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Prestorm enhancements in NmF_2 and total electron content at low latitudes

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[1] The enhancement of electron concentrations in the ionosphere before geomagnetic storms is one of the open questions. Using ionosonde observations and total electron content (TEC) from Global Positioning System (GPS) measurements along longitude 120°E, we analyzed three low latitude pre-storm enhancement events that occurred on 21 April (day 111) 2001, 29 May (day 149) 2003, and 22 September (day 265) 2001, respectively, in the Asia/Australia sector. All three events (and other two cases on 9 August 2000 and 10 May 2002) show quite similar features. The strong prestorm enhancements during these events are simultaneously presented in foF_2 and TEC and enhancements have latitudinal dependence, tending to occur at low latitudes with maxima near the northern and southern equatorial ionization anomaly (EIA) crests and depletions in the equatorial region. This is quite different from what reported by Burešová and Laštovička (2007) for middle latitudes. They found no systemic latitudinal dependence in prestorm enhancements over Europe. It is argued that solar flares are not the main drivers for the enhancements, at least for low-latitude events. Main features of low-latitude prestorm enhancements do not coincide with the solar flare effects. We postulate that the vertical plasma drift or zonal electric field is a likely cause for the low-latitude prestorm enhancements. Its existence is supported by the facts of stronger EIA, the latitudinal coverage of the enhancements as well as the lift of the F layer peak height at an equatorward station during the prestorm enhancements. Moreover, the behaviors of hmF_2 at low latitudes during the prestorm enhancements may possibly be explained in terms of the coupling nature of parallel and perpendicular dynamics at low latitudes (see, e.g., Behnke and Harper, 1973; Rishbeth et al., 1978).

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1. Introduction

[2] During geomagnetic storms, enhanced solar winds, and/or southward interplanetary magnetic fields induce large and global dramatic disturbances of the geospace environment, driving the magnetosphere, thermosphere, and ionosphere strongly deviated from their normal levels. The disturbed ionosphere is manifested as huge increases and/or depletions of electron concentrations relative to normal level. This considerably disturbed behavior of the ionosphere is commonly called as an ionospheric storm. Over decades it has received extensive studies on the description and prediction of the features of the ionospheric storms [e.g., *Araujo-Pradere et al.*, 2004; *Buonsanto*, 1999; *Kane*, 1973; *Kutiev and Muhtarov*, 2001; *Lin et al.*, 2005; *Liu et al.*, 2004] and on understanding of the related processes [e.g., *Fejer*, 2002; *Prolss*, 1995]. At the same time the neutral compositions and circulations also exhibit significant disturbances in association with the increased dissipation of solar wind energy. The coupling nature of the thermosphere-ionosphere system makes the situation even more complicated. Many excellent research articles and reviews on this topic have been published [e.g., *Buonsanto*, 1999; *Danilov*, 2001; *Fejer*, 2002; *Mendillo*, 2006; *Prolss*, 1995], although many properties of the ionospheric disturbances still remain poorly understood due to the complexity of this phenomenon.

[3] There is another intriguing feature in the ionosphere; that is, compared to the background level, in some cases the electron density is greatly enhanced for some hours, even up to a day, prior to the onset of geomagnetic disturbances. Their amplitudes are comparable to the F_2-layer storm effects. This peculiar feature is termed the prestorm enhancement by *Burešová and Laštovička* [2007] or a positive phase before the beginning of a geomagnetic storm by *Danilov* [2001] and *Kane* [1973]. Typical examples of the prestorm enhancement in the maximum electron density (NmF_2) or the critical frequency (foF_2) of the F_2 layer can be found at Chilton (358.7°E, 51.6°N) on 28 October 2003 [*Burešová and Laštovička*, 2007] and at Murmansk on 1 March 1981 [*Danilov*, 2001]. Early works have reported

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Table 1. List of Ionosonde Stations

Name of Stations	Geographic Longitude	Geographic Latitude	Geomagnetic Latitude
Wakkanai	141.7°E	45.4°N	35.8°N
Kokubunji	139.5°E	35.7°N	25.9°N
Wuhan	114.4°E	30.6°N	19.5°N
Okinawa	127.8°E	26.3°N	15.8°N

such pre-storm anomalies. For example, *Kane* [1973] found strong positive effects in foF_2 before the main phase onset (MPO) or storm sudden commencement (SSC) at Ibadan, Kokubunji, and Akita. *Kane* [2005] and *Blagoveshchensky et al.* [2006] also found such prestorm anomalies on 28 October 2003. Unfortunately, it attracted little attention and has been studied much less than the storm-time behavior of the F_2 region. Up to now, we are still lacking of information on the characteristics of this phenomenon and the mechanism responsible for its happening. As a result, the appearance of the prestorm enhancement is listed as one of the unsolved problems by *Danilov* [2001]. Recently, *Burešová and Laštovička* [2007] analyzed the occurrence of the prestorm enhancements in NmF_2 at middle latitudes over Europe and found that about 20–25% of strong storms are accompanied by sufficiently strong prestorm enhancements.

[4] It is known that many ionospheric parameters have a high variability [e.g., *Fejer*, 2002; *Forbes et al.*, 2000; *Laštovička and Šauli*, 1999; *Xiong et al.*, 2006]. One of such variabilities is the large day-to-day changes of the ionosphere even under quiet geomagnetic conditions. There exists a large class of disturbances that are not directly due to geomagnetic activity but have their origin in the atmosphere itself [e.g., *Blagoveshchensky et al.*, 2006; *Laštovička and Šauli*, 1999; *Mikhailov et al.*, 2004, 2007a, 2007b]. Effects of atmospheric waves on the ionosphere were recently

