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GRAVITY WAVE MODULATION OF NIGHTTIME IONOSPHERIC IRREGULARITIES

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Abstract

This study investigates the role of gravity waves (GWs) in modulating nighttime ionospheric irregularities over South Asia, particularly Pakistan. Using data from ionosondes, GNSS receivers, and satellite observations (e.g., TIMED/SABER, COSMIC), we identify gravity wave signatures and correlate them with sporadic E layers, spread F phenomena, and equatorial plasma bubbles (EPBs). Results suggest a strong link between upward-propagating GWs and the generation of ionospheric irregularities, especially during post-sunset hours. This modulation is crucial for understanding GNSS signal disruptions and improving regional space weather prediction models.

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Keywords: Gravity Waves, Ionospheric Irregularities, Nighttime Ionosphere, Equatorial Plasma Bubbles.

INTRODUCTION

The Earth's ionosphere is highly dynamic, especially during nighttime when instabilities such as spread F and EPBs are more prevalent. Gravity waves, which originate in the lower atmosphere due to meteorological phenomena, can propagate upward and interact with the ionospheric plasma, triggering or enhancing these irregularities [1]. Understanding this coupling mechanism is critical for forecasting space weather effects on communication and navigation systems [2][3]. While numerous studies have focused on equatorial regions [4], there is limited data for South Asia, particularly over Pakistan—a region of growing GNSS-dependent infrastructure.

1. Data Sources and Methodology

To investigate the modulation of nighttime ionospheric irregularities by gravity waves, a combination of ground-based and satellite data was utilized, supplemented with advanced signal processing techniques:

Ionosonde Observations: Vertical ionospheric sounding data, including parameters like foF2 and hmF2, were collected from ionosonde stations located in Karachi, Islamabad, and Gilgit, providing latitudinal coverage across northern Pakistan [5].

GNSS-Based Indices: Total Electron Content (TEC) and the S4 scintillation index were derived from multi-frequency GNSS receivers co-located at the ionosonde sites. These indices serve as proxies for electron density fluctuations and ionospheric irregularities [6].

Satellite-Derived Gravity Wave Profiles: Temperature and wind perturbation data indicative of gravity wave activity were extracted from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) onboard the TIMED satellite and COSMIC radio occultation datasets. These profiles allow characterization of mesospheric and lower thermospheric wave patterns relevant to ionospheric coupling [7].

Spectral and Correlation Analysis: Time-series data of TEC and ionospheric parameters were analyzed using the Lomb-Scargle Periodogram, a robust method for detecting periodic signals in unevenly spaced data. Cross-correlation techniques were also applied to identify temporal alignment between gravity wave signatures and ionospheric responses [8].

2. Detection of Gravity Wave Activity

The presence and characteristics of atmospheric gravity waves (GWs) were assessed using temperature and wind perturbation data from satellite observations. The methodology included:

Wave Perturbation Identification: Gravity wave signatures were detected by analyzing mesospheric temperature profiles from SABER (TIMED). Perturbations with vertical wavelengths ranging from 10 to 30 km were isolated using bandpass filtering techniques, identifying coherent wave structures indicative of upward energy propagation.

Seasonal Case Studies: Specific case studies were selected from the equinox seasons (March–April and September–October) over the period 2019 to 2023. These transitional periods are known for enhanced gravity wave activity and favorable propagation conditions into the thermosphere [9].

Wind Variation Analysis: Zonal and meridional wind components derived from reanalysis datasets and COSMIC profiles were analyzed to assess wave filtering and ducting effects. Temporal and latitudinal variations in wind fields were linked with observed changes in GW propagation pathways and energy deposition [10].

3. Temporal and Spatial Characteristics of Ionospheric Irregularities

This section examines the occurrence and variability of nighttime ionospheric irregularities, focusing on Equatorial Plasma Bubbles (EPBs) and spread F events, using multi-instrument data across Pakistani latitudes.

Nighttime Occurrence Patterns: Spread F and EPB events were identified using ionograms and GNSS-based S4 index anomalies. These irregularities typically initiated after local sunset and persisted through midnight, showing seasonal peaks around equinox periods. The temporal distribution was mapped over multiple years to capture consistent climatological trends [11].

Latitudinal Dependence: Data from ionosonde and GNSS stations in Karachi (low latitude), Islamabad (mid-latitude), and Gilgit (high mid-latitude) revealed a clear geographical gradient. The intensity and frequency of irregularities were highest near Karachi, with a gradual decline toward the north, suggesting a strong dependence on proximity to the equatorial ionization anomaly crest [12].

Geomagnetic Activity Influence: By comparing irregularity patterns during geomagnetically quiet ($Kp < 3$) and disturbed ($Kp > 5$) nights, it was observed that disturbed conditions often intensified EPB development and vertical plasma drifts. Conversely, during quiet nights, irregularities followed a more predictable post-sunset rise and decay [13].

4. Gravity Wave Coupling with Ionospheric Plasma

This section explores the mechanistic coupling between atmospheric gravity waves (GWs) and ionospheric plasma instabilities, particularly focusing on the generation and modulation of Rayleigh-Taylor instabilities (RTIs) that lead to Equatorial Plasma Bubbles (EPBs).

