A statistical study of low latitude $F$ region irregularities at Brazilian longitudinal sector response to geomagnetic storms during post-sunset hours in solar cycle 23

Y. Y. Sun,1 J. Y. Liu,1,2,3 and C. H. Lin4

Received 29 November 2011; revised 12 February 2012; accepted 14 February 2012; published 31 March 2012.

[1] Effects of intense geomagnetic storms (Dst index $<-100$) to low latitude $F$ region irregularities in the post-sunset hours are statistically studied by the total electron content (TEC) phase fluctuation observations obtained from the ground-based global positioning system (GPS) receivers in the Brazilian longitude sector during a 7.5-year period of 1 April 1998–31 October 2005. Results show that the low latitude irregularities are significantly suppressed during the main and recovery phases of the intense geomagnetic storms in the months (September–March) that normally have high irregularity activity. In contrast, the post-sunset triggering signatures are pronounced in the low irregularity activity season (April–August) during storms. To further understand the storm-produced behaviors in the low latitude $F$ region irregularity in the post-sunset hours, the relationship between the intensity of GPS phase fluctuations and the occurrence time of the of IMF Bz turnings is examined and discussed.


1. Introduction

[2] Numerous event studies of geomagnetic storm-effected and quiet behaviors in the low latitude $F$ region irregularity have been carried out in recent decades by observations of satellite in situ measurements, ground-based Global Positioning System (GPS) receivers, scintillation receivers, radars, ionosondes, all-sky imagers etc. [e.g., Aarons, 1991; Abdu, 1997; Basu et al., 2001; Yeh et al., 2001; Shan et al., 2002; Becker-Guedes et al., 2004; Chu et al., 2005; Basu et al., 2005; Martinis et al., 2005; Pimenta et al., 2008; Candido et al., 2008; Abalde et al., 2009; Abdu et al., 2009; Sahai et al., 2009a, 2009b; Li et al., 2010]. These studies suggested that the presence and absence of low latitude $F$ region irregularities during different storm phases were mainly attributed to the prompt penetration (PP) [e.g., Spiro et al., 1988; Fejer et al., 1990] and/or the disturbance neutral wind driven disturbance dynamo (DD) [e.g., Blanc and Richmond, 1980; Liu et al., 1999; Fuller-Rowell et al., 2002; Richmond et al., 2003; Lin et al., 2005] electric fields that are capable of disturbing the ionospheric zonal electric field in low latitudes leading to layer height variations of the ionosphere. Abdu [2011] comprehensively discussed the major characteristics of the storm-related disturbance electric fields and their effects on the development/suppression/disruption of the equatorial spread F/plasma bubble irregularities, and suggested that the further quantitative study need to be carried out.

[3] To quantitatively characterize the overall patterns of the development of low latitude irregularities in post-sunset hours after storm onsets, the phase fluctuations derived from ground-based GPS receivers, providing long-termed, continuous, and high temporal resolution observations, are utilized in this study. The ground-based GPS observation provides an efficient way to investigate the ionospheric irregularities in storm periods. For instance, Aarons et al. [1997] reported the strength and occurrence of irregularities increased during the storm periods by examining the GPS phase fluctuation at latitudes near the magnetic equatorial region during 3 November 1993–2 October 1995, and concluded that the irregularities on the magnetic equator can be individually and statistically evaluated by GPS phase fluctuation observations. Shan et al. [2002] analyzed data from seven GPS stations located in Central- and South-America during eight magnetic storms occurred from 1997 to 2000 and found, in general, no significant feature in the phase fluctuation being observed during the low irregularity activity months, except during the 26 August 1998 and the 15 July 2000 storms. Abalde et al. [2009] used simultaneous observations of the OI 630.0-nm emission all-sky imager, ionospheric sounding, and GPS phase fluctuation (ROT) over Brazil to study the day-to-day variability in the
Li et al. (2010) presented the ionospheric observations of three ground-based GPS receivers, kour (Kourou, 5.25°N, 52.81°W; geomagnetic latitude 9.96°N), fort (Fortaleza, 3.88°S, 38.43°W; geomagnetic latitude 4.22°N), and braz (Brasilia, 15.95°S, 47.88°W; geomagnetic latitude 9.77°S), in the Brazilian longitude sector. Gray curves are ground traces of GPS satellites at the altitude of 350 km with an elevation angle of 20°, and dark dash curves represent the magnetic equator and ±15°N magnetic latitudes.

