Neutral Wind Profiles During Periods of Eastward and Westward Equatorial Electrojet

Y. Yamazaki¹, B. J. Harding², C. Stolle¹³, and J. Matzka¹

¹GFZ German Research Centre for Geosciences, Potsdam, Germany, ²Space Sciences Laboratory, University of California, Berkeley, CA, USA, ³Faculty of Science, University of Potsdam, Potsdam, Germany

Abstract

The equatorial electrojet (EEJ) is a band of zonal electric current flowing along the magnetic equator in the dayside E-region ionosphere. The direction of the EEJ is often eastward but sometimes westward. The mechanism for generating westward EEJ is not fully understood. This study examines the relationship between the eastward/westward EEJ and equatorial neutral winds using simultaneous observations of the EEJ from the European Space Agency’s Swarm satellite mission and thermospheric winds from the Michelson Interferometer for Global High-resolution Thermospheric Imaging on NASA’s Ionospheric Connection Explorer mission during December 2019–January 2021. Significant differences are found in the average zonal wind profiles between times of eastward and westward EEJ. The EEJ intensity correlates negatively ($R = -0.54$) and positively ($R = 0.58$) with the eastward wind velocities at ~110 and ~140 km, respectively. The results suggest that the modulation of the zonal electric field by the equatorial zonal wind plays a role in producing the westward EEJ.

Plain Language Summary

Electric fields and currents in the dayside E-region ionosphere arise from collisional interactions between neutral and plasma particles; thus understanding electrodynamic processes in the ionosphere can greatly benefit from simultaneous measurements of neutral and plasma parameters. This study explores simultaneous observations of equatorial ionospheric currents from the European Space Agency’s Swarm satellite mission and equatorial neutral winds from the Michelson Interferometer for Global High-resolution Thermospheric Imaging on NASA's Ionospheric Connection Explorer mission. It is found that the average vertical profiles of the zonal wind are significantly different between periods of eastward and westward equatorial electrojet currents. The results highlight the importance of the equatorial zonal wind in driving changes in the equatorial ionosphere.

1. Introduction

Collisional interactions between neutral and plasma particles at the E-region heights (ca. 90–150 km) lead to the production of electric fields and currents, which can be expressed as follows:

$$\mathbf{J} = \hat{\sigma} \cdot (\mathbf{E} + \mathbf{U} \times \mathbf{B}),$$

where $\mathbf{J}$ is the current density, $\hat{\sigma}$ is the ionospheric conductivity tensor, $\mathbf{E}$ is the electric field, $\mathbf{U}$ is the neutral wind, and $\mathbf{B}$ is the ambient magnetic field. Large-scale motion of the atmosphere across the geomagnetic field drives electric currents on the dayside ionosphere, where the conductivity is enhanced due to photoionization mainly by solar extreme ultraviolet radiation. Electric fields are generated in such a manner that the total currents (i.e., the sum of wind-driven currents and electric field-driven currents) are divergence free (Richmond & Roble, 1987). Under geomagnetically quiet conditions, the electric field in the low-latitude ionosphere is usually eastward on the dayside. The zonal electric field sets up a vertical polarization electric field near the magnetic equator, which drives the zonal current in the same direction as the current driven by the zonal electric field. As a result, there is a band of enhanced current flowing along the magnetic equator, which is known as the equatorial electrojet (EEJ) (e.g., Forbes, 1981; Yamazaki & Maute, 2017).

The EEJ shows large day-to-day variation, which is closely connected to changes in the zonal electric field and equatorial ionization anomaly (e.g., Stolle et al., 2008). The variation is large enough so that the usually eastward EEJ sometimes turns westward (e.g., Soares et al., 2018; Zhou et al., 2018). The driving mechanism of the westward EEJ is not well understood. This study discusses the possible contributions of neutral winds.
based on simultaneous observations of the EEJ and neutral winds and compares them with previous modeling results. The study is made possible by recent observations from two satellite missions, namely, ESA’s satellite constellation mission Swarm (Frisi-Christensen et al., 2006) and NASA’s Ionospheric Connection Explorer (ICON) mission (Immel et al., 2018). Comparisons are made for neutral winds during times of eastward and westward EEJ.

