

A review of the climatology features and mid- and high-latitude forcing of the equatorial electrojet

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Key Points:

- The equatorial electrojet (EEJ) exhibits pronounced local time and longitudinal variations primarily controlled by E-region conductivity, atmospheric tides, and geomagnetic field geometry.
- Mid- and high-latitude forcing, together with solar activity, can significantly modulate EEJ intensity and even reverse its direction.
- Current EEJ models reproduce typical climatological features but remain limited under disturbed conditions.

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Abstract: The equatorial electrojet (EEJ) is a narrow eastward current that flows in the daytime equatorial E region. It is an important part of low-latitude ionospheric electrodynamics. This review presents a synthesis of recent advances in EEJ research. The main topics include historical observations, observation and inversion methods, local time and longitudinal variations, mid- and high-latitude forcing, solar activity forcing, and EEJ models. Ground-based and satellite observations show clear local time and longitudinal variations of the EEJ. These variations are mainly controlled by E-region conductivity, atmospheric tides, and geomagnetic field geometry. Among these factors, nonmigrating tides play a dominant role in the longitudinal pattern. Under disturbed conditions, mid- and high-latitude processes, such as geomagnetic storms, substorms, sudden changes in solar wind dynamic pressure, sudden stratospheric warming events, and subauroral polarization streams, can substantially modify the EEJ intensity and even reverse its direction through coupling processes. In addition, solar activity, including solar flares and solar eclipses, can modulate the EEJ primarily through rapid changes in ionospheric conductivity and associated electrodynamic adjustments. Although physics-based electrodynamic models, data-driven empirical models, and global numerical simulations have provided valuable insights across different scales, their quantitative consistency and capability of reproducing EEJ disturbances remain limited. This review points out several open issues. These include the combined effects of different driving factors, the nonlinear response of the EEJ, and the lack of reliable EEJ models during disturbed conditions. Finally, future studies should focus on combined observations, improved coupling models, and prediction of EEJ variability.

Keywords: equatorial electrojet; local time; longitudinal variations; mid- and high-latitude forcing

1. Historical Observations

The equatorial electrojet (EEJ) refers to a strong east–west current system flowing in the ionospheric E region near the dip equator (Gouin, 1962). Its main characteristics are primarily governed by the geomagnetic field geometry and equatorial ionospheric electrodynamic processes (Yamazaki and Maute, 2017; Lühr et al., 2021). In space, the EEJ is strongly confined. Vertically, it is concentrated in the central E region at altitudes of ~105–110 km. Latitudinally, it is limited to within approximately $\pm 3^\circ$ magnetic latitude, which corresponds to a width of ~600 km. Longitudinally, it extends along the dip equator. The current density typically reaches its maximum near an altitude of ~108 km. The formation of the EEJ arises from the combined effects of anisotropic iono-

spheric conductivity and charge separation processes. Near the dip equator, the geomagnetic field is nearly horizontal and oriented northward. This geometry interacts with the daytime ionospheric field produced by solar radiation. Solar ultraviolet radiation produces abundant ions and electrons in the E region, forming a conductive layer. The horizontal geomagnetic field suppresses vertical Hall currents, leading to charge accumulation at the upper and lower boundaries of the E region. This charge separation establishes an additional upward polarization electric field, which substantially enhances the effective zonal conductivity, commonly referred to as the Cowling conductivity (Cowling and Borger, 1948). As a consequence, the EEJ attains current densities that are significantly larger than those associated with the mid-latitude solar quiet (Sq) current system, making it one of the most pronounced electromagnetic phenomena in the low-latitude ionosphere (Chapman, 1951). Under quiet daytime conditions, the EEJ is generally directed eastward and is driven by the zonal electric field generated by the E-region wind dynamo (Heelis, 2004). However, during dawn and dusk or under geomag-

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netic disturbed conditions, the EEJ may reverse its direction, forming a westward counter-electrojet (CEJ; [Gouin and Mayaud, 1967](#)). This change in current direction makes the EEJ a sensitive indicator of ionosphere–magnetosphere coupling.

Study of the EEJ began with investigations of anomalous geomagnetic variations and developed together with advances in observations and theory. A key milestone was the establishment of the Huancayo geomagnetic observatory in Peru by the Carnegie Institution of Washington between 1919 and 1921, which addressed a critical lack of observations in the southern hemisphere. Situated nearly beneath the dip equator (magnetic latitude 0.59°S), Huancayo later became central to the identification of equatorial geomagnetic anomalies. Early observations in 1922 revealed that the diurnal variation of the horizontal magnetic field (H component) at Huancayo exhibited an unusually large amplitude compared with other stations at similar latitudes. This enhancement occurred exclusively during daytime and vanished at night. Initially, the anomaly was attributed to local crustal effects or instrumental issues. These unusual diurnal variations were formally reported in early studies by [Bartels and Johnston \(1940\)](#). Later, [Egedal \(1947, 1948\)](#) analyzed geomagnetic observational data from multiple stations near the dip equator and demonstrated that the anomalous diurnal variation of the H component was confined to a narrow zone approximately $\pm 2.5^\circ$ around the dip equator (corresponding to an estimated width of ~ 300 km). This result showed that the geomagnetic anomaly was related to intense electric currents flowing in a narrow region above the dip equator, which provided a crucial observational foundation for understanding the equatorial geomagnetic variations ([Egedal, 1947, 1948](#)). [Chapman \(1951\)](#) subsequently coined the term “equatorial electrojet” for this current system. He characterized it as an intense eastward current that flows in the E region along the dip equator, marking the transition of the EEJ from a geomagnetic anomaly to a distinct scientific phenomenon.

During the International Geophysical Year in 1958, new equatorial observatories, such as the Entoto Observatory and Space Science Research Center (EORC) in Addis Ababa, Ethiopia, and the Equatorial Geophysical Research Laboratory (EGRL) in Tirunelveli, India, provided additional evidence supporting Chapman’s theoretical predictions. These observations led to widespread international acceptance of the physical interpretation of the EEJ. In the 1980s, comprehensive review studies by [Forbes \(1981\)](#) and [Rastogi \(1989\)](#) combined ground-based magnetometer data with rocket and early satellite measurements. These works systematically summarized the key climatological features of the EEJ. They showed that the EEJ is a pronounced daytime enhancement with a noontime maximum, disappearance during dawn and dusk, and seasonal dependence with equinoctial maxima. They also suggested a potential coupling between the EEJ and atmospheric tides, laying the groundwork for subsequent dynamical investigations.

Since then, advances in observational techniques have allowed more detailed studies of the EEJ. These techniques include dense ground magnetometer networks, rocket experiments, radar observations, and satellite missions. As a result, the dependence

of the EEJ on local time, longitude, season, and solar activity has been better described. These observations provide important constraints for theoretical models and have greatly improved our understanding of low-latitude ionospheric electrodynamics.

2. Observation and Inversion Methods of the EEJ

The strength and structure of the EEJ exhibit pronounced spatial and temporal variability. These variations reflect both ionosphere–magnetosphere coupling and modulation by atmospheric tides. Accurate measurement of the EEJ current density, spatial structure, and temporal evolution requires multiple observational techniques and robust inversion methods. This section reviews ground-based and satellite-based observations. It explains the main principles, key inversion methods, and representative applications. It also shows how these complementary observations allow quantitative study of the EEJ.

2.1 Ground-based Observations

Ground-based geomagnetic observations are the most basic method for studying the EEJ. By recording magnetic field perturbations induced by the EEJ with ground magnetometers and inferring current characteristics through electromagnetic induction theory, this method offers clear advantages in terms of long-term continuity, stability, and cost effectiveness. Since the early discovery of anomalous daytime variations in the northward magnetic field component at Huancayo, Peru, in the 1920s, ground-based EEJ observation measurements have become a standard observational method.

The EEJ signal is combined with other background magnetic contributions. These include the Sq current system, the main geomagnetic field, and disturbances originating from the magnetosphere. Consequently, effective signal separation represents a critical prerequisite for reliable EEJ inversion. The underlying principle relies on the distinct latitudinal dependence of the EEJ magnetic effect: the EEJ produces a pronounced enhancement of the magnetic field near the dip equator, which decays rapidly with increasing latitude, whereas large-scale current systems such as Sq exhibit relatively smooth spatial gradients at low latitudes ([Yamazaki and Maute, 2017](#)). The difference method uses this contrast by subtracting magnetic measurements at an off-equatorial station from those at an equatorial station. This process removes most background contributions and keeps the EEJ signal. Using observations from two magnetometers separated by roughly 6° – 9° magnetic latitude, [Rastogi and Klobuchar \(1990\)](#) showed that the daytime intensity of the EEJ can be reliably determined. Subsequent work by [Anderson et al. \(2002\)](#) further showed that measurements of the daytime EEJ over the west coast of South America are closely associated with the vertical $E \times B$ drift velocity in the ionospheric F region. [Figure 1](#) illustrates a schematic example of typical noontime latitudinal profiles of the magnetometer H component. A distinct enhancement of up to ~ 100 nT is observed near the dip equator and is superposed on the background Sq variation. By subtracting the H -component values recorded at a station located approximately 6° – 9° from the dip equator from those measured at the equatorial site, the resulting difference predominantly reflects the EEJ contribution. This

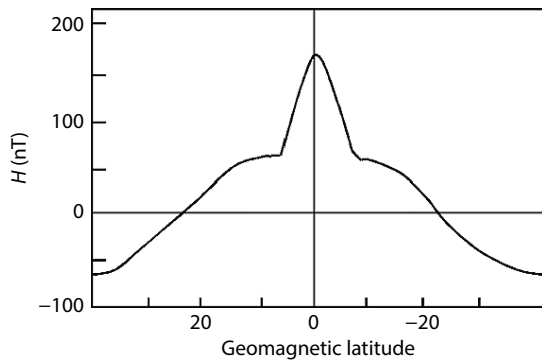


Figure 1. Schematic illustration of the typical latitudinal distribution of the noontime geomagnetic H -component observations. From Anderson et al. (2002).

simple and robust method has been widely applied to investigations of EEJ climatology, seasonal changes, solar-cycle effects, and long-term evolution.

In addition to magnetometers, ground-based radar systems provide information about EEJ electrodynamics. They measure the zonal plasma velocities of E-region electrons through coherent scatter. The physical basis of this approach lies in the control of electrojet plasma-wave phase speeds by the $E \times B$ drift of electrons, in which the vertically polarized electric field is dynamically coupled with the zonal electric field component. Early radar studies primarily utilized single-instrument systems, such as incoherent scatter radars, but their limited temporal coverage, high operational costs, and instrumental complexity restricted long-term EEJ monitoring (Farley, 1985). A major methodological advance was pioneered by Hysell and Burcham (2000), who introduced oblique-incidence and interferometric techniques using the Jicamarca Unattended Long-term investigations of the Ionosphere and Atmosphere (JULIA) radar at Jicamarca, Peru. These methods allow quantitative measurement of EEJ electric fields. The oblique-incidence method reduces neutral wind effects but has low vertical resolution. Interferometry provides vertical resolution but is sensitive to wind variations. Using both methods together gives complementary information. This combined method has guided the design of later ground-based radar studies.

Ground-based systems, including magnetometers and radars, allow continuous monitoring of EEJ variations over local times, seasons, and levels of solar activity. Their limitations include restricted spatial coverage, poor vertical resolution, and susceptibility to local interference. These limits prevent full observation of the global and height-dependent EEJ structure (Yamazaki and Maute, 2017).

2.2 Satellite Observations

Ground-based methods provide precise measurements of local EEJ variability but are inherently limited in spatial coverage. Low-Earth-orbit (LEO) satellite missions overcome this limitation by providing near-global EEJ measurements with onboard magnetometers, which are essential for characterizing its large-scale structure and longitudinal variability. Unlike ground-based measurements at fixed altitudes, satellites measure at varying

heights. Accordingly, EEJ signatures from space are more appropriately interpreted in terms of E-region current density profiles rather than magnetic perturbations alone.

Satellite-based EEJ estimation relies on inversion techniques that relate observed magnetic field residuals to ionospheric current systems. A key methodological challenge in satellite-based EEJ studies is the separation of Sq and EEJ signals. Because Sq amplitudes are much smaller than the main geomagnetic field, uncertainties in main field models and partial wavelength overlap introduce baseline ambiguities (Olsen and Stolle, 2012). In practice, Sq–EEJ separation is commonly achieved through large-scale empirical curve fitting of low- and mid-latitude magnetic residuals, yielding a stable baseline despite its limited physical interpretability. As shown in Figure 2, the black curve represents the residual geomagnetic field obtained by subtracting the main geomagnetic field model from the original data, whereas the gray curve represents the fitting result of the large-scale field. This gray curve separates the contributions of Sq and EEJ, providing a baseline for the EEJ field. Because of the small influence of the main geomagnetic field model on the difference between the black curve and the gray curve, the EEJ field obtained from this inversion has strong robustness in selecting the main geomagnetic field model. This approach has been widely adopted and shown to be robust across different main field models (e.g., Lühr et al., 2004; Manoj et al., 2006; Maus et al., 2007; Alken et al., 2015).

