Effects observed in the ionospheric *F* region in the east Asian sector during the intense geomagnetic disturbances in the early part of November 2004

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[1] The Sun was very active in the early part of November 2004. During the period of 8–10 November 2004, intense geomagnetic disturbances with two superstorms were observed. In a companion paper (hereinafter referred to as paper 1), the effects observed in the *F* region during the intense geomagnetic disturbances in the early part of November 2004 in the Latin American sector were presented. In the present paper, we investigate the effects observed in the *F* region during the intense geomagnetic disturbances in the early part of November 2004 in the east Asian sector. We have used the ionospheric sounding observations at Ho Chi Minh City (Vietnam) and Okinawa, Yamagawa, Kokubunji, and Wakkanai (Japan) in the present investigations. Also, GPS observations in the east Asian sector (several longitude zones) have been used to study the effect in the *F* region during the intense geomagnetic disturbances. The ion density versus latitudinal variations obtained by the DMSP F15 satellite orbiting at about 800 km altitude in the east Asian sector and the magnetic field data obtained at several stations in the Japanese meridian are also presented. Several important features from these observations in both the sectors during this extended period of intense geomagnetic disturbances are presented. The east Asian sector showed very pronounced effects during the second superstorm, which was preceded by two storm enhancements. It should be mentioned that around the beginning of the night on 10 November, ionospheric irregularities propagating from higher midlatitude region to low-latitude region were observed in the Japanese sector. The most intense geomagnetic field H component in that sector was observed on 10 November at $L = 2.8$, indicating that the auroral oval and the heating got further to low latitudes and the ionospheric irregularities observed in the Japanese sector on this night are midlatitude ionospheric disturbances associated with the second superstorm. The absence of ionospheric irregularities in the Japanese sector during the 8 November superstorm suggests that the magnetosphere-ionosphere system was possibly preconditioned (primed) when the second interplanetary structure impacted the magnetosphere.

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1. Introduction

[2] Effects observed in the ionospheric *F* region during geomagnetic superstorms are important space weather issues. As discussed by *Trichtchenko et al.* [2007], during the early part of November 2004, the Sun was very active and during the period 1–7 November there were 11 M- and 2 X-class flares and 9 CMEs (coronal mass ejections) forming two geoeffective interplanetary structures. During the period of 8–10 November two superstorms (considering $|Dst|_{max} > 250$ nT for a superstorm) having $|Dst|_{max} = 373$ nT on 8 November at 0700 UT and $|Dst|_{max} = 289$ nT on 10 November between 1000 and 1100 UT were observed. The geomagnetic disturbances in the early part of November 2004 are considered in the present investi-

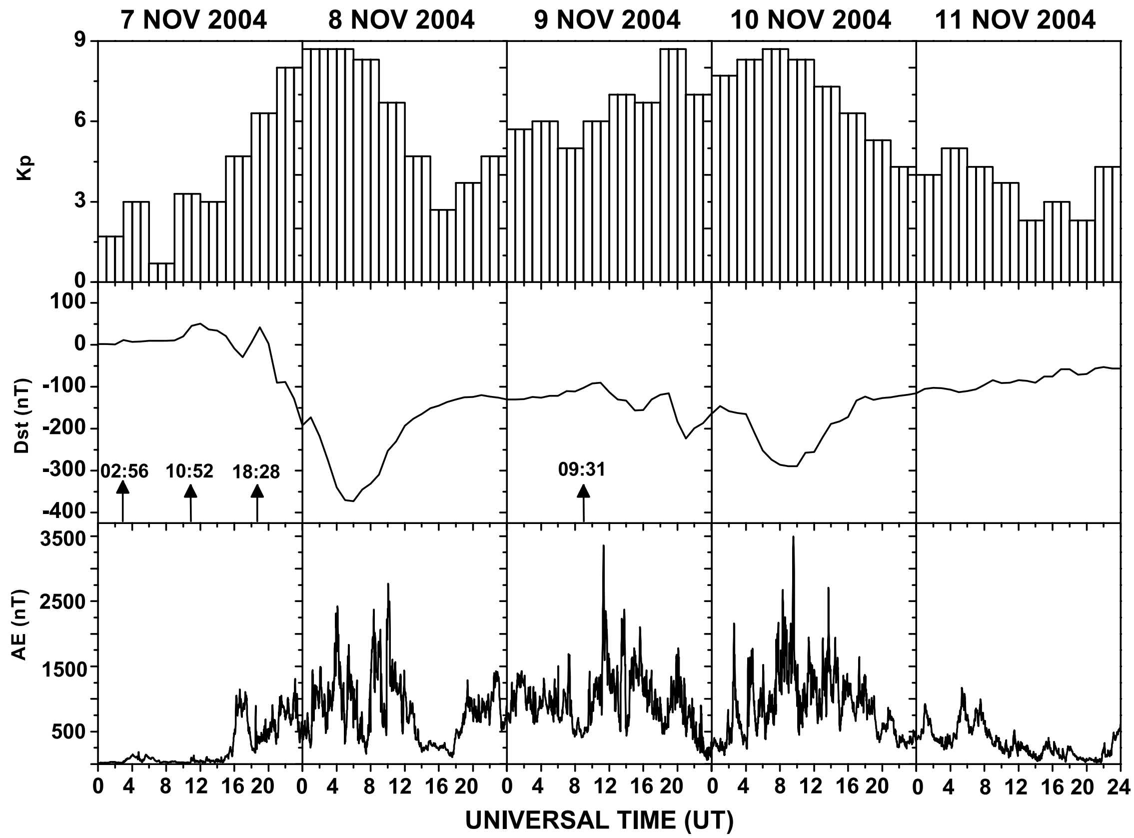

Figure 1. The variations of the *Kp*, *Dst*, and *AE* geomagnetic indices during the period 7–11 November 2004 (from *Sahai et al.* [2009] (paper 1)).

gation as comprising two phases: (1) superstorm on 8 November (hereinafter referred to as phase 1) and (2) superstorm on 10 November (hereinafter referred to as phase 2), which was preceded by two storm enhancements at 1600 and at 2200 UT on 9 November.

