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REVIEW

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Transmission of the electric fields to the low latitude ionosphere in the magnetosphere-ionosphere current circuit

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Abstract

The solar wind energy is transmitted to low latitude ionosphere in a current circuit from a dynamo in the magnetosphere to the equatorial ionosphere via the polar ionosphere. During the substorm growth phase and storm main phase, the dawn-to-dusk convection electric field is intensified by the southward interplanetary magnetic field (IMF), driving the ionospheric DP2 currents composed of two-cell Hall current vortices in high latitudes and Pedersen currents amplified at the dayside equator (EEJ). The EEJ-Region-1 field-aligned current (R1 FAC) circuit is completed via the Pedersen currents in midlatitude. On the other hand, the shielding electric field and the Region-2 FACs develop in the inner magnetosphere, tending to cancel the convection electric field at the mid-equatorial latitudes. The shielding often causes overshielding when the convection electric field reduces substantially and the EEJ is overcome by the counter electrojet (CEJ), leading to that even the quasi-periodic DP2 fluctuations are contributed by the overshielding as being composed of the EEJ and CEJ. The overshielding develop significantly during substorms and storms, leading to that the mid and low latitude ionosphere is under strong influence of the overshielding as well as the convection electric fields. The electric fields on the day- and night sides are in opposite direction to each other, but the electric fields in the evening are anomalously enhanced in the same direction as in the day. The evening anomaly is a unique feature of the electric potential distribution in the global ionosphere. DP2-type electric field and currents develop during the transient/short-term geomagnetic disturbances like the geomagnetic sudden commencements (SC), which appear simultaneously at high latitude and equator within the temporal resolution of 10 s. Using the SC, we can confirm that the electric potential and currents are transmitted near-instantaneously to low latitude ionosphere on both day- and night sides, which is explained by means of the light speed propagation of the TM_0 mode waves in the Earth-ionosphere waveguide.

Introduction

This article reviews the transmission of the electric field and currents from the dynamos in the magnetosphere down to the equatorial ionosphere to better understand the ionospheric and geomagnetic disturbances at mid and low latitudes during substorms and storms. The dynamo for the convection electric field and the Region-1 field-aligned currents (R1 FACs) is reviewed in "Convection electric field and global DP2 currents" section, and that for the shielding/overshielding and the R2 FACs in "Overshielding electric field and CEJ" section. These two kinds of electric fields and currents play a crucial role in the substorm and storm as reviewed in "DP2 and CEJ during the substorm" and "Stormtime electric field and EEJ/CEJ" sections, respectively. The geomagnetic sudden commencement is briefly reviewed in "Electric field and currents during the SC" section as an introduction to the mechanism for the near-instantaneous transmission from the polar ionosphere to the equator as reviewed in detail in "Electric field transmission mechanism" section.

Convection electric field and global DP2 currents

The magnetospheric convection is initiated by the reconnection between the southward interplanetary magnetic

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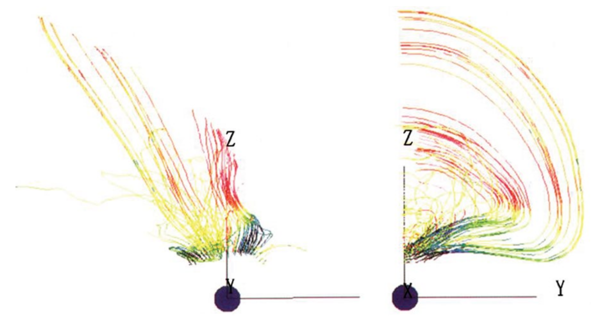

Fig. 1 Dynamo for the convection electric field and the Region-1 field-aligned currents reproduced by the global MHD simulation. The dynamo currents shown with the *red lines* are diamagnetic currents generated by the pressure force of hot plasma (*left*) poleward of the cusp region, (*right*) flowing across the magnetic field lines and driving the R1 FACs down the magnetic field lines into the ionosphere as shown with the *black lines*. The ionosphere is assumed at 3.5 Re in the simulation. (from Fig. 8 of Tanaka 1995)

field (IMF) and the Earth's magnetic field at the magnetopause (Dungey 1961). The convection electric field is generated by the dynamo around the cusp/mantle region where the solar wind energy is converted to the thermal energy of high-pressure plasma (Tanaka 1995). Figure 1 shows dynamo currents with red lines flowing (right) across the magnetic field lines (left) in the tailward cusp/mantle region and the Region-1 field-aligned currents (R1 FACs) with black lines flowing into the polar ionosphere assumed at 3.5 Re in the simulation. The red and black colors in Fig. 1 indicate negative and positive J·E (J: current, E: electric field), respectively, referring to the generation and consumption of the electromagnetic energy. The dynamo provides the dawn-to-dusk convection electric field and the R1 FACs flowing into/up from the polar ionosphere in the morning/afternoon sector, coinciding with the satellite observations (Iijima and Potemra 1976). The dawn-to-dusk electric field propagates near-instantaneously to low latitude (Kikuchi et al. 1996), directing eastward on the dayside and westward on the nightside.

The convection electric field drives the DP2 currents composed of two-cell Hall current vortices at high latitude and zonal currents at the equator (Nishida 1968). The DP2 magnetic fluctuations are well correlated with the southward IMF (Nishida 1968) and occur simultaneously at high latitude and equator (Kikuchi et al. 1996). Figure 2 shows DP2 fluctuations at high latitude (Nurmijarvi) and equator (Mokolo) with the correlation coefficient of 0.9 and no time shift greater than 25 s, suggesting near-instantaneous transmission of the convection electric field to the equator same as for the preliminary impulse (PI) of the geomagnetic sudden commencement (SC) (Araki 1977). The ionospheric currents decrease