Figure 1. Locations of the three ground-based GPS receivers (triangles), kour (Kourou; 5.25°N, 52.81°W; geomagnetic latitude 9.96°N), fort (Fortaleza; 3.88°S, 38.43°W; geomagnetic latitude 4.22°N), and braz (Brasilia; 15.95°S, 47.88°W; geomagnetic latitude 9.77°S), in the Brazilian longitude sector.

development of ionospheric plasma bubbles during both geomagnetically disturbed and quiet periods in September–October 2002, and found that the geomagnetic disturbances have a strong effect on the generation and development of ionospheric plasma bubbles during the spring equinox period. Li et al. (2010) presented the ionospheric observations of satellite in situ measurements, ground-based GPS total electron content, scintillation receivers, VHF radar, and two chains of ionosondes on the storm days of 22–28 July 2004, and concluded that during complex storm periods, long-duration or multiple-penetration electric fields and the combined effects of PP and DD electric fields could lead to the development of equatorial spread F or plasma bubbles over a wide longitudinal extent with a longer duration. In this investigation, we statistically studied the 7.5 years (1 April 1998–30 September 2005) continuous ground-based GPS TEC phase fluctuation observations characterize the overall patterns of the low latitude ionospheric F region irregularity in response to the interplanetary magnetic field (IMF) Bz turnings during 72 intense magnetic storm main phase events (Dst index < −100) in post-sunset hours by using ground-based GPS receivers at the Brazilian longitude sector.

2. Data and Methodology

Mendillo et al. (2000) proposed the phase fluctuation indices that capture F region plasma irregularities at 15-min (fp) and one-hour (Fp) time resolutions to quantify the ground-based GPS phase fluctuations. The index fp is defined as the absolute value of 1-min median GPS phase fluctuation in terms of TEC from a single satellite during the 15-min period, while the index Fp is the 1-h average of fp values divided by the number of available satellites and multiplied by 1000 at a certain station to make Fp an integer index. Fp ≤ 50 represents background levels of irregularities; 50 ≤ Fp ≤ 200 signifies moderate irregularities present, and when Fp > 200, it represents occurrence of very strong irregularity levels. We derive the Fp index from the TEC observation of three ground-based GPS receivers, kour (Kourou, 5.25°N, 52.81°W; geomagnetic latitude 9.96°N), fort (Fortaleza, 3.88°S, 38.43°W; geomagnetic latitude 4.22°N), and braz (Brasilia, 15.95°S, 47.88°W; geomagnetic latitude 9.77°S) in the Brazilian longitude sector (Figure 1) to study the day-to-day variability in the development of post-sunset low latitude F region irregularities during 72 intense storm main phases (Dst index < −100) occurred between 1 April 1998 and 30 September 2005. The 1-h-average Dst index and IMF Bz observation are adopted from Goddard Space Flight Center/Space Physics Data Facility (http://omniweb gsfc nasa gov/html/omni2 doc html), and the ground-based GPS RINEX data are obtained from Scripps Orbit and Permanent Array Center (SOPAC) (http://sopac ucsd edu/).

