



Radio Science

RESEARCH ARTICLE

10.1002/2016RS005966

Special Section:

Ionospheric Effects Symposium
2015

Key Points:

- We examined the relationship between EEJ, TEC, and S_4 index in low-latitude ionosphere
- We found correlation/dependencies between EEJ strengths and TEC anomaly crest separation
- We found little or no correlation between EEJ strengths and S_4 index

Correspondence to:

S. M. Khadka,
sovit.khadka@bc.edu

Citation:

Khadka, S. M., C. Valladares, R. Pradipta, E. Pacheco, and P. Condor (2016), On the mutual relationship of the equatorial electrojet, TEC and scintillation in the Peruvian sector, *Radio Sci.*, 51, 742–751, doi:10.1002/2016RS005966.

Received 1 FEB 2016

Accepted 21 MAY 2016

Accepted article online 31 MAY 2016

Published online 24 JUN 2016

On the mutual relationship of the equatorial electrojet, TEC and scintillation in the Peruvian sector

Sovit M. Khadka^{1,2}, Cesar Valladares², Rezy Pradipta², Edgardo Pacheco³, and Percy Condor³
¹Physics Department, Boston College, Chestnut Hill, Massachusetts, USA, ²Institute for Scientific Research, Boston College, Newton, Massachusetts, USA, ³Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima, Peru

Abstract This paper presents the interrelationship between the equatorial electrojet (EEJ) strength, Global Positioning System (GPS)-derived total electron content (TEC), and postsunset scintillation from ground observations with the aim of finding reliable precursors of the occurrence of ionospheric irregularities. Mutual relationship studies provide a possible route to predict the occurrence of TEC fluctuation and scintillation in the ionosphere during the late afternoon and night respectively based on daytime measurement of the equatorial ionosphere. Data from ground based observations in the low latitudes of the west American longitude sector were examined during the 2008 solar minimum. We find a strong relationship exists between the noontime equatorial electrojet and GPS-derived TEC distributions during the afternoon mediated by vertical $E \times B$ drift via the fountain effect, but there is little or no relationship with postsunset ionospheric scintillation.

1. Introduction

On account of its peculiar properties, low-latitude ionosphere has become one of the most widely studied research areas in the past few decades. Even though forecasting the ionospheric irregularities phenomena is a challenging topic in the scientific community, many researchers have contributed significantly. The interest in the low-latitude ionosphere irregularities has increased recently. This is because the behavior of equatorial ionosphere differs significantly from the behavior of the ionosphere in other regions. The special magnetic field geometry at the geomagnetic equator of the Earth leads to various geomagnetic as well as ionospheric phenomena, many of which are unique. The transport of charged particles along the geomagnetic field lines in the equatorial region is associated with a two-humped latitudinal distribution of electron density, with a minimum at the magnetic equator. Another distinguishing feature of the equatorial ionosphere is the relative abundance of ionospheric electron density irregularities [Cohen, 1967; Onwumechili, 1997; Kelley, 2009]. The equatorial anomaly in the topside ionosphere and its correlation with E region current system near the magnetic equator of the Earth have been studied by many researchers [MacDougall, 1969; Fejer and Kelley, 1980]. Plasma structures are produced in the sporadic E layer, whereas equatorial plasma bubbles (EPB) are produced at low latitudes of the F region ionosphere. Plasma irregularities in the ionosphere are usually field aligned and vary as a function of space and time [Balsley, 1970; Onwumechili and Agu, 1981; Onwumechili, 1997]. Predicting ionospheric irregularities is recognized as one of the highest priorities in the national space weather program implementation plan. This is because by knowing ionospheric electron density irregularities, adverse space weather effects on GPS navigation, telecommunications, and many other technologies can be prevented and will also guide the way to construct better models of irregularity development and, eventually, scintillation prediction [Kintner et al., 2007; Doherty et al., 2004]. Therefore, understanding and forecasting the occurrence and impact of ionospheric irregularities is a critical societal need.

In presence of solar radiation, the electron density in the E region ionosphere starts to increase and the H component (northward) of the magnetic field shows a steady enhancement until around noon, after which it starts decreasing. Such magnetic field behavior is due to an eastward electric field during daytime that causes intense current system to exist in the low latitudes. An intense electric current flowing eastward in the ionospheric E layer in a narrow belt at latitudes ($\pm 2^\circ$) centered at the dip equator is called the equatorial electrojet (EEJ), a term coined by Chapman [1951]. Owing to this electric field and horizontal magnetic field at the equator, $E \times B$ drifts are produced and the electrons (plasma) are lifted to higher altitudes. The plasma lifts to a certain height and then diffuses down along magnetic field lines to the F

region at higher latitudes (15° – 20°). The plasma, diffused down around 15° – 20° latitudes from either sides of magnetic equator creating two plasma crests, is called equatorial ionization anomaly (EIA). The daytime vertical plasma drift in the equatorial F region of the ionosphere is the key transport mechanism for determining the electron density profiles as a function of altitude, latitude, and local time [Deshpande *et al.*, 1977; Chen *et al.*, 2008; Banola *et al.*, 2001]. The equatorial daytime vertical drift is a very important element for ionospheric theoretical models. The strength of the daytime equatorial electrojet can be measured using a pair of magnetometers, one situated on the magnetic equator and the other displaced by 6° to 9° latitude away. The difference between noontime enhancement of the H component observed by two magnetometers placed on and off equator by $\sim 6^{\circ}$ to 9° is related to the equatorial electrojet strengths and also quantitatively with vertical $E \times B$ drift in the F region ionosphere [Rastogi, 1962; Rastogi and Klobuchar, 1990; Anderson *et al.*, 2002, 2004]. In the absence of EEJ, the magnetometers do not provide reliable vertical drifts.

