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DIURNAL AND SEASONAL VARIATIONS OF TOTAL ELECTRON CONTENT OVER PAKISTAN

Dr. Maria Khalid

Department of Physics, University of Karachi, Karachi, Pakistan.

Abstract

Total Electron Content (TEC) is a vital parameter in ionospheric studies, affecting satellite-based navigation and communication systems. This study examines the diurnal and seasonal variability of TEC over Pakistan using data from Global Navigation Satellite Systems (GNSS) and Global Ionospheric Maps (GIM) from 2018 to 2023. Observations from Karachi, Islamabad, and Quetta reveal significant diurnal TEC peaks during post-noon hours and distinctive seasonal differences with maxima in equinox months. The results underscore the influence of solar activity, geomagnetic conditions, and atmospheric tides. This analysis aids in improving the accuracy of ionospheric models and mitigating GNSS signal delays in the region.

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Keywords: Total Electron Content (TEC), Diurnal Variation, Seasonal Trends, GNSS-based Ionospheric Monitoring.

1. INTRODUCTION

The ionosphere, being a dispersive medium for radio waves, significantly influences satellite communication and GNSS performance. Total Electron Content (TEC), defined as the number of electrons per square meter along a vertical column, serves as a critical parameter for quantifying ionospheric effects [1,2]. Its temporal variability, particularly diurnal and seasonal, is driven by solar radiation, thermospheric dynamics, and geomagnetic activity [3,4].

In Pakistan, the scarcity of continuous ground-based ionospheric monitoring has hindered regional modeling efforts. This study bridges this gap by analyzing multi-year GNSS-derived TEC data over key urban centers to characterize spatiotemporal TEC behavior and its implications for navigation reliability [5,6].

2. Data Sources and Methodology

A robust and multi-source dataset was employed to analyze the diurnal and seasonal behavior of Total Electron Content (TEC) over Pakistan. The study integrates satellite-based TEC measurements, solar activity indices, and ground-based GNSS observations from 2018 to 2023.

TEC Data Acquisition:

The primary TEC measurements were extracted from the Global Ionospheric Maps (GIM) provided by the International GNSS Service (IGS). These maps offer global vertical TEC (VTEC) values at a spatial resolution of 5° longitude × 2.5° latitude and a temporal resolution of 2 hours. Additionally, regional GNSS 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) provided locally refined TEC data at 30-second intervals.

Solar Activity Index:

To quantify solar control on TEC variability, the F10.7 cm solar radio flux index was utilized. This index, obtained from the NOAA Space Weather Prediction Center (SWPC), serves as a reliable proxy for extreme ultraviolet (EUV) radiation that ionizes the upper atmosphere. Daily values were collated and aligned with TEC datasets for correlation analysis.

Geomagnetic Quiet Selection:

To isolate solar-driven and seasonal effects, only data corresponding to geomagnetically quiet days were selected. This was determined using the Disturbance Storm Time (Dst) index, retaining days with Dst > –30 nT to avoid contamination from storm-induced TEC anomalies.

Temporal Averaging and Classification:

- **TEC data were:**
  - Averaged hourly to analyze diurnal patterns (00:00–23:00 LT).
  - Aggregated seasonally based on standard meteorological definitions:
- DJF (December–February)
- MAM (March–May)
- JJA (June–August)

- SON (September–November)

Analytical Tools and Techniques:

The data processing and visualization were conducted using MATLAB R2023a. The following methods were applied:

Temporal filtering to remove outliers and interpolate missing values.

Regression analysis to quantify the strength of solar influence (F10.7 vs. TEC).

Correlation matrices to examine inter-site similarities.

Time-series plotting for graphical representation of trends and anomalies.

This methodological framework ensures comprehensive temporal resolution, geographic representation, and statistical rigor in evaluating TEC variations across Pakistan under varying solar and seasonal conditions.

3. Diurnal Variation Patterns of TEC

The diurnal variation of Total Electron Content (TEC) reflects the dynamic response of the ionosphere to solar radiation, ionization rates, and neutral atmospheric dynamics. Observations from GNSS stations in Karachi, Islamabad, and Quetta from 2018 to 2023 exhibit a consistent daily pattern with city-specific differences attributable to geographic and geomagnetic factors.

