On Magnetospheric Source for Positive Ionospheric Storms

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Abstract. We have used statistics to validate an assumption that the intense electron fluxes in the topside equatorial ionosphere can be an important source of the ionization in the low-latitude ionosphere during geomagnetic disturbances. The data on the energetic electrons were obtained from satellite-based POES and DMSP platforms for periods of the 40 major geomagnetic storms (Dst<100 nT) from 1999 to 2006. Ionospheric response to the selected storms was determined with using global ionospheric maps of vertical total electron content (VTEC). Statistical analysis of 7 major magnetic storms allowed finding that the VTEC increases coincided and coexisted with intense 30-keV electron fluxes irrespective of local time and phase of geomagnetic storm. A case-event study of a major storm on 26-27 July 2004 provided experimental evidences in support to the substantial ionization effect of ~10-30 TECU produced by energetic electrons during positive ionospheric storms at low latitudes.

Keywords: Ionospheric positive storm, Energetic electrons, West Pacific sector.

Introduction

Traditionally, it is thought that the energetic electron fluxes (10-50 keV) at heights of <1000 km, below the inner radiation belt (IRB), are invariably weak and certainly less than inside the IRB zone, therefore the particle impact is insufficient to produce appreciable ionization in the topside low-latitude ionosphere, see reviews of Paulikas (1975) and Voss and Smith (1980). Nevertheless, intense fluxes of the quasi-trapped population of energetic electrons were occasionally observed since the beginning of the space era (Krasovskii et al., 1958; 1961; Savenko et al., 1962; Heikkila, 1971). Modern experiments convincingly proved that the energetic electrons of the IRB during a geomagnetic disturbance can penetrate in the forbidden range of drift shells located outside the South Atlantic Anomaly (SAA) region (Evans, 1988; Tanaka et al., 1990; Pinto et al., 1992; Asikainen and Mursula, 2005; Suvorova et al., 2012). However, these phenomena are not completely investigated, and no explanation for the electron injections to so low *L*-shells (<1.2) is yet known. Mentioned above observations showed that the increases of >30 keV electrons were comparable with the auroral zone intensities of $>10^6$ $(cm^2\ s\ sr)^{-1}$, and so it is reasonably to expect a significant ionization impact in the ionosphere.

Comparative analysis of this phenomenon with positive ionospheric storm observed by COSMIC/FS3 satellite has been made recently by Suvorova et al. (2012). They have showed a strong relation between the two phenomena and suggested the energetic electrons as a storm-related ionization source of the topside ionosphere in a wide range of longitudes from Taiwan – Japan region through Pacific to the SAA.

Here we present results of statistical analysis of energetic electron enhancements observed by a fleet of NOAA POES satellites at altitudes ~850 km in the Eastern hemisphere (i.e. $L < 1.2$) in time period from 1999 to 2006. The electron enhancements are considered in relation to positive ionospheric storms identified with using Global Ionospheric Maps (GIM).

Data sources

In this study, we use time profiles of >30 keV and >100 keV electron fluxes measured by polar orbiting POES satellite fleet. The POES satellites have Sun-synchronous polar orbits at altitudes of ~ 800-850 km (~100 minute period of revolution). The orbital planes of POES satellites NOAA-15, NOAA-16, NOAA-17, NOAA-18 and METOP-02 (hereafter P5, P6, P7, P8, and P2, respectively) are 7–19 *LT*, 2–14 *LT*, 10–22 *LT*, 2–14 *LT*, and 0930–2130 *LT* respectively. A Medium Energy Proton and Electron Detector (MEPED) measures particle fluxes in two directions: along and perpendicular to the local vertical direction (see Huston and Pfitzer, 1998; Evans and Greer, 2004). Thus, at low latitudes one detector measures mainly quasi-trapped particles and the other detector - precipitating particles, and vice versa at high latitudes. Hereafter, we will use terms "quasi-trapped" and "precipitating" in respect to the equatorial latitudes on default.