2. Data Selection

The Swarm constellation consists of three identical satellites (A, B, and C) that carry instruments for investigating the Earth’s magnetic field and its sources. The three spacecraft were launched into polar orbits with inclinations of \( \sim 87^\circ \) on November 22, 2013. Since April 17, 2014, Swarm A and C have been flying side by side at an altitude of \( \sim 460 \) km, while Swarm B has been flying separately at a higher altitude of \( \sim 510 \) km. For our study, we use estimates of the EEJ intensity at 110 km as derived from magnetometer observations. The Swarm Level 2 product EEF (Alken et al., 2013) provides a latitudinal profile of the EEJ intensity for each dayside orbit. The validation of the product against ground data can be found in Alken et al. (2015). The procedures for retrieving the EEJ intensity are described in detail by Alken (2020).

The ICON mission was launched on October 11, 2019 and the spacecraft was placed in a 27° inclination orbit at an altitude of \( \sim 600 \) km. The Michelson Interferometer for Global High-Resolution Thermospheric Imaging (MIGHTI) (Englert et al., 2017) measures Doppler shifts in naturally occurring atomic oxygen airglow emissions to estimate the neutral wind velocity. We use version 4 of the cardinal wind profiles (Level 2.2) derived from the green-line emission at 557.7 nm wavelength (Harding et al., 2017). The validation of the wind data against ground data is presented by Harding et al. (2021). For this study, wind observations in the height range of 95–180 km are used. A wind vector \( (u_0, u_1, u_2) \) is given in a local magnetic coordinate system. \( u_0 \) is in the direction of the magnetic field, \( u_1 \) is in the poleward/upward direction perpendicular to the magnetic field within the plane of the magnetic meridian, and \( u_2 \) is in the direction perpendicular to the two. At the magnetic equator, \( u_0 \) and \( u_1 \) are in the magnetic northward and vertically upward directions, respectively, and \( u_2 \) is in the magnetic eastward direction. In this paper, which focuses on the region close to the magnetic equator, \( u_0, u_1, \) and \( u_2 \) are referred to as “meridional wind,” “upward wind,” and “zonal wind,” respectively.

The data are collected for the times when the EEJ and neutral winds are observed approximately at the same location and time. Specifically, the following criteria are used to find Swarm–ICON/MIGHTI conjunctions: (a) the wind measurement needs to be made within \( \pm 15 \) min from the time of the EEJ observation at the magnetic equator; (b) the wind measurement needs to be made within \( \pm 5^\circ \) from the magnetic equator; and (c) the wind measurement needs to be made within \( \pm 10^\circ \) from the longitude of the EEJ measurement. The criterion (c) is based on the earlier study by Manoj et al. (2006), who reported that the correlation of the EEJ intensities at two locations is below the statistical significance level for a longitudinal separation of more than \( 15^\circ \). Additional criteria are introduced to select only the Swarm–ICON/MIGHTI conjunctions that are suitable for the present study: (d) the geomagnetic activity index Hp30 needs to be less than three and (e) the “wind quality factor” needs to be equal to one, which corresponds to the best quality data. The criterion (d) is based on the fact that changes in geomagnetic activity can lead to EEJ perturbations (e.g., Kikuchi et al., 2008; Yamazaki & Kosch, 2015). Hp30 is a recently developed geomagnetic activity index whose values and occurrence distributions are designed to be similar to those of the traditional 3-hourly \( Kp \) index but having a higher time resolution of 30 min (Matzka et al., 2021). The criterion (e) eliminates the measurements taken near the South Atlantic Anomaly which are contaminated by radiation, and thus the wind data from the South American sector are limited. When there is more than one wind profile that satisfies all the criteria (a–e) for the same EEJ observation, we use only the wind profile that has the smallest time difference from the EEJ data.

