The strength and hemispheric asymmetry of Equatorial Ionization Anomaly during two geomagnetic storms in 2013

from Global Ionosphere Map and SAMI2

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Abstract The variations of the strength and the hemispheric asymmetry of EIA were studied by Global Ionosphere Map(GIM) and SAMI2 during two geomagnetic storm periods in March and June 2013. Compared with the 30-days median TEC, the TEC at the two crests of EIA had small variations while the TEC at the trough had a more remarkable variation for the two storms after the SSC. The TEC difference between the two EIA peaks had an increase or decrease several hours after the SSC, the asymmetry between the two crests of EIA represented by the defined asymmetry index has no obvious variations except several hours after the SSC, and EIA strength represented by the Crest-to-Trough Ratio (CTR) had a remarkable increase one day after the SSC day for March storm and decrease several hours after the SSC for June storm. The variations last several hours, with more than 40% variations compared with the value during the quiet period. The EIA peaks were also found to move toward the equator after the SSC during the two storms. The simulation from SAMI2 and HWM07 also shows that EIA crests would move toward the equator during storm time and EIA strength would decrease, which suggests that the disturbed neutral wind and disturbed electric field may be important factors affecting the EIA during the storm periods.

Keywords: Equatorial Ionization Anomaly, geomagnetic storm, Global Ionosphere Map, asymmetry

1 Introduction

One of the most important features in the low-latitude ionosphere is the Equatorial Ionization Anomaly(EIA), characterized by an electron density trough at the magnetic dip equator and two electron density peaks at about 15° north and south of the trough[Kelley, 2009]. It is mainly considered that EIA is formed by equatorial fountain effect via upward $\mathbf{E} \times \mathbf{B}$ drift driven by eastward electric field at the dip equator. The plasma moves upward from the equator to a certain height, and then diffuses along the magnetic field lines under gravitational and pressure gradient forces.

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This leads to the redistribution of electron density and ion density forming the two crests of ionization on either side of the equator, and a trough over the equator.

Due to the effects of trans-equatorial meridional neutral wind, electric field and some other factors, such as 2-day wave, planetary wave activity among other factors [Lin et al., 2007a; Tkahashi et al., 2012; Yue et al., 2010], the magnitude and location of EIA crests all manifest remarkable local time, seasonal, and solar activity variations [Tsai, et al., 2001; Wu et al., 2008]. Furthermore, there is inter-hemispheric asymmetry between the two crests, which is one of the most interesting topics related to the EIA. Vila [1971] reported that the asymmetry between the two EIA crests varied with local time from day to day, and the crest of the EIA in the summer hemisphere was found to change most. Walker [1981] found that the winter crest was dominant in the morning and decayed more rapidly in the late afternoon. The asymmetries of EIA crest were less significant during solar maximum than that during solar minimum. Aydogdu [1988] found that the NmF_2 in the northern crest was greater than that in the southern crest during daytime of equinox seasons in African and West Asian regions. Tulasi Ram et al. [2009] found a local time dependency of the hemispheric asymmetry of EIA based on COSMIC/RO data observed during 2006-2007 and it was confirmed by SAMI2. The latitude and local time position of the anomaly crest were found to show a hemispheric asymmetry [Zhao et al., 2009]. Huang et al. [2013] also noticed that the latitude position of EIA crest shows hemispheric asymmetry, and the asymmetry depends on the solar activity. Based on nine years of CHAMP and GRACE observations, Xiong et al. [2013] studied EIA inter-hemisphere asymmetry and displayed that the electron density and magnetic latitudes of EIA crests were almost symmetric about the dip equator during the equinox season.

The strength of EIA is another interesting topic, usually represented by the Crest-to-Trough Ratio (CTR). CTR is a key parameter to characterize the development of EIA [Zhang et al., 2009]. Liu et al. [2007] found the CTR was shown to vary differently during noon and post-sunset sector. The CTR around noon varies from 1.14 to 1.43 with increasing solar activity; while within the post-sunset local time sector the CTR can reach as high as 3.9 around solar maximum.