Experimental data about electrons in low-energy range 30 eV - 30 keV from the SSJ/4 particle detectors onboard Sun-synchronous polar orbiting DMSP satellites have also been used to substantiate the POES observations. DMSP particles spectrograms are provided online by the Auroral Particle and Imagery Group at the JHU/APL's (http://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=AACGM&type=1). The altitude of the DMSP satellites were 840 km.

Global ionospheric maps (GIM) were acquired from a world-wide network of ground based GPS receivers through website ftp://ftp.unibe.ch/aiub/CODE/ .

Storm-time electron flux enhancements

We have selected 40 major geomagnetic storms (*Dst* < -100 nT) from 1999 to 2006 years. We created and analyzed geographic maps of the peak intensity of >30 keV electrons at ~850 km altitude for the geomagnetically disturbed and quiet days. Usually, the electron fluxes outside the SAA region are weak, irrespectively of geomagnetic conditions, with typical values below 10^2 -10^3 (cm^2 s sr)$^{-1}$ for a quiet or moderately disturbed day. The quiet patterns of both the quasi-trapped and precipitating populations (Figure 1, left) were obtained by accumulating data over multiple orbits. Note that the quasi-trapped (top panel) electron intensities reach up to ~10^5 - 10^6 (cm^2 s sr)$^{-1}$ inside the SAA.

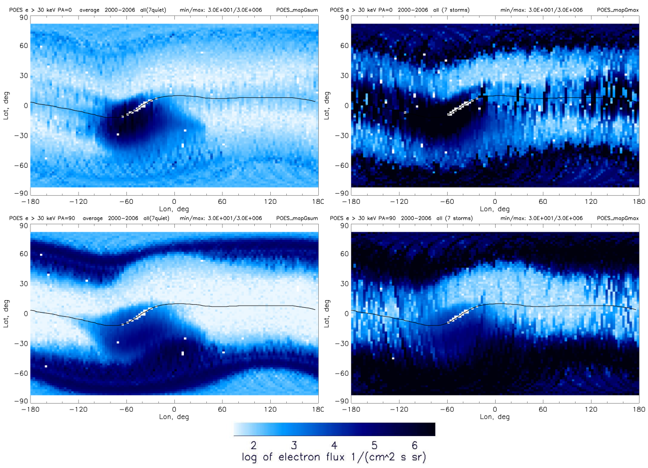

Figure 1: Data retrievals of intensity of the >30 keV electrons flux from POES satellites: (right) disturbed and (left) quiet radiation belt. Patterns for quasi-trapped and precipitating populations are shown on the top and bottom, respectively. These images are composites formed over multiple orbits of the satellites during 7 storm and quiet days from 2000 to 2006 years. The solid curve indicates the geomagnetic equator.

The specific characteristics of the electrons at low latitudes and at altitudes below ~1200 km associate with the forbidden range of drift shells, which is formed at the wide longitudinal range eastward from the SAA region. We have found that for 10 major storms (-150 < *Dst* < -100 nT), the intensity exceeded slightly the background level. Moderate increases of the quasi-trapped electrons of ~10^4 - 10^5 (cm^2 s sr)$^{-1}$ were found for 15 storms. It is interesting that during some superstorms with *Dst* < -250 nT, for example 7 November 2004 and 11 April 2001, the fluxes outside the SAA did not exceed 10^4 (cm^2 s sr)$^{-1}$. Apparently, so weak fluxes can not produce a prominent ionization effect in the ionosphere, because of strong competitive recombination process.

The salient 7 events with the extremely large fluxes of >10^6 (cm^2 s sr)$^{-1}$ in the forbidden zone selected for analysis are listed in Table 1. Figure 1 (right) shows summary patterns of the 30-keV quasi-trapped (top panel) and precipitating (bottom panel) electrons for the selected storms. Here we have to point out that the magnetospheric state is dramatically changed during the geomagnetic storms as seen from the comparison of the global distributions of the energetic electrons in Fig. 1 (left and right panels). At high latitudes, the electron precipitation enhance significantly. The lower boundary of the auroral oval and the outer radiation belt move to the sub-auroral and middle latitudes, respectively, with extreme increase of the electron intensities. At low and equatorial latitudes, the strong quasi-trapped electron fluxes appear practically at all longitudes. Note that very intense fluxes over Taiwan and Pacific Ocean are comparable with the auroral fluxes.