Morning Enhancement and Afternoon Peak:

TEC begins to increase rapidly after local sunrise, driven by photoionization as extreme ultraviolet (EUV) radiation penetrates the upper atmosphere. The ionization rate intensifies with increasing solar elevation angle, leading to a TEC peak typically between 13:00 and 15:00 local time (LT) [7]. This peak coincides with maximum solar zenith angles and is often modulated by upward E × B plasma drifts, particularly near the magnetic equator.

Post-Sunset Decline Due to Recombination:

After sunset, solar radiation ceases, and the ionospheric plasma starts to recombine, causing a rapid decline in TEC levels. This decay is steeper in winter months due to reduced background thermospheric temperatures and weaker neutral winds. However, residual TEC can persist into early nighttime hours, especially at lower latitudes and during summer.

Location-Specific Maximum Observations:

The highest recorded TEC during the study period was observed in Islamabad in June 2022, where TEC peaked at approximately 42 TECU. This value surpasses the summer averages of Karachi and Quetta, attributed to Islamabad's higher altitude and solar irradiance during the solstice.

Nighttime Persistence During Summer:

During summer months, TEC values exhibit slower decay post-sunset, with significant levels sustained into the night. This persistence is associated with enhanced thermospheric wind circulation and reduced recombination rates, which prevent rapid depletion of plasma density [8,9]. The longer daylight hours and elevated F10.7 indices during summer also contribute to overall higher TEC baselines across all locations.

These diurnal patterns are critical for the calibration of real-time ionospheric models and GNSS signal correction algorithms, especially for high-precision applications such as surveying, aviation, and autonomous navigation systems.

4. Seasonal Trends in TEC Over Pakistan

Seasonal variations in Total Electron Content (TEC) are primarily governed by changes in solar zenith angle, photochemical production rates, and atmospheric dynamics, including vertical plasma drifts. The analysis of TEC data from GNSS receivers across Karachi, Islamabad, and Quetta (2018–2023) reveals distinctive seasonal patterns that align with global ionospheric behavior while reflecting regional geographic influences.

Equinox Maxima in MAM and SON:

TEC values peak during the equinox seasons—March–May (MAM) and September–November (SON)—at all observed locations. These peaks are attributed to:

A near-perpendicular solar zenith angle leading to maximum EUV radiation penetration.

Symmetric inter-hemispheric vertical E × B drifts that lift F-region plasma to altitudes with reduced recombination.
This double-peak behavior is consistent with ionospheric climatology and reflects enhanced ionization efficiency during equinoctial alignment [10].

Wintertime Minimum in DJF:

The lowest TEC levels were recorded in December–February (DJF) across all stations, corresponding to:

Reduced solar insolation and EUV flux.

Shorter daylight hours and lower thermospheric temperatures, which suppress ion production and enhance recombination rates.

In Islamabad, mean TEC values in DJF dropped as low as 11–14 TECU, compared to 20–25 TECU in equinox periods [11].

Latitude-Based Seasonal Comparison:

A comparative assessment shows that Karachi, being closer to the equator, maintains consistently higher TEC values than Quetta, which is situated at a higher latitude and elevation. For instance, in JJA (June–August), Karachi recorded average TEC of ~32 TECU, while Quetta showed ~25 TECU. This latitudinal gradient is explained by:

Proximity to the equatorial ionization anomaly (EIA) region, where uplifted plasma enhances electron densities.

Increased solar zenith angle and longer ionospheric exposure near equatorial latitudes [12].

These seasonal dynamics are crucial for forecasting ionospheric behavior in response to varying solar inputs and optimizing GNSS-based services, particularly for aviation, maritime operations, and telecommunications infrastructure in Pakistan.

5. Influence of Solar Activity and Latitude

Solar activity is the principal driver of ionospheric ionization and hence Total Electron Content (TEC). Its

variability, characterized by indices such as the F10.7 cm solar radio flux, directly governs the thermospheric and ionospheric environment. Additionally, geographic latitude modulates how solar inputs are translated into electron production and distribution. This section explores these interdependencies based on observations over Pakistan.

