# Storm Phase Dependence of Penetration of Magnetospheric Electric Fields to Mid and Low Latitudes

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Penetration of the magnetospheric electric fields to the equatorial ionosphere was examined using magnetometer data from high-equatorial latitudes for three geomagnetic storms characterized by the equatorial DP2 current during the main phase and the counter electrojet (CEJ) during the early recovery phase. The equatorial DP2 started simultaneously with the onset of the ring current, and continued for 2–3 h during the main phase, indicating instantaneous transmission of the convection electric field to the equator for the period of ring current development. However, the equatorial DP2 decreased its magnitude concurrently with increase in the auroral electrojet (AEJ) during the late main phase, and changed into the CEJ when the AEJ moved rapidly poleward at the beginning of the recovery phase. It is suggested that the electric field associated with the DP2 current may play a role in driving the ring current, and that the overshielding responsible for the CEJ contributed to reduce electric fields responsible for ring current development.

## 1. INTRODUCTION

It is well known that the convection electric field causes ionospheric currents responsible for the quasiperiodic DP2 magnetic fluctuations at high latitude and at the dayside geomagnetic equator [*Nishida et al*., 1966; *Nishida*, 1968]. *Kikuchi et al*. [1996] demonstrated that the DP2 fluctuation occurred simultaneously at these latitude regions within the temporal resolution of 25 s, and suggested that the convection electric field was instantaneously transmitted to the equatorial ionosphere via the mid latitude. During a geomagnetic storm, strong DP2 current flowed into the mid to equatorial latitude ionosphere [*Wilson et al*., 2001; *Tsurutani et al*., 2004; *Huang et al*., 2005]. *Wilson et al*. [2001] demonstrated that intensified DP2 currents were observed at mid latitudes during a major geomagnetic storm, when a significant electric field was detected by Combined Release and Radiation Effects Satellite (CRRES) inside the ring current. *Wilson et al*. [2001] suggested that the ionospheric electric field responsible for the DP2 current contributed to the development of the storm ring current.

On the other hand, the enhanced convection drives a partial ring current and the field-aligned current (FAC) builds up an electric field with an opposite direction to that of the convection electric field at low latitude [*Vasyliunas*, 1972; *Jaggi and Wolf*, 1973; *Southwood*, 1977; *Senior and Blanc*, 1984]. The time constant of this shielding electric field has been estimated as 17–20 min from magnetometer observations [*Somajajulu et al*., 1987; *Kikuchi et al*., 2000] and 20–30 min from theoretical calculations [*Senior and Blanc*,

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1984; *Peymirat et al*., 2000]. During the storm, however, the shielding is not effective for many hours as suggested by *Huang et al*. [2005]. After the shielding electric field grows, the electric field at mid and low latitudes is often reversed when the convection electric field is decreased abruptly because of the northward turning of the interplanetary magnetic field (IMF) [*Rastogi and Patel*, 1975; *Kelley et al*., 1979; *Fejer et al*., 1979; *Gonzales et al*., 1979; *Kobea et al.*, 2000; *Kikuchi et al*., 2000, 2003]. The reversal of the penetrated electric field was identified as the overshielding electric field [*Kelley et al.*, 1979; *Gonzales et al*., 1979; *Fejer et al.*, 1979] and the reversed current at the equator appears as the counter electrojet (CEJ) [*Rastogi*, 1977, 1997; *Kobea et al*., 1998, 2000; *Kikuchi et al*., 2000, 2003]. The reversed electric field was observed in the inner magnetosphere by CRRES during the recovery phase of the storm [*Wygant et al*., 1998]. The reversed electric field associated with the storm was explained by means of the disturbance dynamo [*Huang et al*., 2001].

Three questions can be raised on the relationship between the storm time electric field and ring current development; (1) Does the DP2 current play a role in ring current evolution? (2) Does the shielding work or not during the main phase of the storm? (3) What is the role of the overshielding in storm evolution? To answer these questions, we analyzed three geomagnetic storms characterized by concurrent development of the ring current and equatorial DP2, which were initiated by a solar wind shock accompanied by the southward IMF, and therefore, their onsets were determined within the temporal resolution of a few minutes. The recovery of these storms was clearly related to reduction in the southward IMF [e.g., *Daglis et al*., 2003]. We used magnetometer data from the geomagnetic equator (Yap, –0.3° GML) and the low latitude (Okinawa, 14.47° GML), to derive the equatorial DP2.