The equatorial ionosphere starts to structure after sunset causing plasma instabilities called equatorial plasma bubbles (EPB). Consequently, one can expect the occurrence of total electron content (TEC) depletions and scintillation in the low latitudes after sunset because of the changes in noontime EEJ strengths and vertical drifts. The TEC distribution is an indicator of ionospheric variability and defined as the total number of electrons integrated along the path from receiver (GPS) to satellite. It is measured in units of TECU (1 TEC unit = 10^{16} el/m²). The EPB that occurs at the bottomside of the F region ionosphere thereby adversely affect the amplitude and phase of the radio waves in various frequency bands. An unusual fluctuation in the phase/amplitude of a radio frequency signal, when it passes through an ionospheric region of random irregularities in electron density that acts as a variable refractive index in the medium, is called ionospheric scintillation. These scintillation phenomena mainly occur in the geomagnetic equatorial region even though observed at all latitudes with less intensity. The signal distortion caused by scintillation can degrade the performance of navigation system and generate errors in received messages. High priority has been given to the study of ionospheric scintillation because of its significant impact on satellite radio communication. Quantitatively, scintillation intensity is measured as scintillation index (S_4) and defined as normalized variance of the signal power [Basu *et al.*, 2002; Valladares *et al.*, 2004; Wernik *et al.*, 2004]. The physical processes concerning the generation, dynamics and decay of scintillations are known to vary widely. Observational results provide consistent evidence that day time EEJ and $E \times B$ drifts are well correlated. Association between postsunset EIA, EPB/scintillation, and $E \times B$ drift is also reported in many research articles. Near sunset prereversal $E \times B$ drifts is the most likely key mechanism responsible for the global large-scale variations in longitudinal distribution of evening EIA enhancement and plasma bubble occurrence rates [Li *et al.*, 2008]. Equatorial plasma bubbles are the prominent candidate for the cause of scintillation in radio wave propagation, but there are almost no studies on correlating daytime EEJ hence vertical $E \times B$ drift and nighttime scintillation. The present study focuses on particular characteristic of scintillation and irregularities. Incorporating such evidences, our study aims to develop a technique to predict the interconnection of disturbances of afternoon GPS-derived TEC and scintillation after sunset on the basis of noontime electrojet strengths.

2. Data Selection and Analysis

The data from a permanent array of geophysical instruments deployed in the low-latitude region of South America have had great impact in the study of equatorial ionospheric phenomena. It has already been revealed that the equatorial vertical $E \times B$ drift velocity is an important parameter for the prediction and analysis of the structures and dynamics of the ionosphere [Scherliess and Fejer, 1999; Kelley, 2009; Stoneback *et al.*, 2011; Stoneback and Heelis, 2014]. Because of its quite different characteristics, the magnetic equator is a unique region in the ionosphere. The low-latitude region along the western meridian of South America is very useful for a long-term study of equatorial ionospheric electrodynamics. This is because the magnetic equator in the Peruvian sector has not changed significantly for more than a decade. The geomagnetic equator passes through Jicamarca (Peru) located at 12° latitude south of the geographic equator.

Data analysis is mostly executed for low solar activity conditions from the stations located in the Peruvian sector. The daily average of the solar radio flux $F_{10.7}$ index was less than 85 during most of this period of extremely low solar activity period and offers an opportunity to study the quiet time relationship at lower

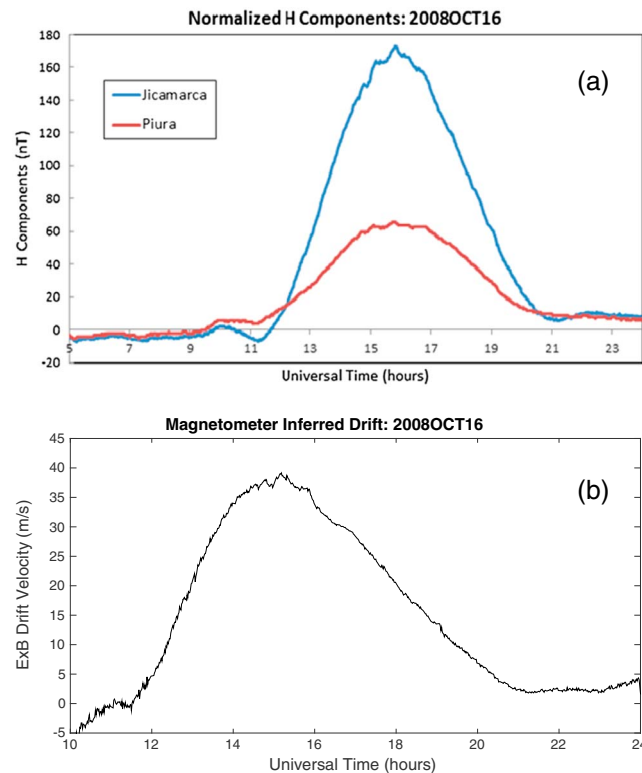


Figure 1. (a) Normalized horizontal component, H , of the Earth from two magnetometer stations; one at EEJ zone (blue curve) in Jicamarca and other off the EEJ zone (red curve) in Piura whose difference refers EEJ. (b) Magnetometer inferred vertical $E \times B$ drift using artificial neural network technique.

[Rastogi and Klobuchar, 1990; Anderson et al., 2002]. The magnetometer inferred vertical drift is accurate if there is ionospheric current in the E layer of the ionosphere. Here an artificial neural network technique has been considered in order to establish the nonlinear relationship between $E \times B$ drift velocities and the most relevant six inputs to the network. Artificial multilayer feed-forward neural networks have powerful function-approximation capabilities for pattern recognition, control, and signal processing [Haykin, 2005]. The six inputs for the neural network we have used are the year, DOY (day of the year), $F_{10.7}$, AP index, LT (local time), and dH (difference of H measured at Jicamarca and Piura), which are regarded as controlling parameters for the vertical drifts. The final output from the neural network training analysis is compared with the desired output which is measured Jicamarca incoherent scatter radar drift in the existing case. The weights in the multilayer neural network are obtained from many epochs of the six inputs in order to calculate the relationship with $E \times B$ drift velocities.

Figure 1a shows the variation of the normalized H components of the Earth against universal time (UT) observed from equatorial magnetometer station, Jicamarca (blue curve), and off-equator station, Piura (red curve). It is clear that there is an enhancement of H at local noon time. The difference of two curves (blue and red) gives the net EEJ contribution to H at the geomagnetic equator. Figure 1b is a sample plot of the $E \times B$ vertical drift velocity using the neural network technique with six inputs as described above. The plot in Figure 1b shows that the $E \times B$ vertical drift gradually increases and becomes maximum around local noontime then starts to decrease gradually following the variation pattern of EEJ. Equatorial electrojet (EEJ) and hence vertical drift strength are key factors that determine the evolution of EIA anomaly formed by TEC distributions. It is a driving force for vertical plasma drift that lifts equatorial plasma to higher altitudes which then diffuses down the Earth's magnetic field lines to form EIA crests around $\pm 15^\circ$ geomagnetic latitude, consequently removing plasma from around the magnetic equator. Having established the quantitative relationship between daytime electrojet strengths and inferred $E \times B$ vertical

solar activity levels than that previously observed. For the current analysis, we have used data from the recent solar minimum years 2008. Measurements from ground based chains of GPS (Global Positioning System) receivers and magnetometers at low latitudes in the Peruvian sector of South America were examined.

