AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE
10.1002/2015JA022251

Key Points:
- Midlatitude electron density enhancement (MEDE) occurs both daytime and nighttime
- Global morphology of MEDE reveals significant longitudinal variation
- **E** × **B** drift, neutral wind, and plasma transport could be possible mechanisms

Correspondence to:
J. Y. Liu,
jyliu@jupiter.ss.ncu.edu.tw

Citation:
Rajesh, P. K., J. Y. Liu, N. Balan, C. H. Lin, Y. Y. Sun, and S. A. Pulinets (2016), Morphology of midlatitude electron density enhancement using total electron content measurements, *J. Geophys. Res. Space Physics*, *121*, 1503–1517, doi:10.1002/2015JA022251.

Received 8 DEC 2015
Accepted 30 DEC 2015
Accepted article online 5 JAN 2016
Published online 3 FEB 2016

Morphology of midlatitude electron density enhancement using total electron content measurements

P. K. Rajesh[1], J. Y. Liu[2,3,4], N. Balan[2,5], C. H. Lin[1], Y. Y. Sun[2], and S. A. Pulinets[6]

[1]Department of Earth Science, National Cheng Kung University, Tainan, Taiwan, [2]Institute of Space Science, National Central University, Taoyuan, Taiwan, [3]Center for Space and Remote Sensing Research, National Central University, Taoyuan, Taiwan, [4]National Space Organization, Hsinchu, Taiwan, [5]Now at National Institute for Space Research, São José dos Campos, Brazil, [6]Space Research Institute, Russian Academy of Sciences, Moscow, Russia

Abstract Using the global ionospheric map of total electron content in 2002–2009, this paper investigates anomalous, midlatitude electron density enhancement (MEDE) bounded by a tropical electron density trough and the usual midlatitude electron density trough at all times (24 h) of the day for the first time. The diurnal, seasonal, and longitudinal variations in the occurrence and strength of MEDE are studied at solar maximum (2002) and long deep solar minimum (2009), and latitude-longitude dependence is examined using the data in 2002–2009. The results show that the MEDE occurs at all times of the day though pronounced at night (2200–0400 LT), and in some cases the daytime occurrence could be more frequent than the corresponding nighttime occurrence. The strength maximizes at around 0400 LT and is weak during daytime. Both the occurrence and strength are, in general, predominant in winter at low solar activity and exhibit significant longitudinal dependence. The **E** × **B** drift, strength, and direction of neutral wind and ionosphere-plasmasphere plasma flow and their day-to-day variations are suggested to account for the existence of MEDE at all times of the day.

1. Introduction

Anomalous enhancement of nighttime electron density, often reported as an increase in *F* region peak electron density (N_mF_2) and/or total electron content (TEC), has been regarded as a characteristic feature of midlatitude ionosphere, whereas theory predicts a rapid decay of the ionization after sunset [*Arendt and Soicher*, 1964; *Evans*, 1965; *Titheridge*, 1968; *Park*, 1971; *Essex*, 1977; *Davies et al.*, 1979]. Several potential sources of ionization have been proposed for the enhancement, such as downward plasma flux [*Arendt and Soicher*, 1964; *Evans*, 1965; *Titheridge*, 1968; *Park*, 1970], conjugate point transfer of ionization [*Evans*, 1965; *Titheridge*, 1968], corpuscular ionization [*Titheridge*, 1968], and westward electric field compressing plasma from high to low L shells resulting in plasmasphere-ionosphere transfer [*Park*, 1971; *Davies et al.*, 1979]. Note that a similar postsunset enhancement of electron density was also reported in the low latitudes [*Titheridge*, 1968; *Young et al.*, 1970; *Essex*, 1977; *Balan and Rao*, 1987; *Su et al.*, 1994; *Farelo et al.*, 2002; *Luan et al.*, 2008; *Liu et al.*, 2013], and shown to be caused by prereversal upward enhancement and following downward enhancement of equatorial vertical plasma drift [e.g., *Balan and Bailey*, 1995], and modulated by neutral wind [e.g., *Le et al.*, 2014]. However, this study focuses only on the features of the midlatitude enhancement.

Several investigations have been conducted to understand the seasonal as well as solar cycle behavior of the midlatitude enhancement [*Tyagi*, 1974; *Balan and Rao*, 1987; *Balan et al.*, 1991, 1994; *Farelo et al.*, 2002; *Dabas and Kersley*, 2003; *Pavlov and Pavlova*, 2005; *Luan et al.*, 2008]. The studies show that the enhancement appears in the premidnight and/or postmidnight period, is pronounced in winter and in low solar activity period, and generally concludes downward plasma flux to be the major cause. In spite of this general consensus, there have been differences and often contradicting observations regarding the occurrence frequency, amplitude of the enhancement, and their temporal, seasonal behaviors and solar activity dependence. *Tyagi* [1974] reported that there is no significant change in the occurrence of TEC enhancement with ascending solar activity, while *Balan et al.* [1994] found that the frequency of occurrence of midlatitude enhancement decreases with increase in solar activity, and the amplitude increases. They further noted that the occurrence and amplitude of the enhancement is larger in winter months. *Jakowski et al.* [1991] and *Mikhailov et al.* [2000a] showed that the occurrence of enhancement is more in winter in solar minimum and summer in solar maximum. *Mikhailov et al.* [2000b] reported that the frequency of occurrence in the postmidnight enhancement is more in winter season, and the pattern is mostly independent of solar activity.

The varying results from earlier analysis have been attributed to the fact that most of the studies were limited to certain geographical regions, and in many analyses no clear distinction was made whether the premidnight peak or the postmidnight peak is being considered [*Farelo et al*., 2002]. There has been no global investigation of the midlatitude enhancement of electron density. Though *Farelo et al*. [2002] analyzed the nighttime N_mF_2 morphology using a network of ionosondes, their study could not reveal any longitudinal characteristics in the occurrence or amplitude of the enhancement, probably limited by the location of the stations used in their work. *Luan et al*. [2008] reported longitudinal variation in the nighttime enhancement of N_mF_2 using Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC) electron density profiles. However, they did not carry out quantitative analysis regarding the occurrence or strength of the enhancement. Moreover, their data were limited to Northern Hemisphere winter in solar minimum period, thereby lacking seasonal, interhemispherical, and solar activity information.

Further, the previous studies that attempted to analyze the characteristics of midlatitude enhancements over a network of stations were based on N_mF_2 values, and the corresponding behavior of TEC on a global perspective was not available. Though TEC variation usually reflects the electron density variation in the F_2 region, it could be influenced by the density variation at other ionospheric heights also, whereas N_mF_2 signifies the electron density at the F_2 peak altitude only. In this work, the TEC data of global ionospheric map (GIM) [*Dow et al*., 2009] for 8 years in 2002–2009 are analyzed to investigate the midlatitude enhancement. The variations of the enhancement with local time (LT), season, and longitude are presented for the solar maximum year of 2002 and solar minimum year of 2009, and its solar activity variation is presented using the 8 years of data. This study focuses on the enhancement over midlatitude region, and the feature described here is henceforth referred as midlatitude electron density enhancement or in short as MEDE. While most of the previous studies focused on nighttime enhancement, this work for the first time investigates the diurnal variation of the occurrence as well as strength of MEDE.

2. Data and Methodology

The Center for Orbit Determination in Europe (CODE) GIM TEC maps available at 5° longitude and 2.5° latitude resolutions, at every 2 h, are analyzed to identify MEDE signatures as a function of longitude and time. The CODE GIM TEC estimation [*Jee et al*., 2010; http://aiuws.unibe.ch/ionosphere] assumes a modified single layer (thin shell) model for ionosphere in Sun-fixed reference frame, with a height approximated to that of the expected peak electron density (~400 km). The TEC maps are obtained using the vertical TEC from a global chain of more than 200 GPS receivers with an elevation cutoff angle of 20°. The electron density representing the spatial TEC distribution is modeled based on spherical harmonic expansion up to degree and order 15. There are about 3328 parameters used to account for the global TEC variation. Piecewise linear functions are used for representation in the time domain. In this study, the years 2002 and 2009 are selected to represent solar maximum and minimum respectively, and the GIM data in each year are classified into different seasons named as follows: March equinox (or M months, March 21 ± 45 days), June solstice (or J months, June 21 ± 45 days), September equinox (or S Months, September 21 ± 45 days), and December solstice (or D months, December 21 ± 45 days). Only those days without being preceded by magnetic storms ($Kp \leq 3$ for three consecutive 3 h periods; $Dst > -50$ nT) by 4 days are considered for the analysis.