## 2. OBSERVATIONS

### *2.1. Selected Geomagnetic Storms*

We analyzed geomagnetic storms on April 18, 2001, November 6, 2001, and September 4, 2002. These three storms were characterized by sudden commencement (SC) immediately followed by ring current development as seen in the SYM-H, which were caused by the solar wind shock accompanied by the southward IMF. On the other hand, the recovery of the three storm events was initiated by the northward turning of the IMF, reduction in the southward IMF, and an impulsive northward deflection embedded in the prolonged southward IMF. To detect the electric field penetrated to low latitudes, we used the equatorial DP2 defined as a difference between *H*-component magnetic fields at the geomagnetic equator, Yap (YAP, 0.3°S GML), and at low latitude, Okinawa (OKI, 14.47°N GML). In deriving the equatorial DP2, we assumed that these two stations are under the same effects of the magnetospheric currents because of their short latitudinal distance, and that the DP2 at low latitude is considerably less than the equatorial DP2. We used the $B_y$ at Cambridge Bay [CBB; 77.21° Corrected Geomagnetic Latitude (CGML), magnetic local time (MLT) = UT – 8] or $B_x$ at Thule (THL; 85.22° CGML, MLT = UT – 3) to infer variations in the polar cap potential (PCP), and used contour maps of the intensity of the westward auroral electrojet (AEJ) derived from the International Monitor for Auroral Geomagnetic Effects (IMAGE) magnetometer array data to infer the location and motion of the auroral oval during the main and recovery phases of the storm. Positive deflections of the $B_x$ (THL) and negative deflections of the $B_y$ (CBB) responded well to the southward IMF, which, therefore, represent variations in PCP.

### *2.2. April 18, 2001 Storm*

The first storm was caused by the southward IMF of magnitude 17 nT accompanied by the solar wind shock as observed by WIND located at (5.6, –227, –132 Re at 01 UT) (Figure 1). The storm ring current developed simultaneously with increases in PCP (upper panel) and AEJ (middle panel), immediately after the SC at 0046 UT (Figure 2), and the development of the ring current continued for 210 min as expressed with the SYM-H (Figure 1). The simultaneous development of the PCP and ring current implies near-instantaneous transmission of the convection electric field to the inner magnetosphere.

PCP and AEJ developed during the early main phase (0046–0310 UT), and the AEJ moved equatorward from 68° to 60° CGML concurrently with the increase in PCP during the late main phase (0330–0415 UT). On the other hand, the equatorial DP2 increased simultaneously with PCP and AEJ, and remained positive during the main phase. This indicates continuous penetration of the convection electric field for more than 3 h during the main phase of the storm, in agreement with the results presented by *Huang et al*. [2005]. It should be noted, however, that the equatorial DP2 decreased conversely to the increase in PCP and AEJ during the late main phase. This converse behavior of the DP2 must be caused by a shielding electric field developed equatorward of the AEJ. The AEJ then moved poleward at 0415 UT, and reached the latitude of 72° CGML at 0500 UT at the beginning of the storm recovery phase. At this time, the DP2 changed into the CEJ at the equator, and the storm changed into the recovery phase at 0430 UT.