[3] In a companion paper [*Sahai et al.*, 2009] (hereinafter referred to as paper 1) [see also *Sahai et al.*, 2004, 2005], the effects observed in the *F* region, during the intense geomagnetic disturbances in the early part of November 2004 in the Latin American sector were presented. Figure 1 (taken from *Sahai et al.* [2009]) shows the time variations of the *Kp*, *Dst*, and *AE* geomagnetic indices for the period 7 November to 11 November 2004. The *Dst* panel (middle) also shows the sudden commencement (SC) times with vertical arrows. The geomagnetic indices indicate an extended period of geomagnetic disturbances covering the period of 7–11 November 2004.

[4] The general characteristics of geomagnetic storms and how the storm-time energy deposited at high latitude drives the energy to mid and low latitudes are discussed in detail in paper 1 and will not be repeated here. In the present paper, we investigate the effects observed in the *F* region during the intense geomagnetic disturbances in the early part of November 2004 in the east Asian sector. In the present work, ionospheric sounding observations obtained at Ho Chi Minh City (10.5°N, 106.3°E; hereinafter referred to as HCM), Vietnam, and Okinawa (26.2°N, 127.8°E; hereinafter referred to as OKI), Yamagawa (31.2°N, 130.6°E; hereinafter referred to as YAM), Kokubunji (35.7°N, 139.5°E; hereinafter referred to as KOK), and Wakkanai (45.5°N, 141.7°E; hereinafter referred to as WAK), Japan, have been used. In addition, GPS observations in the east Asian sector (several longitude zones) have been used to study the effect in the *F* region during the intense geomagnetic disturbances. The ion density versus latitudinal variations obtained by the DMSP F15 satellite orbiting at about 800 km altitude in the east Asian sector and the magnetic field data obtained at several stations close to the Japanese meridian (210 MM (210 Magnetic Meridian)/CPMN (Circum-pan Pacific Magnetometer Network) chain are also presented.

2. Observations

[5] The ionospheric sounding observations from the Japanese stations (WAK, KOK, YAM, and OKI; hereinafter referred to as Japanese ionospheric sounding network (JST = UT + 9 h)) presented in this investigation were obtained from the Web site http://wdc.nict.go.jp/IONO/index.html. At Ho Chi Minh City, Vietnam, VST = UT + 7 h. The GPS data from a large number of stations in the east Asian sector presented in this investigation were obtained from the IGS and GEONET. The two-dimensional maps of TEC variations over Japan, using a network of more that 1000 GPS stations (GEONET), presented in this investigation were provided by the Geographical Survey Institute of Japan. It should be mentioned that only the nighttime

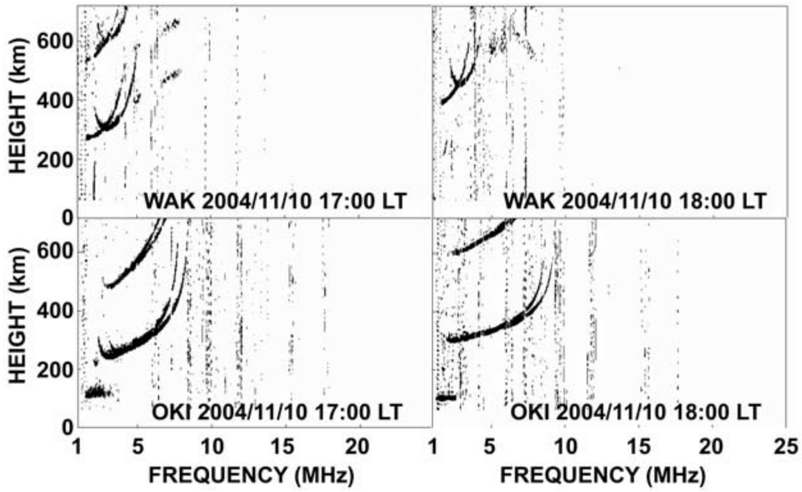

Figure 2. Ionograms obtained at WAK and OKI on 10 November 2004 at 1700 (0800 UT) and 1800 LT (0900 UT).

response of the *F* region in the east Asian sector has been investigated during this geomagnetically disturbed period.

3. Results and Discussion

[6] During the phase 1 of the geomagnetic disturbances on 8 November, no spread *F* was observed at HCM and the Japanese ionospheric sounding network. However, during the phase 2, on the night of 10 November intense spread *F* was observed at the Japanese ionospheric sounding network, but no spread *F* was observed at HCM (a station located in the east Asian sector having a local time difference with the Japanese sector of 2 h (lagging)). These observations during the phase 2 were surprising and needed a detailed investigation.

[7] Figure 2 shows a set of ionograms obtained at WAK and OKI on 10 November at 1700 and 1800 LT. The ionograms at WAK, a midlatitude station, show that during a period of 1 h there was a significant height rise (more than 100 km) and decrease in f_oF_2 (by about 1 MHz). The ionograms at OKI (Figure 2), a low-latitude station, do show some height changes but not to the extent observed at WAK. Reviewing the characteristics of midlatitude spread *F*, *Bowman* [1990] has mentioned that significant height rises and electron density depletions, in general, precede spread *F* occurrence. Figure 3 shows ionograms observed at WAK, KOK, YAM, and OKI at 1845 LT. It is observed that at 1845 LT, spread *F* was observed only at WAK, the most northern station in the Japanese ionospheric sounding network. Figure 4 shows the ionograms observed at WAK, KOK, YAM and OKI at 2030 LT (1 h and 45 min after Figure 3). Now it is seen that all the stations in the Japanese ionospheric sounding network have spread *F*. It should be mentioned that during a period of 1 h and 45 min, spread *F* was observed in a sequential order from WAK to OKI. The present observations are similar to those reported by *Sahai et al.* [2001] and clearly indicate that on this geomagnetically disturbed night midlatitude spread *F* was first generated at a higher midlatitude station (WAK) and then progresses toward a lower-latitude station (OKI). As