Satellite-based EEJ inversions were primarily based on simplified equivalent current representations, most commonly using idealized line currents or narrow currents placed in the E region. These models assume predominantly zonal current flow and have been successfully used to study EEJ signatures (e.g., Jadhav et al., 2002; Ritter et al., 2003; Lühr et al., 2004). Subsequent studies expanded this approach by introducing closed current loops encircling the Earth and aligned with contours of constant quasi-dipole latitude, thereby providing a more physically realistic representation of ionospheric current flow for extracting EEJ signatures from Swarm satellite observations (e.g., Alken et al., 2013, 2015). In addition, the spherical elementary current systems (SECS) method is used to extract EEJ signals from magnetic data (Vanhamäki et al., 2020). More recently, Alken and Egbert (2025) introduced the Loop Principal Components Analysis (LoopPCA) approach. In this method,

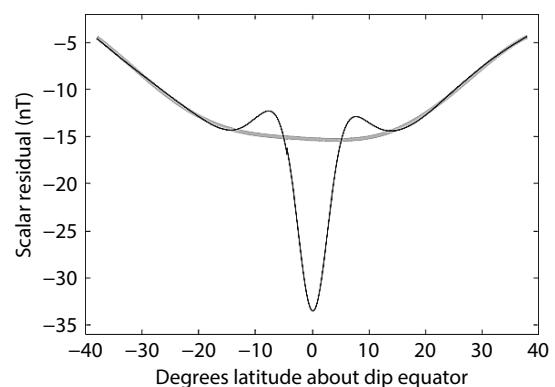


Figure 2. Schematic illustration of Sq–EEJ separation in the satellite magnetic field observations. From Lühr et al. (2004).

the electrojet current system is represented as a superposition of current loops confined to the E region in quasi-dipole coordinates. Principal components analysis (PCA) is used to identify a small number of dominant modes that capture the large-scale toroidal current structure of the EEJ, providing a more flexible and physically consistent framework for satellite-based EEJ inversion. Compared with the line current model and SECS method, the LoopPCA method has achieved significant improvements. The LoopPCA method abandons the idealized assumptions of traditional models, such as pure zonal current and uniform distribution. Instead, the constraint conditions of the current loops are strictly consistent with the observed characteristics of the EEJ (altitude, latitude range, geomagnetic field coupling relationship), making the inversion results more in line with the physical processes of ionospheric electrodynamics. Through the combination of dominant modes based on the linear superposition of current loops, the LoopPCA method can simultaneously characterize the large-scale structure and small- to medium-scale disturbances of the EEJ.

Since the Polar Orbiting Geophysical Observatory (POGO) missions, multiple satellites have advanced EEJ research. Analyses of POGO data first revealed longitudinal variations in EEJ intensity (Cain and Sweeney, 1972), although limited sampling precluded the separation of seasonal and local time effects. The Ørsted mission provided improved magnetic precision, enabling robust identification of the EEJ longitudinal structure and local time dependence under geomagnetic quiet conditions (Jadhav et al., 2002; Ivers et al., 2003). The Challenging Minisatellite Payload (CHAMP) satellite, with its near-polar orbit and dense temporal sampling, further promotes systematic research on the EEJ. Using CHAMP data, Lühr et al. (2004) reconstructed the global distribution of EEJ peak current density and found significant seasonal and longitudinal variations. Subsequent studies combining CHAMP and ground-based magnetometer data analyzed the spatiotemporal characteristics of the noon EEJ after correcting for Sq contributions (Manoj et al., 2006). Alken and Maus (2010a) proposed a method to infer equatorial electric fields from the magnetic signature of the EEJ as observed by the CHAMP satellite as it crosses the dip equator. The Swarm mission further improved spatial resolution through multi-satellite gradient measurements. Alken et al. (2015) inverted Swarm scalar magnetic field data to derive the equatorial eastward electric field, with independent validation from JULIA radar and West African magnetometer networks. More recently, China Seismo-Electromagnetic Satellite (CSES) observations near 14:00 local time (LT) provided additional data support on longitudinal variability, confirming a dominant wave-4 longitudinal pattern attributed to nonmigrating atmospheric tides (Zhou YL et al., 2022). In addition, recent results based on Macau Science Satellite-1A (MSS1A) magnetic field observations further demonstrate that EEJ characteristics can also be reliably derived from this new satellite platform, providing an additional data source for EEJ studies (Huang YY et al., 2025; Rang XY et al., 2025).

3. Local Time Variations of the EEJ

Low-latitude ionospheric currents are strongly influenced by the

coupled effects of solar radiation and large-scale tidal-wind circulation in the upper atmosphere (Doumouya et al., 2003; Heelis, 2004). One of their most prominent characteristics is the pronounced local time dependence. The typical diurnal variation of the EEJ arises from the interaction between migrating tides and ionospheric conductivity variations. Typically, the EEJ flows eastward during daytime, has frequent reversals near dawn and dusk, and exhibits a pronounced weakening or disappearance at night. It is significantly enhanced during daytime (~07:00–18:00 LT) and typically reaches its maximum around local noon (11:00–13:00 LT). This basic pattern has consistently been confirmed by ground-based magnetometers, satellite missions, and radar measurements, which have provided complementary constraints on peak timing, current intensity, and CEJ occurrence (e.g., Jadhav et al., 2002; Doumouya et al., 2003; Ivers et al., 2003; Lühr et al., 2004; Alken and Maus, 2010b; Zhou YL et al., 2018). Beyond the typical daytime pattern, the EEJ exhibits markedly different behavior at night. Owing to the rapid decay of E-region electron density after sunset, the associated Cowling conductivity becomes negligible, effectively suppressing the formation of the EEJ. Therefore, the EEJ is generally much weaker during nighttime under quiet conditions, with weak westward currents along the dip equator (e.g., Forbes, 1981; Lühr et al., 2021). Accordingly, this review primarily focuses on the daytime behavior of the EEJ, when it is most prominent and dynamically significant.

The daytime enhancement of the EEJ is primarily controlled by solar-driven E-region ionization. After sunrise, photoionization rapidly increases electron density and conductivity, leading to a progressive intensification of the EEJ at dawn and a maximum near noon. Following sunset, the rapid decay of electron density reduces E-region conductivity, causing the EEJ to weaken sharply at dusk and become extremely weak at night. Although the diurnal variation is typically single peaked, both the phase and amplitude of the peak vary with season, solar activity, and longitude (Lühr et al., 2021). Physically, the EEJ diurnal behavior reflects the combined effects of E-region conductivity, electric fields, and neutral wind forcing. Photoionization sets the background conductivity, which is highly sensitive to the solar zenith angle and shifts with local sunrise and sunset times (Chandra et al., 2000). Near the dip equator, the nearly horizontal geomagnetic field enables strong Hall–Pedersen coupling and Cowling conductivity enhancement, allowing the EEJ to reach amplitudes several times larger than mid-latitude Sq currents (Cowling and Berger, 1948). Large-scale tidal winds act as the primary driver of low-latitude ionospheric currents, producing morning charge accumulation and evening depletion, to which the EEJ responds only during daytime because of negligible nighttime conductivity (Heelis, 2004). These tidal processes originate from the lower atmosphere and represent an important form of lower atmospheric forcing on the EEJ through upward coupling (e.g., Forbes, 2000; Hagan and Forbes, 2002; Forbes et al., 2003; Lühr et al., 2021; He YB et al. 2026). Neutral winds further modulate the local time evolution of the EEJ. Zonal winds regulate the magnitude and direction of the wind-driven electric field and thus control both EEJ intensity and current reversals, whereas vertical winds indirectly affect polarization electric fields, particularly during the

morning and evening transition periods, and can facilitate CEJ formation (e.g., Richmond, 1973; Forbes and Lindzen, 1976; Stolle et al., 2008; Zhang KD and Wang H, 2022). Figure 3 shows the zonally averaged local time variation of the EEJ for different seasons. The current is typically westward near 06:00 LT, turns eastward around 07:00 LT, increases rapidly to a peak near 11:00 LT, and vanishes after 18:00 LT. The noontime maximum is strongest during equinoxes and weakest during northern hemisphere summer, with a modest delay in the diurnal evolution around the summer solstice (Alken and Maus, 2010a).

In recent decades, more observations from ground magnetometers, LEO satellites, and radars have allowed detailed study of EEJ diurnal variations. These advances are critical for developing diurnal EEJ models and for improving our understanding of ionosphere–neutral atmosphere coupling processes. Ground-based observations were the earliest and remain one of the most effective tools for EEJ studies, as variations in the H component directly reflect current intensity near the dip equator. Typically, stations close to the dip equator record a gradual morning increase in the H component, reaching a maximum near local noon, with amplitudes ranging from several tens to more than 100 nT. By applying the differential method (ΔH) between equatorial and off-equatorial low-latitude stations, the Sq background can be largely removed, enabling robust measurements for long-term EEJ analyses. Using magnetic field data from 26 stations, Doumouya et al. (2003) developed an empirical EEJ model and showed that the current peaks near local noon and weakens to near zero at dawn and dusk. Subsequent studies linked these diurnal features to ionospheric electrodynamic processes (Lühr et al., 2008; Zhou YL et al., 2018). Bhattacharyya and Okpala (2015) applied PCA to quiet-day observations over India. They found that the first three modes could explain 96% of the EEJ variance. Principal component 1 dominates late morning with strong seasonal dependence, whereas principal component 2 controls afternoon variability with little seasonal change. Beyond intensity changes, the EEJ exhibits systematic vertical and latitudinal structural variations. Rocket magnetometer measurements indicate that the noontime EEJ current peaks at altitudes of ~ 107 – 110 km, whereas during morning CEJ phases, the peak descends to ~ 100 – 105 km and the latitu-

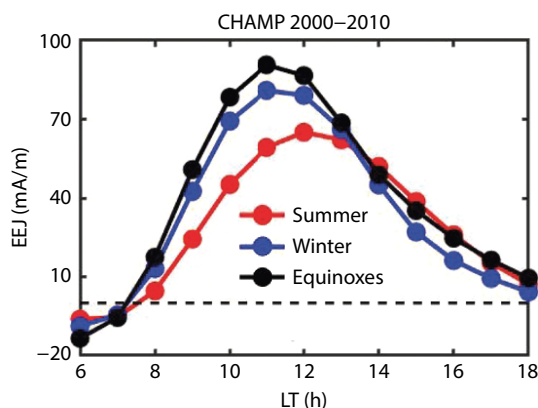


Figure 3. Typical diurnal patterns of the zonal-mean EEJ intensity during different seasons as observed by the CHAMP satellite. From Lühr et al. (2021).

dinal width narrows from ~ 600 km to ~ 500 km (Davis et al., 1967). Satellite observations have further advanced EEJ research by enabling global and multi-local-time coverage. Using Ørsted data from 1999–2000, Jadhav et al. (2002) showed that the globally averaged EEJ magnetic signature peaks at $\sim 11:30$ LT and weakens rapidly near dawn and dusk. Similarly, Lühr and Manoj (2013) found, based on a decade of CHAMP observations, that the EEJ is active primarily between 07:00 and 17:00 LT, with a maximum near 11:00 LT. Swarm observations further revealed a robust local time transition in the current direction (Alken et al., 2015). Figure 4 illustrates the EEJ magnetic signature at five key local times (06:30–17:00 LT) via satellite-measured residuals after removing interference fields. It shows that the early morning CEJ switches to an eastward EEJ after $\sim 07:00$ LT, with the current strength peaking around 11:00–12:00 LT and then decreasing. The figure also reflects signal differences among Swarm A, B, and C satellites due to orbital altitude variations. Compared with ground stations, satellites are better suited to resolving global local time structures, whereas ground observations remain superior for capturing short-term variability and individual CEJ events, highlighting their strong complementarity. Wang H et al. (2020) reported, based on the Thermosphere–Ionosphere–Electrodynamics General Circulation Model (TIEGCM), that the nonmigrating tides contribute significantly to the later local time peak of the EEJ in the Peruvian sector and favor the development of morning CEJs in the context of the International Geomagnetic Reference Field (IGRF).