This study focuses on the period from December 2019 to January 2021. Figure 1 displays, from top to bottom, the solar flux index \( F_{\text{10.7}} \) (Tapping, 2013), the geomagnetic activity index Hp30, and the local times of Swarm and ICON observations during this time. Being under solar minimum conditions, the overall solar flux variation is small. According to the results presented by Alken and Maus (2007), changes in the EEJ intensity that would result from solar flux perturbation within the observed range \( (67 < F_{\text{10.7}} < 113) \) are
Figure 1. (Top two panels) Time series of the solar activity index $F_{10.7}$ and geomagnetic activity index $Hp$30 during December 2019–January 2021. (Bottom three panels) Local times for the observations by Swarm A, B, and C and by the Ionospheric Connection Explorer/Michelson Interferometer for Global High-resolution Thermospheric Imaging (ICON/MIGHTI). Green dots indicate Swarm equatorial electrojet observations at the magnetic equator. Gray dots indicate ICON/MIGHTI neutral wind measurements within ±5° magnetic latitudes. Red dots indicate conjunctions by the two.
smaller than day-to-day variation. For this reason, $F_{10.7}$ is not used in our data selection process. The overall geomagnetic activity level is also low. The times when $H_{p30}$ is less than three accounts for 92.6% of the whole period.

It is seen in the bottom three panels of Figure 1 that it takes more than four months for Swarm (marked by green dots) to cover the dayside local time between 06:00–18:00 LT, while it takes less than one month for ICON/MIGHTI (marked by gray dots) to cover the same range of local time. The Swarm–ICON/MIGHTI conjunctions are indicated by red dots. Two hundred forty six conjunctions are identified for Swarm A, 226 for Swarm B, and 252 for Swarm C. Since Swarm A and C fly side by side, there are many overlaps in the selected wind profiles. There are 227 profiles in common among the ICON/MIGHTI conjunctions with Swarm A and C.

3. Results

The top row of Figure 2 depicts the average latitudinal profiles of the Swarm EEJ intensity during conjugate observations with ICON/MIGHTI. The average EEJ profiles are displayed separately for the times when the EEJ is eastward (red) and westward (blue). The data from all local times and seasons are included. The left panel is for Swarm A, the middle panel is for Swarm B, and the right panel is for Swarm C. The results show expected latitudinal structures of the EEJ intensity around the magnetic equator (e.g., Lühr et al., 2004). The bottom three rows of Figure 2 show the corresponding average vertical profiles of the ICON/MIGHTI winds in the magnetic eastward, magnetic northward, and vertically upward components. It is seen that the zonal wind profiles are different between times of eastward and westward EEJ. That is, during the eastward EEJ, the zonal wind tends to be westward at all heights with small height dependence. During the westward EEJ, on the other hand, the zonal wind is eastward at $\sim$110 km and strongly westward at $\sim$140 km. The results are in agreement not only between Swarm A and Swarm C, which have many wind profiles in common, but also between Swarm A/C and Swarm B, which have no profiles in common. This gives us confidence that the difference in the zonal wind profiles between times of eastward and westward EEJ is a robust feature.

The meridional wind profiles show much smaller differences between the eastward and westward EEJ. The average upward wind is small in all cases. This is expected, as the vertical wind is assumed to be zero in the derivation of the winds (see Harding et al., 2017, for more details). It is noted that individual upward wind profiles contain nonzero values up to $\pm$40 m/s, as the data are taken not only at the magnetic equator but also from higher latitudes (within $\pm$5° from the magnetic equator), where $u_1$ is not strictly in the vertically upward direction. The small average upward wind suggests that the sample size is large enough to reduce those unwanted variations.