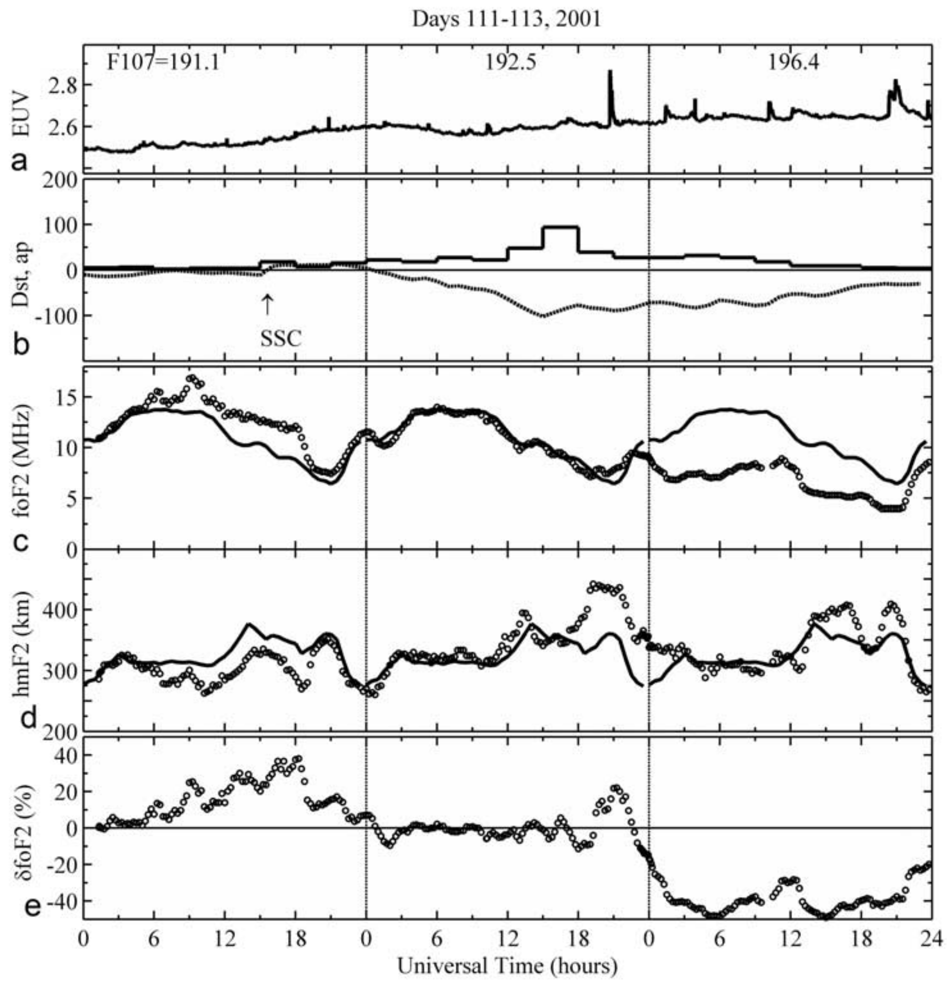

Figure 1. (a) The 15-s averaged SOHO/SEM EUV fluxes (in unit of 10^{10} photons cm^{-2} s^{-1}) at 26–34 nm wavelength band; (b) *Dst* and 3-hourly *ap* geomagnetic indices; (c) the critical frequency of the F_2-layer, foF_2; (d) its height, hmF_2; and (e) the percentage change of foF_2, δfoF_2 (= (foF_2−foF_{2m})/foF_{2m}), over Wuhan during 21–23 April (days 111–113) 2001. Circle points in Figures 1c and 1d show observed values and the solid curves for the median values foF_{2m}, which are evaluated from the 31-d observations centered on 21 April 2001. Here the arrow with SSC in Figure 1b denotes the onset time of the sudden storm commencement (SSC).

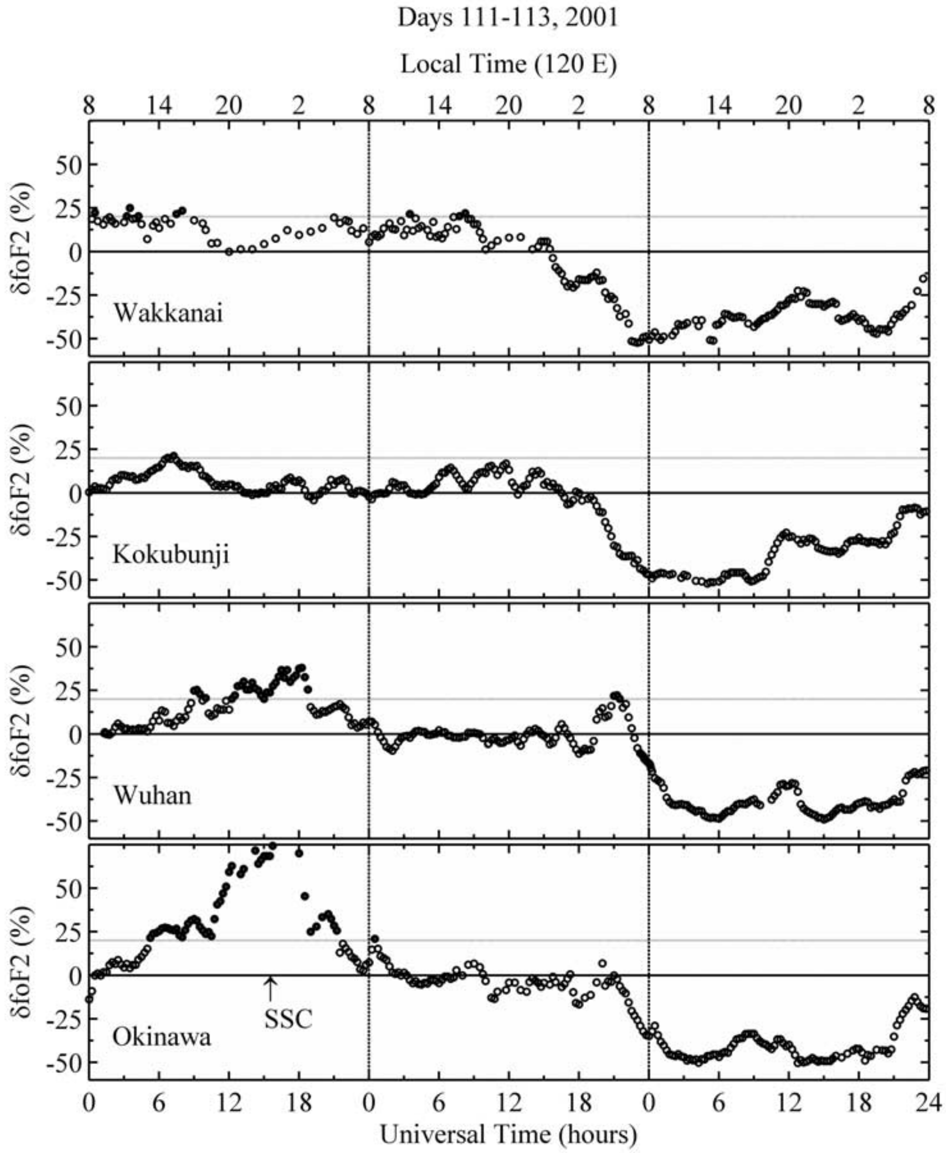

Figure 2. Percentage relative deviations of foF_2, δfoF_2 (=(foF_2−foF_{2m})/foF_{2m}), over Wakkanai, Kokubunji, Wuhan, and Okinawa during 21–23 April (days 111–113) 2001. Here foF_{2m} is the median value of foF_2. Solid circle indicates δfoF_2 > 20%. The arrow with SSC at the bottom denotes the onset time of the sudden storm commencement (SSC).

reviewed by *Laštovička* [2006]. *Mikhailov et al.* [2004] analyzed the morphology of both positive and negative quiet-time F_2-layer disturbances (Q-disturbances). Moreover, *Kutiev et al.* [2006, 2007] analyzed the total electron content (TEC) enhancements occurring outside initial and main phases of geomagnetic storms. They speculated that these poststorm structures are produced mainly by disturbance dynamo electric fields, built up after the main phase of the storms; some events appearing at the end of a prolonged period of low geomagnetic activity can be linked to directly penetrating interplanetary electric field in the equatorial ionosphere. The prestorm enhancements might be a subgroup of such Q-disturbances [*Burešová and Laštovička*, 2007]. Therefore the study on the prestorm enhancement of the ionosphere will have potential applications in the predictions of ionospheric weather and improve our understanding of the ionosphere, especially for the physical processes of the ionospheric storms and the day-to-day variability of the ionosphere.