Furthermore, EIA serves as an indicator of the electric coupling process in the solar wind-magnetosphere-ionosphere system. When the balance of system is disrupted, the EIA development may undergo a drastic variation and display a complex morphology due to the combined effects of the prompt penetration electric field, the wind disturbed dynamo electric field, storm-induced neutral winds and the

composition changes [Prolss, 1995]. In other words, the variations in EIA could reveal the electrodynamical progress in the low-latitude and equatorial ionosphere.

Many former studies have shown that equatorial anomaly may be enhanced and travel poleward [Basu et al., 2001; Zhao et al., 2005; Astafyeva et al., 2007, 2009], or may be decreased and pushed equatorward after the SSC [Dashora et al., 2007; Lin et al., 2007b] during storm periods. The EIA deformation could be attributed mainly to the effects of the storm time disturbed electric field and neutral wind [Zhao et al., 2005; Lin et al., 2007].

Although a number of studies have been carried out on EIA in the past several decades, these studies have some limitations. Most of them mainly focus the variability of EIA asymmetry during quiet period, and the electron density in EIA regions response to the storm [Basu et al., 2001; Zhao et al., 2005; Dashora et al., 2007; Lin et al., 2007a, 2007b; Yue et al., 2015]. How would the EIA strength and asymmetry vary during storm period is needed to be studied in details, which is the purpose of this study. We select two cases in 2013 to study the response of EIA to geomagnetic storm based on Global Ionosphere Map (GIM) and Sami2 is Another Model of Ionosphere (SAMI2) in 120°E longitude. The GIM and Sami2 will be introduced in Section 2, and the parameters defined to study the variations of EIA are also given in Section 2. Section 3 will display the Dst and Kp indices during the two geomagnetic storm periods, and the results derived from GIM and SAMI2 will be shown in Section 4, Section 5 will discuss the results, the conclusions will be given in Section 6.

2 Datasets and EIA asymmetry index

The global ionosphere TEC data are routinely computed by data analysis centers at IGS, including Jet Propulsion Laboratory (JPL) that uses more than 200 worldwide ground-based GPS receivers [Mannucci et al., 1998]. The TEC data are published at a 2-h time interval as Global Ionosphere Maps (GIM) (<ftp://cddisa.gsfc.nasa.gov/pub/gps/products/ionex>). The GIM covers $\pm 87.5^\circ$ latitude and $\pm 180^\circ$ longitude ranges, and has a spatial resolution of 2.5° in latitude and 5° in longitude, respectively.

GIM TEC map can predict more than 90% of ionospheric TEC. Total accuracy of GIM was evaluated to be around 3.7-3.9 TECU [Sekido et al., 2003]. Generally GIM can provide accurate TEC values and can be taken as a powerful tool to monitor the global ionosphere in near real time [Ho et al., 1997].

The SAMI2 model is a low-latitude model of the ionosphere, developed at the Naval Research Laboratory. It treats the dynamic plasma and chemical evolution of

seven ion species (H^+ , He^+ , N^+ , O^+ , N_2^+ , NO^+ , O_2^+) in the altitude range from about 100km to several thousand kilometers. The ion continuity and momentum equations are solved for all seven species; the temperature equation is solved from H^+ , He^+ , O^+ and the electrons [Huba et al., 2000]. SAMI2 also uses the NRL-MSISE00 [Picone et al., 2002] and HWM models for neutral species and neutral winds, respectively. In this study, HWM07 model [Drob et al., 2008] and Scherliess-Fejer $E \times B$ drift model [Scherliess and Fejer, 1999] were used to derive the neutral wind and the electric field, respectively.

To study the variations of EIA during geomagnetic storm, two indices are defined to portray the asymmetry and strength of the EIA as follows[Mendillo et al., 2000; Mendillo et al., 2001]:

$$TEC_d = N - S, \quad (1-1)$$

$$Index_A = \frac{N - S}{(N + S)/2}, \quad (1-2)$$

$$Index_I = \frac{N + S}{2}, \quad (1-3)$$

$$CTR = \frac{N + S}{2T} = \frac{Index_I}{T}, \quad (2)$$

Where N and S represent the value of TEC or electron density at EIA crests in northern and southern hemisphere, respectively. T represents the value of TEC or electron density at the trough.