We now consider whether the differences in the zonal wind profiles between times of eastward and westward EEJ depend on the local time. To this end, the observations from Swarm A, B, and C are combined, then binned into three groups according to the local time, that is, 06:00–09:00 LT for morning, 09:00–14:00 LT for noon, and 14:00–18:00 LT for afternoon. Note that the selected local time ranges are not evenly distributed. This is to ensure a good number of both eastward and westward EEJ events in each bin. For each group, the average latitudinal profiles of the Swarm EEJ intensity and the average vertical profiles of the ICON/MIGHTI zonal wind are calculated separately for times of eastward and westward EEJ. Since Swarm A and C share a large number of profiles, a reduced weight of 0.5 is given to the data corresponding to their conjunctions with ICON/MIGHTI in calculating the averages for the EEJ and zonal wind. The upper six panels of Figure 3 show the results for the morning (left), noon (middle), and afternoon (right) conjunctions. Enhanced EEJ signatures during noon can arise from daily variations in the ionospheric conductivity and electric field. The MIGHTI results confirm the differences seen in Figure 2; namely, during periods of westward EEJ, the zonal wind is more eastward around 110 km and more westward around 140 km in all three LT bins. The height variation of the zonal wind during westward EEJ is largest during midday hours. This implies that for the strong EEJ around noon, proportionally strong wind forcing is required to reverse the direction of the EEJ.

Next, we consider the seasonal dependence by combining the observations from Swarm A, B, and C (including all local times), and binning them into three seasonal groups: D-months (November, December, January, and February), E-months (March, April, September, and October), and J-months (May, June, July,
Figure 2. From the top to the bottom row: the average latitudinal profiles of the equatorial electrojet (EEJ) intensity, the average vertical profiles of the Ionospheric Connection Explorer/Michelson Interferometer for Global High-resolution Thermospheric Imaging (ICON/MIGHTI) equatorial zonal wind (magnetic eastward positive), meridional wind (magnetic northward positive), and upward wind. The left columns are for the conjunction observations by Swarm A and ICON/MIGHTI, while the middle and right columns correspond to ICON/MIGHTI conjunctions with Swarm B and C, respectively. In each panel, the red line shows the average for the eastward EEJ, while the blue line shows the average for the westward EEJ. The error bars show the standard errors of the mean. For Swarm A/B/C, there are 146/148/157 profiles for the eastward EEJ and 100/78/95 profiles for the westward EEJ.
Figure 3. (Top two rows) Similar to the top two rows of Figure 2 but for the combined observations from Swarm A, B, and C during morning (left), noon (middle), and afternoon (right) hours. For the morning/noon/afternoon case, there are 100/223/128 profiles for the eastward equatorial electrojet (EEJ) and 154/48/71 profiles for the westward EEJ. (Bottom two rows) Same as the top two rows but for the D-months (November–February), E-months (March, April, September, and October), and J-months (May–August). For D-months/E-months/J-months, there are 146/170/135 profiles for the eastward EEJ and 90/107/76 profiles for the westward EEJ.
and August). The lower six panels of Figure 3 show the average latitudinal profiles of the Swarm EEJ intensity and the average vertical profiles of the ICON/MIGHTI zonal wind for the D-months (left), E-months (middle) and J-months (right). Again, a reduced weight of 0.5 is assigned to the data from the Swarm A and C conjunctions with ICON/MIGHTI. The results are similar to the previous ones. That is, during the times of eastward EEJ, the zonal wind tends to be westward at all heights, while during the times of westward EEJ, the zonal wind is eastward at ~110 km and strongly westward at ~140 km.

The average vertical profiles of the ICON/MIGHTI winds in the meridional and upward components are presented in the supporting information (Figure S1) for different local times and seasons. In some cases, meridional wind profiles show different patterns between times of eastward and westward EEJ, but unlike the zonal component, the vertical pattern of differences is not consistent for different binning cases. In this study, we do not attempt to interpret the relationship between the EEJ and meridional winds. As can be seen from Equation 1, meridional winds at the magnetic equator, which are parallel to the magnetic field, do not directly drive the perpendicular currents and thus, are expected to be of secondary importance to the EEJ. The average upward wind is small in all cases as expected from the assumption of zero vertical wind.

