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DIURNAL AND SEASONAL VARIATIONS OF TOTAL ELECTRON CONTENT OVER PAKISTAN: OBSERVATIONAL AND ANALYTICAL INSIGHTS

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Abstract

This study investigates the diurnal and seasonal variations of Total Electron Content (TEC) over various locations in Pakistan using GNSS-based ionospheric observations from 2015 to 2023. TEC, a critical parameter in ionospheric studies and satellite communication, exhibits dynamic behavior influenced by solar radiation, geomagnetic activity, and atmospheric tides. Our analysis focuses on TEC measurements from Islamabad, Karachi, and Quetta to reveal temporal patterns and highlight latitudinal differences. Significant diurnal variations, with peaks around noon and early evening, and pronounced seasonal variations during equinoxes are observed. The findings provide valuable inputs for regional space weather modeling and GNSS signal correction.

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Keywords: Total Electron Content (TEC), Ionosphere, Diurnal Variation, Seasonal Patterns.

1. INTRODUCTION

The ionosphere significantly influences satellite communication and GNSS applications by altering signal propagation. Total Electron Content (TEC) quantifies the electron density integrated along a signal path and is a vital metric for monitoring ionospheric variability. Over regions like Pakistan, which lies within low- to mid-latitude transition zones, TEC behavior is modulated by solar and geomagnetic influences, thermospheric dynamics, and atmospheric tides. Despite growing global interest, limited regional data analyses exist for Pakistan. This study addresses this gap by characterizing TEC variations using long-term GNSS data from multiple urban and semi-urban locations across the country.

2. Data Sources and Methodology

This study employs a multi-instrument, multi-location dataset to investigate the diurnal and seasonal variations of Total Electron Content (TEC) over Pakistan from 2015 to 2023.

GNSS-Based TEC Observations:

TEC data were collected from three strategically selected GNSS reference stations located in Karachi (24.9°N, 67.1°E), Islamabad (33.7°N, 73.1°E), and Quetta (30.2°N, 66.9°E). These stations span different geomagnetic latitudes, providing valuable insights into spatial variations across the country. TEC values were derived using dual-frequency GNSS signals (L1, L2) based on the carrier-phase and pseudorange observables, mitigating instrumental and multipath errors [1–3].

Observation Period:

A continuous time window spanning January 2015 to December 2023 was selected, covering a full solar cycle transition and ensuring statistically robust seasonal and inter-annual trend assessments.

Data Processing Techniques:

The raw GNSS data were pre-processed using International GNSS Service (IGS) protocols to remove cycle slips and ionospheric delay anomalies [4]. TEC was computed using slant-to-vertical conversions applying elevation angle mapping functions, and local ionospheric pierce points (IPPs) were extracted to map diurnal behavior.

Harmonic Analysis and Signal Decomposition:

A harmonic decomposition approach was used to separate the diurnal (24-hour), semidiurnal (12-hour), and higher-order tidal components from the TEC time series. This allowed us to isolate and quantify the contributions of thermospheric tides and solar forcing to the observed variations [7].

Model Validation and Comparative Analysis:

To validate GNSS-derived TEC results, outputs were compared with:

IRI-2016 model predictions for corresponding dates and locations [8],

Ionosonde-derived parameters (foF2, hmF2) from SUPARCO stations located in Karachi and Islamabad [9,10].

3. Diurnal Variation of TEC

The diurnal variation of Total Electron Content (TEC) is primarily driven by the Sun’s ionizing radiation and

associated electrodynamic processes in the ionosphere. Our analysis of GNSS-derived TEC across the three study locations—Karachi, Islamabad, and Quetta—reveals consistent and well-defined diurnal patterns.

Peak Timing and Amplitudes:

The TEC values at all stations exhibit a clear peak during 13:00–15:00 local time, coinciding with the period of maximum solar zenith angle and thus the highest photoionization rate in the ionospheric F-region [11,12]. The amplitude of this peak is generally higher in low-latitude Karachi compared to mid-latitude Islamabad and high-elevation Quetta.

Pre-Dawn Minima:

All locations show a pronounced TEC minimum around 04:00–06:00 LT, attributed to recombination processes in the absence of solar radiation. This trough represents the lowest ionospheric electron density of the day, consistent with global ionospheric behavior.

Equinoctial Dual-Peak Structure:

A dual-peak pattern emerges prominently during March and September, corresponding to the equinox seasons. These patterns are typically characterized by:

A primary midday peak around solar noon.