[5] In this paper, we will investigate this prestorm enhancement phenomenon at low latitudes in the Asia/Australia sector by utilizing ionosonde data from Wakkanai (141.7°E, 45.4°N), Kokubunji (139.5°E, 35.7°N), and Okinawa (127.8°E, 26.3°N) of Japan and Wuhan (114.4°E, 30.6°N) of China, and TEC from the global positioning system (GPS). The global GPS measurements make it possible to determine the latitudinal extent as well as their evolution of the prestorm enhancement events. This study will focus on investigating the low-latitude feature and the latitudinal distribution of the prestorm enhancements. We will also

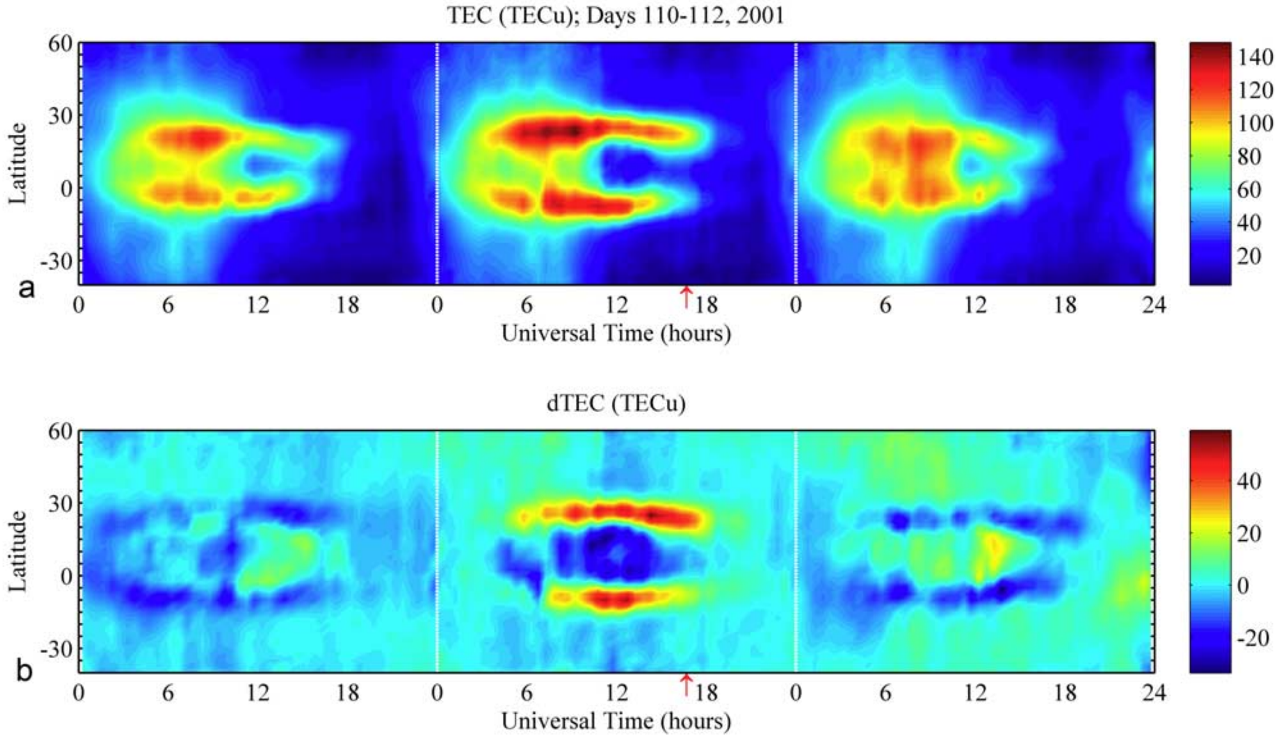

Figure 3. (top) TEC and (bottom) the deviations of TEC (dTEC) from the median values along the 120°E during 20–22 April (days 110–112) 2001. Here the red arrows denote the onset time of the sudden storm commencement (SSC). The median values are evaluated from the 31-d observations centered on 21 April 2001.

compare the features of the low-latitude prestorm enhancements with those of middle latitudes as reported by *Burešová and Laštovička* [2007].

2. Data Source

[6] We will present three prestorm enhancement events that occurred at low latitudes in the Asia/Australia sector on 21 April (day 111) 2001, 29 May (day 149) 2003, and 22 September (day 265) 2001, respectively. All three events we choose had clear main and recovery phases. To isolate possible direct effects of geomagnetic storms, we select these events with quiet geomagnetic activity on some previous days and preceding a strong storm.

[7] The ionosonde data used for the present study were provided from Institute of Geology and Geophysics of Chinese Academy of Sciences and the Web site of National Institute of Information and Communications Technology of Japan. Table 1 lists the information on the ionosonde stations used for this analysis. The ionospheric total electron content (TEC) is derived from Global Positioning System (GPS) receivers along longitude 120°E in the Asia/Australia sector.

[8] The sudden storm commencement (SSC) is often served as a reference time for the onset of a magnetic storm. The reliability of SSC for the storm onset has been argued for a long time. As a result, some investigators choose the main phase onset of the storm instead of SSC as the start time of a storm [e.g., *Prolss*, 1995]. Here we use SSC to indicate the onset of a magnetic storm for storms with a sudden commencement, except for the MPO for the 22 September (day 265) 2001 event because it only had a gradual commencement. The *Dst* index is used to indicate the evolution and intensity of geomagnetic storms.

3. Results

3.1. Event of 21 April (Day 111) 2001

[9] The first prestorm enhancement event considered occurred about 10 h before the 1601 UT SSC on 21 April (day 111) 2001. After the SSC the *Dst* index reached a maximum depression of -102 nT at 1700 UT on 22 April and then recovered. Figure 1 shows the SOHO/SEM EUV fluxes (in unit of 10^{10} photons $\cdot$ cm^{-2} $\cdot$ s^{-1}) at the 26–34 nm wavelength band [*Judge et al.*, 1998] (Figure 1a), *Dst* and *ap* geomagnetic indices (Figure 1b), foF_2 (Figure 1c), hmF_2 (the peak height of the F_2 layer) (Figure 1d), and the percentage deviations of foF_2 (δfoF_2 = (fo$F_2$$-foF_{2\mathrm{m}}$)/fo$F_{2\mathrm{m}}$) (Figure 1e) over Wuhan during 21–23 April 2001. Circle points in Figures 1c and 1d show observed values and the solid curves for the median values fo$F_{2\mathrm{m}}$, which are evaluated from the 31-d observations centered on 21 April 2001.

[10] The prestorm enhancements are described in terms of percentage deviations of foF_2 (δfoF_2) from the reference level. When the maximum value of δfoF_2 exceeds 20%, a prestorm enhancement event occurred, according to the definition of *Burešová and Laštovička* [2007]. As seen in Figure 1, a large positive deviation, δfo$F_2 > 0$ appeared on 21 April (day 111) before the SSC above Wuhan, accom-