2.1. Equatorial Electrojets and Estimation of Vertical Drifts

For the current analysis, magnetometer data from Jicamarca (geog. 11.9°S , 283.1°E , 0.8°N dip latitude) and Piura (geography 5.2°S , 279.4°E , 6.8°N dip latitude) in the Peruvian sector where universal time is local time + 5 h, are used to get the EEJ strengths. The horizontal components of Earth's magnetic field (denoted H) from each station are normalized with its midnight average background values for each day. Then the H component observations from these two magnetometers are subtracted to eliminate the Dst ring current and Sq dynamo contributions to get only the electrojet contribution to H

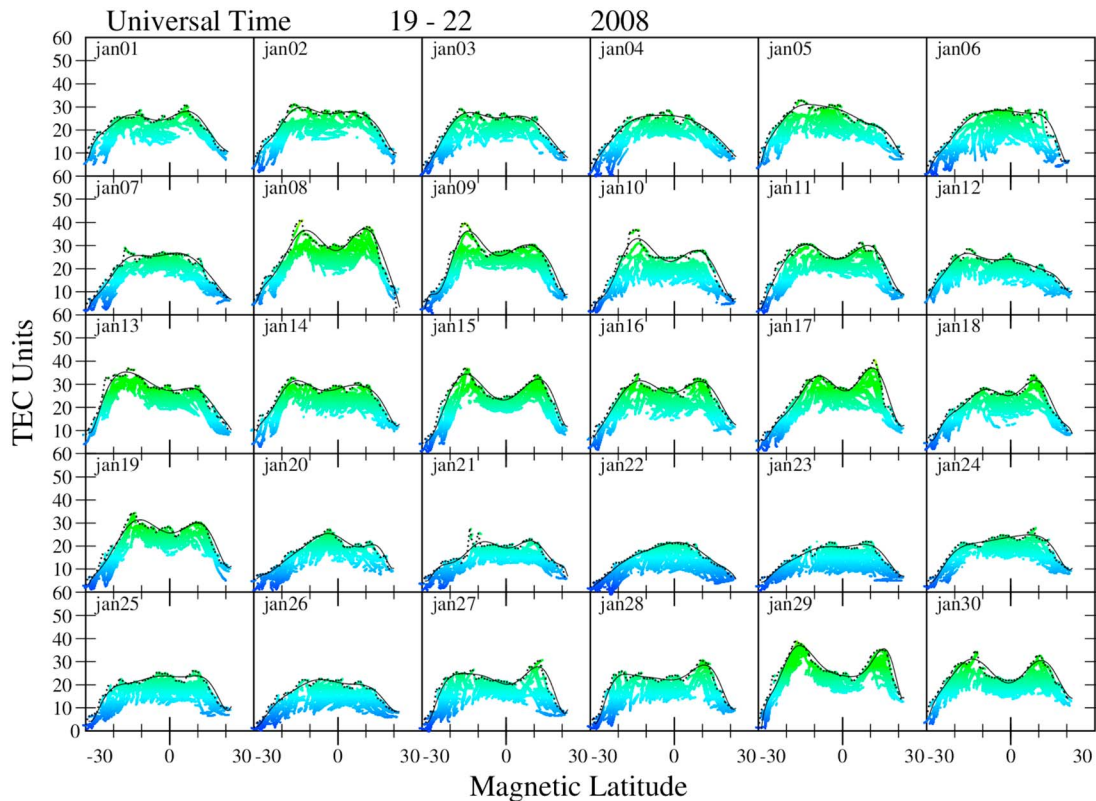


Figure 2. Vertical TEC data during 19–22 UT obtained from GPS networks and their profiles within $\pm 30^\circ$ magnetic latitude in January 2008. Dotted and continuous black curve represent maximum values of TEC data and fitted data points, respectively.

drifts in the ionospheric *F* region in the west coast of South America using the *Anderson et al.* [2004] technique, our next intention is to investigate the dependence of the TEC and nighttime scintillation.

2.2. Determination of Latitudinal TEC Profiles

The equivalent vertical TEC derived from GPS receivers spread along the Peruvian sector (as seen in Figure 1 of *Seemala and Valladares* [2011]) of South America (76°W) at about 12° geographic latitude is used to detect the strength and occurrence of the equatorial anomaly which is caused by vertical plasma drifts in association with EEJ. The current study has been done using vertical TEC data obtained from dual frequency GPS receivers during the low solar activity period of the years 2008 distributed at the magnetic equator and either side of it up to and beyond the ionization anomaly locations in South America. The TEC enhancements that are measured with the LISN (Low-Latitude Ionospheric Sensor Network) and other networks of GPS receivers operating in South American occurred quite often during low solar activity periods [*Valladares and Chau*, 2012]. Crests of TEC anomalies have a limited longitudinal extension whose distributions are determined by the fountain effect that forms EIAs. Figure 2 shows how TEC observed from different GPS stations are extracted for the present analysis. First, TEC data for particular hours are sorted and then plotted against $\pm 30^\circ$ magnetic latitude. On the scatterplot of TEC, a polynomial fit is done about their maximum values. Such extracted polynomial fitted data are then further utilized to get surface plots to see their day to day variability and the shape of the anomalies. Figure 2 shows 30 day of January 2008 data against magnetic latitude during 19–22 UT to indicate the strengths and spatial separations of anomaly peaks in EIAs. The continuous black curves on each of these plots are the polynomial fit on particular magnetic latitude, whereas dotted black points represent maximum data points in each of magnetic latitude. The strength of TEC anomaly is calculated by taking the maximum value of the TEC. Exceptions are seen in the most of the days during and near solstice period. As reported by *Chau et al.* [2009], there was a strong sudden stratospheric warming (SSW) event from 17 to 26 January 2008 which