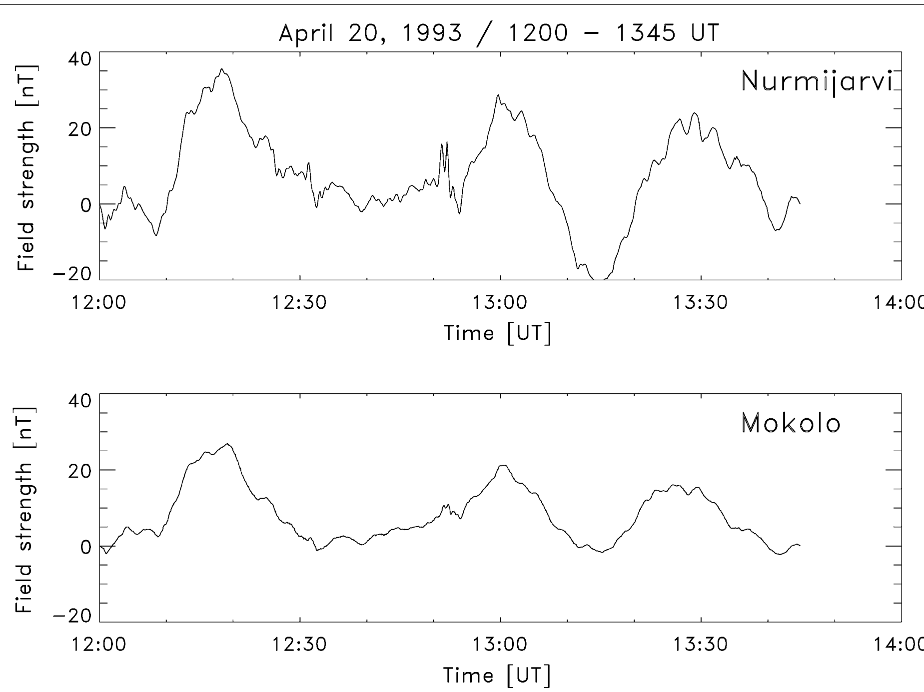

Fig. 2 Quasi-periodic DP2 magnetic fluctuations observed at high latitude (Nurmijarvi) and equator (Mokolo) with the high correlation (corr. coefficient = 0.9) and no time shift greater than 25 s, indicating near-instantaneous transmission of the convection electric field to the equator. (from Fig. 4 of Kikuchi et al. 1996)

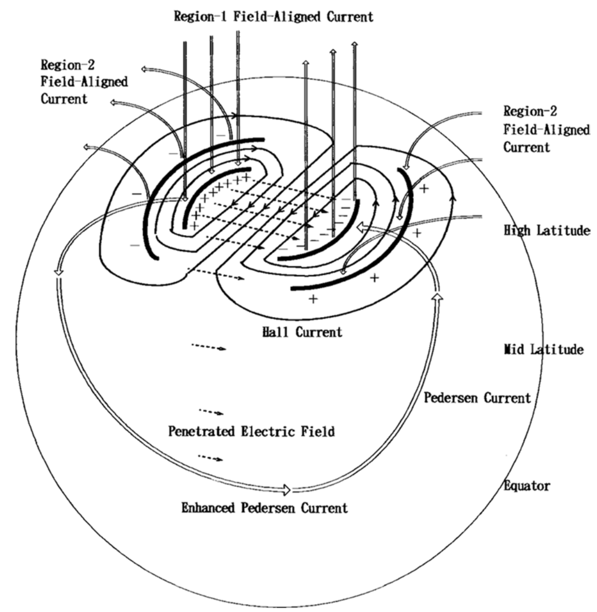

Fig. 3 A schematic diagram of the DP2 ionospheric currents composed of the two-cell Hall currents at high latitudes driven by the dawn-to-dusk convection electric field under the southward IMF condition and the Pedersen currents flowing into the equatorial ionosphere where the current is enhanced by the Cowling effect (EEJ). A current circuit is completed between the EEJ and R1 FACs via the midlatitude Pedersen currents carried by the TM_0 mode wave in the Earth-ionosphere waveguide. (from Fig. 9 of Kikuchi et al. 1996)

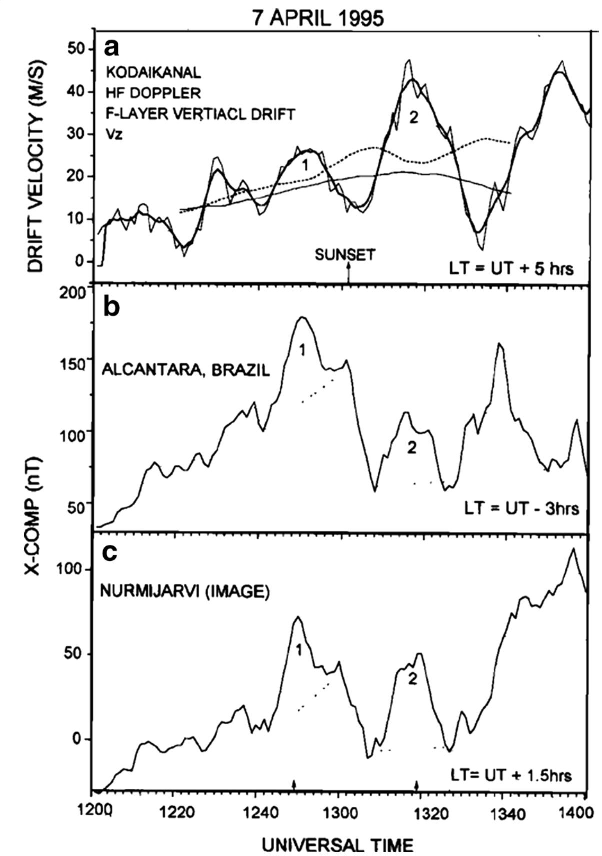

Fig. 4 (*top, thick solid curves*) Vertical drift of the F-region ionosphere observed with the HF Doppler sounder over the equator (KODAIKANAL), which is well correlated with the DP2 magnetic fluctuations at the (*middle*) dayside equator (ALCANTARA) and (*bottom*) afternoon high latitude (NURMIJARVI). The electric field deduced from the drift velocity is significantly enhanced in the evening with the same direction as in the day. (from Fig. 2 of Abdu et al. 1988)

with decreasing latitude because of the geometrical attenuation, but increased at the dayside equator where the currents are intensified by the Cowling effect (EEJ) (Hirono 1952; Baker and Martyn 1953). The enhanced EEJ is an important feature of the equatorward extension of ionospheric currents from the polar ionosphere. Figure 3 shows a schematic diagram of the R1 FACs-EEJ circuit via the polar ionosphere achieved when the R1 FACs dominates over the R2 FACs under the southward IMF condition (Kikuchi et al. 1996). A current circuit is completed by the midlatitude Pedersen currents carried by the TM_0 mode wave in the Earth-ionosphere waveguide (Kikuchi and Araki 1979).

It should be noted that the DP2 electric fields in the evening are significantly enhanced having the same direction as those in the day (Abdu et al. 1988). Figure 4 shows that the eastward electric field in the afternoon-evening hours (upward drift velocity indicated with the thick solid curves in Fig. 4, top) is well correlated with the DP2 currents at the dayside equator (ALCANTARA in the middle) and afternoon high latitude (NURMIJARVI in the bottom). The evening anomaly is a unique feature of the global distribution of the electric potential as calculated by the potential solver with an input of the field-aligned currents in the polar ionosphere (Senior and Blanc 1984; Tsunomura and Araki 1984). Figure 5 shows the electric field calculated for the equator with the model of Tsunomura and Araki (1984) (T and A), Senior and Blanc (1984) (S and B) and Tsunomura (1999) (New), reproducing the evening anomaly with the same direction as in the day and enhanced magnitude.