In addition to the typical diurnal pattern, the EEJ exhibits anomalous behaviors that reflect complex internal coupling and external forcing. The CEJ is the most prominent of these, often associated with changes in neutral winds or electric field polarity, indicating efficient transmission of magnetospheric and thermospheric disturbances to low latitudes. Observations from CHAMP show that CEJ occurrence reaches $\sim 38\%$ near sunrise but drops below 4% around noon, consistent with local-time-dependent wind and tidal forcing (Zhou YL et al., 2018). Counter-electrojet intensity also increases with geomagnetic activity. A clear linear relationship exists between the a_p (planetary 3-hour geomagnetic activity) index and CEJ amplitude, with an increase of 2 nT in a_p corresponding to an enhancement of ~ 1 mA m^{-1} in peak current density (Figure 5a). This enhancement is strongly local time dependent: under moderate activity ($K_p = 2$ – 4), CEJ amplitudes increase mainly during the prenoon hours, whereas during highly disturbed conditions, large amplitudes also occur near noon (Figure 5b). These effects are attributed to westward electric fields driven by disturbance dynamo electric fields (DDEFs). During intense geomagnetic activity, disturbance winds persist to later local times and may remain westward for most of the day, further strengthening the CEJ (Xiong C et al., 2015).

4. Longitudinal Variations of the EEJ

As reviewed above, previous studies have established the typical diurnal behavior of the EEJ under quiet-time conditions, characterized by a rapid enhancement at dawn, a near-noon maximum, and a decay at dusk. However, after removing the effect of local time, extensive observations reveal that the EEJ is not uniform in longitude. At the same local time, its intensity, peak value, and

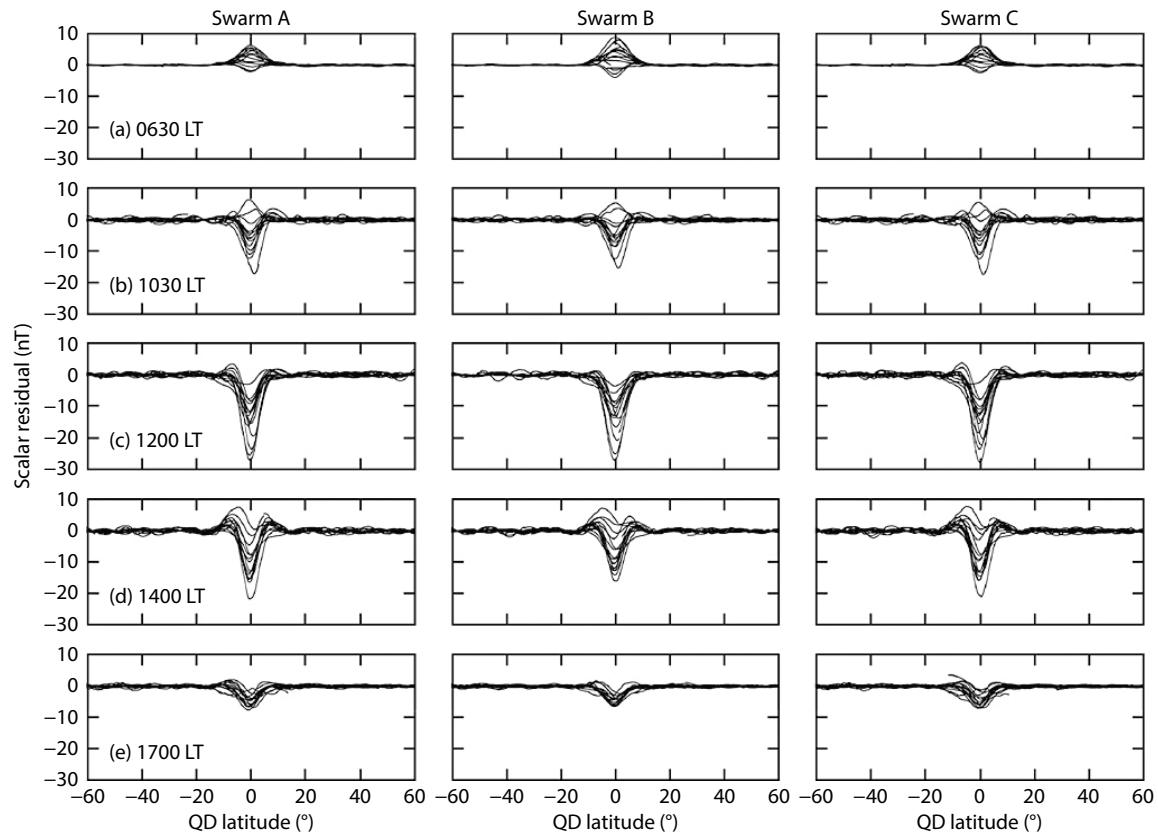


Figure 4. Scalar residual field after contributions from the main field, crustal sources, magnetosphere, and Sq currents, illustrated for five representative days in 2014. Local times are approximate, referring to dayside equator crossings. QD, quasi-dipole. From Alken et al. (2015).

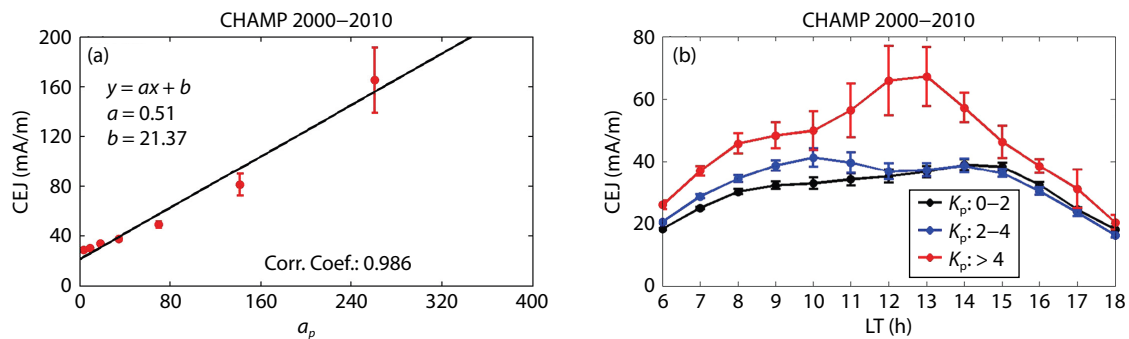


Figure 5. Relationship between the CEJ amplitude and geomagnetic activity. (a) Dependence of the CEJ amplitude on the a_p index. (b) Daily variation of the CEJ amplitude for three distinct geomagnetic activity levels. From Zhou YL et al. (2018).

even current direction can vary strongly with longitude. These longitudinal variations cannot be explained by solar illumination alone. Instead, they reflect the combined influence of longitudinal differences in ionospheric conductivity, nonmigrating atmospheric tides, and the geometry of the geomagnetic field. Consequently, investigating the longitudinal variations of the EEJ is essential for revealing the low-latitude ionospheric electrodynamics and establishing reliable space weather prediction systems.

On a global scale, the EEJ intensity shows multiple peaks, with the wave-4 longitudinal pattern being the most typical. Satellite-based observations from Ørsted, CHAMP, and Swarm consistently show four alternating regions of enhanced and weakened EEJ

intensity around the globe (e.g., England et al., 2006; Alken and Maus, 2007; Lühr et al., 2008). This wave-4 longitudinal pattern is robust in long-term averages and exhibits clear seasonal dependence. Results from the Equatorial Electrojet Model 2 (EEJM-2) further show that the longitude of peak EEJ current density changes with season while the wave-4 structure remains (Figure 6). Ground-based observations support these results. Using ΔH between equatorial and off-equatorial stations, Doumouya et al. (2003) found stronger EEJ intensity over South America and weaker values over the Indian sector, with secondary peaks over the Atlantic and West Africa. These longitudinal differences are inversely related to the strength of the main geomagnetic field at the dip equator. Although the exact ranking of longitude sectors

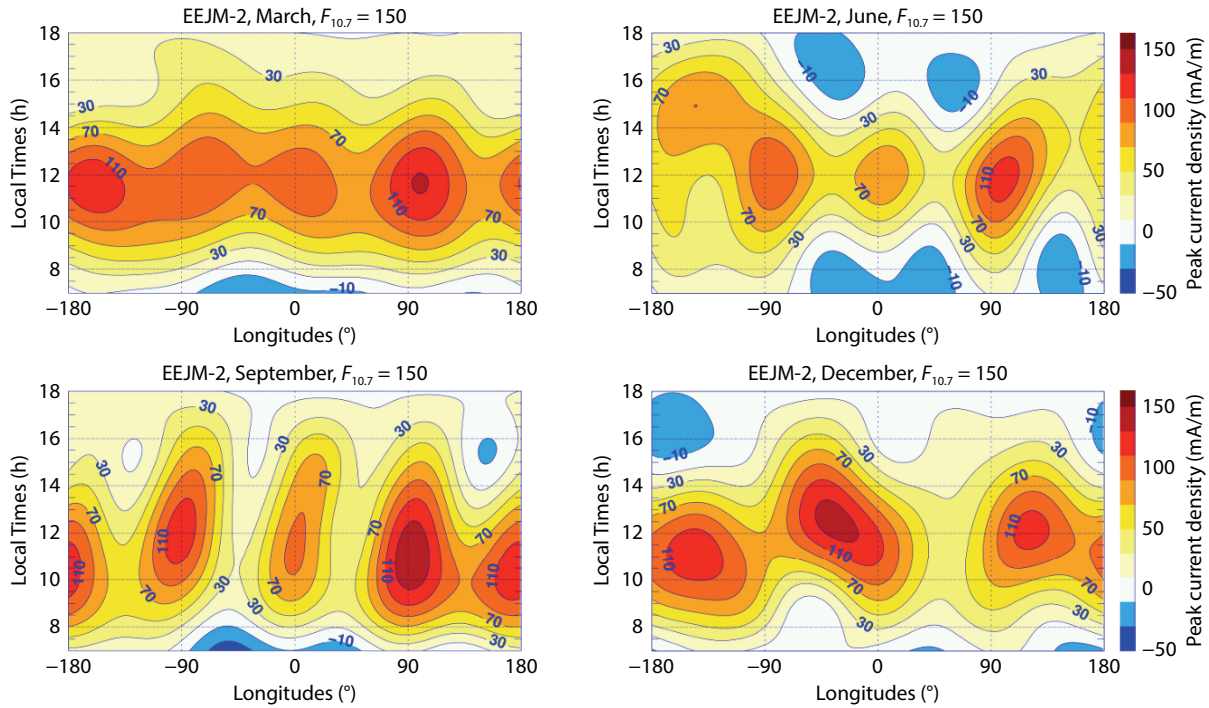


Figure 6. Schematic illustration of the seasonal longitudinal variations of EEJ intensity with respect to local time, based on the EEJ-M2. From Lühr and Manoj (2013).

varies with datasets, seasons, and solar activity levels, persistent longitudinal variation is a well-established feature of the EEJ.

Early studies initially linked the longitudinal variations of the EEJ to changes in ionospheric conductivity along longitude (Rastogi, 1962). However, subsequent observations demonstrated that conductivity variations alone cannot fully explain the observed longitudinal structure of the EEJ (Rastogi, 2006). Before the tidal origin of the EEJ longitudinal structure was firmly established, some studies proposed a possible role of atmospheric tidal modes (Jadhav et al., 2002). Subsequent studies demonstrated that nonmigrating atmospheric tides play a dominant role (e.g., Lühr et al., 2008; Wang H et al., 2020). Combined satellite observations and model studies showed that the wave-4 pattern of the EEJ, especially near the equinox, is closely linked to atmospheric tidal forcing (e.g., England et al., 2006; Alken and Maus, 2007). The diurnal eastward-propagating wavenumber-3 tide (DE3) has been identified as the dominant contributor to the wave-4 longitudinal structure of the EEJ, especially in late boreal summer when its effect peaks (Lühr et al., 2008). The DE3 tide originates from latent heat release by tropical tropospheric convection. It modulates zonal winds in the mesosphere and lower thermosphere, thereby affecting the ionospheric electric field that drives the longitudinal variations of the EEJ. Seasonal changes in the dominant tidal modes lead to corresponding changes in the longitudinal structure of the EEJ. The DE3 is the primary modulating component of the EEJ during August–September, contributing most of the wave-4 longitudinal variation, whereas SW4 and SW3 (semidiurnal westward-propagating wavenumber-4 and wavenumber-3 tides) dominate during December–January and May–June, leading to wave-2 and wave-1 longitudinal patterns, respectively (Lühr and Manoj, 2013). These seasonal transitions have consistently been

observed in Swarm and CHAMP datasets (Zhou YL et al., 2016; Singh et al., 2018). In addition to solar tides, lunar tides affect EEJ intensity. This influence mainly appears as a semidiurnal component. Long-term CHAMP observations show enhanced EEJ strength following new and full moons (Lühr et al., 2012). Both satellite and ground-based measurements indicate that the lunar tidal effect exhibits pronounced longitudinal dependence and is further modulated by season and solar activity (Yamazaki et al., 2017; Yizengaw and Carter, 2017).