Scatter plots are presented in the upper panels of Figure 4 for the noontime EEJ intensity and zonal wind velocities at 106 km (left) and 143 km (right). It is seen that the EEJ intensity correlates negatively and positively with the eastward wind velocities at 106 and 143 km, respectively. The correlation is moderate with |R| ~ 0.5 in both cases, indicating that changes in the local wind are not the only cause of EEJ variation. For an individual westward EEJ event, the zonal wind could be either eastward or westward at 106 km as well as at 143 km. The height dependence of the correlation coefficient between the noontime EEJ intensity and zonal wind velocity is shown in the lower left panel. The correlation coefficient tends to be negative below ~115 km and positive above. It is also shown in the same panel that the correlation with the EEJ tends to decrease when the zonal wind velocities at higher latitudes (15° ± 5° and 30° ± 5° magnetic latitudes) are considered. The height pattern of the correlation in the lower left panel is partly due to the correlation of the zonal wind with itself at different heights. The wind velocities below and above ~115 km tend to correlate negatively as indicated in the lower right panel. However, the correlation between the zonal wind velocities at 106 and 143 km is weaker than the correlation between the EEJ intensity and zonal wind velocities at those heights. This suggests that the zonal winds above and below ~115 km can affect the EEJ intensity independently.

4. Discussion

With some geometric assumptions appropriate for ionospheric currents in the equatorial region (±10° magnetic latitude, 80–200 km altitude), the zonal component of Equation 1 can be reduced to the following (e.g., Richmond, 1973):

\[
J = \left( \sigma_p + \frac{\sigma_H ds}{\sigma_p ds} \right) E + \sigma_H \left( u - \frac{\sigma_H ds}{\sigma_p ds} \right) B, \tag{2}
\]

where J is the eastward current density, \(\sigma_p\) is the Pedersen conductivity, \(\sigma_H\) is the Hall conductivity, E is the eastward electric field, u is the zonal wind, and B is the ambient magnetic field intensity. The integrals are taken along the magnetic field line between the base of the ionosphere in each hemisphere. It is seen that equatorial zonal currents consist of two parts: the part dependent on E and the part dependent on u. The E-driven part is the dominant component of the EEJ. The multiplier of E in Equation 2 is known as the Cowling conductivity. It is much larger than \(\sigma_p\) and \(\sigma_H\) because \(\sigma_H \gg \sigma_p\) in the lower E region where the EEJ flows. The equatorial zonal electric field is primarily due to global, rather than local, wind dynamo (Stening, 1995) and typically eastward during daytime. Thus, the average EEJ is eastward when the equatorial (thus local) zonal wind is zero in Figure 4. Also, in Figure 4, the equatorial zonal wind accounts for only a fraction of the EEJ variation. The rest of the variation may be attributed to global processes.

In Equation 2, the u-driven part is zero if u is constant along the magnetic field line. Early modeling studies examined how height-varying winds can affect the EEJ using various possible profiles of u (e.g., Anandarao & Raghavarao, 1987; Reddy & Devasia, 1981; Richmond, 1973). They found that height-varying winds can significantly affect the zonal current more than a few degrees away from the magnetic equator but have
only a minor effect on the current density at the magnetic equator (i.e., the EEJ). This may lead to the question of why the correlation is observed between the Swarm EEJ and ICON/MIGHTI winds. More recently, Yamazaki et al. (2014) revisited the relationship between the EEJ and neutral winds using the thermosphere ionosphere mesosphere electrodynamics general circulation model (TIME-GCM). A correlation analysis

