A preliminary study of the single crest phenomenon in total electron content (TEC) in the equatorial anomaly region around 120°E longitude between 1999 and 2012

Linfeng Huang\textsuperscript{a,b}, Jinsong Wang\textsuperscript{b,*}, Yong Jiang\textsuperscript{a}, Jiang Huang\textsuperscript{c}, Zhou Chen\textsuperscript{b,d}, Kai Zhao\textsuperscript{a}

\textsuperscript{a} School of Mathematics and Statistics, Nanjing University of Information Science & Technology, Nanjing 210044, China
\textsuperscript{b} National Center for Space Weather, China Meteorological Administration, Beijing 100081, China
\textsuperscript{c} Guangzhou Meteorological Satellite Ground Station, Guangzhou 510640, China
\textsuperscript{d} School of Electronic Information, Wuhan University, Wuhan 430072, China

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Abstract

The diurnal variations in total electron content (TEC) in the equatorial ionisation anomaly (EIA) region are not always represented by two crests on both sides of the magnetic equator. Sometimes, only an obvious single crest is evident at equatorial and low latitudes. In this paper, we focus on analysis of the morphological features of the single crest phenomenon in TEC around 120°E longitude during geomagnetic quiet days (Kp < 4). The variations in TEC are also compared with morphological parameters (foF2 and hmF2) derived from the International Reference Ionosphere extended to Plasmasphere (IRI-Plas) model. Our results show that the single crest phenomenon occurs mainly on days with extremely low solar activity, while the corresponding F2 layer critical frequency showed obvious asymmetry, or even only a single peak.

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1. Introduction

The equatorial ionisation anomaly (EIA) is characterised by the F region electron density trough at the geomagnetic equator, and two crests on either side of the equator at about 15° magnetic latitude (Appleton, 1946). This equatorial anomaly is caused by the so-called fountain effect, which results from the upward vertical drift associated with eastward electric fields produced by the E-region dynamo (Hanson and Moffett, 1966). During the day, the ambient eastward electric field at the geomagnetic equator gives rise to an upward \( \mathbf{E} \times \mathbf{B} \) drift of the F region plasma at the magnetic equator. This rising plasma reaches very high altitudes, but eventually loses momentum, and is then able to diffuse downwards along the magnetic field lines to higher latitudes under the influence of gravity and pressure gradient forces. This results in the formation of a plasma ‘fountain’, which produces an enhanced plasma concentration (crest) at higher latitudes, and a reduced plasma concentration (trough) at the equator. The two basic processes that significantly affect EIA formation are the strength of the equatorial plasma fountain and the thermospheric neutral winds (Balan and Bailey, 1995; Balan et al., 1997; Rishbeth, 2000; Abdu, 2001; Lin et al., 2005). The strength of the plasma fountain is driven by the equatorial
vertical $\mathbf{E} \times \mathbf{B}$ drift. During periods of intense geomagnetic storms, drastic changes can occur in the dynamics, electrodynamics, and chemistry of the ionosphere–magnetosphere system (Gonzales et al., 1979; Fejer and Scherliess, 1995; Scherliess and Fejer, 1997; Richmond et al., 2003; Abdu et al., 2007).

The phenomenon of EIA has been extensively investigated because of its importance in satellite communication applications, and its morphology is now generally understood (e.g. Moffet and Hanson (1965), Walker (1981), Balan and Iyer (1983), Abdu (1997), Richards (2001), Whalen (2004), Lin et al. (2005, 2007), Zhao et al. (2009), McDonald et al. (2011), Huang et al. (2013)). The development and variation of the EIA structure in electron density is also reflected in the ionospheric total electron content (TEC) because it is strongly influenced by the F layer density. By using the technique of radio ionospheric tomography and the Navy Navigation Satellite System (NNSS), Yeh et al. (2001) made TEC measurements to study the motion of the anomaly crest. They found that, on an average day, the EIA crest forms at 09:00 local time (LT) before moving poleward at a speed of $\sim 1^\circ$ in latitude per hour for the next 2 h, reaching its highest latitude where it stays for several hours until early afternoon. The crest then begins to weaken, as it recedes equatorward at a speed of $\sim 0.5^\circ$ in latitude per hour.