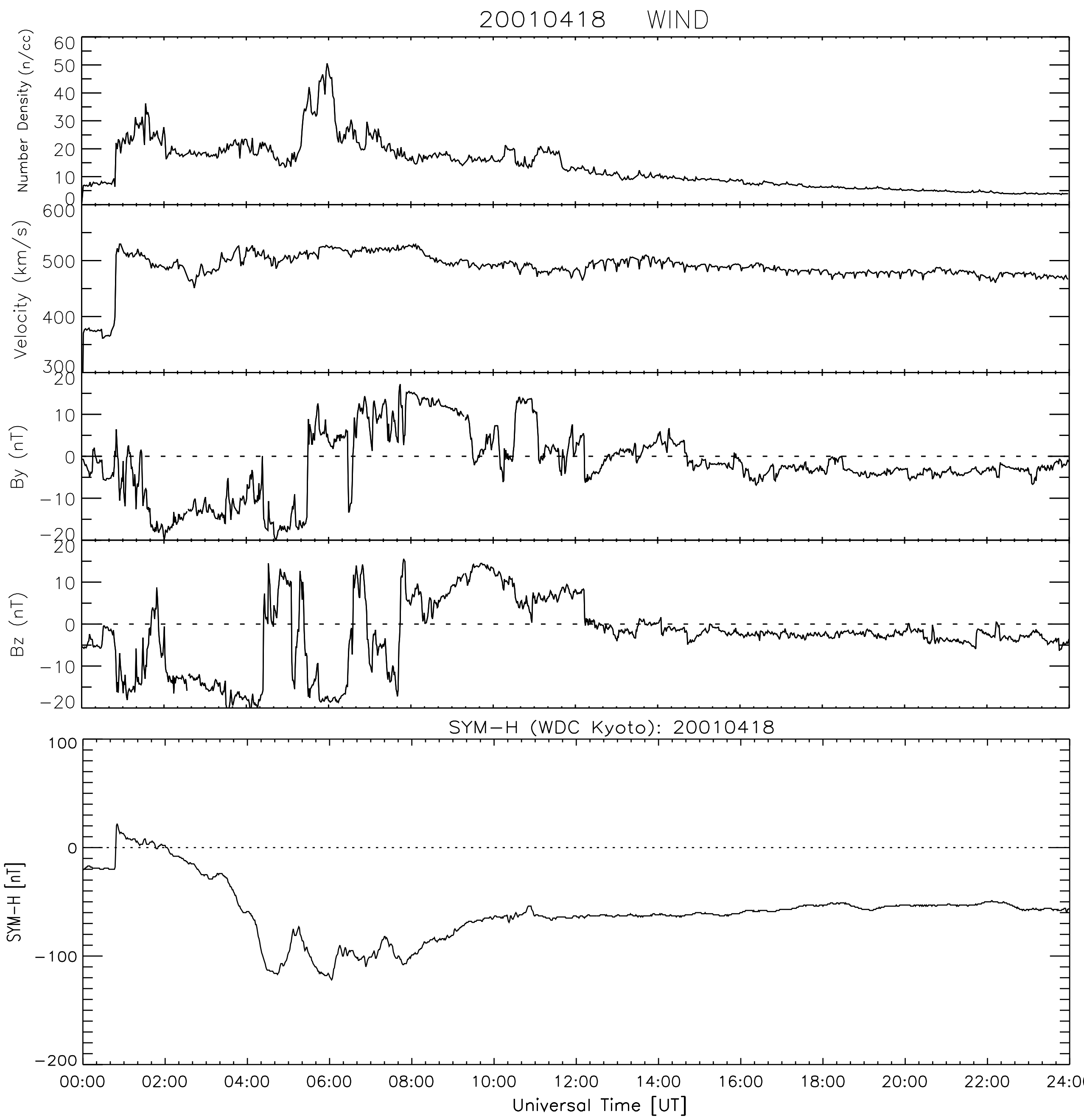


**Figure 1.** From top to bottom, the solar wind number density, velocity, the IMF $B_y$ and $B_z$ observed by WIND at (5.6, –227, –132 Re), and the SYM-H for the April 18, 2001 storm event, are shown.

*2.3. November 6, 2001 Storm*

Figure 3 shows the IMF observed by WIND at (44.1–75.0, 22.0 Re at 02 UT) and SYM-H for the second storm event. The SC started at 0152 UT with the amplitude of 89 nT, and the ring current developed immediately after the SC, being caused by the southward IMF of –55 nT. The ring current continued to develop for 80 min to reach the minimum of –330 nT at 0310 UT, and decayed after 0400 UT, when the southward IMF was decreasing. The PCP increased over