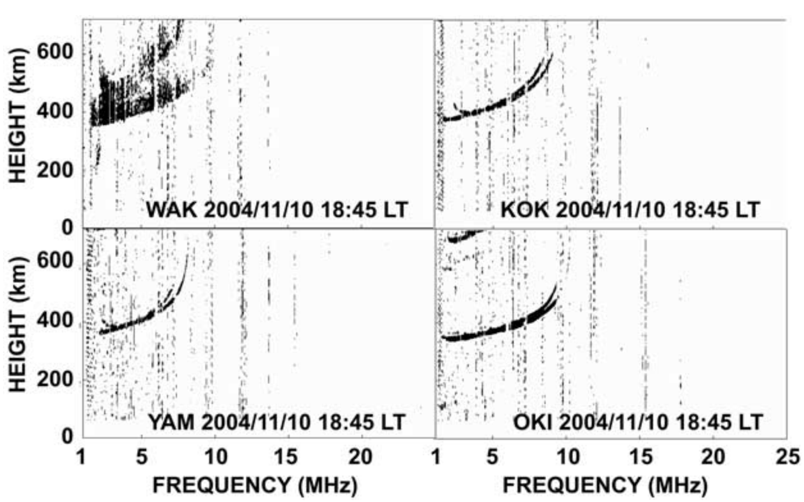

Figure 3. Ionograms obtained at WAK (showing the presence of spread *F*), KOK, YAM, and OKI on 10 November 2004 at 1845 LT (0945 UT).

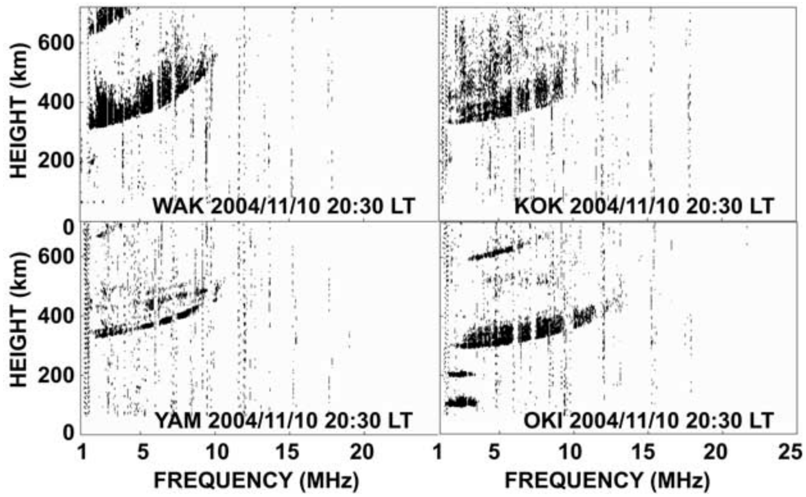

Figure 4. Ionograms obtained at WAK, KOK, YAM, and OKI on 10 November 2004 at 2030 LT (1130 UT), showing the presence of spread *F* at all the stations.

discussed by *Schunk and Sojka* [1996], during geomagnetic storms, there is a large energy input into the ionosphere-thermosphere system at high latitudes. *Buonsanto* [1999] mentioned that the large energy inputs to the upper atmosphere take the form of enhanced electric fields, currents, and energetic particle precipitation heating. Heating at high latitudes causes expansion of the neutral atmosphere resulting in increase of wind speeds and generation of equatorward propagating gravity waves. The ionospheric disturbances at middle and low latitudes observed in Figures 2–8 may be related to medium-scale traveling ionospheric disturbances (MSTIDs) because they occur from high to low latitudes. In particular, Figure 8 shows the MSTID signature.

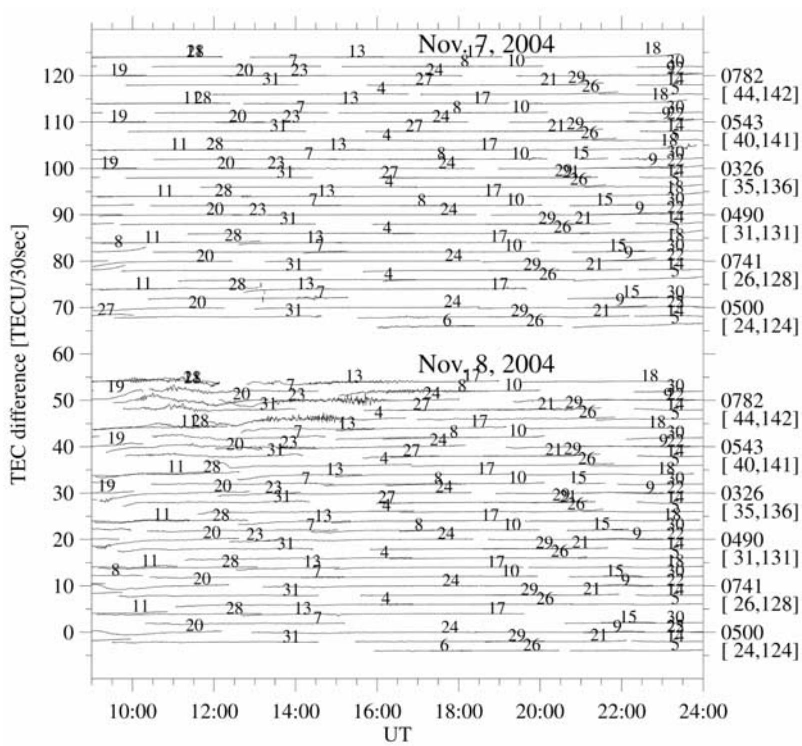

Figure 5. TEC fluctuations (phase) from GPS observations (the Japanese sector) on 7 November (relatively quiet night) and 8 November (during the phase 1 of the geomagnetic disturbances) 2004. The numbers in the brackets on the right-hand side are the geographic latitudes and longitudes of the GPS receivers. The satellite numbers are superposed on the TEC phase data. The numbers (such as 0782 and 0543) on the right-hand side are the GPS station numbers which belong to Geographical Survey Institute of Japan.

