Originally published as:

Liu, J., Zhang, D., Mo, X., Xiong, C., Hao, Y., Xiao, Z. (2020): Morphological Differences of the Northern Equatorial Ionization Anomaly Between the Eastern Asian and American Sectors. - Journal of Geophysical Research: Space Physics, 125, 3, e2019JA027506.

<https://doi.org/10.1029/2019JA027506>

JGR Space Physics

RESEARCH ARTICLE

10.1029/2019JA027506

Special Section:

Equatorial Aeronomy: New results from the 15th International Symposium on Equatorial Aeronomy (ISEA-15) and beyond

Key Points:

- The seasonal variation of the northern EIA crest location is distinctly different between the eastern Asian and American sectors
- Such difference is probably related to the different meridional wind effects due to the displacement of geographic and magnetic equators
- The EIA crest intensity tends to be stronger in the eastern Asian sector in all seasons that may be due to the nonmigrating tides

Supporting Information:

- Supporting Information S1

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Citation:

Liu, J., Zhang, D., Mo, X., Xiong, C., Hao, Y., & Xiao, Z. (2020). Morphological differences of the northern equatorial ionization anomaly between the eastern Asian and American sectors. *Journal of Geophysical Research: Space Physics*, 125, e2019JA027506. <https://doi.org/10.1029/2019JA027506>

Received 24 OCT 2019

Accepted 18 FEB 2020

Accepted article online 22 FEB 2020

Morphological Differences of the Northern Equatorial Ionization Anomaly Between the Eastern Asian and American Sectors

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Abstract The morphological difference of the northern equatorial ionization anomaly between the eastern Asian and American sectors is statistically studied with ground-based total electron content data from 2000 to 2011. The intensity (I_c), latitudinal location (L_c), and occurrence time (T_c) of the daytime equatorial ionization anomaly crest are derived from daytime peak total electron content in time-latitude plots. The main results are as follows. L_c in the two sectors exhibits an apparent difference, especially in solar minimum, during which L_c in the American sector shows an annual variation that is more poleward in northern summer and more equatorward in northern winter, while L_c in the eastern Asian sector shows a semiannual variation that is more poleward around equinoxes and more equatorward around solstices. I_c tends to be stronger in the eastern Asian sector than that in the American sector in all seasons, and this difference increases with the increase of the solar flux index. T_c tends to be earlier in northern winter and later in northern summer in both sectors and shows dependence on solar activity. We demonstrate that the seasonal variation of L_c in the American sector is not dominated by the ionospheric equatorial zonal electric field, and suggest that the difference of L_c between the two sectors is probably related to different meridional wind effects due to the displacement of geographic and magnetic equators. The I_c difference is probably related to the longitudinal wave number-3 and -4 structures driven by tidal forcing from the slower atmosphere.

1. Introduction

The equatorial ionization anomaly (EIA) is the most distinct phenomenon in the daytime low-latitude ionosphere. It is characterized by dual electron density crests at about $\pm 15^\circ$ magnetic latitude (MLAT) and a trough at the dip equator. The formation of the EIA is explained by the fountain effect that describes the plasma motion in the vertical direction and the concurrent diffusion along the magnetic field lines (Balan et al., 2018; Duncan, 1960; Hanson & Moffett, 1966; Kelley, 2009; Martyn, 1947). The morphology and variation mechanism of EIA have been extensively studied in different sectors based on various kinds of data source, such as ionosonde data, total electron content (TEC) from satellite beacons, and in situ satellite measurements (Anderson, 1973; Walker & Strickland, 1981; Walker, 1981; Huang et al., 1989; Su et al., 1997; Tsai et al., 2001; Huang & Cheng, 1996; Lin et al., 2007; Wu et al., 2004, 2008; Stolle et al., 2008; Zhang, Wan, et al., 2009; Zhao et al., 2009; Huang et al., 2013; Luan et al., 2015; Mo et al., 2018). In general, it is found that EIA exhibits diurnal, seasonal, and solar cycle variations, and it is suggested that these features are influenced by various factors, such as the ionospheric electric field, the thermospheric wind, the subsolar point location, and the local geomagnetic field configuration. However, the variation features of EIA may be different in different sectors, and the relative importance of these influence factors is still not thoroughly understood.

The longitudinal difference of the EIA morphology is the main focus of the current research (Anderson, 1973; Walker, 1981; Walker & Strickland, 1981; Su et al., 1995, 1997; Tulasi Ram et al., 2009; Yizengaw et al., 2014). As early as the 1980s, Walker and Strickland (1981) compared the EIA morphology in solar minimum between the eastern Asian and American sectors based on limited f_oF_2 and M3000 data. It was found that the diurnal evolution of EIA in the two sectors has systematic differences, and they attributed the differences to the difference of meridional wind due to the relative location of the subsolar point with respect to the magnetic equator in two sectors, the magnetic declination, and the magnitude of the magnetic field. With simulations from the Sheffield University Plasmasphere-Ionosphere Model, Su et al. (1997)

analyzed the neutral wind effect to the hemispheric asymmetry of the EIA in four longitudinal bands under magnetically quiet equinoctial conditions in solar maximum. It is suggested that the north-south asymmetry of EIA changes with the longitude, which is related to the displacement between the magnetic equator and the geographic equator, as well as the differences in the declination angle. These studies indicated the importance of the structure of the geomagnetic field to the modulation of the EIA evolution; however, they mainly focused on relatively short time ranges (several years) compared to a solar cycle, and the spatiotemporal coverage of the used data source is limited. Besides the above-mentioned influence factors, recent studies showed that the longitudinal distribution of the low-latitude ionosphere is largely related to the tidal and wave forces from lower atmosphere, that is, the nonmigrating tides (England et al., 2006; Immel et al., 2006; Kil et al., 2008; Kil et al., 2011; Scherliess et al., 2008; Wan et al., 2008; Ren et al., 2009; Pedatella et al., 2011) and also the topside ionosphere-plasmasphere electron density distribution (Lee et al., 2013; Li et al., 2018; Pedatella et al., 2011; Shim et al., 2017; Zhong et al., 2017). Thus, it is necessary to study the longitudinal difference of the EIA morphology based on long-term high-resolution data sets.