Figure 1 gives the distribution of the GPS receiver stations used in deriving GIM TEC in 2002 and 2009. In 2002 about 150 receivers distributed worldwide were used, while the number increases to about 250 by 2009. However, the increase in the number of stations does not seem to affect the results presented in this paper. Figure 2 illustrates examples of the MEDE seen in the TEC image, as well as the method of identifying the enhancements for a given longitude sector at global 0000 LT and 1200 LT, on 16 March (day of the year 75) 2009. The global TEC maps plotted at the two local times in Figure 2 (top row) show regions of prominent electron density over low latitudes due to equatorial ionization anomaly (EIA). The secondary peak of enhanced TEC values seen beyond 20° latitude in both hemispheres corresponds to MEDE, described below. Note that MEDE exists globally and could be seen both at local midnight and noontime, peaking at around ±40° latitudes (Figure 2, bottom row). The valley region between EIA and MEDE is named here as tropical electron density trough (TEDT), analogous to the name midlatitude

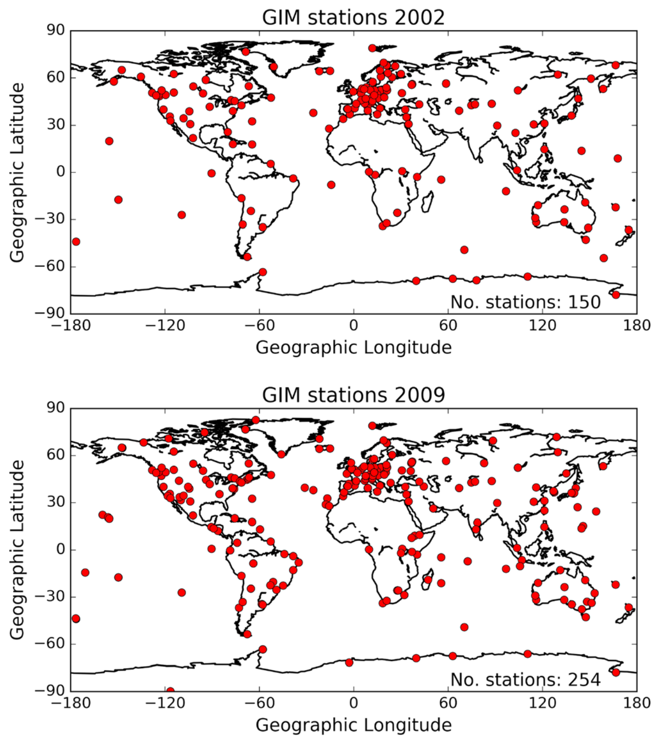

Figure 1. Distribution GPS receivers used in deriving GIM TEC in (top) 2002 and (bottom) 2009. The stations are taken from the GIM data during March equinox in both the years.

electron density trough [e.g., *Tulunay and Sayers*, 1971; *Lee et al.*, 2011]. The latitude profiles of TEC in Figure 2 (bottom row) provide a better representation where the MEDE peak could be well distinguished at midnight as well as noon. The daytime enhancement seems a new feature reported in this work. Both the daytime and nighttime MEDE could also be identified in the corresponding TEC values from Global Positioning System (GPS) measurements, plotted using red circles. The ionospheric electron content derived from the electron density profiles from GPS occultation experiment on board FORMOSAT-3/COSMIC satellites, plotted using blue circles, also exhibits signatures of enhancement near the corresponding MEDE locations in GIM as well as GPS data, despite the fact that the values are seasonal averages in March equinox months. The multi-instrument data (Figure 2) therefore seem to validate the MEDE in GIM TEC.

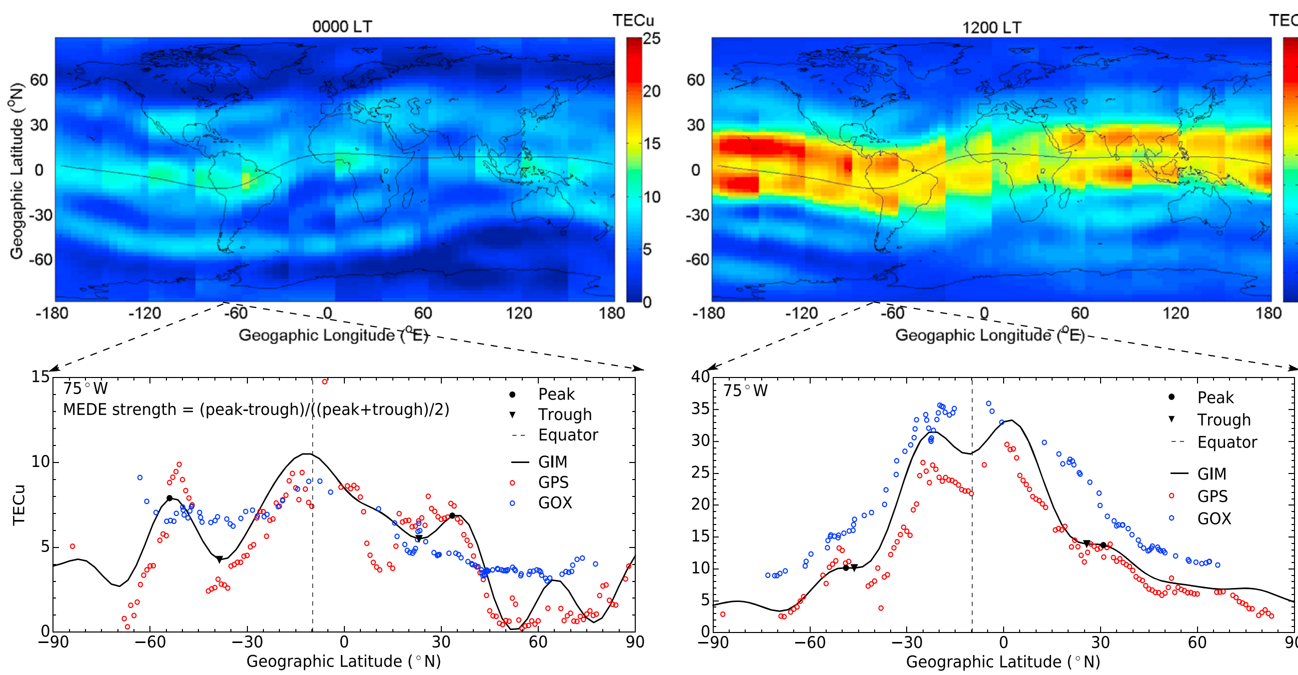

Figure 2. Illustration of midlatitude electron density enhancement (MEDE). The global fixed local time TEC map on day of year (DOY) 075 in year 2009 at (top left) 0000 LT ((top right) l200 LT). The solid black curve is the location of magnetic equator. (bottom row) The solid curves give the corresponding latitude profiles of TEC values at 75°W longitude, revealing the MEDE feature at nighttime as well as daytime. The red circles denote average GPS TEC at the corresponding time periods during DOY 079 ± 3 in 2009, from ground based receivers over 75 ± 7.5°W longitude region. The blue circles are the ionospheric electron content (IEC) from the GPS occultation experiment (GOX) on board FORMOSAT-3/COSMIC satellites. Note that the GOX IEC values are for the M months, and the magnitude is multiplied by a factor of 2 to fit within the corresponding *Y* axis range. While the MEDE feature is evident in the GPS data, its signature could also be noted in the seasonally averaged GOX IEC.

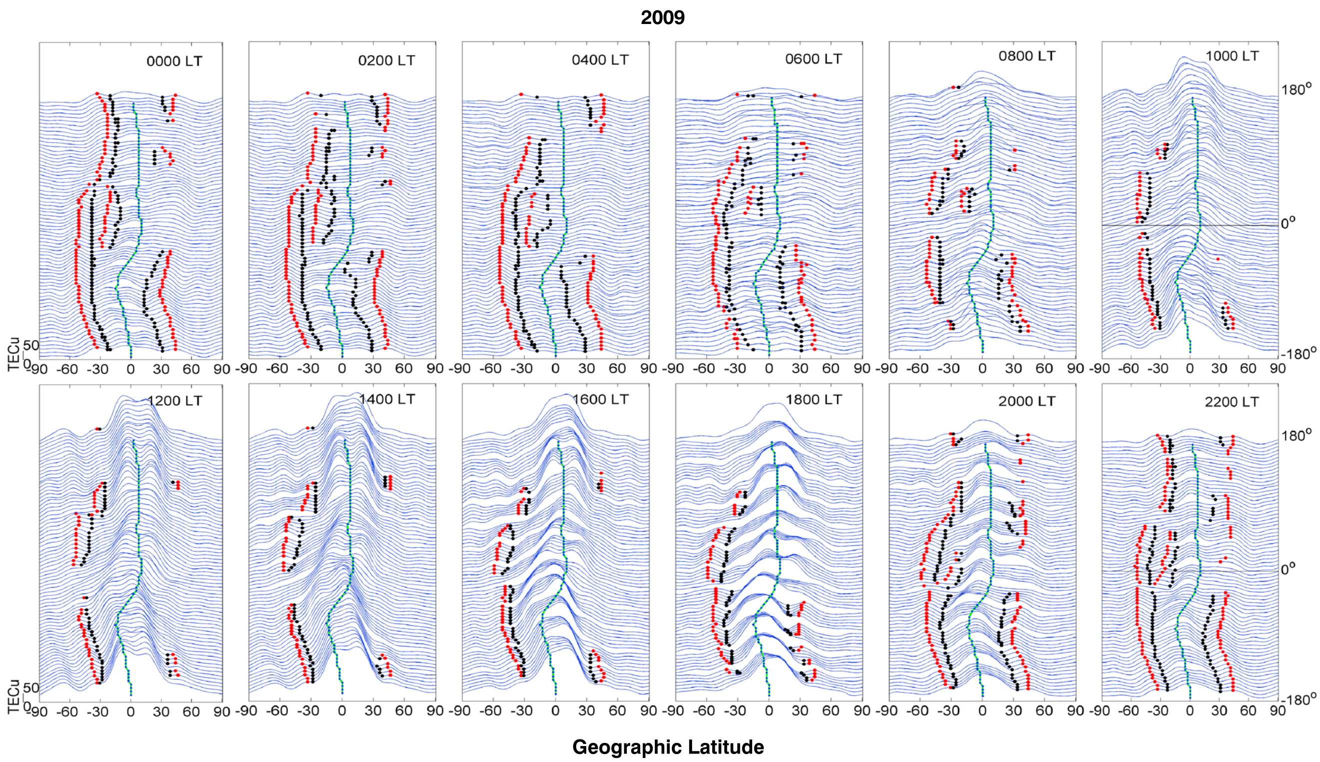

Figure 3. Example of identifying MEDE locations from GIM TEC. The latitude profiles of TEC at every 5° longitude in M months in 2009 for every 2 h intervals are plotted. The green dots denote the magnetic equator. The red and black dots mark the locations of MEDE and tropical electron density trough (TEDT), respectively.