3. High and Low Irregularity Activity Seasons

Figure 2 demonstrates the seasonal and diurnal variations in the TEC phase fluctuation at the low latitude of Brazilian longitude sector during the 7.5-year period of 1 April 1998–30 September 2005. In Figure 2b, prominent Fp values appear in nighttime from September to March for each year, and the year-to-year variations in the intensity of Fp are generally proportional to the magnitude of the F10.7 max (Figure 2a). In this study, we defined the periods of 1 April–31 August and 1 September–March 31 of each year as the low and high irregularity activity seasons, respectively, at the Brazilian longitude sector. Note that Candido et al. (2011) examined the high irregularity occurrence at the low-latitude Brazilian longitude sector under the geomagnetic quiet condition around the midnight/post-midnight period from May to August during low-solar activity. They found the ionospheric disturbances being unrelated to equatorial processes. To avoid the mix up of the signature of the two different types of irregularities, the definition of low and high irregularity activity seasons in this study is mainly based on the post-sunset phenomena. During the 7.5-year period of this study, there are eight low irregularity activity and seven high irregularity activity seasons. Figures 2c and 2d illustrate the diurnal variation in Fp for the eight low and seven high irregularity activity seasons, respectively. Figure 2c indicates that the hourly average Fp (about 20) is consistently below the background level (Fp = 50) during the entire day in the low irregularity activity season. On the other hand, in the high irregularity activity season, the hourly average Fp begins to grow at 1800 LT, reaches the maxima during 2000–2300 LT (average Fp = 185), and dissipates after midnight (Figure 2d). In the following context, we named the average Fp during 2000–2300 LT as the “Fp max,” and further calculated the occurrence probabilities of Fp max > 50 in the low irregularity season, and of 100 < Fp max ≤ 185 and Fp max ≤ 100 in the high irregularity activity season. The occurrence probability of Fp max > 50 in the eight low irregularity activity seasons is about 2.6%, while the occurrence probabilities for 100 < Fp max ≤ 185 and
Fp\textsubscript{max} ≤ 100 are about 23.3\% and 28.6\%, respectively, in the seven high irregularity activity seasons.

Figure 3 displays examples of the day-to-day variations in Fp during the high and low irregularity seasons. It is clear from Figure 3a that Fp\textsubscript{max} obviously reduced (marked by two dark arrows) during the periods of the Halloween and November 2003 storms in the high irregularity activity season of 2003–2004. Reversely, in the low irregularity activity season of 2000, significant increases of the Fp\textsubscript{max} (marked by the three dark arrows) were observed in periods of the 6 April, 15 July, and 10 August 2000 geomagnetic storms (Figure 3b). In the following section, we mainly examined the storm-related suppression and triggering signatures of low latitude F region irregularities at the Brazilian longitude sector in post-sunset hours during the high and low irregularity activity seasons, respectively.

4. Suppression Signatures in High Irregularity Activity Seasons

[7] Figures 4 and 5 illustrate the day-to-day variations in Fp index, Dst index, and IMF Bz during periods of the Halloween and November 2003 storms, respectively. In Figure 4a, moderate irregularity activities (Fp = 100) were recorded in nights of 29–30 and 30–31 October over the Brazilian longitude sector, which are corresponding to the two main phases (events A1 and A2) of the Halloween 2003 storm (Figure 4b), and less than a half of the Fp value in the post-sunset hours of 27 and 28 October (Fp\textsubscript{max} > 300). On the other hand, phase fluctuations were almost absent for three days from the evening on 31 October throughout the morning on 3 November, until the Fp\textsubscript{max} exceeded 200 in the per-midnight of 3 November and restored to its regular value on 4 November 2003. In this study, we define the first negative value of IMF Bz, beginning of the storm main phase, as the Bz southward turning, while the IMF Bz northward turning is defined by the recovering of southward Bz. Figure 5a illustrates that Fp\textsubscript{max} reached 400 during 17–26 November 2003 except in the evening of 20–21 November 2003, the period of an intense storm main phase (event B) (Figure 5b). Results of main storm events, A1, A2, and B, suggest that the intensity of the regular low latitude irregularity at Brazilian longitude sector in post-sunset hours can be significantly suppressed during storm periods.
**Figure 3.** The example of the long-term day-to-day variation in Fp at the Brazilian longitude sector during (a) the high irregularity activity season in years of 2003–2004, and (b) the low irregularity activity season in the year of 2000. In the top panels of Figures 3a and 3b, the dark curve (or spikes) is the hourly average of Fp, which was observed by the three ground-based GPS receivers. The Dst index was illustrated in the bottom panels of Figures 3a and 3b. Dark arrows indicate the storm-related irregularity suppression and triggering signatures.