Although global averages clearly show wavelike longitudinal patterns, they often hide regional differences. Detailed regional studies are therefore needed. Early ground-based measurements indicated that the diurnal variation of the EEJ was strongest over the American sector and weakest over the Indian sector. This contrast was initially explained by longitudinal differences in ionospheric ionization (Rastogi, 1962). Lühr et al. (2004) further linked EEJ longitudinal dependence to variations in the cross-sectional area of the Cowling channel. Shume et al. (2010) disclosed that because of the roles of atmospheric tides, the EEJ over the Pacific region (Peru) is stronger than that over the Atlantic region (Brazil). Using CHAMP data, Wang H et al. (2019) reported a significant negative correlation between the longitudinal variations in EEJ intensity and solar illumination (Figure 7), suggesting a compensatory role of meridional winds. These results indicate that the longitudinal variations in the EEJ arise from the coupled effects of atmospheric tides, ionospheric conductivity, and geomagnetic field geometry, with their relative contributions varying across different longitude sectors. Wang H et al. (2020) found that the nonmigrating tides amplify the disparity in peak intensity of the EEJ between the Peruvian and Indian stations. The tidal-forced TIEGCM reproduces the wave-4 pattern

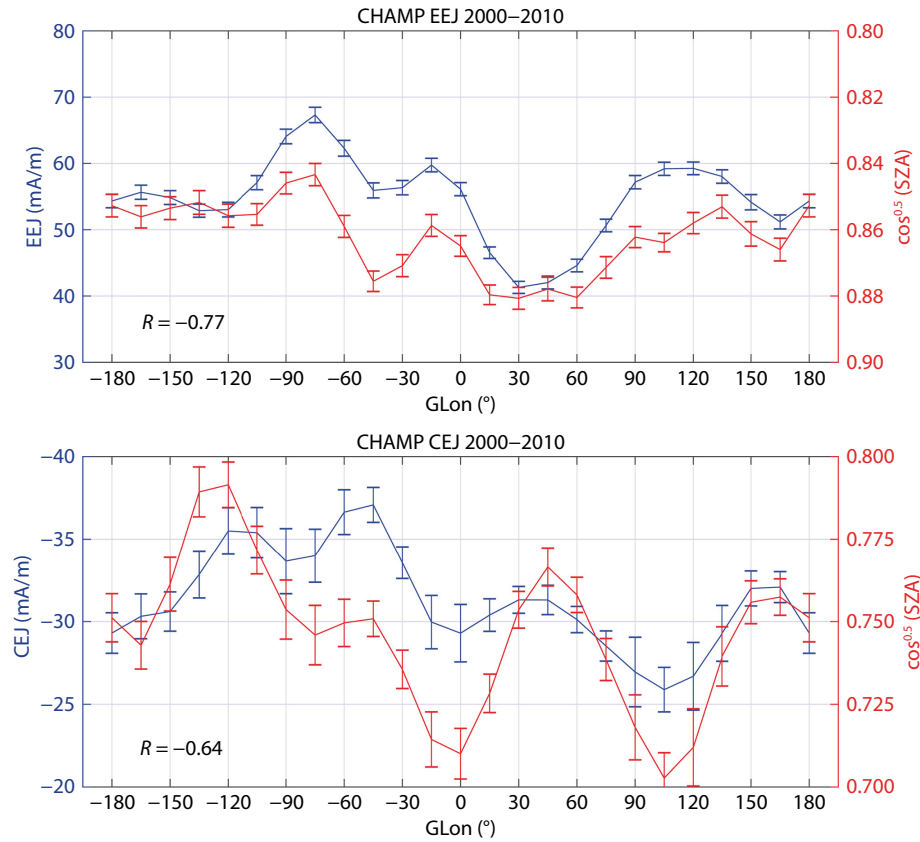


Figure 7. Geographic longitudinal (GLon) variations in the EEJ (top) and CEJ (bottom), along with the corresponding solar insolation effect, represented by $\cos^{0.5}(\text{SZA})$, where SZA is the solar zenith angle. Correlation coefficients are provided, and uncertainties in the binned averages are indicated by the vertical bars. From Wang H et al. (2019).

of the noontime EEJ but underestimates its peak in the East Asian sector, partly because the lower boundary forcing in that longitudinal region is inadequate.

From extensive ground-based and satellite observations, together with numerical model simulations, the dominant longitudinal characteristics of the EEJ can be reasonably well reproduced. It should be emphasized, however, that although the longitudinal pattern under geomagnetic quiet conditions is primarily controlled by nonmigrating atmospheric tides, ionospheric conductivity distributions, and geomagnetic field geometry, it does not remain stationary during disturbed periods. High-latitude forcing processes, including geomagnetic storms, substorms, a sudden change in solar wind dynamic pressure (P_{dyn}), sudden stratospheric warmings (SSWs), and subauroral polarization streams (SAPSs), can modify equatorial ionospheric electric fields, thereby altering EEJ intensity or even triggering a CEJ. The resulting longitudinal responses are often highly uneven. These effects are discussed in the following sections, with a particular focus on the evolution of the EEJ under high-latitude forcing and the related coupling processes.

5. Mid- and High-Latitude Forcing

The EEJ is controlled not only by atmospheric tides and geomagnetic field geometry, but also by strong electric field disturbances and energy input from high latitudes. Extensive observational and

modeling studies have demonstrated that high-latitude electric fields and current systems can rapidly modify the equatorial electric field. This coupling occurs through magnetic field line mapping, ionosphere–magnetosphere coupling, and polar energy deposition. As a result, the intensity of the EEJ can change rapidly and may even reverse direction (e.g., Xiong C et al., 2016; Wang H et al., 2019; Le G et al., 2024; Zhang KD et al., 2024b; Cheng QH et al., 2025). During space weather disturbances, the EEJ often exhibits pronounced perturbations, with changes in magnitude and even a reversal in direction. These responses indicate that the equatorial ionosphere is highly sensitive to high-latitude forcing. Therefore, understanding the mechanisms by which high-latitude processes influence the EEJ is essential for clarifying global ionospheric electrodynamics coupling.

Under geomagnetic quiet conditions, the EEJ is primarily established by the combined effects of E-region neutral winds driven by atmospheric tides and the background ionospheric conductivity, leading to a relatively stable diurnal pattern (England et al., 2006). Under geomagnetic disturbed conditions, however, the equatorial ionospheric electric fields and currents can deviate substantially from their quiet-time behavior (Fuller-Rowell et al., 2002). High-latitude forcing introduces disturbed electric fields at low latitudes mainly through two distinct processes. One is the prompt penetration electric field (PPEF), which arises from the rapid transmission of high-latitude convection electric fields to

low latitudes and is characterized by short-lived, transient disturbances (Nishida, 1968). The other is the DDEF, generated by storm-time thermospheric winds driven by enhanced Joule heating and ion drag, which operates on longer timescales and exhibits delayed responses (Blanc and Richmond, 1980). At equatorial latitudes, the PPEF and DDEF can reach similar amplitudes. They can enhance, weaken, or reverse the EEJ and can reorganize the low-latitude electrodynamic system (e.g., Richmond et al., 2003; Maruyama et al., 2005).

Geomagnetic storms are among the most important high-latitude drivers of EEJ variability. Notably, most intense geomagnetic storms are driven by solar storm activities, such as coronal mass ejections and high-speed solar wind streams, which inject energetic plasma and magnetic disturbances into the near-Earth space environment and serve as an important external forcing of EEJ variability. During storm periods, prolonged southward interplanetary magnetic field (IMF) conditions enable efficient energy transfer from the solar wind into the magnetosphere through enhanced magnetic reconnection. The intensification of magnetospheric convection disrupts the balance between region-1 (R1) and region-2 (R2) field-aligned currents (FACs), allowing convection electric fields to penetrate rapidly to low latitudes as PPEFs (Kikuchi et al., 2008). Figure 8a provides a schematic representation of ionospheric-equivalent currents associated with the PPEF during the southward IMF period. When the IMF B_z turns southward, R1 FACs are stronger than R2 FACs, and this imbalance leads to the penetration of the PPEF into low latitudes, represented by the red curve with arrows. In addition, storm-time Joule heating and ion drag at high latitudes drive strong equatorward thermospheric winds, which are deflected westward by the Coriolis force during their equatorward propagation. Through the disturbance dynamo process, these winds generate westward electric fields on the dayside that oppose the quiet-time eastward field (Blanc and Richmond, 1980; Heelis, 2004). Owing to the relatively slow decay of the disturbed circulation, the DDEF can persist from several hours to several days (Richmond et al., 2003). Observational studies

have demonstrated that the PPEF and DDEF play different roles in storm-time EEJ variability. Using Swarm satellite observations, Astafyeva et al. (2016) showed that PPEFs are the dominant driver of the eastward enhancement of the EEJ during the storm initial phase and at the onset of the main phase. In contrast, Yamazaki and Kosch (2015) found, based on long-term ground magnetometer data from the Indian and Peruvian sectors, that storm-time westward EEJ disturbances are mainly controlled by DDEFs and exhibit pronounced longitudinal dependence. Li QL et al. (2022) further revealed a multi-stage storm response of the EEJ, with westward perturbations dominating during the early recovery phase, followed by sustained eastward enhancement at later stages, both showing clear longitudinal differences. Collectively, these studies indicate that PPEFs dominate the rapid, transient response of the EEJ, whereas DDEFs govern its longer term evolution (e.g., Richmond et al., 2003; Xiong C et al., 2015; Kuai JW et al., 2016; Yizengaw et al., 2016; Pandey et al., 2018).

Substorms, which are associated with localized and rapid energy release in the magnetotail, can also induce significant disturbances in the EEJ (e.g., Kamide et al., 1998; Ebihara et al., 2014). During substorms, overshielding conditions frequently develop at high latitudes. When R1 FACs weaken, the imbalance between the R1 and R2 FACs allows the shielding electric field to become dominant. This shielding field can map to the middle and low latitudes, leading to a weakening or even reversal of the daytime ionospheric electric field (e.g., Kelley et al., 1979; Kikuchi et al., 2000). Wei Y et al. (2009) reported that substorms are often accompanied by westward ionospheric electric fields. These fields result from an overshielding state dominated by enhanced R2 FACs, rather than from IMF northward turning. Wang H et al. (2019) demonstrated that events of both CEJ and high-latitude FACs, when R2 FACs are stronger than R1 FACs, occur more frequently during periods of IMF B_z northward turning and the recovery phase of substorms. Because of strong Cowling conductivity at the dip equator, even small changes in the zonal electric field can strongly weaken or reverse the EEJ (Huang CS, 2020). In contrast, when the IMF

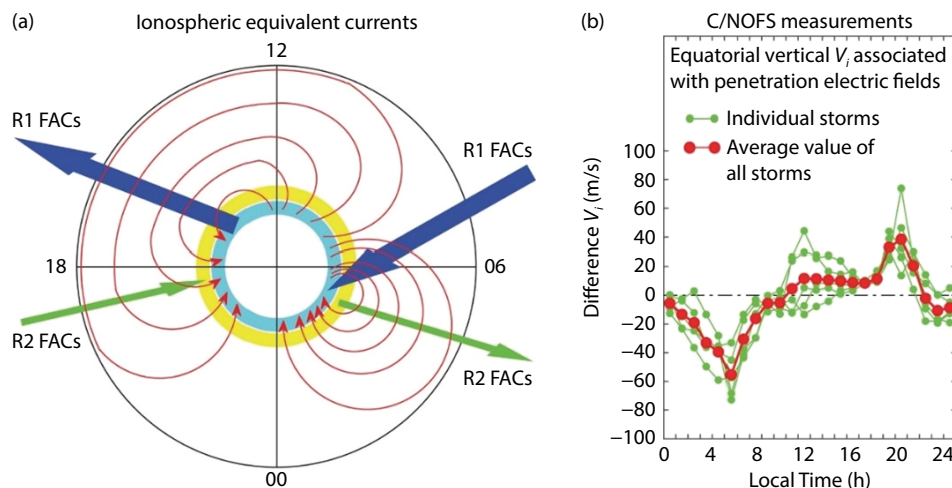


Figure 8. Schematic illustration of ionospheric responses to penetration electric fields. (a) Ionospheric equivalent currents (red curves with arrows) and the associated FACs. (b) Local time variation in equatorial vertical ion drifts observed by the C/NOFS (Communications/Navigation Outage Forecasting System) satellite during geomagnetic storms. From Huang CS (2019).

remains steadily southward, enhanced magnetospheric convection can lead to the penetration of eastward electric fields into the dayside equatorial ionosphere, driving the enhancement of the EEJ (Huang CS, 2009, 2012). Yamazaki and Kosch (2015) showed that EEJ perturbations at substorm onset are initially dominated by eastward electric fields associated with rapid penetration of the dawn–dusk convection electric field. Within approximately one hour, this enhancement typically decays, and westward disturbances become dominant because of the combined effects of developing shielding electric fields and disturbance dynamo processes. During substorms, the neutral winds could also be disturbed and could have an obvious universal time dependence (Wang H et al., 2017). These disturbed winds can propagate to low latitudes and further modify the EEJ through the disturbance dynamo process.

