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A Comprehensive Review of Long-Term Variability and Recent Advances in Equatorial and Low-Latitude Ionospheric Research over the Indian Region (2000–2025)

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Abstract- The equatorial and low-latitude ionosphere over the Indian region has undergone significant changes during the past 25 years (2000-2025), spanning three complete solar cycles. This comprehensive review synthesizes observational evidence from ground-based ionosondes, GPS Total Electron Content (TEC) measurements, satellite missions, and space weather monitoring networks across the Indian longitude sector (60°E-100°E). Key findings reveal systematic variations in the Equatorial Ionization Anomaly (EIA) morphology, with the northern crest showing enhanced TEC values during solar maximum periods and distinctive seasonal asymmetries. Equatorial Spread F (ESF) and plasma bubble occurrence demonstrate strong correlations with solar flux variations, geomagnetic activity, and atmospheric tidal forcing. The review highlights technological advances including the Indian Network for Space Weather Impact Monitoring (InSWIM), improved ionospheric models, and enhanced prediction capabilities. Significant space weather events, including the 2003 Halloween storms, 2015 St. Patrick's Day event, and recent solar cycle 25 disturbances, have provided insights into ionosphere-magnetosphere coupling processes. Climate change effects on the upper atmosphere are emerging as new research frontiers, with evidence for long-term trends in ionospheric parameters. Future challenges include understanding mesosphere-lower thermosphere-ionosphere coupling, developing regional ionospheric models for navigation applications, and preparing for increasing space weather threats to technological infrastructure.

Keywords – Ionosphere, equatorial ionization anomaly, plasma bubbles, space weather, GPS TEC, Indian region.

I. INTRODUCTION

The equatorial and low-latitude ionosphere over the Indian region represents one of the most dynamic and scientifically intriguing domains of the Earth's upper atmosphere. Spanning the geographical coordinates 60°E to 100°E in longitude and extending from the magnetic equator to approximately 35°N latitude, this region encompasses diverse ionospheric phenomena that have attracted intensive research attention over the past quarter-century (Bhardwaj et al., 2016). The unique geophysical characteristics of the Indian sector, including its proximity to the magnetic equator, complex magnetic field geometry, and monsoon-driven atmospheric dynamics, create a natural laboratory for studying ionosphere-thermosphere-magnetosphere coupling processes.

The period from 2000 to 2025 represents a particularly significant epoch in ionospheric research, encompassing portions of solar cycles 23, 24, and the ascending phase of cycle 25. This timeframe has witnessed unprecedented technological advances in ionospheric observation capabilities, from the deployment of dense GPS receiver networks to sophisticated satellite missions and ground-based instrumentation (Choudhary et al., 2025). The advent of the Global Positioning System (GPS) for ionospheric research has revolutionized our understanding of Total Electron Content (TEC) variations, enabling continuous monitoring with high spatial and temporal resolution across the Indian subcontinent.

The equatorial ionosphere over the Indian sector exhibits several distinctive features that distinguish it from other global regions.

The presence of the Equatorial Electrojet (EEJ), a narrow band of enhanced eastward current flowing along the magnetic equator, creates unique electrodynamic conditions that drive the formation of the Equatorial Ionization Anomaly (EIA). This phenomenon, characterized by two crests of enhanced electron density located symmetrically about 15-20° north and south of the magnetic equator, shows pronounced variability over the Indian longitude sector due to complex interactions between

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solar radiation, geomagnetic field configuration, and neutral atmospheric dynamics.

The Indian Ocean represents a unique geographical feature in global ionospheric studies, as it is the only major oceanic region that spans the magnetic equator. This creates distinctive boundary conditions for ionospheric processes, with land-ocean contrasts significantly influencing atmospheric tidal propagation and subsequent ionospheric variability. The monsoon circulation patterns, characteristic of the Indian subcontinent, introduce additional complexity through their effects on lower atmospheric dynamics and subsequent coupling to the upper atmosphere.

During the 25-year period under review, the Indian region has experienced the full range of solar activity conditions, from the declining phase of solar cycle 23 (2000-2008) through the moderate activity of cycle 24 (2008-2019) to the currently ascending phase of cycle 25 (2019-present). This comprehensive solar cycle coverage provides an unprecedented opportunity to understand long-term trends and solar cycle dependencies in equatorial ionospheric processes.

II. OBSERVATIONAL INFRASTRUCTURE AND DATA SOURCES

Ground-Based Networks

The observational foundation for ionospheric research over the Indian region has evolved dramatically since 2000, transitioning from sparse, isolated measurements to comprehensive, coordinated networks. The Indian Institute of Geomagnetism (IIG) operates a meridional chain of ionosondes extending from Thumba (8.5°N, 77°E) near the magnetic equator to Delhi (28.6°N, 77.2°E), providing continuous electron density profile measurements (Rama Rao et al., 2009). These installations have been complemented by the establishment of the Indian Network for Space Weather Impact Monitoring (InSWIM), designed specifically to study space weather effects on the low-latitude ionosphere (Choudhary et al., 2025).

The ionosonde network has been strategically positioned to capture the latitudinal variation of ionospheric parameters across the EIA region. Key stations include Thumba, representing near-equatorial conditions; Hyderabad (17.4°N, 78.4°E) and Waltair (17.7°N, 83.3°E) in the northern EIA crest region; and Ahmedabad (23.0°N, 72.5°E) and Delhi in the off-equatorial zone. These stations provide continuous measurements of critical frequency parameters (foF2, foE, foEs), virtual heights, and electron density profiles, enabling comprehensive characterization of ionospheric morphology and variability.

GPS-based TEC measurements have become the cornerstone of ionospheric monitoring, with the Indian GPS network expanding from fewer than 20 stations in 2000 to over 200 operational receivers by 2025. The integration of International GNSS Service (IGS) stations with regional networks has enabled comprehensive coverage of TEC variations across the Indian longitude sector. The GPS Aided Geo Augmented Navigation (GAGAN) system, developed by ISRO and the Airports Authority of India, has contributed significantly to ionospheric monitoring capabilities while serving its primary navigation augmentation role.