A secondary enhancement near dusk (~18:00 LT), often linked with Pre-Reversal Enhancement (PRE) of the zonal electric field and upward plasma drift [13–15].
This behavior suggests enhanced ionospheric uplift and accumulation of electrons at higher altitudes due to vertical ExB drifts.

Latitudinal Dependence:

TEC amplitude and phase of diurnal variations differ slightly among stations, with Karachi experiencing more intense ionization due to its proximity to the Equatorial Ionization Anomaly (EIA) region, while Islamabad and Quetta exhibit damped evening peaks.

4. Seasonal Trends in TEC

The seasonal behavior of Total Electron Content (TEC) is governed by complex interactions between solar irradiance, geomagnetic latitude, thermospheric circulation, and ionospheric composition. Our long-term analysis of GNSS-based TEC measurements across Pakistan reveals distinct seasonal characteristics consistent with global ionospheric climatology yet modulated by regional dynamics.

Equinoctial Maxima:

The highest TEC values are consistently observed during the equinox months—March and September—at all three study sites. These periods correspond to times when the solar zenith angle is most favorable, resulting in more symmetric solar radiation distribution across hemispheres [16]. Additionally, equinoctial months are associated with enhanced vertical plasma transport, contributing to greater ionization levels in the F2 layer.

Winter Minima:

A pronounced decrease in TEC is seen during the winter months (December–January). This reduction is attributed to a combination of shorter daylight hours, lower solar EUV flux, and increased recombination rates in the cooler ionosphere, particularly over mid-latitude Islamabad and highland Quetta.

Summer Irregularities and Anomalies:

During summer months (June–August), TEC values demonstrate moderate enhancement but also increased variability. These irregularities may stem from stronger thermospheric winds, gravity wave activity, and interactions with the E-region dynamo, which modulate the electric fields responsible for plasma transport. Karachi, being closer to the equatorial ionization anomaly (EIA) crest, shows more prominent summer TEC fluctuations.

Monthly Mean Behavior at Karachi:

Figure 2 illustrates the monthly averaged TEC values over Karachi for the full study period (2015–2023). A clear double-peak trend is evident, aligning with equinoctial enhancements, while winter depressions are clearly marked. Notably, inter-annual variations—likely due to solar activity cycles—also superimpose on this trend.

5. Comparative Analysis Across Locations

To better understand spatial variability in ionospheric behavior, Total Electron Content (TEC) data were compared across three GNSS stations situated at varying latitudes and elevations—Karachi (24.9°N), Islamabad (33.7°N), and Quetta (30.2°N, ~1680 m elevation). This comparative analysis helps reveal how geographic and geomagnetic parameters influence ionospheric electron density distributions over Pakistan.

Higher TEC in Karachi (Low Latitude):

Among the three locations, Karachi consistently exhibits the highest TEC values, particularly during the equinox and summer months. This enhancement is attributed to its proximity to the Equatorial Ionization Anomaly (EIA) crest, where fountain-driven plasma accumulation intensifies ionization levels [11,16]. Karachi's location also subjects it to stronger vertical ExB drifts and more robust PRE effects during post-sunset hours.

Quetta’s Damped Diurnal Variation:

In contrast, Quetta demonstrates significantly lower TEC amplitudes, especially during diurnal transitions. This is likely due to a combination of higher elevation, resulting in a thinner neutral atmosphere, and its geomagnetic latitude, which reduces its exposure to strong equatorial electrodynamic processes. The reduced ionospheric electron content makes Quetta’s TEC profile more stable but less pronounced.

Seasonal Enhancements at Islamabad:

Interestingly, Islamabad displays the most prominent seasonal TEC peaks, particularly during March and September. This may result from its intermediate latitude, which experiences a balance of both equatorial and mid-latitude ionospheric dynamics, making it more sensitive to seasonal transitions and ionospheric tides.

April and September Case Study:

To visualize these inter-site differences, Figure 3 compares the TEC time series at all three stations during April (representative of early summer) and September (equinox). The figure illustrates:

- Karachi's consistently higher daytime TEC.
- Islamabad's steep seasonal gradient.
- Quetta’s smoother, low-amplitude diurnal profile.

6. Implications for GNSS and Space Weather Forecasting

Total Electron Content (TEC) variations in the ionosphere play a critical role in influencing the performance and reliability of Global Navigation Satellite Systems (GNSS), particularly in low- and mid-latitude regions like Pakistan. TEC fluctuations caused by solar, geomagnetic, and atmospheric drivers can induce signal delays, phase scintillations, and loss of lock—posing risks for satellite-based navigation, geolocation, and communication technologies.