Sudden changes in P_{Dyn} can also strongly disturb the EEJ (e.g., Araki and Nagano, 1988; Sibeck, 1990; Nilam et al., 2023; Le G et al., 2024). An increase in P_{Dyn} compresses the magnetopause earthward, leading to an enhancement of magnetopause currents (Araki, 1994), whereas a decrease in P_{Dyn} allows the magnetopause to expand outward under the restoring force of the geomagnetic field, resulting in weakened magnetopause currents (Fujita et al., 2004). Disturbances in P_{Dyn} can disrupt the dynamic balance between R1 and R2 FACs, generating PPEFs that rapidly map to low latitudes. During daytime, the equatorial ionospheric electric field is typically driven eastward by the E-region wind dynamo, and an eastward PPEF associated with a sudden P_{Dyn} enhancement further strengthens the equatorial electric field (e.g., Nilam et al., 2020, 2023). In contrast, a westward PPEF induced by a sudden P_{Dyn} decrease can substantially weaken, or even reverse, the daytime equatorial electric field (e.g., Le G et al., 2024; Cheng QH et al., 2025). Owing to the strong Cowling conductivity, such electric field perturbations produce pronounced disturbances in the EEJ. A typical P_{Dyn} drop event on March 23, 2023, is shown in Figure 9. As illustrated in Figure 9e, a sharp decrease in P_{Dyn} affects the magnetosphere without notable changes in other solar wind parameters. Correspondingly, Figure 9g shows that the EEJ rapidly decreases and reverses westward following the P_{Dyn} drop, indicating that the observed EEJ response is primarily driven by the reduction in P_{Dyn} . Statistical studies further support this interpretation. Zhang JW et al. (2023) reported that decreases in solar wind speed, density, and dynamic pressure lead to an EEJ reduction after a delay of approximately 5 minutes, with the strongest sensitivity to solar wind speed. Cheng QH et al. (2025) further showed strong longitudinal differences in EEJ responses to P_{Dyn} decreases, caused by longitudinal changes in ionospheric conductivity related to the SZA and $F_{10.7}$ (solar radio flux at 10.7 cm).

Sudden stratospheric warming events represent large-scale thermodynamic reorganizations of the wintertime middle- and high-latitude stratosphere, characterized by a rapid weakening or reversal of the polar vortex and a sharp temperature increase (Matsuno, 1971). As a typical manifestation of lower atmospheric forcing, the SSW originates from dynamical processes in the stratosphere and propagates upward, modifying the background wind field and atmospheric stability, thereby altering tidal and planetary wave propagation and ultimately modulating the EEJ

(e.g., Stening, 2011; Sathishkumar and Sridharan, 2013; Yamazaki and Maute, 2017). Recent observational and modeling studies have revealed that SSWs induce pronounced, multi-timescale disturbances in the EEJ. Observations during the 2009 SSW showed that a substantial enhancement of the solar semidiurnal tide was the primary driver of a persistent afternoon CEJ, whereas the lunar semidiurnal tide, despite being intensified, played a secondary role because of its smaller amplitude (Sathishkumar and Sridharan, 2013). The impact of lunar tidal modulation during SSWs is further found to exhibit pronounced longitudinal nonuniformity. Using ground-based magnetometers, CHAMP magnetic observations, and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) temperature data, Siddiqui et al. (2017) demonstrated that the SSW-related enhancement of lunar tidal effects on the EEJ exhibits strong longitudinal dependence, mainly arising from spatially varying E-region conductivity and electric field coupling rather than from intrinsic longitudinal structures of the lunar tide. Numerical simulations highlight the importance of nonlinear wave–tide interactions during SSWs. Results from the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA model) for the September 2019 Antarctic SSW indicate that the 6-day oscillations observed in the EEJ are not directly driven by the quasi-6-day wave (Q6DW) but instead result from 10 to 14 hour waves generated through nonlinear interactions between the Q6DW and the migrating semidiurnal tide. These secondary waves modulate E-region neutral winds and subsequently perturb the equatorial electric field (Miyoshi and Yamazaki, 2020). Further analyses showed that SSWs also amplify the quasi-2-day wave (QTDW), which can indirectly influence the EEJ by modulating the lunar semidiurnal tide (L2). During SSW periods, L2 amplitudes may increase by a factor of 2–4 relative to pre-SSW conditions, underscoring the role of planetary wave–tide coupling in shaping EEJ variability under SSW forcing (Li YX et al., 2021). Zheng ZC et al. (2021) showed that the lunar semidiurnal tide of the EEJ at Peru and the Indian sector was significantly enhanced, with the peak lunar semidiurnal tide of Peru being higher and occurring earlier than that of the Indian sector.

Recently, the behaviors of the EEJ during SAPSs have been disclosed (e.g., Zhang KD et al., 2022a, b). Subauroral polarization streams are typically observed at subauroral or mid-latitudes and represent an important pathway linking magnetospheric processes to low-latitude ionospheric dynamics. By using combined satellite observations from CHAMP and the Defense Meteorological Satellite Program (DMSP), Wang H et al. (2019) found that the EEJ became enhanced before the onset and in the initial phase of a SAPS, and then weakened after approximately 30 minutes. During SAPS periods, the occurrence rate of the CEJ more than doubled compared with quiet conditions. Two potential mechanisms between a SAPS and the EEJ were suggested based on the timescale. The first mechanism was the penetration SAPS electric field within minutes. Using the joint satellite observations from DMSP and Swarm, Zhang KD et al. (2022a) reported that the polarization of the SAPS electric field could drive an obvious local time dependence of EEJ responses: westward in the prenoon and eastward in the postnoon sectors. Figure 10 illustrates the physical mechanism by which the SAPS affects the EEJ: the poleward electric

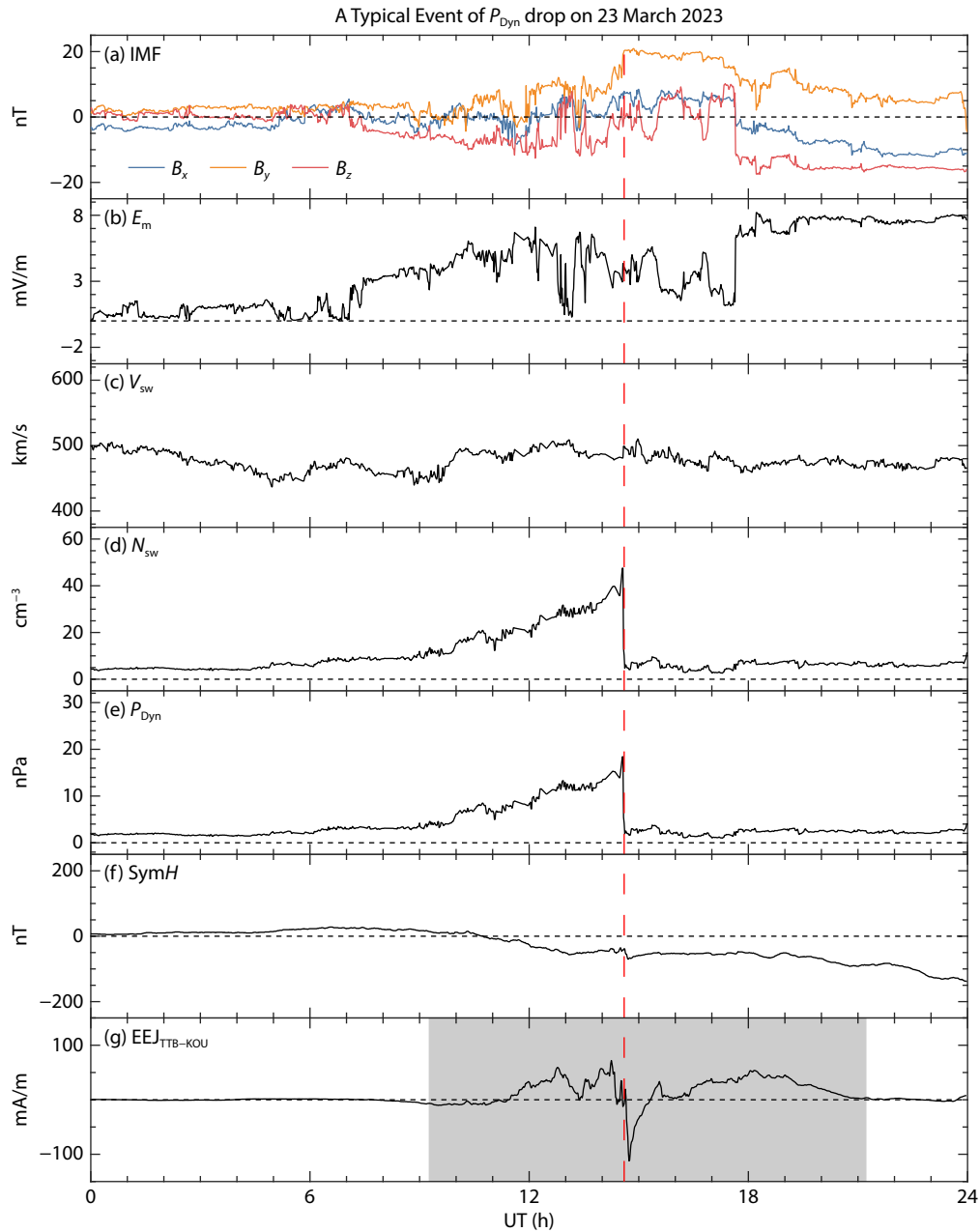


Figure 9. A typical P_{Dyn} drop event on March 23, 2023. (a) IMF components (B_x , B_y , B_z); (b) merging electric field (E_m); (c) solar wind velocity (V_{sw}); (d) solar wind density (N_{sw}); (e) P_{Dyn} ; (f) symmetric disturbance index in the horizontal component (SymH index); (g) EEJ signal (TTB-KOU), where TTB is the Tatuoca Geomagnetic Observatory near Belém, Brazil, and KOU is the Kourou Geomagnetic Observatory in French Guiana. The dashed red line indicates the onset of the sudden decrease in P_{Dyn} . The gray shaded area indicates the daytime (06:00–18:00 LT). From [Cheng QH et al. \(2025\)](#).

field associated with the SAPS penetrates to middle and low latitudes, mapping along geomagnetic field lines to produce an upward electric field in the equatorial E region. This upward field enhances the eastward Hall current and thus modulates the EEJ. In the postnoon sector, the upward electric field strengthens the eastward EEJ, whereas in the prenoon sector, the SAPS-induced westward electric field drives westward EEJ disturbances. The second mechanism was the DDEF resulting from disturbed winds, costing 2–3 hours. The SAPS-driven winds could travel to middle and low latitudes in 2–3 hours, imposing an additional electric

field into the equatorial ionosphere through a wind dynamo ([Wang WB et al., 2012](#)), whereby the strong westward (daytime) and weak eastward (dawn and dusk) EEJ disturbances were generated.

