3-3 Evolution of the Ionospheric Convection due to Changes in the Interplanetary Magnetic Field

HASHIMOTO K. Kumiko

It has been clarified that the night-side ionospheric convection immediately develops due to changes in direction of the solar wind magnetic field. The observational facts are inconsistent with the traditional model of the plasma convection in the magnetosphere-ionosphere coupling system. In order to discuss a role of the ionosphere in the coupling system, we review the models of plasma convection development on the basis of the ground observations and the physical ionospheric model in the 3 D global MHD simulation. It is concluded that the ionosphere would drive (not generate) the convection in the inner magnetosphere, basing on the recent result that plasma convection concurrently develops in the night side ionosphere and inner magnetosphere.

Keywords
Plasma convection, Ionospheric convection, Convection electric field, Magnetosphere-ionosphere coupling system

1 Introduction

Plasma convections in the magnetosphere and the ionosphere play an important role in the energy conversion and transport (distribution) processes after the penetration of the solar wind energy through the magnetopause. Geomagnetic disturbances, substorms, and geomagnetic storms—some of the major topics of the Earth and planetary sciences—can also be viewed as phenomena associated with variations in plasma convection. Historically, the existence of plasma convection was first confirmed through ground-based geomagnetic field observations, and magnetospheric convection was originally studied by projecting the ionospheric convection electric field onto the equatorial plane in the magnetosphere along magnetic field lines. It has been shown that the statistical description of magnetospheric convection based on satellite observation data does not conflict with theoretically predicted magnetospheric convection. However, since there is presently no method available to observe magnetospheric convection as a whole at once, the basic description of magnetospheric convection has been obtained based on data collected from local observations by low-altitude satellites and through projections of the ionospheric convection electric field onto the magnetosphere.

Although the dominant physical processes of the magnetosphere, a magnetohydrodynamic (MHD) medium, are entirely different from those of the ionosphere, which features high conductivity (high atmospheric density) perpendicular to the magnetic field, the two regions are strongly coupled to each other via magnetic field lines. In recent years, the construction of global observation networks consisting of magnetometers and radars has enabled simultaneous observations of variations in ionospheric convection at extremely high temporal resolutions and wide spatial coverage. Such observations have resulted in newly discovered properties, such as the response of the ionospheric convection electric field to solar wind disturbances. Conventional models of the mechanism driving large-scale plasma convection in the magnetosphere have been derived mainly from steady-state convection patterns in the polar ionosphere, and it has been pointed out that such models cannot account for the properties of ionospheric convection that change in response to solar wind disturbances.

Presented in this paper are the properties of ionospheric convection on a global scale determined based on the convection-driving mechanism in the magnetosphere-ionosphere coupled system and also based on a new interpretation of the geomagnetic disturbances caused by these properties. Furthermore, we will discuss the results of recent studies indicating an association between the development of plasma convections and changes in the interplanetary magnetic field (IMF), based on first-ever simultaneous observations in the nightside inner magnetosphere and the ionosphere.

2 Connection Between the Current System and Convection

Records of ground-based observations of magnetic field variations date back a long time.

Scientists in the mid-eighteenth century were already aware of the existence of geomagnetic storms, during which the geomagnetic field on the ground changes dramatically, and that these storms were related to auroral disturbances. In the mid-19 th century, the correlation between geomagnetic disturbances and sunspot numbers was revealed. However, their causal relationship was only slowly clarified through the construction of multiple observation station networks by the Second International Polar Year (1932-1933) and the International Geophysical Year (1957) and by direct observations of solar wind.

The "equivalent current system" is an ionospheric current system formulated based on the assumption that all magnetic field variations observed on the ground are generated by the effects of ionospheric current around an altitude of 100 km. By drawing a 2-D equivalent current system pattern based on statistical analysis of magnetometer data obtained at a restricted number of sites during a geomagnetic storm, Chapman (1935) showed that there were two components to the equivalent current system: a Dst component that flows along latitude lines regardless of longitude, and an SD component that displays daily variations.

The SD component forms a current system that is symmetrical with the Sun-Earth line and that consists of two cells with centers near the terminator on the morning and evening sectors at high latitudes. The current transects the polar cap and flows toward the dayside, and then changes direction toward the nightside, flowing along the latitude lines in the low-latitude region. Generally, the asymmetrical component of the magnetospheric ring current is observed on the ground as magnetic field variations in the middle to low latitudes during geomagnetic storms. Therefore, effects other than those induced by the ionospheric current are also reflected in the SD current in the middle to low latitudes. This results in a 2-cell current pattern with centers in the polar region being distributed only at latitudes higher than the aurora belt.

The electric field in the polar ionosphere can be estimated if the SD current is assumed to flow along equipotential lines. A projection of this potential field onto the magnetosphere along magnetic field lines suggests the existence of an electric field in the day-to-evening direction and the presence of large-scale plasma convection in the magnetosphere.

The development of ground-based geomagnetic observation networks has enabled the determination of equivalent current patterns as a function of time, and has revealed the existence of DP1 currents that accompany substorm expansion phase onset and DP2 currents that reflect large-scale magnetospheric convections. The DP2 current system has a 2-cell current pattern with a convection electric field in the morning-to-evening direction that is similar to the high-latitude SD current pattern. However, as will be discussed in a later section, the DP2 current differs significantly from the SD current in that it is an ionospheric current system that extends from the polar region to the equatorial region.

Similar results have been obtained by direct observations of the electric field using satellites and balloons in the 1970s (Heppner, 1972; Swift and Gurnett, 1973; Mozer and Lucht, 1974).

3 Correlation Between the IMF and Ionospheric Convection

The discovery of the IMF by Pioneer 5 led to Dungey's (1961) proposal of a model in which magnetospheric convection is driven by the reconnection of the Earth's magnetic field with IMF in the dayside (sunward) magnetopause. According to Dungey's model, the magnetic flux in the northern and southern hemispheres, which is connected to the IMF, passes through the polar cap and is transported toward the magnetotail. These magnetic field lines stretching from the northern and southern polar regions meet in the equatorial plane in the magnetotail, and the closed magnetic field line created by their reconnection drifts back toward the Earth. Dungey's model succeeded in explaining the 2-cell current pattern of the SD current. His model assumes an open magnetosphere structure in which the solar wind and magnetospheric magnetic fields reconnect, and can explain the penetration of the solar wind electric field and particles into the magnetosphere across the magnetopause. Therefore, continues to this day to receive strong support as a model of the mechanism driving convection.