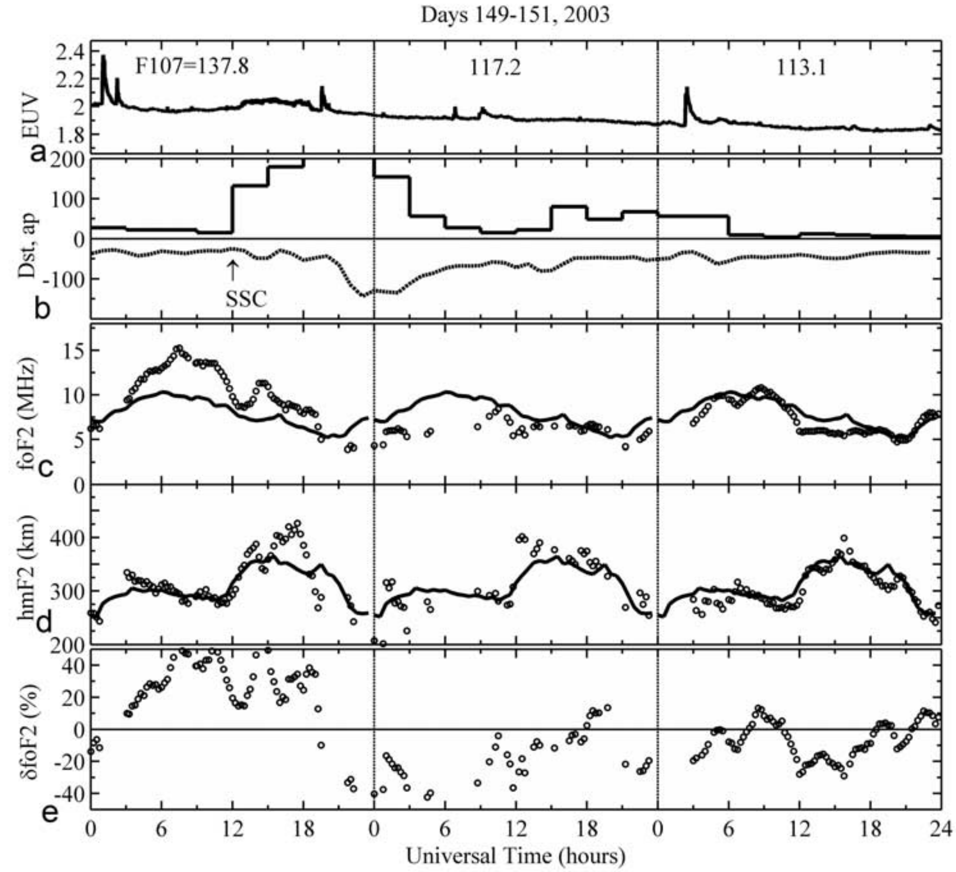

Figure 4. Same as Figure 1 but for 29–31 May (days 149–151) 2003. The median values are evaluated from the 31-d observations centered on 29 May 2003.

panying a lower hmF_2 compared to the reference level. In contrast, over Wuhan foF_2 was a great negative phase during the recovery phase on 23 April, while hmF_2 increased above its reference values during the main and recovery phases of the 22–23 April 2001 storm. From the evolution of SOHO/SEM EUV fluxes (Figure 1a), no strong solar flare event was present during this period. Therefore this prestorm enhancement is a flare-free event.

[11] Figure 2 illustrates the percentage deviations of foF_2, δfoF_2, over Wakkanai, Kokubunji, Wuhan, and Okinawa during 21–23 April (days 111–113), 2001. Positive δfoF_2 (>70%) occurred earlier over Okinawa and was stronger than that over Wuhan. Shortly after δfoF_2 at Okinawa approached the prestorm enhancement level, δfoF_2 at Kokubunji just had a weak positive peak. Note that the behavior of δfoF_2 at Wakkanai is quite different from that of the other three stations. The δfoF_2 at Wakkanai took positive values (around 20%) much earlier than at the other three stations, but it began to drop to the normal state at Wakkanai when the enhancement was developing at other three stations. The observation that the negative phase is observed first at Wakkanai and then propagates to lower latitudes is just what is expected as a consequence of equatorward propagation of neutral composition disturbance from auroral oval [*Prolss*, 1995]. The storm-time behavior at low latitudes in the Japanese sector during this storm has been studied in detail by *Kutiev et al.* [2006].

[12] To show the latitudinal coverage of the prestorm enhancement, GPS TEC along longitude 120°E during 20–22 April (days 110–112) 2001 are plotted in Figure 3a, while the absolute deviations of TEC (ΔTEC) are illustrated in Figure 3b. As can be seen in Figure 3, the equatorial ionization anomaly (EIA) is well developed on 21 April (day 111) 2001. As a result, the values of ΔTEC were enhanced around the northern and southern crests and depleted in the equatorial region on that day. The appearance of the TEC enhancements started before local noon and disappeared at 0200 LT on the second day. The greatest amplitudes are confined at the EIA crest latitudes in the northern and southern hemispheres. The latitudinal coverage of the enhanced ΔTEC is consistent with that of foF_2 shown in Figure 2; that is, the strongest positive δfoF2 appeared at Okinawa.

3.2. Event of 29 May (Day 149) 2003

[13] Figure 4 shows the SOHO/SEM 26–34 nm EUV fluxes (Figure 4a), *Dst* and *ap* indices (Figure 4b), foF_2 (Figure 4c), hmF_2 (Figure 4d), and δfoF_2 (Figure 4e) over Wuhan for 29–31 May (days 149–151) 2003. As shown in Figure 4, the SSC occurred at 1224 UT on 29 May (day 149) 2003. After the SSC, the *Dst* index reached a maximum depression of −144 nT at 23 UT on 29 May 2003 and then recovered.

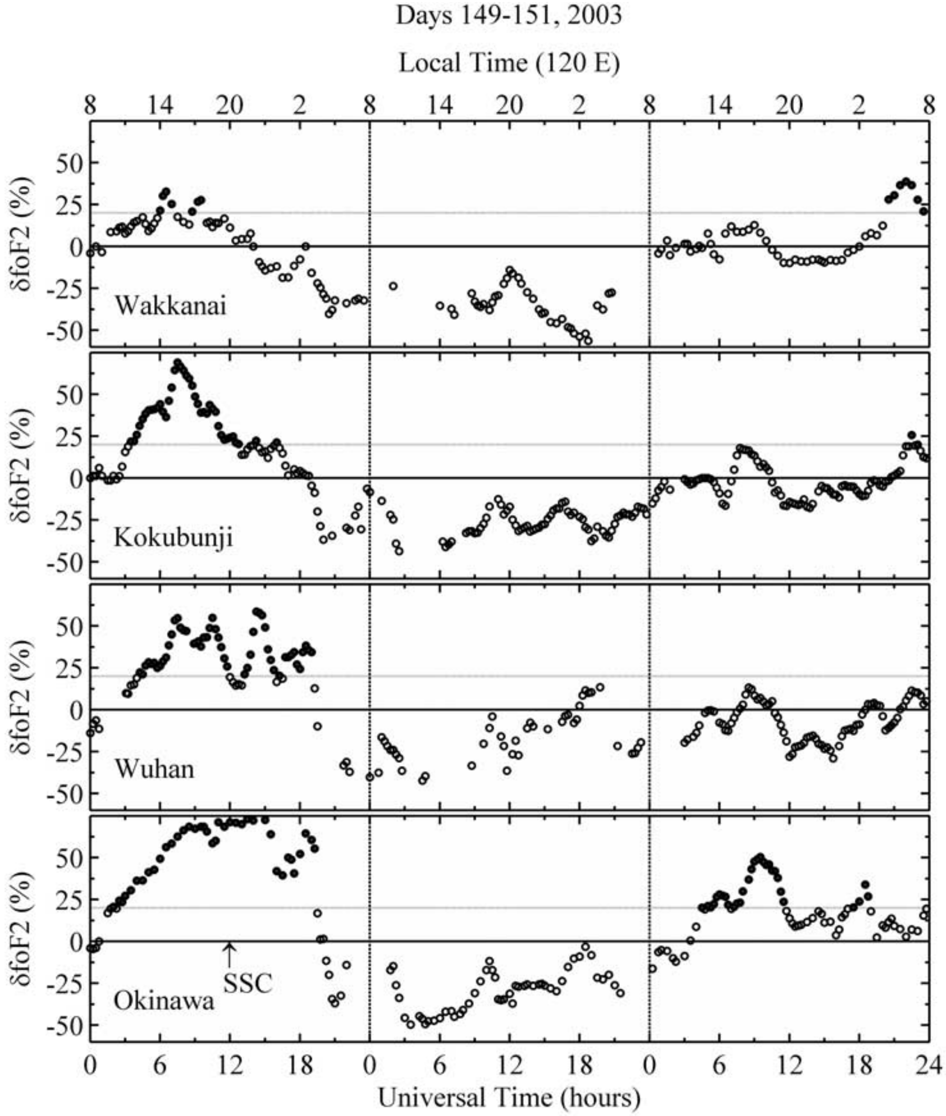

Figure 5. Same as Figure 2 but for 29–31 May (days 149–151) 2003. The median values are evaluated from the 31-d observations centered on 29 May 2003.