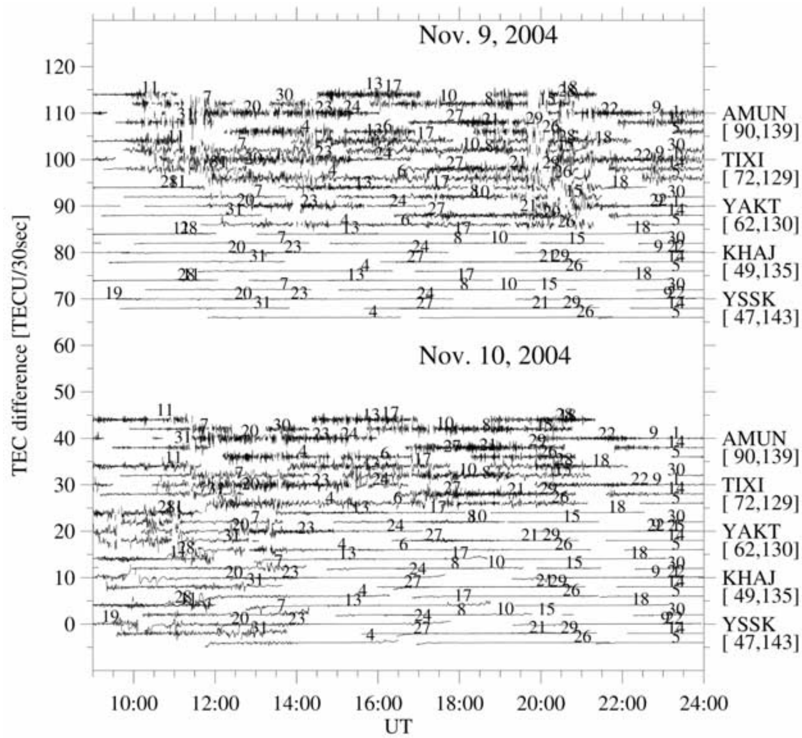

Figure 6. TEC fluctuations (phase) from GPS observations (the high-latitude region) on 9 November (geomagnetically disturbed night) and 10 November (during the phase 2 of the geomagnetic disturbances) 2004. The numbers in the brackets on the right-hand side are the geographic latitudes and longitudes of the GPS receivers. The satellite numbers are superposed on the TEC phase data. The GPS station names AMUN (Amundsen/Scott), TIXI (Tixi), YAKT (Yakutsk), Khaj (Khabarovsk), and YSSK (Yuzhno-Sakhalinsk) are indicated on the right-hand side.

[8] Therefore, in the case studied, auroral heating launch large-scale atmospheric gravity waves and neutral wind disturbances. These neutral waves/disturbances take a few hours to reach midlatitudes, move the *F* region to higher altitudes, and produce spread *F* there, especially in the evening sector. The atmospheric gravity waves can also seed the Perkins instability [*Perkins*, 1973] in the nightside ionosphere.

[9] Figure 5 shows the phase fluctuations of GPS signal in units of TEC variations per 30 s [*Aarons et al.*, 1996; *Sahai et al.*, 2001] observed in the Japanese sector from the GPS network on the nights of 7–8 (relatively geomagnetically quiet) and 8–9 (superstorm-phase 1) November. It should be pointed out that the phase fluctuations as obtained from RINEX data measure large-scale irregularity structures of the order of kilometers [*Aarons et al.*, 1997]. A perusal of Figure 5 shows that there were only small phase fluctuations (kilometer-scale ionospheric irregularities) present in the northern Japanese sector (close to WAK) on the night of 8–9 November. On the night of 9–10 November, Figure 6 shows that the phase fluctuations are limited to very high latitudes (Amundsen/Scott (AMUN), Tixi (TIXI), and Yakutsk (YAKT)), whereas on the night of 10–11 November, the phase fluctuations extend to lower high latitudes (up to Yuzhno-Sakhalinsk (YSSK)) during the early part of the night (up to about 1400 UT (2300 LT)).

[10] Figure 7 shows the phase fluctuations observed in the Japanese sector from the GPS network on the nights of 9–10 (including superstorm-phase 2) and 10–11 (recovery phase after the second superstorm-phase 2). No phase fluctuations were observed in the Japanese sector on the night of 9–10 November, but the night of 10–11 November shows extension (Figure 6, bottom) of the phase fluctuations to mid and low latitudes in the Japanese sector. In addition, Figure 7 (bottom) shows that the phase fluctuations occur at earlier times in the higher midlatitudes in the Japanese sector than at lower latitudes, where the occurrence is at much later part in the night. The results of the phase fluctuations on the night of 10–11 November are very similar to those described earlier on the basis of the ionospheric sounding observations in the Japanese sector.

[11] The midlatitude disturbance observed in the present investigation could be related to the auroral zone disturbances associated with the geomagnetic disturbances through the mechanism of atmospheric gravity waves that are launched owing to enhanced Joule heating in the auroral zone, travel to midlatitudes, and produce traveling ionospheric disturbances (TIDs) [*Bowman*, 1990]. Figure 1 shows that the *AE* geomagnetic index was high during several days prior to the night of 10–11 November.