The diurnal magnetic variation at the geomagnetic equator is often depressed substantially during disturbed periods (Matsushita and Balsley 1972). Matsushita and Balsley (1972) critically discussed that the DP2 fluctuations should be measured negative from the quiettime diurnal variation. However, the good correlation between the DP2 fluctuations at high and equatorial latitudes (Kikuchi et al. 1996) are in favor of measuring positive as was done by Nishida (1968). The depression of the diurnal variation must be caused by a westward electric field due to the disturbance dynamo (Blanc and Richmond

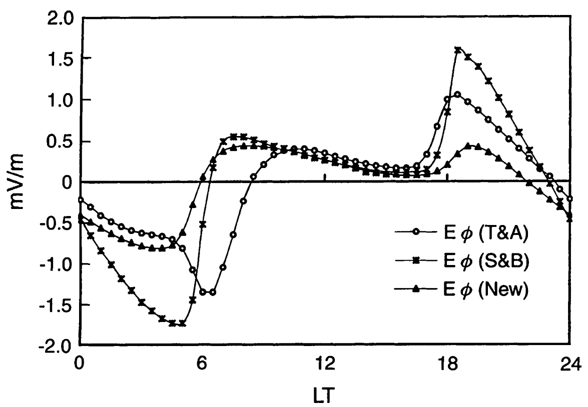

Fig. 5 Electric fields at the equator calculated by the three different potential solvers [T and A (Tsunomura and Araki 1984), S and B (Senior and Blanc 1984), New (Tsunomura 1999)] with an input of field-aligned currents in the polar ionosphere. All the model calculations show the evening anomaly of the electric field in the same direction as in the day with significant enhancement in magnitude. (from Fig. 5 of Tsunomura 1999)

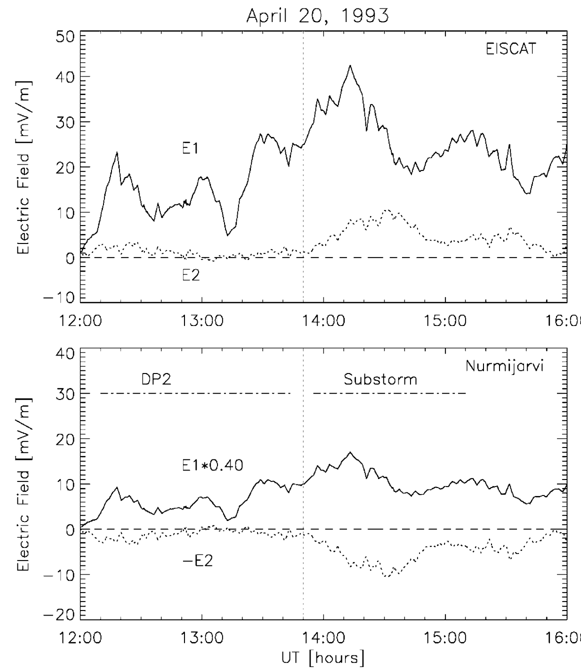

Fig. 6 Convection (E_1) and shielding (E_2) electric fields shown with the *solid* and *dotted lines*, respectively, at the (*top*) auroral and (*bottom*) subauroral latitudes as deduced from the electric field measured by EISCAT and IMAGE magnetometer array data. The convection electric field dominates over the shielding electric field at both latitudes during the growth phase (DP2), while the shielding electric field is intensified and dominates over the convection electric field at subauroral latitude with reduced magnitude (0.4 E_1) because of the geometrical attenuation during the substorm identified with the midnight Pi2. (from Fig. 8 of Kikuchi et al. 2000)

1980), which is activated in the midlatitude thermosphere/ionosphere by the westward thermospheric wind having traveled from the disturbed polar thermosphere.

Overshielding electric field and CEJ

The enhanced convection electric field drives an earthward motion of plasma in the plasma sheet, generating the partial ring current and Region-2 field-aligned currents (R2 FACs) in the inner magnetosphere (Vasyliunas 1972). The partial ring current builds up the shielding electric field with an opposite direction to the convection electric field, which intensifies the electric field at auroral latitude but reduces it at the mid and low latitudes. The time constant of the growth of the shielding has been estimated as 20 min from the magnetometer observations (Somayajulu et al. 1987) and 20–30 min from the theoretical calculations (Peymirat et al. 2000).

When the convection electric field reduces abruptly because of the northward turning of the IMF, the electric field reverses its direction at mid-equatorial latitudes, causing the equatorial counter electrojet (CEJ) (Rastogi 1977). The reversal of the electric field was confirmed by the Jicamarca incoherent scatter radar at the equator, which was identified as the overshielding electric field (Kelley et al. 1979; Gonzales et al. 1979).

DP2 and CEJ during the substorm

The substorm growth phase is initiated by the southward turning of the IMF, which causes the DP2 currents in the ionosphere (McPherron 1970; Kamide et al. 1996). Kikuchi et al. (2000) separated out the convection and shielding electric fields during the substorm as shown in Fig. 6 where the solid/dashed curves indicate the convection/shielding electric fields at (top) auroral and (bottom) subauroral latitudes. The convection electric field dominates during the growth phase before the onset identified with the midnight Pi2 (vertical dotted line); however, the shielding electric field develops after the onset, leading to the overshielding when the shielding electric field dominates over the convection electric field in the recovery of the substorm as shown in Fig. 6 (bottom). The overshielding electric field drives the equatorial CEJ, causing the equatorial enhancement of the negative bay (Kikuchi et al. 2000).

Figure 7 indicates a schematic diagram of the substorm currents composed of the partial ring current, R2 FACs, and the equatorial CEJ with the Hall currents surrounding the R2 FACs causing reversal of the ionospheric currents at midlatitude (Kikuchi et al. 2003). It is to be noted that the overshielding electric field starts to increase at the onset of the substorm and continues