As we know, the deep solar minimum of solar cycles 23/24 is unprecedented, as compared with previous several solar minima. The solar minimum period during 2008–2009 was characterised by lower thermospheric density than the previous solar minimum and also lower than any previously measured (Solomon et al., 2013). Some researchers have investigated the ionosphere during the deep solar minimum and revealed some interesting features. Lühr and Xiong (2010) reported that IRI-2007 is strongly overestimating the equatorial plasma fountain effect during the last deep solar minimum by compared observations with the model results. Chen et al. (2011) reported that the relationship between solar EUV flux and the F10.7 index during the extended solar minimum (2007–2009) is different from that in the previous solar minimum. And the difference can also be seen in the relationship between foF2 and F10.7. Liu et al. (2011) also studied the differences in the ionosphere between solar minima of cycle 23/24 and the preceding cycles.

One of the most interesting topics related to the EIA is the north–south asymmetry of the two crests. The hemispherical asymmetry of the crests, both in magnitude and latitudinal location, is considered to be caused mainly by the neutral winds (Rishbeth, 1972; Walker et al., 1991, 1994; Lin et al., 2007; Xiong et al., 2013). Thus, because the displacement of the magnetic and the geographic equators varies with longitude, the effect of the neutral winds on the EIA also varies with longitude (Walker, 1981). However, sometimes there is only an obvious single crest in TEC at equatorial and low latitudes, as indicated by historical data from solar cycle 23/24. In this paper, we study the features of the single crest phenomenon in TEC, and its correlation with the F2 layer around 120°E longitude, during geomagnetic quiet periods from 1999 to 2012. The results show that the single crest phenomena occurred mainly on days of extremely low solar activity, and that the corresponding F2 layer critical frequency showed obvious asymmetry, or even only a single peak. Observations and model results presented in this study are important to our improved understanding of the morphology of the structure in the equatorial and low-latitude ionosphere. These results will be useful for future modeling of the physical mechanisms responsible for ionospheric longitudinal structure.

2. Data and method of analysis

This analysis employs the Global Ionospheric Maps (GIM) of TEC, foF2, and hmF2 in the IONEX format (ftp://ftp.izmiran.ru/pub/izmiran/SPIM/Maps/). The GIM are generated routinely by the IZMIRAN community with a resolution of 5° longitude and 2.5° latitude, and a temporal interval of one hour. The GIM-TEC was produced from the GPS TEC map provided by the Jet Propulsion Laboratory (JPL) in the IONEX format (Mannucci et al., 1998; Schaer et al., 1998), while the GIM-foF2 and GIM-hmF2 were produced from the JPL GPS TEC IONEX map using the International Reference Ionosphere extended to the Plasmasphere (IRI–Plas) model. The GPS-derived ionospheric TEC maps (TECgps) assimilation technique was applied to reconstruct the foF2 in the magnetic conjugate hemisphere using the IRI–Plas model (Gulyaeva et al., 2011). The performance of IRI–Plas in TECgps assimilation mode was validated using the value of foF2 obtained from ionosondes in the East Asia region by Gulyaeva et al. (2013), who found that the modelled results correspond to the ionosonde observations.

The latitudinal distribution of EIA structure in TEC is normally represented by two crests on either side of the geomagnetic equator, but the structure may be affected by geomagnetic disturbances and even disappear during intense magnetic storms (Zhao et al., 2009). Hence, the data collected on days of magnetic disturbance ($Kp > 3$) were excluded to avoid introducing errors, and then the two groups of data (i.e., two-crest days and single-crest days) were selected for analysis. In addition, the single-crest day represents there is only a single crest in TEC when the EIA TEC strength is strongest during the daytime. The opposite is normal two-crest day. The single crest phenomena can also be divided into the north, south, and magnetic equator single crest. Among them, magnetic equator single crest phenomenon refers to the crest’s latitude position within a $\pm 2.5^\circ$ range (including the boundary) of the magnetic equator.