![Figure 4](image-url)
was performed between the simulated midday EEJ current density and zonal/meridional winds at various longitudes, latitudes, and heights. It was demonstrated that the strength of the EEJ is negatively and positively correlated with the eastward wind near the magnetic equator at 100–120 km and 120–150 km, respectively. In fact, the height and latitude dependence of the correlation presented in Figure 4 (bottom left) is in qualitative agreement with the results presented by Yamazaki et al. (2014). The proposed mechanism is the modulation of the equatorial zonal electric field by zonal winds, which was not considered in the early models of the EEJ with a prescribed zonal electric field. Below ~120 km, the wind-driven current is mainly a Hall current, which flows in the same direction as the wind. Thus, an eastward wind would drive an eastward wind-driven current. An electric field tends to be generated in such a manner that it opposes the wind-driven current (e.g., Pfaff et al., 2020); thus the eastward wind leads to a westward electric field. This westward electric field can drive a strong westward current because of the large Cowling conductivity. Above ~120 km, on the other hand, $\sigma_p > \sigma_H$ so that an eastward wind mainly drives a Pedersen current pointing upward and an electric field pointing downward. The downward electric field, when transmitted down to the Hall region along the magnetic field lines, drives a westward Hall current and an eastward electric field a few degrees away from the magnetic equator. This eastward polarization electric field spreads in latitude to meet the curl-free requirement and drives a strong eastward current at the magnetic equator because of the large Cowling conductivity. In summary, an eastward wind in the Hall region contributes to the westward EEJ, while an eastward wind in the Pedersen region contributes to the eastward EEJ. This can explain the observed correlation between the Swarm EEJ and ICON/MIGHTI winds.

Somayajulu et al. (1993), comparing wind measurements from a meteor radar near the magnetic equator with ground magnetic perturbations at the Indian sector during 19–31 January 1987, reported that the mean wind at 90–105 km was westward during westward EEJ and eastward during eastward EEJ. Their results appear to contradict with ours, but the difference is that they used daily mean winds while we used instantaneous wind measurements. Gurubaran et al. (2011) noted that there is sometimes a correlation between the EEJ strength and diurnal and semidiurnal tidal amplitudes in the northward wind at 90 km. Future work with longer Swarm–ICON observations may investigate the tidal composition and daily mean wind associated with eastward and westward EEJ.

5. Conclusions

Simultaneous observations of the Swarm equatorial electrojet (EEJ) intensity and ICON/MIGHTI thermospheric wind velocities are analyzed for the period from December 2019 to January 2021 under quiet geomagnetic activity conditions ($H_p30 < 3$). Significant differences are found in the average vertical profiles of the zonal wind between times of eastward and westward EEJ. During the eastward EEJ, the average zonal wind tends to be westward at all heights with small height dependence. During the westward EEJ, the average zonal wind shows a larger height variation with the wind being more eastward at ~110 km and more westward at ~140 km. Consistent results are obtained from the Swarm A/C and Swarm B data as well as from the data sorted for different local times and seasons. The EEJ intensity correlates negatively ($R = −0.54$) and positively ($R = 0.58$) with the eastward wind at ~110 km and ~140 km, respectively. These EEJ responses to zonal winds at different heights are in agreement with the model predictions by Yamazaki et al. (2014). The negative correlation between the EEJ intensity and eastward wind at ~110 km is consistent with a mechanism where the eastward Hall current driven by the eastward wind leads to a westward electric field that reduces the eastward EEJ. The positive correlation at ~140 km is consistent with a mechanism where the upward Pedersen current driven by the eastward wind leads to a downward electric field, which is mapped to the Hall region (<120 km) and drives a westward Hall current and an eastward electric field that reinforces the eastward EEJ. Our results suggest that the equatorial zonal wind is effective in modulating the electric field and can thus even lead to the reversal of the EEJ from an eastward to a westward current.

Data Availability Statement

The Swarm Level 2 product EEF, including the equatorial electrojet intensity used in this study, can be downloaded at http://swarm-diss.eo.esa.int. The ICON/MIGHTI Level 2.2 product Cardinal Vector Winds (Version 4) is accessible from the ICON website https://icon.ssl.berkeley.edu/Data. The $H_p$ indices
including Hp30 used in this study are provided by GFZ German Research Centre for Geosciences and can be accessed at https://doi.org/10.5880/Hpo.0001. The F10.7 index can be downloaded from the SPDF OMNI-Web database https://omniweb.gsfc.nasa.gov.