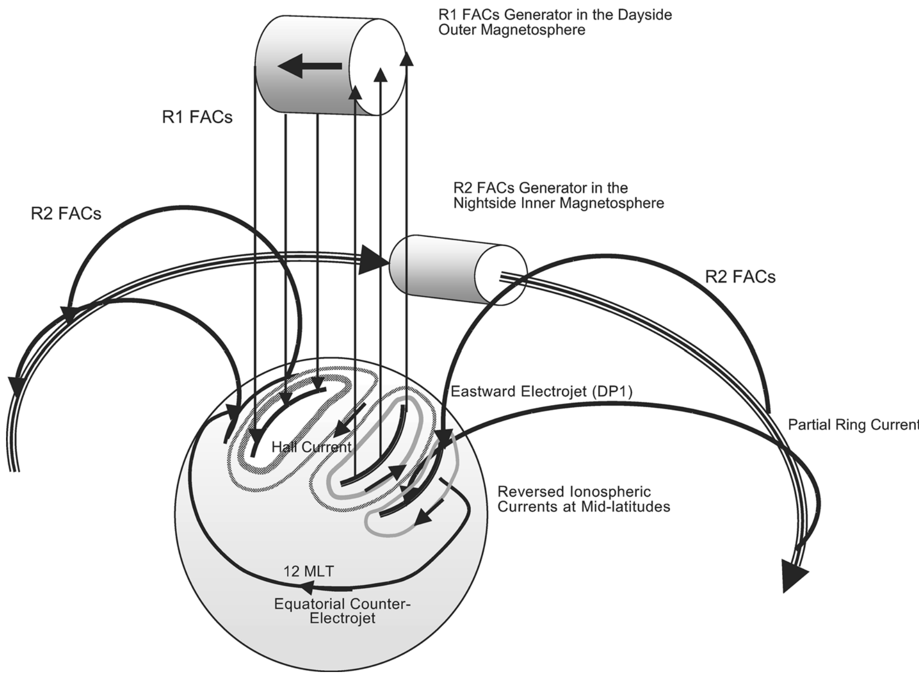

Fig. 7 Schematic diagram of the substorm current circuit composed of the partial ring current, R2 FACs and equatorial CEJ with the Hall currents surrounding the R2 FACs causing the reversal of the ionospheric currents at midlatitude. (from Fig. 11 of Kikuchi et al. 2003)

to grow during the expansion phase under the steady southward IMF condition (Wei et al. 2009; Hashimoto et al. 2011). Hashimoto et al. (2011) showed that both the R1 and R2 FACs develop during the substorm and that the R2 FACs is strong enough to cause overshielding. In contrast, the convection electric field was reported to be dominant during the substorm based on the analyses of the sawtooth events (Huang 2009). The contradictory observations could be due to the solar wind conditions responsible for the isolated and periodic substorms or due to the definition of the substorm whether the sawtooth events are substorms or not. If the sawtooth events were the convection bays, the electric field at low latitude would be the convection electric field same as the DP2 events. The substorm current circuits have been reproduced by the global MHD simulations, showing that the partial ring currents intensified by pressurized plasma in the near-earth magnetotail generate the R2 FACs (Tanaka et al. 2010). Furthermore, the substorm CEJ has been reproduced with the global MHD simulation, supporting the overshielding currents flowing to the equator during the substorm (Ebihara et al. 2014).

Stormtime electric field and EEJ/CEJ

The auroral electrojet expands equatorward during storms, driving the DP2 currents at midlatitudes (Feldstein et al. 1997; Wilson et al. 2001; Kikuchi et al. 2008). Wilson et al. (2001) suggested that the electric field associated with the DP2 currents might have contributed to the development of the storm ring current in the inner magnetosphere. Actually, strong convection electric fields have been observed by CRRES and Akebono at L = 2–6 (Wygant et al. 1998; Shinbori et al. 2005; Nishimura et al. 2006). The electric field is as strong as 46 mV/m during the major storm on 13 March, 1989 (Shinbori et al. 2005). The convection electric field penetrates to the equatorial ionosphere, intensifying the EEJ on the dayside (Kikuchi et al. 2008).

Rastogi (2004) demonstrated that the magnitude of the geomagnetic storm was significantly enhanced at the dayside dip equator, which was caused by the CEJ due to the northward turning of the IMF. Kikuchi et al. (2008) further showed that the geomagnetic storm was enhanced with an equatorial to low latitude amplitude ratio of 2.7 as shown in Fig. 8 where the storm at low latitude (OKI) is caused by the ring current but those at the equator (GAM, YAP) is significantly enhanced by the EEJ. The EEJ derived as a difference between the disturbances at the low latitude and equator is intensified during the main phase (02-04UT, Fig. 9, bottom), while the CEJ develops during the recovery phase (04-06 UT). Both the EEJ and CEJ contribute to the equatorial enhancement of the geomagnetic storm. The recovery phase CEJ was shown to be associated with

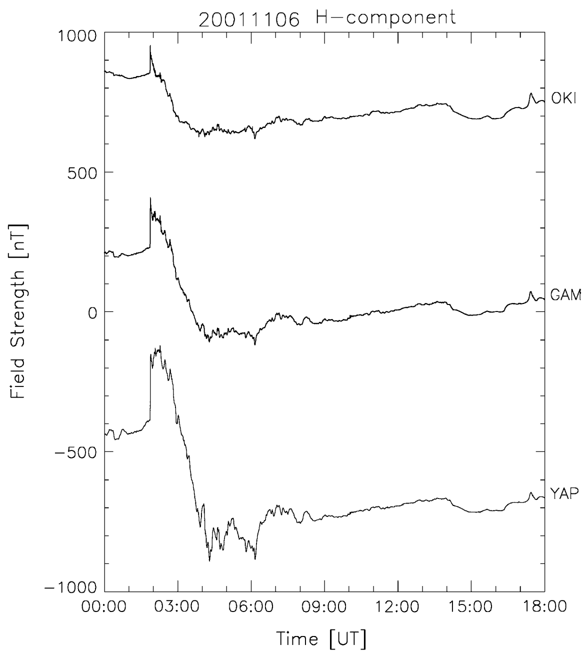

Fig. 8 Geomagnetic storm recorded at low latitude, Okinawa (*OKI*) and equator, Guam (*GAM*) and Yap, Micronesia (*YAP*) in the western Pacific region. The storm is enhanced at YAP with an enhancement ratio of 2.7, caused by combined effects of the main phase EEJ and recovery phase CEJ. (from Fig. 6 of Kikuchi et al. 2008)

the rapid poleward shift of the auroral electrojet as shown with the contours of the ionospheric current intensity in Fig. 9 (top), suggesting that the stormtime CEJ may have been caused by substorms. It is to be noted that the shielding became effective in late main phase and overshielding occurred during the recovery phase in contrast to that Huang et al. (2005) pointed out that the convection electric field continued to penetrate to low latitude for many hours during the storm. The time constant of the overshielding still remains a crucial issue, since the direction of the electric field at midlatitude would play a key role in the generation/decay of the equatorial ionospheric anomaly, magnetic disturbances, and probably ring current development/decay in the inner magnetosphere. Indeed, the overshielding electric field has been detected by the CRRES and Akebono satellites in the inner magnetosphere during the recovery phase (Wygant et al. 1998; Nishimura et al. 2006), which would contribute to the decay of the ring current.