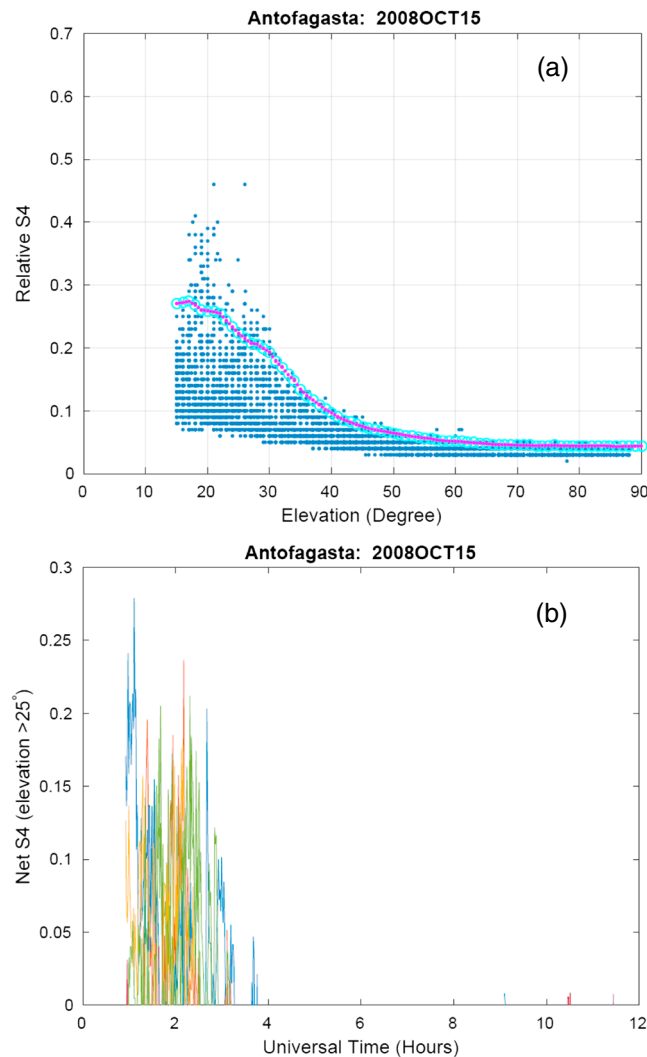


Figure 3. (a) Relative S_4 index observed at Antofagasta GPS station and threshold line (pink) against elevation. (b) Net S_4 index against universal time after subtracting the background and low elevation contribution.

line. We construct a statistical distribution of the general S_4 index as a function of the line-of-sight elevation. The mean value of S_4 index is calculated for each 5° of elevation angle. A threshold value is calculated using the mean value plus two times the standard deviation for each elevation interval. The net values of scintillation (S_4 index) are obtained after removing the effect of the low elevations and background values. Subtracting threshold values from S_4 data gives net S_4 index values.

The example plots shown in Figure 3 illustrate the above procedure. Figure 3a shows altitudinal variations of S_4 index as observed by GPS receiver located at Antofagasta (near the southern crest of the EIAs). The pink line over S_4 data is a model threshold curve which is a border curve between background (below pink curve) and net S_4 index (above pink curve) data. When the model threshold curve is subtracted and plotted against universal time, the result of Figure 3a looks like that in Figure 3b. Figure 3b is the 12 h variation of net S_4 index after sunset.

This study mainly emphasizes the occurrence of ionospheric disturbances phenomena observed via TEC, S_4 index, and associated EEJ accompanied by daytime equatorial vertical $E \times B$ drift from magnetometer data. This paper addresses the linkage of such phenomena with EEJ strength, TEC, and scintillation S_4 index.

strongly affects the daytime, vertical $E \times B$ drift velocities and is largely responsible for the lack of EIA in the afternoon from 20 to 26 January. Our analysis has also replicated the physical evidence as signatures of SSW's impact on EIAs to eliminate its anomaly peaks for those days as seen in Figure 2. The separation of the anomaly peaks is calculated in the unit of latitude by taking the difference of latitudinal location of the crests. That many anomaly peaks look asymmetric might be due to other effects than EEJ, such as meridional neutral winds and composition changes due to magnetic perturbations.

2.3. Determination of Net Ionospheric Scintillation S_4 Index

The strongest level of ionospheric scintillation is observed in the equatorial regions [Rastogi, 1983; Basu et al., 2002; Jiao et al., 2013]. It should be noted here that the term scintillation S_4 index used in this paper refers to the amplitude fluctuations received by GPS. Multipath interference and background scintillation can also produce fluctuations in signal intensity. We develop a model threshold that removed such contamination in the raw S_4 data and gives net S_4 index associated with scintillations. The threshold model has been used to filter scintillation from the raw data. The S_4 index is detrended based on the threshold