[14] The 29 May 2003 event is a strong prestorm enhancement event, which started at Wuhan (see Figure 4) about 8 h and at Okinawa (see Figure 5) 10 h previous to the SSC. Note that at Wuhan a positive δfoF_2 (higher than 50%) appeared on 29 May, while hmF_2 was comparable to the reference level. In contrast, during the main and recovery phases (29–30 May), over Wuhan foF_2 again was a strong negative phase. After SSC, hmF_2 became higher than its reference values.

[15] Figure 5 illustrates δfoF_2 over Wakkanai, Kokubunji, Wuhan, and Okinawa during 29–31 May 2003. On 29 May, positive δfoF_2 over Okinawa occurred earliest and lasted longest with the maximum amplitudes of δfoF_2 about 70%. The maximum value of δfoF_2 at Wakkanai is the smallest (around 30%). Accompanying the SSC, a remarkable negative phase in foF_2 first appeared at Wakkanai, and then propagated equatorward at the end of 29 May, which lasted for the whole day of 30 May.

[16] GPS TEC and ΔTEC along longitude 120°E during 29–31 May (days 148–150) 2003 are plotted in Figure 6, top and bottom. As seen in Figure 6, the EIA had the strongest amplitude on 30 May (day 149) 2003. As a result, the values of ΔTEC again were enhanced around the northern and southern crests on that day. The latitudinal coverage of the enhanced ΔTEC is also consistent with that of foF_2 shown in Figure 5; that is, the strongest positive δfoF_2 appeared at Okinawa.

[17] The evolution of the SOHO/SEM 26–34 nm EUV flux (Figure 4a) indicates that, just before the enhancement in foF_2 over Wuhan, there was an X1.2 flare and an M1.5 flare occurred on 29 May 2003. The X1.2 flare started at 0051 UT, reached its maximum at 0105 UT, and ended at 0112 UT; while the M1.5 flare started at 0209 UT, and reached its maximum at 0218 UT, and ended at 0224 UT. Therefore this enhancement event is occurred just after solar flares; with respect to free electron lifetime, only the first

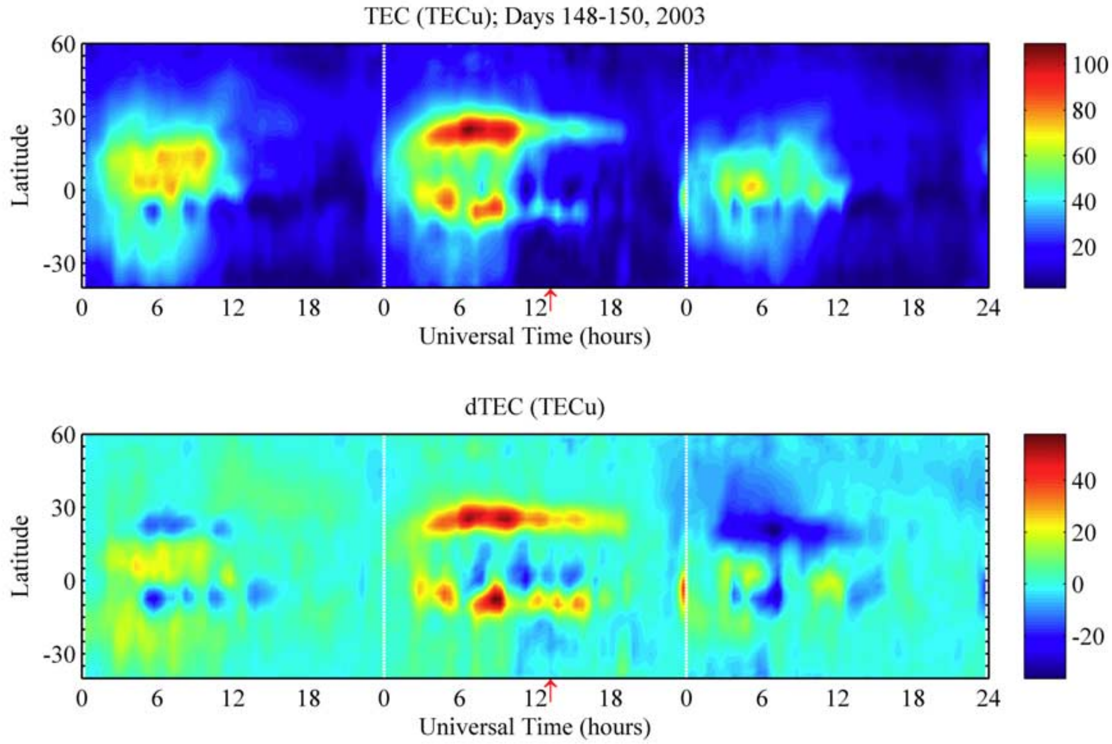

Figure 6. Same as Figure 3 but for 28–30 May (days 148–150) 2003. The median values are evaluated from the 31-d observations centered on 29 May 2003.

part but not the maximum of the prestorm enhancement can be influenced by solar flares.

3.3. Event of 22 September (Day 265) 2001

[18] Figure 7 shows the SOHO/SEM 26–34 nm EUV fluxes (Figure 7a), Dst and ap indices (Figure 7b), foF_2 (Figure 7c), hmF_2 (Figure 7d), and δfoF_2 (Figure 7e) over Wuhan for 22–24 September (days 265–267) 2001. A geomagnetic storm occurred on 23 September (day 266) with a maximum depression of −77 nT at 1900 UT on 23 September. This storm had no SSC, so the MPO is used to indicate the start of the storm. The intensity of the SOHO/SEM 26–34 nm EUV flux (Figure 7a) was quite stable before and during the enhancement event. Hence this enhancement case is a flare-free event.

[19] The 22 September 2001 event also is a strong prestorm enhancement event. As seen in Figures 7 and 8, on 22 September, positive δfoF_2 was first developed over Okinawa around 0600 UT, then that at Wuhan increased to more than 20% around 0900 UT. Moreover, hmF_2 over Wuhan was below the reference level by 30 km just before the enhancement developing at Okinawa. After lasting for 3 h, hmF_2 at Wuhan returned to the reference level. Then δfoF_2 decreased, with values below the threshold level over Okinawa and still higher than 20% at Wuhan. Around 1200 UT, δfoF_2 increased again at Wuhan and Okinawa. The maximum values of δfoF_2 first presented over Wuhan around 0900 UT and shifted to Okinawa around 1800 UT. In contrast, the value of δfoF_2 at Kokubunji was not up to the threshold level (20%). It is distinct that at Wakkanai foF_2 followed the reference values in this case (Figure 8).

[20] Figure 9 illustrates GPS TEC and ΔTEC along longitude 120°E during 22–24 September (days 265–267) 2001. The contour of TEC shows that the EIA on 22 September was stronger and the crests in both hemispheres were expanded poleward, compared to previous days. As a result, the values of ΔTEC were enhanced around the northern and southern crests on that day while the depletion of ΔTEC was found in the equatorial region within two EIA crests.

4. Discussion

[21] *Burešová and Laštovička* [2007] reported the prestorm enhancements in NmF_2 over Europe. Those events occurred at middle latitudes. They found that the middle latitude enhancements tend to occur more often in summer and to be rather absent under high solar activity and do not exhibit a systematic latitudinal dependence.