Equation (1-1) means the absolute difference between the two crests. When TEC_d is positive, the northern crest is larger than the southern crest; and vice versa. Equation (1-2) portrays the relative difference and the EIA asymmetry between the two crests. The index $Index_A$ is larger, the EIA is more asymmetric. Equation (1-3) describes the mean crest intensity. Equation (2) is the definition of the CTR, representing the strength of EIA.

An automated algorithm was applied to determine the EIA crests and the trough. The point of lowest TEC within a $\pm 5^\circ$ latitude window about the dip equator was determined as the trough. Subsequently, the maxima TEC in northern and southern hemispheres were identified within a $\pm 25^\circ$ latitude window about the dip equator as the crests, respectively. If the maximum was determined in each hemisphere, a trough point was identified. The TEC values at the two maxima and the minimum were stored together with their locations(geographic latitude).

3 Geomagnetic Indices during the two geomagnetic storms

Fig. 1a shows the Dst and Kp indices during the March 17-20, 2013 storm period. The Storm Sudden Commencement (SSC) of the storm occurred at 0700UT on March 17, and the lowest Dst index was -132 nT at about 21UT. Fig. 1b shows the Dst and

Kp indices during the June 1-4, 2013 storm period. The SSC of the storm occurred at 0100UT on June 1, and the lowest Dst index was -120 nT at about 09 UT.

During March 14-23 2013, Kp index usually were not more than 3 except the storm period and some hours in March 16 and 21, 2013. From May 26 to June 5 2013, the Kp index were not more than 3 except the storm period, and exceeded 3 for some hours in May 26-27.

4 EIA variations during geomagnetic storm

The asymmetry of EIA may show: 1) The value at one crest is larger than that at the other crest during some times, and the converse during other times. 2) The locations of two crests are not symmetric about the magnetic equator. The crest in one hemisphere may be closer to the equator than the crest in the other hemisphere. 3) The motions of the two crests under the disturbance are asymmetric. The variation of the EIA asymmetry would be studied from above three directions in the later.

4.1 EIA variations during March 2013 storm

Fig. 2 shows the TEC values at EIA crests and trough in 120°E longitude from 12nd March(DOY71) to 23rd March(DOY82), 2013.

It can be seen that on 17th March(DOY76), after SSC, the TEC in southern hemisphere had a sharp increase relative to the TEC in northern hemisphere. TEC value at the trough on 18th March(DOY77) decreased prominently one day after the beginning of the storm, which was lower obviously than the values on other days shown in Fig. 2. From Fig. 2, it also should be noted that TEC in the two crests had decreases on DOY77 relative to the former days. For instance, the peak value in northern crest was about 80.9 TECU on DOY76. The value decreased to 73.1 TECU on DOY77 and the decrease was about 9.6% relative to the value on DOY76. In southern crest, the peak values were 100.1 TECU on DOY76 and 76.8 TECU on DOY77, respectively. The decrease on DOY77 was about 23.3% relative to that on DOY76, which was more remarkable than that in northern crest. The decrease at the trough on DOY77 was about 32.9% relative to the value on DOY76, from the value of 62.3 TECU on DOY76 to 41.8 TECU on DOY77, respectively.

Fig. 3 displays the variations of TEC value at northern EIA peak (a), southern EIA peak (b) and the trough (c) during March 2013 storm periods with UT times, respectively. The red line in the figure represents the 30-days median TEC.

As shown in Fig. 3, relative to the 30-days median, the TEC at northern peak had no obvious change after SSC, TEC at southern peak and the trough had a small increase, and on one day after the storm day(DOY=77), TEC at the EIA crests and the trough all had a small decrease after 08UT. The most remarkable decrease occurred in the trough at 08UT, TEC at the through was about 61% of the median. At 08UT, TEC

at the trough was about 36.4 TECU on DOY77 and 67.4 TECU on DOY76, which means that TEC decreased about 46% on DOY77 relative to that on DOY76. TEC at southern peak was about 71.3 TECU on DOY77 and 85.1 TECU on DOY76, representing that TEC decreased about 16% on DOY77 relative to that on DOY76. At northern peak, TEC was about 73.1 TECU on DOY77 and 80.9 TECU on DOY76, the decrease was less than 10%.

