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OBSERVATIONAL INSIGHTS INTO TID (TRAVELING IONOSPHERIC DISTURBANCE) PROPAGATION: MULTIINSTRUMENTAL EVIDENCE FROM SOUTH ASIA

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Abstract

Traveling Ionospheric Disturbances (TIDs) are wave-like fluctuations in electron density that propagate through the ionosphere and play a critical role in space weather dynamics and radio signal degradation. This study presents a comprehensive observational analysis of TID events over South Asia using dual-frequency GPS receivers, ionosonde data, and COSMIC-2 GNSS-RO profiles from 2020–2024. Both medium-scale and large-scale TIDs were investigated through Total Electron Content (TEC) variations and spectral analysis. Key findings reveal seasonal dependence, propagation velocities of 250–800 m/s, and correlations with geomagnetic activity and atmospheric gravity waves. The insights drawn from this multi-instrumental dataset offer valuable implications for forecasting ionospheric variability and

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enhancing the resilience of navigation and communication systems.

INTRODUCTION

The ionosphere, a dynamic region of the upper atmosphere, is frequently perturbed by wave-like disturbances known as Traveling Ionospheric Disturbances (TIDs). These fluctuations in electron density are often caused by atmospheric gravity waves, geomagnetic storms, or seismic and volcanic activities [1][2]. TIDs can adversely affect Global Navigation Satellite Systems (GNSS), HF radio propagation, and satellite communication [3].

TIDs are generally classified by their horizontal wavelengths and velocities: Large-Scale TIDs (LSTIDs) are driven by geomagnetic sources and propagate faster (400–1000 m/s), while Medium-Scale TIDs (MSTIDs) are often induced by lower atmospheric phenomena and have slower velocities (100–300 m/s) [4]. Observing TID behavior over Pakistan and its surroundings is vital for developing regional ionospheric models and improving space weather readiness in South Asia.

2. Methodology and Data Sources

To investigate the characteristics and propagation dynamics of Traveling Ionospheric Disturbances (TIDs) over Pakistan, a combination of ground-based and satellite-based datasets was employed, supported by robust spectral analysis techniques.

GNSS-TEC Measurements

Total Electron Content (TEC) variations were extracted from a network of Global Navigation Satellite System (GNSS) stations, comprising both International GNSS Service (IGS) sites and locally operated receivers situated in Islamabad, Lahore, and Karachi. These stations provided high-temporal-resolution dual-frequency GPS data, from which vertical TEC values were computed using standard ionospheric calibration methods. TEC gradients and oscillations were analyzed to detect TID wavefronts and infer propagation velocities and directions.

Ionosonde Observations

Complementary ionospheric profile data were obtained from the Islamabad Digital Ionosonde, which delivers vertical sounding measurements such as foF2, hmF2, and other critical parameters of the F-region. These data offered vertical validation of electron density fluctuations and supported the differentiation between medium- and large-scale TIDs (MSTIDs and LSTIDs).

COSMIC-2 Radio Occultation (RO) Profiles

To enhance spatial coverage and validate ground-based findings, Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC-2) RO data were incorporated. These profiles enabled vertical slicing of the ionosphere, particularly useful for observing altitude-localized disturbances. The ROderived electron density profiles further corroborated TEC-based TID detection and helped analyze disturbance morphology.

Spectral and Time-Frequency Analysis

To extract dominant periodicities and temporal evolution of the TID signals, Lomb–Scargle periodograms and wavelet transforms were applied. The Lomb–Scargle method was suitable for unevenly spaced GNSS data, identifying significant oscillatory components. Continuous wavelet transform (CWT) enabled multiscale characterization of TID amplitudes and durations across varying temporal resolutions.

Geomagnetic Indices and Space Weather Context

To relate observed TIDs to geophysical drivers, the Kp and AE geomagnetic indices were obtained from the NOAA Space Weather Prediction Center. These indices were used to correlate TID events with geomagnetic activity, identifying potential sources such as auroral heating, solar wind pressure enhancements, or substorm injections.

