances (TIDs) from detrended VTEC variations and the characterization of small-scale ionospheric irregularities using the rate of total electron content index (ROTI).

The geographical location of the ADIS station is particularly suitable for investigating the relationship between large-scale ionospheric disturbances and equatorial ionospheric irregularities because the station is located close to the magnetic equator. The station is therefore able to provide useful observations of ionospheric variability associated with equatorial electrodynamic processes, atmospheric disturbances, and changes in the background ionospheric plasma environment.



Figure 1. Location of the Addis Ababa GNSS station (ADIS) used in this study.

The GNSS observations showed substantial temporal variability in VTEC during the investigated equinox seasons. After removal of the slowly varying background component, shorter-period fluctuations were identified as TID perturbations. These perturbations varied in amplitude and occurrence with time, indicating that the ionosphere over Addis Ababa was continuously affected

by both large-scale and smaller-scale processes. The derived ROT and ROTI values also exhibited considerable temporal variability. Periods of enhanced ROTI represent intervals of stronger short-term electron-density gradients and therefore provide an indication of increased ionospheric irregularity activity. Comparison of the TID and ROTI parameters provides a statistical approach for determining whether stronger TID perturbations tend to occur simultaneously with enhanced ionospheric irregularities.

3.2 Identification of TID Perturbations

The TID perturbations were obtained by subtracting the background VTEC variation from the observed VTEC. This procedure removes the dominant slowly varying component of the ionospheric electron content and emphasizes shorter-period fluctuations associated with traveling ionospheric disturbances.

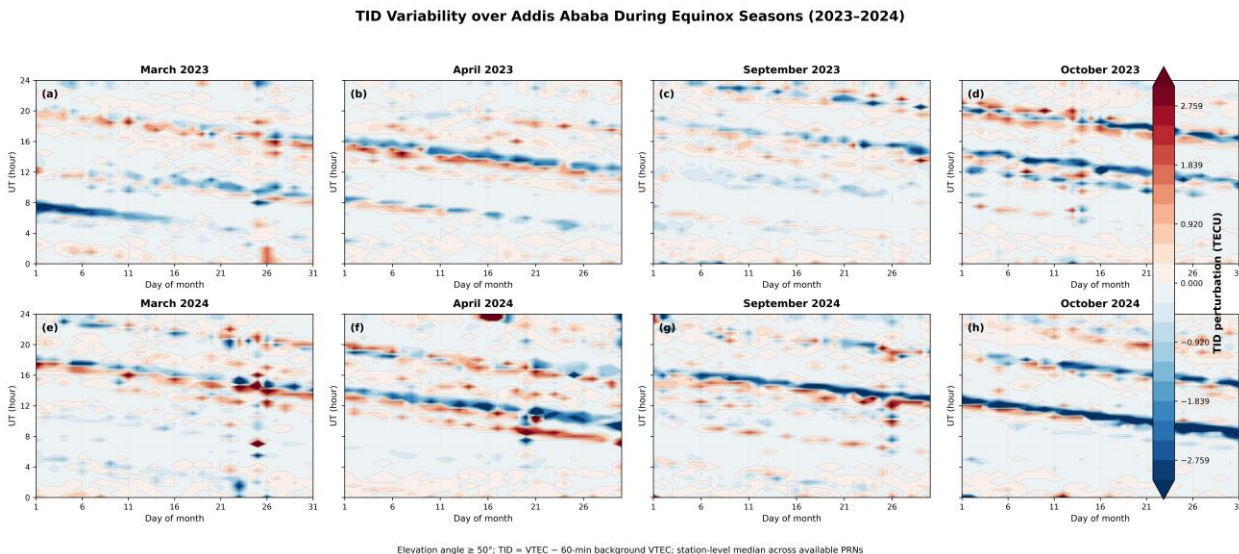


Figure 2. TID variability over Addis Ababa during the equinox seasons (2023–2024).

Figure 2 presents the two-dimensional temporal distribution of TID perturbations observed over Addis Ababa during March, April, September, and October of 2023 and 2024. The TID perturbation was calculated by subtracting the 60-min background VTEC from the observed VTEC. GNSS observations with elevation angles $\geq 50^\circ$ were considered to reduce elevation-dependent effects. Positive TID values represent enhancements relative to the background VTEC, whereas negative values represent depletions.

The contour representation reveals substantial temporal variability in the TID perturbations, with alternating positive and negative structures occurring throughout the observation periods. These

structures indicate departures of the ionospheric electron content from its local background level and provide evidence of short-term variability in the ionosphere over Addis Ababa. The occurrence of organized positive and negative bands suggests that some of the observed perturbations may be associated with propagating ionospheric disturbances. However, identification of their specific atmospheric or electrodynamic sources requires additional information, such as propagation direction, phase velocity, wave period, or independent atmospheric observations.

A pronounced increase in perturbation activity is apparent during several nighttime intervals. Enhanced nighttime variability is particularly relevant at low latitudes because the post-sunset ionosphere is subject to strong electrodynamic changes, including the development of the evening upward plasma drift and subsequent restructuring of the equatorial ionosphere. Such conditions can favor the development of plasma irregularities and may contribute to enhanced TEC variability. Nevertheless, the TID contour plots alone cannot establish that individual perturbations are caused by equatorial plasma bubbles (EPBs); confirmation would require complementary irregularity or scintillation observations.

Daytime perturbations are also evident in several months, although their occurrence and amplitude vary considerably. These daytime variations demonstrate that TID activity is not restricted to the nighttime sector. The differences among individual days indicate substantial short-term variability, which may reflect changes in solar and geomagnetic forcing, thermospheric conditions, and lower-atmospheric forcing.