Nishida (1968) then discovered that the DP2 current in the high-latitude ionosphere and at the dayside geomagnetic equator changes synchronously with the IMF. Thus, large-scale convection in the magnetosphere-ionosphere coupled system was correlated to solar activity via the IMF. The existence of a correlation between the IMF and DP2 current systems implies that the solar wind energy penetrates into the ionosphere, and furthermore that it is transported from the polar region into the equatorial regions. Based on observations of the electric field using satellites and HF radars, it is now known that the ionospheric convection pattern is affected by the combination of different intensities and signs of the N-S component (Bz) and the E-W component (By) of the IMF (e.g. Heppner and Maynard, 1987; Weimer, 1995; Ruohoniemi and Baker, 1998).

4 Ionospheric Current and Field-Aligned Currents

The equivalent current system determined from magnetic field variations on the ground reflects the effects of magnetic fields generated by ionospheric and magnetospheric currents.

The expansion of magnetometer networks has enabled the identification of the effects of ionospheric and magnetospheric currents based on latitude, magnetic local time (MLT), and seasonal (hemispherical) dependencies of magnetic field variations. The ionospheric current can be generally divided into the Hall current and the Pedersen current. The Pedersen current flows in the direction of the electric field at an altitude of approximately 130 km, and the Hall current flows perpendicular to both the electric and magnetic fields at an altitude of approximately 105 km. The ion-neutral and electron-neutral collision frequencies and the electron and ion gyro-frequencies in the ionosphere display altitude-dependency, and the ionospheric current is generated by the difference in the ratios between the collision and gyro frequencies for electrons and ions. The region between altitudes of 90-120 km, where the Hall current is larger than the Pedersen current, is called the dynamo layer.

The Hall current is generated by a combination of $E \times B$ drifting electrons and stationary ions, and in the ideal case of uniform Hall conductivity, the Hall current forms a completely closed system in the ionosphere. Plasma convection at altitudes higher than the dynamo layer features the same pattern as the ionospheric Hall current. Large-scale polar current systems with 2-cell current patterns, such as the SD or the DP2 current systems, determined based on magnetometer observations, can mainly be considered to be the result of the Hall current effect. (However, in the nightside auroral oval, ionospheric conductivity is not uniform, due to the increased precipitation of auroral particles during substorms. In such regions, the effects of secondary electric fields generated by the discontinuity in the conductivity may be observed.) Since there is no current component in the direction of the electric field, Hall currents do not lead to the loss of electromagnetic energy ($E \cdot J = 0$).

On the other hand, since ions move in the direction of the electric field due to incomplete E × B drift caused by the collision of ions and neutrals in the upper boundary of the dynamo layer, a current component is generated in the direction of the electric field. This current parallel to the electric field is called the Pedersen current. If the ionosphere is assumed to feature uniform electric conductivity, the field-aligned currents (FAC) that flow into the ionosphere from the magnetosphere (or vice versa) along magnetic field lines should all connect with Pedersen currents. If we assume the magnetic field lines are perpendicular to the ionosphere in the polar ionosphere, the magnetic field caused by an FAC on the ground is canceled out by the magnetic field caused by the Pedersen current (Fukushima, 1976). Therefore, the effect of the Pedersen current on the magnetic field on the ground is considered to be small. The Pedersen current is mainly composed of ions that move constantly in balance with mechanical resistance from the neutral atmosphere; this thus represents a process of electromagnetic energy loss due to the alignment of the electric field and current in the same direction ($E \cdot J > 0$).

The electric field applied to the ionosphere simultaneously generates the Hall and Pedersen currents. In particular, the distribution of the ionospheric current associated with convection field variations is significant given the effect of the Pedersen current as an energy loss process and in terms of the continuity of the Pedersen current. Nishida (1968) and Kikuchi et al. (1996) have demonstrated that the DP2 magnetic field variations (displaying cycles of approximately one hour) in the polar region is coherent with that in the dayside geomagnetic equator. In contrast to the polar region, the magnetic field lines in the ionosphere at the geomagnetic equator are approximately parallel to the ionosphere. Since the Hall current becomes a vertical current at this point, it cannot continue to flow, creating a vertical polarization electric field in the ionosphere. This polarization electric field strengthens the original Pedersen current, and results in DP2 magnetic field variations in the geomagnetic equator. In other words, the existence of a DP2 magnetic field variation at the equator indicates that ionospheric convection is experiencing energy loss due to the Pedersen current that is distributed from the polar region to the equator.

The energy to drive ionospheric convection accompanying energy loss is supplied from the magnetosphere. The FAC connecting the magnetosphere and the ionosphere was discovered by geomagnetic field observations made by polar-orbiting satellites (e.g. Zmuda et al., 1970; Zmuda and Armstrong, 1974). The FAC consists of Region 1 FAC, which is directed downward (flowing into the ionosphere) in the morning sector and upward (flowing out of the ionosphere) in the evening sector, and Region 2 FAC, which is distributed at lower latitudes than Region 1 FAC and in opposite directions: downward in the evening sector and upward in the morning sector (Iijima and Potemra, 1976). These FACs form the circuit that connects the ionospheric Pedersen current and the magnetospheric current.

The FACs not only satisfy the continuity of electric currents, but have also been theoretically shown to play an important role in transferring the kinetic momentum (perpendicular to the magnetic field) of the magnetospheric convection to the ionosphere (Southwood and Kivelson, 1991; Iijima, 2000). Plasma convection motion in the magnetosphere-ionosphere coupled system and the FACs are two physical manifestations of a single physical process, and cannot be separated from each other. Therefore, discussing the mechanism driving plasma convection is equivalent to discussing the supply and transfer of momentum in a coupled system; it is also the same as discussing the creation of a current generation mechanism and the distribution of the current systems within the magnetosphere-ionosphere current system.