6. Solar Activity Forcing of the EEJ

Solar activity represents a fundamental external driver of the ionosphere–thermosphere system and plays a crucial role in modulating the EEJ. In contrast to mid- and high-latitude electrodynamic forcing, which primarily affects the EEJ through magnetosphere–

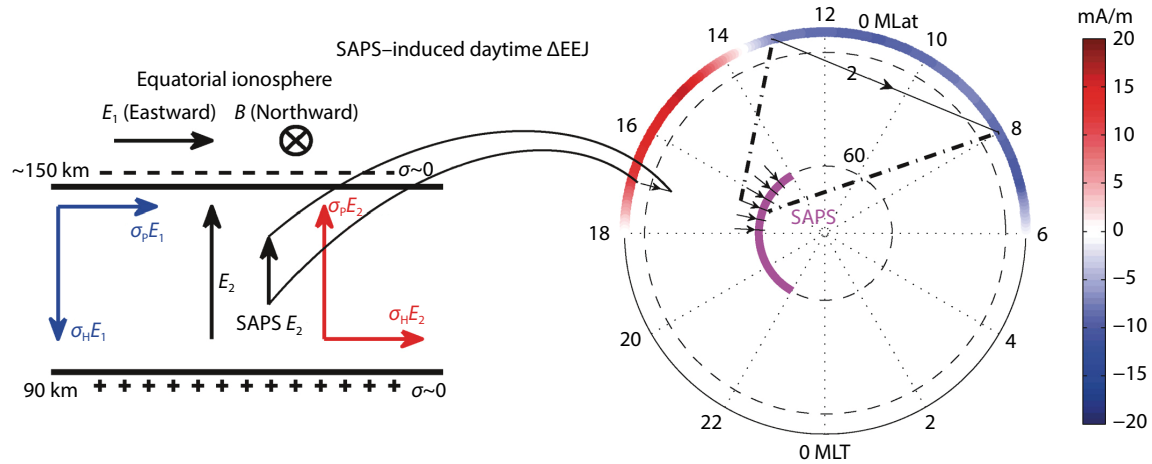


Figure 10. Conceptual illustration of SAPS-driven electric fields and the corresponding Δ EEJ. The left panel presents the typical EEJ formation mechanism. The right panel depicts the SAPS (magenta line) with the associated poleward electric field (small black arrows) in the SAPS channel. The B is the geomagnetic field, E_1 is the daytime eastward electric field, E_2 is the upward polarization electric field, SAPS E_2 is the upward polarization electric field owing to SAPS, σ_H and σ_P are Hall and Pedersen conductivity, respectively. From Zhang et al. (2022a).

ionosphere coupling processes, solar activity influences the EEJ mainly through radiative forcing and associated changes in ionospheric conductivity. Depending on the nature of solar radiation perturbations, these effects can be broadly classified into enhancement processes (e.g., solar flares) and depletion processes (e.g., solar eclipses). In particular, transient solar events such as solar flares and solar eclipses provide unique opportunities to investigate the sensitivity of the EEJ to rapid variations in solar radiation (e.g., Rastogi et al., 1997, 1999; Tomás et al., 2008; Manju, 2016; Abdu et al., 2017; Aa et al., 2020; Zhang KD and Wang H, 2022; Zhang KD et al., 2025).

Solar flares are extreme space weather events that induce a sudden increase in solar X-ray and extreme ultraviolet irradiance. The intensified radiation generates additional ionization throughout the ionosphere, driving a wide range of ionospheric disturbances that can severely disrupt navigation and communication systems. A direct consequence of this rapid ionization enhancement is a corresponding increase in ionospheric conductivity (e.g., Liu HX et al., 2007; Nogueira et al., 2015; Gopika et al., 2021; Liu J et al., 2021). Early observational studies demonstrated that solar flares significantly affect the EEJ by enhancing E-region ionization and conductivity. Using a chain of geomagnetic observatories in the Indian sector, Rastogi et al. (1997) showed that flare-induced geomagnetic perturbations resemble an augmentation of the pre-existing Sq current system, with prominent positive enhancements in the horizontal component H near the magnetic equator and distinct latitudinal variations in the vertical component Z . Subsequent work comprehensively established that the direction of the EEJ response strictly follows the preflare current state: solar flares amplify the eastward EEJ during quiet conditions but intensify westward currents when a CEJ or partial CEJ is present, resulting in negative H perturbations at equatorial stations (e.g., Rastogi et al., 1999, 2013).

Beyond this conductivity-driven response, several studies have revealed more complex electrodynamic behaviors associated with

solar flares. Sripathi et al. (2013) reported similar behavior during the intense 2011 X7 flare over India, observing a rapid transition to CEJ, suppressed H at the equator, enhanced H at low latitudes, and pronounced D-region absorption accompanying the EEJ depression. In addition, Xiong B et al. (2014) identified strong electrodynamic modulation during the 2005 X1.5 flare event. As shown in Figure 11, the EEJ intensity increased sharply, whereas the F-region vertical $E \times B$ drift decreased simultaneously, indicating a clear negative correlation that deviated from the typical quiet-time relationship. This anomaly arose from flare-enhanced Cowling conductivity, which disturbs the ionospheric dynamo and weakens the dayside eastward electric field, highlighting the key role of electrodynamic coupling in the flare-driven EEJ response. Mao T et al. (2017) extended previous results to the West Pacific sector, confirming that solar flares enhance the EEJ under quiet conditions, in agreement with the classic conductivity–amplification mechanism. They provided new insight that post-flare enhancements in southward meridional winds can generate westward dynamo electric fields, which further weaken the dayside eastward electric field and lower the F_2 peak height.

The EEJ response to solar flares becomes even more complex under disturbed geomagnetic conditions. Abdu et al. (2017) demonstrated that the EEJ response to intense solar flares becomes drastically more complex during geomagnetically disturbed periods, in contrast to quiet-time conditions. They showed that the DDEF near sunrise can drive an unusually strong westward (reverse) EEJ, whereas westward overshielding electric fields during storm recovery can suppress and delay the expected flare-induced eastward EEJ enhancement. More recently, using the TIEGCM numerical model, Chen JJ et al. (2021) provided a unified physical explanation for these electrodynamic responses. As shown in Figure 12, the model reproduces two contrasting behaviors: a noontime flare enhances the eastward EEJ, whereas a flare near sunrise produces a pronounced CEJ. These results indicate that flare-enhanced E-region conductivity generally strengthens the current intensity, but its interaction with back-

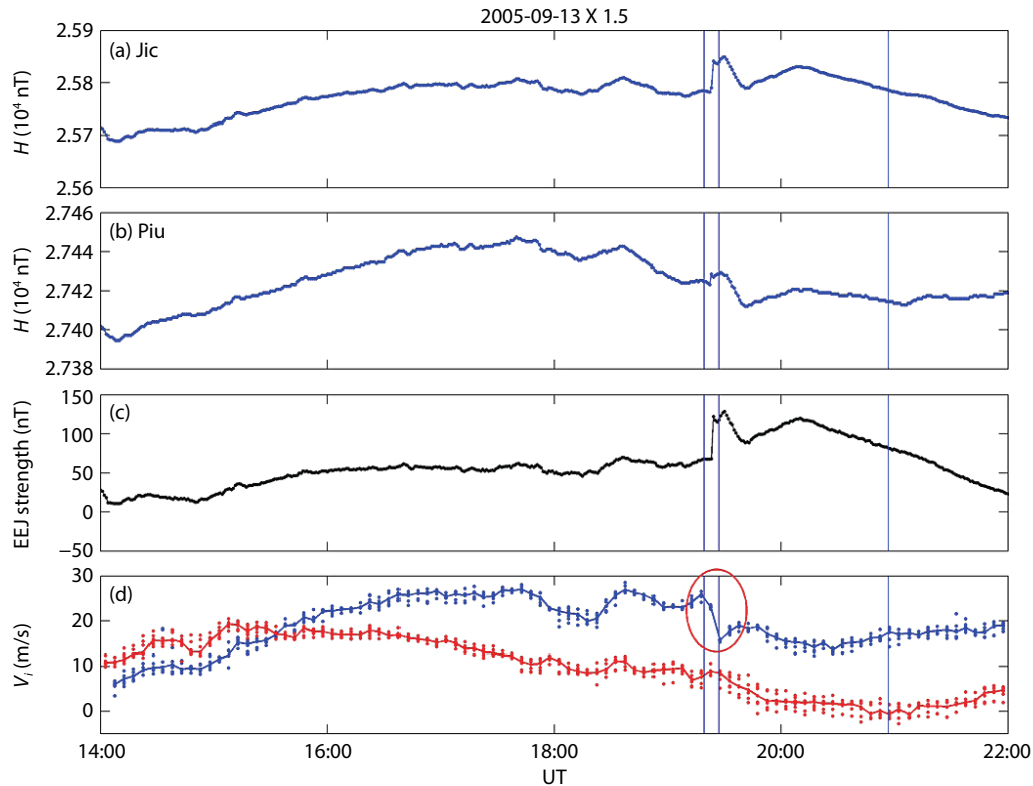


Figure 11. Temporal variations of the (a, b) geomagnetic H component at Jicamarca (Jic) and Piura (Piu), (c) EEJ intensity, and (d) F-region vertical $E \times B$ drift velocity during the X1.5 flare on September 13, 2005. The red symbols in (d) represent the quiet-day reference. The three vertical lines mark the flare onset, peak, and end time, respectively. From Xiong B et al. (2014).

ground electric fields determines whether the EEJ is enhanced or reversed.

Solar eclipses provide a special perspective on the influence of solar radiation on the ionosphere–thermosphere coupling system by producing a temporary and localized reduction in solar irradiance (Rishbeth, 1968). During a solar eclipse, solar ultraviolet, extreme ultraviolet, and X-ray radiation are blocked. This sudden decrease in photoionization leads to rapid declines in electron density, ionospheric conductivity, and neutral temperature, which further disturb the ionospheric electrodynamic processes (e.g., Jakowski et al., 2008; Momani et al., 2010; Zhang KD and Wang H, 2022). A series of studies have explored the response of the EEJ during solar eclipses (e.g., Jakowski et al., 2008; Tomás et al., 2008; Zhang KD and Wang H, 2022; Choudhary et al., 2024; Zhang KD et al., 2025). Tomás et al. (2007) found, based on CHAMP observations, that the EEJ weakened by nearly 40% during the 2005 low-latitude eclipse. In a follow-up multi-event analysis, Tomás et al. (2008) further confirmed that the EEJ is suppressed near the dip equator, often followed by a CEJ 1–3 hours after the eclipse, indicating that the reduced conductivity dominates the weakening of the EEJ. During the 2010 annular solar eclipse crossing the magnetic equator, St-Maurice et al. (2011) observed a strong CEJ shortly after maximum obscuration. They further revealed that the zonal electric field reversed westward and peaked approximately one hour before the end of the local eclipse, which was closely linked to eclipse-induced neutral wind dynamo and conductivity gradient effects.

Recent studies have further demonstrated that both photochemical and electrodynamic processes contribute to the EEJ response during solar eclipses. Zhang KD and Wang H (2022) noted that the EEJ was reduced by more than 29% during the 2020 total solar eclipse, with weakened electric fields and reversed zonal winds as the main causes, whereas E-region conductivity changes played a secondary role. Using numerical simulations for the 2006 total solar eclipse, Zhang KD et al. (2025) further quantified the eclipse-induced EEJ variations and their driving mechanisms. As shown in Figure 13, the EEJ underwent a noticeable suppression during the eclipse, accompanied by a reduction in the zonal electric field and a substantial depletion of Cowling conductivity. These results indicate that the weakening of the EEJ arises from the combined effects of reduced E-region conductivity and changes in the wind-driven electric field, with their relative contributions varying depending on the event and local conditions.