Comparison between 2023 and 2024 indicates noticeable inter-annual differences in the magnitude and temporal distribution of the TID perturbations. Several periods in 2024 exhibit larger positive and negative deviations than the corresponding periods in 2023. These differences are consistent with the substantially different solar-activity conditions during the two years. However, the stronger perturbations observed in 2024 should not be attributed solely to increased solar EUV radiation without considering other controlling factors, including geomagnetic activity, thermospheric winds, electrodynamic forcing, and lower-atmospheric variability. The quantitative relationship between TID amplitude and external space-weather parameters is therefore examined separately in the subsequent statistical analysis.

Seasonal differences are also apparent among the equinox months. March and April show several intervals of enhanced and organized perturbations, while September and October display different temporal distributions and amplitudes. These differences indicate that the occurrence of TIDs is not uniform between the two equinox periods. The observed seasonal asymmetry may be related to changes in solar illumination, thermospheric conditions, neutral winds, and electrodynamic forcing. Because the present analysis is based on a single GNSS station, however, the results primarily characterize the temporal variability observed over Addis Ababa and cannot by themselves establish the regional propagation characteristics of the disturbances.

Overall, Figure 2 demonstrates substantial diurnal, seasonal, and inter-annual variability in TID perturbations over Addis Ababa during the 2023–2024 equinox seasons. The two-dimensional representation provides a clear visualization of the timing, persistence, and relative amplitude of the perturbations and establishes the observational basis for the subsequent analysis of the relationship between TID activity and ionospheric irregularity intensity.

Both positive and negative TID perturbations were observed. Positive perturbations correspond to enhancements relative to the background VTEC, whereas negative perturbations indicate reductions. Since the statistical analysis focuses on disturbance magnitude rather than the direction of the perturbation, the absolute value of TID was used to define the TID amplitude.

The occurrence of these perturbations indicates that the ionosphere over Addis Ababa experienced significant short-term variability during the equinox seasons. Such variations may be associated with atmospheric wave activity, large-scale traveling ionospheric disturbances, changes in thermospheric winds, and geomagnetic forcing.

3.3 ROTI Variability

The temporal derivative of VTEC was used to calculate ROT, while ROTI was subsequently obtained as the standard deviation of ROT over the selected observation intervals. Enhanced ROTI indicates increased short-term variability in TEC and is commonly used as a GNSS-based indicator of ionospheric irregularity activity.

ROTI Variability over Addis Ababa During Equinox Seasons (2023-2024)

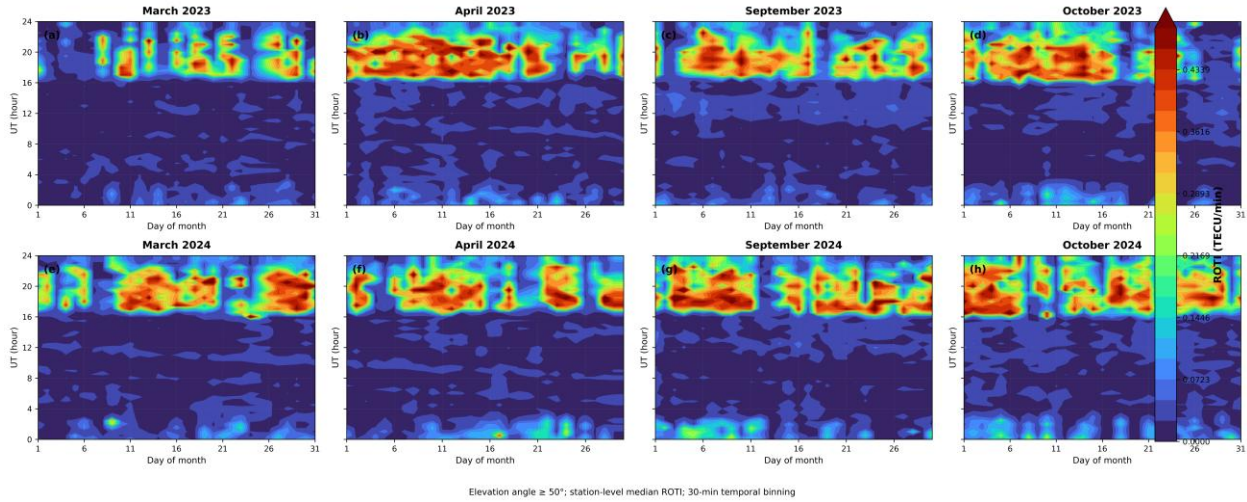


Figure 3. ROTI variability over Addis Ababa during the equinox seasons (2023–2024).

To investigate the temporal variability of ionospheric irregularities over Addis Ababa, the Rate of TEC Index (ROTI) was calculated from the GNSS observations and represented as two-dimensional contour plots for the equinox months of March, April, September, and October in 2023 and 2024 (Figure 3). ROTI is defined as the standard deviation of the rate of TEC change over a specified time interval and is widely used to characterize short-period ionospheric TEC fluctuations and irregularity activity. It can also serve as a proxy for scintillation-related irregularities when dedicated scintillation observations are unavailable; however, ROTI should not be interpreted as a direct measurement of the amplitude scintillation index S_4 .

Diurnal Variability and Post-Sunset Enhancement

A pronounced diurnal asymmetry is evident in the ROTI distributions. During much of the daytime sector, approximately 04:00–14:00 UT (07:00–17:00 local time), ROTI values are generally low, indicating comparatively weak short-term TEC fluctuations. In contrast, enhanced ROTI activity occurs predominantly during the evening and nighttime sector, particularly from approximately 16:00 to 24:00 UT (19:00–03:00 local time). The occurrence of enhanced nighttime ROTI is consistent with the well-established tendency for low-latitude ionospheric irregularities to develop after sunset.