[12] Figure 8 shows a sequence of TEC maps obtained between 1130 UT to 1230 UT, from more than 1000 GPS stations in Japan, for the nights of 8–9 November (phase 1) and 10–11 November (phase 2). Figure 8b clearly shows the presence of medium-scale traveling ionospheric disturbances (MSTIDs), with ionized structures moving from

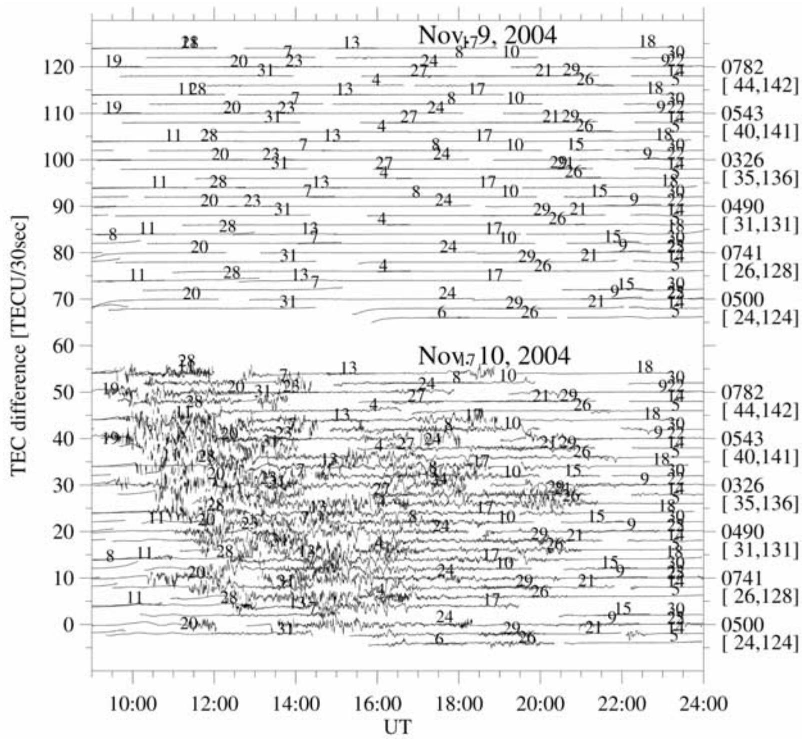

Figure 7. TEC fluctuations (phase) from GPS observations (the Japanese sector) on 9 November (geomagnetically disturbed night) and 10 November (during the phase 2 of the geomagnetic disturbances) 2004. The numbers in the brackets on the right-hand side are the geographic latitudes and longitudes of the GPS receivers. The satellite numbers are superposed on the TEC phase data. The numbers (such as 0782 and 0543) on the right-hand side are the GPS station numbers which belong to Geographical Survey Institute of Japan.

northeast to southwest. As pointed out by *Hargreaves* [1992], wavefronts of MSTIDs are typically oriented about 45° from the vertical. The present observations of MSTIDs during geomagnetic disturbance are similar in the Japanese sector, as reported by *Sahai et al.* [2001]. *Shiokawa et al.* [2005] have shown that MSTIDs occur during both geomagnetically quiet and active times. Possibly the sources for the ionospheric disturbances are different. During the geomagnetically active times, the possible sources are Joule heating in the auroral zones or disturbed thermospheric winds, whereas during the geomagnetically quiet times, the possible sources are disturbances in the tropospheric region.

[13] Figure 9 shows the ion density plots from the DMSP F15 satellite orbiting at an altitude of about 800 km for the three longitude zones (left-hand panels, about 170°E (east of Japanese sector); right-hand top panel, about 130°E (Japanese sector); and right-hand bottom panel, 110°E (Vietnamese sector)) on 10 November. The DMSP observations indicated no equatorial spread *F* in the Vietnamese sector, midlatitude spread *F* in the Japanese sector, and copious equatorial spread *F* including the storm-induced big bubbles [*Kil et al.*, 2006] in the east of Japanese sector. The spread *F* in the east of Japanese sector could be associated with penetration electric fields during the main phase of the magnetic storm. The interplanetary magnetic field (IMF) was strongly southward before 1100 UT on 10 November and became weakly southward after that. As studied by *Huang et al.* [2005, 2007] and *Maruyama et al.* [2005, 2007], penetration electric fields can continuously exist for several hours during the main phase of magnetic storms as long as the IMF remains southward. In the case of 10 November, eastward penetration electric fields would occur on the dayside and in the evening sector and move the *F* layer to higher altitudes. Therefore, the equatorial plasma bubbles in Figure 9 must be caused by penetration electric fields.

[14] Later, neutral wind disturbances will reach the equatorial region and generate a westward dynamo electric field in the evening equatorial ionosphere. The dynamo electric field will move the *F* region downward and suppress spread *F* there. Note that the DMSP satellite is fixed in local time. The transition from eastward penetration electric field to westward dynamo electric field provides a better interpretation of the variation of equatorial plasma bubbles (east Japanese sector) to quiet equatorial *F* region (Japanese and Vietnamese sectors). The transition from eastward penetration electric field to westward dynamo electric field can also be used to explain the difference of the observations in the Japanese and Vietnam sectors. The east of Japanese region moves into the evening sector early (when the penetration field dominates) than the Vietnam region (when the westward dynamo electric field dominates). The latitudinal variations may indeed exist. However, we need to consider the contributions from different processes.

[15] Figure 10 shows the phase fluctuations of GPS signals on the nights of 9–10 and 10–11 November at Mariana Island (15.2°N, 145.7°E; hereinafter referred to as CNMR),