For each storm, in Table 1 we present the following main characteristics of the electron enhancements: local time (*LT*), the maximum value of the *Dst*-index for a storm and the current storm phase (initial, main or recovery).

Table 1: List of the Storms with Great Electron Enhancements in the Topside Ionosphere in the Western Pacific sector.

Storm day	Quiet day	LT	Dst	Storm phase	dVTEC*, TECU
15 Jul 2000	2 Jul	07	-340	main	20
29 Oct 2003	11-12 Oct	07-11	-400	main	15
30 Oct 2003	11-12 Oct	07-10	-400	main	30
27 Jul 2004	3-4 Aug	07-14	-200	main/rec	35
9 Nov 2004	5-6 Nov	07-10	-250	rec	15
15 May 2005	5-6 May	18-02	-300	rec	20
14 Dec 2006	4-5 Dec	10-15	-200	rec	40

*The positive ionospheric storm dVTEC is estimated within longitudinal range of 120-170°E.

For each disturbed period, we have determined a quiet day on the base of comprehensive analysis of the solar, heliospheric, and geomagnetic conditions. The initial criteria for the quiet day were *AE* < 100 nT and *Dst* >-20 nT. Also, we excluded the days with high solar activity manifested by X-class flares and SEP events, which are monitored by GOES satellites. Finally, the additional constraints were imposed on fast large-amplitude variation of the IMF Bz value, high solar wind velocity (>400 km/s), and sharp and large increase of the solar wind dynamic pressure, which can cause a weak auroral activity, a strong magnetosphere compression, and also disturbances in the radiation belt (increases of particle fluxes). Our method of the quiet day selection allows revealing of ionization effect (if any) of the energetic electrons with accuracy better than ~10 TECU. These quietest days, listed in Table 1, have been used to calculate the ionospheric ionization enhancements (positive ionospheric storms).

From Table 1, one can see that the great electron enhancements occur predominantly in the morning and daytime sectors (except of only one case at the evening/night). All listed storms were major, with the minimal *Dst* ≤ -200 nT. However, taking into account all statistics of 40 major storms, we did not find any regularity in the event occasions related to the storm intensity. Though 7 major storms do not present large statistics, the data show almost equal frequency of the great flux occurrence during the main phases (4 events) and the recovery phase (3 events). Further work is needed to obtain more statistically significant results.

Positive ionospheric storms

In this section, we present a detailed analysis of the energetic electron fluxes and positive ionospheric storms at low latitudes in the Eastern hemisphere. In the previous study (Suvorova et al., 2012) we analyzed the positive ionospheric storm occurred in the daytime sector on 15 December 2006 (see the last row in Table 1). Here we consider an example of the positive storm in the morning - noon sector (07-14 LT) on 26-27 July 2004.

Figure 2 shows the fluxes of energetic electrons (>30 keV and >100 keV), observed by POES satellites P5, P6, and P7, and geomagnetic activity during the storm. The enhancements of the >30 keV electrons in the Eastern hemisphere are observed by P5, P6 and P7 during ~15 min passes in the low-latitude region at ~0040 UT (lon. 90°), ~0220 UT (lon. 60°), ~0250 UT (lon. 120°), ~0345 UT (lon. 160°), and ~0530 UT (lon. 130°) on 27 July. The enhancements are characterized by smooth profiles that indicate to non-sporadic electron penetration to the topside ionosphere. The smooth shape and limited life time indicate to a gradual and relatively fast transport of the electrons in the magnetosphere. The intense fluxes of the electrons persist for a few hours, mainly when the *Dst* index increases after the IMF Bz has sharply turned north. The earliest flux increases are observed by the P5 satellite at dawn (06-07 *LT*), then in an hour the intense fluxes are sequentially observed at prenoon (10 *LT*) by P7. The further increase of electron flux by an order of magnitude (~10^7 (cm^2 s sr)$^{-1}$) is detected by P6 at ~0345 UT (14 *LT*) in postnoon (160° longitude). At the time, a strong magnetosphere compression has occurred following the solar wind dynamic pressure increase (Kuznetsov et al., 2009).