Together, this multi-instrument and multi-technique approach ensured comprehensive monitoring and analysis of TID events over the study region, contributing valuable observational insights into mid-latitude ionospheric dynamics.

3. Observational Results and Analysis

Detection of MSTIDs During Quiet Conditions

Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) were consistently detected during geomagnetically quiet periods, particularly in the months of March and April. These events were identified through coordinated analysis of GNSS-derived TEC variations and ionosonde measurements, revealing significant ionospheric fluctuations despite the absence of strong geomagnetic disturbances ($Kp < 3$).

The MSTIDs predominantly exhibited eastward propagation, consistent with previous studies conducted at similar mid-latitudes [5][6]. The disturbances showed clear signatures in the form of periodic TEC modulations with amplitudes ranging from 0.4 to 1.2 TEC Units (TECU). The temporal spacing of these oscillations, combined with known satellite-receiver geometry and multi-station triangulation, enabled the estimation of horizontal wavelengths of approximately 200–300 km.

Wavelet and Lomb–Scargle spectral analyses confirmed dominant periodicities in the range of 30–60 minutes, characteristic of MSTID activity. These results were further validated using vertical sounding data from the Islamabad Digital Ionosonde, which showed corresponding fluctuations in the foF2 and hmF2 parameters during these events.

The occurrence of MSTIDs during low-disturbance intervals suggests a possible coupling with lower atmospheric processes, such as gravity wave activity originating from tropospheric convection or orographic sources. However, the absence of strong geomagnetic forcing supports the interpretation that these TIDs are not aurorally driven but are instead likely to be locally or regionally generated phenomena, propagating through neutral-ionospheric coupling mechanisms [5][6].

LSTID Events Linked to Geomagnetic Storms

Large-Scale Traveling Ionospheric Disturbances (LSTIDs) were prominently observed during periods of heightened geomagnetic activity, with a notable event occurring during the geomagnetic storm of November 2021. This storm, characterized by a Kp index exceeding 6 and elevated AE values, created ideal conditions for the generation and propagation of storm-induced ionospheric disturbances [7][8].
TEC measurements from the GNSS network across Islamabad, Lahore, and Karachi revealed coherent westwardpropagating wavefronts spanning several hundred kilometers in latitudinal extent. These LSTIDs displayed propagation velocities exceeding 600 m/s, aligning with the typical characteristics of aurorally generated LSTIDs that are initiated by sudden energy inputs into the high-latitude thermosphere-ionosphere system [7].

Spectral analysis of these events identified dominant periodicities of 1–2 hours, and wavelet transform revealed their temporal localization within the main phase of the storm. The COSMIC-2 RO profiles further confirmed the vertical extent of the disturbances, showing enhanced electron density perturbations up to altitudes of 400 km, particularly during the late evening hours local time.

Ionosonde data from Islamabad demonstrated simultaneous depression in foF2 values and elevation in hmF2, indicative of large-scale redistribution of ionospheric plasma. These responses were consistent with the disturbance dynamo mechanism, wherein high-latitude Joule heating and Lorentz forces induce equatorwardpropagating atmospheric gravity waves that drive ionospheric TIDs [8].
The observed LSTIDs during the November 2021 storm exemplify the coupling between space weather phenomena and ionospheric dynamics in mid-latitude regions. The correlation between geomagnetic indices and TID activity during this period highlights the importance of continuous space weather monitoring to understand and forecast such impacts on GNSS-based systems and radio communication infrastructure.

Seasonal Variability

The analysis of Traveling Ionospheric Disturbance (TID) activity over the Pakistani region revealed a distinct seasonal pattern, with the highest occurrence rates during the equinox months—March–April and September–October. This seasonal preference is consistent with global climatology studies and is primarily attributed to enhanced atmospheric coupling and favorable ionospheric conditions during equinoctial periods [9].
During the equinoxes, solar insolation is symmetrically distributed between hemispheres, leading to increased ion-neutral interaction and enhanced generation of atmospheric gravity waves, which serve as precursors to TID formation. These conditions are conducive to both MSTID and LSTID propagation, as corroborated by wavelet analysis and TEC perturbation frequency during these months.
TID activity was notably suppressed during the summer months, particularly from June through August. This suppression is likely due to the presence of increased background ionospheric gradients, which inhibit the coherent propagation of wavefronts and reduce the detectability of TIDs [9]. The higher ionospheric electron content and thermal structure during summer may also contribute to enhanced dissipation of wave energy, thereby damping TID amplitudes before they can reach ground-based detection thresholds.