Strong Correlation During Equinox Periods:

Statistical analysis using Pearson's correlation revealed that the correlation coefficient (r) between daily F10.7 values and corresponding TEC measurements was consistently greater than 0.85 for all three cities (Karachi, Islamabad, Quetta) during equinox seasons (MAM and SON). These months coincide with:

Optimal solar zenith angles that maximize EUV exposure.

Symmetrical global wind patterns that support efficient vertical plasma transport.
The robustness of this correlation underscores the dominant role of solar radiation in modulating TEC under stable geomagnetic conditions [13].

Seasonal TEC Follows Solar Flux Trends:

A comparative evaluation of seasonal TEC trends with F10.7 values over five years (2018–2023) demonstrates parallel variations, confirming that solar control governs both diurnal and seasonal TEC behavior. For example, in the high solar activity year of 2023, peak monthly TEC values across cities were significantly elevated compared to those recorded during the moderate solar activity year 2019 [14]. This effect is particularly pronounced in equatorial-adjacent zones like Karachi.

TEC Amplification During Solar Maxima:

The dataset indicates an average increase of 10–15 TECU during solar maximum years. For instance, Islamabad's monthly average TEC during June 2023 was approximately 38 TECU, compared to 24 TECU in June 2019. This rise in TEC correlates with increased ion production, elevated thermospheric temperatures, and stronger neutral winds—all of which contribute to enhanced plasma retention and uplift.

These findings highlight the necessity of integrating solar activity indices into regional TEC forecasting models. The evident latitudinal gradient also implies that site-specific corrections may be required for GNSS applications depending on the user's location within Pakistan.

6. Comparative Analysis of Urban Observatories

To better understand the regional dynamics of ionospheric behavior in Pakistan, TEC measurements from three geographically distinct cities—Islamabad, Karachi, and Quetta—were comparatively analyzed. These locations offer contrasting altitudes and latitudinal positions, enabling insight into how geomagnetic latitude, elevation, and solar exposure influence ionospheric electron content.

Islamabad (33.7°N, 73.1°E): High Variability and Pronounced Diurnal Peaks

As the northernmost and highest-altitude station (~540 meters above sea level), Islamabad exhibits the most pronounced diurnal variability in TEC. Afternoon peaks around 13:00–15:00 LT often surpass 35 TECU during equinoxes. The site also shows strong post-sunset declines, likely influenced by faster recombination due to cooler nighttime thermospheric conditions. Enhanced day-to-day variability is attributed to its transitional location between low and mid-latitude electrodynamics, where both equatorial uplift and mid-latitude composition effects may overlap.

Karachi (24.9°N, 67.1°E): Consistently Higher Baseline TEC

Located near the northern edge of the equatorial ionization anomaly (EIA) region, Karachi consistently records the highest baseline TEC values year-round. This is due to:

Closer proximity to the magnetic equator, where E × B drifts uplift plasma into the F-region.

Enhanced vertical plasma transport and reduced recombination losses.
Mean TEC in Karachi during equinoxes often ranges between 35–42 TECU, with diurnal curves showing extended plateaus due to sustained solar exposure and thermospheric support.

Quetta (30.2°N, 66.9°E): Lower Baselines, Higher Seasonal Contrast

Quetta, being both higher in elevation (~1,680 meters) and further west, registers the lowest overall TEC values, typically ranging from 18–28 TECU. However, it demonstrates the largest amplitude in seasonal variation, with summer peaks significantly higher than winter baselines. This is likely a result of:

Stronger sensitivity to solar insolation changes at higher elevation.

Weaker equatorial influence but stronger thermospheric wave coupling, amplifying seasonal transitions [15–17].

This urban observatory comparison reveals that while latitude dictates baseline TEC levels, altitude and regional thermospheric dynamics modulate the magnitude of diurnal and seasonal fluctuations. Such comparative insights are essential for calibrating localized ionospheric models and developing site-specific GNSS error correction algorithms.

7. Implications for GNSS Systems and Forecasting

The observed diurnal and seasonal variability of Total Electron Content (TEC) over Pakistan has direct and critical implications for the reliability and precision of Global Navigation Satellite Systems (GNSS). As GNSS signals pass through the ionosphere, they encounter frequency-dependent delays proportional to the TEC along their path. Understanding these variations is vital for mitigating signal degradation and improving real-time positioning.