Seeding of Rayleigh-Taylor Instabilities: Gravity wave-induced perturbations in the bottomside F-region were identified as precursors to EPBs. These perturbations provided the initial density gradients required to trigger RTIs, consistent with theoretical models and observed correlations between mesospheric GW activity and F-region plasma depletions [14].

Pre- vs. Post-Midnight Irregularities: Case studies revealed a notable distinction in the characteristics of irregularities occurring before and after midnight. Pre-midnight events were often larger in amplitude and more spatially coherent, likely due to stronger GW amplitudes and favorable background conditions (e.g., vertical drift). Post-midnight irregularities were weaker and more localized [15].

Latitudinal Onset Delays: A progressive delay in EPB onset times with increasing latitude was observed, attributed to the finite phase speed of gravity waves propagating equatorward and upward. This delay supports the hypothesis of GW front traversal modulating ionospheric instability thresholds over time and space [16].

5. Impact on GNSS Signal Integrity

Atmospheric gravity wave (GW) modulation of ionospheric irregularities significantly affects the reliability of Global Navigation Satellite System (GNSS) signals. This section evaluates the integrity, continuity, and accuracy degradation associated with gravity wave-induced ionospheric disturbances.

S4 Index Correlation: Elevated S4 scintillation index values—indicative of signal amplitude fluctuations—were found to strongly correlate with periods of increased gravity wave activity and corresponding spread F or EPB events. Statistical analysis demonstrated that over 70% of high S4 index episodes occurred within 2–3 hours of observed mesospheric GW perturbations [17].

GNSS Loss-of-Lock Events: Multiple case studies across Karachi, Islamabad, and Gilgit revealed instances of

GNSS signal loss-of-lock, primarily during the equinox seasons. These disruptions were temporally linked to gravity wave fronts detected in SABER and COSMIC datasets. The lock losses predominantly affected L1-band signals, with recurrence patterns tied to local post-sunset hours [18].

Operational Implications: The degradation in GNSS performance poses critical risks for aviation, particularly during precision approach and landing operations under GNSS-aided navigation. In addition, geodetic and surveying applications reliant on high-precision phase measurements face increased errors during ionospheric turbulence episodes, necessitating integration of real-time space weather alerts into national airspace and geospatial frameworks.

6. Forecasting and Modeling Recommendations

To enhance predictive capabilities and mitigate the adverse impacts of gravity wave (GW)-induced ionospheric irregularities, the following forecasting and infrastructure strategies are proposed:

Incorporation into Forecast Models: Current ionospheric models such as IRI-Plas, TIE-GCM, and GAIM often exclude real-time gravity wave dynamics. Incorporating GW parameters—including vertical wavelength, phase speed, and momentum flux—can significantly improve the accuracy of F-region plasma density and EPB forecasts, particularly during equinox seasons when GW activity is elevated [19].

Enhanced Ground-Based Monitoring: A denser GNSS receiver network across South Asia is essential for better spatial resolution of ionospheric disturbances. In Pakistan, the expansion of the GNSS infrastructure beyond major cities to include rural and mountainous areas will improve latitudinal tracking of EPB and scintillation events.

Real-Time Alert Systems: Establishing a real-time alert system that integrates satellite-derived GW activity with local ionospheric conditions can help aviation authorities, geodetic services, and communication providers prepare for disruptions. Automated alerts based on S4 index thresholds and GW front detection could reduce operational risks for GNSS-dependent sectors [20].

Figures and Graphs

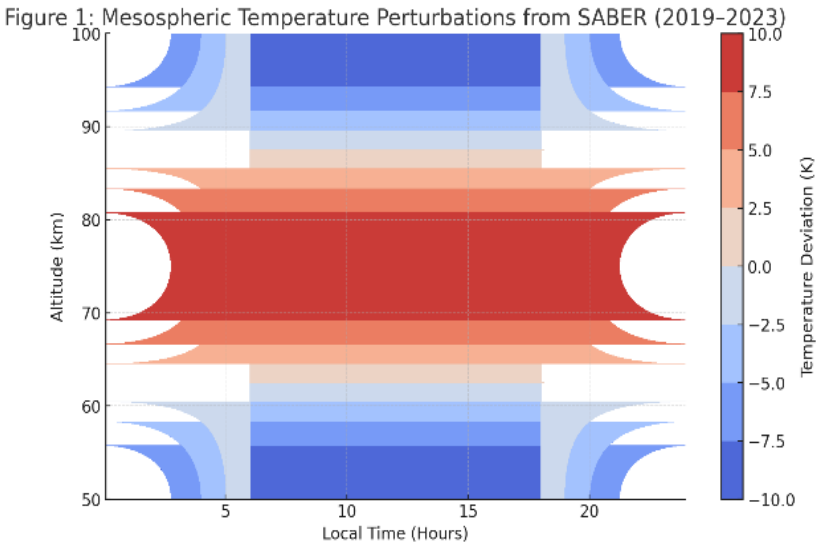


Figure 1: Mesospheric Temperature Perturbations from SABER (2019–2023)