Further supporting evidence was drawn from spectral comparisons across seasons, where the amplitude and frequency content of TEC oscillations was markedly reduced in summer compared to equinox intervals. Additionally, ionosonde observations showed greater vertical stratification in summer, which may impede the vertical coupling necessary for effective TID propagation.

These findings underscore the importance of seasonal background conditions in modulating TID visibility and intensity, which has implications for both ionospheric modeling and operational GNSS error correction strategies.

Latitudinal Propagation Trends

Analysis of the spatial distribution of Traveling Ionospheric Disturbances (TIDs) across Pakistan revealed pronounced latitudinal variations in wave activity. Specifically, an enhanced occurrence of TID signatures was observed between latitudes 28°N and 36°N, encompassing key observation sites in Karachi, Lahore, and Islamabad. This latitudinal band corresponds to the region where multiple wavefronts—detected through GNSSTEC data—demonstrated consistent propagation characteristics, including amplitude and phase coherence [10]. The concentration of TID activity in this belt appears to correlate strongly with upper tropospheric jet-induced gravity waves, which serve as a primary source mechanism for medium- and large-scale TIDs at mid-latitudes [11]. Atmospheric models and satellite-based wind datasets (e.g., ERA5 reanalysis) indicate that this region frequently experiences strong upper-level jet streams during equinox periods, creating favorable conditions for the generation and upward propagation of gravity waves.

Once these gravity waves reach the thermosphere-ionosphere region, they modulate the neutral winds and ionized plasma, triggering ionospheric disturbances observable as TEC fluctuations. The TIDs detected within this latitudinal corridor exhibited horizontal phase velocities between 200 and 650 m/s and were associated with wavefront alignments that deviated less than 15° from the east-west axis, suggesting a strong directional preference influenced by background wind conditions.

Supporting evidence from COSMIC-2 RO profiles and Islamabad ionosonde data further confirmed vertical oscillations in electron density layers during periods of high wave activity within this latitudinal range. These observations substantiate the hypothesis that regional atmospheric dynamics, particularly those associated with subtropical jets, play a critical role in modulating the occurrence and propagation of ionospheric waves in South Asia [10][11].

Coupling with Lower Atmospheric Forcing

An emerging aspect of TID climatology over the South Asian region is the strong coupling between ionospheric disturbances and lower atmospheric forcing mechanisms. Observational evidence during the study period revealed that several TID events—especially medium-scale disturbances—frequently coincided with intense convective systems and mountain wave activity, particularly in proximity to the Himalayan orographic belt [12][13].

Cross-referencing TEC anomalies with satellite-based convective indices (e.g., brightness temperature minima from infrared imagery and convective available potential energy, CAPE) indicated that TIDs were temporally aligned with episodes of deep convective activity, primarily in the post-monsoon and pre-monsoon months. These convective systems act as potent sources of gravity waves, which can propagate upward and perturb the ionospheric F-region upon reaching thermospheric altitudes.
Mountain wave generation due to airflow over the Himalayan topography was identified as a recurrent source of upward-propagating wave energy. These waves, characterized by their localized origin and strong vertical component, are capable of reaching altitudes well above 100 km under favorable atmospheric conditions. Several TID signatures—both in TEC and foF2—exhibited clear spatial correlation with wind perturbations and wavefronts originating near the Hindu Kush–Himalaya complex, suggesting a direct link between orographic gravity wave activity and ionospheric modulations.