In order to carry out further analysis, the latitude profiles of TEC values at different local times are examined to identify the tropical troughs and MEDE peaks that are beyond ±20° of the magnetic equator to avoid the EIA affecting the results; it is unlikely for the EIA peak to occur beyond ±20° latitudes under quiet conditions. Using the latitudinal profiles of TEC, the locations of tropical trough and MEDE peak are identified as the latitudes where the TEC slope becomes 0, with the first zero slope (toward higher latitudes) corresponding to the trough and second zero slope corresponding to MEDE peak. Figure 3 gives the example for identifying MEDE signatures globally, at different local times. Since the latitudinal variation of GIM TEC is rather smooth, identification of the MEDE is relatively unambiguous when exists, and hence, no particular threshold is used to determine the peak. In some cases the peak bifurcates so that two peaks could be marked, and in such cases the prominent peak is considered. Once a peak is identified, its location is noted, occurrence is counted, and strength of the MEDE is calculated as $\text{Strength} \equiv \frac{\text{Peak} - \text{Trough}}{(\text{Peak} + \text{Trough})/2}$, where Peak is the TEC value at MEDE and Trough is the TEC value at the corresponding TEDT. The division by (Peak + Trough)/2 instead of Trough avoids the possibility of abnormally large apparent strength when Trough becomes very small; division by (Peak + Trough)/2 also has some bias on the value of Trough. For each longitude and season, the location, occurrence, and strength of MEDE are obtained for every 2 h time interval for which GIM TEC data are available. Finally, the occurrence counted is represented in percentage relative to the total observations. Hereafter, any quantitative reference to the occurrence stands for the magnitude in percentage. It can be seen in Figure 3 that the MEDE exists at all local times, although in some longitude sectors it could not be identified. Further, the longitudes near 90°W and 90°E seem to reveal most pronounced MEDE features throughout the day, especially in the Southern Hemisphere.

3. MEDE Morphology

Figure 4 shows the global distribution of MEDE occurrence (first and second rows) and strength (third and fourth rows) in different seasons in the solar minimum year 2009. The figure reveals that the MEDE, in general,

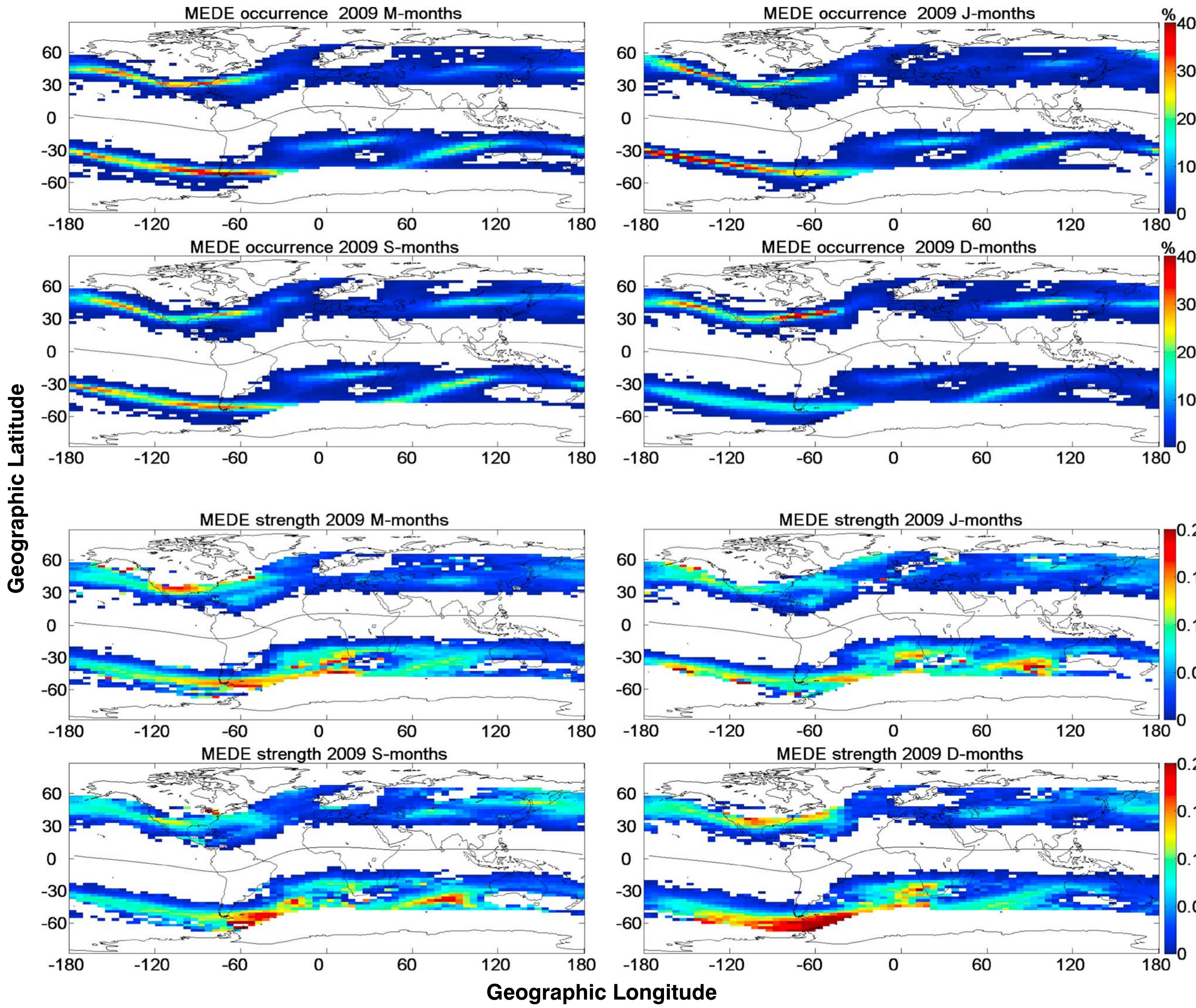

Figure 4. (first and second rows) Global occurrence and (third and fourth rows) strength of MEDE in 2009. The values shown are averaged over all local times.

appears about 25° farther to the magnetic equator and spreads over a latitudinal span of about 30° in both hemispheres. There is significant longitudinal variation in MEDE, with the occurrence and strength being predominant in 40–180°W longitudes. In addition, significant occurrence could also be observed between 60° and 180°E longitudes in the Northern Hemisphere and between 40°W and 130°E in the Southern Hemisphere. In general, the longitudes from 40°W to 60°E in the Northern Hemisphere appear as region of least occurrence or where the MEDE feature could not be extracted from the TEC data, whereas in Southern Hemisphere the minimum occurrence is between 130 and 180°E. While the general longitudinal pattern of occurrence remains the same in all seasons, the percentage of occurrence does vary. In the equinoctial months, both the hemispheres show similar occurrence pattern, with slightly larger values in the Southern Hemisphere. However, in solstices, the percentage of occurrence is more in the winter hemisphere compared to the summer hemisphere, and this seasonal difference is more noticeable in the Southern Hemisphere.

The longitude distribution of MEDE strength in the Northern Hemisphere in 2009 is mostly identical to its occurrence with more values at 30–180°W and peak around 100°W. The MEDE also appears relatively stronger between 60° and 180°E, leaving the longitude belt of 60°E–30°W, as a region of weaker MEDE in the Northern Hemisphere, where the occurrence is also least. By contrast, in the Southern Hemisphere, MEDE