Meanwhile, some studies focused on the hemispheric asymmetry of the EIA morphology and their analysis also helps to understand the longitudinal difference of the EIA morphology (Walker & Strickland, 1981; Su et al., 1997; Tsai et al., 2001; Tulasi Ram et al., 2009; Zhang, Wan, et al., 2009; Zhao et al., 2009; Huang et al., 2013; Luan et al., 2015). Tsai et al. (2001) studied the EIA variations in the Asian area with TEC data in 1997. Their results showed that the seasonal variation of the EIA crest location is apparently different between the northern and southern EIA, and this is attributed to the combined effect of the trans-equatorial wind from the subsolar point and the auroral equatorward wind. Xiong et al. (2013) showed that the magnitudes of EIA crests at two hemispheres reverse during the solstice seasons, and the reverse of the EIA interhemispheric asymmetry shows also dependence on altitude. Besides, Zhao et al. (2009) investigated the EIA morphology in the Asia-Australia sector during 1996–2004 and showed that the northern *L*_c exhibits a different seasonal variation pattern with the southern *L*_c.

Since the 1990s, the TEC derived from the Global Positioning System (GPS) has been proved to be a useful tool in the research of ionospheric morphology and disturbances (Ho et al., 1996; Mannucci et al., 1998; Zhang & Xiao, 2005). In recent years, as its spatiotemporal coverage improves, the GPS TEC has been used in the study of the long-term and seasonal variations of EIA and some new results were provided (Wu et al., 2008; Zhang, Wan, et al., 2009; Zhao et al., 2009; Huang et al., 2013; Mo et al., 2018). Wu et al. (2008) statistically studied the EIA morphology around Taiwan with TEC from nine GPS receivers between 1994 and 2003. Their results of the intensity and occurrence time of the EIA crest were consistent with Huang and Cheng (1996) with TEC from U.S. Navy Navigation Satellite System. Moreover, they reported that the EIA crest location in the eastern Asian sector has a semiannual variation; that is, it has higher latitudes around equinoxes and lower latitudes around solstices. This semiannual variation was most significant in the solar minimum period and was suggested to be related to the seasonal variation of the $E \times B$ drift. Such findings and explanation were different from Huang and Cheng (1996), which reported that the EIA crest location has the lowest latitudes around the northern hemisphere summer and suggested that this seasonal variation is due to the trans-equatorial wind. Thus, the dominant influence factor of the seasonal variation of the EIA crest is still an open question.

Furthermore, such long-term analysis studies of the EIA with GPS TEC were mainly conducted in the eastern Asian sector. The American sector also has high spatiotemporal coverages of GPS receiver data, but comparatively, similar long-term analysis at this longitude sector is seldom reported. In this research, we report the long-term and seasonal variations of the northern EIA in the American sector with GPS TEC from 2000 to 2011 and revisit the eastern Asian results for comparison. Distinct long-term and seasonal morphological differences of the EIA crest exist between the two sectors, especially in the seasonal variation of the EIA crest location in solar minimum period, and the influence factors are discussed in detail.

2. Data and Methods

In this study, the GPS TEC, the in situ CHAMP (CHALLENGING Mini-satellite Payload) electron density, and the EEJ intensity from the magnetometer data are used.

The TEC data used in this study have two sources. One is the Madrigal database of the Massachusetts Institute of Technology, which provides global vertical TEC (VTEC) maps with a spatiotemporal

Figure 1. An example of the VTEC data coverage of the Madrigal database in a 0.5-hr window (12:00–12:30 UT, 10 June 2009) for the (a) eastern Asian and (b) American sectors. Blue stars illustrate the four GPS receivers of CMONOC. The black dashed lines enclose the studied areas in each sector, with the upper and lower lines showing the magnetic latitudes of 0° and 30°N. Blue triangles depict the locations of magnetometers. The red dot lines show the dayside track of the CHAMP satellite on 10 June 2009.

resolution of 1° longitude $\times$ 1° latitude $\times$ 5 min (Rideout & Coster, 2006). Figure 1 shows an example of the data coverage of this data set in a 0.5-hr window (12:00–12:30 universal time, 10 June 2009) with grey areas. The dashed lines enclose the studied regions in the (a) eastern Asian (100°E – 130°E) and (b) American (60°W – 90°W) sectors, within the same magnetic latitudinal range of 0° – 30°N . However, the data coverage around the northern EIA crest of the eastern Asian sector is limited. So data from four GPS receivers around the EIA region in the eastern Asian sector are also used to derive the TEC, whose locations are marked in Figure 1a with black stars. To be specific, they are GUAN (23.2°N , 113.3°E ; $\sim 13.4^\circ\text{N}$, MLAT), QION (19.0°N , 109.8°E ; $\sim 9.2^\circ\text{N}$, MLAT), XIAM (24.4°N , 118.1°E ; $\sim 14.7^\circ\text{N}$, MLAT), and YONG (16.8°N , 112.3°E ; $\sim 7.0^\circ\text{N}$, MLAT) that are affiliated to the Crustal Movement Observation Network of China. The method of calculating VTEC from the GPS data is described in Zhang, Zhang, and Xiao (2009) and Zhang et al. (2010). During the calculation, the cutoff elevation angle is 30° .

The daily EIA parameters are estimated with the time-latitude plot (TLP) from the daily VTEC maps. To derive TLPs, it is assumed that, within the studied longitudinal sector, which is narrow, the longitudinal variation of VTEC at a specific magnetic latitude only depends on the local time change. As a result, the universal time (UT) of the VTEC data is first transformed to local time (LT) with $\text{LT} = \text{UT} + \text{longitude}/15^\circ$, where longitude is the longitude of each data point. Then, the VTEC data in each studied sector are filled into bins with a spatiotemporal resolution of $0.5 \text{ hr} \times 1^\circ$ magnetic latitude. The final bin value is the averaged VTEC of each bin. Finally, a series of TLPs from 2000 to 2011 is obtained. Figure 2 gives an example of TLPs in both sectors on the same date as Figure 1. The unit of VTEC is TECU ($1 \text{ TECU} = 10^{16} \text{ electrons m}^{-2}$).

Then, with these TLPs, the intensity, latitudinal location, and occurrence time of the daytime EIA crest can be defined based on the method of previous papers (Huang & Cheng, 1996; Wu et al., 2008; Zhao et al., 2009). In short, these researches defined the intensity of the EIA crest as the largest TEC in the EIA contour chart in latitude versus time coordinates. However, as shown in Figure 2, such a method can be easily influenced by the data quality if only picking out the largest data point. Thus, in this study, the previous method is revised as follows. Firstly, only data between 08:00 and 18:00 LT have been taken into account, as previous studies showed that T_c is around 14:00 LT (Huang & Cheng, 1996; Wu et al., 2008; Zhao et al., 2009), and the cutoff at 18:00 LT helps reduce the possible contamination from the postsunset enhancement (Farley et al., 1986). Then, the following method is conducted to select data points that represent the most developed EIA crest. First, the bin value is removed as an outlier if it is not within plus/minus 3 times the standard deviation (σ) of the mean of all the bin values in the studied spatiotemporal range (08:00–18:00 LT; 0° – 30°N , MLAT). Then, data points within the top 5% of magnitudes are picked out. Next, to further remove outliers according to the