Digital ionosondes installed at multiple locations have replaced analog systems, providing enhanced measurement capabilities including automatic scaling, drift measurement, and real-time data processing. The Modern Ionospheric Communication Analyzer (MONICA) systems deployed across the network offer improved temporal resolution and measurement accuracy, enabling detailed studies of rapid ionospheric variations associated with space weather events.

Scintillation monitoring networks have been established to track amplitude and phase fluctuations in GPS signals, providing direct measurements of ionospheric irregularity effects on satellite communications. The Indian Space Research Organisation has deployed GPS Ionospheric Delay Receiver (GIDR) systems at multiple locations, enabling real-time assessment of scintillation conditions and their impact on navigation accuracy.

Satellite Missions and Space-Based Observations

The past 25 years have witnessed an unprecedented expansion in satellite-based ionospheric observations relevant to the Indian region. The COSMIC/FORMOSAT-3 mission, launched in 2006, provided radio occultation measurements that significantly enhanced our understanding of global ionospheric structure, including detailed profiles over the Indian Ocean sector. These measurements have been particularly valuable for validating and improving ionospheric models, as they provide independent observations of electron density profiles with global coverage.

The Swarm constellation, operational since 2013, has delivered high-precision magnetic field and plasma density measurements, enabling studies of field-aligned currents and equatorial electrojet variations specific to Indian longitudes. The three-satellite configuration allows for detailed investigation of ionospheric current systems and their temporal evolution, providing insights into the electrodynamics driving ionospheric variability over the Indian sector.

The Communication/Navigation Outage Forecasting System (C/NOFS) satellite, operational from 2008 to 2015, provided detailed in-situ measurements of plasma densities, irregularities, and electric fields in the equatorial ionosphere.

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These observations have been crucial for understanding the physics of equatorial spread F and plasma bubble development over the Indian longitude sector.

Recent missions including the NASA ICON and ESA Solar Orbiter have contributed to understanding thermosphere-ionosphere coupling and solar wind effects on the Indian sector ionosphere. The ICON mission, in particular, has provided simultaneous measurements of neutral winds, plasma motions, and atmospheric composition, enabling detailed studies of ion-neutral coupling processes.

The planned Indian space weather mission, Aditya-L1, positioned at the Sun-Earth L1 Lagrange point, promises to enhance our predictive capabilities for space weather events affecting the Indian region. This mission will provide comprehensive solar observations, including solar wind parameters, solar energetic particles, and coronal mass ejection characteristics, enabling improved space weather forecasting for the Indian sector.

Indian satellite missions including the Indian National Satellite System (INSAT) and Indian Regional Navigation Satellite System (IRNSS/NavIC) have contributed both operational data and scientific observations. The IRNSS constellation, in particular, provides an opportunity for comparative studies of ionospheric effects on different GNSS systems operating over the same geographical region.

Data Integration and Quality Control

The integration of multiple data sources requires careful attention to quality control and cross-validation procedures. Standardized data formats and processing protocols have been developed to ensure compatibility between different observational systems. The establishment of the Space Weather Data Center at ISRO provides a centralized repository for multi-instrument ionospheric observations, facilitating coordinated research efforts.

Automated quality control procedures have been implemented to identify and flag potentially erroneous data points, while manual validation processes ensure the reliability of critical datasets. Inter-calibration studies between different instrument types and measurement techniques have been conducted to understand systematic biases and ensure data consistency across the observational network.

III. SOLAR CYCLE VARIATIONS AND LONG-TERM TRENDS

Total Electron Content Evolution (2000-2025)

The evolution of ionospheric TEC over the Indian region during the past 25 years reflects the complex interplay between solar forcing, geomagnetic activity, and thermospheric dynamics. Rao et al. (2019) conducted comprehensive analyses of GPS-derived TEC measurements from multiple stations across the Indian subcontinent, revealing systematic variations associated with solar cycles 23 and 24. Their findings indicate peak TEC values during the solar maximum periods (2000-2002 and 2012-2015) with enhancement factors of 2-3 relative to solar minimum conditions.

The solar cycle 23 declining phase (2000-2008) provided an excellent opportunity to study the ionospheric response to decreasing solar activity. TEC measurements showed a gradual decline in background ionization levels, with the most pronounced changes occurring in the F2 peak region. The deep solar minimum of 2008-2009 resulted in historically low TEC values, with some stations recording minimum values 70-80% below solar maximum levels.

Solar cycle 24, characterized by moderate activity levels compared to previous cycles, demonstrated unique ionospheric responses over the Indian sector. The cycle exhibited an unusual double-peaked structure in solar activity, reflected in corresponding ionospheric variations. Peak TEC values during cycle 24 were generally lower than those observed during cycle 23, consistent with the overall weaker solar activity levels.

The ascending phase of solar cycle 25 (2019-present) has already shown interesting developments, with some indicators suggesting potentially stronger activity levels than cycle 24. Initial TEC observations indicate rapid increases in ionization levels, particularly during equinoctial periods when solar zenith angles are optimal for ionospheric production over the Indian region.

The northern Equatorial Ionization Anomaly (EIA) crest, typically located around 15-20°N over the Indian region, shows pronounced seasonal and solar cycle dependencies. During solar maximum periods, the anomaly crest intensifies and migrates poleward, reaching latitudes of 22-25°N during equinoctial months. Rajput et al. (2024) analyzed plasma density trends at Hyderabad (17.4°N, 78.4°E), demonstrating that the EIA crest exhibits maximum strength during March-April and September-October, with amplification factors exceeding 1.5 during high solar activity periods.

Statistical analyses of long-term TEC variations reveal several important characteristics. The annual and semiannual components show systematic variations with solar cycle phase, with the semiannual component becoming more prominent during solar maximum periods. Harmonic analysis indicates that the dominant periodicities in TEC variations are associated with solar rotation (27 days), seasonal changes, and solar cycle effects.

Diurnal TEC variations exhibit complex patterns that depend on season, solar activity level, and geomagnetic conditions. During solar maximum periods, the diurnal amplitude can

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exceed 40-50 TECU over the Indian region, while solar minimum conditions typically show amplitudes of 10-15 TECU. The timing of maximum and minimum TEC values shows systematic shifts with season and solar activity, reflecting changes in the balance between ionization and recombination processes.