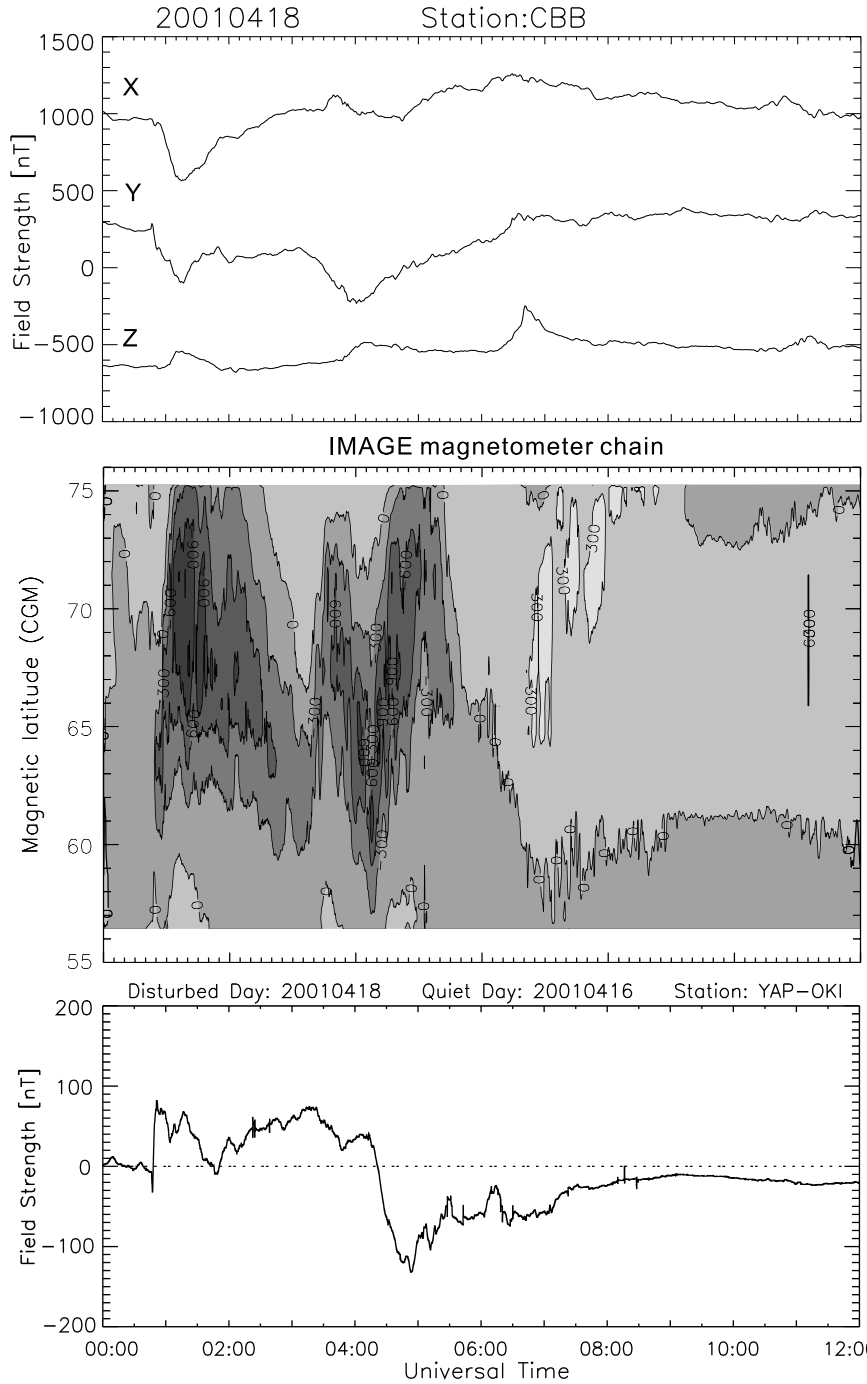


**Figure 2.** *X*-, *Y*-, and *Z*-component magnetic fields at Cambridge bay (CBB) (top panel), contour map of the westward auroral electrojet (AEJ) intensity derived from the IMAGE magnetometer array (middle panel), and the equatorial DP2 derived from the *H*-component magnetic fields at the geomagnetic equator (Yap) and low latitude (Okinawa) (bottom panel) for the April 18, 2001 storm event.

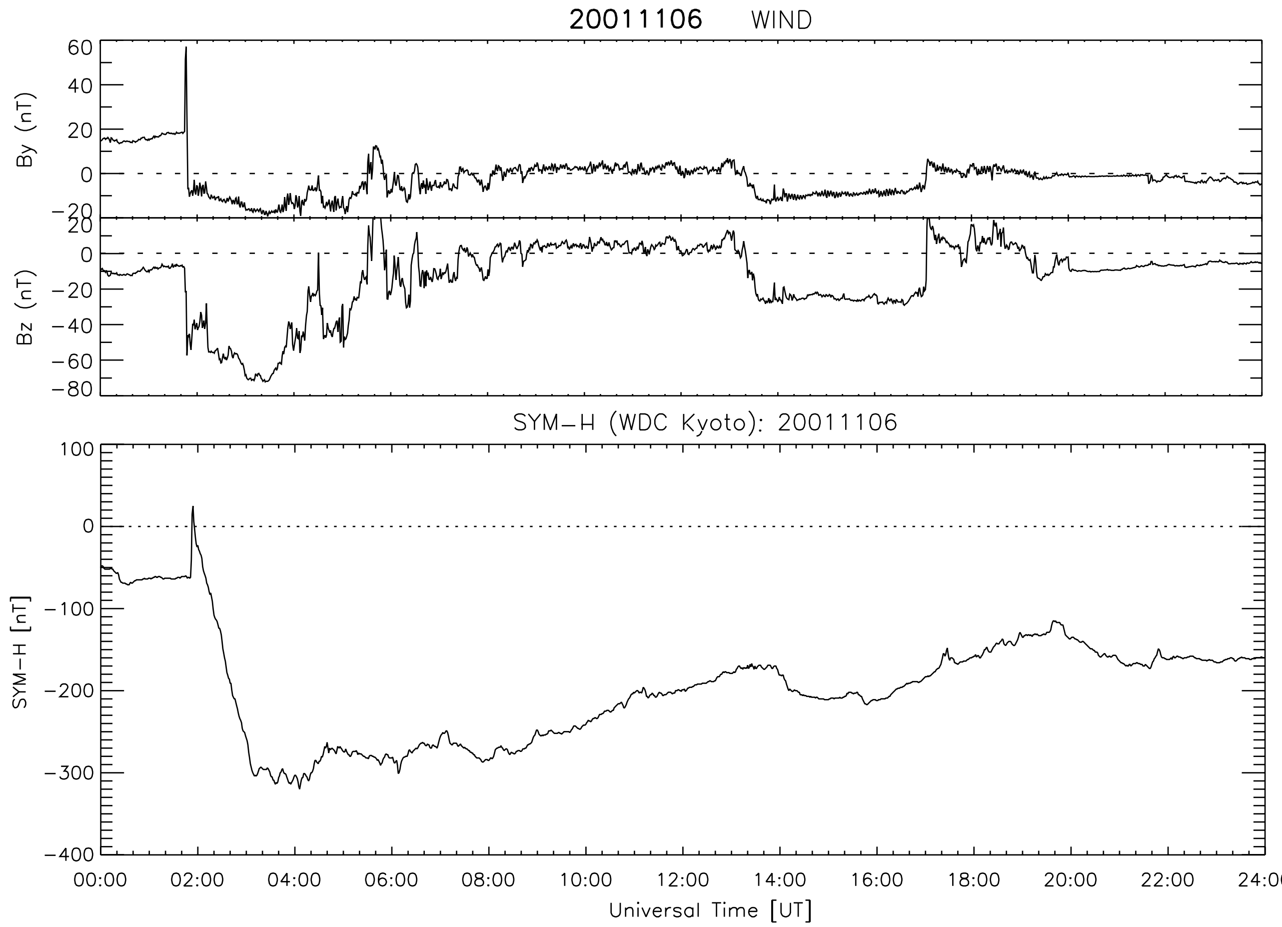


**Figure 3.** From top to bottom, the IMF $B_y$ and $B_z$ observed by WIND at (44.1–75.0, 22.0 Re), and the SYM-H for the November 6, 2001 storm event, are shown.