[22] To investigate the characteristics of the prestorm enhancements at low latitudes, we have presented three prestorm enhancement events at low latitudes. Other two cases with similar features in the Asia/Australia sector are the 9 August 2000 and 10 May 2002 events (figures are not shown here). The main features of these events can be summarized as: (1) intense enhancements before the storm are simultaneously presented in foF_2 and TEC at low latitudes; (2) low latitudes enhancements exhibit a latitudinal dependence, tending to occur with peaks around latitudes of the EIA crests in the southern and northern hemispheres; (3) hmF_2 at Wuhan may be higher, below, or around the reference levels accompanying the foF_2 and

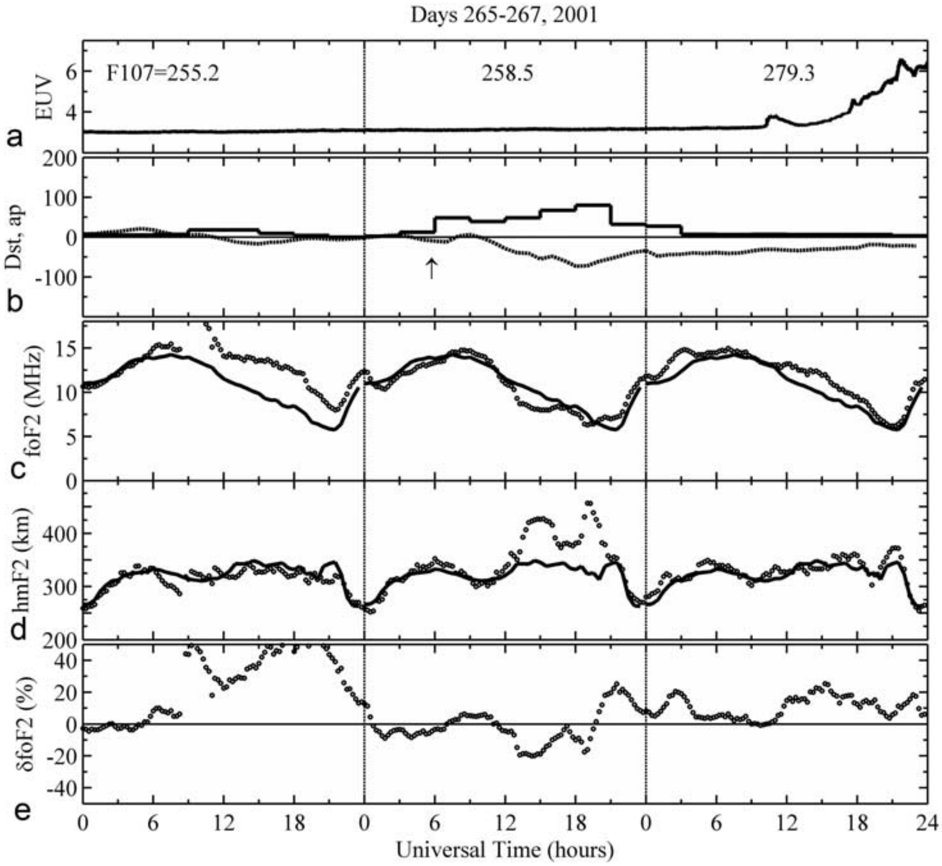

Figure 7. Same as Figure 1 but for 22–24 September (days 265–267) 2001. The median values are evaluated from the 31-d observations centered on 22 September 2001. There was no SSC during this storm.

TEC enhancements; and (4) solar flares are not the main drivers for the enhancements.

[23] When discussing the potential sources of the prestorm enhancements, *Burešová and Laštovička* [2007] excluded mechanisms related to solar flare, soft particle precipitation, and magnetospheric electric field, although its origin remained to be unclear. To add the complexity of this phenomenon, the present study reveals a different pattern at low latitudes compared to what reported by *Burešová and Laštovička* [2007] for middle latitudes. This discrepancy suggests that different physical mechanisms are responsible for the changes of the electron concentration at different latitudes and/or longitude sectors, which is worthwhile for further investigation.

[24] At low latitudes the most important parameters responsible for the F_2-layer ionization are solar EUV fluxes, neutral compositions and temperature, and dynamical processes including neutral winds as well as electrical fields. It is well known that the direct impact of solar flares on the Earth's ionosphere leads to sudden ionospheric disturbances which occur in the daytime. There was one event (29 May 2003) partly coinciding with solar flares. However, evidence clearly supports that solar EUV fluxes should not be responsible for the occurrence of the prestorm enhancements, at least not the dominant source. First, the solar flare effects should be expected to follow the control of the solar zenith angle [e.g., *Wan et al.*, 2005]. The largest TEC enhancement caused by solar flares occurs in the subsolar region. In contrast, the enhancements in foF_2 and TEC prior to geomagnetic storms are seen only around the northern and southern crests of EIA and depletion in the equatorial area. Thus the latitudinal coverage shown in Figures 3, 6, and 9 is not in agreement with that of solar flare effects. Second, solar flare effects are at daytime and generally last for less than 1 h, seldom taking hours [*Le et al.*, 2007; *Tsurutani et al.*, 2005], while the prestorm enhancements can occur at daytime and nighttime and last for many hours (even up to more than 15 h) before they return to the background levels. Finally, fluctuations in EUV fluxes during those events are not great enough to induce the observed δfoF_2, according to the investigation of *Liu et al.* [2006].

[25] In the case of the prestorm enhancements, the geomagnetic activity is low. There is still neither the depleted [O]/[N_2] nor storm circulations changes. In fact, we cannot detect remarkable changes in thermospheric [O]/[N_2] during 10 May 2002 and 29 May 2003 events from the observations of the Global Ultraviolet Imager (GUVI) onboard the NASA TIMED (Thermosphere, Ionosphere, Mesosphere Energetics, and Dynamics) satellite, which provides information on thermospheric [O]/[N_2] [*Strickland et al.*, 2004].

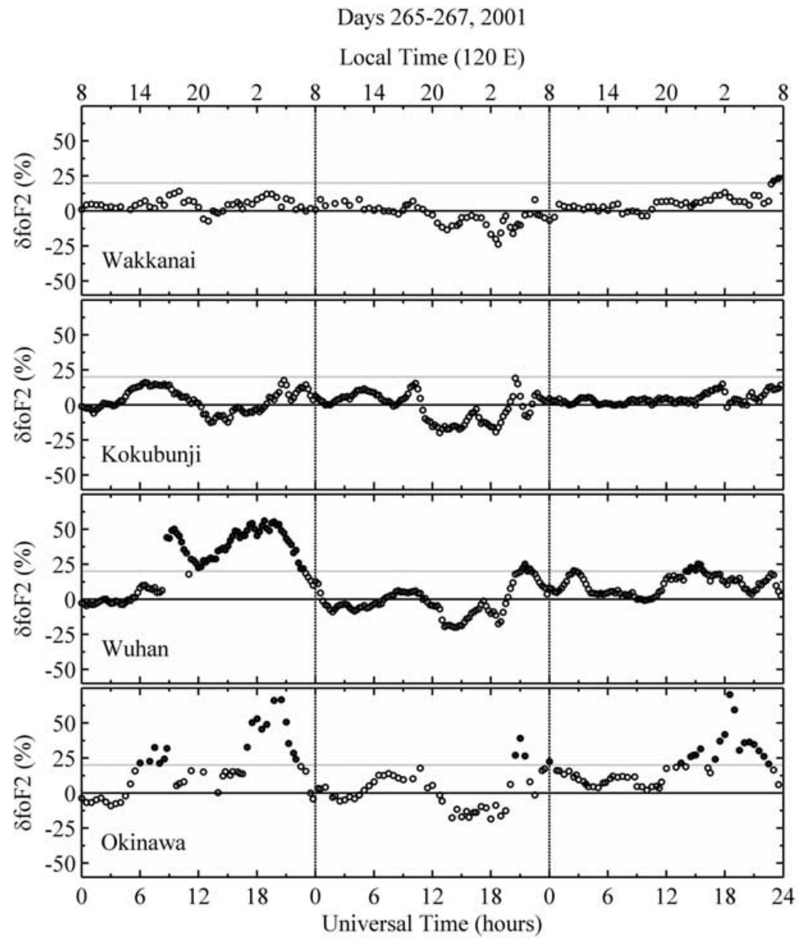

Figure 8. Same as Figure 2 but for 22–24 September (days 265–267) 2001. The median values are evaluated from the 31-d observations centered on 22 September 2001. There was no SSC during this storm.