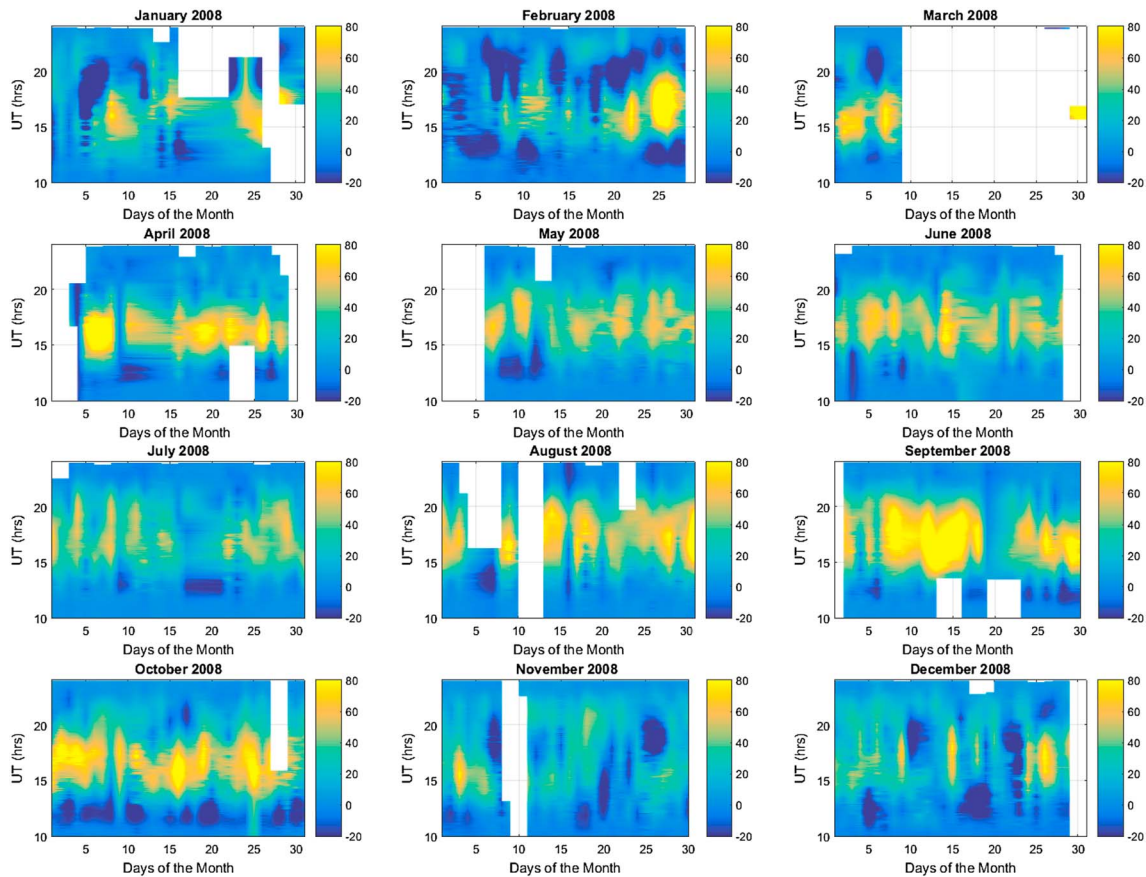


Figure 4. Surface plots showing the day-to-day variability of EEJ during 10–24 UT of the day observed using magnetometers located at Jicamarca and Piura stations during solar minimum 2008.

3. Concurrent Observations of EEJ, TEC, and S_4 Index

The data plots presented here are chosen from the pool of analysis that has been done for the year 2008. The results of the day-to-day analysis of EEJ, TEC, and S_4 data of 2008 are demonstrated in the comparative surface plots in Figures 4–6. For each of the monthly plots, EEJs are clearly seen enhanced and centered about local noon (17 UT) time. The characteristics of the surface plot in Figure 4 show that local noontime EEJ is more intense during/around equinox months than that in solstice months. Latitudinal TEC variations during 19–20 UT on equinox and solstice days in Figure 5 show a similar variation pattern as that seen in electrojet variations. The location, strengths, and the span of the anomaly crests show a large degree of variability. From visual inspection of Figure 4, it can be said that the EEJ on March and September equinox (around ± 30) days become strong and a similar pattern is followed by TEC profiles in Figure 5. The corresponding distributions of EEJ and TEC are faint in June and December solstice days. These observations show that local late afternoon TEC variations are very dependent on the corresponding EEJ variations near local noontime. This relationship study can support the idea of forecasting TEC fluctuations a few hours earlier than their occurrence by knowing EEJ at low latitudes.

On the other hand, the net S_4 variation observed from GPS stations in the Peruvian longitude sector does not show any concrete relationship with daytime EEJ variation during equinox and solstice days. In Figure 6, day-to-day variation of net S_4 during 00–12 UT has greater values not only during equinox but also beyond. As seen in Figure 6, net S_4 is higher in January as well as in November. The next section presents the case study events for the correlation analysis between EEJ and the net S_4 index. This study corroborates that there is not a strong relationship between peak value of EEJ and S_4 index in solar minimum periods.

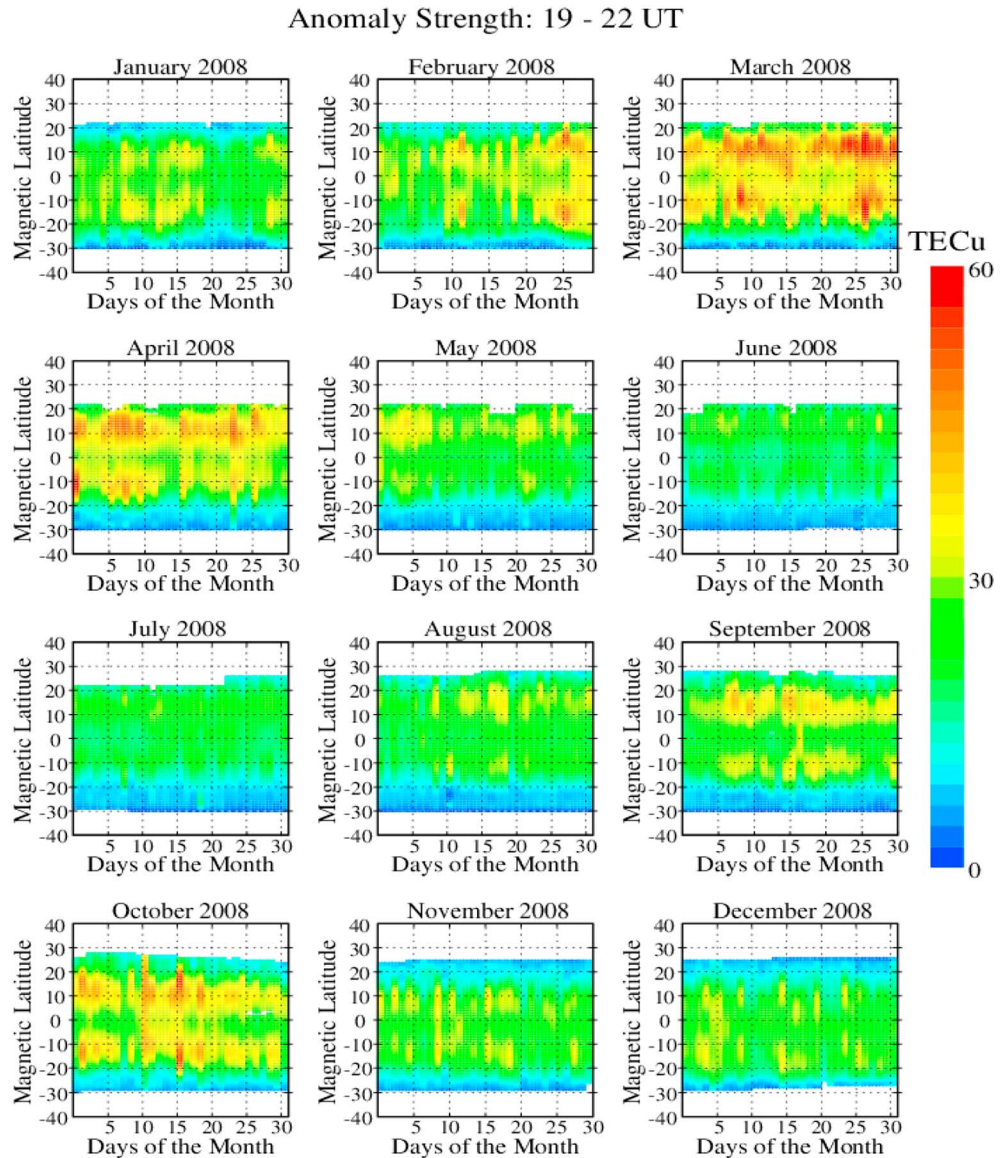


Figure 5. Latitudinal distributions of day-to-day variability TEC profiles within $\pm 30^\circ$ from magnetic equator in the Peruvian sector.