two time intervals, 0150–0340 UT and 0410–0550 UT, as seen in the *X*-component of the magnetic field at THL (upper panel, Figure 4). In correspondence to the first PCP increase, the AEJ developed immediately after the SC at mid latitudes (55–60° CGML) centered at 57° CGML (middle panel, Figure 4), and remained strong with a magnitude of 2000 nT for the first time interval. The AEJ then moved rapidly poleward to the auroral latitude centered at 67°, and remained high with a magnitude of 2000 nT for the second time interval. The equatorial DP2 developed simultaneously with the increase in PCP and AEJ, and remained positive with a peak amplitude of 280 nT until 0340 UT, and then the DP2 turned into the CEJ (lower panel, Figure 4). It should be noted that the equatorial DP2 started to decrease at 0240 UT, whereas the AEJ was strengthened with the peak at 0300 UT and remained high until 0340 UT. The decrease in equatorial DP2 indicates growth of the shielding electric field during the late growth phase, and the CEJ occurred due to overshielding during the early recovery phase. The rapid poleward motion of the AEJ implies a contraction of the auroral oval and would decrease the convection electric field at low latitudes. As a result, the overshielding occurred at lower latitudes and caused the CEJ at the equator. It should be stressed that the storm went into the recovery phase, when the overshielding occurred.

### *2.4. September 4, 2002 Storm*

Figure 5 shows the solar wind parameters observed by WIND located at (63.8, 40.5, −6.5 Re at 02 UT) and SYM-H. The SC started at 0150 UT, and the ring current developed at 0210 UT, which was caused by the southward IMF of −19 nT. The ring current developed for 140 min, and started to decay at the time of an impulsive positive deflection of the