Figure 2. Examples of TLPs in the (a) eastern Asian and (b) American sectors on 10 June 2009. Black dashed lines mark the studied time range of 08:00–18:00 LT. White dots illustrate the selected data points, and I_c is the averaged VTEC of these data points. The location and local time of the black stars show L_c and T_c .

local time and magnetic latitude, an empirical spatiotemporal area (marked as dashed squares in Figure 2) is chosen with the local-time range of 5 hr and the magnetic-latitude range of 10° which centers at the point with the mean local time and magnetic latitude of the selected data points. If the selected data point lies out of this spatiotemporal area, it was removed as an outlier. After this, we further manually checked all the TLPs to remove days with evident bad data. In the end, the intensity (I_c), latitudinal location (L_c), and occurrence time (T_c) of the daytime EIA crest are defined as the averaged VTEC, averaged latitudinal location, and averaged occurrence time of the remaining selected data points. In other words, I_c , L_c , and T_c in this study reflect the averaged characteristics of the daytime EIA region with the strongest magnitude. In Figure 2, the white dots illustrate the remaining selected data points, and the location and local time of the black stars show the L_c and T_c . The averaged VTEC of the data points marked by the white dots is I_c .

As a comparison, the intensity and location of the EIA crests are also estimated with the in situ CHAMP electron density data. The orbit inclination of CHAMP is 87.3° , and its mission period (15 July 2000 to 19 September 2010) is coincident with the TEC data period we have used. The CHAMP onboard Planar Langmuir Probe provided in situ electron density measurements with a temporal resolution of 15 s. We used the CHAMP electron density data from 15 May 2001 to 21 February 2010. These data were extracted for each sector between 08:00 and 18:00 LT in the same longitudinal bands as those in the VTEC method. In Figure 1, the red dots show the tracks of the CHAMP electron density data on the same date as the VTEC. If the track is across the latitudinal boundaries of the studied areas, the maximum value and the corresponding latitude are extracted as the intensity and location of the northern EIA crest at the CHAMP altitude. It should be noted that since the local time of the satellite track is changing day by day (about 1 hr per 11 days), the extracted intensity and location of the EIA crests at the CHAMP altitude do not reflect the most developed EIA (like I_c and L_c), but reflect the averaged characteristics of EIA between 08:00 and 18:00 LT at the CHAMP altitude. In addition, although there is always a CHAMP track in the studied longitudinal bands

as wide as 30° since the longitudinal range between the adjacent daytime tracks of CHAMP is about 23° , there are no data during specific periods of the year because it needs about 130 days for CHAMP to sample all local time.

In addition to the ground-based TEC and CHAMP in situ electron density, the EEJ data have also been used. The EEJ intensity is estimated with the difference of the horizontal component (H) of the magnetic field between a magnetometer on the dip equator and the other one aside (Anderson et al., 2002; Kane, 1973; Rastogi & Klobuchar, 1990). This parameter is commonly used as the proxy of the equatorial vertical drift considering their good linear relationship (Anderson et al., 2002). In the American sector, the utilized magnetometer stations are located at Huancayo (HUA; 12.0°S , 75.3°W ; $\sim 2.3^\circ\text{S}$, MLAT) and Fuquene (FUQ; 5.5°N , 73.7°W ; $\sim 15.1^\circ\text{N}$, MLAT). In the eastern Asian sector, the magnetometer stations of Bac Lieu (BCL; 9.3°N , 105.7°E ; $\sim 1.4^\circ\text{S}$, MLAT) and Qiongzhou (QGZ; 19.0°N , 109.8°E ; $\sim 9.20^\circ\text{N}$, MLAT) are with eligible locations for the dual-station method. However, the magnetometer from QGZ provides data that starts only from the year 2009.

Considering the lack of data in the eastern Asian sector, the EEJ intensity in the Indian sector was used as a substitute. The reasonability of this replacement is as follows. As Rastogi (2006) suggested, the day-to-day fluctuation in the range of H from BCL is similar to that from an Indian station, Alibag (ABG; 18.6°N , 72.9°E ; $\sim 10.5^\circ\text{N}$, MLAT). In addition, Mo et al. (2018) suggested that it is acceptable to use the EEJ intensity in the Indian sector to replace the EEJ intensity in the eastern Asian sector when the latter sector lacks magnetometer data. To further demonstrate this point, Figure S1 gives the relationship of the averaged EEJ intensity (07:00–14:00 LT) between the Indian sector and the eastern Asian sector during 2009–2011 (in the supporting information). This averaged EEJ intensity between 07:00 and 14:00 LT is going to be used in the following analysis. For the Indian sector, the utilized stations are Tirunelveli (TIR, 8.7°N , 77.8°E ; $\sim 0.2^\circ\text{N}$, MLAT) and ABG, and for the eastern Asian sector, the utilized stations are BCL and QGZ. It shows that the averaged EEJ intensities in the two sectors exhibit a good linear relationship ($r = 0.59$). In addition, Figure S2 gives the relationship of the EEJ intensity from the CHAMP magnetometer in the longitudinal band of 100°E – 130°E and 60°E – 90°E from 20 July 2000 to 12 September 2010 between 07:00 and 18:00 LT (in the supporting information). For each dot, the local time difference of the EEJ intensities in the two sectors is less than 0.02 hr, and they also show a good linear relationship ($r = 0.53$). Thus, in the following analysis, we use the EEJ intensity from the Indian sector to replace that in the eastern Asian sector during the same local time. Note that we did not use the CHAMP EEJ intensity since there are no data during some continuous days in the studied longitudinal sectors.

The geomagnetic storm has enormous influences on the ionospheric morphology (Rishbeth & Mendillo, 2001), so data with daily $K_p > 3$ are removed in this study. Meanwhile, the solar activity is represented with the P index (Liu et al., 2006). This index is defined as $P = (F_{10.7} + F_{10.7A})/2$ where $F_{10.7A}$ is the 81-day running average of $F_{10.7}$. Both K_p and $F_{10.7}$ were downloaded from the FTP service of the National Oceanic and Atmospheric Administration.

3. Results

3.1. Solar Cycle Variations of I_c , L_c , and T_c

Figures 3a and 4a give the variations of I_c in the eastern Asian and American sectors from 2000 to 2011, respectively. The black dots, red lines, and error bars indicate the daily values, the monthly means of the daily values, and the standard deviations of the monthly means of the daily values of I_c . Grey dots show the variation of the P index during the same period. On the whole, I_c in the two sectors exhibits similar solar-cycle and seasonal variations. In the long term, I_c weakens with the decrease of the P index. This reflects the dominant effect of solar radiation on the ionospheric electron density. Besides, I_c has an evident seasonal variation. It is stronger around equinoxes and weaker around the northern hemisphere summer than winter. This feature is more distinct in solar maximum than in solar minimum.