Longitudinal and Seasonal Asymmetries

One of the most intriguing aspects of ionospheric behavior over the Indian region is the presence of significant longitudinal gradients and seasonal asymmetries that distinguish this sector from other global regions. The Indian Ocean sector, characterized by unique magnetic field configurations and land-ocean contrasts, exhibits distinctive TEC patterns that deviate from zonally averaged models.

Longitudinal variations in TEC across the Indian sector (60°E-100°E) can exceed 20-30% of the mean values, with systematic patterns that persist across multiple solar cycles. These variations are attributed to several factors including magnetic field declination changes, land-ocean contrasts affecting tidal propagation, and regional differences in thermospheric composition and dynamics.

The wave-4 longitudinal structure, a prominent feature of equatorial ionospheric morphology, shows distinctive characteristics over the Indian sector. This pattern, attributed to eastward propagating diurnal tides in the lower atmosphere, creates systematic enhancements and depletions in TEC that vary predictably with longitude. Over the Indian region, the wave-4 structure interacts with regional geographic features, creating complex interference patterns that modify the simple four-peak global structure.

Seasonal asymmetries in ionospheric behavior over the Indian region are pronounced and show systematic variations with solar activity level. The March-April and September-October periods, corresponding to equinoctial conditions, consistently show maximum TEC values and enhanced plasma bubble activity. However, the relative strength of these two equinoctial peaks varies systematically, with the October peak generally stronger during solar maximum periods and the March peak dominating during solar minimum conditions.

The annual asymmetry, characterized by differences between corresponding months in opposite seasons, shows complex dependencies on geographic location within the Indian sector. Northern stations typically show stronger winter values relative to summer, while equatorial stations exhibit more symmetric seasonal variations. This latitudinal dependence reflects the interplay between solar zenith angle effects, magnetic field geometry, and thermospheric dynamics.

During the ascending phase of solar cycle 25 (2020-2025), emerging evidence suggests modifications in traditional seasonal patterns, potentially linked to changing solar wind characteristics and evolving atmospheric composition. Some preliminary observations indicate shifts in the timing and magnitude of seasonal TEC maxima, though longer observational periods will be required to establish statistical significance.

The implications of these changes for space weather prediction and ionospheric modeling remain active areas of investigation. Regional models must account for these systematic patterns to provide accurate predictions of ionospheric conditions over the Indian sector. The development of machine learning approaches that can capture complex nonlinear relationships between solar-terrestrial parameters and ionospheric response shows promise for improving prediction capabilities.

IV. EQUATORIAL SPREAD F AND PLASMA IRREGULARITIES

Plasma Bubble Morphology and Evolution

Equatorial Spread F (ESF) phenomena and associated plasma bubble structures represent critical aspects of ionospheric variability over the Indian region. Sekar and Chakrabarty (2011) provided comprehensive reviews of ESF investigations using optical and radio techniques, establishing fundamental understanding of plasma bubble initiation and evolution processes. These irregularities, manifesting as depletions in plasma density, significantly impact radio wave propagation and satellite communications.

The initiation of plasma bubbles typically occurs during post-sunset hours when the F-layer height increases due to the pre-reversal enhancement (PRE) of the eastward electric field. Over the Indian sector, this process shows distinctive characteristics related to the local magnetic field configuration and neutral atmospheric conditions. The generalized Rayleigh-Taylor instability mechanism, driven by gravitational and pressure gradient forces in the presence of density gradients, provides the fundamental physics underlying bubble development.

Observational studies using multiple diagnostic techniques have revealed the complex three-dimensional structure of plasma bubbles over the Indian region. Optical observations using 630.0 nm airglow emissions show that bubbles can extend to altitudes exceeding 1000 km, with horizontal scales ranging from tens to hundreds of kilometers. The bubbles exhibit complex internal structures, including bifurcation, branching, and the development of secondary instabilities.

Recent observations during solar cycle 24 revealed enhanced ESF activity during the equinoxes, with bubble apex heights reaching 800-1000 km over the Indian sector. The seasonal dependence of ESF occurrence shows maximum activity during March-April and September-October, coinciding with periods of maximum plasma fountain efficiency and optimal

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conditions for instability growth. Winter months typically show suppressed ESF activity, while summer conditions exhibit intermediate occurrence rates.

Solar cycle dependencies in ESF occurrence are pronounced, with maximum activity during solar maximum periods when high F-region heights and steep density gradients provide optimal conditions for instability development. During solar minimum periods, ESF occurrence rates can decrease by factors of 3-4 compared to solar maximum conditions, though significant year-to-year variations are observed.

The influence of geomagnetic activity on ESF development over the Indian region is complex and depends on multiple factors including the timing, intensity, and duration of disturbances. Prompt penetration electric fields associated with geomagnetic storms can either enhance or suppress ESF activity depending on their direction and timing relative to local time. Disturbance dynamo effects, developing with delays of several hours after storm onset, can significantly modify the normal ESF climatology.

Thokuluwa (2025) investigated the generation of plasma bubbles during the 17 March 2015 geomagnetic storm, demonstrating how enhanced electric fields can trigger irregularity formation even during typically quiet local time periods. The study revealed that super-storm conditions can fundamentally alter normal ESF climatology, leading to unexpected plasma bubble development during morning and afternoon hours when such activity is normally absent.

Scintillation Effects and Communication Impacts

Ionospheric scintillation, caused by small-scale plasma irregularities, poses significant challenges to trans-ionospheric radio systems including GPS navigation and satellite communications. The Indian region, situated in the equatorial anomaly zone, experiences some of the most severe scintillation effects globally, particularly during post-sunset hours and equinoctial seasons.

Amplitude scintillation, characterized by rapid fluctuations in received signal strength, can reach severe levels ($S4 > 0.8$) over the Indian region during disturbed conditions. These fluctuations occur on timescales of seconds to minutes, causing degradation in signal quality and potential loss of lock in GPS receivers. The frequency dependence of scintillation effects means that L-band signals used by GPS are particularly susceptible to ionospheric irregularities.

Phase scintillation, measured by the $\sigma\varphi$ index, can exceed 2-3 radians during severe scintillation events over the Indian sector. This parameter is particularly important for precise positioning applications, as phase measurements are crucial for achieving centimeter-level accuracy. Strong phase scintillation can make carrier phase measurements unusable, forcing receivers to rely on less precise code-based positioning.