4. Discussion

We have conducted a careful analysis of magnetometer, GPS, and scintillation data to draw some conclusions on the role of daytime electric fields on the TEC distributions and S_4 scintillation index. The strong Electrojet current in the E region ionosphere associated equatorial vertical $E \times B$ plasma drift in the F region ionosphere, and the accompanying noontime enhancement of H component, might be connected to electron density irregularities and corresponding plasma bubbles that show an indication of the TEC disturbances after sunset in the F region ionosphere.

The study of the daytime equatorial electrojet can provide a precise and reliable signature for forecasting ionospheric dynamics. The data presented in Figure 7 supports the statement that the studies of noontime EEJ have some sort of preinformation on the forthcoming ionospheric plasma behavior. As demonstrated in Figure 4, EEJ reflects an intense band of eastward electric field at local noontime along the magnetic equator. The daytime eastward current in E region ionosphere regulates the strength of EEJ as well as vertical drift. Strong EEJ makes greater vertical drift. EEJ looks stronger during March and September equinoxes seasons than that in June and December solstice seasons as shown in Figure 4. There are well-formed late afternoon

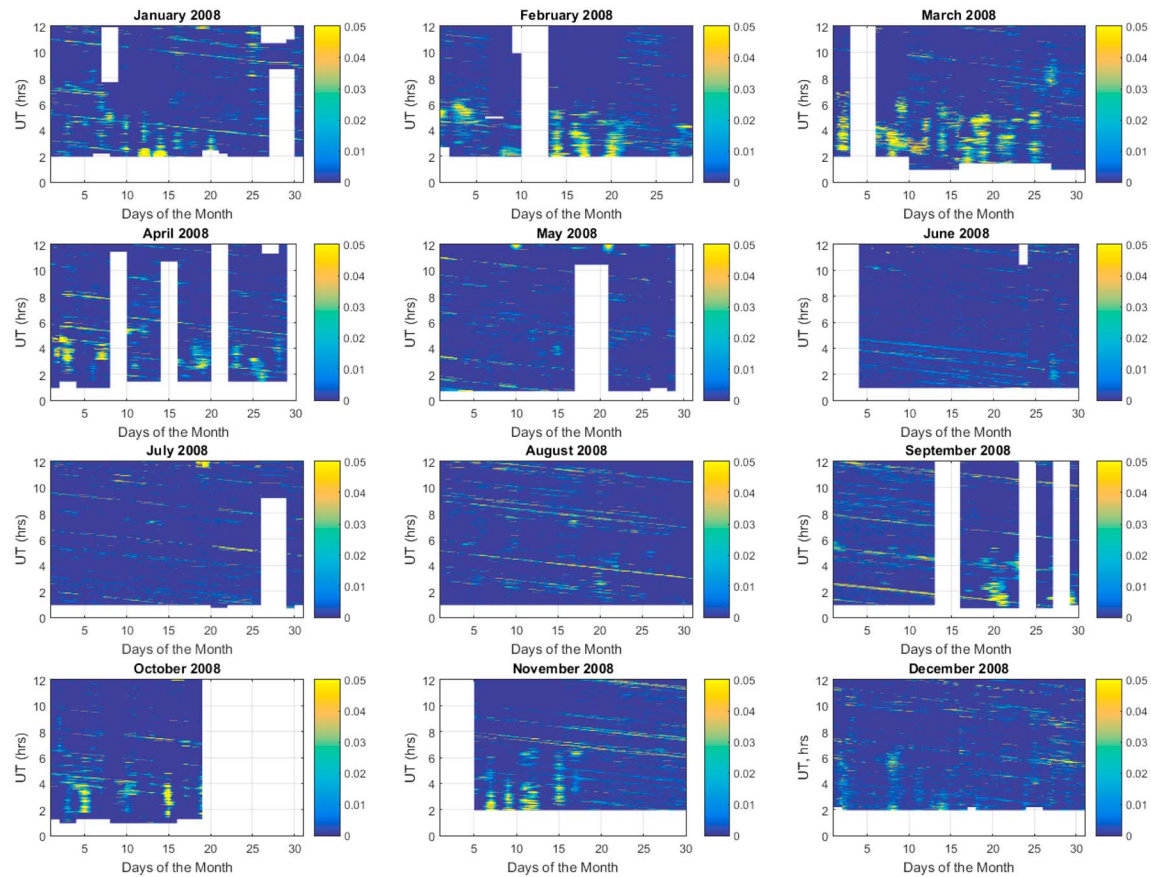


Figure 6. Day-to-day variability of scintillation S_4 index during 00–12 UT obtained from GPS receivers spread on magnetic equator to either sides of anomaly region during solar minimum 2008.

anomaly crests if there is a strong corresponding noontime EEJ. The transport of the low-latitude ionospheric plasma controls the TEC distribution which is originated by the vertical $E \times B$ drift and electrojet; both of these are driven by eastward electric field. TEC distributions most of the days are not placed symmetrically with respect to the magnetic equator and do not have the same latitudinal span of anomaly crests as seen in Figure 5. We have chosen clear anomaly crest periods in September equinox and analyzed for ± 30 days from the equinox day to see the dependence of anomaly separation on EEJ strengths. The strengths and separation of anomaly crests shown in Figure 5 are in good agreement with the EEJ strengths. The correlation plot in Figure 7a gives a clear picture of the linear dependence of peak values of late afternoon (19–22 UT) TEC and Figure 7b that of the separation of the anomaly crests on the noontime EEJ strength. By comparing the TEC in Figures 5 and 7a and 7b, it can be said that higher EEJ and hence vertical drift causes higher electron density in the equatorial ionization anomaly regions and also cause the EIA crests to move farther from the magnetic equator region. The simultaneous study of the dependence of EIA strengths and the separation of anomaly crests upon the noontime electrojet is one of the main aspects of this analysis.