To further show the solar cycle and seasonal variations of I_c , Figure 5 gives the relationship between the monthly averaged P index and monthly averaged I_c during the studied period. Different seasons are marked with different colors (spring: March to May, summer: June to August, autumn: September to November, winter: December to February). It shows that I_c and P index exhibit a good linear relationship for both

Figure 3. Variations of (a) I_c , (b) L_c , and (c) T_c derived from the VTEC data with daily $K_p \leq 3$ in the eastern Asian sector from 1 January 2000 to 31 December 2011. Grey dots in (a) depict the daily P index. Grey dots in (b) depict the polynomial fitting of the monthly L_c . Red curves show the monthly averaged values, and red error bars illustrate the monthly standard deviations. Black bars in (d) give the number of data points for each month.

the eastern Asian ($r = 0.93$) and American ($r = 0.90$) sectors. The solar activity dependence of I_c is apparent. However, the increasing rates of I_c with P are different for different seasons. They are higher in equinox seasons and weaker in the northern hemisphere summer. Moreover, it is interesting to note that, although the seasonal and solar cycle variations of I_c are similar in the two sectors, its value seems larger in the eastern Asian sector than that in the American sector. Such difference of I_c will be confirmed further by the CHAMP electron density data in the following text and be discussed in detail in section 4.

Similarly, Figures 3b and 4b give the variations of L_c in the eastern Asian and American sectors from 2000 to 2011, respectively. For the eastern Asian sector (Figure 3b), unlike I_c , L_c does not vary significantly with the P index. However, it still exhibits a weak solar cycle dependence, with higher latitudes in solar maximum than in solar minimum. To show it clearly, a three-order polynomial fitting was conducted to the monthly means of L_c , and the result is shown with the grey dot line in Figure 3b that corresponds to the y axis on the right. This feature is also reported by Mo et al. (2018). Besides, the 12-year averaged magnetic latitude is $13.2^\circ \pm 2.7^\circ\text{N}$. On the other hand, it seems that L_c in the eastern Asian sector exhibits a seasonal variation, but it is not very distinct compared to the studied latitudinal range of 0° – 30°N (MLAT). In contrast, in the American sector (Figure 4b), the solar cycle and seasonal dependence of L_c is very distinct. As the solar activity decreases, L_c shows a much clearer annual variation, with higher latitudes in the northern hemisphere summer and lower latitudes in the northern hemisphere winter. If focusing on the monthly averaged L_c in December, it shows a good correlation with the P index ($r = 0.82$; figure not shown here). In solar minimum, the variation range of L_c reaches $\sim 15^\circ$ and is significantly larger than that in the eastern Asian sector. Correspondingly, the 12-year averaged magnetic latitude is $12.3^\circ \pm 4.4^\circ\text{N}$. Such significant differences in the solar cycle and seasonal dependence of L_c between the eastern Asian and American sectors have not been clearly reported in previous studies.

Figure 4. Similar to Figure 3 but for the American sector.

Figures 3c and 4c give the variations of T_c from 2000 to 2011, in the two sectors, respectively. Different from the variations of L_c in two sectors, the variations of T_c in two sectors seem similar. The day-to-day variation of T_c is quite significant since most of the standard deviations are larger than 1 hr. Meanwhile, T_c exhibits an annual variation, especially in solar minimum, which occurs earlier in the northern hemisphere winter (~13:00–14:00 LT) and later in the northern hemisphere summer (~15:00–16:00 LT). In the long term, T_c does not show a linear relationship with the P index. On the whole, the above characteristics of T_c are

Figure 5. The relationship between the monthly averaged P index and the monthly averaged f_oF_2 for the (a) eastern Asian and (b) American sector. The seasons are marked with different colors. Correlation coefficients are listed aside.

Figure 6. Variations of the (a) intensity and (b) location of the EIA crest in the eastern Asian sector between 08:00 and 18:00 LT derived from the CHAMP electron density data during 2001–2010 with daily $K_p \leq 3$. The data points between 14:00 and 16:00 LT are marked with red. Grey dashed lines in (a) and (b) depict the monthly I_c and L_c in Figure 3, respectively.

consistent with previous studies in the eastern Asian sector with different observations during different solar cycles (Huang et al., 1989; Huang & Cheng, 1996; Wu et al., 2008; Zhao et al., 2009).

In the above results, I_c and especially L_c show apparent differences in the two sectors. As a verification of the differences, Figures 6 and 7 give the (a) intensity and (b) location of the EIA crest at CHAMP altitude derived from the CHAMP electron density data during 2001–2009 in the eastern Asian and American sectors. The data between 14:00 and 16:00 LT are marked with red as this is the time interval where the I_c occurs most frequently. As a comparison, the monthly mean variations of I_c and L_c in Figures 3 and 4 are plotted with grey dashed lines that correspond to the right axis. In Figures 6a and 7a, the EIA crest intensity at CHAMP altitude in both sectors weakens from solar maximum period (around the year 2001) to solar minimum period (around the year 2008). Besides this, it seems to exhibit a seasonal variation that is similar to I_c , with stronger intensity around equinoxes and weaker intensity around solstices, for example, in the year 2004. However, considering the local time shift of the CHAMP data that we mentioned in section 2, such seasonal patterns are not as much clear in different years. In addition, the EIA crest intensity at CHAMP

Figure 7. Similar to Figure 6 but for the American sector.

Figure 8. The monthly averaged L_c in the (a) eastern Asian and (b) American sectors in solar maximum (red) and minimum (blue). Error bars show the monthly standard deviations. Horizontal dashed lines give the 12-month averages.

altitude seems stronger in the eastern Asian sector than in the American sector, especially in solar maximum. In Figures 6b and 7b, the EIA crest location at CHAMP altitude of the two sectors exhibits significant differences that are similar to L_c . In the American sector, the EIA crest location at CHAMP altitude seems to exhibit annual variations with higher latitudes around the northern hemisphere summer and lower latitudes around the northern hemisphere winter. Comparatively, the seasonal dependence of the EIA crest location at CHAMP altitude in the eastern Asian sector is not as distinct.