The temporal characteristics of scintillation over the Indian region show systematic patterns related to local time, season, and solar activity. Scintillation typically begins 1-2 hours after sunset and can persist until midnight or later during disturbed conditions. The onset time shows seasonal variations, occurring earlier during equinoxes when ESF activity is enhanced.

Spatial characteristics of scintillation events reveal the complex structure of ionospheric irregularities. Scintillation-causing irregularities typically have scale sizes ranging from hundreds of meters to several kilometers, with the most effective scattering occurring at Fresnel-scale sizes (approximately 500 m at GPS frequencies and ionospheric heights). The anisotropic nature of these irregularities, with field-aligned extensions much larger than cross-field dimensions, affects the scintillation characteristics observed by ground-based receivers.

Multi-frequency scintillation observations have provided insights into the spectral characteristics of ionospheric irregularities over the Indian region. The power spectral density of irregularities typically follows a power law with indices ranging from -2 to -4, depending on the scale size range and generation mechanism. These spectral characteristics are important for understanding the physical processes responsible for irregularity generation and evolution.

Barad et al. (2025) analyzed ionospheric responses to the 23-24 April 2023 G4-class geomagnetic storm, revealing complex interactions between storm-time electric fields and existing plasma structures. Their observations showed that geomagnetic disturbances could both suppress existing ESF activity through enhanced background densities and trigger new irregularity formation through modified electrodynamic processes.

The impact of scintillation on practical applications has become increasingly important as reliance on satellite-based systems has grown. Aviation applications are particularly sensitive to scintillation effects, as GPS-based navigation systems used during precision approaches can experience significant degradation during scintillation events. The Required Navigation Performance (RNP) specifications for aircraft operations can be compromised when scintillation-induced positioning errors exceed acceptable limits.

Maritime navigation applications also face challenges from ionospheric scintillation, particularly for vessels operating in coastal waters where precise positioning is crucial for safe navigation. The Differential GPS (DGPS) systems used for maritime navigation can experience reduced accuracy during scintillation events, potentially affecting the safety of marine operations.

Prediction and Mitigation Strategies

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The development of effective prediction and mitigation strategies for ESF and scintillation effects has become a priority for space weather services. Empirical models based on statistical relationships between solar-terrestrial parameters and ESF occurrence have shown reasonable success for climatological predictions but limited capability for day-to-day forecasting.

Physics-based models incorporating detailed electrodynamics and plasma physics have shown promise for ESF prediction, though computational requirements and input parameter uncertainties remain challenging. The coupling between neutral atmospheric dynamics and ionospheric electrodynamics is particularly complex and difficult to model accurately.

Machine learning approaches are being explored for scintillation prediction, with some promising results for short-term forecasting based on patterns in historical data. Neural networks and support vector machines have shown capability for identifying conditions conducive to scintillation development, though the physical interpretation of these models remains limited.

Mitigation strategies for scintillation effects include receiver design improvements, signal processing techniques, and system-level approaches. Advanced GPS receivers incorporate sophisticated tracking algorithms that can maintain signal lock during moderate scintillation conditions. Multi-frequency receivers can exploit the frequency dependence of scintillation to improve positioning accuracy during disturbed conditions.

V. SPACE WEATHER IMPACT ASSESSMENT

Major Storm Events and Regional Responses

The 25-year period under review has witnessed several significant space weather events that have profoundly impacted the ionosphere over the Indian region. The Halloween storms of October 2003, characterized by extreme solar proton events and geomagnetic disturbances, provided unprecedented insights into storm-time ionospheric dynamics. These events demonstrated the vulnerability of technological systems to space weather, motivating enhanced monitoring and prediction efforts.

The Halloween storm sequence began with a series of X-class solar flares and associated coronal mass ejections (CMEs) that reached Earth between October 29-31, 2003. The resulting geomagnetic storms achieved Kp values exceeding 8, representing severe to extreme geomagnetic conditions. Over the Indian region, these storms produced dramatic ionospheric responses including enhanced TEC at low latitudes, suppression of normal diurnal variations, and significantly modified plasma bubble activity.

GPS TEC measurements during the Halloween storms showed peak values exceeding 150 TECU over the Indian sector, representing increases of 200-300% above quiet-time levels. The enhanced TEC persisted for several days, gradually returning to normal levels as geomagnetic conditions improved. Ionosonde observations revealed elevated F2-layer peak heights and enhanced critical frequencies, consistent with the TEC enhancements observed by GPS.

The 17-18 March 2015 St. Patrick's Day geomagnetic storm represents another landmark event, extensively studied across the Indian longitude sector. Multiple investigations revealed complex storm-time responses, including enhanced TEC at low latitudes, suppression of normal diurnal variations, and modified plasma bubble activity (Ramsingh et al., 2015). The storm highlighted the need for improved regional ionospheric models capable of capturing localized space weather effects.

The St. Patrick's Day storm was triggered by a CME that reached Earth on March 17, 2015, resulting in a sudden storm commencement and subsequent development of intense geomagnetic activity. The storm achieved a minimum Dst value of -223 nT, qualifying as an intense geomagnetic storm by standard definitions. Over the Indian region, the storm produced complex ionospheric responses that varied significantly with local time, season, and magnetic latitude.

During the main phase of the St. Patrick's Day storm, prompt penetration electric fields penetrated to equatorial latitudes, modifying the normal electrodynamic processes that drive ionospheric structure. Enhanced eastward electric fields during daytime hours led to increased plasma fountain efficiency, resulting in enhanced TEC in the EIA region. Conversely, enhanced westward electric fields during nighttime hours suppressed normal F-region uplift, leading to reduced plasma bubble activity.

The recovery phase of the St. Patrick's Day storm was characterized by disturbance dynamo effects that persisted for several days after the initial geomagnetic disturbance. These effects, caused by storm-induced changes in thermospheric circulation, produced westward electric fields at equatorial latitudes that opposed normal dynamo processes. The result was continued suppression of F-region heights and plasma fountain activity for 2-3 days following the storm.

Ranjan et al. (2023) conducted detailed analyses of ionospheric variability during December 2006, a period characterized by multiple space weather events including coronal mass ejections and solar flares. Their multi-instrument approach, incorporating GPS TEC, ionosonde, and satellite observations, revealed systematic relationships between solar wind parameters and ionospheric responses over Indian longitudes.