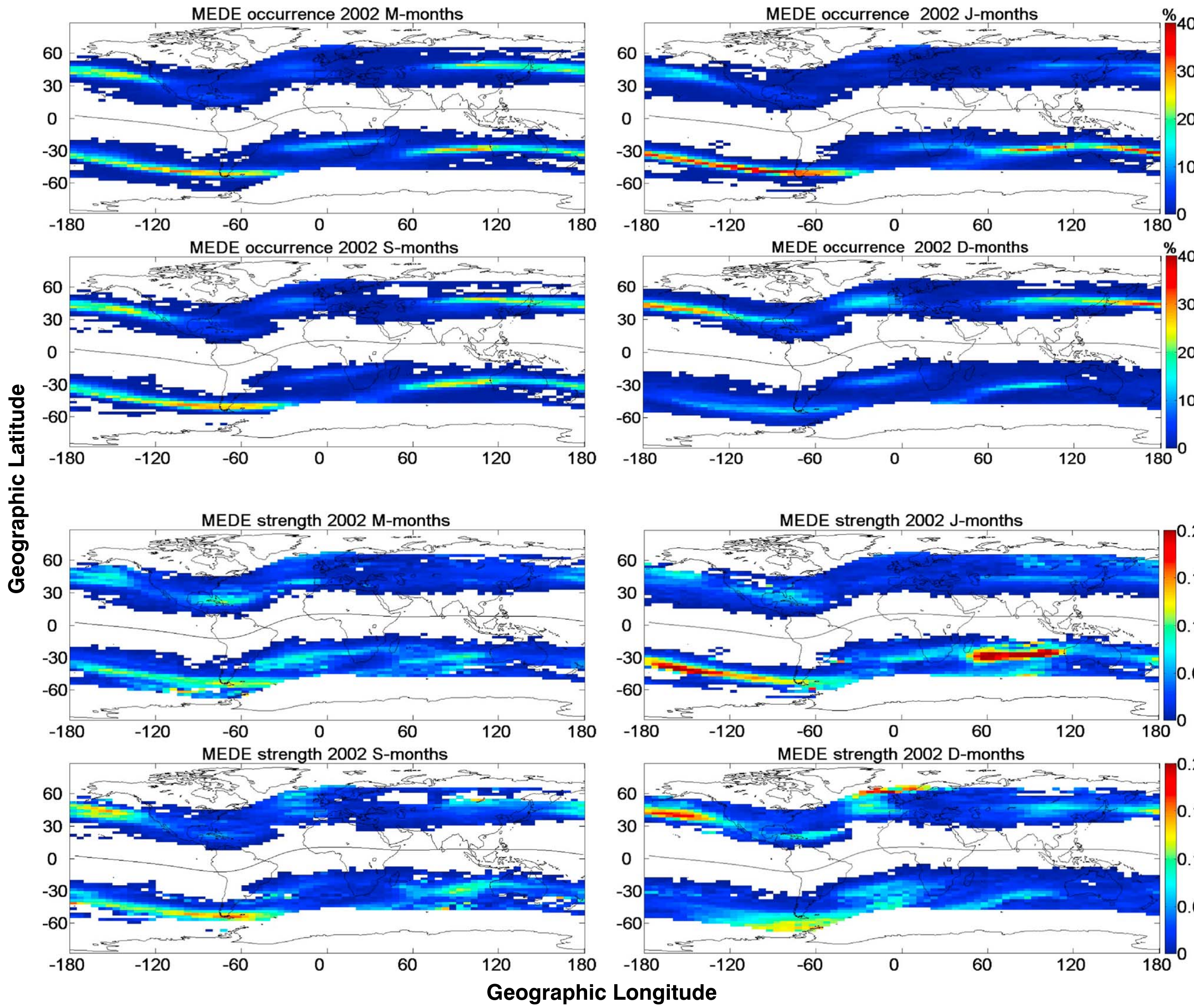

Figure 5. (first and second rows) Global occurrence and (third and fourth rows) strength of MEDE in 2002. The values shown are averaged over all local times.

is stronger between 120°W and 120°E longitudes, of moderate strength from 120° to 180°W, and least strength between 120° and 180°E longitudes. Note that in D months in the Southern Hemisphere, MEDE appears strongest between 20° and 100°W longitudes. Excluding this region, the strength appears to be slightly more in the winter months than in summer, though the seasonal dependence is not as obvious as in the case of occurrence.

Figure 5 is similar to Figure 4, but for the solar maximum year 2002. In the Northern Hemisphere, the occurrence is mostly limited in the longitudes to the west of 120°W and east of 60°E. In the Southern Hemisphere significant occurrence could be noted to the west of 30°W and east of 60°E, with lesser occurrence in the region in between. The latitudinal range of MEDE occurrence is mostly identical to that in 2009. In this case also, the occurrence in winter hemisphere is more than that in the summer hemisphere. The distribution of the strength of MEDE is mostly similar to that of the occurrence. In general, the strength is more in the Southern Hemisphere, where the maximum value is over 60°–120°E longitudes in J months. The strength also shows distinct seasonal variation with more values in winter hemisphere.

Figures 4 and 5 suggest that the MEDE occurrence and strength are, in general, more in the Southern Hemisphere in the longitudes to the west of ~40°W and the occurrence is less in the longitudes around 0°.

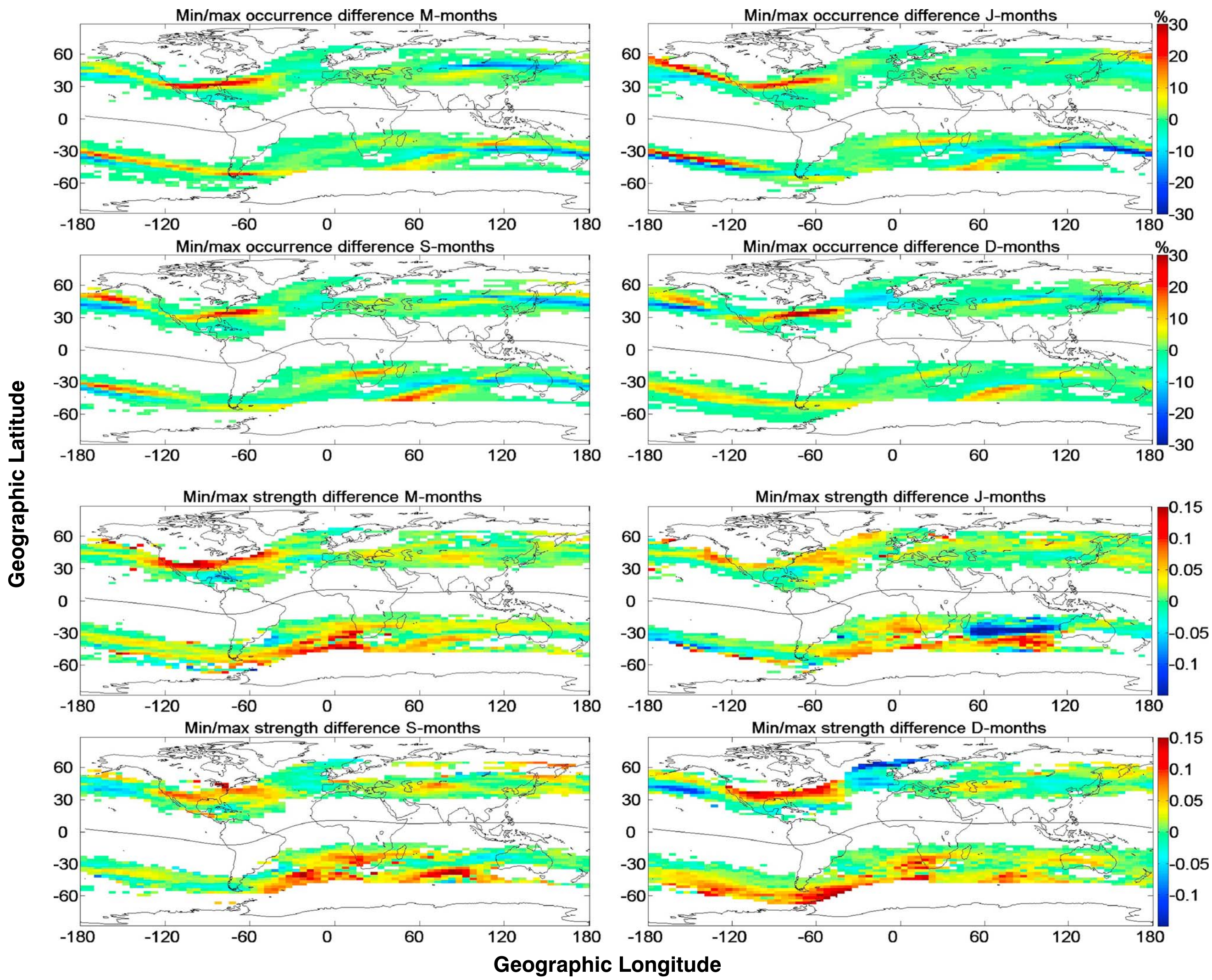

Figure 6. Difference in occurrence and strength of MEDE between solar minimum (2009) and solar maximum (2002).

It can be further seen that the occurrence and strength depend on solar activity, with both tending to decrease with increase in solar flux. However, the relative difference in the occurrence of MEDE between western (to the west of 40°W) and eastern (to the east of 60°E) longitudes is lesser in high solar activity year. In other words, there appears to be an increase in the MEDE occurrence in the eastern longitudes with solar activity. The solar activity differences illustrated in Figure 6 confirm that in the eastern longitudes the percentage of occurrence is more in solar maximum than in solar minimum, and vice versa in the western longitudes. Unlike occurrence, the MEDE strength is stronger over all the longitudes in solar minimum than in solar maximum.

Figure 6 further demonstrates that there is a slight shift in the location of MEDE occurrence in the two years. Detailed analysis of the shift of MEDE location with solar activity has been carried out using 8 years of data in 2002–2009, and the results at selected longitudes are shown in Figure 7. It can be seen that there is no consistent poleward or equatorward shift of the latitude of peak MEDE with solar activity in different longitudes. In the longitudes between 30°W and 30°E, there is either no shift or an equatorward shift in one hemisphere with no shift in the opposite hemisphere. In the longitudes centered at 10°E (first row), there is almost no shift with solar activity (2002–2009) in either Northern Hemisphere or Southern Hemisphere. As shown in Figure 7 (second row), in the longitudes centered at 60°E there is an equatorward shift with decreasing solar activity in the Northern Hemisphere and a poleward shift in the Southern Hemisphere.

