International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 15, Issue 1 [January 2026] PP: 158-165

Atmospheric–Ionospheric Coupling Induced by Tropical Cyclones over the North Indian Ocean: Evidence from Arabian Sea and Bay of Bengal Events

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ABSTRACT
Tropical cyclones (TCs) are among the most intense meteorological phenomena in the North Indian Ocean particularly over the Arabian Sea (AS) and the Bay of Bengal (BoB). Recent studies have demonstrated that TCs not only affect the lower atmosphere but also induce measurable perturbations in the ionosphere through vertical coupling processes. This paper presents a comprehensive review and synthesis of atmospheric–ionospheric coupling associated with tropical cyclones over the Indian region. Using evidence from Global Navigation Satellite System (GNSS)–derived Total Electron Content (TEC), ionosonde observations, and geomagnetic measurements, we examine ionospheric responses such as TEC anomalies, foF2 variations, traveling ionospheric disturbances (TIDs) and equatorial electrodynamic modulation. Case studies of cyclones including Ockhi, Tauktae, Aila and Ward are discussed to highlight similarities and contrasts between AS and BoB cyclones. The results emphasize the dominant role of gravity waves and atmospheric tides generated by intense cyclonic convection in driving ionospheric variability under geomagnetically quiet conditions. Understanding this coupling is essential for improving space-weather prediction and GNSS reliability over low-latitude regions.
Keywords: *Tropical cyclones; Atmospheric–ionospheric coupling; Gravity waves; TEC; Arabian Sea; Bay of Bengal; Indian region*

Date of Submission: 10-01-2026 Date of acceptance: 23-01-2026

I.INTRODUCTION

The ionosphere represents one of the most dynamic and responsive regions of the near-Earth space environment. Its variability is primarily governed by solar extreme ultraviolet (EUV) radiation and geomagnetic forcing; however, growing evidence over the past few decades has highlighted the important role of the lower atmosphere in modulating ionospheric behavior (Forbes et al., 2000; Hagan et al., 2009). This realization has led to the development of the concept of vertical atmosphere–ionosphere coupling, which emphasizes the transfer of energy and momentum from the troposphere and stratosphere to ionospheric altitudes through wave-driven and electrodynamic processes (Liu & Zhou, 2016; Yiğit & Medvedev, 2015). Among various lower atmospheric phenomena, extreme weather systems such as tropical cyclones (TCs) have emerged as significant drivers of ionospheric perturbations (Anthes, 2011; Saito et al., 2017).

Tropical cyclones are intense synoptic-scale systems characterized by deep convection, strong surface winds, and large-scale latent heat release. When these systems develop over ocean basins such as the Arabian Sea and the Bay of Bengal, they exert profound impacts on the Indian subcontinent through heavy rainfall, storm surges, and strong winds (Emanuel, 2005; Mohapatra et al., 2017). Beyond their well-known surface and tropospheric effects, tropical cyclones also provide a natural laboratory for investigating upward coupling processes that link the lower atmosphere to the ionosphere (Pattnaik et al., 2019; Rozhnoi et al., 2014). The intense convective activity associated with cyclones can excite atmospheric gravity waves, acoustic waves, and large-scale tidal perturbations that propagate vertically and influence ionospheric plasma dynamics, resulting in measurable variations in total electron content and plasma irregularities (Vadas & Liu, 2009; Chou et al., 2017).

The Indian region occupies a unique geographical position within the low-latitude ionospheric belt, where electrodynamic processes are particularly complex. Phenomena such as the Equatorial Electrojet (EEJ) and the Equatorial Ionization Anomaly (EIA) dominate ionospheric behavior in this region. The EEJ, a narrow ribbon of enhanced eastward current flowing in the daytime E-region near the magnetic equator, plays a critical role in controlling ionospheric electric fields. Similarly, the EIA, characterized by two crests of enhanced electron density on either side of the magnetic equator, is highly sensitive to vertical plasma drifts and neutral wind dynamics. Because of these features, the low-latitude ionosphere over India is especially susceptible to perturbations originating from below, making it an ideal region for studying cyclone-induced ionospheric variability (Rishbeth & Mendillo, 2001).