The stormtime current circuits are composed of the R1 FAC-EEJ during the main phase and the R2 FAC-CEJ during the recovery phase, which are similar to those of the substorm growth and expansion phases, respectively. It should be noted, however, that the CEJ occurs even during the storm main phase (Fejer et al. 2007), which could have been caused by the disturbance dynamo activated by the preceding storm activities. It should be reminded that the disturbance dynamo begins to work with a time lag of several hours from the beginning of storm and continues to work for, say, 10 h (Fejer and Scherliess 1997). In contrast, the overshielding develops quickly responding to the solar wind conditions and substorm activities. The latitude and local time distribution of the ionospheric electric field would enable us to distinguish the overshielding from the disturbance dynamo.

Electric field and currents during the SC

The ionospheric currents achieved during the geomagnetic sudden commencement (SC) are similar to the DP2 currents except that the time scale of the SC is as short as a few minutes or even less. The SC is composed of the preliminary impulse (PI) and main impulse (MI) superimposed on the stepwise increase (DL) (Araki 1994). The PI and MI with typical time scales of 1 and 5 min are caused by the ionospheric currents driven by the dusk-to-dawn and dawn-to-dusk electric fields, respectively. The DL is caused by the compressional MHD waves launched by the intensified magnetopause currents (Tamao 1964). Both the PI and MI are characterized by the equatorial enhancement (Araki 1994) and the electric fields on the day- and night sides are opposite to each other except that the electric fields in the evening are in the same direction as in the day (Kikuchi 1986). The evening anomaly of the PI and MI electric fields leads to the fact that they are potential fields transmitted with the ionospheric currents, similar to the convection electric fields.

Electric field transmission mechanism

Using the SC, we can confirm the simultaneous occurrence at high latitude and equator within the temporal resolution of 10 s. Araki (1977) found that the PI started simultaneously at the equator (KO in Fig. 10) and high latitude (PB, CO, SI) and suggested that the equatorial PI is caused by the polar electric field having propagated to the equator instantaneously. The instantaneous transmission of the polar electric field was explained by means of the TM_0 mode electromagnetic waves propagating at the speed of light in the Earth-ionosphere waveguide (Kikuchi and Araki 1979). The TM_0 mode is equivalent to the TEM (transverse electromagnetic) mode in the two-conductor transmission line. As seen in Fig. 10, the equatorial PI looks isolated from the high latitude PI. This is because the propagation of the electric field suffers severe geometrical attenuation (Kikuchi and Araki, 1979) and no or small PI is observed at mid and low latitudes (FR, TU, HO). Figure 11 shows a schematic diagram of the three-layered Earth-ionosphere waveguide

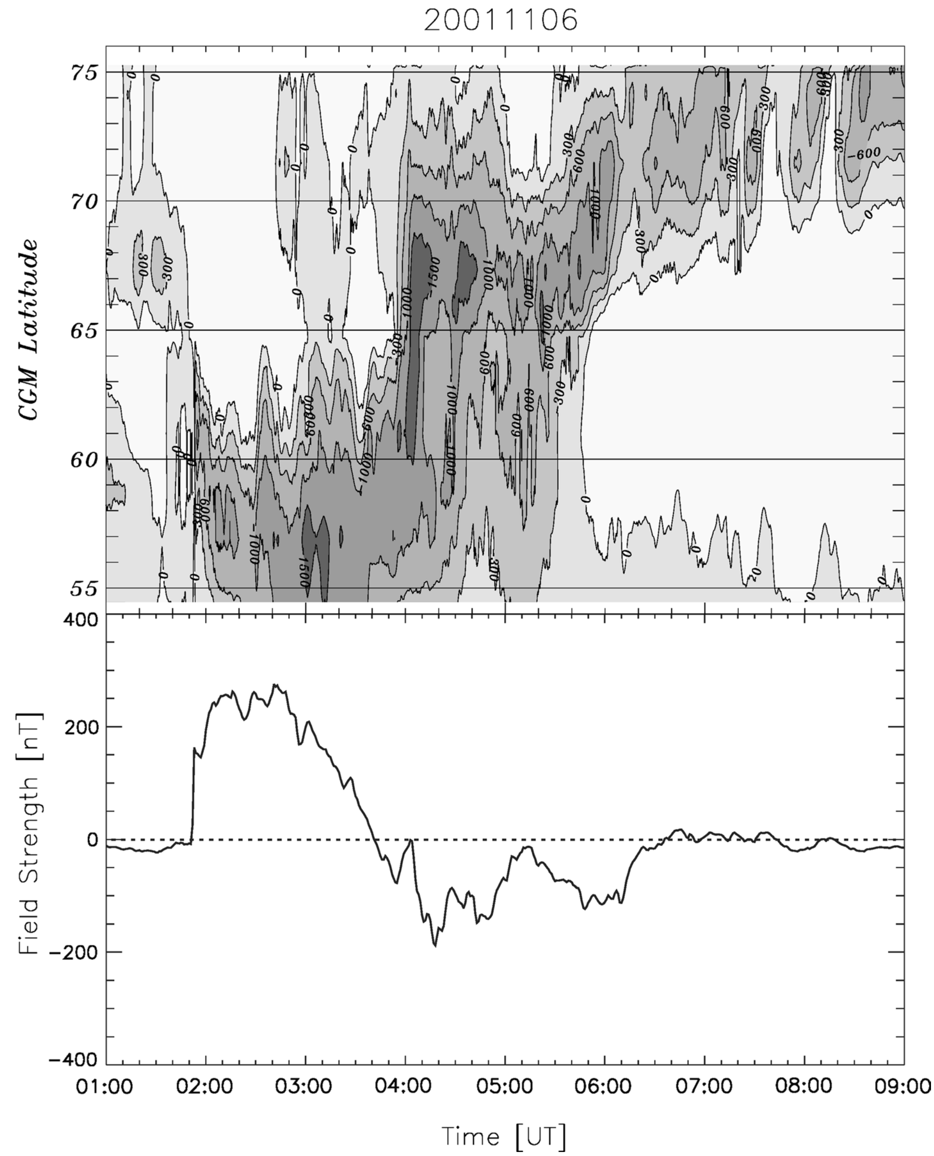

Fig. 9 (*bottom*) Equatorial electrojet obtained as a difference between the geomagnetic storms at OKI and YAP, which is composed of the EEJ and CEJ during the main and recovery phases, respectively. (*top*) The auroral electrojets shown with the contours of current intensity develop at mid-latitude below 60° corrected geomagnetic latitude (CGM) during the main phase, while they shift to the auroral latitude (60–70° CGM) during the recovery phase (from Fig. 8 of Kikuchi et al. 2008)