Another analysis is done to obtain information of nighttime scintillation index S_4 based on corresponding daytime electrojet strength. For the dependence analysis, looking at the S_4 data distributions against EEJ variation, the correlation is studied in two regimes as in Figures 7c and 7d. S_4 data demonstrated in Figures 7c and 7d are taken from Cuzco GPS station located near the magnetic equator region during 00–12 UT in 2008. There is a signature of linear dependence of S_4 index (>0.2) on peak value of EEJ as shown in Figure 7c but the linear curve looks parallel to the x axis for S_4 index (<0.2) in Figure 7d. Slight dependence of nighttime S_4 index with value greater than 0.2 is seen with daytime peak value of EEJ, but no correlation is seen with it if S_4 index value goes below 0.2. There are many factors that inhibit nighttime scintillation. One clue is that the scintillation should be interpreted on the basis of the starting time of magnetic disturbance. This study

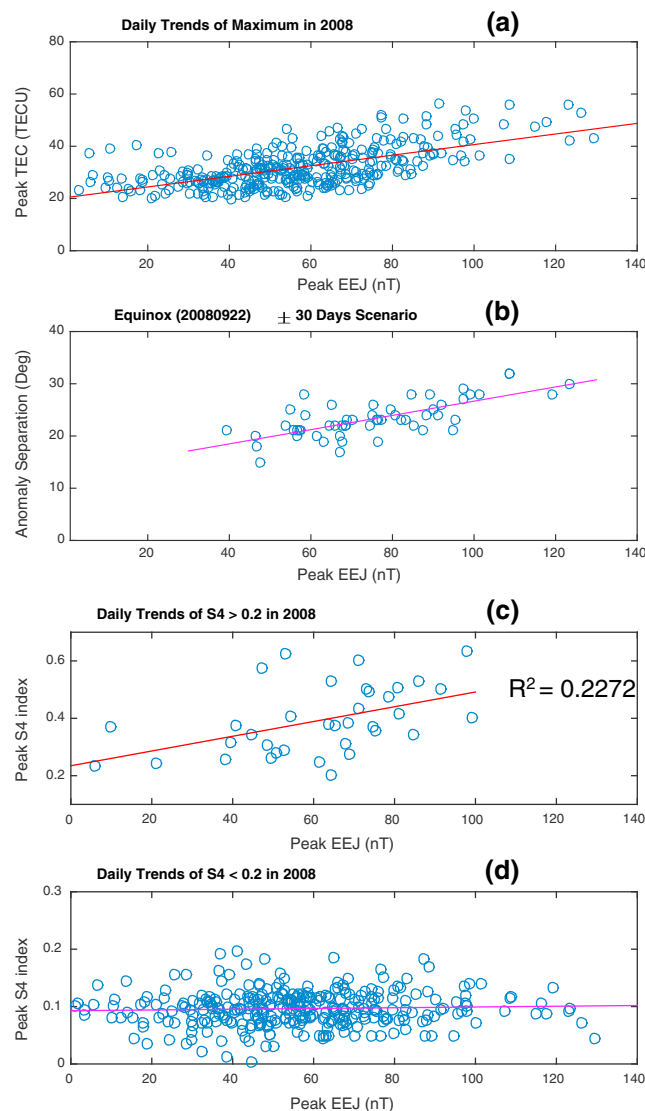


Figure 7. Correlation analysis of the daily trends of the peak value of equatorial electrojet data in the year 2008 with (a) maximum TEC during 19–22 UT, (b) the separation of the anomaly crests on equinox (22 September) ± 30 days, (c) S_4 index greater than 0.2, and (d) S_4 less than 0.2 observed during 00–12 UT.

ometers, ionosondes, GPS receivers, and radar measurements is needed to establish the precise relationships between them under various background conditions. As in the polar region, the equatorial region is also highly susceptible to ionospheric scintillations during strong solar activity periods. Extending the analysis to solar maximum conditions with a larger database of nighttime S_4 index (above 0.2) will certainly be worthwhile project in accessing correlations with peak values of daytime EEJ. Collection of long-term statistics relating magnetometer-derived drifts and radar-measured drifts can contribute significantly to a more economical way to characterize the occurrence of ionospheric irregularities. The development of such model and statistical relations can help in real-time ionospheric monitoring and improvement in GPS navigation capabilities.

References

- Anderson, D., A. Anghel, K. Yumoto, M. Ishitsuka, and E. Kudeki (2002), Estimating daytime vertical $E \times B$ drift velocities in the equatorial F -region using ground-based magnetometer observations, *Geophys. Res. Lett.*, 29(12), 1596, doi:10.1029/2001GL014562.
- Anderson, D., A. Anghel, J. Chau, and O. Veliz (2004), Daytime vertical $E \times B$ drift velocities inferred from ground-based magnetometer observations at low latitudes, *Space Weather*, 2, S11001, doi:10.1029/2004SW000095.

also reveals that the noontime EEJ is not a good predictor for the nighttime ionospheric scintillation in the low latitude during low solar activity periods.

5. Summary and Conclusions

A comparative study of electrojet current strength, TEC, and S_4 scintillation index from magnetometers and GPS receivers at low-latitude stations has been conducted to investigate potential predictive signatures for the occurrence of disturbances in the equatorial ionosphere. We found that days with higher value of the equatorial electrojet and hence higher daytime vertical $E \times B$ drift are associated with higher TEC values and a greater separation of the equatorial anomaly crests. But there is no apparent correlation with the S_4 scintillation index observed later during the nighttime. Minor correlation of peak value of electrojet with net S_4 greater than 0.2 likely exists, but there is no correlation at all below 0.2 for the solar minimum year 2008. This research study suggests that there is a clear association between magnetometer observed daytime EEJ and the strength and distribution of GPS-derived TEC during late afternoon in magnetic low latitudes. However, there is little correlation between peak EEJ and the corresponding S_4 scintillation index observed after sunset.

A large data set on EEJ strength, $E \times B$ drift velocity, and TEC using magnet-

Acknowledgments

The authors would like to thank Claudio Brunini and Mauricio Gende of the Geocentric Reference System for the Americas (SIRGAS) and Michael Bevis from Ohio State University-Central and Southern Andes GPS Project (OSU-CAP) for providing GPS data. Hector Mora from the Colombian Institute of Geology and Mining (INGEOMINAS) provided RINEX files from several stations in Colombia. One of the authors, Valladares, was partially supported by Air Force Research Laboratory contract FA8718-09-C-0041 and NSF grants ATM-1135675 and ATM-1242476. The Low-Latitude Ionospheric Sensor Network (LISN) is a project led by Boston College in collaboration with the Geophysical Institute of Peru and other institutions that provide information in benefit of the scientific community. We thank all organizations and persons that are supporting and operating receivers in LISN. We thank Robert Sheehan for his helpful comments and suggestions on the paper. The TEC values presented in this publication are stored in the LISN web page (<http://lisn.igpp.gob.pe>).