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The December 2006 period was notable for a series of moderate to strong geomagnetic storms that provided opportunities to study cumulative space weather effects. The storms occurred during solar minimum conditions, allowing investigation of ionospheric responses under low background activity levels. Despite the low solar activity, the storms produced significant ionospheric disturbances over the Indian region, demonstrating the sensitivity of the equatorial ionosphere to geomagnetic forcing.

Statistical analyses of storm-time ionospheric responses over the Indian region have revealed several systematic patterns. Positive ionospheric storms, characterized by enhanced TEC and F2-layer parameters, are more common during daytime hours and at equatorial latitudes. Negative storms, showing suppressed ionospheric parameters, typically occur during nighttime hours and at higher magnetic latitudes.

The seasonal dependence of storm-time ionospheric responses shows enhanced effects during equinoctial periods when background ionospheric activity is already elevated. Winter storms tend to produce more negative phase effects, while summer storms show more mixed responses. These seasonal variations reflect the complex interplay between storm-induced processes and normal seasonal variations in ionospheric parameters.

GPS Navigation and Communication System Vulnerabilities

The increasing dependence on satellite-based navigation and communication systems has heightened awareness of space weather vulnerabilities. GPS positioning accuracy over the Indian region shows significant degradation during disturbed ionospheric conditions, with errors exceeding several meters during severe storms. These impacts affect critical applications including aviation navigation, precision agriculture, and emergency services.

Single-frequency GPS receivers are particularly vulnerable to ionospheric disturbances, as they cannot measure or correct for ionospheric delays directly. During disturbed conditions, positioning errors in single-frequency systems can exceed 10-20 meters over the Indian region, rendering them unsuitable for applications requiring high accuracy. The problem is exacerbated during scintillation events when signal tracking can be lost entirely.

Dual-frequency GPS receivers can estimate ionospheric delays using the dispersive nature of the ionosphere, providing some mitigation against ionospheric effects. However, during severe disturbances, the assumptions underlying ionospheric delay estimation can break down, leading to degraded performance even in sophisticated receivers. Scintillation effects can disrupt both frequency bands simultaneously, eliminating the benefits of dual-frequency operation.

Real-Time Kinematic (RTK) GPS systems, which rely on carrier phase measurements to achieve centimeter-level accuracy, are extremely vulnerable to ionospheric disturbances. Cycle slips caused by scintillation can reset the ambiguity resolution process, requiring re-initialization periods that can last several minutes. During severe scintillation events, RTK systems may be unable to maintain the required accuracy for precision applications.

The Wide Area Augmentation System (WAAS) and similar satellite-based augmentation systems face particular challenges in the Indian region due to the high occurrence rate of ionospheric irregularities. These systems require accurate models of ionospheric delays across large geographical areas, but the rapid spatial and temporal variations characteristic of the equatorial ionosphere make such modeling extremely difficult.

Demyanov and Yasyukevich (2021) comprehensively assessed space weather risk factors for Global Navigation Satellite Systems (GNSS), identifying the Indian region as particularly susceptible to ionospheric effects due to its equatorial location and complex magnetic field geometry. Their analysis emphasized the need for real-time ionospheric correction capabilities and robust backup navigation systems.

Communication systems operating in the HF band are severely affected by ionospheric disturbances over the Indian region. The high occurrence rate of spread F conditions can make HF communications unreliable, particularly during nighttime hours when such communications are normally most effective. Military and aviation HF communications systems require backup capabilities to maintain operations during disturbed ionospheric conditions.

Satellite communication systems operating at L-band and higher frequencies can experience scintillation effects that degrade signal quality and reduce system availability. The problem is particularly severe for low-elevation angle links where the signal path through the ionosphere is longest. Adaptive techniques including power control and diversity reception are employed to mitigate these effects.

Operational Space Weather Services

The recognition of space weather impacts on technological systems has led to the development of operational space weather services tailored for the Indian region. The Space Weather Services and Applications (SWSA) program at ISRO provides real-time monitoring and forecasting capabilities for various user communities including aviation, maritime, and power grid operators.

Real-time monitoring systems provide continuous assessment of ionospheric conditions over the Indian region using

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networks of GPS receivers, ionosondes, and scintillation monitors. These systems generate automated alerts when ionospheric conditions exceed predetermined thresholds, enabling users to take appropriate mitigation actions.

Forecasting services attempt to predict ionospheric conditions 1-3 days in advance using a combination of empirical models, physics-based simulations, and statistical techniques. While day-to-day predictability remains limited, these services can provide valuable guidance for mission planning and risk assessment.

User-specific services have been developed for critical applications including aviation and maritime navigation. These services provide tailored products that address the specific needs of different user communities, including navigation accuracy assessments and communication reliability predictions.

International cooperation through organizations like the International Space Environment Service (ISES) enables sharing of observations and forecasting expertise. The Indian space weather community actively participates in global coordination efforts, contributing regional expertise and receiving benefits from international collaborations.

VI. TECHNOLOGICAL ADVANCES AND MODELING DEVELOPMENTS

Observational Capabilities Enhancement

The past 25 years have witnessed revolutionary advances in ionospheric observation capabilities over the Indian region. The deployment of sophisticated ground-based instruments, including GPS scintillation monitors, ionospheric sounders, and optical imagers, has enabled unprecedented monitoring of ionospheric phenomena. The Indian Space Research Organisation (ISRO) has played a pivotal role in developing indigenous space weather monitoring capabilities, including the planned Aditya-L1 mission for solar observations.

Digital signal processing advances have transformed ionospheric measurement capabilities. Modern ionosondes incorporate sophisticated signal processing algorithms that can extract weak echoes from noisy backgrounds, enabling measurements under conditions that would have been impossible with earlier analog systems. Adaptive filtering techniques and digital beamforming have improved measurement accuracy and reduced interference from man-made sources.

Multi-instrument approaches have become standard practice, combining GPS TEC measurements with ionosonde electron density profiles, satellite in-situ observations, and ground-based optical measurements. This integrated approach has revealed new insights into ionosphere-thermosphere coupling processes and improved understanding of regional ionospheric variability. Data fusion techniques enable combining information from diverse sources to create comprehensive pictures of ionospheric state and evolution.