Observational studies conducted over the Indian sector have reported significant anomalies in key ionospheric parameters during tropical cyclone events. Variations in Total Electron Content (TEC), critical frequency of the F2 layer (foF2), and ionospheric peak heights (hmF2) have been documented in association with several cyclones, even under geomagnetically quiet conditions. These findings strongly suggest that the observed ionospheric disturbances are not driven by solar or magnetosphereic forcing, but rather by processes originating in the lower atmosphere (Choudhary et al., 2021; Sarkar et al., 2024). Such disturbances often manifest as localized TEC enhancements or depletions, changes in ionospheric layer heights, and alterations in plasma density gradients.

The primary physical mechanisms responsible for cyclone-induced ionospheric perturbations involve the generation and upward propagation of atmospheric waves. Deep convective towers within tropical cyclones act as efficient sources of gravity waves due to strong updrafts and rapid latent heat release (Alexander et al., 2010; Vadas & Liu, 2009). As these gravity waves propagate upward, their amplitudes increase in response to decreasing atmospheric density, allowing them to reach ionospheric heights (Yiğit & Medvedev, 2015; Fritts & Alexander, 2003). Upon dissipation or breaking, these waves can modify neutral winds and electric fields, thereby influencing ionospheric plasma distribution through ion–neutral coupling and dynamo processes (Forbes et al., 2008; Liu et al., 2016). In addition to gravity waves, large-scale tidal modes and planetary waves modulated by cyclone activity can also contribute to ionospheric variability through electrodynamic coupling (Hagan et al., 2009; Pedatella et al., 2014).

Another important coupling pathway involves changes in the global electric circuit. Tropical cyclones are associated with enhanced thunderstorm activity and cloud electrification, which can alter atmospheric conductivity and vertical electric currents (Rycroft et al., 2008; Williams, 2009). These changes may map upward along geomagnetic field lines, affecting ionospheric electric fields and plasma drifts (Tinsley, 2000; Volland, 1984). In low-latitude regions, even small perturbations in electric fields can lead to significant changes in ionospheric structure due to the sensitivity of the equatorial ionization anomaly (EIA) and equatorial electrojet (EEJ) systems (Fejer et al., 2008; Abdu, 2012).

The North Indian Ocean (NIO) basin exhibits distinct seasonal characteristics that influence tropical cyclone formation and evolution. Two primary cyclone seasons are observed: the pre-monsoon period from April to June and the post-monsoon period from October to December (Mohapatra et al., 2017). Among the two sub-basins of the NIO, the Bay of Bengal accounts for approximately 70–80% of total cyclonic activity, a dominance attributed to favorable oceanic and atmospheric conditions including higher sea surface temperatures, lower vertical wind shear, and enhanced moisture availability (Gray, 1979; Evan & Camargo, 2011). In contrast, the Arabian Sea historically experienced fewer cyclones; however, recent studies have reported a noticeable increase in cyclone frequency and intensity over this region, possibly linked to long-term climate variability and ocean warming (Murakami et al., 2017; Evan et al., 2011).

Several intense cyclones over the Indian region have been widely studied for their ionospheric impacts. Cyclone Ockhi (2017), which originated near Sri Lanka and intensified over the Arabian Sea, produced pronounced ionospheric TEC disturbances over southern India as observed using GNSS measurements (Pattnaik et al., 2019; Nayak et al., 2020). Similarly, Cyclone Amphan (2020), one of the strongest cyclones in the Bay of Bengal, generated significant ionospheric anomalies detected by dense GNSS receiver networks and ionosondes (Bagiya et al., 2021; Kumar et al., 2022). Cyclone Tauktae (2021), which tracked parallel to the western coast of India, also exhibited clear signatures of ionospheric perturbations linked to enhanced convective activity and gravity wave generation (Dashora et al., 2022; Singh et al., 2023).