At equatorial and low latitudes, the post-sunset ionosphere is strongly influenced by changes in the electrodynamics of the F region, including the pre-reversal enhancement (PRE) of the eastward

electric field. The associated upward plasma drift can increase the susceptibility of the bottomside F region to the generalized Rayleigh–Taylor instability, which provides a mechanism for the generation and subsequent evolution of equatorial plasma irregularities. Such irregularities can develop into equatorial plasma bubbles and produce enhanced TEC gradients and fluctuations along GNSS signal paths. Therefore, the nighttime enhancement observed in the ROTI contours is physically consistent with enhanced low-latitude irregularity activity. However, because the present analysis uses ROTI from a single ground station, the contour plots alone do not provide sufficient evidence to identify individual structures specifically as equatorial plasma bubbles.

The persistence of enhanced ROTI into the post-midnight sector also indicates that the irregularity activity is not restricted to the immediate post-sunset period. The duration and intensity of nighttime enhancements vary substantially from day to day, suggesting that the generation and evolution of irregularities are modulated by changing ionospheric and geophysical conditions.

Inter-Annual Variability

A comparison between 2023 and 2024 reveals clear inter-annual differences in the magnitude and temporal distribution of ROTI enhancements. Although the dominant nighttime pattern is present in both years, several intervals in 2024 exhibit stronger and more persistent ROTI enhancements than those observed during corresponding periods in 2023. In particular, enhanced ROTI extends farther into the post-midnight sector during several periods of 2024.

The stronger activity observed in 2024 is consistent with the different solar and geophysical conditions prevailing during the two years. The progression of Solar Cycle 25 toward its maximum was accompanied by enhanced solar and geomagnetic activity, which can modify the background ionospheric density, electrodynamics, thermospheric conditions, and the probability of developing low-latitude irregularities. Recent studies have likewise reported increasing ionospheric perturbation activity as Solar Cycle 25 approached its peak.

Nevertheless, the difference between 2023 and 2024 should not be attributed exclusively to solar EUV forcing. Geomagnetic activity, thermospheric winds, electric-field variability, and lower-atmospheric forcing can also influence the generation and evolution of low-latitude irregularities. Consequently, the observed increase in ROTI during 2024 is interpreted here as an indication of

enhanced irregularity activity under different solar-geophysical conditions rather than as direct evidence of a single controlling mechanism.

Implications for GNSS Observations

The repeated occurrence of enhanced nighttime ROTI has important implications for GNSS observations over Addis Ababa. Increased ROTI indicates stronger short-period TEC fluctuations and the presence of ionospheric irregularities along the observed GNSS signal paths. Such irregularities can contribute to phase fluctuations, cycle slips, positioning errors, and, under sufficiently strong conditions, loss of signal lock.

However, a specific ROTI threshold should not be interpreted universally as demonstrating severe scintillation. The relationship between ROTI and conventional scintillation indices such as S_4 depends on sampling interval, satellite elevation, irregularity scale size, and other observational factors. In particular, studies using 30s GNSS observations have demonstrated that ROTI is useful for identifying irregularity activity but has limitations as a quantitative substitute for dedicated scintillation measurements.

Therefore, the elevated ROTI intervals identified in Figure 3 should be interpreted as periods of enhanced ionospheric irregularity activity and increased potential for GNSS signal degradation rather than as direct measurements of severe scintillation. The results nevertheless demonstrate that the post-sunset sector represents an important period of ionospheric variability over Addis Ababa, particularly during the higher solar-activity conditions of 2024.

Overall, Figure 3 demonstrates a strong diurnal dependence of ionospheric irregularity activity, characterized by relatively low ROTI during much of the daytime and enhanced ROTI predominantly after sunset. The results also reveal substantial day-to-day, seasonal, and inter-annual variability. The enhanced activity observed during several intervals in 2024 provides an important observational basis for examining the relationship between ionospheric irregularities, TID activity, and external solar-geophysical drivers in the subsequent statistical analyses.

3.4 Statistical Relationship Between TID Amplitude and ROTI

The relationship between TID amplitude and ROTI was investigated using Pearson correlation and linear regression. The analysis was performed using the absolute TID amplitude, $|TID|$, and ROTI at corresponding observation epochs.