It should be noted that the CHAMP satellite orbit is at ~ 450 km in the beginning and gradually decreases to ~ 300 km at the end of 2009. Therefore, the long-term variations of the intensity and location in Figures 6 and 7 are also influenced by the altitude changing of the satellite orbit. However, this will not greatly influence the comparison between the two sectors since the CHAMP satellite flew over the two sectors at similar altitudes on a given day. Besides, the intensity and location of the EIA crests at the CHAMP altitude in our results reflect the averaged characteristics between 08:00 and 18:00 LT. In addition, since the EIA structure is three dimensional, the variations of the EIA crest intensity and location at CHAMP altitude are also influenced by the vertical movement of the EIA structure. Comparatively, the I_c and L_c were derived from the vertical integral data of VTEC. Nevertheless, it can be seen from the comparison between the CHAMP results (dots) and the VTEC results (grey dashed lines) that the variation features of the two kinds of parameters are generally consistent with each other. Thus, it further shows that the EIA morphology exhibits distinct differences between the eastern Asian and American sectors, especially the difference in the seasonal variation of the EIA crest location.

3.2. Seasonal Variations of L_c and T_c

In section 3.1, the seasonal variation of EIA peak parameters can be roughly identified. Now the features of the seasonal variation of EIA will be revealed further in different solar activity phases in the two sectors. The seasonal variation of the EIA crest intensity has been extensively studied previously. Therefore, in this section, we mainly focus on the seasonal variations of L_c and T_c . Figures 8 and 9 show the seasonal characteristics of L_c and T_c under different solar activities in the eastern Asian and American sectors, respectively. The solid lines illustrate the monthly averaged values in solar maximum (2000–2002, red) and solar minimum (2007–2009, blue). The dashed lines show the yearly averaged values, and the error bars give the monthly standard deviations. Note that the red and blue curves are staggered to avoid the error bars from covering each other.

In the eastern Asian sector (Figure 8a), L_c tends to be higher in solar maximum than in solar minimum. This solar cycle dependence is also seen in Figure 3a, although it is not as clear. To be specific, the 12-month averaged L_c and standard deviation are 14.0°N (red dashed line) and 2.8° , respectively, in solar maximum, and they are 12.2°N (blue dashed line) and 2.2° , respectively, in solar minimum. Meanwhile, L_c exhibits

Figure 9. Similar to Figure 8 but for the monthly averaged T_c .

seasonal characteristics. In solar maximum, it is lowest around the northern hemisphere summer. This feature has been reported by Huang et al. (1989) as well as Huang and Cheng (1996). In solar minimum, it is lower around solstices and higher around equinoxes, thus showing a semiannual variation. This feature has also been reported by previous researches (Mo et al., 2018; Wu et al., 2008; Zhao et al., 2009), and it is suggested to be related to the semiannual variation of the equatorial electric field (Mo et al., 2018; Wu et al., 2008).

In the American sector (Figure 8b), the characteristic of L_c is significantly different from that in the eastern Asian sector. In solar maximum, the 12-month averaged L_c and standard deviation are 12.6°N (red dashed line) and 3.0° , respectively. In solar minimum, the 12-month averaged L_c and standard deviation are 11.8°N (blue dashed line) and 3.0° , respectively. Its seasonal variation range is much larger than that in the eastern Asian sector. It exhibits an apparent annual variation that moves equatorward in the northern hemisphere winter and moves poleward in the northern hemisphere summer. The significant difference of L_c between the eastern Asian and American sectors is discussed in detail in section 4.1.

In Figure 9, T_c generally shows a similar annual trend for both sectors, which is earlier in the northern hemisphere winter and later in the northern hemisphere summer. It should be noted that an exception is the T_c in the American sector in solar maximum in October and November. This may be attributed to the strong post-sunset enhancement phenomenon. The postsunset enhancement of TEC in the low-latitude ionosphere is related to the prereversal enhancement of the equatorial vertical drift. With the vertical drift data from Jicamarca Observatory in Peru (12.0°S , 76.9°W ; $\sim 2.3^\circ\text{S}$, MLAT), Fejer et al. (1979) suggested that the prereversal enhancement of the equatorial F region vertical drift is much more common and pronounced in solar maximum. When the crest of the postsunset enhancement is strong and occurs close to the daytime EIA crest in local time, the crests at daytime and postsunset hours are not easy to be separated. In this condition, the 18:00 LT limitation in our data process cannot totally prevent the daytime EIA crest from being contaminated from the values of postsunset hours. Thus, the significantly later T_c in years 2001 and 2002 around October and November (see Figure 4c) is probably due to the pronounced postsunset enhancement during these periods. Meanwhile, such influence is limited in other periods in our data process.

The seasonal variation pattern of T_c is generally attributed to the seasonal variation of the trans-equatorial wind in previous studies (Huang & Cheng, 1996; Lin et al., 2007; Wu et al., 2008). On the other hand, T_c also exhibits apparent solar cycle and longitudinal differences. In the eastern Asian sector (Figure 9a), the 12-month averaged T_c and standard deviation are 14.8 LT (red dashed line) and 0.9 hr, respectively, in solar maximum; while they are 14.2 LT (blue dashed line) and 1.0 hr, respectively, in solar minimum. On the whole, T_c is relatively later by about 0.6 hr in solar maximum than in solar minimum, and the difference is more significant during the northern hemisphere summer and especially winter. In the American sector (Figure 9b), the 12-month averaged T_c and standard deviation are 14.5 LT (red dashed line) and 0.9 hr, respectively, in solar maximum, while they are 14.8 LT (blue dashed line) and 1.0 hr, respectively, in solar

Figure 10. The relationship between the monthly averaged EEJ intensity and the monthly averaged L_c for the (a) eastern Asian and (b) American sector. The seasons are marked with different colors. Correlation coefficients are listed aside.

minimum. On the whole, T_c is relatively later by about 0.3 hr in solar minimum than in solar maximum, which is more significant from March to September. Comparatively, the relative occurrence time of T_c under different solar activities seems to be opposite in the two sectors.

4. Discussion

The results show apparent differences of the EIA morphology between the eastern Asian and American sectors, especially in the L_c and I_c . In general, the evolution of EIA at geomagnetic quiet period may be influenced by the combined effect of variety of factors, such as the equatorial zonal electric field, the meridional and zonal wind, the intensity and structure of the geomagnetic field, and the initial plasma distribution (Huang & Cheng, 1996; Mo et al., 2018; Tsai et al., 2001; Walker & Strickland, 1981; Wu et al., 2008; Zhang et al., 2012). In the following text, these influence factors to the longitudinal difference of L_c and I_c are discussed separately in detail.

4.1. The Longitudinal Difference of Seasonal Variation of L_c

In this study, the difference of the seasonal variation of the EIA crest location is the most distinct difference of EIA parameters between the eastern Asian and American sectors. It is mentioned above that such difference is probably caused by the combined effect of several factors. The question is whether there is a dominant factor of the seasonal variation of L_c .