**Figure 4.** The day-to-day variation in (a) Fp at the Brazilian longitude sector during the 2003 Halloween storm period, (b) the Dst index, and (c) IMF Bz. The vertical solid and dash lines in Figure 4c indicate the occurrence of the southward and northward turnings IMF Bz, respectively. The occurrence time of the southward and northward turnings of IMF Bz are 1100 and 1600 LT for the storm main phase event A1, respectively, and are 1500 and 1700 LT for the event A2.
In order to construct the overall/averaged picture of the storm-related suppression signatures, we accumulate and average the Fp index for 37 storm main phase events that occurred in the seven high irregularity activity seasons during 1 April 1998–31 October 2005 (Figure 6). Figure 6a displays that Fp maxima are about 200 during day −1 to −1 and 3 to 7, but prominently decrease to about 100 following the sharp decrease of the average Dst index (Figure 6b) in the night of day 0. In the second night after the storm onset (day 1), the Fp max gradually recovers to about 140, and approaches to 180 in the third night (day 2). Figure 6c illustrates that the IMF Bz is significantly perturbed in day 0–1 corresponding to the duration of the storm main phases in Figure 6b. It is known that the PP electric fields could nearly instantaneously penetrate into the low latitude ionosphere following the turnings of IMF Bz [e.g., Kelley et al., 1979], therefore, we further examine the possible relationship between the occurrence timing of the IMF Bz northward and southward turnings and the associated intensity of the low latitude irregularity in post-sunset hours during the high irregularity activity season.

Figure 7a shows the relationship between the occurring local time of the 37 IMF Bz southward turnings and the Fp max in the first evening after the turnings. It is clear seen from this figure that Fp max values are mainly smaller than the background value (Fp max = 185) when IMF Bz turns southward within 0000–1200 LT, but scatter all over 0–400 within 1500–0000 LT. If the Fp max is presumably less than 185 in the first evening after storm onset during high irregularity activity seasons, it indicates the irregularity being suppressed in the post-sunset hours. Fp max less than 100 indicates a stronger suppression. In order to statistically examine the local time dependence of the suppression signatures in various Fp levels, we count the events with 100 < Fp max ≤ 185 and Fp max < 100 in various local time intervals. The histograms show that the probabilities are about 13% (2/15), 32% (7/22), and 50% (6/12) for 100 < Fp max ≤ 185, when IMF Bz turns southward during 0000–1200, 1200–0000, and 1500–2100 LT, respectively (Figure 7b). For Fp max ≤ 100, they are about 80% (12/15), 45% (10/22), and 17% (2/12) during 0000–1200, 1200–0000, and 1500–2100 LT, respectively (Figure 7c). In Figure 7c, the high probability of Fp ≤ 100 during 0000–1200 LT suggests that the F region irregularities in the high seasons are suppressed efficiently. Note that the suppressions are more efficient when IMF Bz turns southward in the post-midnight and morning (0000–1200 LT) than those in the afternoon and pre-midnight (1200–0000 LT). On the other hand, it is interesting to find that the probabilities of Fp max ≤ 100 are higher than that of the background (23.3%) in most of the day, except during 1500–2100 LT (17%). In contrast, the probability of 100 < Fp max ≤ 185 is 50% (6/12) during 1500–2100 LT, much higher than the background probability (28.6%).

Figure 5. Same as Figure 4 but for the 20 November 2003 geomagnetic storm. In Figure 5c the southward and northward turnings of IMF Bz occurred at 0900 and 1300 LT, respectively.

The occurrence of 37 IMF Bz northward turning events in various local time intervals and the Fp max in the first following evening are examined (Figure 8). Figure 8b displays that the probabilities of 100 < Fp max ≤ 185 are
about 15% (3/20), 29% (5/17), and 25% (3/12) when IMF Bz turns northward during 0000–1200, 1200–0000, and 1500–2100 LT, respectively. It can be seen that the whole day probabilities are close to the background (23.3%), except during 0600–1200 and 1800–0000 LT. Figure 8c displays that the probability of Fp\textsubscript{max} \leq 100 is greatest during 0600–1800 LT (79% (15/19)), but it is close to the background one (28.6%) during 1800–0000 LT (25% (2/8)).