In addition to these electrodynamic changes, significant modifications in the ionospheric plasma distribution have been widely reported. Aa et al. (2020) observed a 30%–50% reduction in total electron content (TEC) along the path of the December 2019 annular eclipse, which they primarily attributed to reduced solar irradiation. Likewise, Choudhary et al. (2024) reported pronounced TEC depletion during the 2019 annular eclipse, followed by an unusual post-eclipse enhancement in the afternoon sector, highlighting the complex and time-dependent plasma response to eclipse-induced electrodynamic perturbations. These results indicate that solar eclipse effects are not confined to the E-

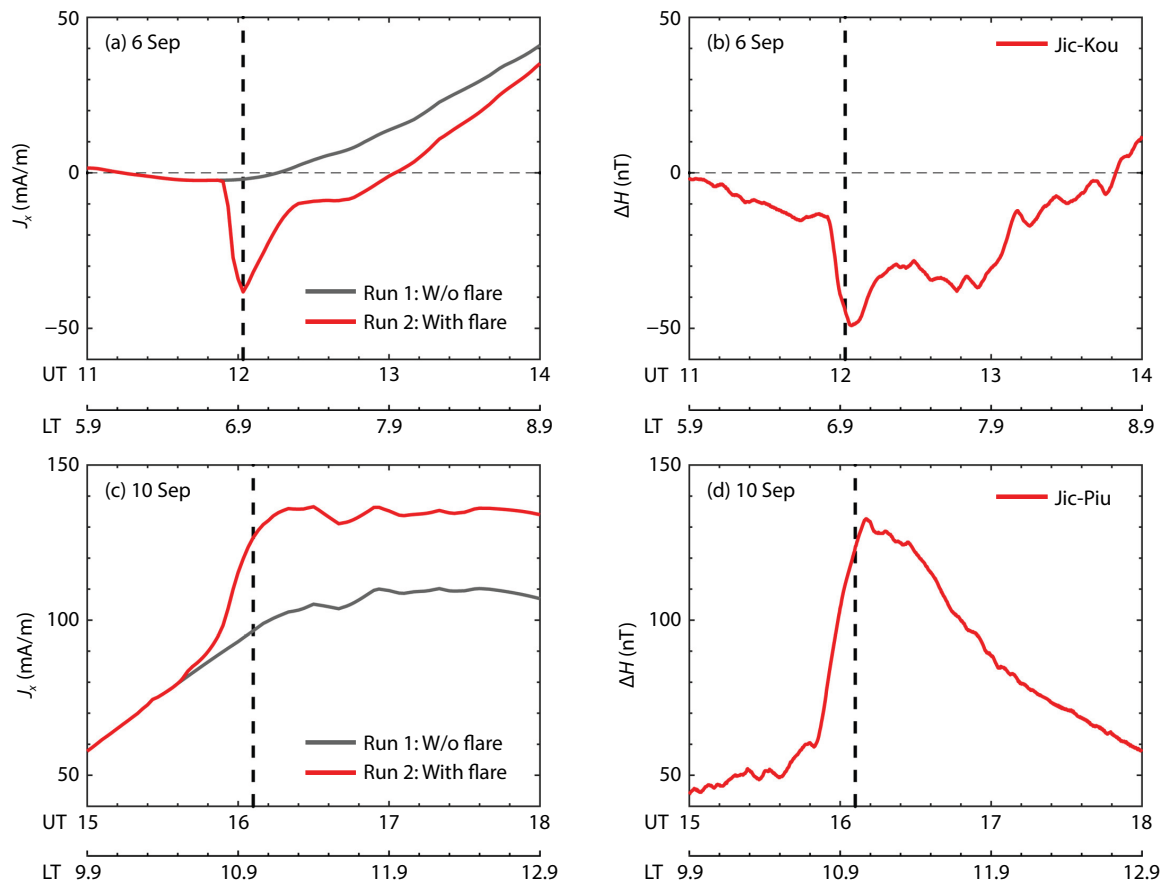


Figure 12. Responses of the EEJ to solar flares in simulations and observations. (a, c) Height-integrated eastward current density from the TIEGCM simulations without (Run 1, gray lines) and with (Run 2, red lines) flares at Jicamarca on September 6 and 10, 2017. (b, d) Scaled differences of the geomagnetic component observed by magnetometers at Jic-Kourou (Kou) (September 6) and Jic-Piu (September 10). The dashed vertical lines mark flare peak times. The bottom axes show the local time at Jicamarca. From [Chen JJ et al. \(2021\)](#).

region electrodynamics but can propagate to the F region and equatorial ionization anomaly through modified plasma transport processes.

In summary, solar activity affects the EEJ through two fundamentally different pathways: enhancement of ionospheric conductivity during solar flares and depletion during solar eclipses. The resulting EEJ response reflects a complex interplay between photochemical processes and electrodynamic coupling, with their relative importance depending on local time, background conditions, and geomagnetic activity.

7. Models of the EEJ

A clear understanding of the EEJ relies not only on long-term observations from different platforms, but also on reliable EEJ models. Models are important for explaining the physical processes that control the EEJ, for estimating the role of different driving factors, and for describing and predicting EEJ behavior during disturbed space weather conditions. In general, existing EEJ models can be broadly categorized into two classes: physics-based electrodynamic models (e.g., [Chapman, 1951](#); [Untiedt, 1967](#); [Richmond, 1973](#); [Forbes and Lindzen, 1976](#)) and data-driven empirical models (e.g., [Dourmouya et al., 2003](#); [Alken and Maus, 2007](#); [Hamid et al., 2015](#); [Tulasi Ram et al., 2024](#)). These models

differ in complexity, applicable spatial and temporal scales, and research focus, each offering distinct strengths while also exhibiting inherent limitations.

Physics-based electrodynamic models are based on ionospheric electrodynamics. They solve simplified forms of Maxwell's equations together with ion and electron momentum equations. These models include key physical factors such as neutral winds and ionospheric conductivity. [Chapman \(1951\)](#) idealized the equatorial ionosphere as a thin conducting layer and invoked the Cowling effect to explain the pronounced enhancement of the EEJ, establishing the theoretical foundation for subsequent studies. However, this early formulation assumed purely zonal currents, neglected meridional and vertical current components, and did not account for tidal wind forcing, limiting its ability to explain the latitudinal extent of the EEJ and its diurnal and seasonal variability. [Untiedt \(1967\)](#) introduced meridional currents and current functions, thus developing a more self-consistent framework that quantified a typical EEJ width of ~ 320 km and demonstrated that the magnetic field generated by meridional currents is comparable to ground magnetic perturbations. [Richmond \(1973\)](#) further highlighted the role of vertical currents, showing that their coupling can enhance EEJ intensity by $\sim 30\%$ and clarifying the closure of currents in the meridional plane, thereby providing key theoretical

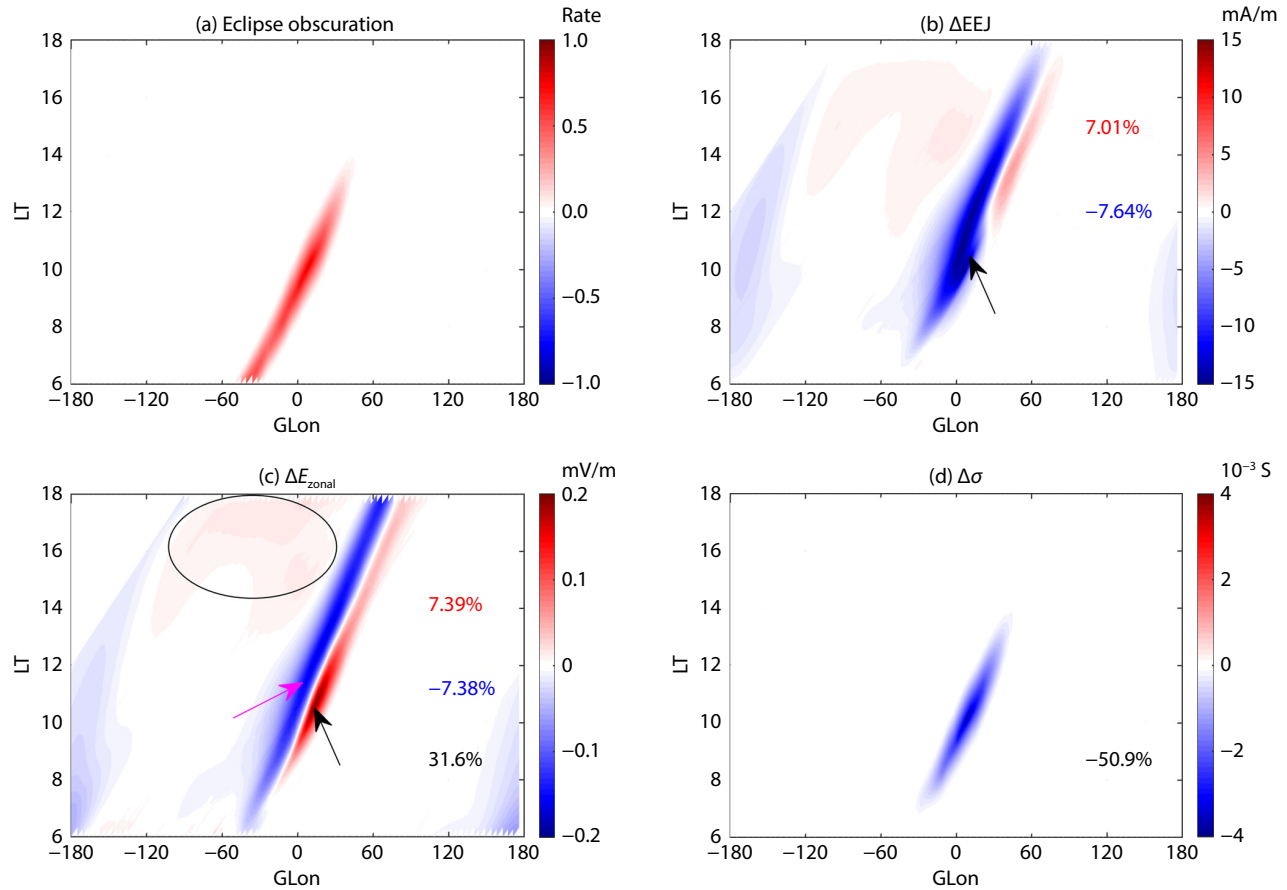


Figure 13. Spatiotemporal patterns of solar obscuration, ΔEEJ , ΔE_{zonal} , and $\Delta\sigma$ at the dip equator. The residuals are differences between eclipse and no-eclipse runs. The percentages in black show the maximum conductivity reduction and electric field changes, whereas the percentages in blue and red denote the average suppressed and enhanced perturbations, respectively. GLon, geographic longitude. From Zhang KD et al. (2025).

support for three-dimensional modeling. Forbes and Lindzen (1976) incorporated solar tides into a global dynamo framework and developed the first fully coupled three-dimensional model. These studies show that physics-based models have improved step by step by adding physical processes that were not included before and have developed from simple descriptions into fully coupled electrodynamic systems.

In contrast, data-driven empirical models are built directly from observations. They use statistical methods to describe the relationship between the EEJ and its controlling factors. Their main goal is to improve description and prediction rather than to resolve physical processes in detail. Doumouya et al. (2003) developed an empirical EEJ model based on data from 26 pairs of ground magnetometers and identified major longitudinal features. However, the assumption of symmetric Gaussian profiles limited its ability to represent asymmetric diurnal variations and solar activity effects. Alken and Maus (2007) combined dip equator crossings from multiple LEO satellites to construct a global EEJ model with full longitudinal coverage, achieving high consistency with radar observations and establishing a widely used reference for ionospheric studies. Hamid et al. (2015) further reported a negative correlation between EEJ intensity and the main geomagnetic field strength, although the limited solar-cycle coverage restricted assessment of solar activity modulation. More recently,

Tulasi Ram et al. (2024) analyzed nearly two solar cycles of ground-based magnetic observations and developed the Indian Equatorial Electrojet (IEEJ) model, a regional empirical model for the Indian sector (60°E–100°E). Using the PCA method, the model quantitatively characterizes the diurnal, seasonal, and solar-cycle variability of both the EEJ and the CEJ. Validation against ground-based observations showed that the IEEJ model accurately reproduces the EEJ and the morning CEJ. Owing to its robust statistical performance, the IEEJ model provides a reliable reference for validating numerical models, such as the TIEGCM, in the South Asian low-latitude ionosphere. Figure 14 further illustrates the model performance by comparing the diurnal variations of modeled (red curves) and observed (blue curves) EEJs for four consecutive days under two typical conditions: October 2022 (high solar activity, equinox) and June 2019 (low solar activity, summer). The model successfully reproduces the key features of the EEJ, including the strong eastward current in high solar activity periods and the frequent occurrence of the westward CEJ in summer low solar activity periods. Most deviations between modeled and observed values fall within the standard deviation range of EEJ day-to-day variability, confirming the reliability of the model in short-term applications. Physics-based electrodynamic models and data-driven empirical models of the EEJ are complementary rather than competing frameworks. Physics-based models provide mechanis-