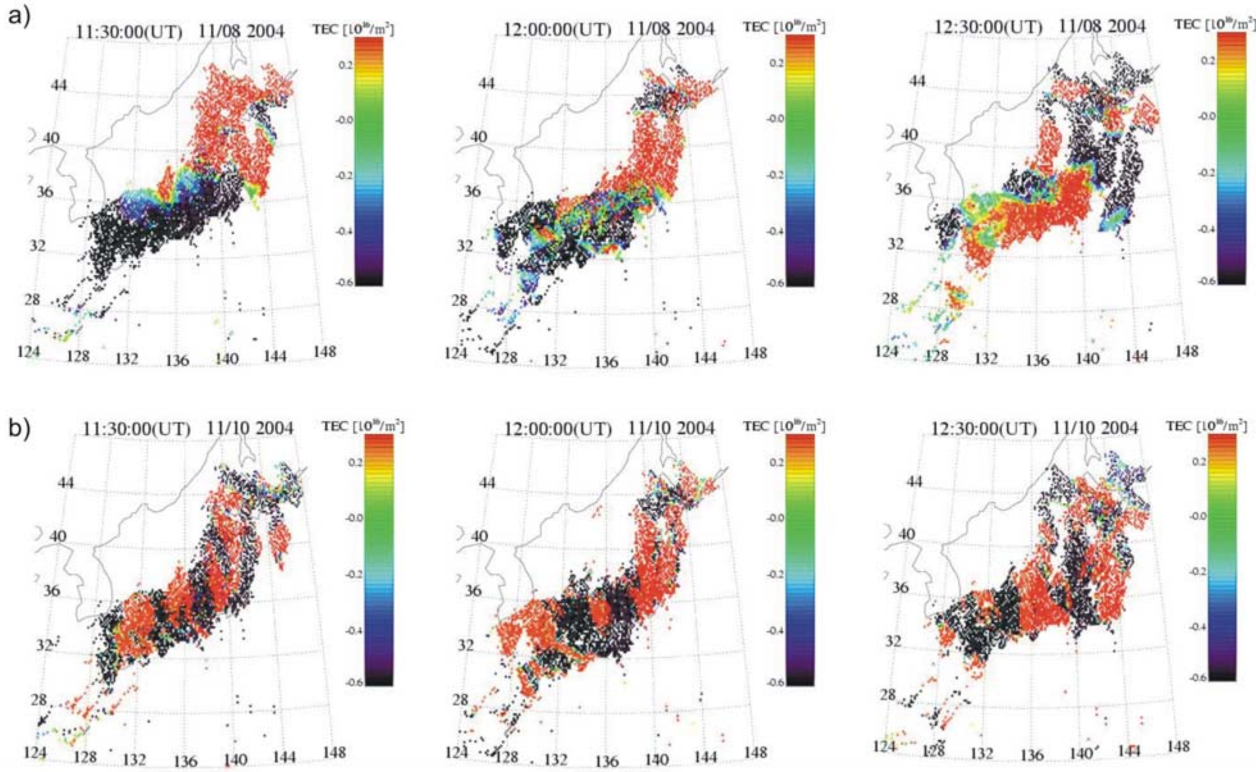

Figure 8. Two-dimensional maps of TEC variations over Japan obtained from a network of more that 1000 GPS receivers on (a) 8 November (during the phase 1 of the geomagnetic disturbances) and (b) 10 November (during the phase 2 of the geomagnetic disturbances) 2004 during the period of 1130 UT (2030 LT) and 1230 UT (2130 LT). On 10 November alternate bands with high and low TECs are seen to move from northeast to southwest (MSTIDs).

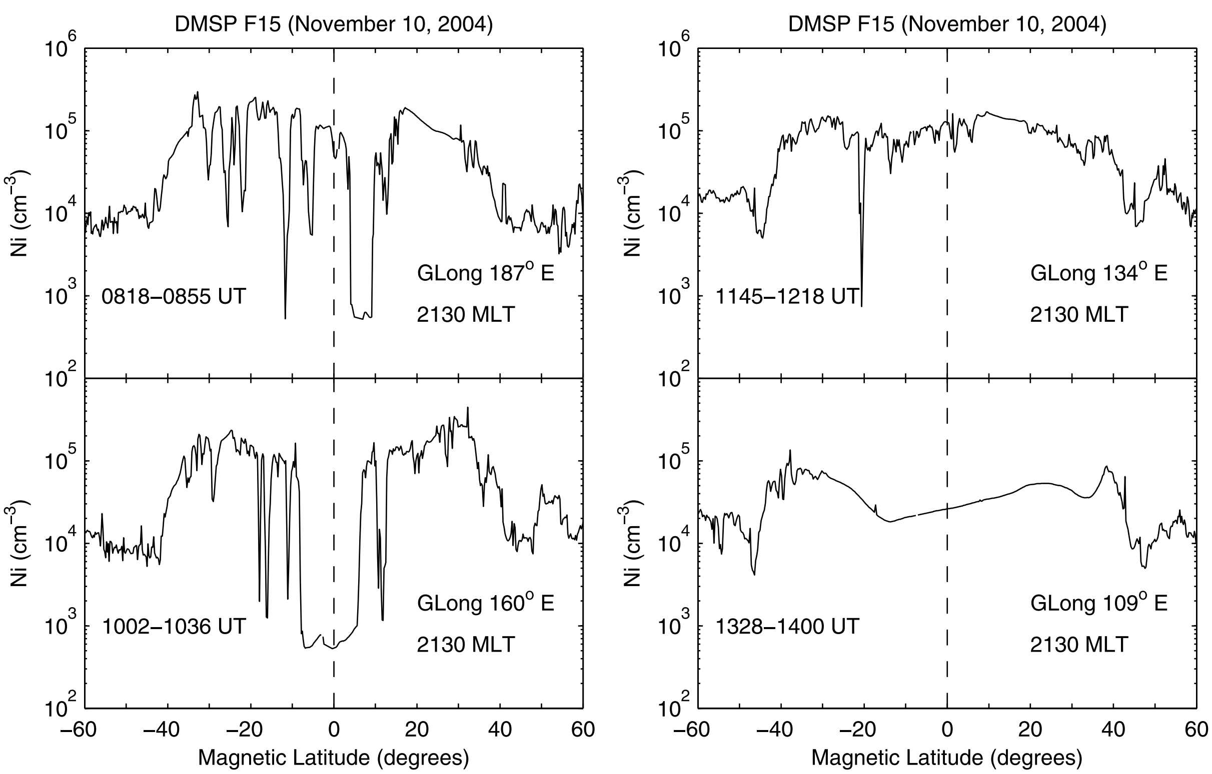

Figure 9. Variations of the ion density observed from the DMSP F15 satellite orbiting at an altitude of about 800 km in three longitude zones in the east Asian sector.