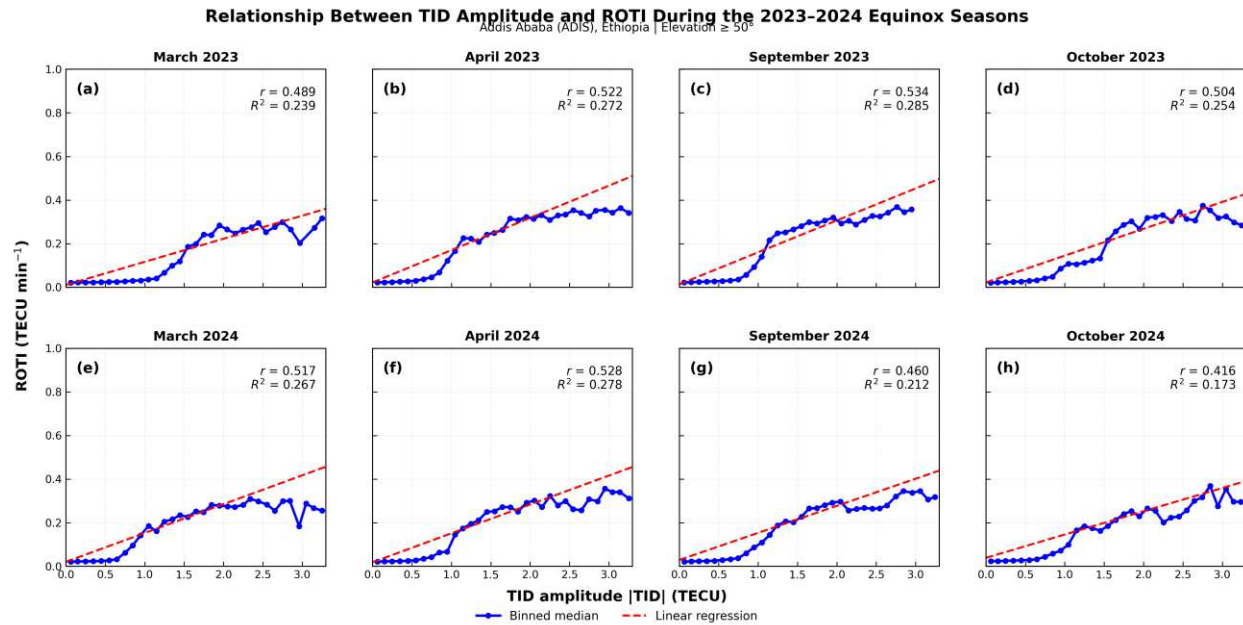


Figure 4. Relationship between TID amplitude and ROTI during the 2023–2024 equinox seasons at Addis Ababa (ADIS), Ethiopia. Blue solid curves represent binned median ROTI values, while red dashed lines indicate linear least-squares regression. The Pearson correlation coefficient (r) and coefficient of determination (R^2) are shown for each month. GNSS observations with satellite elevation angles $\geq 50^\circ$ were used.

The statistical relationship between TID amplitude and ROTI was consistently positive throughout the 2023–2024 equinox seasons at Addis Ababa. Pearson correlation coefficients ranged from 0.416 in October 2024 to 0.534 in September 2023, indicating weak-to-moderate to moderate positive associations. The corresponding coefficients of determination ranged from 0.173 to 0.285, showing that TID amplitude alone explained approximately 17–29% of the observed variability in ROTI. The strongest relationship occurred in September 2023 ($r = 0.534$, $R^2 = 0.285$), whereas the weakest occurred in October 2024 ($r = 0.416$, $R^2 = 0.173$). Despite the month-to-month and interannual variations in correlation strength, the consistently positive correlations suggest that enhanced TID activity tends to coincide with increased ionospheric irregularity activity. The departure from a strictly linear response, particularly at larger TID amplitudes, further indicates that ROTI variability is influenced by additional ionospheric and geophysical processes.

3.5 Temporal Coupling Between TID Amplitude and ROTI

To investigate the temporal relationship between large-scale Traveling Ionospheric Disturbances (TIDs) and small-scale ionospheric irregularities, a segment-based cross-correlation analysis was

performed between TID amplitude and the Rate of TEC Index (ROTI) during the 2023 and 2024 equinox seasons.

Figure 5 shows the cross-correlation coefficients as a function of time lag from -120 to $+120$ min. A positive lag indicates that variations in TID amplitude precede corresponding variations in ROTI. Positive correlation peaks were identified for all eight month–year combinations, with maximum correlation coefficients ranging from $r = 0.21$ in September 2023 to $r = 0.39$ in April 2024. In seven of the eight cases, the maximum correlation occurred at a lag of $+5$ min, whereas April 2024 exhibited a longer optimal lag of $+35$ min.

The predominance of positive lags indicates that enhanced TID amplitude generally preceded subsequent increases in ROTI. The relatively short optimal lags of $+5$ to $+35$ min suggest a close temporal association between the two types of ionospheric variability. The variation in both correlation strength and optimal lag, however, indicates that the response was not uniform throughout the investigated periods. These results therefore provide statistical evidence for a temporal association between TID activity and subsequent ionospheric irregularity variability at ADIS, but do not by themselves establish a direct causal relationship.

3.5.2 Physical Interpretation of the TID–ROTI Relationship

The observed positive time lags are consistent with the hypothesis that TID-related plasma perturbations may contribute to the subsequent development or enhancement of small-scale ionospheric irregularities. TIDs introduce spatial and temporal perturbations into the ionospheric plasma distribution and can modify local plasma-density gradients. Under favorable electrodynamic conditions, such perturbations may influence the development of plasma instabilities and consequently contribute to enhanced small-scale irregularity activity.

The predominance of the $+5$ min lag suggests that, during most of the investigated periods, the temporal response between TID activity and ROTI enhancement was relatively rapid. The longer $+35$ min lag observed in April 2024 indicates that the response time can vary with the prevailing ionospheric conditions. Such variability may arise from changes in background electron density, electric fields, neutral winds, plasma-density gradients, and other electrodynamic processes. Therefore, the observed lag structure is consistent with a possible TID contribution to irregularity

development, but additional observations would be required to identify the specific physical mechanism responsible for the observed response.

3.5.3 Multi-Driver Nature of Ionospheric Irregularities

The moderate correlation coefficients ($r = 0.21 - 0.39$) indicate that TID amplitude is only one component of the variability observed in ROTI. Small-scale ionospheric irregularities are influenced by multiple interacting processes, including background plasma-density gradients, electric-field variability, vertical plasma drift, neutral-wind forcing, and geomagnetic activity. Consequently, periods of enhanced TID activity do not necessarily correspond to proportionally enhanced ROTI.

The observed correlations therefore suggest that TID activity may contribute to the variability of small-scale irregularities while other physical processes simultaneously control their magnitude and evolution. The moderate rather than strong correlations are consequently consistent with a complex ionospheric system in which TIDs interact with, rather than exclusively determine, the processes responsible for irregularity development.

3.5.4 Interannual Variability

The comparison between 2023 and 2024 demonstrates variability in both the strength and timing of the TID–ROTI relationship. Although positive correlations were observed during all investigated periods, the correlation coefficients and optimal time lags differed between individual months. In particular, April 2024 showed the strongest cross-correlation ($r = 0.39$) but also the longest optimal lag (+35 min), whereas most other periods exhibited maximum correlations at +5 min.