Recent developments in 3-D MHD simulation models involving solar wind, the magnetosphere, and the ionosphere have been successful in reconstructing the magnetosphere-ionosphere current system in a coupled system of these three different regions. Tanaka (1995) was the first to show that a dynamo of the current system connected to the ionospheric Pedersen current (referred to as Region 1 FAC) is formed on the higher latitude side of the dayside cusp during a southward IMF. The results of this simulation show that the Region 1 FAC dynamo is formed within the magnetopause currents, thus indicating that a current generator within the magnetosphere is driving the plasma convection. Similar current systems have also been reconstructed by other MHD simulation models; it can thus be concluded that the Region 1 FAC connected to the dayside polar ionosphere mainly transfers the momentum of the large-scale plasma convection in the magnetosphere to the ionosphere.

5 The Convection Reconstruction Process Associated with IMF Variations

The polarity of the IMF changes constantly, with periods of several tens of minutes to several hours. Since the energy that drives the magnetosphere-ionosphere convection supplied from the solar wind is dependent on the magnetic field polarity, velocity, and density of the solar wind, the magnetosphere-ionosphere convection changes constantly under unsteady solar wind conditions. It was not until in recent years to expand the observation from the polar regions to the geomagnetic equator and to realize observations with higher temporal resolution, that variations in ionospheric convections could be discussed in terms of shorter time spans, i.e., from several seconds to a minute. Furthermore, direct and simultaneous observation of the ionospheric F layer plasma flow over a wide area has been made possible by a SuperDARN HF radar network consisting of 15 units installed in the southern and northern polar regions. With these magnetometer networks and SuperDARN HF radars extending from the polar region to the equator, it is now possible to study the ionospheric convection development process outside the constraints of conventional steady-state models.

5.1 Response of the Polar Ionospheric Convection to IMF Variations

Since magnetic reconnection at the dayside magnetopause is most efficient when the IMF turns south, the rate of solar wind energy influx into the magnetosphere is greatest during a southward IMF. To clarify the energy influx process (the convection development process), the response of the ionospheric convection to a sudden southward turning of the IMF was investigated.

Ever since the Dungey model was proposed, it has been widely accepted that the development of the magnetospheric convection is driven by the transport via solar winds of magnetic flux that has undergone reconnection of the IMF and geomagnetic field from the dayside magnetopause to the magnetotail. Cowley and Lockwood (1992) proposed an ionospheric convection model (the CL model) in which the development and decay of ionospheric convection are attributed to the balance between open magnetic flux (newly connected to solar winds through magnetic reconnection at the dayside magnetopause) and closed magnetic flux (at the magnetotail, formed by reconnection). The region of magnetic reconnection on the magnetopause projected onto the ionosphere is called the merging line. In the ionosphere, an increase in the magnetic flux that crosses the merging line from low-latitude to high-latitude regions increases the total amount of magnetic flux in the polar cap. The momentum perpendicular to the magnetic field supplied from solar winds is transported by the magnetic flux in the CL model. When the magnetospheric convection is projected onto the ionosphere along magnetic field lines, the convection cells with centers at both ends of the dayside ionosphere merging line spread to the nightside with time, which means that it should take several tens of minutes for a new convection enhanced by the southward IMF to be propagated to the magnetotail. The variations in magnetosphere-ionosphere convection are equivalent to the variations in the current system.

The movement of the 2-cell pattern convection of the ionosphere from the dayside to nightside as it expands represents the movement of the current dynamo region. Thus, the CL model has successfully explained the cross correlation between the magnetic field variations observed in the dayside polar region and the morning- or evening-sector magnetic field variations and has also explained the time lag in the development of convection observed by local radar observations (Etemadi et al., 1988; Todd et al., 1988 ; Saunders et al., 1992).

New features of convection have been obtained along with the expansion of the magnetometer and radar observation networks. Based on a study using data from a magnetometer network, Ridley et al. (1988) have shown that, during the development of a 2-cell convection accompanying a southward turning of the IMF, the potential field of the polar ionosphere increases simultaneously (with a temporal resolution of 1 min.) on the dayside and nightside around 10 MLT and 15 MLT at a geomagnetic latitude of 80˚. The centers of the 2-cell potential field were found to be nearly stationary. On the other hand, based on SuperDARN HF radar observations, Ruohoniemi and Greenwald (1998) have shown that the velocity of the F layer plasma begins to increase simultaneously (temporal resolution of 2 min.) on the dayside and nightside in response to a sudden southward turning of the IMF. The simultaneous development of dayside and nightside convection in the polar ionosphere indicates simultaneous development from the dayside magnetopause to the magnetotail, even extending into the inner magnetosphere. This lack of an observed time lag between the initiation of the development of the convection electric field in the nightside ionosphere and the dayside ionosphere is essentially inconsistent with the conventional models of ionospheric convection development (with a time lags on the order of several tens of minutes in the nightside ionosphere under the CL model).

In a strongly coupled magnetosphere-ionosphere system, the FACs transfer the electric field and momentum of the magnetospheric convection to the ionosphere. The initiation of convection development in the dayside and nightside ionosphere indicates that the energy transport in the direction traversing the magnetic field is significantly rapid. It should be noted here that Ridley et al. (1988), Murr and Hughes (2001), and Kikuchi et al. (1996) have all demonstrated the simultaneous development of the convection electric field on the dayside and nightside or the polar and equatorial regions using ionospheric DP2 currents that were determined from geomagnetic field observations on ground. In other words, there must be a Pedersen current simultaneously covering the dayside to nightside ionosphere and the polar to equatorial regions that persists for several hours. The energy lost due to the Pedersen current is replenished by electromagnetic energy in the form of a Poynting flux, and the Pedersen current must be connected with the current generator via FACs in the polar ionosphere. Recent magnetosphere-ionosphere convection models based on 3-D MHD simulations show that the ionospheric convection changes pattern and then develops within a few minutes following the IMF variation (Lopetz et al., 1999) and that plasma convection in the inner magnetosphere begins to develop simultaneously with this process (Slinker et al., 2001). These models support the results of recent observations.