Advanced GPS receiver technology has enabled new types of ionospheric measurements. Software-defined receivers can track multiple GNSS constellions simultaneously, providing improved spatial and temporal coverage. High-rate GPS measurements at 1 Hz or higher enable detection of rapid ionospheric variations associated with traveling ionospheric disturbances and other dynamic phenomena.

Optical imaging systems have been deployed across the Indian region to monitor airglow emissions associated with ionospheric processes. All-sky cameras operating at 630.0 nm wavelength provide real-time images of plasma bubble development and evolution, while 557.7 nm cameras monitor F-region irregularities. These systems have revealed the complex three-dimensional structure of ionospheric irregularities and their temporal evolution.

Radar systems including coherent scatter radars and incoherent scatter radars have provided detailed measurements of ionospheric plasma properties. The Gadanki MST radar (13.5°N, 79.2°E) has been particularly valuable for studying equatorial ionospheric processes, providing measurements of plasma drift velocities, electron density profiles, and irregularity characteristics with high temporal resolution.

Very Low Frequency (VLF) radio observations have been used to study ionospheric absorption and lower ionospheric properties. VLF transmitter signals propagating in the Earth-ionosphere waveguide show systematic variations related to ionospheric conditions, providing an additional diagnostic tool for ionospheric monitoring.

Ionospheric Modeling and Prediction Systems

Significant progress has been achieved in developing regional ionospheric models specifically tailored for the Indian sector. The International Reference Ionosphere (IRI) model has undergone continuous improvements, with enhanced representation of equatorial and low-latitude phenomena. However, regional models incorporating local geographic and geomagnetic characteristics have shown superior performance for space weather applications.

The Sheffield University Plasmasphere Ionosphere Model (SUPIM) has been adapted for Indian longitude studies, incorporating realistic magnetic field configurations and thermospheric inputs. This physics-based model solves the coupled continuity and momentum equations for multiple ion

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species, providing detailed predictions of ionospheric structure and dynamics.

The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM) has been extensively used for studying ionospheric processes over the Indian region. This comprehensive model couples thermospheric dynamics with ionospheric electrodynamics, enabling investigation of the complex feedback processes that drive ionospheric variability. Regional ionospheric models have been developed specifically for the Indian sector, incorporating local geographic features and observational constraints. These models show improved performance compared to global models, particularly for capturing the distinctive longitudinal and seasonal variations characteristic of the Indian region.

Data assimilation techniques have been implemented to combine model predictions with observational data, creating optimal estimates of ionospheric conditions. Kalman filtering and variational assimilation methods have been applied to GPS TEC data, ionosonde measurements, and satellite observations to create real-time ionospheric specification products.

Machine learning and artificial intelligence techniques are increasingly being applied to ionospheric prediction, with promising results for TEC forecasting and scintillation warning systems. Neural networks have been trained on historical ionospheric data to identify patterns and relationships that can be used for prediction purposes. Support vector machines and random forest algorithms have shown particular promise for classification problems such as predicting the occurrence of scintillation events.

Deep learning approaches using recurrent neural networks and long short-term memory (LSTM) networks have been applied to time series prediction of ionospheric parameters. These methods can capture complex nonlinear relationships and long-term dependencies in ionospheric data, potentially improving prediction accuracy compared to traditional statistical methods.

Communication and Navigation System Improvements

The recognition of ionospheric impacts on satellite-based systems has driven significant improvements in receiver design and signal processing techniques. Modern GPS receivers incorporate sophisticated tracking algorithms that can maintain signal lock during moderate scintillation conditions, reducing the frequency of navigation solution outages.

Multi-constellation GNSS receivers can track satellites from GPS, GLONASS, Galileo, and BeiDou systems simultaneously, providing improved availability and accuracy. The diversity of satellite signals helps maintain positioning capability even when some signals are affected by ionospheric disturbances.

Adaptive antenna arrays and beamforming techniques have been developed to mitigate multipath and interference effects that can be exacerbated during ionospheric disturbances. These systems can dynamically adjust their reception patterns to optimize signal quality and reduce error sources.

Ionospheric correction algorithms have been improved to provide better estimates of ionospheric delays under disturbed conditions. Multi-frequency techniques can estimate ionospheric delays more accurately, while regional correction models provide improved performance over wide areas.

Real-time ionospheric monitoring systems provide immediate feedback on ionospheric conditions, enabling adaptive system responses. GPS receivers can adjust their processing parameters based on current ionospheric conditions, improving accuracy and reliability during disturbed periods.

VII. EMERGING RESEARCH FRONTIERS AND FUTURE DIRECTIONS

Climate Change Effects on the Upper Atmosphere

An emerging area of research involves understanding how climate change in the lower atmosphere affects ionospheric behavior. Evidence suggests that increasing greenhouse gas concentrations may be altering thermospheric composition and temperature structure, with potential implications for ionospheric dynamics. Long-term trend analyses using the 25-year dataset reveal subtle but potentially significant changes in ionospheric parameters that may be linked to anthropogenic climate change.

The theory of upper atmospheric cooling due to increased CO2 concentrations predicts systematic changes in thermospheric density and composition. These changes could affect ionospheric production and loss processes, potentially leading to long-term trends in ionospheric parameters. Observational evidence for such trends is beginning to emerge from long-term datasets, though separating climate change signals from natural variability remains challenging.

Changes in lower atmospheric dynamics associated with climate change may affect the propagation of atmospheric waves to the upper atmosphere. Modified wave activity could alter the normal patterns of ionospheric variability, potentially affecting the reliability of empirical models based on historical data. The monsoon circulation patterns characteristic of the Indian region may be particularly sensitive to climate change effects.

Long-term changes in atmospheric composition, including increasing concentrations of greenhouse gases and changing distributions of water vapor, may affect ionospheric chemistry and dynamics. These changes could modify the normal

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relationships between solar activity and ionospheric response, requiring updates to existing models and prediction systems.

Secular changes in the Earth's magnetic field, including the ongoing weakening of the dipole field and movement of the magnetic poles, may interact with climate change effects to produce complex trends in ionospheric behavior. The South Atlantic Anomaly, a region of weakened magnetic field, continues to expand and intensify, potentially affecting ionospheric conditions over an increasingly large area.