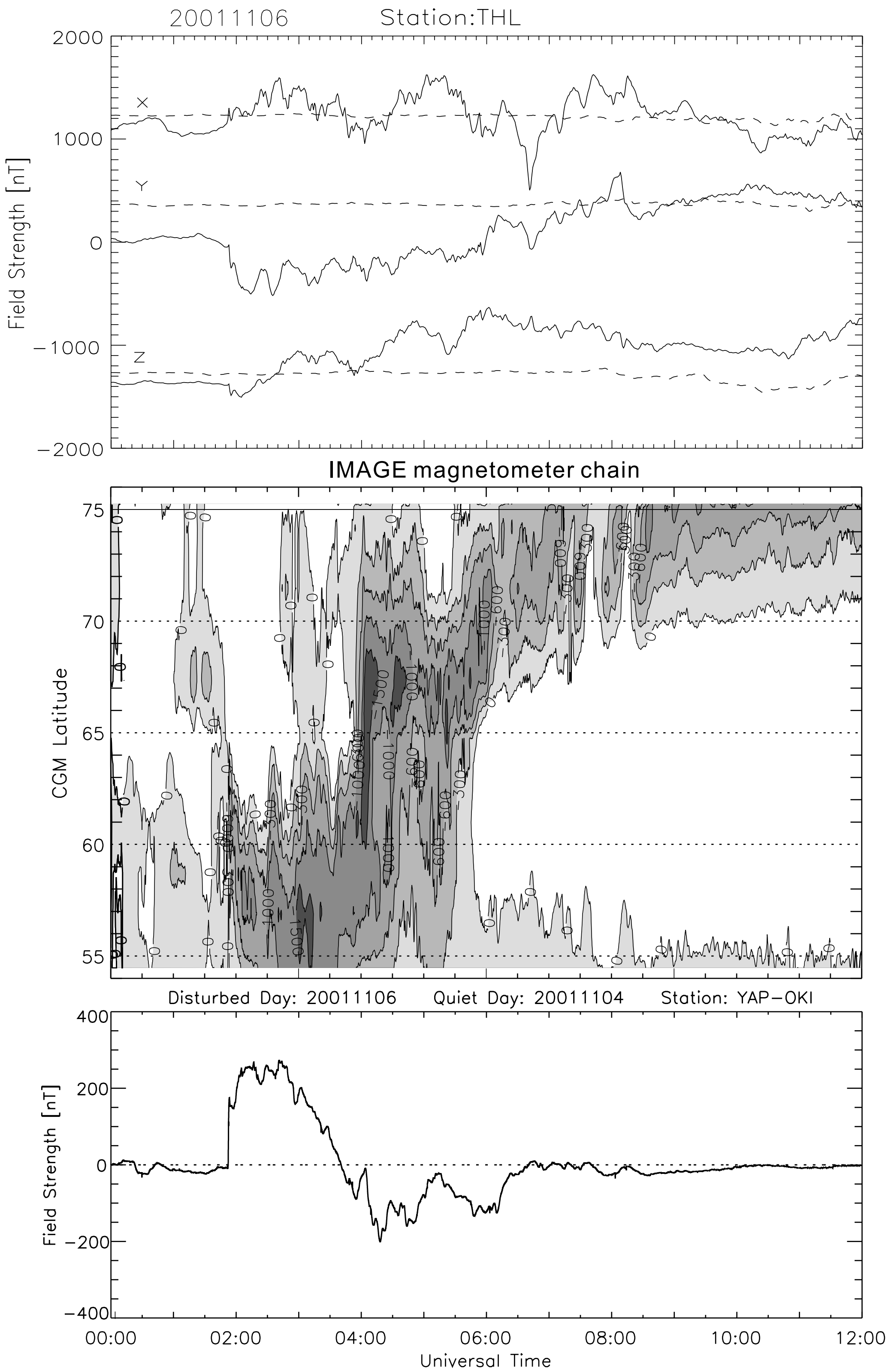


**Figure 4.** *X*-, *Y*-, and *Z*-component magnetic fields at Thule (THL) (top panel), contour map of the westward AEJ intensity derived from the IMAGE magnetometer array (middle panel), and the equatorial DP2 derived from the *H*-component magnetic fields at the geomagnetic equator (Yap) and low latitude (Okinawa) (bottom panel) for the November 6, 2001 storm event.

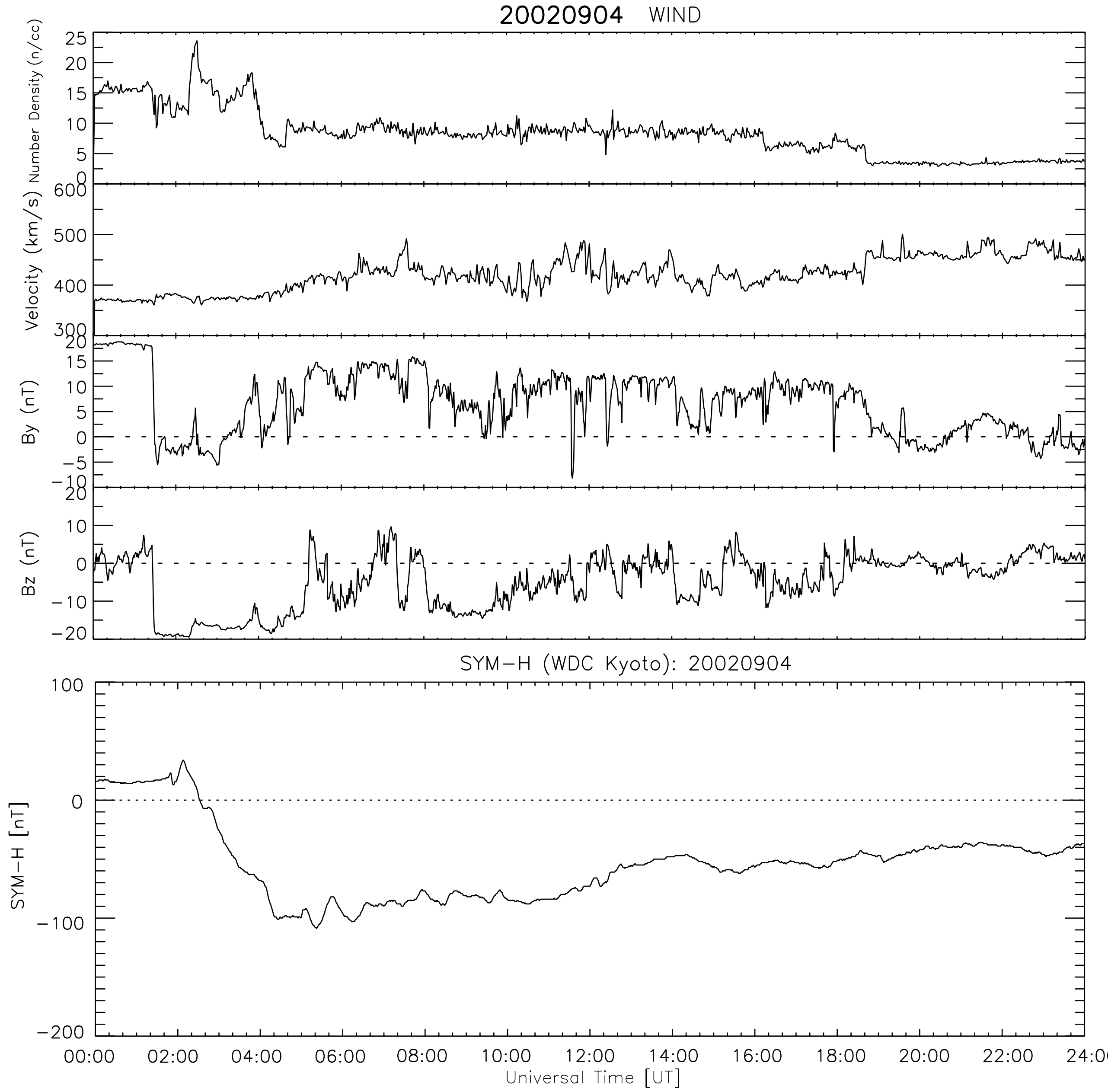


**Figure 5.** From top to bottom, the solar wind number density, velocity, the IMF $B_y$ and $B_z$ observed by WIND at (63.8, 40.5, –6.5 Re), and the SYM-H for the September 4, 2002 storm event, are shown.

IMF at 0400 UT. The southward IMF increased again for 30 min, but the ring current did not develop again as seen in the SYM-H (Figure 5).