The electrons with higher energies, >100 keV and > 300 keV, were also detected by POES satellites at the same time. It is interesting that the >100 keV electron flux (shown in Fig. 2) was much weaker than of >30 keV electrons in the forbidden zone, but >30 and >100 keV electrons had same intensities inside the SAA area. The >300 keV electron flux (not shown) increased only inside the SAA. Hence in the energy range from 30 to 300 keV, the spectrum of energetic electrons near the edge of the IRB was descending.

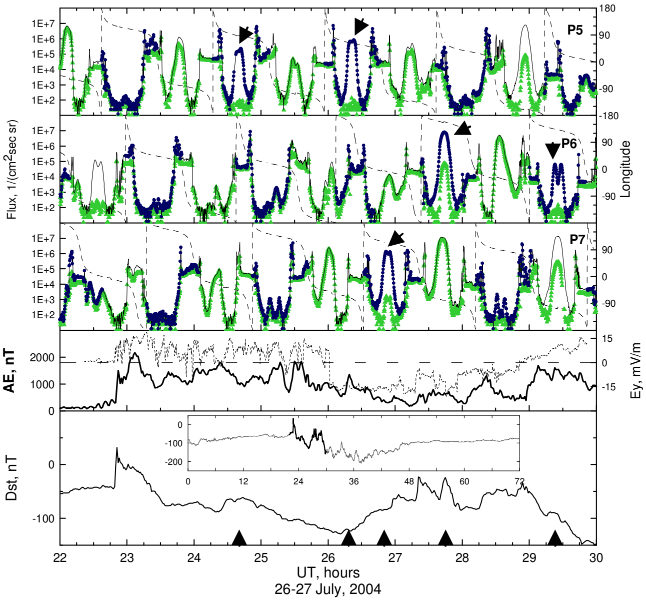

Figure 2. (From top to bottom) The fluxes of the >30-keV (solid curves, left axis) and >100 keV (green trianges, left axis) electrons observed by NOAA-15 (P5), NOAA-16 (P6), and NOAA-17 (P7) and the geographic longitudes (dashed curves, right axis) along the satellite orbit; AE index, the IMF Ey (eastward) measured by ACE upstream monitor with ~30 min delay and Dst index (two bottom panels) during the time period 22 - 06 UT on 26 - 27 July 2004. The Dst index during two days of 26 - 27 July is shown inside the small box, the time interval is indicated by dark color. The dotted segments on the tree upper panels indicate the >30 keV electron fluxes at longitudes from 0° to 180°. The great electron enhancements over Eastern hemisphere are pointed by arrows.

The spectrum of electrons with lower energies is measured by DMSP satellites. Figure 3 shows the spectrum of electron energy flux in the range below 30 keV observed by DMSP F14 at 0256 UT (~70° lon.). The spectrum is ascending at energies from 1 to 30 keV.

As it was shown above, three highest fluxes (≥10^6 (cm^2 s sr)$^{-1}$) appeared during partial recovery phase from 2 to 4 UT and were accompanied by the induced interplanetary electric field of dawnward direction (*E*y < 0). Hence, the mechanism of the prompt penetrating electric field (PPEF) does not work at this time. The auroral activity was not very strong (AE ~ 1500 nT) within 3 hours before and moderate (AE ~ 500 nT) during the interval considered. It is unlikely that such auroral activity could produce strong Joule heating and results in fast and significant change of the neutral wind circulation. Under the circumstances one may not expect a significant ionospheric response at the beginning of the superstorm main phase (23-06 UT) with the maximum intensity at 14 UT on 27 July. Nevertheless, we will show below, that relatively strong positive ionospheric storm was occurred during this time interval.