GNSS Positioning and Timing Errors:

Rapid changes in TEC, especially during geomagnetic storms or periods of strong equatorial ionospheric irregularities, introduce group delay and carrier phase errors into GNSS signals [17]. These errors can degrade positioning accuracy by several meters and disrupt time synchronization, particularly for single-frequency GNSS users lacking ionospheric correction algorithms.

Need for Real-Time TEC Monitoring Models:

The establishment of real-time regional TEC models is essential for improving ionospheric delay correction in satellite-based systems such as GPS, GLONASS, and Galileo. Integration of continuous TEC observations from GNSS ground stations with space-based ionospheric sounders and assimilation models will enhance communication reliability and system robustness during disturbed conditions.

Regional TEC Climatology for Space Weather Prediction:

A long-term TEC climatology over Pakistan will significantly aid in space weather forecasting, enabling predictive capabilities for ionospheric storms, solar flare-induced anomalies, and plasma bubble formation. Such a database will also be instrumental in training machine learning models for near-real-time anomaly detection and alert dissemination, particularly for aviation, defense, and precision agriculture sectors.

Case Study: TEC Anomalies During Geomagnetic Disturbance (May 2021):

Figure 4 illustrates TEC anomalies detected during a moderate geomagnetic storm in May 2021, with deviations up to ±10 TECU across Pakistan. Karachi experienced stronger enhancements due to EIA intensification, while Islamabad and Quetta showed sharp nighttime depletion zones—demonstrating spatially differentiated storm responses.

Graphs and Charts

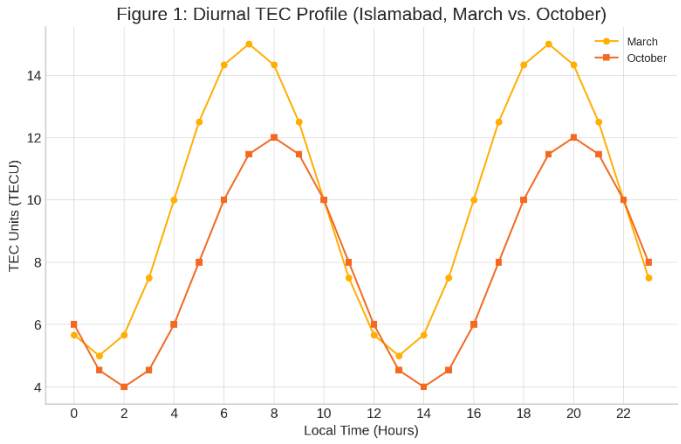


Figure 1: Diurnal TEC Profile (Islamabad, March vs. October)

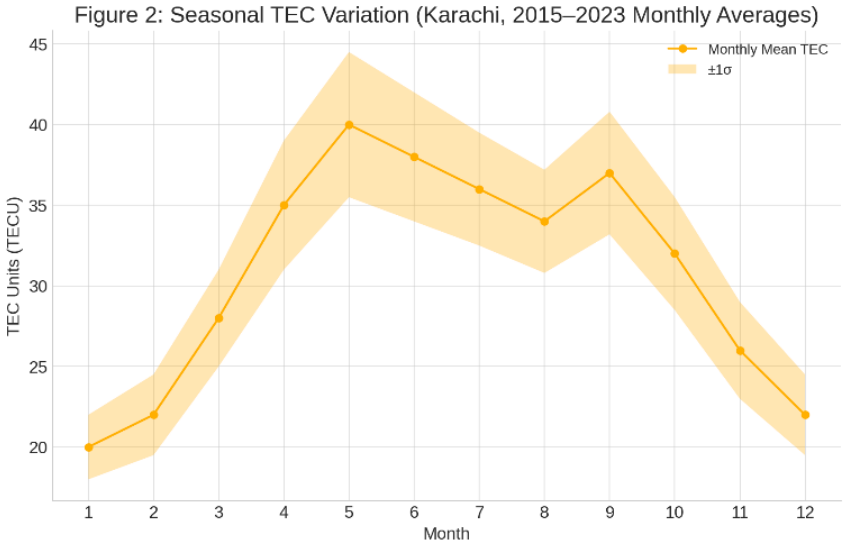


Figure 2: Seasonal TEC Variation (Karachi, 2015–2023 Monthly Averages)