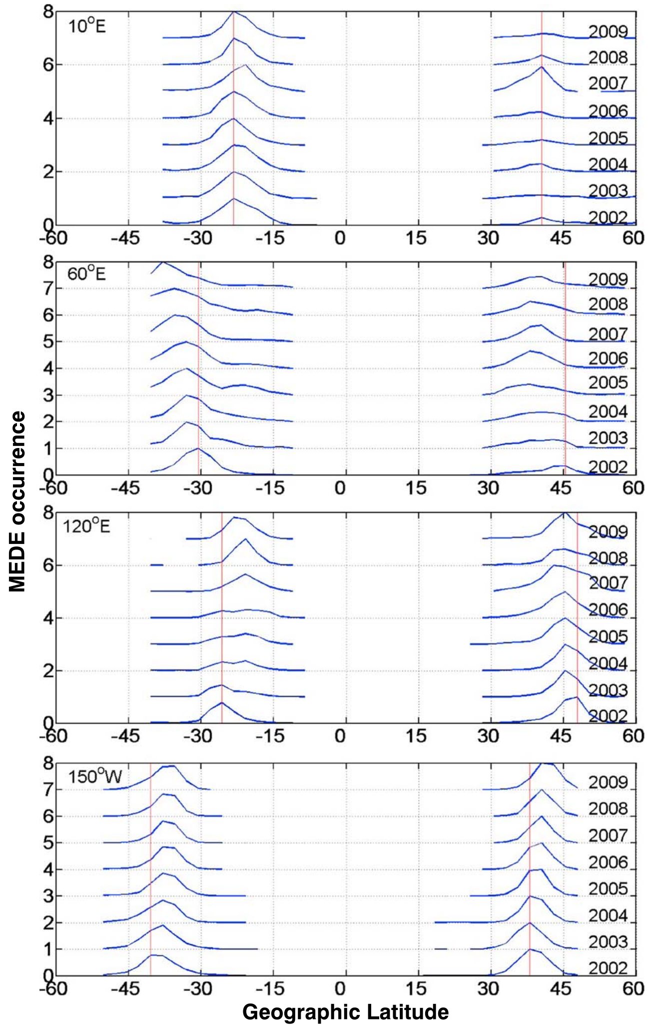

Figure 7. Shift in the location of MEDE occurrence with solar activity at selected longitudes (noted in the figure). For each panel, the *Y* axis represents the MEDE occurrence in each year normalized to have a maximum value of 1 and incremented by 1 per year from 2002 to 2009.

In the longitudes centered at 120°E (Figure 7, third row), there seems a general equatorward shift with decreasing solar activity in both Northern and Southern Hemispheres, and in the longitudes centered at 150°W (Figure 7, fourth row) there seems a general poleward shift in the Northern Hemisphere and equatorward shift in the Southern Hemisphere.

As mentioned above, previous studies of MEDE dealt with the anomalous increase of nighttime electron density. Figure 8 shows the local time (24 h) variations of the occurrence and strength of MEDE for the first time in different seasons in 90°E and 90°W longitudes. The figure reveals that MEDE is predominantly a nighttime phenomenon with 80–100% occurrence in most cases. In some cases the daytime occurrence is equally significant (Figures 8a, 8b, and 8d) or at times even more pronounced (Figure 8c) than the nighttime values. Further, the nighttime occurrence generally shows a premidnight peak around 2000–2200 LT and a postmidnight peak around 0400–0600 LT, though such a preference is not discernable in all the cases, and the percentage of occurrence at other intervals at night also appear equally significant in the seasonal average. The hemispheric difference of MEDE can be appreciated from a comparison of Figures 8a and 8b, which shows more frequent occurrence in the Southern Hemisphere than in Northern Hemisphere at all local times. The longitudinal difference of MEDE can be appreciated from Figures 8c and 8d where the daytime and nighttime occurrences have opposite behavior in 90°E and 90°W longitudes. Figure 8e for J months and Figure 8f for D months reveal the seasonal differences resulting in single or multiple (premidnight and postmidnight) peaks in the nighttime occurrence. Though MEDE, in general, is more frequent in solar minimum, the tendency could be different; for example, Figures 8g and 8h indicate that in the eastern longitudes centered at 90°E MEDE is frequent at solar maximum (2002).

The diurnal variation of the strength of MEDE seems to be more-or-less identical in different seasons, longitudes, and solar activity levels. It can be seen that the strength (Figure 8, solid curves) increases from around 1800 LT, reaches peak value around 0400 LT, drops to very small values by 0800 LT, and remains less during daytime. The local time variation of the strength of MEDE (defined in section 2) appears to be independent of its occurrence, though at night the strength increases when the occurrence is also usually more frequent. In order to further verify the relationship between the occurrence and strength of MEDE, the scatterplot between the two for the years 2009 and 2002 is given in Figure 9, where black and red dots correspond to nighttime and daytime, respectively. It can be seen that the general behavior is similar in both the years 2009 and 2002, with mostly a linear variation that eventually approaches saturation where there is no

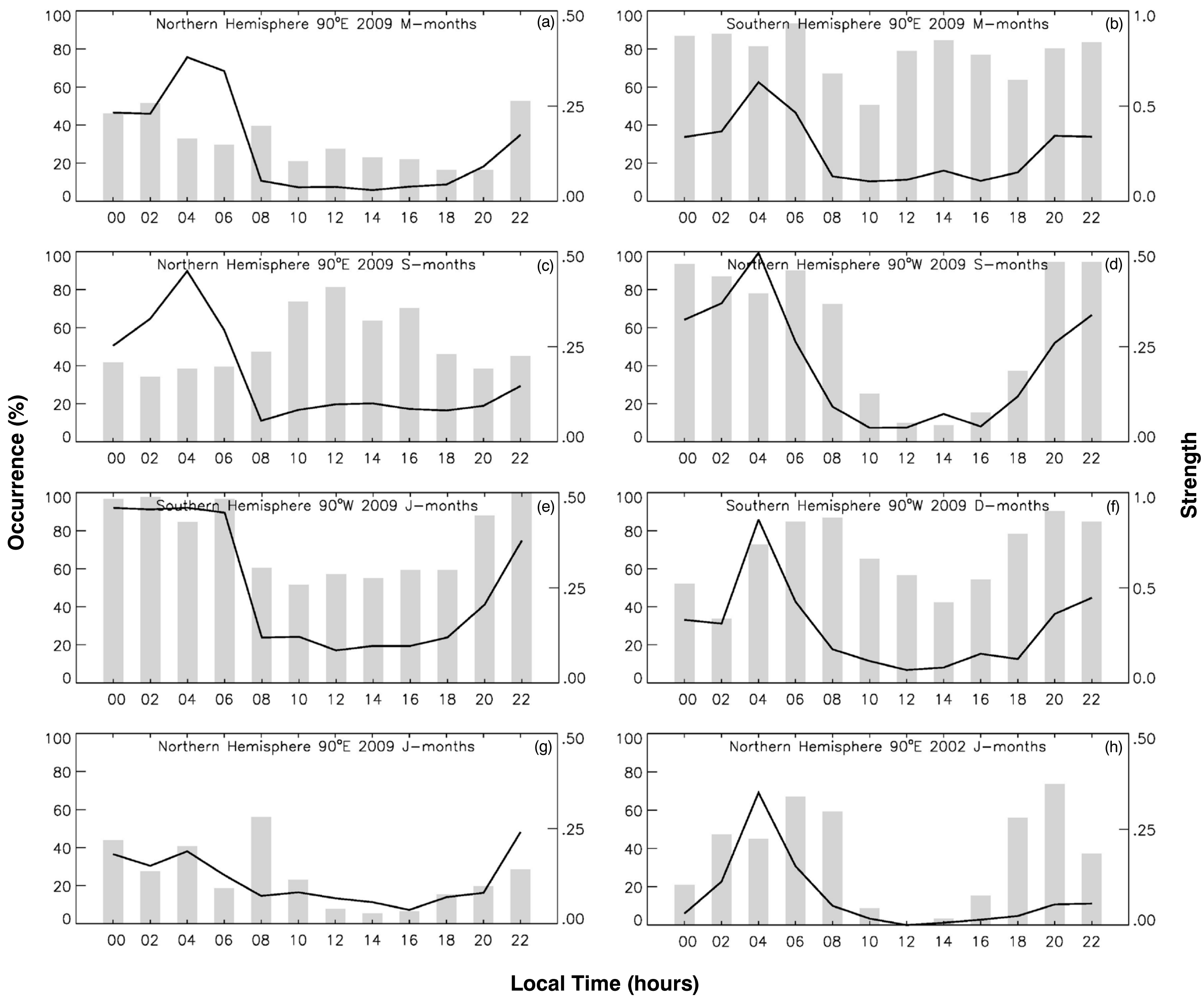

Figure 8. Occurrence and strength of MEDE at selected longitudes and seasons in Northern and Southern Hemispheres. The histograms give the occurrence, and black lines denote the strength of MEDE.

apparent change in the occurrence even though strength increases. However, the solar activity difference in the occurrence could still be observed with lesser data points in 2002 beyond 60% of occurrence level compared to that in 2009. Moreover, the slope of the linear portion is steeper in solar maximum than in solar minimum. In 2009, the occurrence saturates when strength reaches ~0.3, whereas in 2002 it happens when the strength is ~0.2.