Fig. 1 shows a schematic diagram of the EIA structure. To assess the north–south asymmetry relative to the equator trough, a new asymmetry index (AI) was introduced to characterise the EIA parameters (e.g. TEC and foF2), defined as follows:
AI = sgn \( X_{nc} - X_{sc} \) \( \{ 1 - \min(X_{nc}, X_{sc}) \}
- X_{et}\}/\max(X_{nc}, X_{sc}) - X_{et}\} \).}

Here, sgn represents the signum function, and \( X \) represents the parameter (e.g. TEC or foF2) for the northern (nc) and southern (sc) crests and the equator trough (et) of EIA, but not including the condition of magnetic equator single crest. Positive and negative values of AI represent the stronger of the northern and southern crests, respectively. If there is no northern crest, AI = 1.0. Similarly, if there is no southern crest, AI = −1.0.

Previous research (e.g. Liu et al. (2006)) found that the improved index \( P = (F10.7 + F10.7A)/2 \) can better represent solar EUV variability; consequently, we used the \( P \) index as the solar proxy in this paper. Here, F10.7A is the 81-day average of the F10.7 values centred on the day of interest. The seasonal division refers to the Northern Hemisphere unless stated otherwise. In the present study, we describe the morphological features of the single crest phenomenon in magnetic low-latitude regions and near the magnetic equator based on statistics from three parameters: TEC, foF2, and hmF2 around 120°E longitude during the period 1999–2012. Long-term records or model data are essential for accurate analysis of the single crest phenomenon under different levels of solar activity, and for capturing the variations of the parameters with season and solar activity.

3. Observations and statistics

3.1. Statistical distribution of single-crest days

Fig. 2 shows the statistical analysis of the single-crest days under different solar activity conditions from 1999 to 2012. Here, the \( P \) index was used to classify days with low solar activity as having \( P < 100 \), days with medium solar activity as 100 \( \leq P \leq 150 \), and days with high activity as 150 \( < P \) (Huang et al., 2013). It is clear that the north, south, and magnetic equator single crest phenomena are most frequent during the summer, winter, and autumn months, respectively, during periods of low solar activity. Among them, the number of days for different single crest phenomena shows a well-defined seasonal difference, being most frequent around the June solstice (north single-crest days), less around the September equinox (south single-crest days), and least around the March equinox (magnetic equator single-crest days). In addition, the number of single-crest days is significantly reduced with the rise in solar activity. The single crest phenomenon rarely occurred during periods of high solar activity. Therefore, the main objective of this paper is to analyse the single crest phenomenon in TEC during periods of low solar activity.

3.2. Latitudinal distribution of TEC for different single crests

Fig. 3 shows the latitudinal distributions of the average of TEC values at local time under low solar activity. An obvious single crest occurs at the equatorial and low latitudes in each case. The occurrence time of the peak values was 14:00–16:00 LT.

4. Comparisons with F2 layer model results

At 120°E longitude, the magnetic equator is located at \( \sim 10^\circ N \). We compare TEC with F2 layer parameters for normal days of two-crested EIA structure, as well as the difference between the parameters during days with high and low solar activity. Fig. 4 gives the latitudinal distribution of the mean values of TEC, foF2, and hmF2 for high and low solar activity during the normal two-crest days at 15:00 LT, a time close to the diurnal maximum in TEC. It is clear that TEC and the critical frequency of the two
crests from high to low solar activity are reduced, as well as the height of the F2 layer. The results point to a weakening of the EIA crests with declining solar activity. Fig. 4 also shows that the asymmetry of the two-crested structure of TEC and foF2 during periods of low solar activity is less pronounced than in periods of high solar activity, as deduced by comparing the size of the corresponding AI index. Similarly, the asymmetry in TEC is less pronounced than in foF2 for the corresponding period of solar activity. In addition, the peak of hmF2 moves closer to the geographic equator when solar activity is low.