terminated by the fully ionized magnetosphere (Kikuchi 2014). The positive electric potential ($+V_0$) is transmitted with the downward FAC (thick arrow) to the left end of the waveguide, providing the vertical electric field, E_{zV} in the waveguide, which excites the TM_0 mode wave propagating with the horizontal Poynting flux, S_{xV}, at the speed of light. The TM_0 mode wave carries electric currents in the ionosphere and on the ground, which are connected by the displacement current on the wave front of the TM_0 mode wave. The same propagation mechanism works for the negative potential of the upward FAC. Then, a current circuit is completed between the magnetospheric dynamo and the equatorial ionosphere as schematically shown in Fig. 12, which allows the dynamo current to flow into the global ionosphere and further into the ground even in a steady state. Under an assumption of an east–west symmetry, the positive and negative potentials meet and cancel each other in the noon-midnight meridian. The ionosphere with zero-potential is effectively connected to the ground with zero-potential. Thus, the noon-midnight meridian can be replaced with a perfectly conducting sheet as shown with the vertical

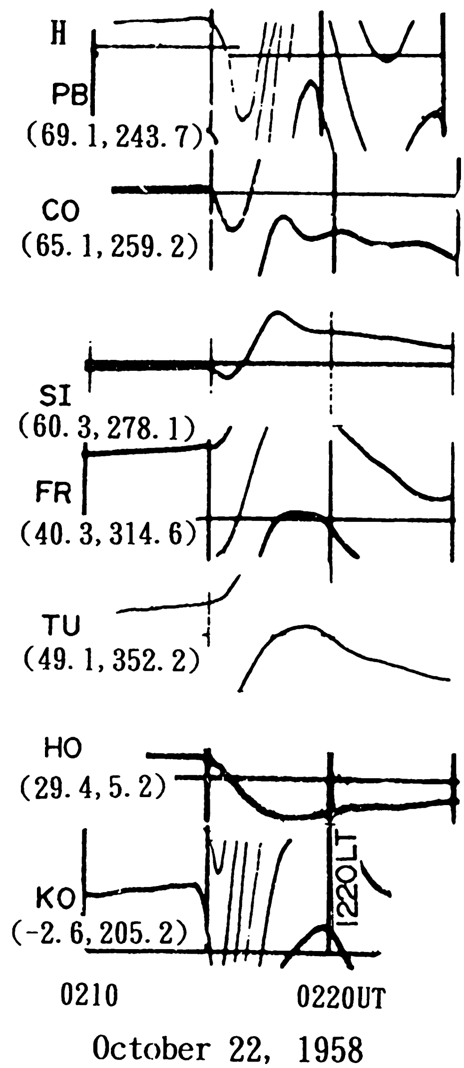

Fig. 10 The preliminary impulses (PI) at high latitude (PB, CO, SI) and equator (KO), beginning simultaneously within the temporal resolution of 10 s, while no or small PI is observed at mid and low latitudes (FR, TU, HO). The simultaneity of the onset suggests the instantaneous transmission of the polar electric field to the equator (from Fig. 7 of Araki 1977)

dashed line at noon, on which downward and upward currents of the same amount are supposed to take part in the duskside and dawnside current circuits driven by the positive and negative potentials, respectively. Replacing the waveguide with the finite-length parallel plane transmission line, Kikuchi (2014) calculated the electric potential and currents in the ionosphere and showed that the ionospheric currents grow to the steady-state value with the time constant of a few to 10s of seconds, depending on the ionospheric conductivity. The transmission line model well explains the instantaneous onset of the PI at all latitudes and delayed peak at the equator by 20 s (Takahashi et al. 2015). The global distribution of the steady-state currents is readily calculated using the potential solver (Tsunomura and Araki 1984).

Since the TM_0 mode wave has no low cutoff frequency, the propagation suffers no attenuation at all frequencies (Budden 1961). However, the TM_0 mode waves suffer geometrical attenuation causing the intensity at low latitude to be less than 10 percent of the source field (Kikuchi and Araki 1979). Because of the geometrical attenuation, the ionospheric currents depending on the ionospheric conductivity are too weak to cause the PI at low latitude (Fig. 10). However, the electric field is strong enough to be detected by the HF Doppler sounder (Kikuchi 1986). The electric field associated with the ionospheric currents is transmitted by the Alfven wave upward into the F-region ionosphere and the inner magnetosphere (Kikuchi 2014), which leads to the coherent variations of the ground magnetic field and ionospheric motion at the geomagnetic equator, as observed by the HF Doppler sounders (Abdu et al. 1988) and by the Jicamarca incoherent scatter radar (Kikuchi et al. 2003). The upward transmission of the Poynting flux into the inner magnetosphere has been observed by the satellites (Nishimura et al. 2010), causing the quick development of the electric field in the inner magnetosphere (Nishimura et al. 2009), ring current (Hashimoto et al. 2002), and so on.

Conclusion

The convection electric field is transmitted by the Alfven wave from the dynamo in the outer magnetosphere to the polar ionosphere, accompanying the R1 FACs and driving the DP2 currents composed of ionospheric Hall currents at high latitude and the Pedersen currents amplified by the Cowling effect at the dip equator. The convection electric field is transmitted to low latitude near-instantaneously by the TM_0 mode waves in the Earth-ionosphere waveguide, resulting in high correlation of the DP2 fluctuations between high latitudes and equator during storm and substorms. The electric field associated with the DP2 currents is transmitted into the F-region ionosphere and into the inner magnetosphere, causing quick response of the low latitude ionosphere and ring current development when the cross polar cap potential increases. The overshielding electric field together with the R2 FACs causes reversal of the ionospheric electric field at midlatitude and the counter electrojet at the equator during substorm expansion phase and storm recovery phase. The same current circuit is achieved in the ionosphere during the geomagnetic sudden commencements, attesting the instantaneous transmission of the electric field and currents from the polar ionosphere to the equator. The evening anomaly of the electric field directing in the same direction as in the