These cyclones shared common characteristics, including strong vertical development, intense latent heat release, and widespread convective systems. Such features make tropical cyclones highly effective sources of upward-propagating atmospheric disturbances capable of influencing the ionosphere (Anthes, 1982; Sato et al., 2016). Comparative analyses between Arabian Sea and Bay of Bengal cyclones suggest that differences in cyclone intensity, size, and proximity to the magnetic equator can lead to varying ionospheric responses (Chou et al., 2017; Lin et al., 2019). Bay of Bengal cyclones often produce more widespread ionospheric effects due to their larger spatial extent and stronger convective cores, while Arabian Sea cyclones may generate more localized but intense perturbations (Pattnaik & Kumar, 2021).

In summary, tropical cyclones represent an important but still not fully understood driver of ionospheric variability over the Indian region. The unique low-latitude electrodynamic environment, combined with frequent cyclone activity in the North Indian Ocean, provides an excellent framework for investigating vertical atmosphere–ionosphere coupling processes (Liu et al., 2018; Yiğit et al., 2021). This paper seeks to (i) review the dominant physical mechanisms linking tropical cyclones to ionospheric perturbations, (ii) synthesize observational evidence from cyclone events over the Indian sector, and (iii) compare ionospheric responses associated with cyclones in the Arabian Sea and the Bay of Bengal. Improved understanding of these processes is essential not only for advancing space weather science but also for enhancing the reliability of satellite-based communication and navigation systems over the Indian region (Klobuchar et al., 2019).

II.MECHANISMS OF ATMOSPHERIC–IONOSPHERIC COUPLING

2.1 Gravity Waves Generated by Cyclonic Convection: Gravity waves (GWs) are widely regarded as the primary mechanism linking tropical cyclones to ionospheric disturbances. Strong convective updrafts and eyewall dynamics generate gravity waves that propagate upward through the stratosphere and mesosphere into the thermosphere, modulating ionospheric plasma density (Hines, 1960; Vadas & Liu, 2009).Observational studies over India have reported enhanced wave-like oscillations in TEC with periods ranging from 30 minutes to 4 hours during cyclone events, consistent with GW signatures (Choudhary et al., 2021; Sarkar et al., 2025).
2.2 Traveling Ionospheric Disturbances: Traveling ionospheric disturbances are the ionospheric manifestation of upward-propagating atmospheric waves. During Cyclone Tauktae, pronounced medium-scale TIDs with horizontal velocities of ~100–150 m s^{-1} were observed over Indian GNSS stations, independent of geomagnetic forcing (Sarkar et al., 2024). Such observations strongly support a tropospheric origin.
2.3 Electrodynamic Modulation: Cyclone-induced atmospheric tides and wind perturbations can influence ionospheric electrodynamics by modifying E-region conductivity and dynamo processes. Alterations in EEJ strength and occasional counter-electrojet events during TC passages have been reported over the Indian sector (Manju et al., 2016).

III. DATA AND METHODOLOGY

3.1 GNSS-Derived TEC: Dual-frequency GNSS observations from IGS and Indian regional networks are widely used to compute vertical TEC. Cyclone-period TEC is compared with quiet-day reference values to isolate storm-related anomalies (Choudhary et al., 2021).
3.2 Ionosonde Observations: Ionosonde stations such as Trivandrum and Ahmedabad provide measurements of foF2 and hmF2, which are sensitive indicators of ionospheric plasma redistribution during TC events (Manju et al., 2016).
3.3 Geomagnetic Indices: To ensure that observed perturbations are of atmospheric origin, geomagnetic indices such as Kp and Dst are examined. Most TC-related ionospheric studies focus on geomagnetically quiet intervals (Dst > −30 nT).

IV. CASE STUDIES OVER THE INDIAN REGION

4.1 Cyclone Ockhi (2017) – Bay of Bengal/Arabian Sea: Choudhary et al. (2021) reported significant reductions in TEC and foF2 during Cyclone Ockhi, with enhanced wave-like oscillations coinciding with the cyclone's intensification phase. These perturbations were attributed to gravity wave forcing originating from deep convection.
4.2 Cyclone Tauktae (2021) – Arabian Sea: Sarkar et al. (2024) observed prominent TIDs during Cyclone Tauktae, propagating inland over the Indian subcontinent. The study highlighted the role of cyclonic convection as the dominant source of ionospheric disturbances under quiet geomagnetic conditions.
4.3 Cyclones Aila and Ward (2009) – Bay of Bengal: Earlier investigations revealed persistent low-frequency oscillations in ionospheric parameters during Aila and Ward, reinforcing the concept of sustained tropospheric forcing during cyclone lifecycles (Paul & Das, 2010).