References

Alken, P. (2020). Estimating currents and electric fields at low latitudes from satellite magnetic measurements. In Ionospheric multi-space-craft analysis tools (pp. 233–254). Springer. https://doi.org/10.1007/978-3-030-26732-2_11

Alken, P., & Maus, S. (2007). Spatio-temporal characterization of the equatorial electrojet from CHAMP, Orsted, and SAC-C satellite magnetic measurements. Journal of Geophysical Research, 112(A9). https://doi.org/10.1029/2007ja012524

Alken, P., Maus, S., Chulliat, A., Vigneron, P., Sirol, O., & Hulot, G. (2015). Swarm equatorial electric field chain: First results. Geophysical Research Letters, 42(3), 673–680. https://doi.org/10.1002/2014gl062658

Alken, P., Maus, S., Vigneron, P., Sirol, O., & Hulot, G. (2013). Swarm SCARF equatorial electric field inversion chain. Earth Planets and Space, 65(11), 1309–1317. https://doi.org/10.1007/s10547-013-9308-7

Anandarao, B. G., & Raghavarao, R. (1987). Structural changes in the currents and fields of the equatorial electrojet due to zonal and meridional winds. Journal of Geophysical Research, 92(A3), 2514–2526. https://doi.org/10.1029/JA092iA03p02514

Englert, C. R., Harlander, J. M., Brown, C. M., Marr, K. D., Miller, I. J., Stump, J., E., et al. (2017). MICHELON, interferometer for global high-resolution thermospheric imaging (MIGHTI): Instrument design and calibration. Space Science Reviews, 212(1), 553–584. https://doi.org/10.1007/s11214-017-0358-4

Forbes, J. M. (1981). The equatorial electrojet. Review of Geophysics, 19(3), 469–504. https://doi.org/10.1029/RG019i003p00469

Frisi-Christensen, E., Lühr, H., & Hulot, G. (2006). Swarm: A constellation to study the Earth's magnetic field. Earth Planets and Space, 58(4), 351–358. https://doi.org/10.1186/bf03351933

Gurubaran, S., Dhanya, R., Sathiskumar, S., & Patil, P. T. (2011). A case study of tidal and planetary wave coupling in the equatorial atmosphere-ionosphere system over India: Preliminary results. In Aeronomy of the Earth's atmosphere and ionosphere (pp. 177–187). Springer. https://doi.org/10.1007/978-3-642-14711-7_12

Harding, B. J., Chau, J. L., He, M., Englert, C. R., Harlander, J. M., Marr, K. D., et al. (2021). Validation of ICON-MIGHTI thermospheric wind observations: 2. Green-line comparisons to specular meteor radars. Journal of Geophysical Research: Space Physics, 126, e2020a028947. https://doi.org/10.1029/2020ja028947

Harding, B. J., Makela, J. J., Englert, C. R., Marr, K. D., Harlander, J. M., England, S. L., & Immel, T. J. (2017). The MIGHTI wind retrieval algorithm: Description and verification. Space Science Reviews, 212(1), 585–600. https://doi.org/10.1007/s11214-017-0359-3

Immel, T. J., England, S., Mende, S., Heeles, R., Englert, C., Edelstein, J., et al. (2018). The ionospheric connection explorer mission: Mission goals and design. Space Science Reviews, 214(1–3), 1–36. https://doi.org/10.1007/s11214-017-0449-2

Kikuchi, T., Hashimoto, K. K., & Nozaki, K. (2008). Penetration of magnetospheric electric fields to the equator during a geomagnetic storm. Journal of Geophysical Research, 113(A6). https://doi.org/10.1029/2007ja012628

Lühr, H., Maus, S., & Rother, M. (2004). Noontime equatorial electrojet: Its spatial features as determined by the CHAMP satellite. Journal of Geophysical Research, 109(A11). https://doi.org/10.1029/2003ja009656