This variability indicates that the temporal coupling between TID activity and small-scale irregularities is sensitive to the prevailing ionospheric and electrodynamic environment. Differences in solar activity, background ionization, electric-field conditions, neutral-wind dynamics, and geomagnetic forcing between 2023 and 2024 may contribute to the observed changes. Thus, the results emphasize that the TID–ROTI relationship should be considered a variable statistical association rather than a fixed response.

Overall, the cross-correlation analysis demonstrates a consistent tendency for TID amplitude variations to precede ROTI variations at ADIS, with optimal delays of 5–35 min. The results

support a possible role of TIDs in the evolution of small-scale ionospheric irregularities, while the moderate correlations and interannual variability indicate that the observed irregularity activity results from the combined influence of TIDs and other ionospheric and electrodynamic processes.

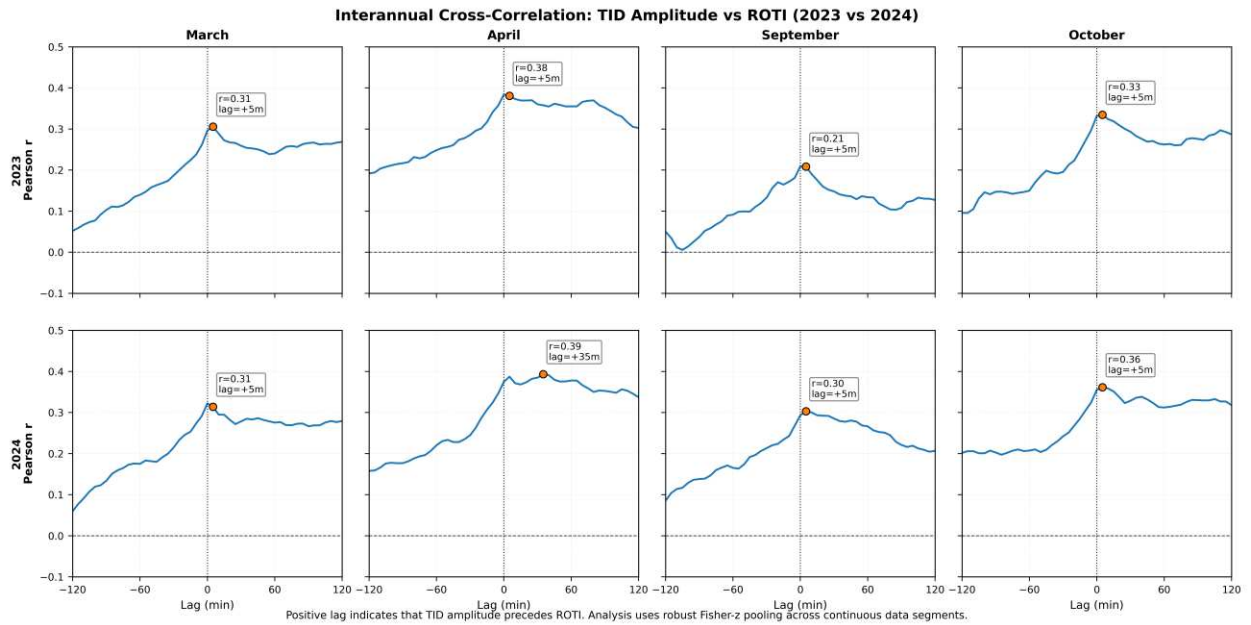


Figure 5. Interannual cross-correlation analysis between TID amplitude and ROTI at the Addis Ababa (ADIS) GNSS station during the 2023 (top row) and 2024 (bottom row) equinox seasons. The x-axis represents the time lag (min), with positive lag values indicating that variations in TID amplitude precede corresponding variations in ROTI. Orange markers indicate the maximum positive cross-correlation coefficient (r) and its corresponding optimal time lag for each month. The predominantly positive lags indicate a consistent temporal association in which TID perturbations generally precede subsequent ROTI variations, supporting a possible coupling between large-scale TID activity and small-scale ionospheric irregularities.

3.6 Solar and Geomagnetic Conditions

The solar and geomagnetic conditions during the investigated equinoctial periods were characterized using the **Dst**, **Kp**, and **F10.7 indices**. The Dst and Kp indices were used to describe geomagnetic activity, while F10.7 was used as a proxy for variations in solar extreme-ultraviolet (EUV) activity. The temporal variations of these indices during the 2023–2024 equinoctial seasons

are presented in Figures 6–8, providing the solar and geomagnetic context for interpreting the observed temporal variability of TIDs and ionospheric irregularities over Addis Ababa.