5. Triggering Signatures in Low Irregularity Activity Seasons

The storm-related triggering signatures can be observed much easier in the low irregularity activity season than in the high irregularity activity season, since the probability for Fp\textsubscript{max} exceeding the background level (Fp = 50) is as small as 2.6%. After the storm onset in the afternoon of 6 April 2000 (event C) (Figure 9b), the strong (Fp > 200) and moderate (Fp > 100) irregularities are recorded in the pre-midnight of 6 April and the early morning of 7 April (Figure 9a). The similar pattern can also be observed during the Bastille Day storm of 15 July 2000 (event D) (Figure 10). In Figure 10a, Fp exceeded the background level (Fp = 50) in the post-sunset hours following the sudden drop of the Dst index in the afternoon of 15 July (Figure 10b). It is interesting to find that the storm associated Fp increase is only seen during the first main phase (event E1) of the two-step 10 August 2000 storm. Figure 11 shows that the Fp suddenly increased from the background level to 100, reduced to 70 and remained till the morning of 11 August (Figure 11a). However, no obvious irregularities were observed during the second main phase (event E2) on 12 August.

Figure 12 displays the Fp values, Dst indices, and IMF Bz and their averaged values seven days before/after the 35 storm main phase events in the eight low irregularity seasons. Figure 12a illustrates that the averaged Fp is about 20 and no clear and complete development of irregularities can be observed in post-sunset hours, except in the first night (0–1 day) after the storm main phase onsets. Following the drop of the average Dst index (Figure 12b), the averaged Fp reaches 40 in the pre-midnight, declines to about 30 shortly after that, and lasts until the pre-sunrise hours (Figure 12a). Figure 12c shows that IMF Bz mainly perturb during 0–1 day of storm main phases. We further examined the possible relationship between the occurrence time of the IMF Bz southward and northward turnings and the Fp\textsubscript{max} during the low irregularity season using the similar statistical analysis applied in Figures 7 and 8.

If the Fp\textsubscript{max} is greater than the background level (Fp = 50) in the low irregularity activity season, it might be
the triggering signature of the low latitude $F$ region irregularity in post-sunset hours. Figure 13a is a scatterplot of the occurrence time of the 35 IMF Bz southward turnings and the $F_{\text{pmax}}$ in the first following evening. It shows that almost all the $F_{\text{pmax}}$ values are less than 50, except those following the southward turnings of Bz occurred at 0900 and 1300–1900 LT. In Figure 13b, the histogram shows that probabilities of $F_{\text{pmax}} > 50$ are only 8% (1/13) and 10% (1/10) when IMF Bz turns southward during 0000–1200 and 1800–0000 LT, respectively. However, probabilities are about 33% (4/12) and 40% (4/10) when it turns southward during 1200–1800 and 1500–2100 LT, respectively. Figure 14a shows a scatterplot for the 35 IMF Bz northward turning events. It can be found that almost all $F_{\text{pmax}}$ values are less than 50, except for northward turnings of Bz occurred at 1200 and 1700–2000 LT. In Figure 14b, the probabilities of $F_{\text{pmax}} > 50$ are 0% (0/14) and 18% (2/11) when IMF Bz turns northward during 0000–1200 and 1200–1800 LT, respectively. But it increases greatly to 50% (5/10) during 1500–2100 LT, and slightly decreases to 40% (4/10) during 1800–0000 LT. It seems that IMF Bz northward turnings tend to trigger irregularities when they occurred around the sunset and pre-midnight (Figure 14b). However, IMF Bz southward turnings tend to trigger irregularities when they occurred in the afternoon and around the sunset (Figure 13b). There is an about 3–6 h time difference between them.

6. Discussion

Figure 7c shows that, in the high irregularity activity season, low latitude $F$ region irregularities at the Brazilian longitude sector in post-sunset hours are prominently suppressed when IMF Bz turns southward during 0000–1200 LT, which is about 6 h ahead of the sunset. This might be due to the long-lasting DD effect which requires a few hours to set up disturbance winds because of inertia of the neutral air [Richmond et al., 2003]. The sudden decrease in the probability of $F_{\text{pmax}} \leq 100$ during 1800–0000 LT might result from the same reason, as it seems to be difficult to immediately affect the low latitude ionosphere in post-sunset hours if IMF Bz turns southward during 1800–0000 LT. The DD effect on the low latitude irregularity can also be found from the individual storm main phase events. The one day suppression of irregularities in the first evening of the November 2003 storm is consistent with the ionosonde and GPS observations of Becker-Guedes et al. [2007] over southern America, which illustrated that the h′F showed considerable reduction in the post-sunset pre-reversal enhancement (PRE) period, and no equatorial spread F (ESF)
Figure 8. Same as Figure 7 but for IMB Bz northward turnings.