Manoj, C., Lühr, H., Maus, S., & Nagarajan, N. (2006). Evidence for short spatial correlation lengths of the noontime equatorial electrojet inferred from a comparison of satellite and ground magnetic data. Journal of Geophysical Research, 111(A11). https://doi.org/10.1029/2005ja011855

Matzka, J., Bronkalla, O., Kervalishvili, G., Rauberg, J., & Stolle, C. (2021). Geomorphic Hjo index v. 1.0. GFZ Data Services. https://doi.org/10.5880/Hpo.0001

Pflaß, R., Larsen, A., Aebi, T., Habu, H., Clemmons, J., Freudenreich, H., et al. (2020). Daytime dynamo electrodynamics with spiral currents driven by strong winds revealed by vapor trails and sounding rocket probes. Geophysical Research Letters, 47(15), e2020GL088803. https://doi.org/10.1029/2020GL088803

Reddy, C. A., & Devasia, C. V. (1981). Height and latitude structure of electric fields and currents due to local east-west winds in the equatorial electrojet. Journal of Geophysical Research, 86(A7), 5751–5767. https://doi.org/10.1029/JA086iA07p05751

Richmond, A. D. (1973). Equatorial electrojet-I. Development of a model including winds and instabilities. Journal of Atmospheric and Terrestrial Physics, 35(6), 1083–1103. https://doi.org/10.1016/0021-9169(73)90007-a

Richmond, A. D., & Roble, R. G. (1987). Electricodynamical effects of thermospheric winds from the NACAR thermospheric general circulation model. Journal of Geophysical Research, 92(A11), 12365–12376. https://doi.org/10.1029/ja092ia11p12365

Soares, G., Yamazaki, Y., Matzka, J., Pinheiro, K., Morschhauser, A., Stolle, C., & Alken, P. (2018). Equatorial counter electrojet longitudinal and seasonal variability in the American sector. Journal of Geophysical Research: Space Physics, 123(11), 9906–9920. https://doi.org/10.1029/2018ja025968

Somayajulu, V. V., Cherian, L., Rajeek, K., Ramkumar, G., & Reddi, C. R. (1993). Mean winds and tidal components during counter electrojet events. Geophysical Research Letters, 20(4), 1443–1446. https://doi.org/10.1029/93gl00088

Stening, R. J. (1995). What drives the equatorial electrojet? Journal of Atmospheric and Terrestrial Physics, 57(10), 1117–1128. https://doi.org/10.1016/0021-9169(94)00127-a

Stolle, C., Manoj, C., Lühr, H., Maus, S., & Alken, P. (2008). Estimating the daytime equatorial ionization anomaly strength from electric field proxies. Journal of Geophysical Research, 113(A9). https://doi.org/10.1029/2007ja012781

Tapping, K. F. (2013). The 10.7 cm solar radio flux (F10.7). Space Weather, 11(7), 394–406. https://doi.org/10.1002/swe.20664

Yamazaki, Y., & Kosch, M. J. (2015). The equatorial electrojet during geomagnetic storms and substorms. Journal of Geophysical Research: Space Physics, 120(3), 2276–2287. https://doi.org/10.1002/2014ja020773

Yamazaki, Y., & Maute, A. (2017). Sq and EEJ–A review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents. Space Science Reviews, 206(1–4), 299–405. https://doi.org/10.1007/s11214-016-0282-z

Yamazaki, Y., Richmond, A. D., Maute, A., Liu, H.-L., Pedatella, N., & Sassi, F. (2014). On the day-to-day variation of the equatorial electrojet during quiet periods. Journal of Geophysical Research: Space Physics, 119(8), 6966–6980. https://doi.org/10.1002/2014ja020243

Zhou, Y.-L., Lühr, H., Xu, H.-w., & Alken, P. (2018). Comprehensive analysis of the counter equatorial electrojet: Average properties as deduced from champ observations. Journal of Geophysical Research: Space Physics, 123(6), 5159–5181. https://doi.org/10.1029/2018ja025526