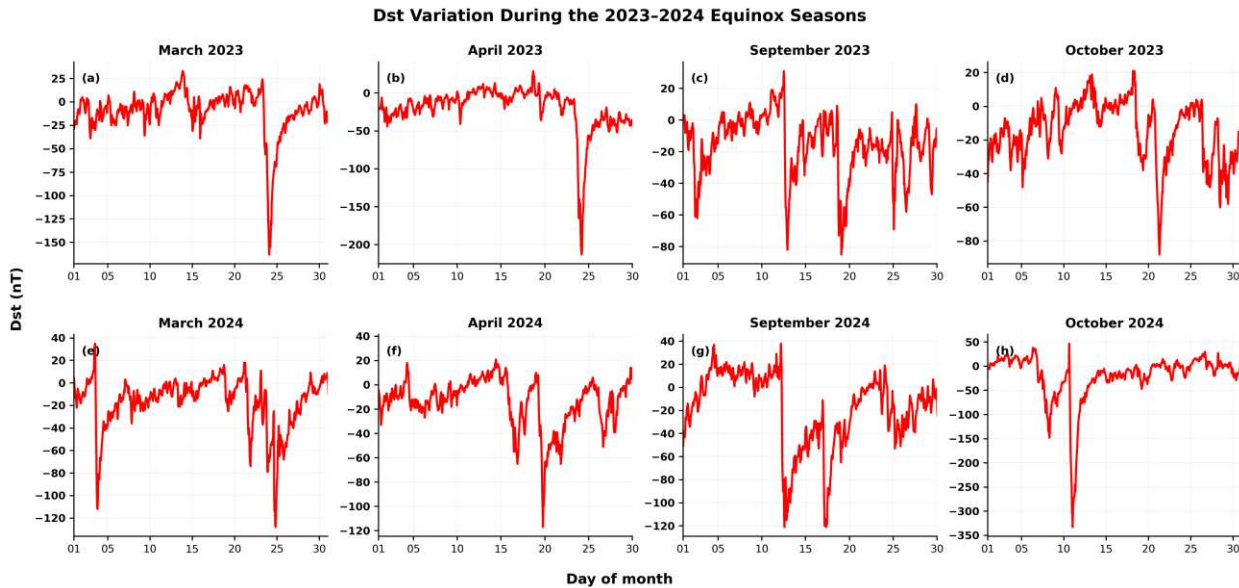


Figure 6. illustrates the temporal variation of the Dst index during the equinoctial months of 2023 and 2024.

The results show substantial variations in geomagnetic activity throughout the analyzed periods. During 2023, pronounced negative Dst excursions occurred mainly in late March and late April, with minimum values of approximately -165 nT and -215 nT, respectively. September and October 2023 generally exhibited weaker disturbances, although several short-duration negative excursions were observed. In comparison, the 2024 equinox seasons exhibited several pronounced geomagnetic disturbances. Strong negative excursions were observed in March and April, while September 2024 showed major disturbances around days 13 and 18. The strongest depression in the analyzed periods occurred in October 2024, when Dst decreased to approximately -330 nT around day 11. These variations indicate substantial changes in geomagnetic activity during the study period and provide the geomagnetic context for examining the associated temporal variations in GNSS-derived ionospheric irregularities.

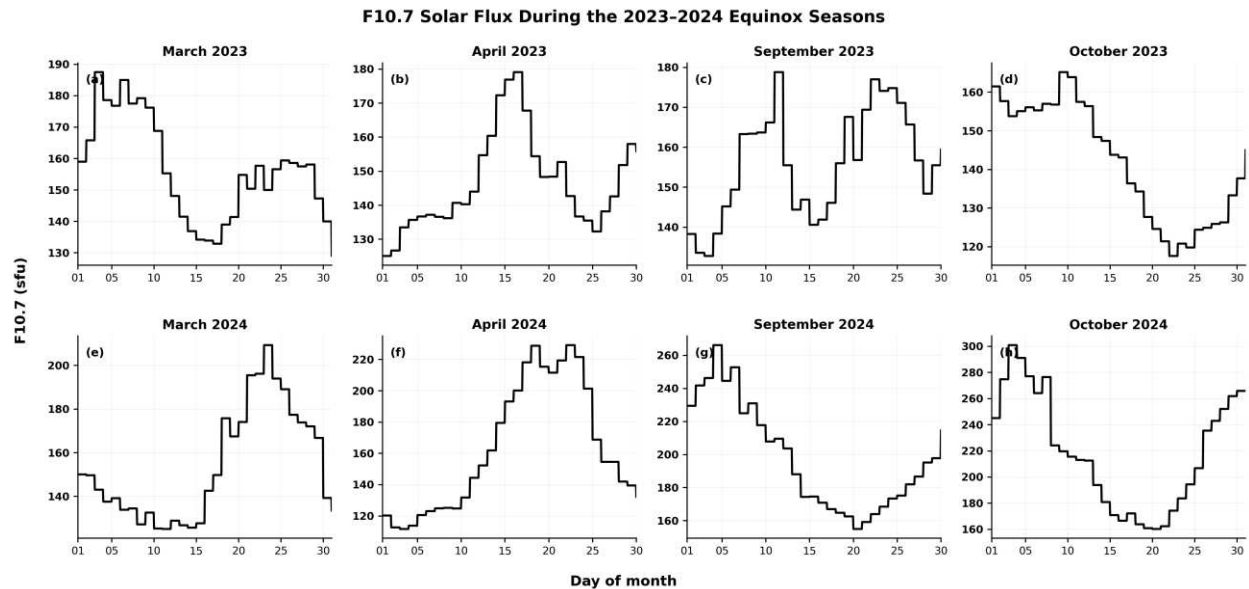


Figure 7 presents the temporal variation of the F10.7 solar radio flux during the equinoctial months of 2023 and 2024.

The F10.7 values show considerable temporal variability throughout the study period, with generally higher levels during the 2024 equinox seasons. In 2023, F10.7 ranged approximately from 118 to 190 sfu, with the highest values observed during March and September. In contrast, the 2024 observations show substantially enhanced solar flux, reaching more than 200 sfu in March, above 220 sfu in April, approximately 265 sfu in September, and nearly 300 sfu in October. The particularly high F10.7 values during September and October 2024 indicate an enhanced solar-activity background during these periods. These variations provide important solar-activity context for interpreting the observed GNSS-derived ionospheric variability and irregularities during the 2024 equinox seasons.