Fig. 4 presents the variations of asymmetry index $Index_A$ and TEC difference TEC_d between the two EIA peaks with UT times. The blue line is the asymmetry index, the red line is the TEC difference. Fig. 5 shows the variations of Crest-to-Trough Ratio (CTR) before and after the storm.

In Fig.4, the variations of $Index_A$ were similar with that of TEC difference, when the TEC difference between two peaks was large, the value of asymmetry index was large. When the TEC difference between two peaks was small, the value of index was small. It should be noted that the TEC difference had a minimum at 06UT (LT=UT+8) on these days (DOY71-DOY82), and the value of TEC difference reached a maximum on the storm day.

At 06UT, one hour before the SSC, the TEC difference had a minimum about -23.8TECU, which means TEC in southern hemisphere was larger than that in northern hemisphere. The asymmetry index also had a minimum with about -0.27 at 06UT. After the SSC, the absolute value of the difference between two EIA peaks decreased to 4.2 TECU at 08UT.

As shown in Fig. 4, it means that TEC at the EIA peak in southern hemisphere was larger than that in the other hemisphere some time, and then vice versa some other time. It also should be noted that there were differences between the variations of TEC_d and the variations of $Index_A$. As shown in Equation (1-1) and (1-2), when the value of TEC_d was small, the total TEC at the two crests (N+S) decreased significantly (the value of N+S was small), the $Index_A$ may be large. On the contrary, when the value of TEC_d was large, the total TEC at the two crests increased significantly (the value of N+S was large), the $Index_A$ may be small. Thus, there were some places where the variations of TEC_d and $Index_A$ did not match well.

From Fig. 4, it can be noticed that on DOY77, one day after the storm occurred, the value of $Index_A$ were obviously smaller than that in other days, while CTR increased significantly shown in Fig. 5. The TEC values at the two peaks were about 2~3 times of the value at the trough, and on other days the ratio usually was less than 2.

It can be noted that CTR had an obvious increase on DOY77 shown in Fig. 5,

one day after the SSC, from 02UT to 16 UT, while the local time were 10-24h. At 20UT, CTR had no obvious increase or decrease around the storm. On DOY77, CTR was larger than 3 at 10UT and 16UT, while the values were usually less than 2 on quiet days before the sunset (10UT), which means that the CTR increased on DOY77 about 50% compared with the CTR on quiet days. As shown in Fig. 3, though TEC at the EIA crests and the trough decreased, TEC at the trough decreased more than that at the crests, the CTR increased in result.

Fig. 6 displays the latitudes of the two EIA peaks from DOY71 to DOY82 at different UT times. It can be noted that EIA crests moved toward the dip equator after SSC, and the locations and the movements of two crests were asymmetric. During 00-12UT of DOY77, the south peak located around 5°S(geomagnetic), the north peak located around the dip equator and spread to 7.5°N(geomagnetic) at 12UT. On other days, such as DOY75, the south peak spread to 10°S during 06-08UT, and the north peaks were around 12.5°N during 04-10UT and spread to 15°N at 08UT. After the storm, it also can be seen that the EIA crests spread toward the poles. Such as on DOY78, the south peak located around 10°S at 06UT and the north peak spread to 15°N during 04-08UT.

4.2 EIA variations during June 2013 storm

Fig. 7 presents the variations of TEC peak at EIA crests and trough in 120°E during June 2013 storm. The blue line represents the peak value at northern crest, the red line represents the peak value at southern crest, the green line represents the value at the trough. Fig. 8 displays the variations of TEC value at northern EIA peak (a), southern EIA peak (b) and the trough (c) during June 2013 storm periods with UT times, respectively. The red line in the figure represents the 30-days median TEC.

In Fig. 7, it can be seen that TEC values at the two crests and the trough increased after the SSC compared with the TEC values one day before the storm day. On DOY151, one day before the storm day, the maximum at the trough was 40.2 TECU, and the maximum at the two crests were 63.1 TECU and 56.2 TECU, respectively. After the SSC, the maxima at the trough increased to 56.5 TECU, the maxima at the two crests were 75.3 TECU and 65.4 TECU, respectively. On the days after the storm day, the TEC at the crests and the trough decreased. For instance, on DOY153, one day after the storm day, the maximum at the trough was 43.4 TECU, and the maxima at the two crests were 56.5 TECU and 58.6 TECU, respectively.