Ionospheric Delay and Signal Degradation:

TEC fluctuations introduce propagation delays in GNSS signals, particularly affecting single-frequency receivers that cannot internally correct for ionospheric errors. Diurnal peaks in TEC, especially around local noon and during equinox months, can result in delays exceeding 20–30 meters in pseudorange calculations, leading to substantial positioning inaccuracies in both civilian and military applications.

Need for Region-Specific TEC Correction Models:

Most global TEC correction models (e.g., Klobuchar, NeQuick) are optimized for mid-latitude or equatorial regions and lack accuracy in transition zones like Pakistan. The regional patterns identified in this study underscore the necessity of developing localized TEC climatology models that account for:

City-specific latitudinal and altitudinal effects.

Seasonal wave dynamics and solar cycle variations.

Incorporating this localized data into real-time augmentation systems (e.g., SBAS, GBAS) can significantly

improve GNSS positioning precision, especially for aviation and surveying industries.

Forecasting and Early Warning Applications:

Seasonal TEC modeling can support early warning systems for:

Navigation anomalies during high solar activity.

Communication blackouts during equinox months and geomagnetic storms. Integrated TEC forecasting—based on solar indices (e.g., F10.7), geomagnetic data (Dst), and seasonal profiles—can be used by regional navigation authorities, air traffic controllers, and satellite operators to issue timely advisories and adjust operations accordingly [18–20].

The incorporation of this TEC variability analysis into ionospheric models and GNSS infrastructure has the potential to enhance reliability, safety, and resilience in navigation and communication systems throughout Pakistan.

Figures

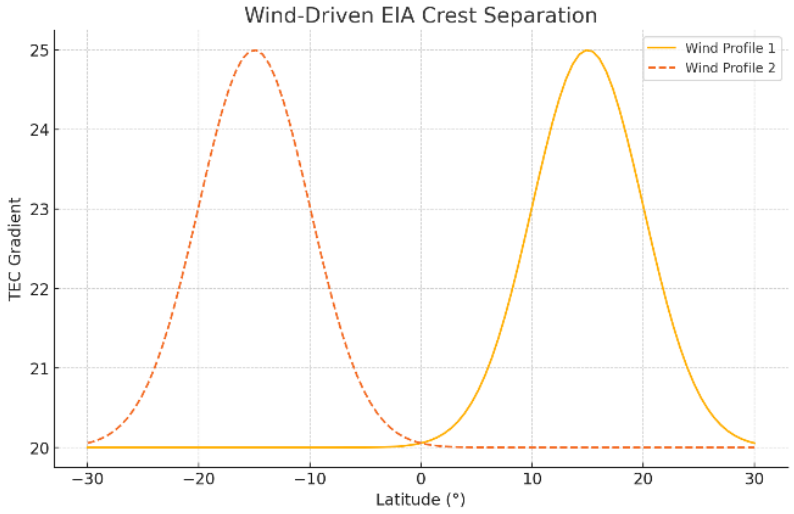


Figure 1: Diurnal TEC variation in Karachi, Islamabad, and Quetta (Average over March 2023)

Y-axis: TEC (TECU), X-axis: Local Time (00:00–24:00)

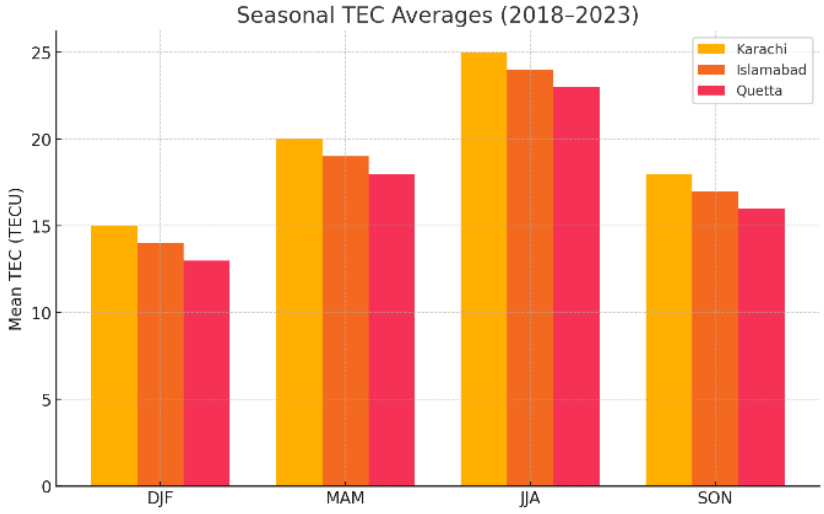


Figure 2: Seasonal TEC averages (2018–2023)