Mesosphere-Lower Thermosphere-Ionosphere Coupling
Advances in observational capabilities have highlighted the importance of mesosphere-lower thermosphere-ionosphere (MLTI) coupling in driving ionospheric variability. Atmospheric waves propagating from the lower atmosphere can significantly modulate ionospheric structure and dynamics, particularly in the equatorial region. Understanding these coupling mechanisms is crucial for developing comprehensive models of the Earth's upper atmosphere system.

Gravity waves generated by tropospheric weather systems can propagate to ionospheric heights, depositing momentum and energy that affects ionospheric dynamics. The seasonal variation of gravity wave activity, related to monsoon dynamics over the Indian region, may contribute to the observed seasonal asymmetries in ionospheric parameters.

Planetary waves with periods of days to weeks can modulate ionospheric conditions through their effects on thermospheric dynamics and composition. These waves can produce systematic day-to-day variations in ionospheric parameters that are independent of solar and geomagnetic forcing, complicating prediction efforts.
Tidal waves, particularly the diurnal and semidiurnal components, play crucial roles in driving ionospheric dynamics. The interaction between solar heating and atmospheric tides creates complex patterns of ionospheric variability that show systematic variations with season and solar activity. Understanding these interactions is essential for accurate ionospheric modeling and prediction.

Sudden stratospheric warming events can affect ionospheric conditions through their influence on atmospheric wave propagation and thermospheric dynamics. These events, occurring primarily during winter months, can produce ionospheric disturbances that persist for weeks, demonstrating the importance of whole-atmosphere coupling processes.

Artificial Intelligence and Machine Learning Applications
The application of artificial intelligence and machine learning techniques to ionospheric research has accelerated rapidly in recent years. These approaches offer the potential to identify complex patterns and relationships in ionospheric data that may not be apparent through traditional analysis methods.

Deep learning approaches using convolutional neural networks have been applied to ionospheric imaging and pattern recognition problems. These methods can automatically identify features in ionospheric maps and time series data, potentially improving our ability to detect and classify ionospheric disturbances.

Ensemble learning methods combine multiple prediction models to improve overall accuracy and reliability. These approaches can account for model uncertainties and provide confidence intervals for predictions, which is crucial for operational space weather applications.

Unsupervised learning techniques such as clustering and dimensionality reduction can identify hidden patterns and relationships in large ionospheric datasets. These methods can reveal new insights into ionospheric processes and help identify optimal combinations of parameters for prediction purposes.

Reinforcement learning approaches are being explored for adaptive control of ionospheric correction systems. These methods can learn optimal strategies for adjusting system parameters in response to changing ionospheric conditions, potentially improving the performance of navigation and communication systems.

Multi-Physics Coupling and System Science Approaches
The recognition that ionospheric processes are embedded within a complex system of coupled physical processes has led to increased emphasis on multi-physics modeling approaches. These models attempt to capture the full range of interactions between different components of the Earth system, from the lower atmosphere to the magnetosphere.

Coupled atmosphere-ionosphere-magnetosphere models represent the current state-of-the-art in comprehensive space weather modeling. These models solve the coupled equations describing neutral atmosphere dynamics, ionospheric physics, and magnetospheric processes, providing a self-consistent description of the entire system.

Data-driven approaches using large datasets from multiple sources are being developed to identify system-level patterns and relationships. These approaches can reveal coupling mechanisms that may not be apparent from individual datasets or traditional analysis methods.

Network science approaches are being applied to understand the connectivity and information flow within the ionospheric system. These methods can identify critical nodes and pathways that control system behavior, potentially leading to improved prediction capabilities.

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Complexity science approaches recognize that ionospheric behavior may exhibit emergent properties that arise from the interactions between multiple simpler processes. Understanding these emergent behaviors is crucial for predicting system response to perturbations and for developing effective mitigation strategies.

VIII. CONCLUSIONS AND FUTURE OUTLOOK

The past 25 years of ionospheric research over the Indian region have yielded fundamental insights into equatorial and low-latitude ionospheric processes. Key achievements include comprehensive characterization of TEC variations across multiple solar cycles, detailed understanding of ESF and plasma bubble phenomena, and significant advances in space weather impact assessment. The establishment of sophisticated monitoring networks and development of regional ionospheric models have enhanced our predictive capabilities and improved space weather services.

The systematic study of ionospheric behavior over the Indian region has revealed several distinctive characteristics that distinguish this sector from other global regions. The unique combination of magnetic field geometry, geographic features, and atmospheric dynamics creates complex patterns of ionospheric variability that require specialized modeling approaches. The longitudinal variations in TEC and plasma bubble activity, the seasonal asymmetries in ionospheric parameters, and the distinctive responses to geomagnetic disturbances all represent important contributions to global ionospheric understanding.
The technological advances achieved during this period have been remarkable, transitioning from sparse observational networks to comprehensive monitoring systems capable of real-time space weather assessment. The development of GPS-based ionospheric monitoring has been particularly transformative, enabling continuous measurement of ionospheric conditions with unprecedented spatial and temporal resolution. The integration of multiple measurement techniques has provided new insights into the complex three-dimensional structure and dynamics of ionospheric irregularities.

The impact of space weather on technological systems has become increasingly apparent as society's dependence on satellite-based services has grown. The vulnerability of GPS navigation and satellite communication systems to ionospheric disturbances has motivated significant investment in understanding and mitigating these effects. The development of space weather services tailored for the Indian region represents an important practical application of scientific research to societal needs.

Looking toward the future, several challenges and opportunities emerge. The increasing complexity of the space environment, driven by growing satellite populations and space debris, requires enhanced monitoring and modeling capabilities. The planned deployment of mega-constellations of satellites will create new challenges for space weather assessment and prediction, as these systems will be exposed to ionospheric effects across a wide range of altitudes and orbital parameters.

Climate change effects on the upper atmosphere represent a new frontier requiring long-term observational programs and sophisticated modeling approaches. The potential for systematic changes in thermospheric and ionospheric properties due to increasing greenhouse gas concentrations could affect the reliability of empirical models based on historical data. Understanding these changes will be crucial for maintaining accurate space weather prediction capabilities in a changing climate.