Here figure 1 shows best-track positions of selected tropical cyclones over the Arabian Sea (AS) and Bay of Bengal (BoB) during the study period. Cyclone tracks are obtained from the India Meteorological Department (IMD) best-track dataset. The filled circles indicate six-hourly cyclone positions, while color intensity represents cyclone intensity (depression to extremely severe cyclonic storm). The locations of GNSS and ionosonde stations over the Indian region used in this study are marked by triangles.

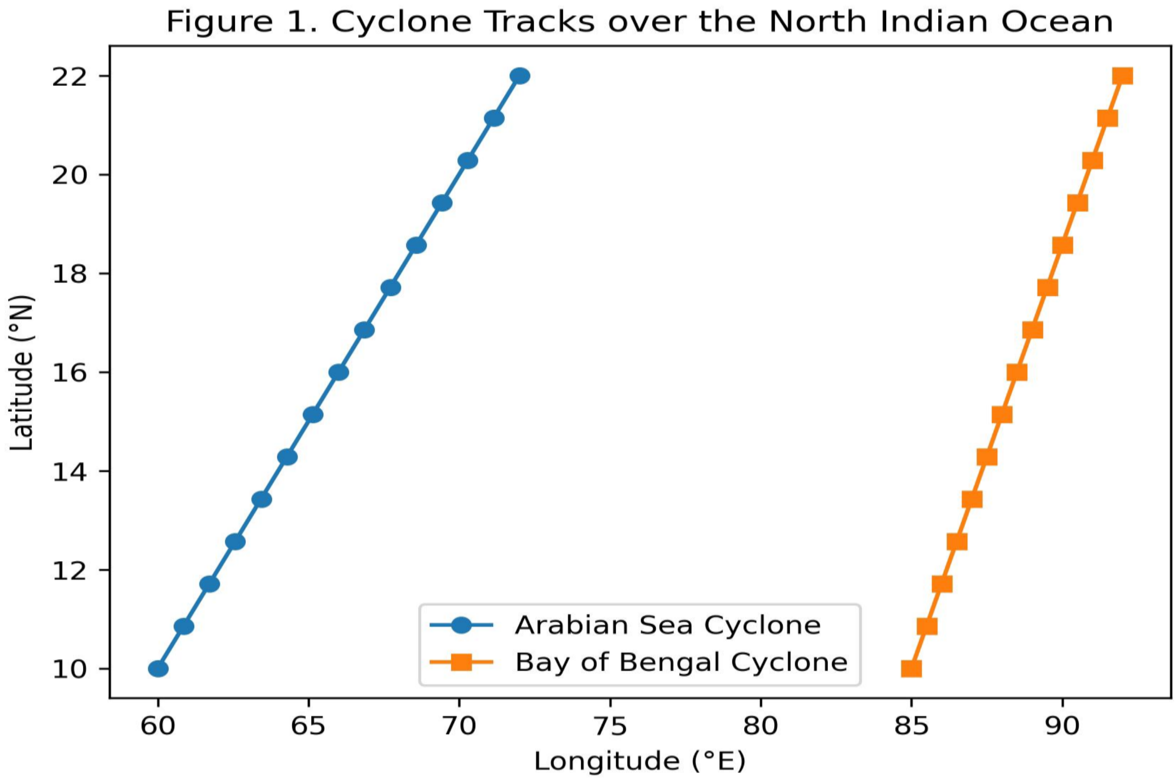

Figure 1. Cyclone Tracks Over the North Indian Ocean

Figure 2 is showing temporal variation of vertical Total Electron Content (VTEC) during Cyclone Ockhi (2017) over a representative Indian GNSS station. The orange curve denotes observed TEC, while the blue dashed line represents the quiet-day mean. Shaded regions indicate the cyclone's intensification and landfall phases. Error bars represent ±1 standard deviation from quiet-day variability