4. Discussion

Though the phenomenon of midlatitude electron density enhancement (MEDE) has been of interest to ionospheric physicists for past several decades, the studies so far were focused on its nighttime occurrence or were limited to certain geographic locations or seasons. Traditionally, most of the researchers analyze TEC or N_mF_2 data as a function of time to identify premidnight and/or postmidnight enhancements at their respective observing location(s). The present study carries out a comprehensive analysis of the diurnal (24 h) features of MEDE occurrence and strength in different seasons on a global scale. The results demonstrate that MEDE exists at all local times and depends on longitude, season, and solar activity. The MEDE characteristics during daytime have not been analyzed in the past. Probably, the only report of a daytime

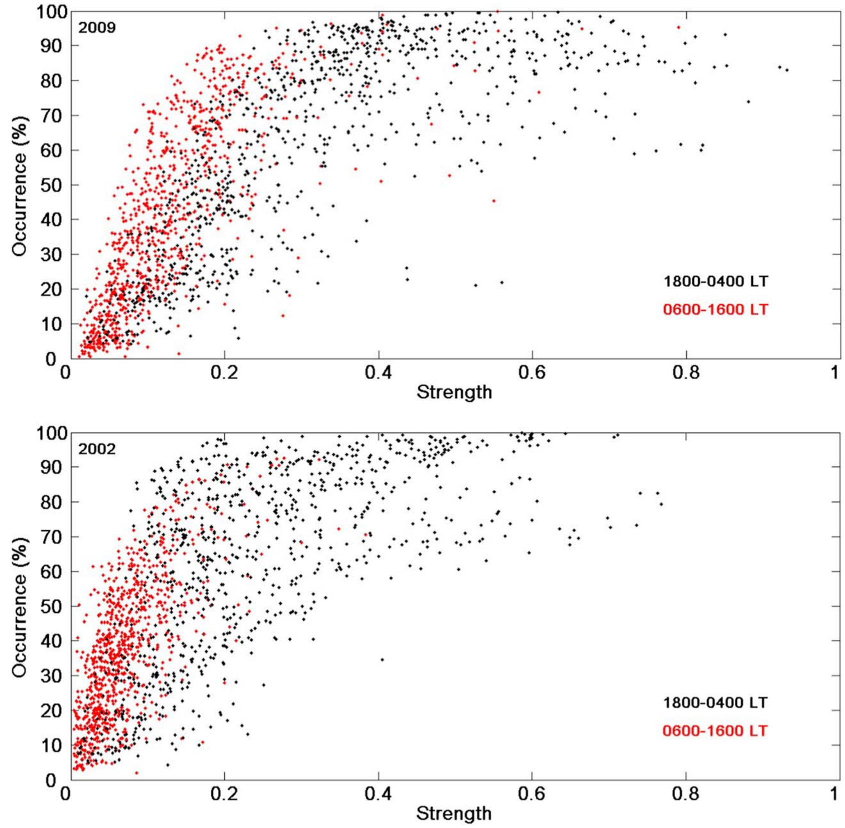

Figure 9. Scatterplot of strength and occurrence of MEDE in 2009 and 2002. The colors denote the nighttime and daytime data points.

enhancement poleward to the equatorial ionization anomaly (EIA) peaks is about "winter spur" by *Thomas* [1963]. However, the winter spur, evidently a winter phenomenon, occurs at higher dip latitudes of about 70° and is different from the MEDE reported here.

4.1. Daytime Occurrence and Mechanism

Most of the previous studies of MEDE features are done by analyzing the temporal variation of electron density at a given location, and hence, any daytime abnormal increase is naturally ignored, and the nighttime enhancement in the absence of known ionizing sources received more attention. The methodology adopted here (section 2) to examine the latitude distribution of TEC as a function of time enables the identification of midlatitude enhancements at all local times. As the equatorial plasma fountain and EIA gain strength, the separation between the tropical electron density trough (TEDT) and MEDE becomes narrower; that might have also resulted in the feature being overlooked during daytime. In addition, the strength of the MEDE is much less during daytime compared to nighttime, even when the occurrence is comparable. The much larger background electron density during daytime, together with the EIA, results in very small difference between the daytime MEDE and TEDT.

The diurnal variation described here shows that the enhancement could exist throughout the day (Figure 8). Thus, any attempt to explain the feature only by focusing on the nighttime occurrence might not provide complete information, and hence, to understand the cause of the enhancement, it is necessary to examine the daytime generation as well. Note that while the nighttime occurrence is mostly above 80%, rarely falling below 30%, the daytime occurrence remains mostly below 40% but sometimes levels with or even exceeds the nighttime occurrence percentage. Further, the nighttime enhancement have been shown to peak in the premidnight (2000–2200 LT) and/or postmidnight (0200–0400 LT) period [*Farelo et al.*, 2002, and the references cited therein], which mostly agrees with results reported here, but the

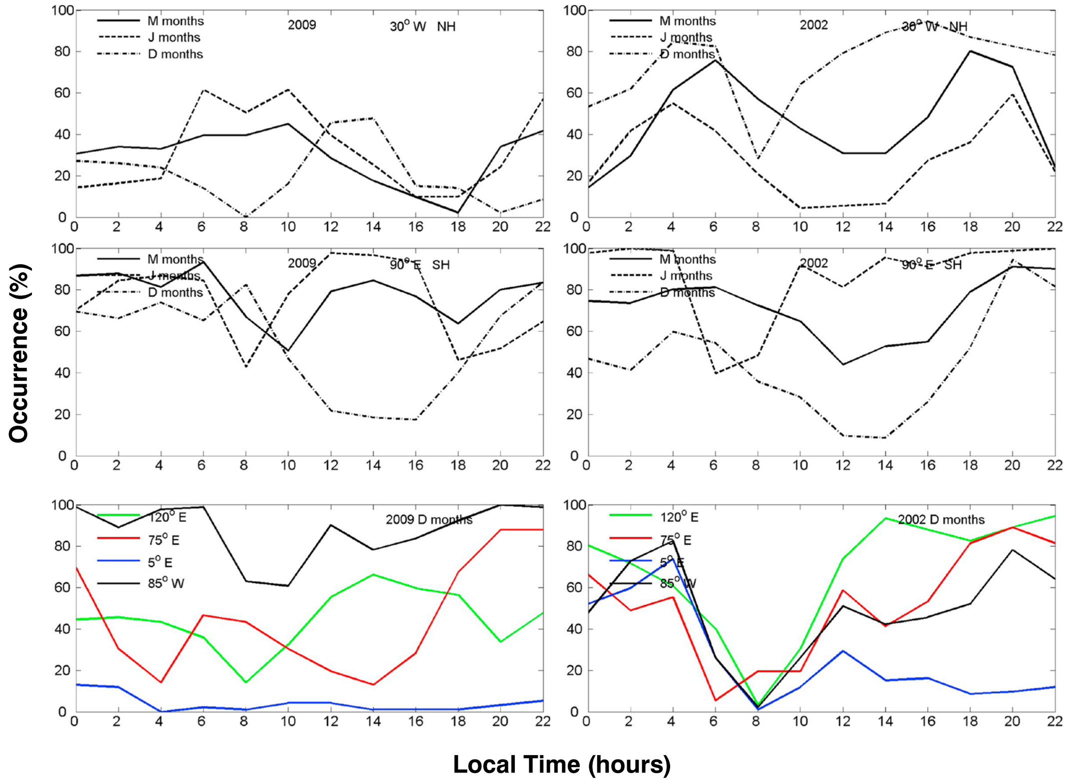

Figure 10. MEDE occurrence in (left column) solar minimum and (right column) solar maximum as a function of local time. (top row) At 30°W in the Northern Hemisphere in different seasons. (middle row) At 90°E in the Southern Hemisphere in different seasons. (bottom row) At selected longitudes in D months in the Northern Hemisphere.

daytime occurrence does not show any noticeable time preference. Downward plasma diffusion from plasmasphere has been the most widely suggested mechanism to produce the nighttime enhancement of electron density [*Arendt and Soicher*, 1964; *Evans*, 1965; *Titheridge*, 1968; *Park*, 1970], which cannot explain the daytime observation.

The existence of the tropical trough is essential for the identification of MEDE. In terms of plasma flow, since the trough falls between the equatorial-low latitude region dominated by EIA and midlatitude region dominated by ionosphere-plasmasphere plasma flow, the trough (and hence MEDE) becomes frequent and dominant when (and where in longitude) EIA becomes weak and plasmasphere to ionosphere (and reverse) plasma flow at midlatitudes is strong (weak). At night, EIA becomes weak both in strength and latitudinal extent, and midlatitude plasma flow is generally from plasmasphere to ionosphere; that explains the frequent occurrence of (tropical trough and) MEDE at night. The daytime EIA also becomes comparatively weak on days when the upward equatorial-low-latitude $\mathbf{E} \times \mathbf{B}$ drift is weak, which is found to be true especially in some longitudes [e.g., *Fejer*, 1991]. On those days the upward daytime $\mathbf{E} \times \mathbf{B}$ drift at middle latitudes (and hence the daytime loss of plasma from midlatitude ionosphere to plasmasphere) can also be weak; this combined with the weak daytime EIA can cause daytime MEDE. In addition, (1) if the generally poleward daytime meridional neutral wind [e.g., *Kawamura et al.*, 2002] becomes weak at midlatitudes and (2) a reverse wind flows from auroral to subauroral latitudes, they can contribute to the daytime MEDE by convergence of plasma due to the oppositely directed winds; an equatorward wind at subauroral latitudes seems possible due to auroral heating though mild on quiet days. In short, depending on the strength of $E \times B$ drift and strength and direction of neutral wind, MEDE can exist at all time of the day though the conditions are more favorable at night than during daytime.

The influence of the strength of EIA on daytime MEDE occurrence could be noted in Figure 10 (top and middle rows), which displays the local time variation of MEDE occurrence in selected longitudes (30°W and 120°E). It can be seen that, in summer (winter) the daytime MEDE is more (less) in the morning hours than in the evening, especially for 2009. This might be related to the hemispheric asymmetry of EIA with stronger crest in winter hemisphere in the morning and summer hemisphere in the afternoon [e.g., *Lin et al*., 2007] and further indicates that MEDE is better identified when EIA is weaker.