According to the fountain effect theory, the equatorial zonal electric field in the lower F region drives the vertical plasma drift via $E \times B$. Thus, it is natural to think that the seasonal variation of L_c may be dominated by the seasonal variation of the equatorial electric field. This interpretation was proposed in previous papers when explaining the semiannual variation of L_c in the eastern Asian sector (Mo et al., 2018; Wu et al., 2008). Wu et al. (2008) suggested that the semiannual variation of the northern EIA crest location is related to the seasonal variation of $E \times B$ drift. Mo et al. (2018) analyzed the relationship between EEJ and EIA crest locations and found a good linear relationship. It was demonstrated that the seasonal dependence of EIA crest location is related directly to the zonal electric field, rather than to the solar flux.

Thus, we analyzed the correlation between the EEJ intensity and L_c to test whether the equatorial zonal electric field accounts for the difference of L_c between the two sectors. As reported by Stolle et al. (2008), a typical response time of the EIA to the variation of EEJ strength is about 2–4 hr. Considering that T_c is around 14:30 LT in both sectors, Figure 10 depicts the relationship between the monthly average of the daily mean (07:00–14:00 LT) EEJ intensity and the monthly average of the L_c in the (a) eastern Asian and (b) American sectors. Different seasons are marked with colors. Note that, as mentioned in section 2, the EEJ data in the eastern Asian sector have been replaced with that in the Indian sector. It can be seen that, in the eastern Asian sector (Figure 10a), L_c is in good correlation with the EEJ intensity ($r = 0.55$). This is consistent with previous

Figure 11. Variations of the intensity and location of the EIA crests in the (a) northern and (b) southern hemispheres in the Asia-Australian sector derived from the one-GPS-receiver method with the VTEC data. The used stations are GUAN and BAKO. The dot color illustrates the EIA intensity.

research and suggests that the electric-field explanation may be still suitable for our results in the eastern Asian sector. However, in the American sector (Figure 10b), the correlation between EEJ intensity and L_c is low ($r = 0.18$). Clearly, this poor linear relationship results from the data in the northern hemisphere summer (June, July, August) and spring (mainly May), and it is due to the fact that the EEJ intensity in the American sector exhibits a semiannual variation (not shown here) while L_c in the American sector exhibits an annual variation. Thus, it suggests that, at least in the American sector, the equatorial electric field cannot be treated as the dominant factor for the seasonal variation of L_c .

It shows in Figure 1 that the most distinct background difference between the two sectors is that their dip equators are in different hemispheres. Previous observation and model studies have demonstrated that the combined effect of the displacement of the dip equator and the trans-equatorial neutral wind may lead to an apparent difference in the diurnal evolution of EIA between the eastern Asian and American sectors (Walker, 1981; Walker & Strickland, 1981; Su et al., 1997). Therefore, the displacement of the dip equator may be a key factor in causing such a longitudinal difference in the solar cycle and seasonal variation patterns of L_c . Model simulation studies are needed to make this clear in further research. In the following text, some observation results are provided to support our hypothesis. Given that the dip equator in the eastern Asian sector is in the northern hemisphere while the dip equator in the American sector is in the southern hemisphere, if the displacement of the dip equator is a key factor to the longitudinal difference of the solar cycle and seasonal variation patterns of L_c , the southern L_c in the eastern Asian sector and the northern L_c in the American sector would exhibit a similar characteristic.

To confirm this, Figure 11 illustrates the variations of the averaged intensity and location of the EIA crests in the (a) northern and (b) southern hemispheres derived from the single-GPS-receiver method with VTEC data (Mo et al., 2018). This method can be treated as the TLP method with only one GPS receiver but demands that the selected GPS station should be located around the EIA crest region. Mo et al. (2014, 2018) showed that the averaged intensity and location of the EIA region from this method reflect well the characteristics of the EIA region in quiet times and during the sudden stratospheric warming event. In this study, the used stations are GUAN (23.2°N, 113.3°E; ~12.8°N, MLAT) in the northern hemisphere and BAKO (6.5°S, 106.9°E; ~16.7°S, MLAT) in the southern hemisphere, respectively, which are around the EIA crest regions. The color of the dots reflects the averaged EIA intensity. In Figure 11a, the solar cycle and seasonal dependence of the averaged intensity and location of the northern EIA is consistent with our results in the eastern Asian sector with the TLP method. In Figure 11b, the averaged location of the southern EIA exhibits a clear seasonal variation in solar minimum (around the year 2008). It is more poleward around the southern hemisphere summer and approaches the magnetic equator around the southern hemisphere winter. Comparatively, such seasonal variation pattern is not much noticeable in solar maximum (around the year 2001). The seasonal and solar cycle features of the variation of the averaged

location of the southern EIA in the Asia-Australian sector are similar to the features of the location of the northern EIA in the American sector in Figures 4b and 7b. Therefore, it supports our hypothesis that the displacement of the dip equator may be a key factor in the longitudinal difference of the solar cycle and seasonal variation patterns of L_c .

The question is, what is the specific physical process. In fact, there are plenty of studies involving the discussion about the seasonal variation of L_c . Huang and Cheng (1996) suggested that the trans-equatorial wind may suppress the upwind diffusion of the fountain effect and lead to the lower L_c in the northern hemisphere summer in the eastern Asian sector. This explanation aimed at the observations of the northern EIA in the eastern Asian sector. Clearly, it is not suitable for the variations of L_c of the northern EIA in the American sector or the southern EIA in the eastern Asian sector since they are in higher latitudes in the corresponding summer. To improve the trans-equatorial wind explanation, Tsai et al. (2001) introduced the auroral equatorward wind as a balanced force, and the seasonal variation of L_c is attributed to the competition of the two forces. They suggested that the southern L_c is closer to the dip equator in the southern hemisphere winter since the northward auroral equatorward wind overcomes the southward trans-equatorial wind and prevents the plasma from moving southward.

Meanwhile, some model studies indicated that the trans-equatorial wind might function in another way. Abdu (2005) provided a simulation result (see their Figure 14) of the EIA structure with the Sheffield University Plasmasphere-Ionosphere Model. It shows that if a northward thermospheric wind of 100 m/s is added to an EIA structure, both the northern and southern EIA crests move southward. However, Abdu (2005) did not provide detailed information about the added wind. Nonetheless, his result was supported by another simulation study by Nanan et al. (2012) in the American-Brazilian sector in solar minimum with Sheffield University Plasmasphere-Ionosphere Model. In the simulation focusing on the solar minimum, the model inputs are the vertical $E \times B$ drift velocity at the equator from the C/NOFS satellite measurements in 2009 between 0° and 60°W , the neutral wind velocities from the HWM91 model, and the neutral densities and temperatures from the MSIS86 model. Their results showed that in June solstice (with the southward trans-equatorial wind), if the neutral wind from HWM91 is added to a run with $E \times B$ drift and no wind, the northern EIA crest in 14:00 LT becomes stronger and northward, while the southern one becomes weaker and northward. In conclusion, these studies suggested that the trans-equatorial wind would cause L_c to move upwind. This result is not thoroughly understood. Nonetheless, it is well consistent with the behavior of the northern L_c in the American sector.