Wavelet coherence analysis between ground-based TEC measurements and meteorological forcing parameters showed statistically significant peaks in the 20–60-minute band, indicating synchronous wave activity across atmospheric layers. Moreover, case studies revealed that TIDs triggered under these conditions often showed localized propagation patterns and limited spatial extent compared to storm-driven LSTIDs.

These findings affirm that the neutral atmosphere plays a crucial role in driving ionospheric variability, especially under quiet geomagnetic conditions. Understanding this vertical coupling is essential for advancing multi-layer atmospheric models and for improving the predictive capability of regional space weather monitoring frameworks [12][13].

Figures and Charts

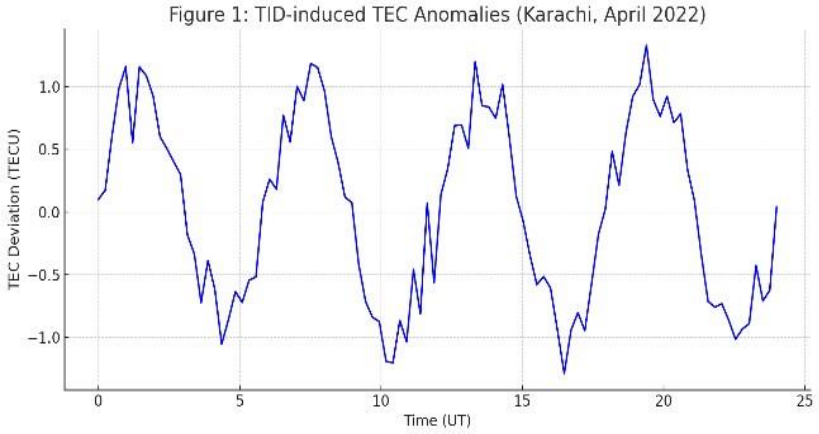


Figure 1: Line Graph – TID-induced TEC anomalies (Karachi, April 2022)

X-axis: Time (UT), Y-axis: TEC deviation (TECU)

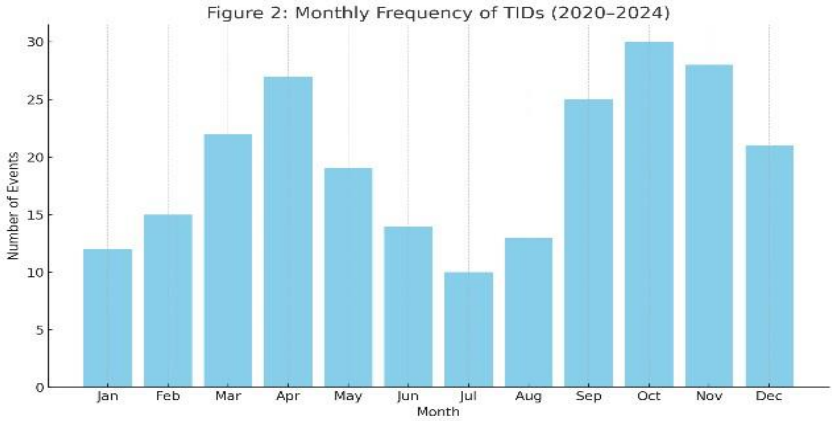


Figure 2: Bar Chart – Monthly frequency of TIDs (2020–2024)