The development of operational space weather prediction systems tailored for Indian longitude sector applications remains a priority for protecting technological infrastructure and ensuring reliable satellite-based services. These systems must incorporate the unique characteristics of the Indian region while maintaining compatibility with global space weather services. The integration of artificial intelligence and machine learning techniques offers promising approaches for improving prediction accuracy and system performance.

The Indian region will continue to serve as a natural laboratory for ionospheric research, with unique geophysical characteristics providing insights applicable to global understanding of ionosphere-magnetosphere-thermosphere coupling processes. The proximity to the magnetic equator, the complex magnetic field geometry, and the distinctive atmospheric dynamics create opportunities for studying fundamental physical processes under conditions that cannot be replicated elsewhere.

Continued investment in observational infrastructure will be essential for maintaining and improving our understanding of ionospheric processes. The planned Aditya-L1 mission represents an important step toward enhanced space weather monitoring capabilities, while continued development of ground-based networks will provide the foundation for long-term trend analysis and process studies.

International collaboration will remain crucial for advancing ionospheric research and space weather services. The Indian space weather community has established strong partnerships with international organizations and research institutions, contributing regional expertise while benefiting from global knowledge and resources. These collaborations will be

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essential for addressing the complex challenges of space weather prediction in an increasingly interconnected world.

The integration of ionospheric research with broader Earth system science approaches offers new opportunities for understanding the role of the ionosphere within the global climate system. The recognition that ionospheric processes are connected to atmospheric dynamics, ocean circulation, and terrestrial weather patterns opens new avenues for interdisciplinary research and collaborative investigations.

Education and workforce development will be critical for ensuring the continued advancement of ionospheric research and space weather services. The complexity of modern ionospheric research requires interdisciplinary expertise spanning physics, mathematics, computer science, and engineering. Developing educational programs that can train the next generation of ionospheric researchers and space weather professionals will be essential for maintaining research capabilities and operational services.

The societal relevance of ionospheric research continues to grow as our dependence on space-based technologies increases. Understanding and predicting ionospheric behavior is no longer purely a scientific pursuit but has become essential for maintaining the technological infrastructure that supports modern society. The Indian region, with its unique characteristics and growing technological capabilities, will continue to play a crucial role in advancing our understanding of ionospheric processes and their impacts on human activities.

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Open Research Section
Data Availability Statement
GPS TEC data are available from the International GNSS Service (https://igs.org/). Ionosonde data can be accessed through Digital Ionogram Database (https://giro.uml.edu/). Geomagnetic indices are provided by the International Service of Geomagnetic Indices (https://isgi.unistra.fr/). Solar activity data are available from the NOAA Space Weather Prediction Center (https://www.swpc.noaa.gov/) and the Royal Observatory of Belgium (https://www.sidc.be/).

Software Availability
Data analysis was performed using MATLAB R2024a.
Conflict of Interest Statement
The authors declare no conflicts of interest related to this research.
Ethics declaration: Not applicable.

REFERENCES

1. Barad, R. K., S. Sripathi, R. Singh, B. Gayathri, et al. (2025), Observations and modeling investigations of ionospheric response to 23-24 April 2023, G4-class geomagnetic storm over Indian sector, Space Weather, doi:10.1029/2024SW004253.
2. Bhardwaj, A., T. K. Pant, R. K. Choudhary, D. Nandy, et al. (2016), Space weather research: Indian perspective, Space Weather, 14, 1-12, doi:10.1002/2016SW001521.
3. Choudhary, R. K., K. M. Ambili, C. Vineeth, A. Potdar, et al. (2025), Indian Network for Space Weather Impact Monitoring (InSWIM): An initiative to observe and model the low latitude ionosphere over the Indian longitudes, Advances in Space Research, 75, 1-15, doi:10.1016/j.asr.2024.11.047.
4. Dabbakuti, J. R. K. K., R. Peesapati, S. K. Panda, and S. Thummala (2021), Modeling and analysis of ionospheric TEC variability from GPS-TEC measurements using SSA model during 24th solar cycle, Acta Astronautica, 178, 24-35, doi:10.1016/j.actaastro.2020.08.034.
5. Demyanov, V. V., and Y. V. Yasyukevich (2021), Space weather: Risk factors for global navigation satellite systems, Solar-Terrestrial Physics, 7(2), 28-47, doi:10.12737/stp-72202104.
6. Rajput, M., P. R. Shreedevi, R. K. Choudhary, et al. (2024), Exploring ionospheric plasma density trends in the Indian equatorial crest region under varying solar activity conditions, Journal of Atmospheric and Solar-Terrestrial Physics, 253, 106154, doi:10.1016/j.jastp.2024.106154.
7. Rama Rao, P. V. S., S. Gopi Krishna, et al. (2009), Geomagnetic storm effects on GPS based navigation, Annales Geophysicae, 27, 2101-2110, doi:10.5194/angeo-27-2101-2009.
8. Ramsingh, S., S. Sripathi, S. Sreekumar, et al. (2015), Low-latitude ionosphere response to super geomagnetic storm of 17/18 March 2015: Results from a chain of ground-based observations over Indian sector, Journal of Geophysical Research: Space Physics, 120, 10,864-10,882, doi:10.1002/2015JA021509.
9. Ranjan, A. K., M. V. Sunil Krishna, et al. (2023), Variability of Ionosphere Over Indian Longitudes to a Variety of Space Weather Events During December 2006, Space Weather, 21, e2023SW003595, doi:10.1029/2023SW003595.

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10. Rao, S. S., M. Chakraborty, S. Kumar, and A. K. Singh (2019), Low-latitude ionospheric response from GPS, IRI and TIE-GCM TEC to Solar Cycle 24, Astrophysics and Space Science, 364, 216, doi:10.1007/s10509-019-3701-2.
11. Sekar, R., and D. Chakrabarty (2011), A review of the recent advances in the investigation of equatorial spread F and space weather effects over Indian sector using optical and other techniques, in Aeronomy of the Earth's Atmosphere and Ionosphere, pp. 259-280, Springer, doi:10.1007/978-94-007-0326-1_18.
12. Thokuluwa, R. (2025), Generation of enigmatic equatorial ionospheric plasma blobs during the 17 March 2015 super geomagnetic storm period over the Indian region, Scientific Reports, 15, 627, doi:10.1038/s41598-025-00627-w.

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