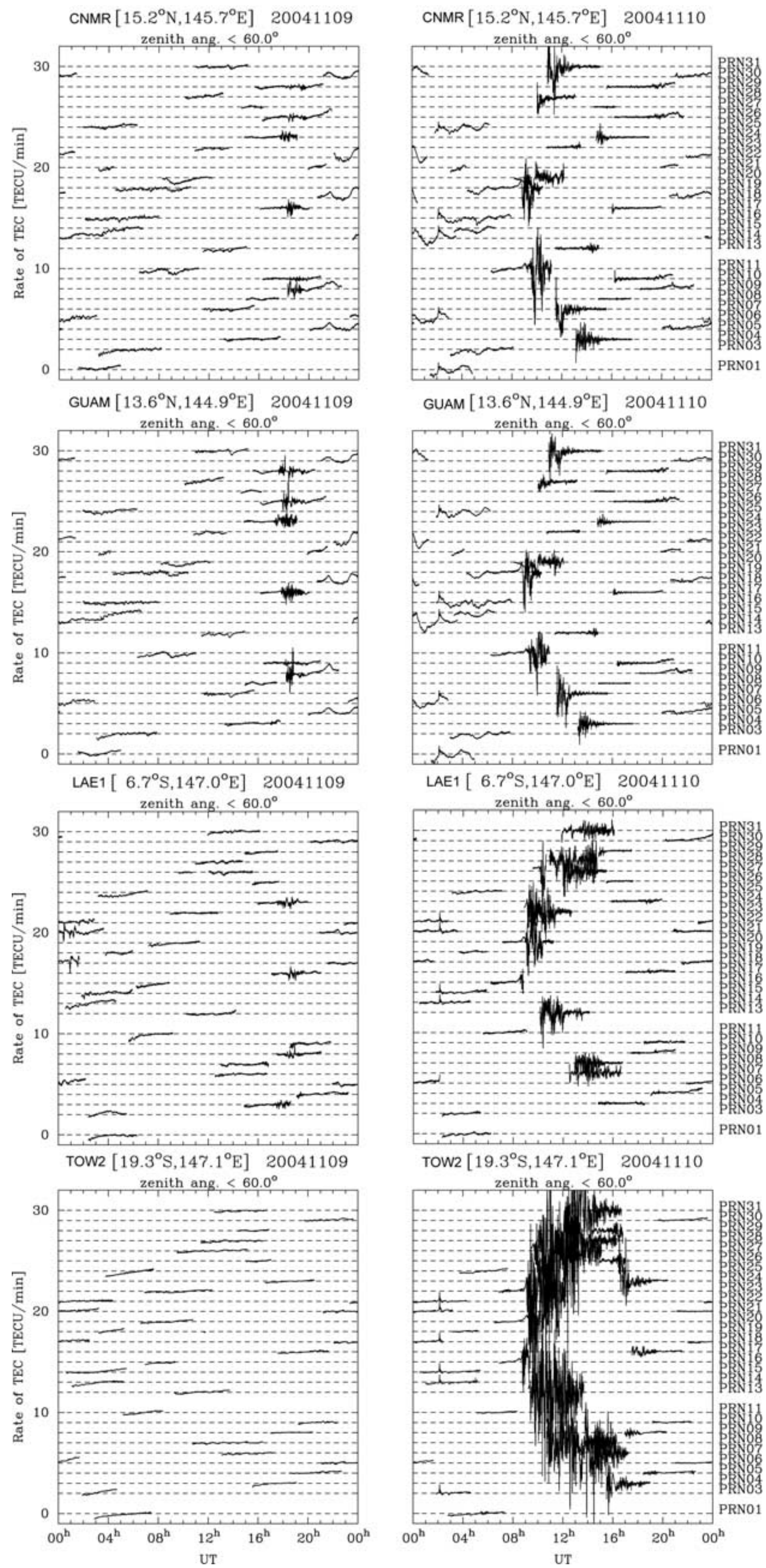

Figure 10. TEC fluctuations (phase) from GPS observations on 9 November (geomagnetically disturbed night) and 10 November (during the phase 2 of the geomagnetic disturbances) 2004 at Mariana Island, Guam, Papua, and Townsville. The satellite numbers are also shown at the right-hand side.