5.2 Convection Electric Field Propagation Model

Ridley et al. (1998) and Slinker et al. (2000) have attributed the instantaneous developments of convection electric fields in the nightside ionosphere and inner magnetosphere accompanying IMF variation to magnetosonic wave (fast compressional wave) propagation.

However, there are serious drawbacks to this explanation, since electric fields propagated by magnetosonic waves are rotational electric fields (not divergent fields, as is the case with convection electric fields) and since the momentum of the magnetospheric convection (or the Poynting flux) cannot be transferred to the ionosphere. Theoretical support for a model of ionospheric convection driven by magnetosonic waves propagating through the magnetosphere has yet to be presented. Furthermore, it has been theoretically proven by Strangeway and Raeder (2001) that the energy loss due to Joule heat is of significantly magnitude in the ionosphere to prevent the propagation of magnetosonic waves.

On the other hand, Song et al. (2000) and Hashimoto et al. (2002) have indicated the possibility that plasma convection is driven by solar wind energy supplied through the magnetopause, past the ionosphere, and finally into the inner magnetosphere. Based on 3-D MHD simulations, Song et al. (1999) have shown that a convection cell is formed in a due north IMF that does not come into contact with the boundary with the solar winds; in other words, this cell is composed of closed magnetic field lines. This plasma convection cell corresponds to FACs like the Region 1 FAC. To explain the driving mechanism of this cell, Song et al. (2000) have proposed a model in which the momentum is supplied to the plasma convection together with the Pedersen current on the low latitude side by the spreading of the potential field (carried into the polar ionosphere by NBZ current) to the low latitude ionosphere. They have thus adopted a different approach to support the proposition that ionosphere-magnetosphere coupling plays an important role in the transfer of magnetospheric convection momentum.

Based on the analysis of data provided by INTERMAGNET magnetometers and magnetic field variations deduced by particle simulation model of ring currents, Hashimoto et al. (2002) have shown that when the ionospheric convection electric field (DP2 geomagnetic disturbance) decreases with northward turning of the IMF, a change occurs simultaneously (with a temporal resolution of 1 min.) in the plasma pressure distribution that generates ring currents. Although asymmetrical plasma pressure distribution near the ring current orbit is observed at some MLT, all variations start simultaneously with the decrease in ionospheric convection electric field at all MLT. Hashimoto et al. (2002) have proposed a model in which the electric field variations, which are transmitted from the dayside magnetosphere to the nightside ionosphere (from high to low latitudes) and the inner magnetosphere, accompany the transfer of Poynting flux in the 3-D electric circuit formed by the FAC and the ionospheric Pedersen current.

Some problems also remain in models that stress the importance of magnetosphere-ionosphere coupling in plasma convection variations. The first is the extreme attenuation of the convection due to Joule heat loss in the highly conductive ionosphere, which would hinder the horizontal propagation of the Poynting flux (Strangeway and Raeder, 2001). Assuming the Earth-ionosphere waveguide model by Kikuchi and Araki (1979), Hashimoto et al. (2002) showed that it was possible for the potential field to spread into the nightside ionosphere through the propagation of the Poynting flux from the ionosphere to the Earth. However, several problems remain. One is the need for an explanation of the generation of a vertical electric field below the ionosphere by the dayside Region 1 FAC; another is the lack to date of a quantitative evaluation of attenuation of convection during propagation from the dayside to the nightside. (Section 4 presents one approach to resolving this problem.) Furthermore, a third problem is that a Poynting flux propagating from the nightside ionosphere to the magnetosphere has never been confirmed by observation.

Observations of the development (variations) of a convection electric field suggest that the Poynting flux supplied from the dayside magnetosphere is not completely lost in the ionosphere, and that a certain portion does propagate to the nightside and the inner magnetosphere. However, the results of satellite observations of electric and geomagnetic fields indicate that most of the Poynting flux propagates from the magnetosphere to the ionosphere. In the future, a quantitative estimation must be made of the energy required to promote the development of plasma convection in the magnetotail.

5.3 Model of the Ionosphere Based on 3-D MHD Simulation Models

To study the effect of magnetosphere-ionosphere coupling, 3-D MHD simulations have from the start used physical models of the ionosphere at altitudes lower than the inner boundary of the magnetosphere. Ever since the presentation of the Fedder and Lyon model (1987), many 3-D MHD simulation models of the solar wind-magnetosphere-ionosphere coupled system have used the following two equations to define the boundary conditions within the magnetosphere (Fedder et al., 1995; Song et al., 1999 ; Raeder et al., 2000; Tanaka, 2000).

$$J_{//} = \nabla_{\perp} \cdot (\Sigma \cdot \nabla \Phi) \quad (1)$$

$$v = B \times \nabla \Phi / B^2 \quad (2)$$

where

$J_{//}$: field-aligned current (FAC)

Σ : electric conductivity tensor

Φ : electric potential

B : magnetic flux density

v : plasma drift velocity

The first equation is for the conservation of current for FAC and the Pedersen current, and shows that the ionospheric potential field can be uniquely determined by FAC and the electric conductivity model of the ionosphere. By using the determined potential field, the plasma flow velocity can be calculated from Eq. (2), which can then be projected onto the inner boundary of the magnetosphere along magnetic field lines. Equation (1) is equivalent to stating that the Poynting flux that has entered the polar ionosphere together with FACs crosses the magnetic field (horizontally) and propagates to middle to low latitude regions. On the other hand, Eq. (2) is equivalent to stating that the convection electric field propagates to the inner magnetosphere along magnetic field lines from the middle to low latitudes or from the nightside polar ionosphere. No conclusions have yet been drawn regarding the mechanism propagating the convection perpendicular to the magnetic field within the ionosphere, but the rapid development (variation) process of the nightside magnetosphere-ionosphere convection revealed by recent observations and MHD simulations implies that the convection electric field propagates from the ionosphere into the inner magnetosphere.