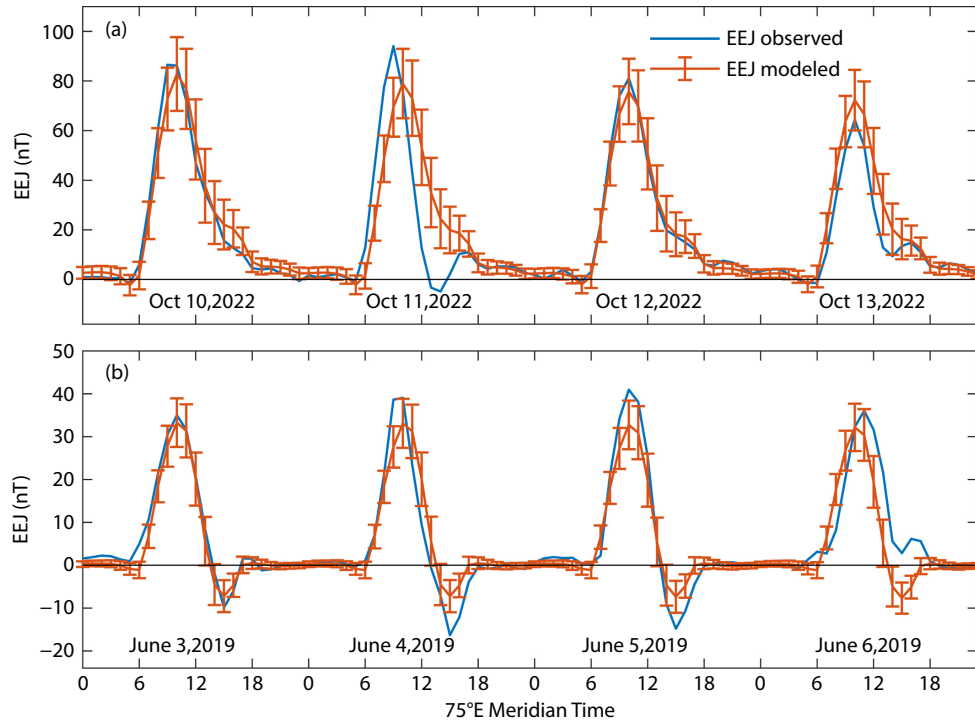


Figure 14. Day-to-day comparison of modeled (red) and observed (blue) EEJ diurnal variations over four consecutive days in October 2022 (top panel) and June 2019 (bottom panel). From [Tulasi Ram et al. \(2024\)](#).

tic understanding, whereas empirical models offer observational constraints and validation. For instance, the tides driving mechanisms identified by [Forbes and Lindzen \(1976\)](#) directly inform the PCA component selection in the empirical model of [Tulasi Ram et al. \(2024\)](#), and the wave-4 longitudinal pattern reported by [Alken and Maus \(2007\)](#) supports the atmospheric tidal theory proposed by [England et al. \(2006\)](#). Despite significant progress, key challenges remain. First, longitudinal coverage is still limited: many empirical models focus on individual longitudinal sectors (e.g., [Tulasi Ram et al., 2024](#)), whereas global models often lack sufficient resolution to capture small-scale longitudinal variability (e.g., [Manoj et al., 2006](#); [Alken and Maus, 2007](#)). Second, geomagnetic disturbance effects are inadequately represented because most models are fundamentally based on historical statistical relationships, so their capability of representing extreme disturbance conditions is limited.

Global physics-based numerical models have become increasingly important for simulating the coupled thermosphere–ionosphere system. Among them, the TIEGCM has been widely used because of its ability to self-consistently simulate the coupled dynamics, electrodynamics, and thermospheric responses to solar and geomagnetic forcing ([Richmond et al., 1992](#)). Numerous studies have shown that the TIEGCM successfully reproduces the basic diurnal variation of the EEJ, including daytime enhancement and near-noon maxima, as well as latitudinal magnetic signatures ([Dombia et al., 2007](#)). [Figure 15](#) illustrates the modulation of the spatiotemporal evolution of the EEJ by nonmigrating tides. By incorporating nonmigrating tides, the model captures the characteristic wave-4 longitudinal pattern of the EEJ, broadly consistent with CHAMP observations ([Wang H et al., 2020](#)). Under disturbed

conditions, the TIEGCM simulates the rapid penetration of high-latitude electric fields into low latitudes, enabling investigation of PPEF and disturbance dynamo effects on the EEJ during geomagnetic storms ([Zhang KD et al., 2024a](#)). The model has also been applied to solar eclipse events, quantifying eclipse-induced EEJ weakening and post-eclipse recovery ([Zhang KD et al., 2025](#)). Nevertheless, notable limitations persist. The TIEGCM generally underestimates EEJ magnetic amplitudes and peak intensities in the East Asian sector, with simulated peak times delayed by ~1–2 hours relative to observations ([Dombia et al., 2007](#); [Wang H et al., 2020](#)). In addition, the parameterization of nonmigrating tides remains incomplete, particularly with respect to lunar tidal components, leading to longitudinal shifts in EEJ extrema ([Wang H et al., 2020](#)). The model also has limited skill in simulating afternoon CEJs and the persistence of EEJ disturbances following transient events such as solar eclipses ([Zhang KD et al., 2025](#)).

Overall, EEJ modeling has evolved from simple theoretical descriptions to empirical statistical models and fully coupled global simulations. Physics-based electrodynamic models clarify the fundamental formation mechanisms of the EEJ, empirical models efficiently capture long-term statistical behavior, and global models enable investigation of EEJ responses to multi-source forcing. Despite these advances, important limitations remain, particularly in observational constraints, representation of electrodynamic processes, and treatment of cross-scale coupling. Future progress will rely on improved multi-platform data assimilation and refined parameterization of high-latitude forcing to better reproduce disturbed conditions. Advances in high-resolution global modeling are therefore essential for developing an integrated EEJ framework that balances physical consistency and

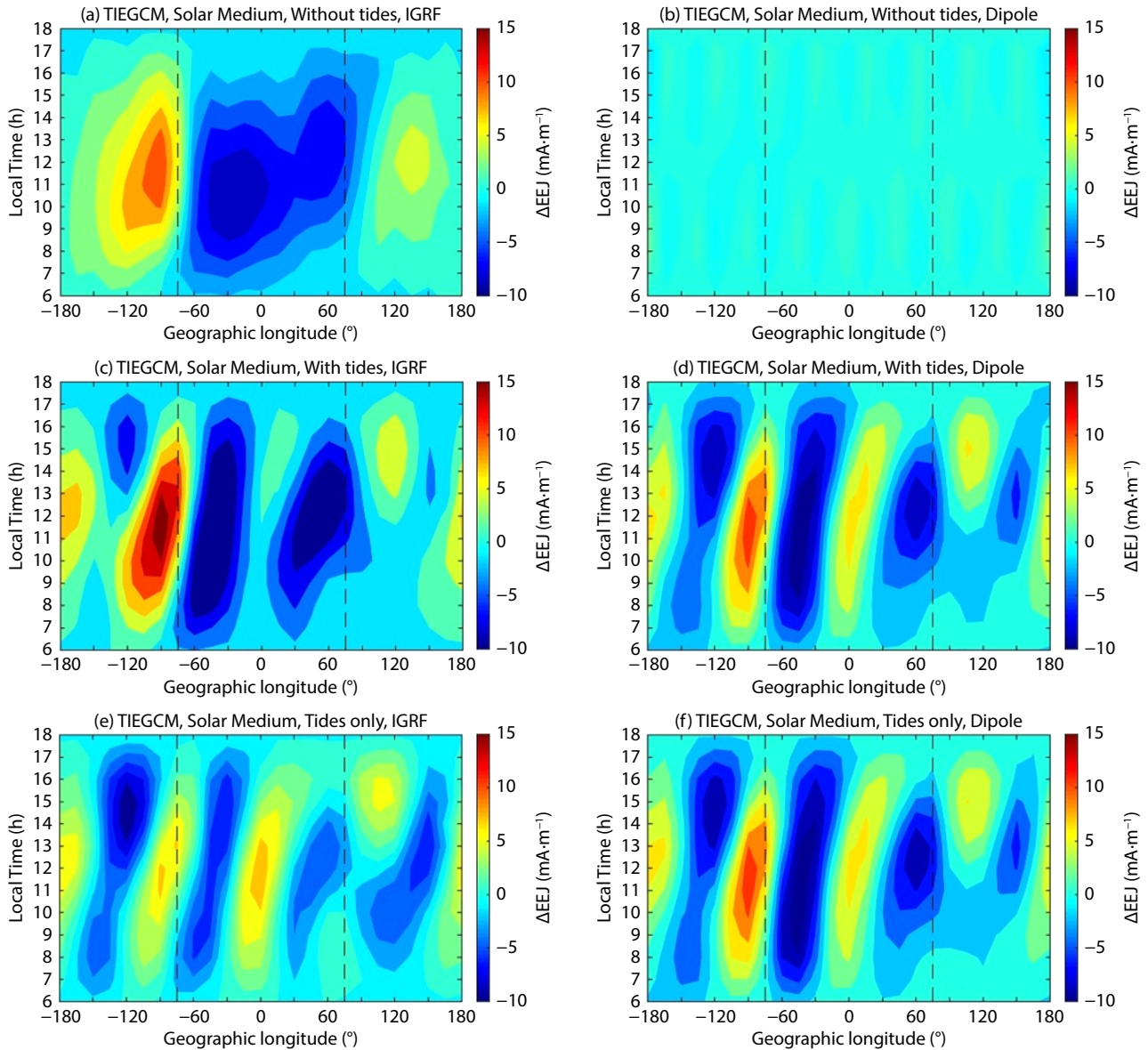


Figure 15. Longitudinal and local time variations of the EEJ simulated by the TIEGCM. The left set of panels (a, c, e) presents results in the IGRF frame, and the right set (b, d, f) corresponds to the zero-tilt dipole. Panels (a) and (b) incorporate nonmigrating tides at the lower boundary, panels (c) and (d) do not, and panels (e) and (f) illustrate the net influence of these tides. The vertical dashed black lines mark 75°W and 75°E longitudes. From Wang H et al. (2020).

predictive capability.

8. Summary and Open Issues

This article provides a systematic review of the main features of the EEJ. It covers observational and inversion techniques, diurnal and longitudinal variability, mid- and high-latitude forcing, solar activity forcing and recent advances in EEJ models. Results from ground-based and satellite observations clearly show that the EEJ has strong diurnal and longitudinal variations on a global scale. These variations are mainly controlled by E-region ionospheric conductivity, atmospheric tides, and geomagnetic field geometry. Among these factors, nonmigrating tides play a dominant role in shaping the wave-4 longitudinal pattern of the EEJ. Under disturbed conditions, mid- and high-latitude processes such as

geomagnetic storms, substorms, sudden changes in P_{Dyn} , SSWs, and SAPs can significantly modify the intensity of the EEJ and may even reverse its direction through coupling processes. Furthermore, solar activity, including solar flares and solar eclipses, can modulate the EEJ primarily through rapid changes in ionospheric conductivity and associated electrodynamic adjustments. Existing theoretical models, empirical models, and global numerical simulations have provided important insights into EEJ behavior across different spatial and temporal scales. However, their quantitative consistency and capability of reproducing disturbed conditions remain limited.

Despite these advances, several important issues remain unresolved. First, no unified quantitative framework exists for the multi-factor coupling mechanisms that govern the longitudinal variabil-

ity of the EEJ. It is accepted that eastward-propagating nonmigrating atmospheric tides play a dominant role in the wave-4 pattern of the EEJ (Lühr et al., 2008; Wang H et al., 2020). However, westward-propagating tidal components, such as the semidiurnal SW3 during the fall equinox and SW4 in December solstice months, also play a significant role (Lühr and Manoj, 2013). The underlying mechanisms that drive these contributions are still poorly understood. In addition, Soares et al. (2022) analyzed the tidal composition of the EEJ on a yearly basis, but the observed tidal components in the EEJ do not always match those in the neutral winds responsible for driving the current (Yamazaki et al., 2024). Thus, tidal wind components contributing to the EEJ need further investigation to be identified. And the relative sensitivities of different longitude sectors to tides, ionospheric conductivity, and geomagnetic field effects have yet to be systematically evaluated. Second, the nonlinear responses of the EEJ to geomagnetic storms, sudden changes in P_{Dyr} , and SSW events remain incompletely understood. Equatorial electrojet disturbances during sawtooth isolated substorms have been shown to be driven by substorm-induced electric fields modulated by IMF B_z variations (e.g., Huang CS, 2009; Zhong YF et al., 2024). However, Hayashi et al. (2025) found no significant dayside equatorial electric field penetration during isolated substorms, leading to minimal EEJ changes and highlighting a strong event-type dependence. Moreover, Cheng QH et al. (2025) demonstrated that the longitudinal differences in ΔEEJ are likely produced by the superposition of a PPEF generated by both the IMF B_z changes and the sudden decrease in P_{Dyr} . These results indicate that EEJ responses cannot be attributed to a single driver, but rather to the combined effects of multiple high-latitude forcing processes. Therefore, future studies should focus on a more refined and quantitative characterization of IMF B_z regulation and its synergistic interactions with other high-latitude drivers. By integrating multi-platform observations, improving global coupled models, and incorporating data assimilation and machine learning techniques, the simulation and prediction of the EEJ can be substantially enhanced. Such advances will deepen our understanding of low-latitude ionospheric electrodynamics and improve the application of EEJ modeling in space weather research.

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