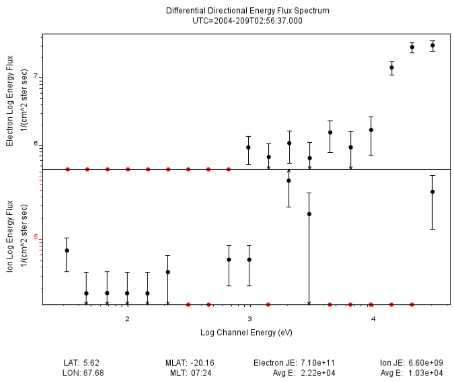

Figure 3. The spectrum of electron (upper panel) and ion (lower panel) energy flux in the range below 30 keV observed by DMSP F14 at ~0256 UT at ~70°E longitude. The fluxes of electrons with energies > 1 keV are characterized by an ascending spectrum.

Figure 4 shows two-hour global ionospheric maps (GIM) of residual VTEC (dVTEC) from 22 UT to 04 UT. The dVTEC is calculated as a difference between the storm and quiet days indicated in Table 1. At low latitudes, one can clearly see development of daytime positive ionospheric storm occupying a wide longitudinal sector from 120°E to 30°W. From 23 to 02 UT, when the interplanetary electric field was eastward, the ionization gradually enhanced in the crest region of equatorial ionization anomaly (EIA) located in the West Pacific sector at the dayside. The spatial distribution of VTEC increases was not uniform and consisted of a number of spots of enhanced ionization. The maximum dVTEC of ~35 TECU was observed after 2 UT in the separated spot around noon in the Southern hemisphere and persisted for ~4 hours. Spots of strong ionization of ~40 TECU were also revealed at the SAA longitudes and in the East Pacific sector at the afternoon and dusk. Note, that the EIA crest at local noon hours was restricted to within ±15° geomagnetic latitudes (Ngwira et al., 2012) and did not expand to the low or middle latitudes, as expected from the penetration electric field and the equatorward neutral wind mechanisms (e.g., Kelley, 2009).

Here we want to point out a spot of moderate ionization enhancement of ~15 TECU at morning hours (8 – 11 *LT*), which at first appeared over West Pacific around 140°E, then moved westward from Taiwan following the noon meridian. While the postnoon positive storm is a common phenomenon during geomagnetic storms, the appearance of ionospheric storms at morning hours (<10 *LT*) is still an unclear issue, especially when operation of the general drivers is tenuous or absent.

Now, we compare the particle and ionospheric patterns during the geomagnetic disturbances. In Figure 5, we show a summary geographic map of >30 keV electron fluxes observed by satellites P5, P6, P7 on 26-27 July 2004. From 2 to 4 UT, strong electron enhancements of >10^6 (cm^2 s sr)$^{-1}$ were observed in a wide longitudinal range from 60°E to ~30°W, i.e. from the forbidden zone of Indo-China and Pacific to SAA. We find the spatial pattern of >30 keV electron enhancements very similar to spatial distribution of the positive ionospheric storm (see Fig.4). The time interval of the electron enhancements overlap with the increases of VTEC. Hence, we suggest that the energetic electrons contribute to the redundant ionization of the ionosphere.

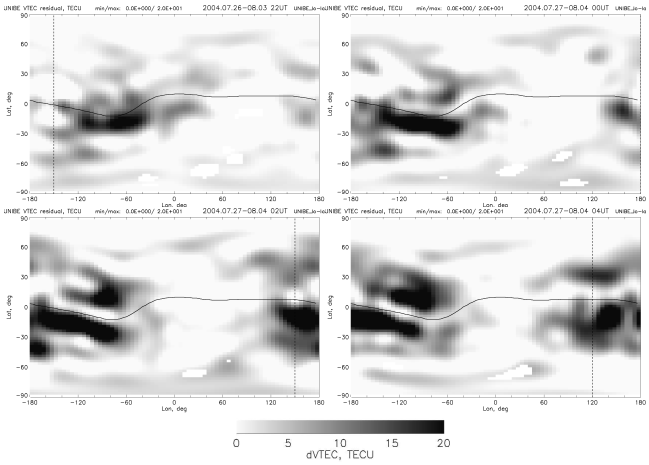

Figure 4. Sequence of two-hour geographic maps of positive storms from 22 to 04 UT on 26-27 July 2004. The solid curve and vertical dashed line indicate, respectively, the geomagnetic equator and local noon.