[26] Strong electron density enhancements are frequently observed during geomagnetic storms [*Kelley et al.*, 2003; *Kutiev et al.*, 2006, 2007; *Lin et al.*, 2005; *Liu et al.*, 2004]. *Kutiev et al.* [2006, 2007] observed strong TEC enhancements at the end of recovery phase of geomagnetic storms. They found that most of the enhancements are part of the equatorial crest region during nighttime and with structures in the whole latitude range considered at daytime. The enhancement events can take place 1–3 d after the storm main phase. *Kelley et al.* [2003] explained the daytime midlatitude enhancement as a result of a strong auroral electric field penetrating into middle and low latitudes during the initial phase of the storm. *Kutiev et al.* [2007] also regarded the enhancements in TEC are mainly produced by the upward electrodynamic drifts caused by a polarization electric field at low and equatorial latitudes.

[27] It is well known that the electric field plays an important role in maintaining the F_2 layer ionosphere at equatorial and low latitudes during both geomagnetically quiet and active conditions [*Fejer*, 2002]. A more likely cause for the low-latitude prestorm enhancements is the enhanced zonal electric field or vertical plasma drift. This is supported by the fact of a better developed EIA presenting in those events. During daytime the equatorial ionization is lifted across magnetic field lines up to higher altitudes due to the electric field produced by dynamo action in the E region, until it starts to slide down to higher latitudes along magnetic field lines due to neutral winds and plasma diffusions assisted by gravity and plasma pressure gradients. This is the so-called equatorial fountain effect [e.g., *Moffett*, 1979; *Stening*, 1992; *Lin et al.*, 2005]. As a result, a clear minimum in electron concentrations is seen close to the magnetic equator and two crests away from the equator in both hemispheres. If, as we suggested, the low-latitude prestorm enhancement can be attributed to enhanced zonal electric fields or vertical plasma drifts, the narrow latitudinal extent of positive ΔTEC (the greatest amplitude is confined at the EIA crest latitudes) can be explained. At the same time, when this can take place, a depletion of electron concentrations in the equatorial region will occur, which actually can be found in the equatorial region of Figures 3, 6, and 9.

[28] Researches indicated that during geomagnetic storms, equatorial electrodynamics is affected by directly penetrated magnetospheric electric fields and the disturbed wind dynamo [*Fejer*, 2002]. Low-latitude F region dynamics is often affected directly by solar wind-magnetosphere interactions. The signature of bow shock, the sudden storm commencement (SSC), used in the present analysis, is only a part of the all possible forcing from solar wind-magneto-

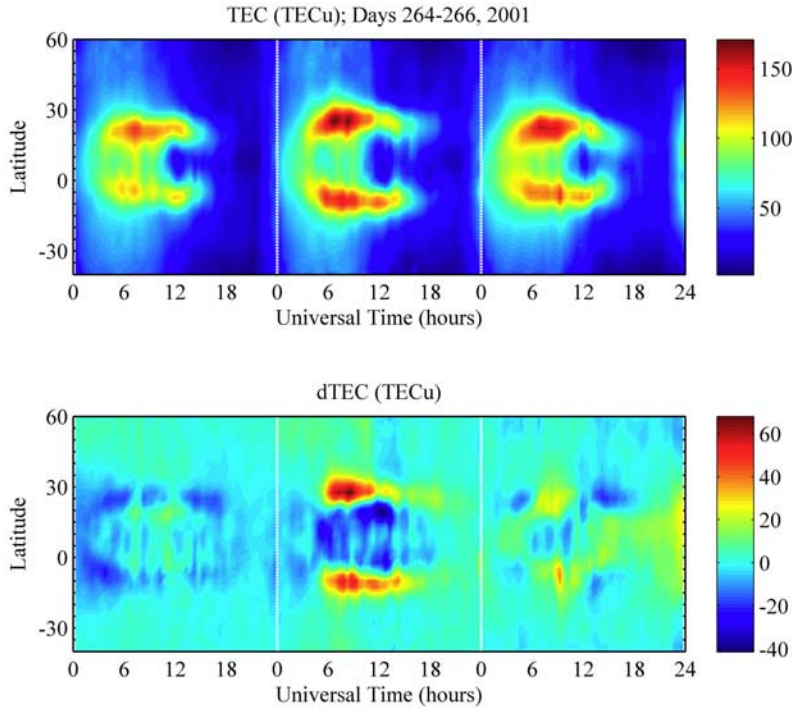

Figure 9. Same as Figure 3 but for 21–23 September (days 264–266) 2001. The median values are evaluated from the 31-d observations centered on 22 September 2001.

sphere impact. It has been shown in the literature that the y-component of the solar wind electric field can be directly mapped to the equatorial ionosphere, giving rise of a penetration electric field and a vertical drift. The penetration drifts decrease with an average time constant of 20 min to within 1 h. Another kind of disturbed electric field associated with magnetic activity is the thermospheric wind driven dynamo electric fields. After magnetic quieting, the disturbance dynamo drifts disappear about 6 h [*Fejer*, 2002] or with longer time delays of about 20–30 h [*Scherliess and Fejer*, 1997].

[29] To show the possible influence from the solar wind, Figure 10 shows the evolutions of solar wind parameters (southward component of solar wind magnetic field B_z and dawn-dusk component of electric field E_y) from the ACE satellite in the three cases considered. E_y is estimated from the solar wind velocity and B_z, in a way similar to that of *Kutiev et al.* [2007]. No correction was made to account for the traveling time from L1 point and the Earth magnetosphere.

[30] For the first event (the 21 April 2001 event), auroral activity is low on 20 and 21 April, but solar wind exhibits some changes: B_z makes a weak negative turn at 0700 UT on 21 April, at the time when E_y exhibits a small but prolonged increase of about 1 mV/m. Although the magnitude of E_y is too small, it possibly produces an observable effect on ionosphere, if it is not shielded for 6–7 h. It is puzzled, however, that the enhancement already started about 3 h before the B_z southward turning. On the other hand, on 17 April, 5 d before this event, the geomagnetic activity is high. Although auroral activity is low on 20 and 21 April, there is still possible that the 21 April enhancement is a post-storm effect of the previous activity as reported by *Kutiev et al.* [2007].

[31] The 29 May 2003 event occurred in a disturbed month. *Dst* and *ap* indices are low before the event, although the solar wind and auroral activity is not quite quiet, as indicated by Figure 10b. Continuous heating of auroral thermosphere by electrojet current and particle precipitation assures a significant flow of disturbed winds to lower latitudes, which would generate disturbance dynamo electric field on 29 May. If this disturbed electric field produces an upward $\mathbf{E} \times \mathbf{B}$ drift, this case can be explained.