5.4 Development of Ionospheric Convection and Its Relationship to Inner Magnetospheric Convection (Event Observed on March 26, 1998)

According to the Dungey's convection model, the energy that drives convection supplied through the dayside magnetopause is thought to be transported from the dayside to the nightside magnetosphere and to the inner magnetosphere. Therefore, it must be determined whether the rapid development of the ionospheric plasma convection coincides with the convection in the inner magnetosphere that is coupled through magnetic field lines. This section will discuss the relationship between the development process of ionospheric convection observed by magnetometer and Super-DARN HF radars and the changes in the shape of magnetic field lines associated with the development of ionospheric convection observed by geostationary satellites. The results of this study point to the possibility that, within a magnetosphere-ionosphere coupled system, the ionosphere promotes the development of such convection in the inner magnetosphere.

Fig.1 shows the solar wind velocity, ion density, and magnetic field observed by the WIND satellite on March 26, 1998. The WIND satellite observed a switching of the IMF Bz (N-S component) from the positive (north) to negative (south) at position (213, −21, −14) (in Earth radii units) at approximately 09:50 UT. This DP2 magnetic field variation accompanying variations in IMF can be identified through synchronous magnetic field variations from the polar cap to the dayside middle to low latitude regions. Fig.2 shows the H (N-S) component of the magnetic field (observed from two stations in the polar cap and by the magnetometer network) aligned from the high to middle latitude regions (geomagnetic latitude of 75-56°) at 13 MLT. At 11:00 UT, all stations began to observe an increase in the H component of the magnetic field, which indicates that the convection electric field in the ionosphere had begun to increase.

At the same time, the onset of the growth phase of a substorm was observed by the geostationary satellite GOES 9 on the nightside (at geomagnetic lat. and long. of 4.91° and 296.02°, respectively). Fig.3 shows the temporal changes in the three components of the magnetic field (He: Earthward; Hp: northward parallel to the dipole axis; Hn: perpendicular to He and Hp). GOES 9 was positioned near 00:20 MLT at 11:00 UT. At 11:06 UT (represented by the solid vertical line), the He component began to increase and the Hp compo-

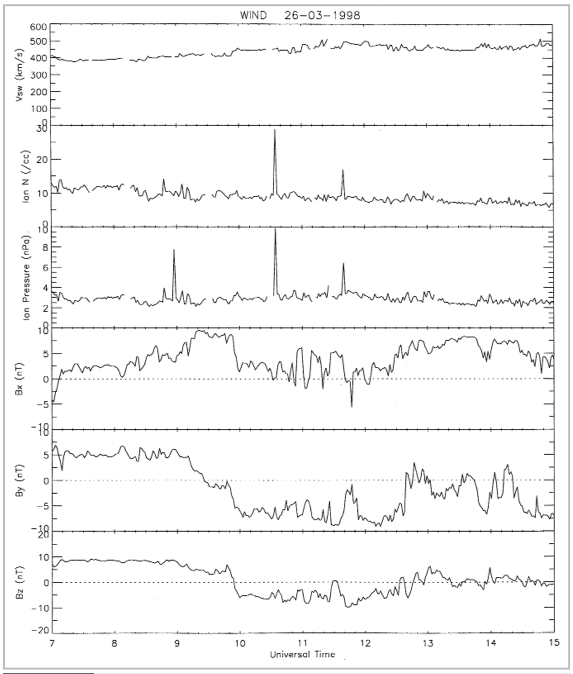

Fig.1 Solar wind velocity, ion density, and magnetic field variations observed by the WIND satellite on March 26, 1998.
The WIND satellite was positioned at (213, −21, −14) (units in Re and in GSM coordinates) at about 10:00 UT.

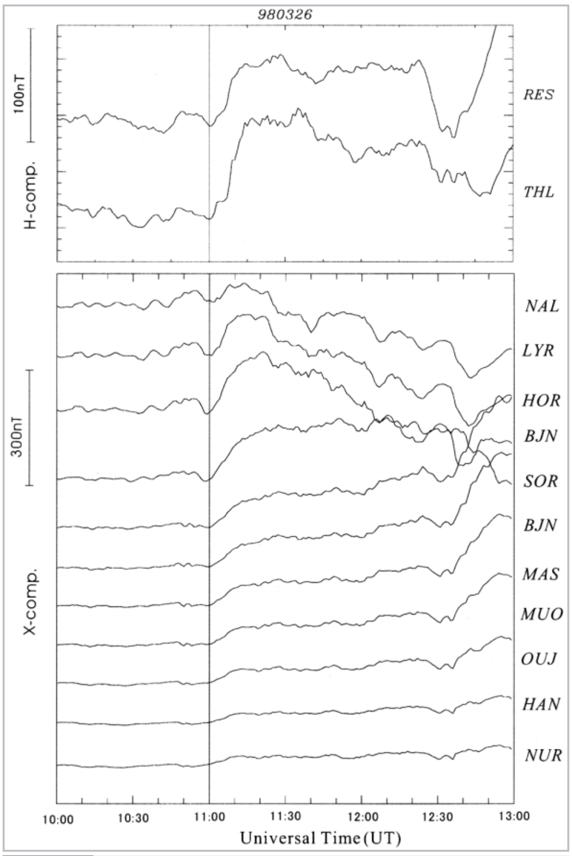

Fig.2 (Top) The H components of the magnetic field at Resolute Bay (03:30 MLT at 11:00 UT) and at Thule (08:10 MLT at 11:00 UT) in the polar cap; and (Bottom) the H component of the magnetic field from high to middle latitudes observed by the IMAGE magnetometer network (13:10 MLT at 11:00 UT). The solid vertical lines represent the start of the increase in the convection field.