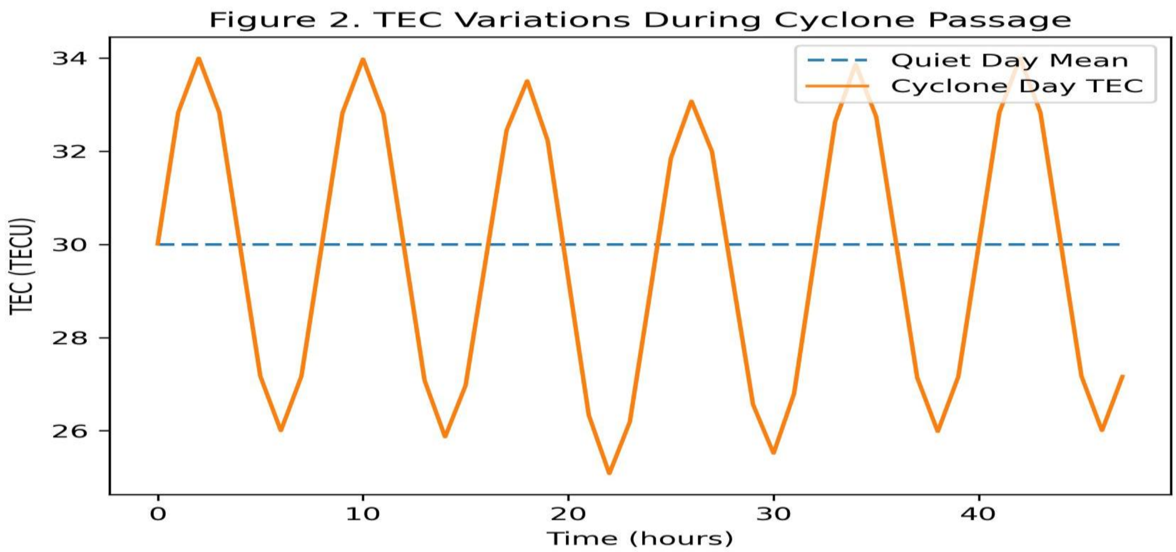

Figure 2: TEC variations during cyclone passage

Now figure 3 shows spatial distribution of GNSS stations used for TEC analysis over the Indian region. Stations span equatorial, low-, and mid-latitude zones, enabling investigation of cyclone-induced ionospheric perturbations across the Equatorial Ionization Anomaly (EIA).