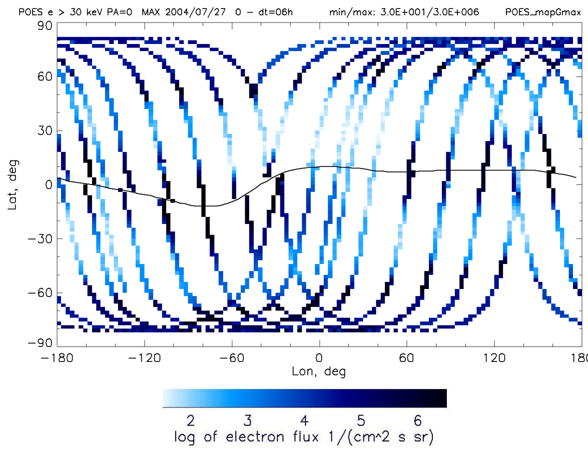

Figure 5. Geographic map of >30 keV electron fluxes on 26-27 July 2004. The strong electron enhancements near equator appeared from 2 to 4 UT.

The magnitude of positive ionospheric storms, observed in the Taiwan and West Pacific region and accompanied by the energetic electron enhancements of above 10^6 (cm^2 s sr)$^{-1}$, is presented in the last column of Table 1. Six out of 7 positive storms occur at morning-noon hours (07 - 14 LT). The dVTEC varies in a wide range from 10 to 40 TECU. It seems that the ionization effect of the energetic electrons might be considered as an important supplement to the other general drivers of the dayside ionosphere, especially in the morning sector.

Discussion

We studied a relationship between the quasi-trapped energetic electrons and the ionospheric ionization for major geomagnetic storms from 1999 to 2006 years. We have analyzed storm-time events, when the inner radiation belt approached the heights of the topside low-latitude ionosphere. During such events, a dramatic increase of the particles flux of few orders of the magnitudes relative to the pre-storm level was observed. Here we focus on the Taiwan and the West Pacific sectors, where these salient events occur very rarely.

During the same time intervals and in the same spatial region, positive ionospheric storms with magnitude of ~10 to 40 TECU were observed. As an example, we have considered geomagnetic storm on 26 - 27 July 2004, the third in a series of three successive geomagnetic storms occurred during the time period of 22 - 27 July 2004 due to a sequence of coronal mass ejections. Note that the electron fluxes during the first, strong storm (*Dst* ~100 nT) on 22 July were moderate ~10^5 (cm^2 s $sr)^{-1}$, and very weak during the second, major, storm (*Dst* ~150 nT) on 25 July, and the second activation of the third, superstorm, (*Dst* ~200 nT) on 27 July.

This series of the intense disturbances attract attention up to date because of the successive storms result in specific thermosphere-ionosphere-magnetosphere system response (Burke et al., 2007; Kunitsyn et al., 2005, 2007, 2008; Kuznetsov et al., 2009; Lazutin, 2012; Lazutin et al., 2008; Li et al., 2010; Ngwira et al., 2012; Pedatella et al., 2008; Shang et al., 2008). Main features are the following: significant changes in the longitudinal structure of the EIA (Pedatella et al., 2008), the EIA crest enhancements are restricted by the low-latitudes (Ngwira et al., 2012), long-duration positive storms and moderate positive storms at middle latitudes (Ngwira et al., 2012), increases of the F layer height observed at the Eastern longitudes and at low-/middle latitudes (Shang et al., 2008; Ngwira et al., 2012), enhanced ionospheric scintillation activity during low-occurrence winter/summer seasons (Shang et al., 2008; Li et al., 2010), wide longitudinal (~180°) development of the equatorial and low-latitude ionospheric irregularities in American and Southeast Asia sectors (Li et al., 2010), rapid thermospheric density response to *Dst* index variation (Burke et al., 2007) and rapid rebuilding of the radiation belt (Kuznetsov et al., 2009; Lazutin et al., 2008; Lazutin, 2012). The results of recent studies of these storm-time events posed challenges to the standard mechanisms of the positive storm.