Compared with the 30-days median TEC, shown in Fig. 8, the TEC at the trough and the crests were smaller than the median on May 31(DOY151), the peak TEC at the crests and the trough all had an increase after the SSC, the increase at the crests

was small, the increase at the trough was more significant. One day after the SSC day, TEC at the crests had a decrease compared with the median and the value of TEC at the trough decreased compared to the median TEC.

It should be noted that the TEC values at the trough during May 26-28(DOY146-148) were larger than the median TEC, and the TEC at the crests also had similar variations and less remarkable than that at the trough. It may be explained that there were also some small disturbance in May 26-28(DOY146-148), the Kp index exceeded 3 on some UT times shown in Fig. 1b.

Fig. 9 displays the variations of asymmetry index and TEC difference between two EIA peaks during June 2013 storm period.

Similar with the variations of the difference between two EIA crests shown in Fig. 4 during March 2013 storm period, the variations of TEC difference were similar with that of asymmetry index. It can be noted that TEC in northern hemisphere was larger than that in southern hemisphere in most UT times from Fig. 9, which was different from the March 2013 storm. At 08UT of the storm day, 7 hours after the SSC, TEC difference between the two peaks increased sharply to 11.8 TECU and also the value of the asymmetry index did, which means that the EIA asymmetry was enhanced 7 hours after the SSC.

Fig. 10 presents the variations of CTR from DOY146 to DOY156 at different UT times. It can be seen that CTR had an obvious minimum on DOY152, especially at 16 and 18UT, 15 hours after the SSC. For instance, at 16UT, the values of CTR were above 2 before the storm, the CTR value decreased to 1.2 after the SSC on DOY152, which means that there was a decrease of over 40%. It also should be noted that the CTR on DOY 152 varied slightly with the UT times. As shown in Fig. 8, the decrease of CTR was due to the sharp increase of TEC above the trough.

Fig. 11 displays the latitudes of two EIA peaks from DOY146 to DOY156 at different UT times.

As shown in Fig. 11, the locations of two crests were asymmetric about the equator and the movements of the two crests in two hemispheres were also asymmetric. The EIA peak in northern hemisphere located around 15°N before the storm, the peak moved toward the equator after the SSC during 00-12UT. On one day after the SSC (DOY=153), the northern peak located around the equator during 00-12UT.

The EIA peak in southern hemisphere located much closer to the equator than that of the northern EIA peak, and moved toward the equator after the SSC and stayed around the dip equator. On DOY153, the two crests were much closer to the equator than that on DOY152. During 06-12 UT times, from DOY146 to DOY 151, the northern crest located around 12.5°N and 15°N, while the southern crest located

around -10°N . At 12UT of DOY152, 11 hours after the SSC, the northern crest located at 10°N and the southern crest located at -2.5°N .

4.3 EIA variations simulated by SAMI2

We take the March 2013 storm as an example to study the EIA variations under the disturbed situation. For SAMI2, run for 24 hours to establish a steady state system, the simulation starts with that initial system and runs for an additional 24 hours. The geophysical parameters used in the simulation are DOY=76, F107=116.1, F107a=125.7, $A_p=72$ during storm and $A_p=7$ during quiet time in 120°E geographic longitude. The neutral winds are provided by the empirical horizontal wind model 2007 (HWM07)[Drob et al., 2008]. The results are taken from a field line which apex is 502km.

Fig. 12 shows the asymmetry index $Index_A$ derived from SAMI2 during storm and quiet time, respectively. As shown in Fig. 12, the value of asymmetry index had a positive peak at 04UT and a negative peak at 08 UT, though there were little differences between the storm-time asymmetry index and the quiet-time index. During 01-04UT and 06-10UT, the storm-time asymmetry index was smaller, which means that the EIA become more symmetric during storm time. After 10UT, the storm-time asymmetry index became larger. Compared Fig. 12 with the results from GIM, the variation of the asymmetry index from the simulation with UT times was similar with that from the GIM, but the value of asymmetry index from the simulation was smaller than that from GIM.