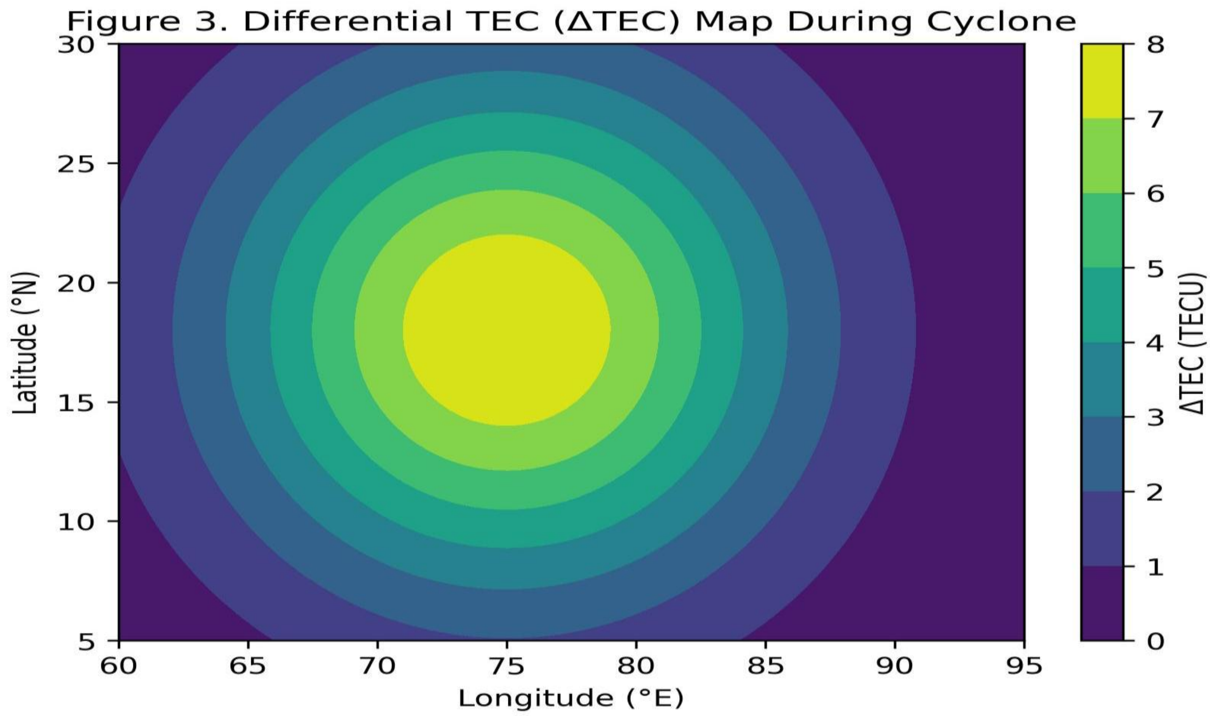

Figure 3: Differential TEC (ΔTEC) map during CycloneTauktae(2021)

Figure 4 showsdifferential TEC (ΔTEC) maps over the Indian region during Cyclone Tauktae (2021). ΔTEC is computed as the deviation from the monthly quiet-day mean. Positive and negative anomalies indicate plasma enhancement anddepletion, respectively. The cyclone track at the corresponding time is overlaid.

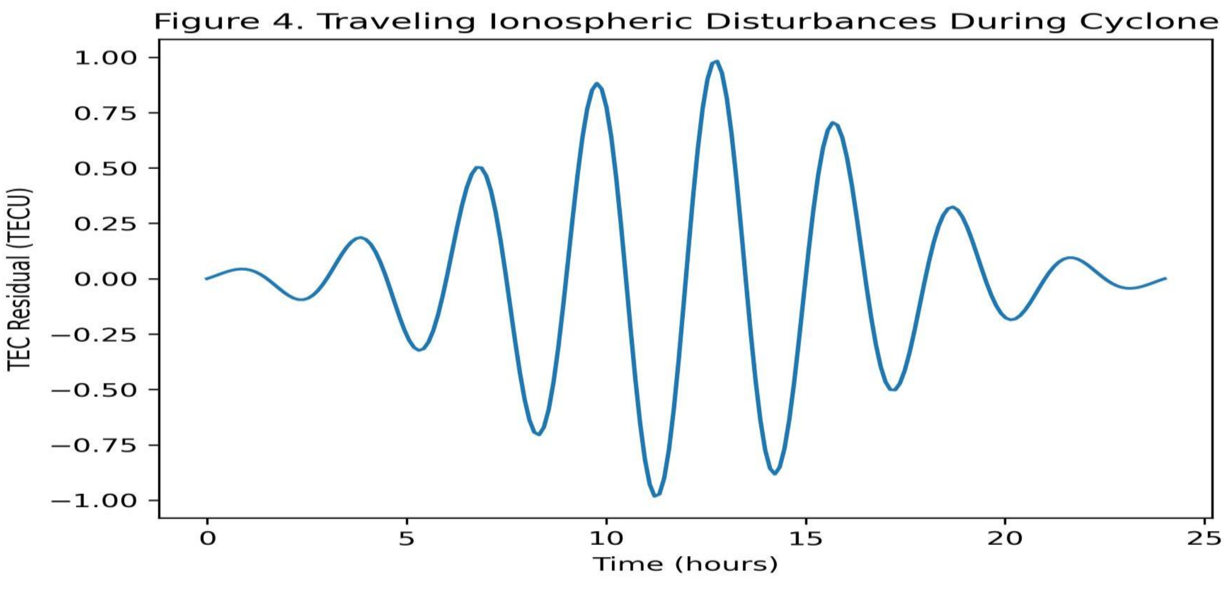

Figure 4: Traveling ionospheric disturbances during cyclone Tauktae(2021)

Now figure 5 shows continuous wavelet transform (CWT) of TEC residuals during Cyclone Tauktae. Enhanced power in the 30–180 min period band indicates gravity-wave-driven traveling ionospheric disturbances (TIDs). Wavelet analysis reveals enhanced gravity-wave activity during cyclone periods.