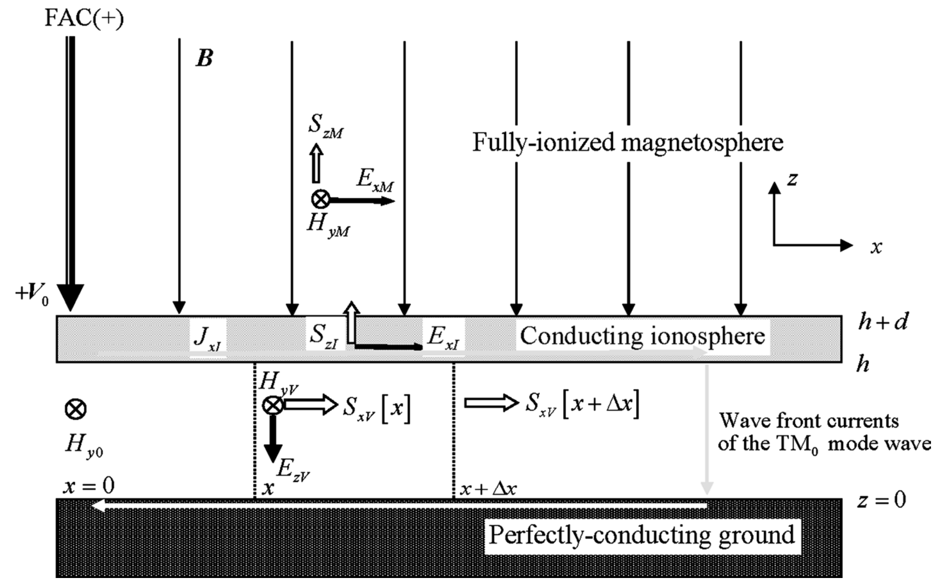

Fig. 11 Three-layered Earth-ionosphere waveguide model explaining the instantaneous transmission of the electric potential ($+V_0$) and currents (J_{xI}) given by the downward field-aligned current [FAC(+)] at the left end of the model. The TM_0 mode wave consisting of the vertical electric field (E_{zV}) and magnetic field (H_{yV}) perpendicular to the propagation plane propagates at the speed of light, carrying electric currents in the ionosphere and on the ground and transporting the Poynting flux (S_{xV}) consisting of E_{zV} and H_{yV} to low latitude. A fraction of the Poynting flux ($S_{zI} = S_{xV}$ $[x + \Delta x] - S_{xV}$ $[x]$) is transmitted into the ionosphere and another fraction into the inner magnetosphere (S_{zM}). (from Fig. 1 of Kikuchi 2014)

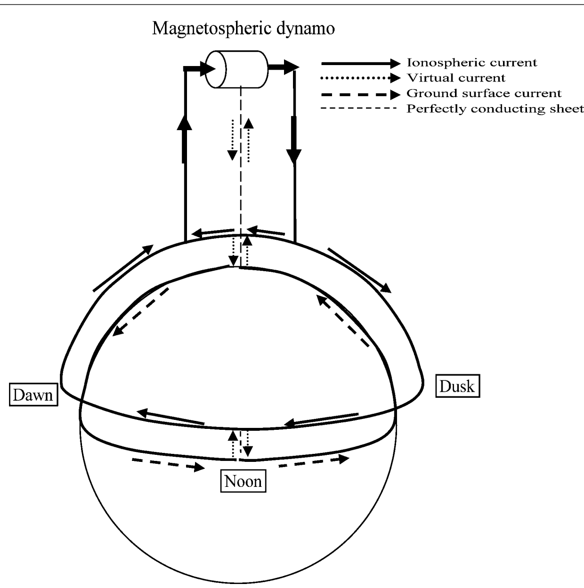

Fig. 12 Magnetosphere-ionosphere-ground current circuit achieved in a steady state. The east–west symmetry leads to the zero-potential in the noon-midnight meridian, which can be replaced with the perfectly conducting sheets (*dashed lines*). Downward and upward currents of the same amount are supposed to connect the ionospheric currents to the ground surface currents in the duskside and dawnside current circuits driven by the positive and negative potentials, respectively. (from Fig. 12 of Kikuchi 2014)

day and enhanced magnitude is a unique feature of the electric potential in the global ionosphere, which is commonly observed during the DP2 and SC events.

Authors' contributions

The author, TK wrote the whole manuscript with his knowledge and experience on the convection electric field and its transmission mechanism. The coauthor, KH provided the author with knowledge about the substorm over-shielding based on her experience in this specific field. The selection and preparation of the figures are also due to coauthors efforts. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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References

Abdu MA, Sastri JH, Luhr H, Tachihara H, Kitamura T, Trivedi NB, Sobral JHA (1988) DP 2 electric field fluctuations in the dusk-time dip equatorial ionosphere. Geophys Res Lett 25:9. doi:10.1029/98GL01096

Araki T (1977) Global structure of geomagnetic sudden commencements. Planet Space Sci 25:373–384

Araki T (1994) A physical model of the geomagnetic sudden commencement. Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves, Geophysical Monogr 81:183–200

Baker WG, Martyn DF (1953) Electric currents in the ionosphere I. The conductivity. Phil Trans R Soc London Ser A 246:281–294

Blanc M, Richmond AD (1980) The ionospheric disturbance dynamo. J Geophys Res 85:1669–1686

Budden KG (1961) The wave-guide mode theory of wave propagation. Academic Press Inc, London, pp 33–34

Dungey JW (1961) Interplanetary magnetic field and the auroral zones. Phys Rev Lett 6:47

Ebihara Y, Tanaka T, Kikuchi T (2014) Counter equatorial electrojet and overshielding after substorm onset: global MHD simulation study. J Geophys Res Space Physics 119:7281–7296. doi:10.1002/2014JA020065

Fejer BG, Scherliess L (1997) Empirical models of storm time equatorial zonal electric fields. J Geophys Res 102(A11):24047–24056

Fejer BG, Jensen JW, Kikuchi T, Abdu MA, Chau JL (2007) Equatorial Ionospheric Electric Fields During the November 2004 Magnetic Storm. J Geophys Res 112:A10304. doi:10.1029/2007JA012376

Feldstein YI, Grafe A, Gromova LI, Popov VA (1997) Auroral electrojets during geomagnetic storms. J Geophys Res 102:14223–14235

Gonzales CA, Kelley MC, Fejer BG, Vickrey JF, Woodman RF (1979) Equatorial electric fields during magnetically disturbed conditions 2. Implications of simultaneous auroral and equatorial measurements. J Geophys Res 84:5803–5812

Hashimoto KK, Kikuchi T, Ebihara Y (2002) Response of the magnetospheric convection to sudden interplanetary magnetic field changes as deduced from the evolution of partial ring currents. J Geophys Res 107(A11):1337. doi:10.1029/2001JA009228

Hashimoto KK, Kikuchi T, Watari S, Abdu MA (2011) Polar-equatorial ionospheric currents driven by the region 2 field-aligned currents at the onset of substorms. J Geophys Res 116:A09217. doi:10.1029/2011JA016442

Hirono M (1952) A theory of diurnal magnetic variations in equatorial regions and conductivity of the ionosphere E region. J Geomag Geoelectr Kyoto 4:7–21

Huang C-S (2009) Eastward electric field enhancement and geomagnetic positive bay in the dayside low-latitude ionosphere caused by magnetospheric substorms during sawtooth events. Geophys Res Lett 36:L18102. doi:10.1029/2009GL040287