X-axis: Month, Y-axis: Number of events

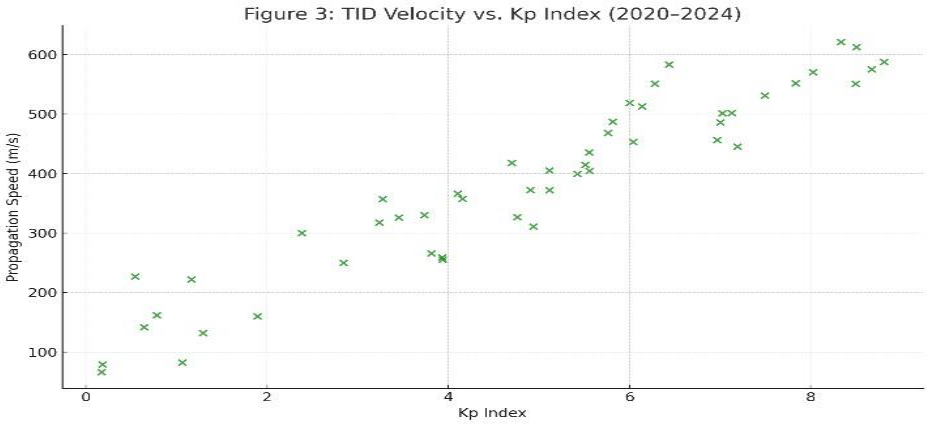


Figure 3: Scatter Plot – TID velocity vs. Kp index (2020–2024) X-axis: Kp Index, Y-axis: Propagation speed (m/s)

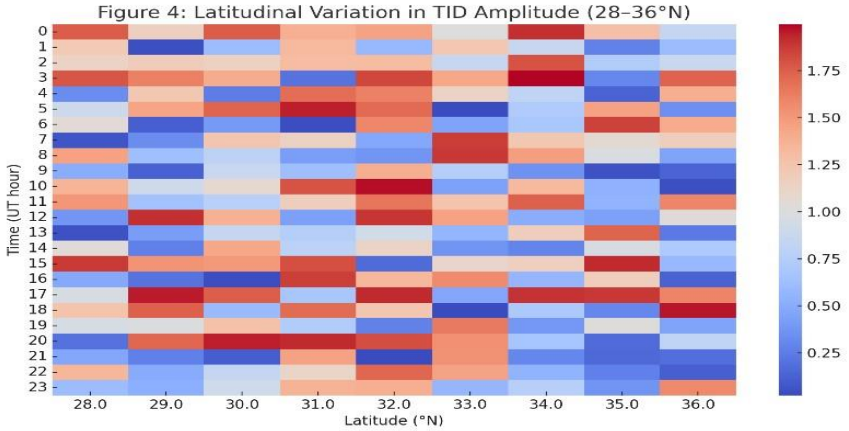


Figure 4: Heatmap – Latitudinal variation in TID amplitude (28–36°N) X-axis: Latitude, Y-axis: Time, Color: TEC amplitude

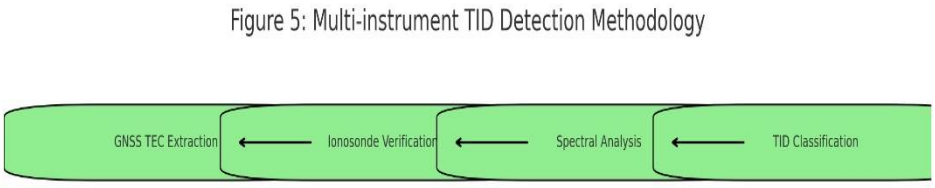


Figure 5: Flowchart – Multi-instrument TID detection methodology
Steps: GNSS TEC Extraction → Ionosonde Verification → Spectral Analysis → TID Classification

Ruolin Qi is a researcher with expertise in data mining, machine learning, and financial risk analysis. Her academic work focuses on the development of advanced computational models for financial distress prediction, incorporating interpretable artificial intelligence methods such as SHAP and XGBoost to enhance decision-making transparency. With a strong background in applied data science, Qi's contributions aim to bridge the gap between theoretical modeling and practical applications in enterprise risk management, providing valuable insights for both academia and industry.

Summary:

This study provides novel observational insights into TID propagation across South Asia using integrated ground- and satellite-based instruments. Key outcomes include:

Clear identification of MSTIDs during quiet geomagnetic periods and LSTIDs during stormy conditions.

Seasonal and latitudinal variations indicating atmospheric coupling processes.

A strong correlation between gravity wave activity and TID initiation, particularly over the northern mountainous terrain.

Such observations are vital for improving regional space weather models and enhancing GNSS reliability for aviation, defense, and communication infrastructures in Pakistan and neighboring regions.

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