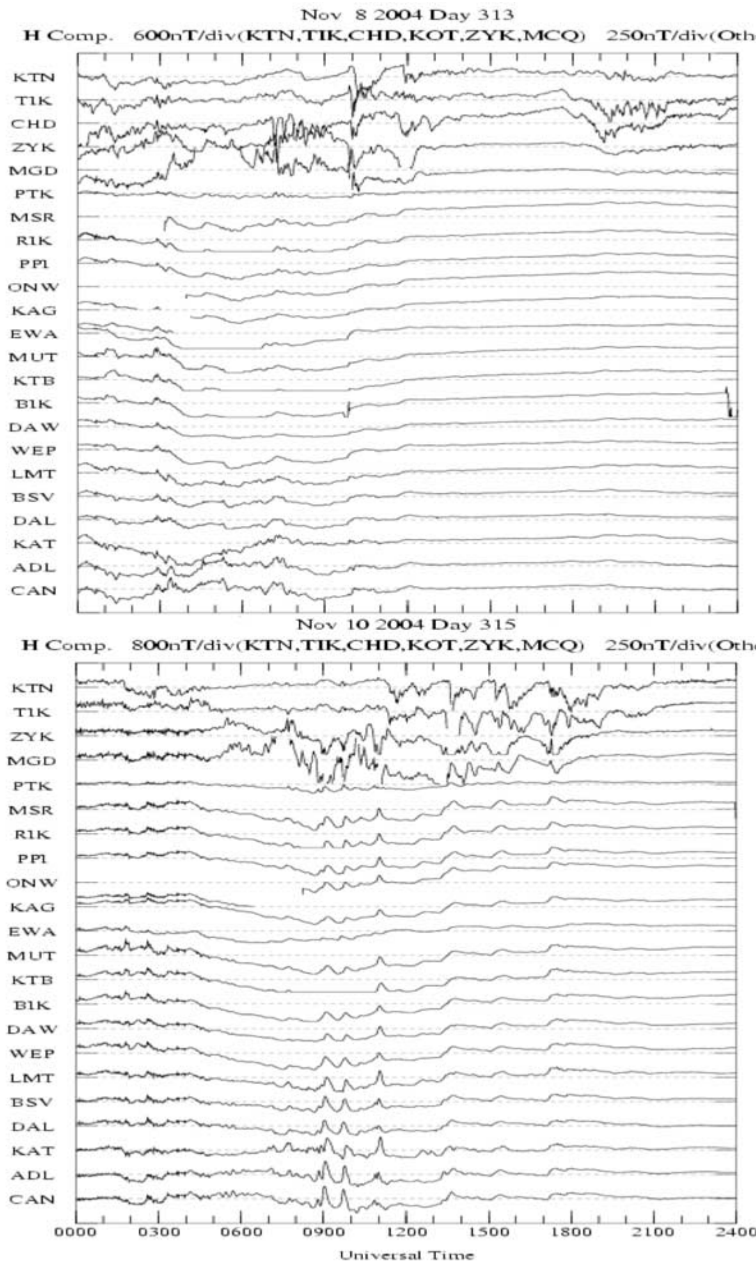

Figure 11. The 210 MM magnetic field data (H component) on (top) 8 November (during the phase 1 of the geomagnetic disturbances) and (bottom) 10 November 2004 (during the phase 2 of the geomagnetic disturbances).

U.S.A., USGS Guam Observatory (13.8°N, 144.9°E; hereinafter referred to as GUAM), Guam, University of Technology, Lae (6.7°S, 147.0°E: hereinafter referred to as LAE1), Papua New Guinea, and Townsville (19.3°S, 147.1°E; hereinafter referred to as TOW2), Australia. It is observed from Figure 10 that there were strong phase fluctuations on the night of 10–11 November, indicating the presence of equatorial spread *F*, in the longitude zone east of the Japanese sector. The present results also agree with the DMSP satellite observations presented earlier. It should be pointed out that the response of the *F* region in three longitudinal sectors (Vietnamese, Japanese, and east of the Japanese), differing only by about 35°, exhibited so different characteristics during the phase 2 of the geomagnetic disturbances. The penetration electric fields are global in nature and their effects on the ionosphere vary with local time. The equatorial ionospheric irregularities observed east of the Japanese sector could again be associated with penetration of magnetospheric electric fields to the equatorial region during the rapid decrease of *Dst* on 10 November (Figure 1) [*Wygant et al.*, 1998; *Basu et al.*, 2001, 2005].

[16] Figure 11 shows the 210 MM magnetic field data observed on 8 and 10 November obtained in the Japanese longitude sector. On 8 November (phase 1), a substorm started at 0948 UT. The high-latitude bay shows this is an ordinary-size substorm with ~600 nT at Tixie (TIK; 71.59°N, 128.78°E) Kotel'nyy (KTN: 75.94°N, 137.71°E),

and Chokurdakh (CHD; 70.62°N, 147.89°E) (auroral zone in Siberia). A little larger variation was observed at Zyryanka (ZYK; 65.75°N, 150.78°E) (L = 4, subauroral zone), indicating that the auroral oval and associated heating just expands to the lower latitudes during the main phase of this large storm. However, on 10 November (phase 2), three substorms seem to occur sequentially, as identified by midlatitude positive-H bays. The Pi2 pulsations (onset of substorms) are at (1) 0843 UT, (2) 0936 UT, and (3) 1045 UT. The most intense H variation was observed at Magadan (MGD; 60.0°N, 150.9°E; $L = 2.8$), indicating that the oval and the auroral heating got further to lower latitudes. The substorm size is very large (~1000 nT at MGD) (please note that the vertical scale is 250 nT/division for MGD but 800 nT/division for ZYK). Thus, it seems ZYK shows the most H-field variation. These complementary magnetic field data substantiate why the response of the *F* region was so different during the phase 2 (10 November), as compared with the phase 1 (8 November).

[17] Multistep *Dst* development and ring current composition changes during the 4–6 June 1991 magnetic storm has been discussed by *Kozyra et al.* [2002] [see also *Kamide et al.*, 1998]. The phase 2, which includes two intense and one superstorm, is fairly similar to the geomagnetic disturbances investigated by *Kozyra et al.* [2002], which discussed the importance of (1) the mass-dependent decay of the ring current during the early recovery phase and (2) the role of preconditioning in multistep ring current development. The results of the present investigation, during the phase 2, indicate the important role of preconditioning in multistep ring current development during the early recovery phase. The absence of ionospheric irregularities in the Japanese sector during the 8 November superstorm suggests that the magnetosphere-ionosphere system was possibly preconditioned (primed) when the second interplanetary structure impacted the magnetosphere. Obviously more observations that are similar to the present investigations are necessary to confirm the important role of preconditioning during geomagnetic disturbances.

4. Conclusions

[18] In the present paper, we have presented results from the nighttime ionospheric sounding observations in Vietnam and the Japanese sector, and GPS observations from the Japanese longitude sector and east of the Japanese longitude sector, during the intense geomagnetic disturbances (two strong phases) in the early part of November 2004. In a companion paper [*Sahai et al.*, 2009], we have presented results from the ionospheric sounding and GPS observations in the Latin American sector. It should be pointed out that, in the Latin American sector, unusual *F* region responses were observed in both the phases 1 and 2, although different in nature. In the present investigation, in the east Asian sector, the results indicate much more intense effects during the phase 2 (10 November), as compared with the phase 1 (8 November). The main results are summarized below:

[19] 1. Intense *F* region midlatitude spread *F* was observed on the night of 10 November. This could be associated with Joule heating or disturbance winds from the auroral region. Unusual *F* layer uplifting at WAK preceded the observed spread *F*. In addition, first the spread *F* was observed at WAK and then in a sequential way moved to OKI.

[20] 2. During the period of intense geomagnetic disturbances from 7 to 11 November, virtually no spread *F* was observed at HCM in Vietnamese sector, a sector slightly west of the Japanese sector.

[21] 3. Strong equatorial spread *F* was observed in the east of Japanese sector, possibly associated with prompt penetration of magnetospheric electric fields to the equatorial region.

[22] 4. The DMSP F15 satellite orbiting at about 800 km also shows different *F* region responses in three longitudinal zones so close to each other.

[23] 5. The present investigation indicates that the behavior of the nighttime *F* region during intense geomagnetic disturbance could be very different in close-by longitudinal sectors.

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