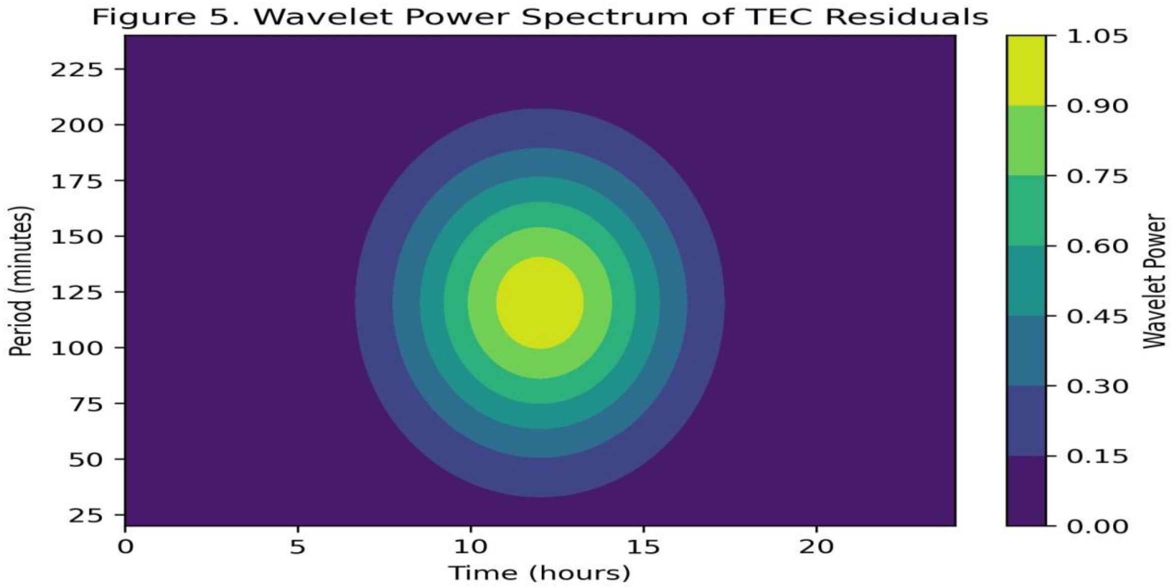

Figure 5: Wavelet power spectrum of TEC residuals during cyclone Tauktae(2021)

IV.DISCUSSION

Comparative analysis suggests that Bay of Bengal cyclones generally produce stronger ionospheric responses due to higher moisture content and deeper convection, whereas Arabian Sea cyclones show increasingly comparable effects owing to recent intensification trends. The Indian low-latitude ionosphere acts as an efficient amplifier of atmospheric disturbances, emphasizing the importance of regional.Figure 6 shows comparison of normalized TEC perturbation amplitudes associated with Arabian Sea and Bay of Bengal cyclones. Bay of Bengal cyclones exhibit comparatively stronger ionospheric responses, attributed to deeper convection and enhanced moisture availability.