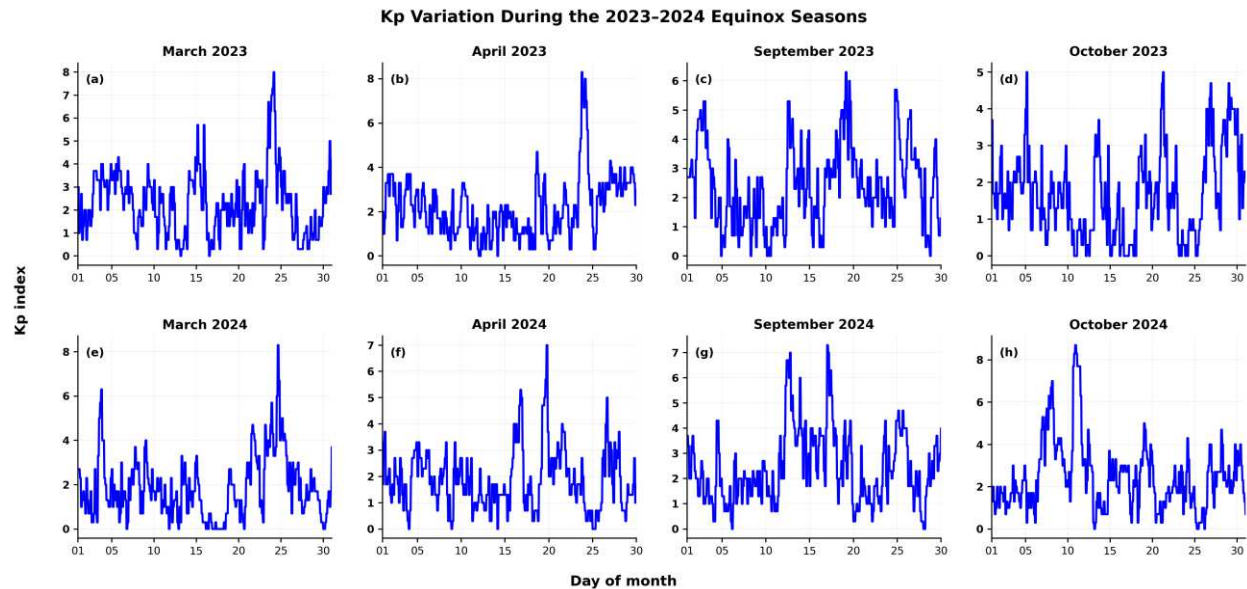


Figure 8. Geomagnetic activity during the 2023–2024 equinoctial seasons.

The figure presents the temporal variation of the planetary Kp index during March, April, September, and October of 2023 and 2024. The results demonstrate considerable short-term variability in geomagnetic activity throughout the study periods. During 2023, pronounced enhancements occurred around 23–25 March and 23–24 April, when Kp reached approximately 8, while September exhibited several moderate-to-strong activity intervals with Kp values approaching 6. October 2023 was comparatively less disturbed, although several short-lived enhancements reached $Kp \approx 5$. During 2024, enhanced geomagnetic activity was particularly evident in late March, mid-to-late April, September, and early October. The strongest enhancement occurred in October 2024, when Kp approached 9, while Kp values of approximately 7–8 were also observed during March, April, and September. These intervals of enhanced geomagnetic activity provide important background conditions for examining the possible relationship between magnetospheric forcing, traveling ionospheric disturbances, and ionospheric irregularities over Addis Ababa. The coexistence of quiet and disturbed intervals within each equinoctial season also provides a useful basis for assessing whether the TID–ROTI relationship changes under different levels of geomagnetic activity.

3.7 Comparison Between 2023 and 2024

The two-year analysis was performed to assess the consistency of the statistical relationship between TID amplitude and ROTI under different background solar and geomagnetic conditions.

Figure 9 compares the monthly median absolute TID amplitude ($|TID|$), ROTI, Pearson correlation coefficient (r), and coefficient of determination (R^2) for the four investigated equinox months in 2023 and 2024. The comparison shows a positive TID–ROTI relationship in both years, although the strength of the relationship varies among months and between years. This seasonal and interannual variability indicates that the relationship is not uniform throughout the investigated periods and may depend on the prevailing ionospheric and geophysical conditions.

The 2024 dataset contained **608,140 observations**, of which **602,924 observations** corresponded to the four selected equinox months. After temporal processing and quality-control procedures, **321,723 unique station epochs** were obtained. The median sampling interval was approximately **0.500 min**, consistent with the 30-s GNSS observation interval, and **358 gaps longer than 5 min** were identified. The monthly numbers of usable station epochs were **79,995** in March, **77,209** in April, **79,613** in September, and **84,906** in October. The large number of observations and station epochs provided substantial temporal coverage for the statistical analysis. Nevertheless, differences between 2023 and 2024 should be interpreted in the context of variations in solar activity, geomagnetic forcing, atmospheric conditions, and data availability. Therefore, the year-to-year comparison assesses the consistency of the observed TID–ROTI relationship but does not by itself establish a direct dependence on the solar cycle.

Comparison of TID amplitude, ROTI, and TID-ROTI relationship during the 2023-2024 equinox seasons at ADIS