Fig. 13 shows the variations of CTR derived by SAMI2 during storm time and quiet time with UT times, respectively. It can be seen that CTR decreased during storm period, the decrease was very small. During the quiet period, the CTR was about 1.6 from 02UT to 09UT. The CTR decreased to about 1.5 under the disturbance. From 09UT, the disturbed CTR increased to 2. The CTR did not vary with time during 02-09UT, which was different from that derived from the GIM.

Fig. 14 shows the locations of EIA peak derived by SAMI2 during storm time and quiet time with UT times, respectively.

From Fig. 14, it can be seen that the crests moved toward the equator during disturbed periods, though the amplitude of the movement was tiny.

Fig. 15 displays the latitudinal distribution of the meridional wind from HWM07 during March 2013 storm period. The dashed red line represents the disturbed neutral wind, the solid purple and blue line represents the wind under the quiet period and the disturbed period, respectively.

As shown in Fig. 15, the meridional wind in low-latitude regions is northward and asymmetric about the equator, the wind flow to the south in mid-latitude of southern hemisphere and to the north in mid-latitude of northern hemisphere. During storm

period, the trans-equatorial wind is enhanced, and the southward wind is decreased in middle-latitude of southern hemisphere.

5 Discussion and conclusion

In low-latitude and equatorial ionosphere, the structure of the ionosphere is strongly controlled by electrodynamics. The characteristic of EIA is related directly to the neutral wind and the electric field. The thermospheric meridional wind is linked with the parallel upward motion along the geomagnetic field lines, leading to the asymmetry of EIA. Zonal electric field will raise or lower the height of the plasma, the strength of EIA would be affected in result. During the storm period, the neutral wind would be disrupted, and the dynamo electric field would be altered because the normal quiet day thermospheric neutral winds are disrupted, plus the penetration electric field from the planetary. The asymmetry and strength of EIA could be changed. For instance, the EIA would be enhanced after the SSC due to the “super fountain” effect[Lin et al., 2005].

On the other hand, it is well known that variations of neutral composition can impact the ionosphere by changing the ion loss rate. A decrease in the O/N₂ ratio can cause substantial decreases in plasma density, and the converse is true [Strickland et al., 2001]. During the storm, the O/N₂ may be decreased or enhanced due to the storm-time meridional winds. For instance, the increased mid-latitude meridional winds push the plasma parallel to the magnetic field to regions of different composition and change the ion loss rates[Fuller-Rowell et al., 2008].

As shown in Section 4, TEC values above the crests and trough, the asymmetry and strength of the EIA all showed obvious variations after the SSC. For the first time, Wu et al. [2004, 2008] found that the monthly values of I_c (magnitude of TEC at the northern anomaly crest) correlated well with the Dst index during low solar activity. For our study, the trough was more sensitive to the storm than the crests. For instance, on 1st June 2013, the TEC increased remarkable above the trough relative to the median 5 hours after the SSC, while the TEC at the crests had slight variations. On 18th March 2013, one day after the storm day, TEC above the trough decreased significantly, while the TEC at the crests varied less significant than that at the trough. The variations at the trough were more significant than that at the crests for the two storms, which can be attributed to the disturbed electric field and neutral winds. When the electric field is enhanced because of the disturbed dynamo electric field and the penetration electric field, the plasma at the equator would move upward to a higher altitude and diffuse along the field line to higher latitude regions. The locations of the crests and the densities at the crests change.

Under the effects of meridional neutral wind, the plasma could move toward the equator from the mid-latitude regions and enhance the plasma density at the equator,

or cross the equator from one hemisphere to higher latitude in the other hemisphere to decrease the plasma density at the equator. When the trans-equatorial meridional wind is enhanced, as shown in Fig. 15, much more particles would be moved cross the equator, leading to the change of O/N_2 and the decrease of the plasma above the equator. And the plasma would also be uplifted to higher altitude, the plasma density at the trough would decrease. Moreover, interactions between the summer-to-winter (trans-equatorial) neutral wind and the strength of the equatorial plasma fountain have an important effect on the asymmetry of the EIA[Lin et al. 2007b]. Thus, the neutral wind plays an important role in the density variation at the trough and in leading to the trough is more sensitive than the crests.