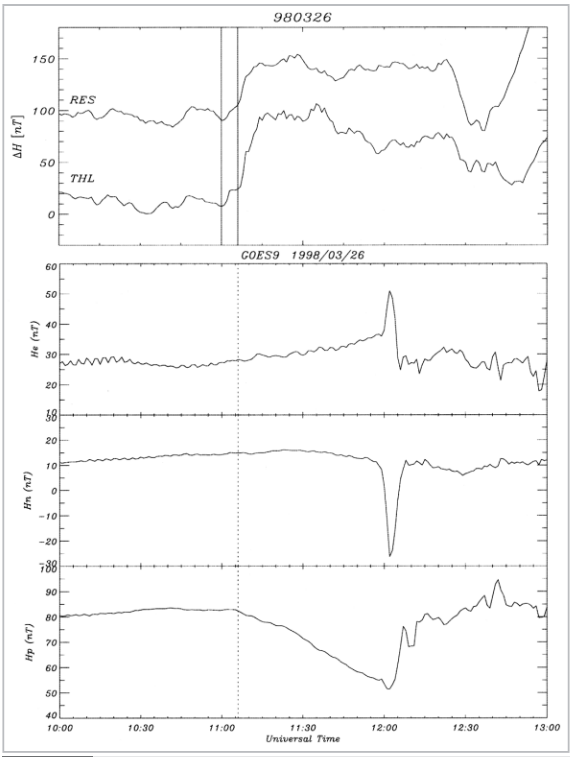

Fig.3 *(Top) Same as top figure in Fig.2. (Bottom) Three components of the magnetic field observed by the GOES 9 geostationary orbital satellite (at geomagnetic latitude and longitude of 4.91° and 296.02°, respectively).*

The solid vertical line and dashed line represent the start of the increase in the convection field and the start of changes in the magnetic field at the GOES 9 observation point, respectively.

nent began to decrease. This change in the magnetic field corresponds to the thinning of the magnetotail that is characteristic of the substorm growth phase (plasma sheet thinning). This extension of magnetic field lines offset from the dipole magnetic field signifies an increase in the westward (morning to evening) electric field near the equatorial plane in the inner magnetosphere in a geostationary orbit (altitude of approximately 36,000 km). This results in acceleration of the plasma convection by the Earthward $E \times B$ drift. This geomagnetic field observation by GOES 9 indicates that the increase in the convection electric field in the inner magnetosphere began no later than six minutes after the initiation of development of the ionospheric convection electric field. This report represents the first observation of such rapid onset of electric field development in the inner magnetosphere. The changes in the ionospheric plasma convection pattern observed by HF radars in the polar regions were believed to offer an effective explanation of the time lag (six minutes) following the initiation of the development of the ionospheric convection electric field.

Fig.4 shows the ionospheric plasma convection pattern before and after the nightside inner magnetospheric convection had begun to change, and represents a polar coordinate plot of the 2-D plasma velocity vectors in the polar ionosphere (F layer) observed by six HF radar units installed near the aurora belt in Finland, Iceland, Canada, and Alaska. The center of the plot corresponds to the geomagnetic north pole, and the outer circle corresponds to the geomagnetic latitude of 65°. The top and bottom panels are for 12 MLT and 0 MLT, respectively. The figure shows the polar ionospheric convection as seen from the sky above the north pole. Figure 4 (a) and (b) shows the plasma convection pattern at 10:56-10:58 UT and 11:08-11:10 UT, respectively.

It can be seen from Fig. 4 (a) that two plasma convection cells are centered around 10 MLT and 17 MLT near the geomagnetic latitude of 83°. The direction of the plasma flow is clockwise and counterclockwise in the morning and afternoon sectors, respectively. Near the 12 MLT meridian, the plasma flows from the pole towards lower latitudes (sunward). These two convection cells are referred to as "reversed 2 cells" because their direction of convection is opposite that of the 2-cell plasma convection generated during southward IMF. The reversed 2-cell pattern is regarded as characteristic of the plasma convection pattern observed for a northward IMF Bz component. A part of the normal 2-cell convection, with a center near the geomagnetic latitude of 75°, is seen on the lower latitude side of the reversed cell in the afternoon sector. However, its plasma flow velocity is smaller than that of the reversed cell. The convection cells in the morning and afternoon sectors of the reversed 2-cell correspond to the upward and downward FAC, respectively, and

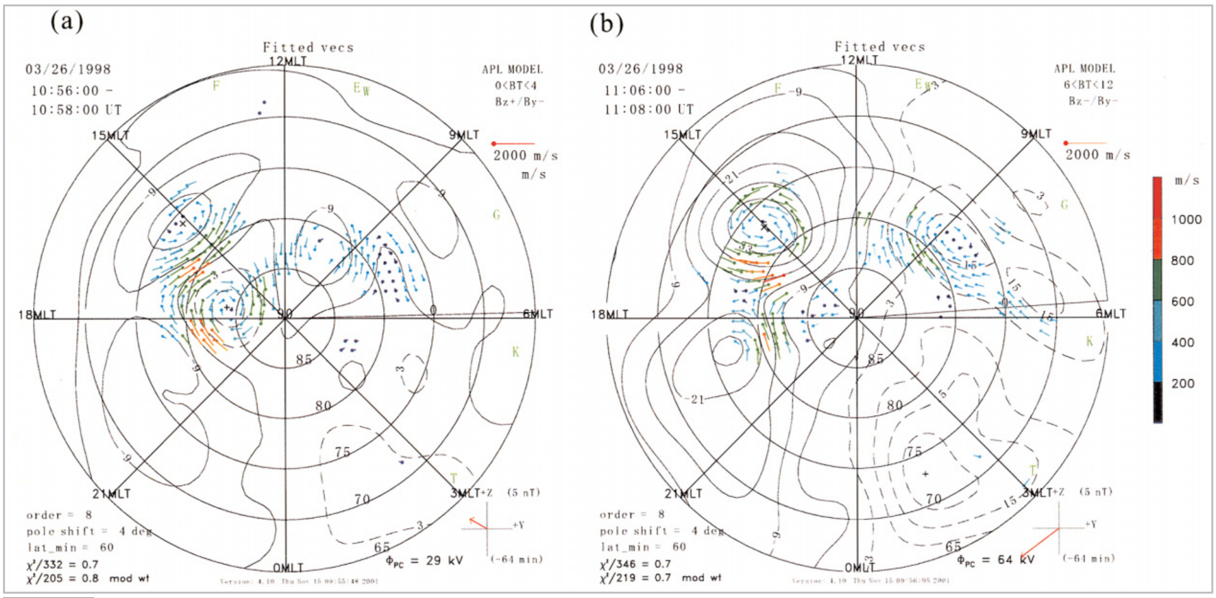

Fig.4 *2-D vector diagram of plasma flow in the ionospheric F layer observed by SuperDARN HF radars.*

The contours represent equipotential lines drawn based on an APL convection map model. The center is the magnetic north pole and the circles represent latitudes spaced at 5˚ intervals.

these FACs are called NBZ currents. Results of 3-D MHD simulations show that the dayside NBZ current forms a current system connected to the spatially small dynamo region created on the lower latitude side of the dayside cusp (Tanaka, 1995).