To show it clearly, Figure 12 gives a schematic picture of L_c in the (a) eastern Asian and (b) American sectors based on results in Figure 8 in solar minimum. Dot-dashed, dashed, and solid lines illustrate the locations of the Tropic of Cancer or Capricorn, the magnetic equator, and the geographic equator, respectively. Arrows indicate the direction of the trans-equatorial wind while gridlines illustrate the L_c in the northern hemisphere summer (red) and the northern hemisphere winter (blue). Note that the relative positions of L_c in solar minimum in Figure 8. In the American sector (Figure 12b), the northern hemisphere summer trans-equatorial wind blows southward; meanwhile, L_c is in the northern hemisphere but still far from the Tropic of Cancer ($\sim 23.5^\circ\text{N}$). In the northern hemisphere winter, the trans-equatorial wind blows northward, and the corresponding L_c is in the southern hemisphere. In short, L_c in the American sector tends to go upwind seasonally. In the eastern Asian sector (Figure 12a), L_c locates in a similar latitude below the Tropic of Cancer in the northern hemisphere summer and winter. However, according to the upwind tendency described above, the northern hemisphere summer L_c should be more northward. This may be attributed to the fact that the magnetic equator here is in the northern hemisphere and thus relatively close to the Tropic of Cancer. As a result, in the northern hemisphere summer solstice, the subsolar point is at the Tropic of Cancer and induces a robust thermal pressure in this area. When the plasma diffuses northward along the magnetic field line, this thermal pressure blocks it from moving to higher latitudes. The net result is a semi-annual variation of the northern L_c in the eastern Asian sector. Comparatively, the dip equator in the American sector is in the southern hemisphere and thus relatively far from the Tropic of Cancer, which leaves sufficient space for the plasma to diffuse northward.

It can be seen that, although the specific physical process is still an open question, the thermospheric wind is suggested by different papers to be an important influence factor in causing the asymmetric variation of L_c in

Figure 12. Schematic pictures for the combined effect of the trans-equatorial wind and the displacement of the geographic and magnetic equators in the (a) eastern Asian and (b) American sectors based on data in Figure 8 in solar minimum. Dot-dashed, dashed, and solid lines illustrate the relative locations of the tropic of Cancer or Capricorn, the magnetic equator, and the geographic equator, respectively. Directions of the trans-equatorial winds are illustrated with colored arrows for the northern hemisphere summer (red) and winter (blue). Gridlines show the L_c around northern hemisphere summer (red) and winter (blue) solstices.

different regions in solar minimum. Moreover, it is mentioned hereinabove that the longitudinal difference of L_c is much more apparent in solar minimum than in solar maximum. This may be due to the stronger electric field in solar maximum than in solar minimum, so correspondingly, the influence of the neutral wind is relatively less in solar maximum.

In addition, the direction of the magnetic declination may influence our results of the seasonal variation of L_c . The studied area of the American sector (90°W – 60°W ; 0° – 30°N , MLAT) includes the regions of positive and negative magnetic declination while that of the eastern Asian sector includes only negative magnetic declination. Considering that the magnetic declination in the region of 75°W – 60°W and 0° – 30°N (MLAT) is negative, to check the influence of the magnetic declination to L_c , Figure 13a shows the comparison between the seasonal variations of L_c during 2009 (blue) from Figure 4b and the seasonal variations of L_c during 2009 with the similar method that described in section 2 but with a narrower longitudinal band of 75°W – 60°W (red, denoted as $L_{c'}$). The dots are the daily values, the lines are the monthly mean values, and the error bars are the standard deviations of the monthly mean values. It shows that $L_{c'}$ exhibits slightly lower magnetic latitudes than L_c in most months. Thus, it seems that including the area of positive magnetic declination will make the L_c at higher latitude, but the seasonal variation pattern does not change.

Figure 13. (a) The comparison between the seasonal variations of L_c (blue) and $L_{c'}$ (red), with a similar method but a narrower longitudinal band of 75°W – 60°W during 2009. (b) Similar to (a) but for I_c and $I_{c'}$. The dots are the daily values, the lines show the monthly mean values, and the error bars depict the standard deviations of the monthly mean values.

Figure 14. The rearrangement of data in Figure 5 according to seasons. Oblique lines show the linear fittings for the eastern Asian (red) and American (blue) sectors.

Therefore, it suggests that the different patterns of the seasonal variation of I_c between the eastern Asian and American sectors are not due to the difference of the magnetic declination in the two sectors.

4.2. The Longitudinal Difference of I_c

Another interesting result is that I_c seems stronger in the eastern Asian sector than in the American sector. To show this clearly, data in Figure 5 are rearranged according to seasons and depicted in Figure 14. Oblique lines show the linear fittings of data in the eastern Asian (red) and American (blue) sectors. It can be seen that, for the same solar flux P index, I_c tends to be stronger in the eastern Asian sector in all four seasons. The difference is more significant under higher solar activity conditions and reaches ~ 20 TECU during solar maximum period.

Such a longitudinal difference of I_c cannot be attributed to the following factors. First, the EEJ intensity in the American sector is much stronger than that in the eastern Asian sector (see Figure 10). This suggests that the equatorial electric field is stronger in the American sector than in the eastern Asian sector. Moreover, the magnitude of the background magnetic field is stronger in the eastern Asian sector than in the American sector. Consequently, the vertical drift should be stronger in the American sector, and more plasma should be transported to the EIA region in the American sector. Besides, taking the equinox as an example, I_c in the American sector is around the geographic equator, while I_c in the eastern Asian sector is around the Tropic of Cancer. Consequently, the solar zenith angle of the northern EIA crest in the American sector is smaller, which means that the photoionization process contributes more to the background VTEC in the American sector than in the eastern Asian sector. Thus, the observation result that I_c is relatively stronger in the eastern Asian sector cannot be attributed to the difference of solar zenith angle.

Moreover, considering the difference of the magnetic declination in the two sectors, Figure 13b provides a comparison that is similar to Figure 13a but for I_c (blue) and I_c' (red; 75°W – 60°W). It shows that including the area of positive magnetic declination will make I_c slightly stronger in magnitude in the American sector, and the seasonal variation pattern does not change. Thus, including the area of positive magnetic declination in the American sector is probably not the reason for the relatively weaker I_c in the American sector than in the eastern Asian sector.