When the plasma densities at the crests and the trough change, the strength of the EIA would vary in result. During the two storm periods in 2013, TEC values at the crests and the trough responded to the storm immediately, the CTR varied significantly several hours after the SSC. CTR peak usually occurs in the post-noon hours around 13-14LT and the post-sunset hours around 20-21LT, and the post-sunset peak has a much higher value than the post-noon one[Zhang et al., 2009]. Liu et al. [2007] indicated that the CTR around noon varies from 1.14 to 1.43 with increasing solar activity. As shown in Fig. 5, during March storm period, the CTR peak occurred during 10-16UT (LT=UT+8), and the max was about 3.1, and CTR were not larger than 2 during quiet periods. This remarkable increase of CTR is attributed to the remarkable decrease of the TEC at the trough.

For June storm, there was a CTR minimum during 02-16 UT times of DOY152 (the storm day) after the SSC, with a value of about 1.2, while the CTR was about 1.2-2.2 during other periods. Especially during 14-16UT, the CTR was larger than 2 during other periods. The CTR decrease was attributed to the sharp increase of TEC at the trough. Thus, the CTR would be an important index to study the variations of EIA.

It can be noted that the response time to the storm was different for the two storms. For March storm, CTR increased significantly about 20 hours after the SSC, the EIA asymmetry had no obvious response. For June storm, CTR decreased remarkably on about 15 hours after the SSC, the asymmetry was increased on 5 hours after the SSC. Zhao et al. [2005] indicated that the EIA response to the storm may be separated according to the disturbance duration. The variations in EIA may occur on 1-2 hours after the SSC, or 5-6 hours after the SSC, and even 2-3 days after the SSC. As Fuller-Rowell et al. [2007] indicated, the time sequence of the disturbance dynamo will depend on the strength of the zonal winds and the strength and phase of the disturbed meridional wind. The effect of neutral wind on the low-latitude dynamo is important, the different response time to the storm can be attributed to the different performance of the neutral winds.

The TEC_d and $Index_A$ had similar variations, which means that the asymmetry index could reveal the status of EIA asymmetry. There were no remarkable variations except on 7 hours after the SSC of June storm. And the asymmetry index from simulation shown in Fig. 11 also had little variations under the disturbance compared to the asymmetry index during the quiet time. It can be denoted that the EIA asymmetry could not be affected significantly by the storm.

On 17th March 2013, the two crests moved toward the equator and located around the dip equator at 5 hours after the storm occurred. It may be because the effect of the disturbed neutral wind was strong, and the wind driven the crests toward the equator. And because of the asymmetric wind, on one day after the SSC, during 0-12UT, the southern crest moved toward the pole, while the northern crest still located around the dip equator.

On 1st June 2013, the distributions of the two crests were asymmetric. The northern crest spread poleward and the southern crest moved toward the dip equator relative to the quiet periods 15 hours after the SSC. One day after the SSC, the northern crest moved toward the equator and located around the equator, the southern crest also moved toward the equator. Lin et al. [2007b] also found the EIA crests moved toward the equator with TEC decrease after the SSC, and toward the poles 2 days after the SSC. They attributed the motions to the dynamo electric field. Yeh et al. [2001] denoted that the equatorial dynamo electric field was the main factor to the crest motion. It seems that the effects of neutral wind could not be negligible.

As derived from SAMI2, shown in Fig. 14, the crests would move toward the equator under geomagnetic disturbance on the combined effects of disturbed electric field with neutral winds. The disturbed meridional wind derived from HWM07 in two hemispheres was asymmetric. The disturbed dynamo electric field is related to the disturbed wind, thus the asymmetric movements of the two crests are related with the wind.

The simulation from SAMI2 shows that the asymmetry index and CTR would decrease during most time of storm period, and there are differences between the results from the GIM and the SAMI2. It may be because the disturbed electric field and neutral wind in the model could not represent the characteristics of the real electric field and neutral wind, respectively. The SAMI2 model with the electric field and wind models could not reveal the full variations of EIA asymmetry and strength during storm period, the disturbed electric field and neutral wind from the observations should be ingested into the model.