Fig.4 (b) shows the plasma convection pattern immediately after the beginning of the increase in the convection electric field (extension of magnetic field lines) of the nightside inner magnetosphere, as observed by the GOES 9 satellite. It can be seen that the reversed 2-cell pattern in the polar cap has disappeared, and that a normal 2-cell convection (in the opposite direction as that of the DP2 current) has clearly developed. This is attributed to the development of Region 1 FAC. The switchover from the northward reversed 2-cell pattern to a normal 2-cell convection pattern signifies a change in the current system (i.e., a change in the dynamo region). In other words, when there is a major change in the orientation of the IMF Bz component, the location of magnetic reconnection to the magnetospheric magnetic field at the magnetopause is shifted to a great degree, and both the location of dynamo formation and the electric field generation capacity change significantly.

The switchover between these two convection patterns is clarified in Figs. 5 (a)-(d), which show the temporal variations in the line-of-sight velocities of plasma flow along the four solid lines in the top right panel of Fig.5 observed by HF radars positioned at points indicated by circled letters (F: Finland; E: East Iceland; W: West Iceland; G: Goose Bay, Canada). The horizontal axis represents time (in UT) and the vertical axis represents the distance from radar (geomagnetic latitude for Fig.5 (a)) along the solid line in the top right panel in Fig.5.

The color scale shows the line-of-sight velocities of F layer plasma. The positive and negative velocities correspond to direction toward and away from the radar, respectively. Since the Finland HF radar was located near 13 MLT at 11:00 UT, the plasma flow at latitudes higher than geomagnetic latitude of 84˚ (shown in blue in Fig.5 (a)) corresponds to the plasma flow heading from the pole near the meridian toward lower latitudes (sunward), which is a reversed 2-cell plasma flow.

It can be seen that the velocity of the sunward plasma flow at latitudes higher than the geomagnetic latitude of 84˚ (shown in blue)

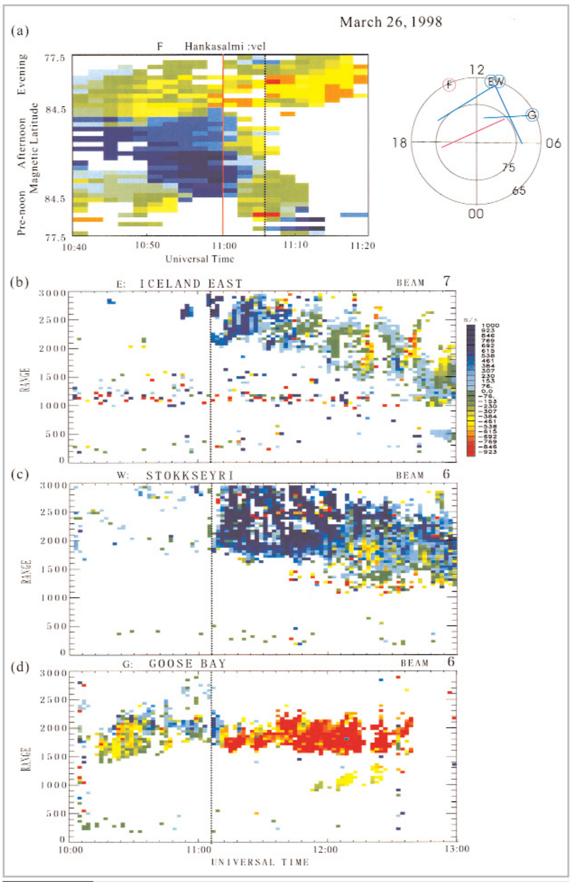

Fig.5 *(Top Right) The blue dots show the position of the four radar units: in Finland, west Iceland, east Iceland, and Goose Bay (Canada).*

(a) The line-of-sight velocity of plasma flow observed by the Finland radar, shown by the pink solid line in the top-right panel. The vertical and horizontal axes represent latitude and universal time, respectively. (b)-(d) The line-of-sight velocities of plasma flows along the three blue lines in the top-right panel. The vertical axis represents the distance from radar (range), and the color scale shows the line-of-sight velocity of the F layer plasma flow.

begins to decrease simultaneously with the initiation of increase in the ionospheric convection electric field at 11:00 UT. The plasma convection in the polar cap changes completely into an anti-sunward convection (yellow-green) by 11:06 UT. In contrast, the line-of-sight velocity (echo intensity) of plasma flow on the low latitude side shown in Figs.5 (b), (c), and (d) begins to increase almost simultaneously at all MLT at 11:06 UT. As indicated in Fig.4 (b), this echo intensity represents the change in plasma flow velocity in the morning-sector and evening-sector convection cells of the 2-cell convection featuring centers in the dayside. The onset of convection development in the inner magnetosphere observed by a geostationary satellite was simultaneous with the onset of the dayside plasma convection.

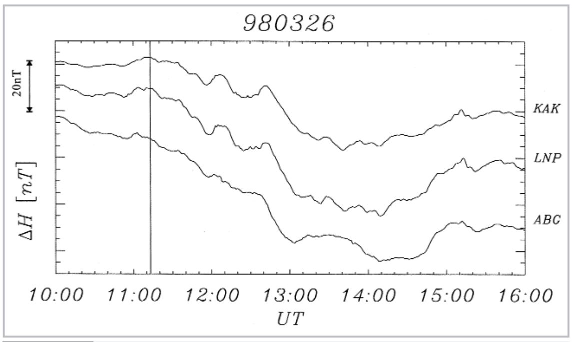

Fig.6 *The H component of the magnetic field observed at three low-latitude stations (Kakioka, Lunping, and Alibag) from the afternoon to nightside.*

The solid vertical line represents the start of ring current development.