[32] During the 22 May 2003 event, B_z exhibits two negative turns at 0400 UT and 0800 UT on 22 May 2001 (see Figure 10c). The second turn lasts for more than 6 h. Unfortunately, the solar wind velocity is not available during this event. However, we can assume from B_z that these sudden changes of solar wind parameters allow a direct penetration of magnetospheric electric field to low latitude ionosphere.

[33] Both our analysis and that of *Burešová and Laštovička* [2007] indicate that the prestorm enhancements are not accompanied by a corresponding change of hmF_2. Such hmF_2 behaviors during prestorm enhancements may be possibly explained in terms of the coupling nature of parallel and perpendicular dynamics at low latitudes [e.g., *Behnke and Harper*, 1973; *Rishbeth et al.*, 1978]. Previous observations display the mirror effect or anticorrelation of the plasma drift velocity components parallel to and perpendicular to the geomagnetic field. Although these components have different physical causes, they are not at all decoupled and the resulting vector plasma motion is nearly horizontal at low latitudes! Therefore during these events if

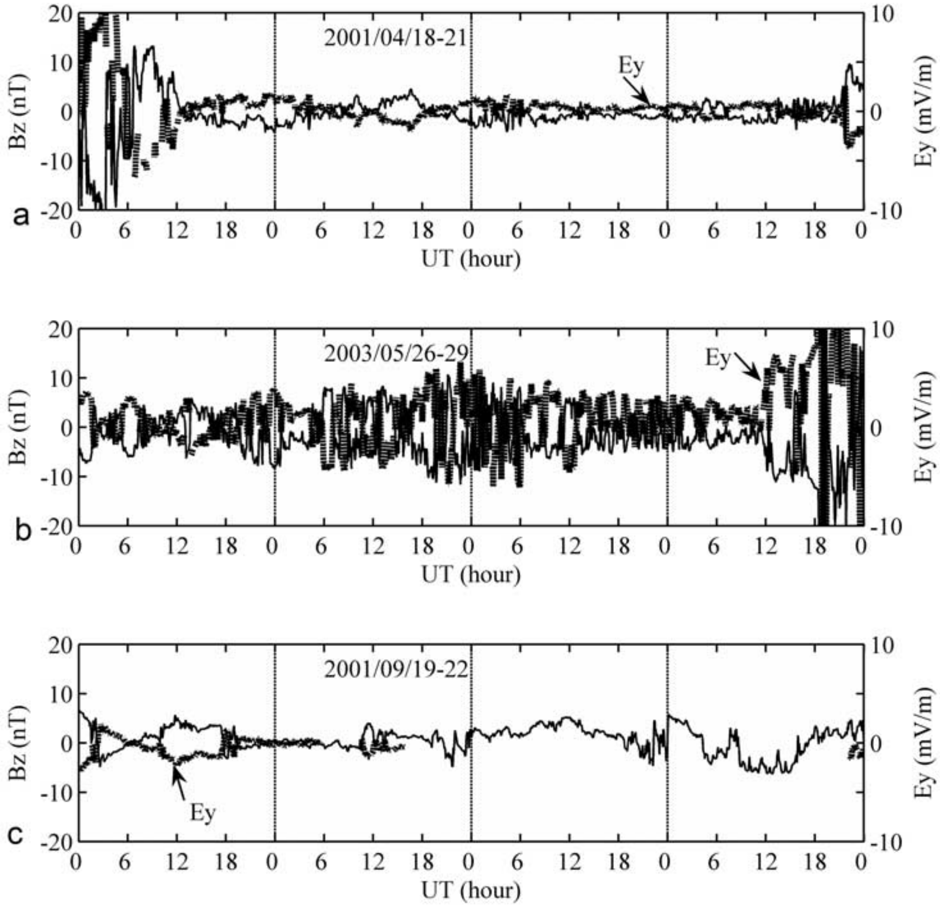

Figure 10. Evolutions of solar wind parameters (B_z and E_y) from the ACE satellite during the three cases considered.

stronger electric fields exist, it will cause the plasma move poleward and enhance the equatorial fountain effect. Hence the EIA in foF_2 and TEC will be well-developed and the EIA crests shift to higher latitudes. These possible consequences actually have been observed in our events. Moreover, the simultaneous stronger field-aligned ion flows, due to the mirror effect [*Behnke and Harper*, 1973], tends to cancel out the possible shift of the peak height of the F_2 layer at low latitudes, resulting nearly horizontal motion. Note that this mirror effect only operates on low latitudes and becomes ineffective with decreasing dip angle. In the lower latitude and equatorial regions, hmF_2 should be lifted above the reference level. This is verified by the hmF_2 observations made at the Hainan station with a dip angle of about 25° (figures not shown here). Although stronger electric fields are often found during storms [e.g., *Lin et al.*, 2005], we do not know how this postulated change in the zonal electric field takes place. It is a question at present.

5. Summary

[34] To reveal the behaviors of the prestorm enhancements in the low-latitude ionosphere, we analyzed some low-latitude events using measurements from four ionosonde stations and GPS TEC along longitude 120°E in the Asia/Australia sector. The main results of this investigation may be listed as follows:

[35] Strong enhancements before the storm onset are simultaneously presented in foF_2 and TEC at low latitudes. All three events (and other two cases on 9 August 2000 and 10 May 2002) show remarkable similarities features. These enhancements have a latitudinal dependence, tending to occur at a narrow latitudinal region with maxima around the northern and southern EIA crests. During the low-latitude enhancements, electron concentrations are depleted in the equatorial region. This is the major difference from what reported by *Burešová and Laštovička* [2007]. Moreover, hmF_2 at Wuhan may be above, below, or around the reference level when foF_2 and TEC are enhanced, which agrees with *Burešová and Laštovička* [2007].

[36] It has been verified that the solar flare effects are not the main drivers for those low-latitude enhancements. We suggest that the vertical plasma drift or zonal electric field is a more likely cause for the low-latitude prestorm enhancements. The existence of the enhanced zonal electric field or vertical plasma drifts in those events is supported by the fact of stronger EIA, the latitudinal coverage of the enhancements as well as the peak height variation at an equatorward station. In contrast, the hmF_2 behaviors at Wuhan during prestorm enhancements may possibly be explained in terms of the coupling nature of parallel and perpendicular dynam-

ics at low latitudes [e.g., *Behnke and Harper*, 1973; *Rishbeth et al.*, 1978].

[37] However, we cannot certainly answer what cause the zonal electric field or vertical plasma drifts becoming stronger in those events. They may be either an aftermath of a previous geomagnetic activity or directly mapping to the equatorial ionosphere from the solar wind electric fields, effects of planetary atmospheric waves, and so on. The longitudinal and solar activity dependences of the low-latitude prestorm enhancement are unclear at present. Further investigation needs to provide a statistical picture of the prestorm enhancements.

[38] **Acknowledgments.** The *Ap* and *F*107 indices are downloaded from the SPIDR web http:/spidr.ngdc.noaa.gov/. Ionospheric data are provided from WDC for Ionosphere, Tokyo, National Institute of Information and Communications Technology. The SEM/SOHO EUV data is downloaded from the Web site http://www.usc.edu/dept/space_science/semdatafolder/. The ACE solar wind data are provided by CEDAR Data System from the Principal Investigator D. J. McComas of Southwest Research Institute. This research was supported by National Natural Science Foundation of China (40725014, 40674090) and National Important Basic Research Project (2006CB806306).

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