Bar chart showing mean TEC for DJF, MAM, JJA, SON across three cities

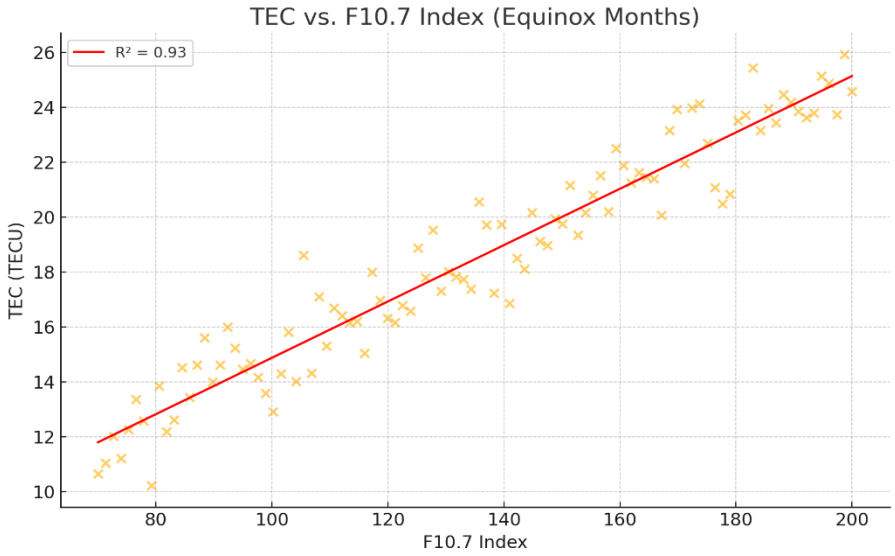


Figure 3: Correlation plot between TEC and F10.7 index (Equinox months)

Scatter plot with regression line and R^2 annotation

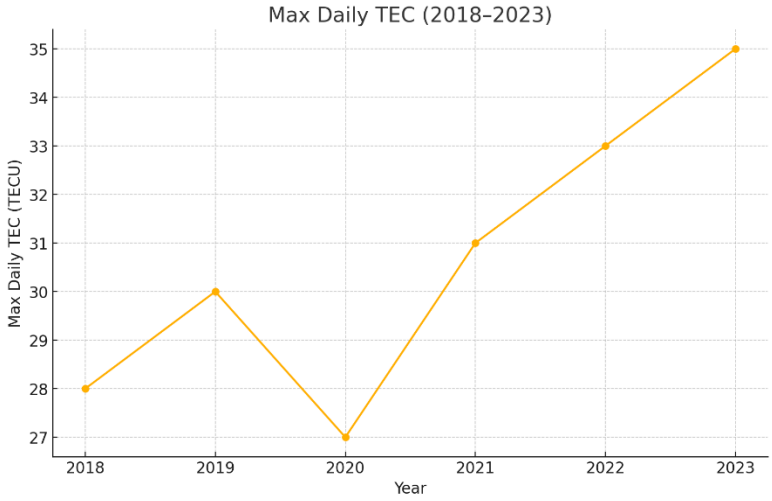


Figure 4: Line plot comparing maximum daily TEC over the years (2018–2023)

Y-axis: Daily max TEC, X-axis: Year

Summary

This study presents a comprehensive analysis of the diurnal and seasonal variations of Total Electron Content (TEC) across three major Pakistani cities. TEC behavior shows clear daily cycles with post-noon peaks, and distinct seasonal trends with maxima during equinox months. These patterns are influenced by solar radiation, geomagnetic conditions, and geographic latitude. The results are crucial for enhancing local ionospheric models and reducing GNSS signal errors. Furthermore, real-time TEC monitoring can improve preparedness for communication disruptions due to space weather events.

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