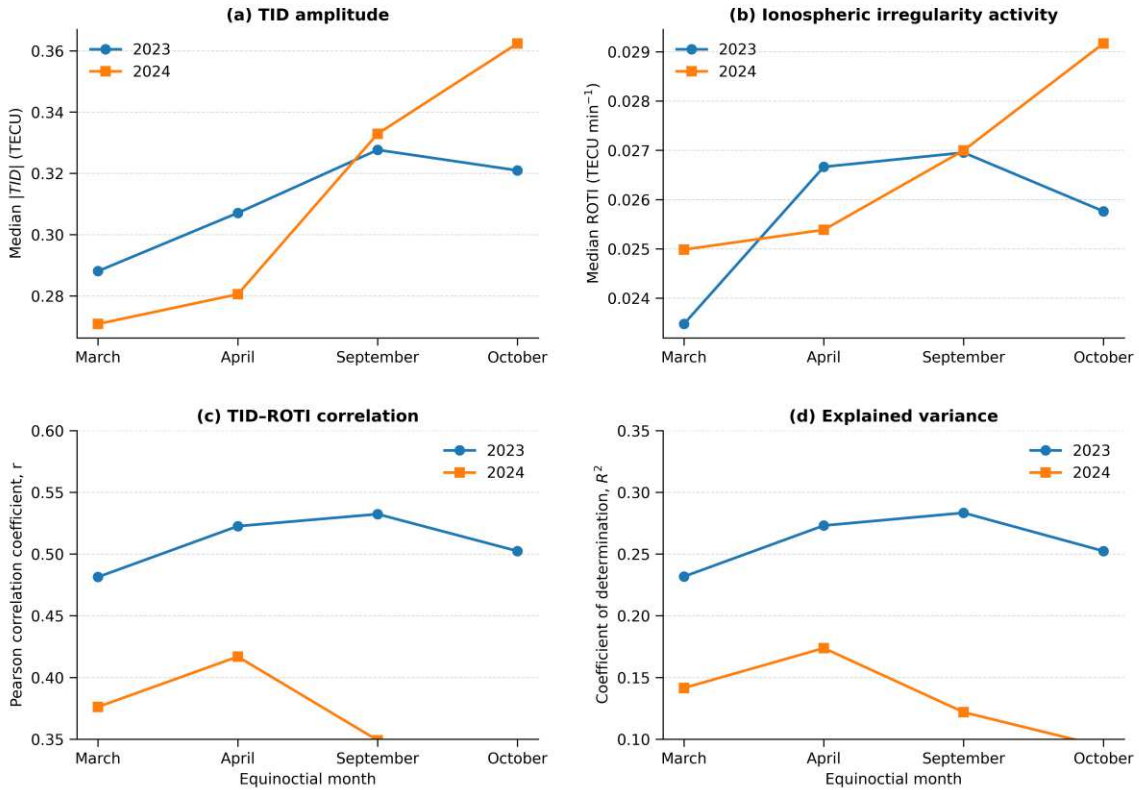


Figure 9. Comparison of the TID–ROTI relationship between the 2023 and 2024 equinox seasons at the Addis Ababa (ADIS) GNSS station, Ethiopia. Panels (a) and (b) show the monthly median absolute TID amplitude ($|TID|$) and ROTI, respectively, while panels (c) and (d) present the corresponding Pearson correlation coefficient (r) and coefficient of determination (R^2). The comparison illustrates seasonal and interannual variability in the statistical relationship between traveling ionospheric disturbances and small-scale ionospheric irregularities.

3.8 Limitations of the Analysis

Several limitations should be considered when interpreting the results. The analysis is based on a single GNSS station (ADIS), and therefore the findings represent local ionospheric variability over Addis Ababa and cannot be directly generalized to the entire Ethiopian region. TID amplitude and ROTI characterize different aspects and timescales of ionospheric variability, so their statistical relationship should not be interpreted as a direct one-to-one physical relationship. Furthermore, correlation, regression, and cross-correlation indicate statistical associations but do not establish causality. The Dst, Kp, and F10.7 indices provide useful solar and geomagnetic context but do not fully represent local electrodynamic and thermospheric conditions. Finally, the analysis is limited

to the equinox months of 2023 and 2024; additional years, seasons, and stations are needed to assess the broader applicability of the observed TID–ROTI relationship.

4. CONCLUSION

This study investigated the statistical relationship between traveling ionospheric disturbances (TIDs) and small-scale ionospheric irregularities over Addis Ababa, Ethiopia, during the 2023–2024 equinox seasons using GNSS-derived VTEC and ROTI observations. The results demonstrate a consistent positive association between TID amplitude and ROTI, although the strength of the relationship varies among months and between years.

The cross-correlation analysis revealed positive temporal lags, indicating that TID amplitude variations generally preceded subsequent ROTI variations by several minutes. This temporal association suggests that large-scale ionospheric perturbations may contribute to subsequent small-scale ionospheric variability. However, the moderate correlation strengths indicate that TID amplitude alone does not explain the observed ROTI variability. Other atmospheric, electrodynamic, solar, and geomagnetic processes are also likely to contribute to the development and evolution of ionospheric irregularities.

The study provides a quantitative statistical assessment of the TID–ROTI relationship over Addis Ababa and contributes to the observational understanding of large- and small-scale ionospheric variability in the East African low-latitude region. Nevertheless, the analysis is based on a single GNSS station and a limited set of equinox months, which restricts the spatial and temporal generalization of the findings.

Future studies should extend the analysis to multiple GNSS stations, additional seasons, and longer time periods. The inclusion of electric-field, neutral-wind, thermospheric, and other ionospheric observations would further help clarify the physical processes underlying the observed TID–ROTI relationship. Such multi-station and multi-instrument investigations would provide a more comprehensive understanding of the coupling between traveling ionospheric disturbances and small-scale ionospheric irregularities.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The 30-s GNSS observations used in this study were obtained from the International GNSS Service (IGS) data repository through the Crustal Dynamics Data Information System (CDDIS). Geomagnetic and solar activity data used for the analysis were obtained from the corresponding publicly available data repositories cited in the manuscript. All data sources are publicly accessible.

Author Contributions (CRediT Taxonomy)

Tesfay Ljalem Weldeslassie conceived the study, developed the methodology, processed and analyzed the GNSS data, conducted the statistical and cross-correlation analyses, prepared the visualizations, and wrote the original draft of the manuscript.

Tesfau Hagos Tadesse contributed to the interpretation and validation of the results and reviewed and edited the manuscript.

Gebregiorgis Abraha Fikade provided supervision and academic guidance, contributed to the validation and interpretation of the results, and reviewed and edited the manuscript.

Yikdem Mengesha Gebrehiwot provided supervision and academic guidance, contributed to the validation and interpretation of the findings, and reviewed and edited the manuscript.

All authors read and approved the final manuscript.

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