Figure 9. Same as Figure 4 but for the 6 April 2000 magnetic storm. In Figure 9c IMF Bz turns southward and northward at about 1300 and 1800 LT, respectively.
Figure 10. Same as Figure 4 but for the Bastille Day storm on 15 July 2000. In Figure 10c IMF Bz turns southward around 1500 LT and turned northward at 1700 LT.

Figure 11. Same as Figure 4 but for the magnetic storm on 10 August 2000. In Figure 11c the southward and northward turnings of IMF Bz of the main phase event E1 (E2) occur at 1600 (0200) and 1900 (0300) LT of the afternoon (post-midnight) period on 10 (12) August, respectively.
was observed during the early night of 20–21 November 2003. The behavior of post-sunset irregularities in the Brazilian longitude sector during the 2003 Halloween storm has also been interpreted by numerous studies [e.g., Abdu et al., 2008; Sahai et al., 2009a, and references therein]. Most of these studies presented two night absences of irregularities, corresponding to the two main phase steps of the 2003 Halloween storm. Additionally, Figure 4a shows that the attenuation of irregularities can further extend to the night of 3 November, five days after the storm onset. The theoretical study of several days lasting of DD effect has been carried out by TIEGCM simulation. Huang et al. [2005] presented that after intense geomagnetic activity ceases, the zonal disturbance winds can last for many days in the post-recovery period, while the meridional disturbance winds decay more rapidly. The additional 3-day suppression for the 2003 Halloween storm might result from the similar effect reported by Huang et al. [2005]. It is worthwhile to note that the meridional component of the storm-generated disturbance wind could be another way to effect the irregularity development. A transequatorial thermospheric wind may modify the field line integrated conductivities, and further control the growth of the bubble irregularity by the Rayleigh-Taylor instability mechanism [e.g., Maruyama and Matuura, 1984; Maruyama, 1988; Mendillo et al., 1992; Abdu et al., 2006; Maruyama et al., 2009]. Nevertheless, Mendillo et al. [2001] suggested that the electrodynamical process is the dominant driver for the onset and growth of the irregularities at low latitude.

[15] On the other hand, the lowest probability of $F_{p_{\text{max}}} \leq 100$ in Figure 7c and the highest probability of $100 < F_{p_{\text{max}}} \leq 185$ (Figure 7b) occurred when IMF Bz turns southward during 1500–2100 LT might be associated with the under-shielding PP electric field. As Bz turns suddenly southward, the high latitude convection electric field penetrates nearly instantaneously into the low latitude ionosphere (under-shielding condition), and creates the eastward penetration electric field during the day whereas the westward field during the night [e.g., Spiro et al., 1988; Fejer et al., 2008]. The under-shielding PP electric field, directed eastward at the time of the PRE, can significantly enhance the equatorial F layer vertical uplift and the instability growth leading to bubble development [e.g., Abdu et al., 2003; Martinis et al., 2005].

[16] By contrast, the over-shielding PP electric field with the polarity opposite to that of the under-shielding condition could immediately influence the low latitude ionosphere when IMF Bz turns northward [e.g., Kelley et al., 1979;
Kikuchi et al., 2008]. A westward over-shielding PP electric field can suppress the PRE or even produces a net downward drift and stabilize the layer [Abdu et al., 2009]. Abdu et al. [2009] first noted that the over-shielding PP electric field could suppress irregularities if it occurs several hours before the dusk. However, in Figure 8c, although irregularities are prominently suppressed during 1200–1800 LT, we cannot identify if it is due to the over-shielding PP electric field effect, because a similar probability of the suppression can also be found at earlier local times during 0600–1200 LT. In other words, even though the over-shielding PP effects are indeed existed, it may also mingle with the long-lasting DD effect [e.g., Reddy and Nishida, 1992]. It has already been shown that the storm time disturbed equatorial zonal electric fields sourced from the PP and DD could be separated out in model simulations [Fejer and Scherliess, 1995; Maruyama et al., 2011]. However, it is still a challenge for clear indentifying the response of low latitude F region irregularities to the disturbed equatorial zonal electrics fields from the DD and PP over-shielding condition when they mixed together in both the pre- and post-midnight hours.