Fig. 5 shows the mean variations of the parameters (TEC, foF2, and hmF2) for the two-crest and single-crest days during the seasons of the most frequent occurrence of the single crest phenomena. The following conclusions can be drawn from Fig. 5. (1) The absolute AI values are substantially larger during the single-crest days than during the two-crest days. (2) During the single-crest days, the strength of the two-crested structure in foF2 is weaker and the mean solar activity of the corresponding period is lower. (3) There is no obvious difference in variations in hmF2 between the periods with two crests and the single-crest days.

To investigate variations of the AI index in detail, scatterplots of AI against P during the months of different seasons for the two-crest and single-crest days are shown in Fig. 6. The most striking feature of these scatterplots is the much larger absolute values of AI on single-crest days when solar activity is extremely low. Except for June solstice, single-crest days occur only for $P < 140$. On some days, the values of AI even approach 1.0; i.e., there is only one north peak. Larger absolute values of AI occur on the two-crest days in different seasons (Fig. 6), generally during periods of high solar activity. Fig. 6 shows another important result in December. The afternoon single crest phenomenon is evident in the summer hemisphere, and also for the double crest situation the crest is stronger in the summer hemisphere. While, as solar activity increase for the double crest situation, the crest is stronger in the winter hemisphere. In June, similar situation occurs but not that significant.
5. Discussion

The day-to-day variability of the EIA region is a well-known characteristic of the ionosphere. When both the stronger equatorial plasma fountain effect and equatorward winds are present, the EIA strength is enhanced more significantly, as the equatorward winds play a role in increasing the plasma accumulation at the poleward-extended EIA crests. These two effects are considered theoretically by Lin et al. (2005), and their investigation...
shows that a stronger plasma fountain effect is indeed the major driver for producing stronger and poleward-extended EIA crests. It is straightforward to conclude that a weaker equatorial plasma fountain lifts less plasma from lower to higher altitudes, and this results in weaker and equatorward-contrasted crests, or even we cannot see the obvious two-crested structure. Huang et al. (2013) used more than a solar cycle (2000–2011) of TEC data around 110°E longitude to study the hemispheric asymmetry between the northern and southern crest regions of EIA during geomagnetic quiet periods. Their research shows that the crests are weaker, and the latitude distance between the two crests is reduced, during periods of low solar activity. Furthermore, the northern crest of EIA moves equatorward in winter, and the southern crest moves equatorward in boreal summer and poleward in winter, during periods of low solar activity.

Photochemical processes caused by solar extreme ultraviolet (EUV) radiation also play an important role in the formation of the anomaly. The low radiation that may makes the crest insignificant. Photoionization in the ionosphere can produce more electrons, and thus enhance the background electron density. A larger peak in the equatorial anomaly would be expected on days with high solar activity. In fact, this effect has been demonstrated, and research shows a positive linear relationship between the value of the equatorial anomaly and the sunspot number (Huang and Cheng, 1996). Galav et al. (2010) reported that the value of TEC around the anomaly crest shows a strong correlation with the F10.7 index, and that the EIA crest weakens, as well as showing temporal and spatial contraction, during the declining phase of solar activity. Lin et al. (2007) found obvious seasonal asymmetries in both layer height and electron density, and the interactions between the cross-equatorial neutral winds and the strength of the ionospheric fountain effect play an important role in driving the asymmetric development of the EIA structure.

To avoid the effects of magnetic disturbance, only data from geomagnetically quiet days were used in this paper. Possible phenomena in the low- and equatorial-latitude ionosphere on days of extremely low solar activity conditions are unique. Observations show that the diurnal variations in TEC in the EIA region are not always represented by two crests on both sides of the magnetic equator. Sometimes, there is only an obvious single crest at equatorial and low latitudes, especially on days of extremely low solar activity. We think, an important reason for the phenomenon is that the solar dependence of the afternoon zonal electric field in the ionospheric F region according to the results of Fejer et al. (2008). Their study shows that the longitudinal dependency of the daytime vertical drifts is much stronger than reported earlier, especially during December and June solstice. Fig. 2 shows that the north, south, and magnetic equator single crest phenomena are most frequent in the summer, winter, and autumn months, respectively, during periods of low solar activity. In addition, the number of single-crest days around the summer solstice is greater than around the winter solstice. This may be related to the position of the subsolar point, which is round 120°E much closer to the magnetic equator in the summer Northern Hemisphere than in the summer Southern Hemisphere, resulting in different types of cross-equatorial winds in the equator region (Huang et al., 2013).