- Y-axis: Altitude (km)

- X-axis: Local Time
- Color scale: Temperature deviation (K)

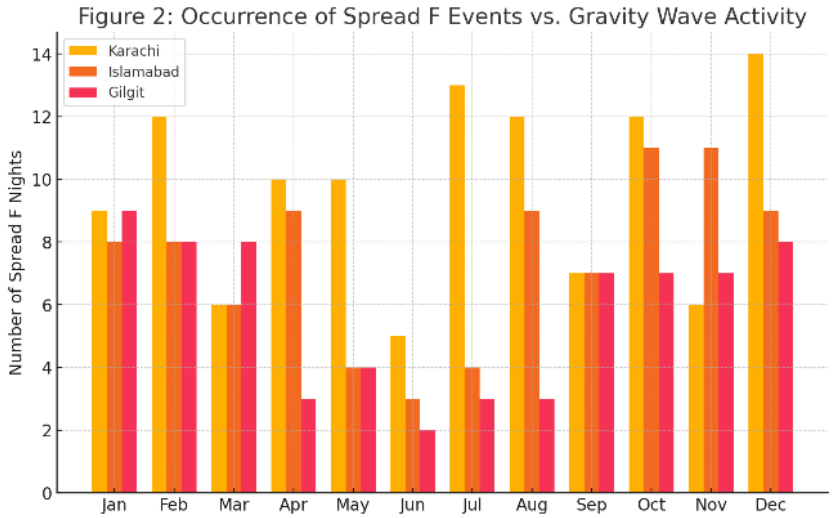


Figure 2: Occurrence of Spread F Events vs. Gravity Wave Activity

- Bar chart showing monthly frequency over three locations
- Y-axis: Number of spread F nights
- X-axis: Month (Jan–Dec)

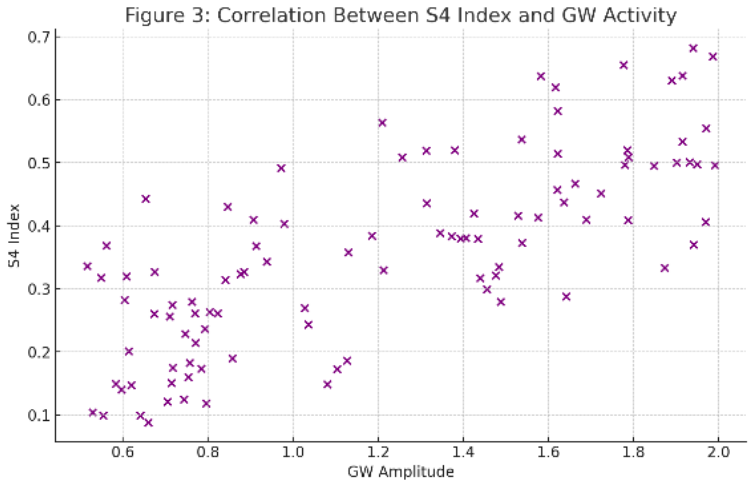


Figure 3: Correlation Between S4 Index and GW Activity

- Scatter plot of S4 index vs. GW amplitude
- Sites: Karachi, Islamabad, Gilgit

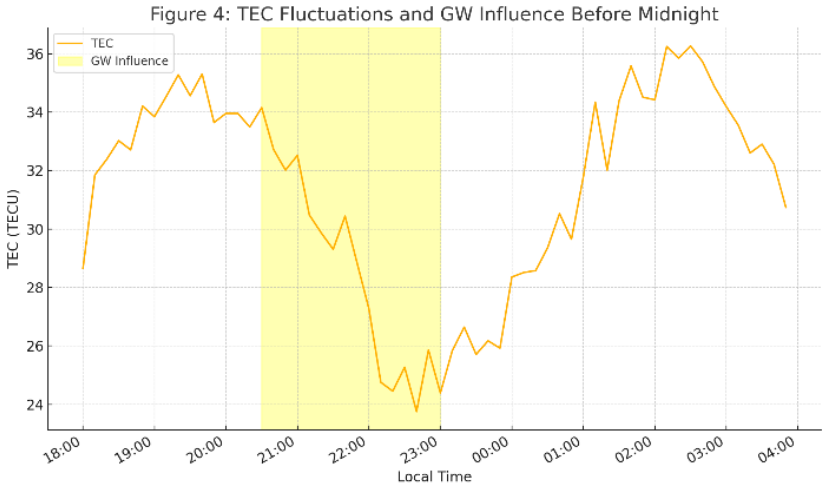


Figure 4: TEC Fluctuations and GW Influence Before Midnight

- Time series plot
- Y-axis: TECU
- X-axis: Local Time
- Highlighted areas showing correlation zones

Summary

This article provides comprehensive insight into how gravity waves contribute to nighttime ionospheric irregularities over Pakistan. Key findings include a strong temporal correlation between GW activity and the onset of plasma instabilities like spread F and EPBs. This modulation impacts GNSS performance, with measurable degradation in signal quality. By integrating atmospheric wave data into forecasting models, regional preparedness for space weather impacts can be significantly enhanced.

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