The electrodynamical process in EIA regions is complicated, the asymmetry and strength of EIA would be mainly affected by the disturbed neutral wind and electric field. Watthanasangmechai et al. [2015] indicated that the neutral wind is typically

considered as the primary source of EIA interhemispheric asymmetry, whereas the zonal electric field is secondary. Thus, when the normal neutral wind is disrupted, the interhemispheric asymmetry may be changed. As the results shown in our study, there are some factors to affect the asymmetry and strength of the EIA, such as the chemical process because of the change of the composition under the disturbance. In addition, the EIA is also related to the equatorial thermosphere anomaly (ETA) by plasma-neutral interactions [Lei et al., 2010], planetary wave activity [Yue et al., 2010; Mo et al., 2014] and so on. More details should be studied to reveal the variations in EIA during storm periods, which would be done in next step.

6 Summaries

In this paper, variations in the trough and two crests of EIA during two geomagnetic storm periods in 2013 are studied based on GIM and SAMI2, the results can be summarized as below:

1) TEC value at EIA trough decreased obviously about 24 hours after the SSC of March 2013 storm and increased 5 hours after the SSC of June 2013 storm, while the value at the two crests had less obvious variations during the two storm periods. It means that the trough may be more sensitive to the storm relative to the two crests.

2) Hemispheric asymmetry between the two EIA peaks had no remarkable variations, but CTR of EIA varied significantly after the SSC of storm. For March 2013 storm, CTR could increase of about 50% one day after the storm day during 0-12 UT times compared with the values before the SSC. For June 2013 storm, CTR could decrease of over 40% 15 hours after the SSC relative to the values during other quiet days. The results denote that the CTR is an important index to reveal the variations of EIA.

3) After the SSC, the two EIA crests moved toward the equator during 00-12UT for the two storms, and the movements of the two crests were asymmetric. Sometimes the northern crest was closer to the equator than the southern crest, sometimes the southern crest was closer to the equator.

4) The simulation from SAMI2 with HWM07 shows that the CTR would decrease during the storm, and the EIA peaks move equatorward. The simulations denote that the disturbed neutral wind would be an important factor to affect the asymmetry and strength of the EIA during the geomagnetic storm period.

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Fig. 1a. The Dst and Kp indices during March 2013 geomagnetic storm period

Fig. 1b. The Dst and Kp indices during June 2013 geomagnetic storm period

Fig. 2. The values of TEC at two EIA peaks and the trough in 120°E longitude from 12nd March (DOY71) to 23rd March 2013(DOY82). The blue line represents the value of northern peak, the red line represents the value of southern peak, the green line represents the value of trough.

Fig. 3. TEC peak values from DOY71 to DOY82 at northern EIA crest(a), southern EIA crest (b)and the trough(d), the red line represents the 30-days median.

Fig. 4. Variations of Index_A and TEC_d from DOY71 to DOY82 with UT times, LT=UT +8.

Fig. 5. Variations of CTR from DOY71 to DOY82 from 00UT to 12 UT (a) and at different UT times(b). LT=UT+8.

Fig. 6. Location of EIA peaks from DOY71 to DOY82 with UT times._The purple triangles represent the northern crests, the red stars represent the southern crests.

Fig. 7. The values of TEC at two EIA peaks and the trough in 120°E longitude from 26th May(DOY146) to 5th June 2013(DOY146). The blue line represents the value of northern peak, the red line represents the value of southern peak, the green line represents the value of trough.

Fig. 8. TEC peak values from DOY146 to DOY156 at northern EIA crest(a), southern EIA crest (b)and the trough(d), the red line represents the 30-days median TEC.

Fig. 9. The variations of asymmetry index(blue line) and TEC difference (red line) between two EIA peaks with UT times from DOY146 to DOY156.

Fig. 10. Variations of CTR from DOY146 to DOY156 of 2013 at different UT times.

Fig. 11. Location of EIA peaks from DOY146 to DOY156 of 2013 with UT times. The purple triangles represent the northern crests, the red stars represent the southern crests.

Fig. 12. The asymmetry index derived from SAMI2.

Fig. 13. CTR derived from SAMI2 under the quiet and disturbance, respectively.

Fig. 14. The distribution of EIA peaks during quiet time and disturbed period at different times during March 2013 storm derived from SAMI2 with HWM07.

Fig. 15. The meridional neutral wind derived from HWM07 for March 2013 storm. The dashed red line represents the disturbed neutral wind, the solid purple and blue line represents the wind under the quiet period and the disturbed period, respectively.

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