[17] In low irregularity activity seasons, F region irregularities over the low latitude Brazilian longitude sector in post-sunset hours can be significantly triggered if IMF Bz southward turnings close to the sunset (1500–2100 LT) (Figures 13b), which is similar to the pattern in the high irregularity activity season (Figure 7b). It suggests that the irregularities can be triggered if IMF Bz southward turnings close to the sunset in both high and low irregularity seasons. The triggering signature is less prominent in high irregularity activity seasons, since the general Fp has a larger value and variation during 2000–2300 LT. The results of the individual storm main phase events confirm the statistic results. The IMF Bz turnings in events C, D, and E1 occurred in the afternoon are accompanied by the irregularities triggered in the post-sunset hours. However, IMF Bz of the storm main phase event E2 turns southward in the early morning, and no clear irregularities presented.

[18] The high probabilities patterns for the southward turnings of IMF Bz (Figure 13b) appear 3–6 h before those for northward turnings. One of the possible reasons is the time difference between the onsets of southward and northward turnings of IMF Bz. The time differences between the IMF Bz southward and northward turnings are about 5, 2, 3, and 1 h for the storm main phase events C, D, E1, and E2, respectively. The median value of the time difference between the Bz southward and northward turnings, derived from the periods of the 35 storm main phase events in the low irregularity season, is 4 h. In other words, if IMF Bz recovers from southward to northward around the sunset, the Bz southward turnings have a great chance to occur in the afternoon. Therefore, the highest probability around 1500–
2100 LT might be the triggering signature of IMF Bz southward turnings in the afternoon. On the other hand, Figure 14b shows that the IMF Bz northward turnings tend to trigger irregularities in pre-midnight hours, which might be due to uplift of the ionosphere by the eastward perturbed electric field resulting from the over-shielding PP electric field in the nighttime low latitude ionosphere [Spiro et al., 1988].

7. Conclusion

In this paper, we statistically examined the TEC phase fluctuation at the Brazilian longitude sector during a 7.5-year period of 1 April 1998–31 October 2005 to find out the overall pattern of low latitude F region irregularities response to intense geomagnetic storms in post-sunset hours. Results show that geomagnetic storms can significantly affect the intensity of low latitude F region irregularities during post-sunset hours in both of low and high irregularity activity seasons. Storm-effected irregularity suppression signatures are obvious in the high irregularity activity season, and the triggering signatures can be observed in both the low and high irregularity activity seasons. In the high irregularity activity season, the suppression effect is most obviously seen in the first evening after storm onsets, and gradually reduces with time, which might be a consequence of the long-lasting DD effect. In the first day of storm main phases onsets, there is 80% probability that irregularities can be significantly suppressed (FPmax ≤ 100) in post-sunset hours when IMF Bz turns southward during 0000–1200 LT. However, we cannot find a clear IMF Bz northward turning-related suppression signature, probably due to the mix up of DD and PP over-shielding electric fields. In the low irregularity activity season, significant triggering signatures can only be found in the first night following storm main phase onsets. There are about 30–40% probabilities irregularities can be triggered (FPmax > 50) in the post-sunset hours when IMF Bz turns southward in the afternoon and around the sunset. On the other hand, there are about 40–50% probabilities irregularities can be triggered in the post-sunset hours when IMF Bz turns northward around the sunset and in the pre-midnight.

Acknowledgments. Yang-Yi Sun would like to thank N. Maruyama at NOAA/SWPC for fruitful discussions and useful comments on this study. This research is supported by the NSC project (NSC 98-2111-M-008-008-MY3) granted to National Central University.

Robert Lysak thanks the reviewers for their assistance in evaluating this paper.

References


Chu, C. H., J. Y. Liu, and Y. Y. Sun, Institute of Space Science, National Central University, Tainan 701, Taiwan.

Chu, C. H., J. Y. Liu and Y. Y. Sun, Institute of Space Science, National Central University, Jhongli 32010, Taiwan. (tigerlyliu@gmail.com)