4.2. Longitudinal Variation

In addition to the day-night differences discussed above, the MEDE distribution (Figures 4 and 5) indicates significant longitudinal dependence in the occurrence. Most of the previous studies of the nighttime enhancements were limited to single locations and hence do not reveal the global features. Though *Farelo et al*. [2002] attempted to investigate the N_mF_2 variation using data from a network of ionosondes, probably lack of sufficient coverage prevented them from identifying any noticeable longitudinal variation. *Luan et al*. [2008], addressing the nighttime enhancement in the Northern Hemisphere in winter months in solar minimum period, did show that longitudinal differences exist in the occurrence. The results described here confirm significant longitudinal variation in the occurrence with sharp differences (e.g., about 70–80% in solar minimum) near the longitudes of 50°W and 60°E (Figure 4).

The observed longitudinal variation of MEDE could result from the possible longitude variations of the sources discussed above. The longitudinal differences in the strength of EIA and plasma transport from ionosphere to plasmasphere could be the factors that affect the longitudinal variation of daytime MEDE. Further analysis carried out using FORMOSAT-3/COSMIC N_mE_2 values indicates that the differences in the strength of EIA agree with the observed longitudinal difference in MEDE occurrence (figure not shown). The longitudinal and seasonal variations in the strength of EIA could be influenced by the corresponding variations of neutral wind, $\mathbf{E} \times \mathbf{B}$ drift, displacement of geomagnetic and geographic equators, solar zenith angle, etc. [*Fejer*, 1991; *Lin et al*., 2007; *Su et al*., 1997; *Tulasi et al*., 2009; *Balan et al*., 2013]. In addition, the possible longitudinal differences in the daytime meridional wind (latitudinal gradients of poleward wind and/or a reversal in the high latitude circulation) could also influence the MEDE occurrence as explained above.

The longitude differences in MEDE occurrence revealed in this study could explain some of the previously reported features of the nighttime enhancement. Figure 10 (bottom row) gives the MEDE occurrence as a function of local time and longitude in D months for solar minimum and solar maximum at selected longitudes. It can be seen from the figure that depending on the longitude, the local time variation of the occurrence could yield either single (e.g., premidnight peak at 75°E in 2009 and 120°E in 2002, postmidnight peak at 5°E in both 2002 and 2009) or multiple peaks (e.g., 75°E and 85°W in 2002) at nighttime. Note that over the longitudes where the nighttime MEDE is very frequent (for example, over American (85°W) sector in solar minimum), separate premidnight and postmidnight peaks could not be resolved, resulting in a single broad peak centered at midnight. Thus, such differences in the occurrence of the enhancements described in some of the earlier investigations [e.g., *Jakowski et al*., 1991; *Mikhailov et al*., 2000a; *Farelo et al*., 2002] could partly be related to the longitude being discussed.

Previous studies mostly reported a decrease in the nighttime enhancement with increase in solar activity, especially in the premidnight period [e.g., *Jakowski et al*., 1991; *Mikhailov et al*., 2000a; *Farelo et al*., 2002]. The global analysis in this study suggests that longitude could play a role in the solar activity variation of MEDE, showing an increase in the occurrence over eastern longitudes with increase in solar activity (Figures 4–6). The increase is seen for both the premidnight and postmidnight occurrences in winter months, while in summer and equinoxes the increase is apparent mainly in the premidnight period (Figure 10). Similarly, the reversal of the season of peak occurrence (from winter in solar minimum to summer in solar maximum) shown in the previous studies could have resulted due to the shift in the latitude of the peak occurrence with solar activity (Figure 7). The previous reports are based on measurements made at fixed latitudes. Thus, a poleward or equatorward shift in the latitude of peak occurrence could manifest as a reversal of the seasonal occurrence pattern with solar activity in such studies, even in the absence of any such real change occurring.

It is important to note that while describing the longitudinal variation in the MEDE occurrence using GIM TEC data, one has to be careful about the possibility that results could be affected by the nonuniform distribution of the GPS receivers used (Figure 1). The lack of stations can make the identification of MEDE feature difficult. However, the GIM map indeed reveals MEDE over most of the longitudes and is apparently more noticeable in the Sothern Hemisphere (Figure 2). Further, MEDE occurrence and strength appears pronounced over longitudes (for example over 120–180°W) where stations are less, in the same way as over longitudes (60–90°W) with a dense GPS network (Figures 2, 4, and 5). Thus, the results reported here are unlikely to be influenced by the nonuniform distribution of GPS stations. Another factor to consider, especially when discussing solar activity differences, is the fact that there are about 100 additional receiver stations in 2009 compared to 2002 (Figure 1). However, the solar activity variation in the MEDE remains similar over longitudes where new stations were added, when compared to longitudes with no new stations. Moreover, most of the new stations are added in the Northern Hemisphere, but the similar solar activity variation of MEDE strength could be seen in both hemispheres (Figure 6). This again suggests that the results are not significantly affected by the difference in the number of stations in different years.

4.3. MEDE Strength

Similar to the occurrence, MEDE strength also shows solar activity variation where, in general, there is a decrease with increase in solar activity in all seasons. However, there are often contradictory reports regarding the amplitude of the nighttime enhancement in the earlier investigations, showing an increase with solar activity [*Tyagi*, 1974; *Balan et al*., 1991] or decrease [*Mikhailov et al*., 2000a; *Farelo et al*., 2002] and in some cases no variation [*Bertin and Papet-Lepine*, 1970]. One of the major differences in these studies arises from the definition of the amplitude discussed, with some studies using the absolute value of the enhancement [*Tyagi*, 1974; *Balan et al*., 1991], while in some other cases the ratio of the increase to the nighttime lowest value of the quantity being measured (N_mF_2 or TEC) is used [*Mikhailov et al*., 2000a; *Farelo et al*., 2002]. When the enhancement is considered with respect to the background value, there will be a decrease with increase in solar activity, even if the corresponding absolute value might show an increase. Such effects are partly avoided in the current definition of the strength, by normalizing the TEC enhancement (peak to trough difference) with the average of trough and peak TEC.

Further, it can be seen that while the local time distribution of the occurrence varies with season, and longitude, the strength displays a consistent pattern, peaking at around 0400 LT (Figure 8). This is expected, as the strength depends on the magnitude of the enhancement with respect to the average trough-peak TEC value, while occurrence is counted whenever there is an enhancement in TEC. Thus, the new definition results in the MEDE strength to maximize around 0400 LT when the background density is usually minimum and remains very weak during daytime when the background density is more. Note that while the local time variation of strength and occurrence appear to be independent of each other, the behavior of the two displayed in the scatterplots (Figure 9) indicates very consistent relationship. The linear variation of the two quantities corresponds to the evening (morning) hours when the background density decreases (increases). Though the strength increases at night with decrease in density, the occurrence is mostly 90% or more, and thus appear to saturate.

In order to further explain the observed features of MEDE, modeling studies of MEDE are being carried out using SAMI2 (sami2 is another model of ionosphere) [*Huba et al*., 2000] by incorporating neutral wind velocities from horizontal wind model-93 [*Hedin et al*., 1996] and $\mathbf{E} \times \mathbf{B}$ drift velocities from empirical models [*Scherliess and Fejer*, 1999]. Results will be presented in a follow-up paper (under preparation).

5. Conclusion

Analysis of global TEC data reveals some new features of midlatitude electron density enhancement (MEDE) bounded between tropical and midlatitude electron density troughs. Unlike earlier reports, the MEDE occurs at all times of the day though the occurrence is frequent at night. The occurrence and strength of MEDE depend strongly on longitude, hemisphere, and solar activity. With longitude, the most frequent and least frequent occurrences are generally centered at 90°W and 0° longitudes. In general, the occurrence and strength of MEDE are maximum in winter season and in the Southern Hemisphere and in low solar activity period. The strength of MEDE becomes maximum at around 0400 LT when the background TEC is less, and a minimum during daytime when the background TEC is more. In conclusion, MEDE seems a feature of the midlatitude ionosphere existing at all local times and points to the possibility of a mechanism(s) operating at all times. The $\mathbf{E} \times \mathbf{B}$ drift, neutral wind, and ionosphere-plasmasphere plasma flow and their day-to-day variations are suggested to account for the existence of MEDE at all time of the day, and the conditions are more favorable at night than during daytime.

Acknowledgments
The authors would like to thank C. Y. Chang and F. Y. Chang for their help in preliminary data processing. The authors also thank the anonymous reviewers for their valuable comments and suggestions that have helped to improve the manuscript. The GIM TEC data used in this work are obtained from the Center for Orbital Determination in Europe website (http://aiuws.unibe.ch/ionosphere/), and the source of the GPS data is http://sopac.ucsd.edu/. The FORMOSAT-3/COSMIC data have been taken from http://tacc.cwb.gov.tw/. This work is supported by the Ministry of Science and Technology grants MOST 103-2628-M-008-001 to National Central University, Taiwan and 103-2111-M-006-003-MY3 and 103-2923-M-006-002-MY3 to National Cheng Kung University, Taiwan.

References

Arendt, P. R., and H. Soicher (1964), Downward electron flux at 1000 km altitude from electron content measurements at mid-latitudes, *Nature*, *4962*, 983–984, doi:10.1038/204983a0.