The AEJ developed at auroral latitudes (65–70° CGML) during the early main phase (0200–0250 UT) (middle panel, Figure 6). On the other hand, the AEJ intensified at lower latitudes (58–64° CGML) during the late main phase (0250–0420 UT), and then intensified at auroral latitude (62–67° CGML) during the early recovery phase. These temporal and latitudinal behaviors of the AEJ are similar to those of the first and second events.

The equatorial DP2 increased at 0150 UT from the negative level that might be caused by previous disturbances, and remained positive until 0410 UT (lower panel, Figure 6). The

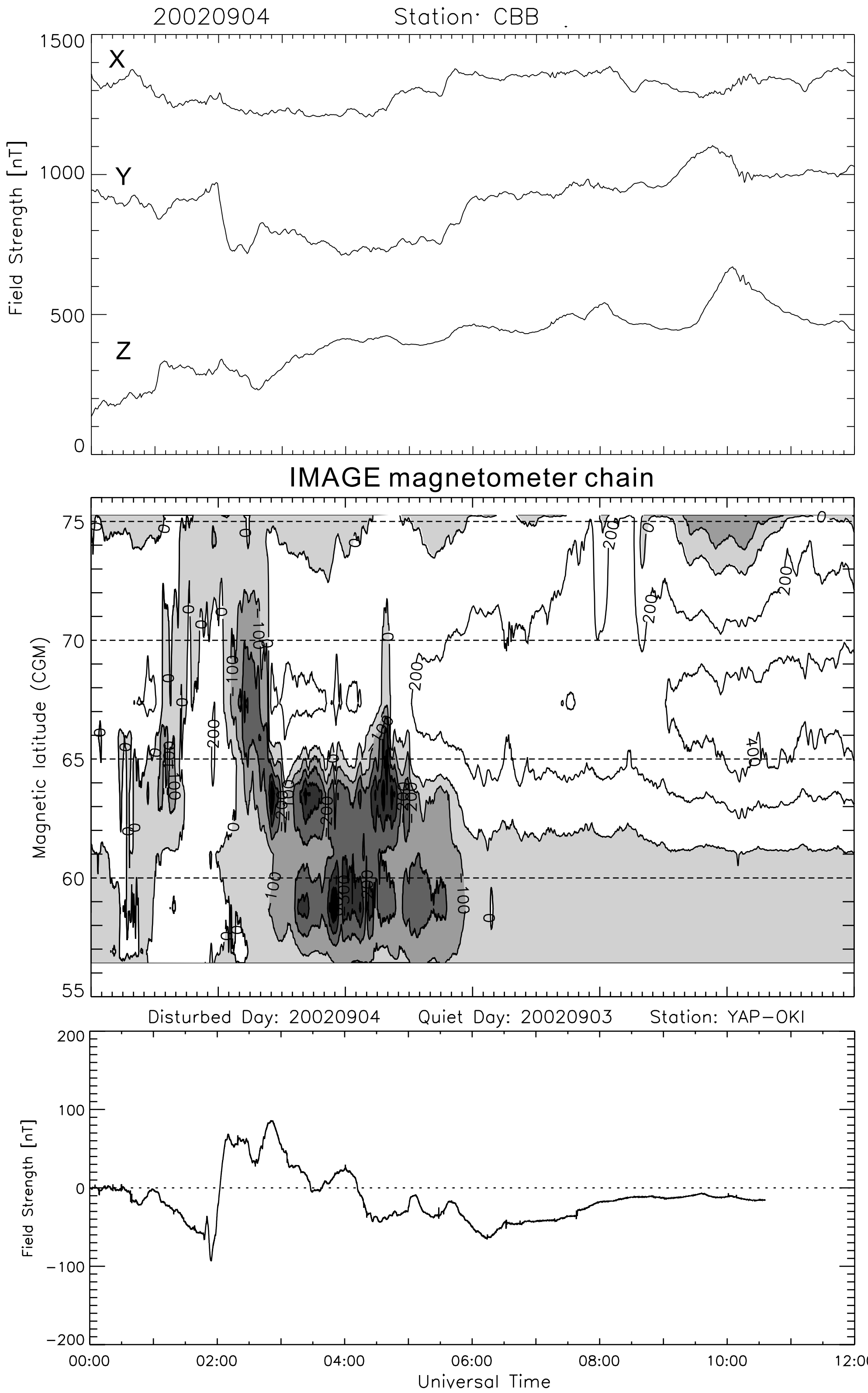


**Figure 6.** *X*-, *Y*-, and *Z*-component magnetic fields at Cambridge bay (CBB) (top panel), contour map of the westward AEJ intensity derived from the IMAGE magnetometer array (middle panel), and the equatorial DP2 derived from the *H*-component magnetic fields at the geomagnetic equator (Yap) and low latitude (Okinawa) (bottom panel) for the September 4, 2002 storm event.

equatorial DP2 decreased gradually with some fluctuations over the period of the equatorward shift of the AEJ (0250–0420 UT) during the late main phase. The CEJ then occurred at 0410 UT, a little earlier than the onset of the poleward shift of the AEJ, and continued for about 3 h during the early recovery phase. These latitudinal and temporal variations are very similar to those of the first and second events, suggesting growth of the shielding electric field during the late main phase. It is remarkable that the southward IMF became strong again after the impulsive northward deflection, but it did not increase the ring current again, probably because of the significant growth of the overshielding electric field. It is suggested that the overshielding contributed to the decay of the ring current.