As the maximum electron density is around the F2 peak, we further compared the peaked structure in TEC with the F2 layer parameters (foF2 and hmF2) derived from the IRI–Plas model. From high to low solar activity, the strength of TEC and foF2 obviously decreased, as did the height of the F2 layer (Fig. 3). The results point to the weakening and decreasing asymmetry of the EIA crests with declining solar activity. The maximum height of the F2 layer at equatorial and low latitudes did not change significantly during the single-crest period, and the peak values of foF2 were smaller by about 0.5–2.0 MHz (Fig. 5). The smaller values of foF2 on the single-crest days imply higher levels of electron density prevailing at roughly the same levels.

Xiong et al. (2013) found that the electron density and the magnetic latitudes of the EIA crests are almost symmetrical about the dip equator around the equinoxes, but there is a well-defined interhemispheric asymmetry of the EIA crests around the solstices, which is based on the averages of observations over all longitudes by CHAMP and GRACE. An obvious asymmetry occurs in the F2 layer, with significantly larger absolute AI values during the single-crest days (Fig. 6). This occurs because the studied period was at the solar minimum, and the P index varied within a small range (65–80). Besides, there was only one north peak, with the values of AI equal to 1.0, in the F2 layer on most single-crest days in September. There are larger absolute values of AI for the two-crest periods from different seasons, but these generally appear during periods of high solar activity. The results from Fig. 6 reflect that the asymmetry of crest structure behaves different in December during low and high solar activity. The results from Chen and Liu (2010) also shows that the foF2 northern crest increases faster than that of southern one as solar flux increase in December.

As the cross-equatorial component of the neutral wind is negligible during the equinoxes, the EIA structure is expected to develop symmetrically over the magnetic equator. In addition, Fig. 6 indicates a seasonal asymmetry between the March and September equinoxes on low solar activity days, with higher AI indexes and more single-crest days occurring in September relative to March. The results from the equinox months presented here contradict the previous study by Xiong et al. (2013). However, the magnetic declination angle is small at 120°E longitude, so the morphological differences in the ionosphere between the March and September equinoxes during periods of low solar activity require further study.

It is well known that there is significant longitudinal variation in both the peak altitude and density of EIA. In addition, the longitudinal variations show different
characteristics, which may be due to the differences in equatorial vertical drift, magnetic declination, and neutral winds at different longitudes (Lin et al., 2007). In this paper, we only presented the features of the single crest phenomena around 120°E longitude, but this could be extended by studying the single crest phenomena at other longitudes.

6. Conclusions

Using ionospheric maps covering more than a solar cycle from the period 1999–2012, this paper analysed the behaviour of the single crest phenomenon in TEC around 120°E longitude during geomagnetic quiet periods. The main results can be summarized as follows.

1. There are weaker and equatorward-contracted EIA crests during periods of low solar activity. The asymmetry of the two-crested structure of TEC and foF2 during periods of low solar activity is less pronounced than during periods of high solar activity. Moreover, the asymmetry in TEC is less pronounced than in foF2 for the corresponding period of solar activity.

2. The north, south, and magnetic equator single crest phenomena are frequent in summer, winter, and autumn months, respectively, on low solar activity days. There is a significant morphological difference in the number of occurrence days of single crest phenomena between the March and September equinoxes during periods of low solar activity.

3. When single crest phenomena occurred on extremely low solar activity days ($P < 80$), the corresponding F2 layer critical frequency (foF2) showed obvious asymmetry, or sometimes only a single peak, especially around the September equinoxes. During the single-crest days, the mean values of the asymmetry index (AI), obtained from TEC and foF2, were much larger than the normal two-crest days in the seasons of the most frequent occurrence of the single crest phenomena.

In this study, we have considered only the features of the single crest phenomena in the Southeast Asian sector (120°E). The morphological characteristics of the single crest phenomenon at different longitudes, and the asymmetry at the March and September equinoxes, require further analysis.

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