- Balsley, B. B. (1970), Equatorial electrojet: Seasonal variation of the reversal times, *J. Geophys. Res.*, *75*(22), 4369–4371, doi:10.1029/JA075i022p04369.
- Banola, S., B. M. Pathan, and D. R. K. Rao (2001), Strength of the equatorial electrojet and geomagnetic activity control on VHF scintillations at the Indian longitudinal zone, *Indian J. Radio Space Phys.*, *30*, 163–171.
- Basu, S., K. M. Groves, S. Basu, and P. J. Sultan (2002), Specification and forecasting of scintillations in communication and navigation links: Current status and future plans, *J. Atmos. Sol. Terr. Phys.*, *64*(16), 1745–1754, doi:10.1016/S1364-6826(02)00124-4.
- Chapman, S. (1951), The equatorial electrojet as detected from the abnormal electric current distribution above Huancayo, Peru and elsewhere, *Archiv Meteorol. Geophysik Bioklimatol. Ser. A*, *4*(1), 368–390, doi:10.1007/BF02246814.
- Chau, J. L., B. G. Fejer, and L. P. Goncharenko (2009), Quiet variability of equatorial $E \times B$ drifts during a sudden stratospheric warming event, *Geophys. Res. Lett.*, *36*, L05101, doi:10.1029/2008GL036785.
- Chen, C. H., J. Y. Liu, K. Yumoto, C. H. Lin, and T. W. Fang (2008), Equatorial ionization anomaly of the total electron content and equatorial electrojet of ground-based geomagnetic field strengths, *J. Atmos. Sol. Terr. Phys.*, *70*(17), 2172–2183, doi:10.1016/j.jastp.2008.09.021.
- Cohen, R. (1967), The equatorial ionosphere, in *Physics of Geomagnetic Phenomena*, edited by S. Matsushita and W. Campbell, Academic Press, New York.
- Deshpande, M. R., R. G. Rastogi, H. O. Vats, G. Sethia, J. A. Klobuchar, A. R. Jain, B. S. Subbarao, V. M. Patwari, A. V. Janve, and R. K. Rai (1977), Effect of electrojet on the total electron content of the ionosphere over the Indian subcontinent, *Nature*, *267*, 599–600, doi:10.1038/267599a0.
- Doherty, P., A. J. Coster, and W. Murtagh (2004), Space weather effects of October–November 2003, *GPS Solutions*, *8*(4), 267–271, doi:10.1007/s10291-0040109-3.
- Fejer, B. G., and M. C. Kelley (1980), Ionospheric irregularities, *Rev. Geophys.*, *18*(2), 401–454, doi:10.1029/RG018i002p00401.
- Haykin, S. (2005), *Neural Networks: A Comprehensive Foundation*, 2nd ed., Pearson Education, Delhi, India.
- Jiao, Y., Y. T. Morton, S. Taylor, and W. Pelgrum (2013), Characterization of high-latitude ionospheric scintillation of GPS signals, *Radio Sci.*, *48*, 698–708, doi:10.1002/2013RS005259.
- Kelley, M. C. (2009), *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, 2nd ed., Academic Press, San Diego, Calif.
- Kintner, P. M., B. M. Ledvina, and E. R. de Paula (2007), GPS and ionospheric scintillations, *Space Weather*, *5*, S09003, doi:10.1029/2006SW000260.
- Li, G., B. Ning, L. Liu, B. Zhao, X. Ye, S.-Y. Su, and S. Venkatraman (2008), Correlative study of plasma bubbles, evening equatorial ionization anomaly, and equatorial prereversal $E \times B$ drifts at solar minimum, *Radio Sci.*, *43*, RS4005, doi:10.1029/2007RS003760.
- MacDougall, J. W. (1969), The equatorial ionospheric anomaly and equatorial electrojet, *Radio Sci.*, *4*(9), 805–810, doi:10.1029/RS004i009p00805.
- Onwumechili, C. A. (1997), *The Equatorial Electrojet*, Gordon and Breach Science Publishers, Netherlands.
- Onwumechili, C. A., and C. E. Agu (1981), Longitudinal variation of equatorial electrojet parameters derived from POGO satellite observation, *Planet. Space Sci.*, *29*(6), 627–634, doi:10.1016/0032-0633(81)90111-2.
- Rastogi, R. G. (1962), Longitudinal variation in the equatorial electrojet, *J. Atmos. Terr. Phys.*, *24*(12), 1031–1040, doi:10.1016/0021-9169(62)90158-7.
- Rastogi, R. G. (1983), Equatorial electrojet and radio scintillations, *J. Atmos. Terr. Phys.*, *45*(10), 719–728, doi:10.1016/S0021-9169(83)80030-0.
- Rastogi, R. G., and J. A. Klobuchar (1990), Ionospheric electron content within the equatorial F_2 layer anomaly belt, *J. Geophys. Res.*, *95*(A11), 19,045–19,052, doi:10.1029/JA095iA11p19045.
- Scherliess, L., and B. G. Fejer (1999), Radar and satellite global equatorial F region vertical drift model, *J. Geophys. Res.*, *104*(A4), 6829–6842, doi:10.1029/1999JA900025.
- Seemala, G. K., and C. E. Valladares (2011), Statistics of total electron content depletions observed over the South American continent for the year 2008, *Radio Sci.*, *46*, RS5019, doi:10.1029/2011RS004722.
- Stoneback, R. A., and R. A. Heelis (2014), Identifying equatorial ionospheric irregularities using in situ ion drifts, *Ann. Geophys.*, *32*, 421–429, doi:10.5194/angeo-32-421-2014.
- Stoneback, R. A., R. A. Heelis, A. G. Burrell, W. R. Coley, B. G. Fejer, and E. Pacheco (2011), Observations of quiet time vertical ion drift in the equatorial ionosphere during the solar minimum period of 2009, *J. Geophys. Res.*, *116*, A12327, doi:10.1029/2011JA016712.
- Valladares, C. E., and J. L. Chau (2012), The low-Latitude Ionospheric Sensor Network: Initial results, *Radio Sci.*, *47*, RS0L17, doi:10.1029/2011RS004978.
- Valladares, C. E., J. Villalobos, R. Sheehan, and M. P. Hagan (2004), Latitudinal extension of low-latitude scintillations measured with a network of GPS, *Ann. Geophys.*, *22*, 3355–3175, doi:10.5194/angeo-22-3155-2004.
- Wernik, A. W., L. Alfonsi, and M. Materassi (2004), Ionospheric irregularities, scintillation and its effect on systems, *Acta Geophys. Pol.*, *52*(2), 237–249.