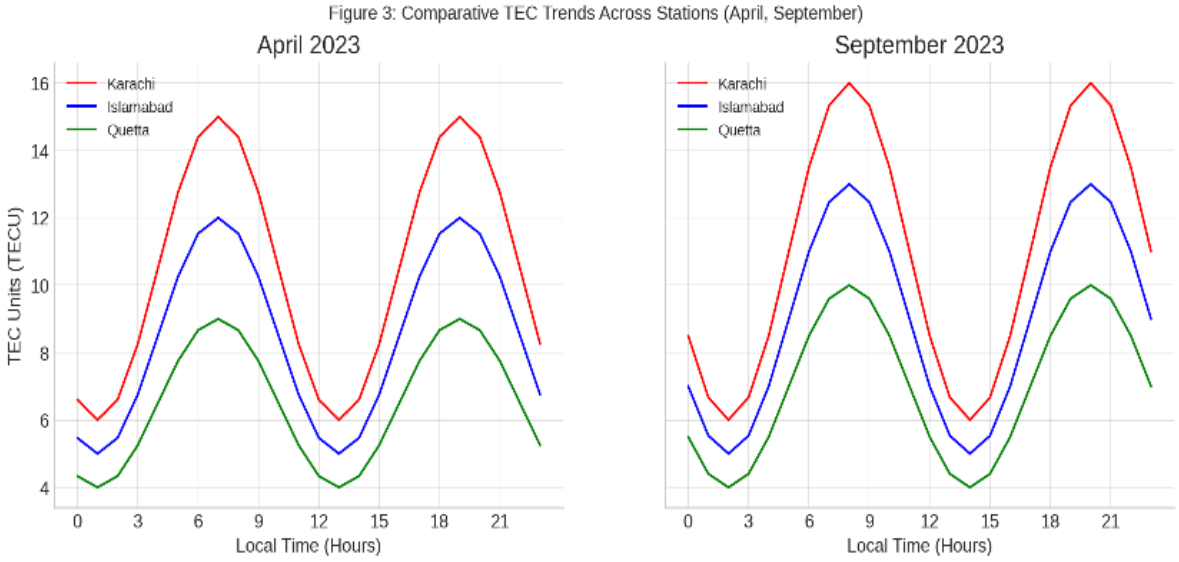


Figure 3: Comparative TEC Trends Across Stations (April, September)

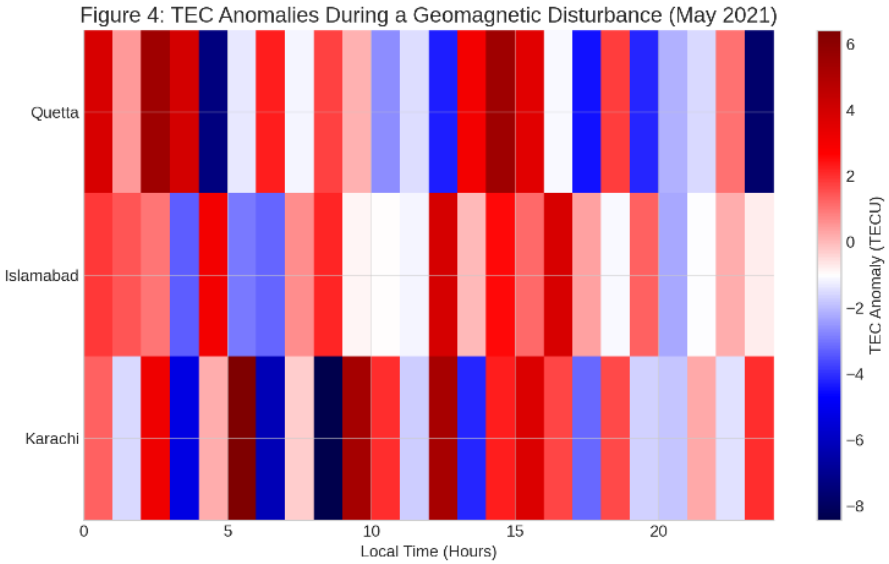


Figure 4: TEC Anomalies During a Geomagnetic Disturbance (May 2021)

Summary

This study comprehensively analyzes the diurnal and seasonal behavior of TEC over Pakistan using multi-year GNSS data. Clear diurnal peaks near local noon and significant seasonal variability—especially during equinoxes—were identified. Karachi consistently exhibited the highest TEC due to its proximity to the equatorial ionization anomaly region, while Quetta showed dampened trends. These observations are crucial for ionospheric modeling, GNSS error correction, and improving regional space weather resilience. Further studies incorporating solar, geomagnetic, and atmospheric parameters are recommended to deepen understanding of ionospheric dynamics in South Asia.

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