Balan, N., and G. J. Bailey (1995), Equatorial plasma fountain and its effects: Possibility of an additional layer, *J. Geophys. Res.*, *100*(A11), 21,421–21,432, doi:10.1029/95JA01555.

Balan, N., and P. B. Rao (1987), Latitudinal variations of nighttime enhancements in total electron content, *J. Geophys. Res.*, *92*(A4), 3436–3440, doi:10.1029/JA092iA04p03436.

Balan, N., G. J. Bailey, and R. Balachandran Nair (1991), Solar and magnetic activity effects on the latitudinal variations of nighttime TEC enhancement, *Ann. Geophys.*, *9*, 60–69.

Balan, N., G. J. Bailey, R. Balachandran Nair, and J. E. Titheridge (1994), Nighttime enhancements in ionospheric electron content in the northern and Southern Hemisphere, *J. Atmos. Terr. Phys.*, *56*(1), 67–79, doi:10.1016/0021-9169(94)90177-5.

Balan, N., P. K. Rajesh, S. Sripathi, S. Tulasiram, J. Y. Liu, and G. J. Bailey (2013), Modeling and observations of the north–south ionospheric asymmetry at low latitudes at long deep solar minimum, *Adv. Space Res.*, *53*, 724–733, doi:10.1016/j.asr.2013.12.019.

Bertin, F., and J. Papet-Lepine (1970), Latitudinal variation of total electron content in the winter at middle latitudes, *Radio Sci.*, *5*(6), 899–906, doi:10.1029/RS005i006p00899.

Dabas, R. S., and L. Kersley (2003), Study of mid-latitude nighttime enhancement in *F* region electron density using tomographic images over the UK, *Ann. Geophys.*, *21*, 2323–2328, doi:10.5194/angeo-21-2323-2003.

Davies, K., D. N. Anderson, A. K. Paul, W. Degenhardt, G. K. Hartmann, and R. Leitinger (1979), Nighttime increases in total electron content observed with the ATS 6 radio beacon, *J. Geophys. Res.*, *84*(A4), 1536–1542, doi:10.1029/JA084iA04p01536.

Dow, J. M., R. E. Neilan, and C. Rizos (2009), The International GNSS Service in a changing landscape of Global Navigation Satellite Systems, *J. Geod.*, *83*, 191–198, doi:10.1007/s00190-008-0300-3.

Essex, E. A. (1977), High to low latitude variations in the evening summer total electron content and *F*-region electron density, *J. Atmos. Terr. Phys.*, *39*, 1155–1158, doi:10.1016/0021-9169(77)90023-X.

Evans, J. V. (1965), Cause of the midlatitude winter night increase in foF_2, *J. Geophys. Res.*, *70*(17), 4331–4345, doi:10.1029/JZ070i017p04331.

Farelo, A. F., M. Herraiz, and A. V. Mikhailov (2002), Global morphology of night-time N_mF2 enhancements, *Ann. Geophys.*, *20*, 1795–1806, doi:10.5194/angeo-20-1795-2002.

Fejer, B. G. (1991), Low latitude electrodynamic plasma drifts: A review, *J. Atmos. Terr. Phys.*, *53*(8), 677–693, doi:10.1016/0021-9169(91)90121-M.

Hedin, A. E., et al. (1996), Empirical wind model for the upper, middle and lower atmosphere, *J. Atmos. Sol. Terr. Phys.*, *58*, 1421–1447, doi:10.1016/00219169(95)00122-0.

Huba, J. D., G. Joyce, and J. A. Fedder (2000), Sami2 is another model of the ionosphere (SAMI2): A new low-latitude ionosphere model, *J. Geophys. Res.*, *105*, 23,035–23,053, doi:10.1029/2000JA000035.

Jakowski, N., A. Jungstand, L. Lois, and B. Lazo (1991), Night-time enhancements of the F_2-layer ionization over Havana, Cuba, *J. Atmos. Sol. Terr. Phys.*, *53*, 1131–1138, doi:10.1016/0021-9169(91)90062-C.

Jee, G., H.-. B. Lee, Y. H. Kim, J.-. K. Chung, and J. Cho (2010), Assessment of GPS global ionosphere maps (GIM) by comparison between CODE GIM and TOPEX/Jason TEC data: Ionospheric perspective, *J. Geophys. Res.*, *115*, A10319, doi:10.1029/2010JA015432.

Kawamura, S., N. Balan, Y. Otsuka, and S. Fukao (2002), Annual and semiannual variations of the midlatitude ionosphere under low solar activity, *J. Geophys. Res.*, *107*(A8), 1166, doi:10.1029/2001JA000267.

Le, H., L. Liu, Y. Chen, H. Zhang, and W. Wan (2014), Modeling study of nighttime enhancements in *F* region electron density at low latitudes, *J. Geophys. Res. Space Physics*, *119*, 6648–6656, doi:10.1002/2013JA019295.

Lee, I. T., W. Wang, J. Y. Liu, C. Y. Chen, and C. H. Lin (2011), The ionospheric midlatitude trough observed by FORMOSAT-3/COSMIC during solar minimum, *J. Geophys. Res.*, *116*, A06311, doi:10.1029/2010JA015544.

Lin, C. H., J. Y. Liu, T. W. Fang, P. Y. Chang, H. F. Tsai, C. H. Chen, and C. C. Hsiao (2007), Motions of the equatorial ionization anomaly crests imaged by FORMOSAT-3/COSMIC, *Geophys. Res. Lett.*, *34*, L19101, doi:10.1029/2007GL030741.

Liu, L., Y. Chen, H. Le, B. Ning, W. Wan, J. Liu, and L. Hu (2013), A case study of postmidnight enhancement in *F*-layer electron density over Sanya of China, *J. Geophys. Res. Space Physics*, *118*, 4640–4648, doi:10.1002/jgra.50422.

Luan, X., W. Wang, A. Burns, S. C. Solomon, and J. Lei (2008), Midlatitude nighttime enhancement in *F* region electron density from global COSMIC measurements under solar minimum winter condition, *J. Geophys. Res.*, *113*, A09319, doi:10.1029/2008JA013063.

Mikhailov, A. V., M. Forster, and T. Y. Leschinkaya (2000a), On the mechanism of the post-midnight winter N_mF_2 increases: Dependence on solar activity, *Ann. Geophys.*, *18*, 1422–1434, doi:10.1007/s00585-000-1422-y.

Mikhailov, A. V., T. Y. Leschinkaya, and M. Forster (2000b), Morphology of N_mF_2 night-time increases in the Eurasian sector, *Ann. Geophys.*, *18*, 618–628, doi:10.1007/s00585-000-0618-5.

Park, C. G. (1970), Whistler observations of the interchange of ionization between the ionosphere and the protonosphere, *J. Geophys. Res.*, *75*(22), 4249–4260, doi:10.1029/JA075i022p04249.

Park, C. G. (1971), Westward electric fields as the cause of nighttime enhancements in electron concentrations in midlatitude *F* region, *J. Geophys. Res.*, *76*(19), 4560–4568, doi:10.1029/JA076i019p04560.

Pavlov, A. V., and N. M. Pavlova (2005), Mechanism of the post-midnight winter night-time enhancements in N_mF_2 over Millstone Hill during 14–17 January 1986, *J. Atmos. Sol. Terr. Phys.*, *67*(4), 381–395, doi:10.1016/j.jastp.2004.11.004.

Scherliess, L., and B. G. Fejer (1999), Radar and satellite global equatorial *F* region vertical drift model, *J. Geophys. Res.*, *104*, 6829–6842, doi:10.1029/1999JA900025.

Su, Y. Z., G. J. Bailey, and N. Balan (1994), Night-time enhancements in TEC at equatorial anomaly latitudes, *J. Atmos. Sol. Terr. Phys.*, *56*, 1619–1628, doi:10.1016/0021-9169(94)90091-4.

Su, Y. Z., S. Fukao, and G. J. Bailey (1997), Modeling studies of the middle and upper atmosphere radar observations of the ionospheric *F* layer, *J. Geophys. Res.*, *102*(A1), 319–327, doi:10.1029/96JA02994.

Thomas, J. O. (1963), The electron density distribution in the F_2 layer of the ionosphere in winter, *J. Geophys. Res.*, *68*(9), 2707–2718, doi:10.1029/JZ068i009p02707.

Titheridge, J. E. (1968), The maintenance of the night ionosphere, *J. Atmos. Terr. Phys.*, *30*(11), 1857–1875, doi:10.1016/0021-9169(68)90028-7.

Tulasi, R. S., S. Y. Su, and C. H. Liu (2009), FORMOSAT-3/COSMIC observations of seasonal and longitudinal variations of equatorial ionization anomaly and its interhemispheric asymmetry during the solar minimum period, *J. Geophys. Res.*, *114*, A06311, doi:10.1029/2008JA013880.

Tulunay, Y. K., and J. Sayers (1971), Characteristics of midlatitude trough as determined by electron density experiment on ARIEL 3, *J. Atmos. Terr. Phys.*, *33*(11), 1737–1761, doi:10.1016/0021-9169(71)90221-2.
Tyagi, T. R. (1974), Electron content and its variation over Lindau, *J. Atmos. Terr. Phys.*, *36*(3), 475–487, doi:10.1016/0021-9169(74)90127-5.
Young, D. M. L., P. C. Yuen, and T. H. Roelofs (1970), Anomalous nighttime increases in total electron content, *Planet. Space Sci.*, *18*(8), 1163–1179, doi:10.1016/0032-0633(70)90210-2.