The positive ionospheric storm on 26 - 27 July was described with considering the following observational and theoretical aspects: prompt penetration of the electric field to the low-latitude ionosphere, disturbance dynamo electric field, effects of the equatorward neutral wind, and thermospheric density changes (Shang et al., 2008; Li et al., 2010; Ngwira et al., 2012; Burke et al., 2007). These studies have clearly demonstrated that some observed features can not be explained by the mentioned above standard mechanisms and alternative approaches are needed to develop. For example, Burke et al. (2007) suggest a method to quantify effects of the stormtime thermospheric density changes, Ngwira et al. (2012) considered mid-latitude particle precipitation as a source for the observed daytime TEC enhancements at the Southern middle latitudes.

In the present study we also have showed some discrepancies between the existing mechanisms and observations of the positive storm. Particularly, in the considered time interval at 02 - 05 UT on 27 July, during the partial recovery phase, the PPEF and equator neutral wind mechanisms fail to explain existing strong positive storm at the low-latitudes.

On the other hand, we have found a large 30-keV electron flux enhancements up to >10^6 (cm^2 s $sr)^{-1}$ at ~800-900 km in a wide longitudinal range from local morning above West Pacific to local evening and midnight above SAA. The intense fluxes of energetic electrons overlap well the region of positive ionospheric storm. Detailed analysis of the low energy and thermal electrons detected, respectively, by POES and DMSP satellites has shown that there is a prominent peak at ~30 keV in the storm-time energy spectra of the electrons. The feature is similar to that indicated by Leiu et al. (1988).

Kudela et al. (1992) have revealed multiple energy peaks in the electron spectra within 20-400 keV at altitudes 500-2500 km during undisturbed conditions. The lowest one at 30 keV was observed in the trapped electron population at *L* ~ 1.23 – 1.34 and at altitudes above 800 km. Suvorova et al. (2012) show that during strong magnetic storms, the energetic electrons undergo a fast radial *ExB* transport to lower *L*-shells (*L* ~1.05) on the night side. Fast inward transport of electron radiation belt due to induced electric field was revealed for the July 2004 storms (Lazutin, 2012). Note that storm-time generation of the electric fields in the inner magnetosphere is still poorly understood. The electrons drift azimuthally toward east along the drift shells whose altitude above the Pacific region decreases with increasing longitude. In the morning sector, the energetic electrons can reach and ionize the topside ionosphere. The ionization effect of the intense fluxes of energetic electrons is estimated to be ~20 TECU at heights of ~400 to 800 km. Rising F layers during July 2004 events were reported by several authors (see above). Hence, direct ionization of the topside ionosphere by quasi-trapped energetic electrons can be considered as an important contribution to the low-latitude positive ionospheric storms occurred at morning-noon hours in the longitudinal sector of Taiwan - West Pacific sector. There are some indications of the substantial ionospheric effect of energetic electrons in the East Pacific and SAA regions. But that is a subject of further investigation.

Summary and conclusion

From the case-event analysis of the magnetic storm on 26-27 July 2004, we demonstrate that the positive ionospheric storm observed in the West Pacific sector at morning-noon hours during the partial recovery phase can be explained rather by the direct ionization produced by intense fluxes of quasi-trapped energetic electrons in the topside ionosphere than by the effects of PPEF and/or equatorward neutral winds.

From statistics of major storms, an appearance of the >30 keV electron fluxes with intensities $>10^6$ (cm^2 s sr)$^{-1}$ under the radiation belt at L<1.2 is of rare occasion (~30%). Though the phenomenon has a certain relation with the geomagnetically disturbed state of the magnetosphere, we did not find an evident dependence on the geomagnetic storm magnitude.

Our analysis of 7 positive ionospheric storms in the Taiwan and Western Pacific sector contributes to the resolving the issue of positive ionospheric storms. We show that the energetic electron enhancements is an important source of the ionization in the topside ionosphere and, thus, they can be considered as a supplement to the general ionospheric drivers.

Acknowledgments

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