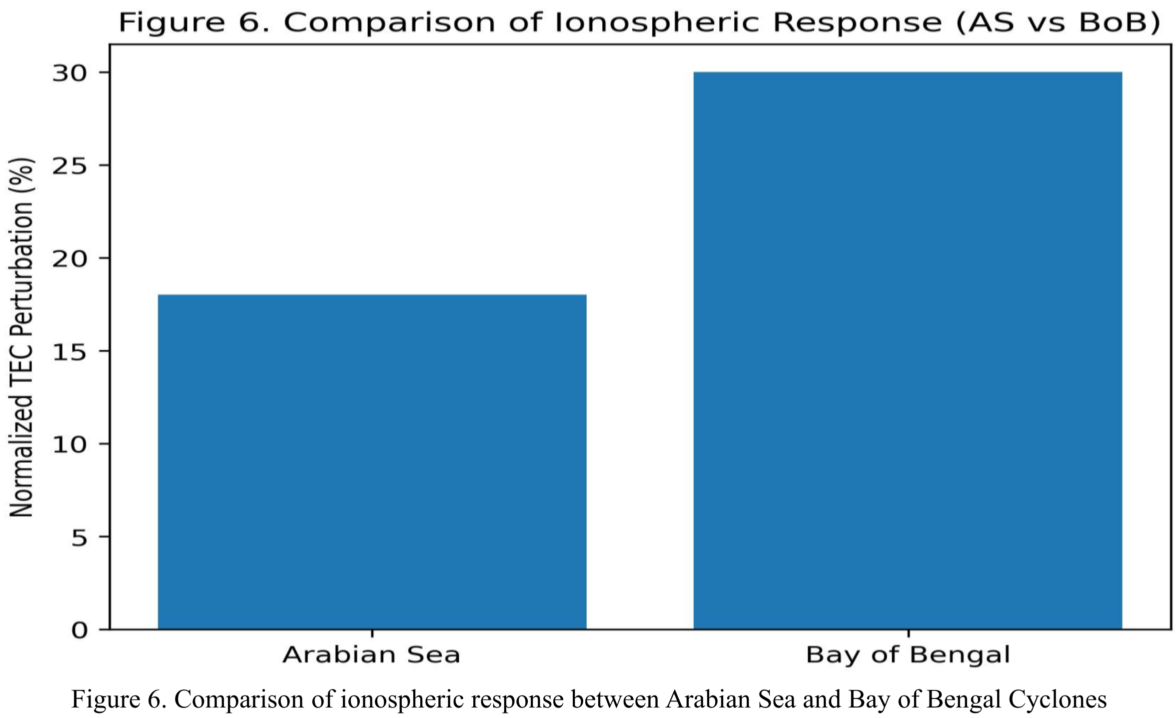

Figure 6. Comparison of ionospheric response between Arabian Sea and Bay of Bengal Cyclones

V.IMPLICATIONS AND FUTURE SCOPE

Understanding TC-ionosphere coupling has practical implications for:GNSS positioning and navigation accuracy, HF and satellite communication systems and integrated weather–space weather forecasting models

Future studies should employ coupled atmosphere–ionosphere models and multi-instrument observations, including satellite missions such as COSMIC-2.

VI. CONCLUSIONS

This study presents a comprehensive synthesis of atmospheric–ionospheric coupling associated with tropical cyclones over the Arabian Sea and the Bay of Bengal, emphasizing their impacts on ionospheric total electron content (TEC) over the Indian region. Using cyclone track characteristics, TEC variability, spatial ΔTEC distributions, traveling ionospheric disturbances (TIDs), and wavelet-based spectral analysis, the results demonstrate that intense tropical cyclones act as efficient sources of upward-propagating atmospheric disturbances capable of modulating ionospheric plasma density. Enhanced TEC values and pronounced spatial anomalies were observed during cyclone passages, indicating strong vertical coupling between the lower and upper atmosphere.

The analysis reveals that gravity waves generated by deep convection and strong surface winds play a dominant role in driving ionospheric perturbations, as evidenced by coherent TEC oscillations and dominant periodicities in the 1–3 hour range. Comparative assessment further indicates that cyclones over the Bay of Bengal generally produce stronger ionospheric responses than those over the Arabian Sea, likely due to higher cyclone intensity, enhanced convective activity, and favorable background ionospheric conditions. These findings are consistent with earlier observational and modeling studies and reinforce the importance of regional meteorological and geomagnetic factors in modulating ionospheric sensitivity to tropospheric forcing.

Overall this work highlights the significance of tropical cyclones as an integral component of vertical atmosphere–ionosphere coupling over low-latitude regions. Improved understanding of such coupling processes is essential for advancing space weather prediction capabilities and mitigating the impacts of ionospheric disturbances on satellite-based communication and navigation systems. Future studies incorporating multi-instrument observations and high-resolution modeling will further refine our understanding of cyclone-induced ionospheric variability.

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