Huang C-S, Foster JC, Kelley MC (2005) Long-duration penetration of the interplanetary electric field to the low-latitude ionosphere during the main phase of magnetic storms. J Geophys Res 110:A11309. doi:10.1029/2005JA011202

Iijima T, Potemra T (1976) The Amplitude Distribution of Field-Aligned Currents at Northern High Latitudes Observed by Triad. J Geophys Res 81:13. doi:10.1029/JA081i013p02165

Kamide Y, Sun W, Akasofu S-I (1996) The average ionospheric electrodynamics for the different substorm phases. J Geophys Res 101:A1. doi:10.1029/95JA02990

Kelley MC, Fejer BG, Gonzales CA (1979) An explanation for anomalous equatorial ionospheric electric fields associated with a northward turning of the interplanetary magnetic field. Geophys Res Lett 6:301–304

Kikuchi T (1986) Evidence of transmission of polar electric fields to the low latitude at times of geomagnetic sudden commencements. J Geophys Res 91:3101–3105

Kikuchi T (2014) Transmission line model for the near-instantaneous transmission of the ionospheric electric field and currents to the equator. J Geophys Res Space Physics 119:1131–1156. doi:10.1002/2013JA019515

Kikuchi T, Araki T (1979) Horizontal transmission of the polar electric field to the equator. J Atmos Terr Phys 41:927–936

Kikuchi T, Lühr H, Kitamura T, Saka O, Schlegel K (1996) Direct penetration of the polar electric field to the equator during a DP2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar. J Geophys Res 101:17161–17173

Kikuchi T, Luehr H, Schlegel K, Tachihara H, Shinohara M, Kitamura T-I (2000) Penetration of auroral electric fields to the equator during a substorm. J Geophys Res 105:23251–23261

Kikuchi T, Hashimoto KK, Kitamura T-I, Tachihara H, Fejer B (2003) Equatorial counterelectrojets during substorms. J Geophys Res 108(A11):1406. doi:10.1029/2003JA009915

Kikuchi T, Hashimoto KK, Nozaki K (2008) Penetration of magnetospheric electric fields to the equator during a geomagnetic storm. J Geophys Res 113:A06214. doi:10.1029/2007JA012628

Matsushita S, Balsley BB (1972) A question of DP2 magnetic fluctuations. Planet Space Sci 20:1259–1267

McPherron RL (1970) Growth phase of magnetospheric substorms. J Geophys Res 75(28):5592–5599

Nishida A (1968) Coherence of geomagnetic DP2 magnetic fluctuations with interplanetary magnetic variations. J Geophys Res 73:5549–5559

Nishimura Y, Shinbori A, Ono T, Iizima M, Kumamoto A (2006) Storm-time electric field distribution in the inner magnetosphere. Geophys Res Lett 33:L22102. doi:10.1029/2006GL027510

Nishimura Y, Kikuchi T, Wygant J, Shinbori A, Ono T, Matsuoka A, Nagatsuma T, Brautigam D (2009) Response of convection electric fields in the magnetosphere to IMF orientation change. J Geophys Res 114:A09206. doi:10.1029/2009JA014277

Nishimura Y, Kikuchi T, Shinbori A, Wygant J, Tsuji Y, Hori T, Ono T, Fujita S, Tanaka T (2010) Direct measurements of the Poynting flux associated with convection electric fields in the magnetosphere. J Geophys Res 115:A12212. doi:10.1029/2010JA015491

Peymirat C, Richmond AD, Kobea AT (2000) Electrodynamic coupling of high and low latitudes: simulations of shielding/overshielding effects. J Geophys Res 105(A10):22991–23003

Rastogi RG (1977) Geomagnetic storms and electric fields in the equatorial ionosphere. Nature 268:422–424

Rastogi RG (2004) Westward electric field in the low latitude ionosphere during the main phase of magnetic storms occurring around local midday hours. Sci Lett 27:69–74

Senior C, Blanc M (1984) On the control of magnetospheric convection by the spatial distribution of ionospheric conductivities. J Geophys Res 89:261–284

Shinbori A, Nishimura Y, Ono T, Iizima M, Kumamoto A, Oya H (2005) Electrodynamics in the duskside inner magnetosphere and plasma sphere during a super magnetic storm on March 13–15, 1989. Earth Planets Space 57:643–659

Somayajulu VV, Reddy CA, Viswanathan KS (1987) Penetration of magnetospheric convective electric field to the equatorial ionosphere during the substorm of March 22, 1979. Geophys Res Lett 14:876–879

Takahashi N, Y Kasaba, Shinbori A, Nishimura Y, Kikuchi T, Ebihara Y, Nagatsuma T (2015) Response of ionospheric electric fields at mid-low latitudes during sudden commencements. J Geophys Res Space Physics 120:4849–4862. doi:10.1002/2015JA021309

Tamao T (1964) The structure of three-dimensional hydromagnetic waves in a uniform cold plasma. J Geomag Geoelectr 48:89–114

Tanaka T (1995) Generation Mechanisms for Magnetosphere-Ionosphere Current Systems Deduced from a Three-Dimensional MHD Simulation of the Solar Wind-Magnetosphere-Ionosphere Coupling Processes. J Geophys Res 100:A7. doi:10.1029/95JA00419

Tanaka T, Nakamizo A, Yoshikawa A, Fujita S, Shinagawa H, Shimazu H, Kikuchi T, Hashimoto KK (2010) Substorm convection and current system deduced from the global simulation. J Geophys Res 115:A05220. doi:10.1029/2009JA014676

Tsunomura S (1999) Numerical analysis of global ionospheric current system including the effect of equatorial enhancement. Ann Geophysicae 17:692–706

Tsunomura S, Araki T (1984) Numerical analysis of equatorial enhancement of geomagnetic sudden commencement. Planet Space Sci 32:599–604
Vasyliunas VM (ed) (1972) The interrelationship of magnetospheric processes, Earth's Magnetospheric Processes. BM McCormac, London, pp 29–38
Wei Y et al (2009) Westward ionospheric electric field perturbations on the dayside associated with substorm processes. J Geophys Res 114:A12209. doi:10.1029/2009JA014445
Wilson GR, Burke WJ, Maynard NC, Huang CY, Singer HJ (2001) Global electrodynamics observed during the initial and main phases of the July 1991 magnetic storm. J Geophys Res 106(A11):24517–24539
Wygant J, Rowland D, Singer HJ, Temerin M, Mozer F, Hudson MK (1998) Experimental evidence on the role of the large spatial scale electric field in creating the ring current. J Geophys Res 103(A12):29527–29544. doi:10.1029/98JA01436