## 3. DISCUSSION AND CONCLUSION

We have shown three storm events initiated by the shock-associated southward IMF and recovered by a decrease in the southward IMF. The equatorial DP2 started to increase simultaneously with the ring current development as well as the PCP and AEJ. These facts imply that the convection electric field penetrated simultaneously into the equatorial ionosphere and inner magnetosphere. The fast mode wave propagates across the magnetic field line, carrying an inductive electric field to the equatorial ionosphere. However, the electric field associated with the fast mode wave never causes currents responsible for the ground magnetic perturbations, but tends to shield the incoming magnetic perturbations [*Kikuchi and Araki*, 1979a]. Furthermore, the fast mode in the ionospheric *F* region suffers great attenuation because of the dominant electron-neutral particle collision frequency [*Strangeway et al*., 2001]. As a result, the ionosphere behaves as an incompressible medium for the ultralow frequency range perturbations [*Kivelson and Southwood*, 1988]. The instantaneous transmission of the convection electric field to the equator has been explained by means of the zeroth-order transverse magnetic ($TM_0$) mode wave in the Earth–ionosphere waveguide [*Kikuchi et al*., 1978; *Kikuchi and Araki*, 1979b], which propagates horizontally at the speed of light. The $TM_0$ mode wave accompanies electric currents in the ionosphere and on the ground, which are connected by the displacement current at the wave front of the $TM_0$ mode wave. The ionospheric current generates an electric field in the ionospheric finite conductivity, which is mapped upward along the field lines by the Alfven waves, with no attenuation under a condition of large ionospheric conductance to Alfven conductance ratio [*Kikuchi*, 2005]. Indeed, strong electric field penetrated to the inner magnetosphere as observed by CRRES and Akebono satellites during geomagnetic storms [*Burke et al*., 1998; *Wilson et al*., 2001; *Shinbori et al*., 2005]. The electric field would drive the plasma convection in the inner magnetosphere, causing the development of the storm ring current. *Wilson et al*. [2001] suggested close relationship between the DP2 currents and the electric field in the inner magnetosphere. We are able to suggest that the development of the polar–equatorial ionospheric currents has an impact on the ring current evolution.

The convection electric field penetrates instantaneously to low latitudes, but suffers from shielding in about 20 min for substorm events [*Somajajulu et al*., 1987; *Kikuchi et al.*, 2000]. *Huang et al*. [2005], however, suggested that the penetration continued for many hours during the main phase of the storm. Indeed, the equatorial DP2 continued for 2–3 h during the main phase of the storms analyzed in this paper (Figures 2, 4, and 6). It should be noted, however, that shielding electric field became effective during the late main phase, for example, 1 h after the onset of the main phase of the November 6, 2001 storm event. The growth of the shielding electric field resulted in the overshielding when the convection electric field decreased because of the reduction in the southward IMF at the beginning of the recovery phase. It should be noted that the overshielding occurred when the IMF remained southward during the storm events, whereas it occurs when the IMF turns northward during the substorm [*Rastogi and Patel*, 1975; *Kelley et al*., 1979; *Kikuchi et al*., 2003]. The distinct feature of the stormtime overshielding may be due to the fact that the ring current is much stronger and the location of the R1 and R2 FACs is far equatorward from the auroral latitude.

The growth of the shielding electric field accompanied the equatorward shift of the AEJ, and the AEJ moved rapidly poleward at the beginning of the recovery phase. These latitudinal motions of the AEJ may be a signature of the substorm. The substorm may play a crucial role in initiating the storm recovery phase as suggested by *Iyemori and Rao* [1996] and *Ohtani et al*. [2001]. Continuous reduction in the southward IMF is needed for the recovery of the storm [e.g., *Ohtani et al*., 2001], which is valid for the first two storm events analyzed above. On the other hand, the southward IMF increased again after the impulsive northward deflection in the third event, but it never intensified the ring current again. The overshielding may have contributed to end the development of the ring current, and initiate the storm recovery phase.

In conclusion, there are two types of equatorial electrojet during the storm. One is the DP2 current driven by the penetrated convection electric field during the main phase, which occurs concurrently with the enhancement in PCP and AEJ. The other is the CEJ caused by the overshielding electric field during the recovery phase, which was accompanied by the rapid poleward shift of the AEJ. The substorm may have played a role in the transition of the storm into the recovery phase, as has been suggested by *Iyemori and Rao* [1996] and *Ohtani et al*. [2001]. In addition, we suggest that overshielding electric fields may have played a role in the storm recovery, reducing the electric fields that influence ring current development in the inner magnetosphere. From the electric current viewpoint, the R1 and R2 FACs flowed into the dayside equatorial ionosphere via the polar ionosphere, driving the equatorial DP2 and CEJ, during the main and recovery phases, respectively.

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