A possible candidate for explaining the longitudinal difference of I_c is the wave number-3 and -4 structures (England et al., 2006; Immel et al., 2006; Kil et al., 2008, 2011; Scherliess et al., 2008; Wan et al., 2008; Ren et al., 2009; Pedatella et al., 2011). In short, they are wave-like structures that have been reported in the equatorial ionospheric parameters, such as airglow emission and TEC, when considering the longitudinal distribution of these parameters in a specific local time band. Kil et al. (2011) mentioned that the wave structure has a pronounced crest near 90°E in most months. With the plasma density and vertical plasma drift data

from the first Republic of China satellite (~ 600 km) from March 1999 to June 2004 between 12:00 and 16:00 LT with $Kp \leq 3^+$ and $130 < F_{10.7} < 200$, they suggested that the longitudinal asymmetry of the crest intensity is probably associated with the phases of the wave number-3 and -4 structures. To be specific, they demonstrated that the phase difference between the wave number-3 and -4 structures is smaller around 0° and 90°E , and thus, the superposition amplifies the crest intensity in those regions. Meanwhile, the phase difference is large between 150°E and 60°W , and thus, the destructive superposition weakens the crest intensity in that region. In our study, the eastern Asian sector is near 90°E , and the American sector is near 60°W . Besides, the occurrence time of I_c , which is T_c , is around 14:30 LT in both sectors. Thus, the relatively stronger I_c in the eastern Asian sector than in the American sector is probably due to the longitudinal asymmetry of the crest intensity of the wave number-3 and -4 structures.

Nevertheless, it should be noted that, since the TEC is an integral value, the longitudinal difference of I_c is more likely to be a combined effect of the longitudinal variations of the ionosphere at different altitudes. For instance, the contributions of the TEC from the topside ionosphere and plasmasphere were studied (Lee et al., 2013; Pedatella et al., 2011; Shim et al., 2017; Zhong et al., 2017). It was shown that the TEC data in the topside ionosphere and plasmasphere at low latitudes exhibit significant longitudinal variation. However, this longitudinal variation has seasonal dependence. To be specific, the topside ionosphere-plasmasphere TEC in the American sector shows a maximum during the northern hemisphere winter and a minimum during the northern hemisphere summer (Pedatella et al., 2011; Zhong et al., 2017). Such seasonal-dependent longitudinal variations were suggested to be related to the geomagnetic field configuration. Comparatively, our results show that I_c is relatively stronger in the eastern Asian sector than in the American sector during all seasons. Thus, the longitudinal variation of the topside ionosphere-plasmasphere TEC may not be the main influence factor of the I_c difference, but it may contribute to the I_c difference during the northern hemisphere summer. In addition, with the electron density data from the Constellation Observing System for Meteorology Ionosphere and Climate satellites by the GPS radio occultation technique during geomagnetic quiet time periods ($Kp < 3$) of 2008, Pedatella et al. (2011) found that the TEC data between 250 and 800 km averaged between 12:00–18:00 LT and 10° – 20°N (MLAT) exhibit a clear longitudinal difference that has seasonal dependence. It seems that this averaged TEC is larger in the American sector than in the eastern Asian sector during the northern hemisphere spring in their Figure 5, which shows a different feature compared to our I_c result.

On the whole, the evolution of EIA is a very complicated process. It is dominated by the photochemical processes (photoionization and recombination) and the dynamical processes ($E \times B$ drift, wind drift, and diffusion). Besides, it is also influenced by factors like the subsolar point location, the geographic location of the geomagnetic equator, and the declination of the geomagnetic field. In addition, the ionosphere at different altitudes may exhibit different characteristics. Thus, the solar cycle and seasonal variations of the EIA parameters are probably influenced by a combined effect of different factors. To clarify the importance of these factors, it needs more observations and model studies in the further.

5. Summary

The morphological differences of the northern EIA crest between the eastern Asian and American sectors are statistically studied with GPS VTEC from 2000 to 2011. Main results are summarized as below:

1. The most distinct difference of the northern EIA parameters between the eastern Asian and American sectors is the seasonal variation of the EIA crest location, especially in the solar minimum period. In the eastern Asian sector, L_c exhibits a semiannual variation that is more poleward around equinoxes and more equatorward around solstices, while in the American sector, L_c exhibits an annual variation that is more poleward in the northern hemisphere summer and more equatorward in the northern hemisphere winter. In addition, L_c also shows solar cycle variations in both sectors.
2. The linear relationship between the monthly averaged EEJ intensity and monthly averaged L_c is good in the eastern Asian sector ($r = 0.55$) but poor in the American sector ($r = 0.19$). This suggests that the seasonal variation of L_c is not dominated by the seasonal variation of the ionospheric equatorial zonal electric field in the American sector. We suggest that the dominant influence factor of the seasonal variation of L_c is the meridional wind at ionospheric height, and the displacement of the geographic and magnetic equators is probably a key factor to the difference of L_c between the two sectors.

3. I_c tends to be stronger in the eastern Asian sector than in the American sector in all seasons, and such difference increases with the increasing solar activity. A possible candidate for explaining the longitudinal difference of I_c is the wave number-3 and -4 structures in the low-latitude ionosphere.
4. The different EIA morphologies between the two longitudinal sectors can also be identified with CHAMP electron density data. Besides, T_c has similar annual variations in the two sectors, which tends to be earlier in the northern hemisphere winter and later in the northern hemisphere summer, and the seasonal variation of T_c shows dependence on solar activity.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (41674157). The VTEC map data were downloaded from the Madrigal online database (<http://cedar.openmadrigal.org/>) of the MIT Haystack Observatory. The GPS data of the CMONOC were provided by Guanglin Yang (yglyang@cma.gov.cn) of the China Meteorological Administration (<http://www.cma.gov.cn/en2014/>). The CHAMP electron density and magnetometer data were managed by the Deutsches GeoForschungsZentrum Potsdam (<https://www.gfz-potsdam.de/en/home/>). The authors want to thank Patrick Alken for providing the EEJ data derived from the CHAMP magnetometer data. The ground-based magnetometer data in the Indian sector were downloaded from the World Data Center for Geomagnetism (<http://wdc.kugi.kyoto-u.ac.jp/>), and those in the American sector were downloaded from the online service of the Low-latitude Ionospheric Sensor Network (<http://lisn.igpp.gov.pe/data/>). The magnetometer data of BCL were from the Magnetic Data Acquisition System project (<http://magdas2.serc.kyushu-u.ac.jp/datausage/index.html>) and were provided by A. Yoshikawa (yoshi@geo.kyushu-u.ac.jp) by filling in a data application form. F_{10} and K_p indices were downloaded from the online service of the NOAA (<ftp://ftp.ngdc.noaa.gov>).

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