Fig.6 shows the H component of the geomagnetic field on the ground at middle to low latitude regions in the evening sector. It can be seen that the H components begin to decrease simultaneously at 11:13 UT. This indicates that a westward (asymmetrical) ring current has begun to develop at 5-6 Re from Earth in the equatorial plane of the magnetosphere. Since the ring current is generated as a result of increased plasma pressure in the inner magnetosphere due to the development of Earthward plasma convection in the nightside magnetosphere, the development of a ring current indicates that there is an increase in the westward electric field in the geostationary orbit (Hashimoto et al., 2002).

In summary, the results of the above analysis suggest the following scenario for the convection development process.

The southward turning of the IMF Bz component initiated the development of a Region 1 FAC dynamo in the magnetopause, and the FAC potential field began to penetrate into the ionosphere at 11:00 UT. Since the NBZ current system for northward IMF was still present, the Region 1 FAC potential field is considered not to have been sufficiently intense to appear in echoes of HF radars. It took approximately six minutes for the NBZ current to weaken and completely disappear (11:06 UT). At the same time (11:06 UT), the Region 1 FAC potential field strengthened rapidly, accompanying simultaneous strengthening of the westward electric field in the nightside inner magnetosphere, and plasma convection was accelerated.

As a result, plasma sheet thinning occurred near the geostationary orbit, and a decrease was observed in the N-S component of the geomagnetic field on the ground due to the ring current.

6 Conclusions

An explanation of the mechanism driving plasma convection in the magnetosphere-ionosphere coupled system must be able to account for the ionospheric convection properties that accompany a process of energy loss. It must also explain the temporal variations that cannot be obtained from the properties of an average polar ionospheric convection, and as well as account for the properties of the ionospheric convection that extends into the middle to low latitudes. As revealed by recent studies, ionospheric convection is essentially different from a simple projection of the magnetospheric convection; this conclusion entails a reinvestigation of the mechanism driving plasma convection. Future studies must be carried out to understand the energy influx process to clarify the mechanism driving convection in the magnetosphere-ionosphere coupled system.

Therefore, it will become increasingly important to elucidate the properties of ionospheric convection.

References

1 Chapman, S., "The electric current system of magnetic storms", J. Geophys. Res., 40, 349-365, 1935.

2 Cowley, S. W. H. and M. Lockwood, "Excitation and decay of solar wind-driven flows in the magnetosphere system", Ann. Geophysicae, 10, 103-115, 1992.

3 Dungey, J.W., "Interplanetary magnetic field and the auroral zones", Phys. Rev. Lett., 6, 47, 1961.

4 Etemadi, A., S. W. H. Cowley, M. Lockwood, B. J. I. Bromage, D. M. Willis, and H. Luhr, "The dependence of high-latitude dayside ionospheric flows on the north-south component of the IMF, a high time resolution correlation analysis using EISCAT "POLAR" and AMPTE UKS and IRM data", Planet. Space Sci., 36, 471,1988

5 Fedder, J. A. and J. G. Lyon, "The solar wind-magnetosphere-ionosphere current-voltage relationship", Geophys. Res. Lett., 14, 880-883, 1987.

6 Fukushima, N., "Generalized theorem for no ground magnetic effect of vertical currents connected with Pedersen currents in the uniform-conductivity ionosphere", Rep. Ionos. Space Res. Jap., 30, 35, 1976.

7 Fedder, J. A. and J. G. Lyon, "The earth's magnetosphere is 165 Re long: self-consistent currents, convection, magnetospheric structure, and processes for northward interplanetary magnetic field", J. Geophys. Res., 100, 3623-3635, 1995.

8 Hashimoto, K. K., T. Kikuchi, and Y. Ebihara, "Response of the magnetospheric convection to sudden IMF changes as deduced from the evolution of partial ring currents", J. Geophys. Res., in printing.

9 Heppner, J. P., "Polar cap electric field distributions related to the inter planetary magnetic field direction", J. Geophys. Res., 77 ,4877-4887, 1972.

10 Heppner, J. P., and N. C. Maynard, "Empirical high-latitude electric field models", J. Geophys. Res., 92, 4467, 1987

11 Iijima, T. and T. A. Potmra, "Large-scale characteristics of field-aligned currents associated with substor-

mms", J. Geophys. Res., 83, 5971-5979, 1976
12 Iijima, T., "Field-aligned currents in geospace: Substance and significance, Magnetospheric Current Systems", AGU Monograph 118, 107-129, 2000.
13 Kikuchi, T. and T. Araki, "Horizontal transmission of the polar electric field to the equator", J. Atmos. Terr. Phys., 41, 927-936.
14 Kikuchi, T., H. Lühr, T. Kitamura, O. Saka, and K. Schlegel, "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, 1996.
15 Lopez, R. E., M. Wiltberger, J. G. Lyon, C. C. Goodrich, and K. Papadopoulos, "MHD simulations of the response of high-latitude potential patterns and polar cap boundaries to sudden southward turnings of the interplanetary magnetic field", Geophys. Res. Lett., 26, 967-970, 1999.
16 Mozer, F. S. and P. Lucht, "The average auroral zone electric field", J. Geophys. Res., 79, 1001-1006, 1974
17 Murr, D. L. and W. J. Hughes, "Reconfiguration timescales of ionospheric convection", Geophys. Res. Lett., 28, 2145-2148, 2001
18 Nishida, A., "Coherence of geomagnetic DP2 magnetic fluctuations with interplanetary magnetic variations", J. Geophys. Res., 73, 5549-5559, 1968.
19 Raeder, J., O. Vaisberg, V. Smirnov and L. Avanov, "Reconnection driven lobe convection: Interball tail probe observations and global simulations", J. Atmos. Terr. Phys., 62, 833-849, 2000.
20 Ridley A. J., G. Lu, C.R. Clauer, and V. O. Papitashvili, "A statistical study of the ionospheric convection response to changing interplanetary magnetic field conditions using the assimilative mapping of ionospheric electrodynamics technique", J. Geophys. Res., 103, 4023-4039, 1998.
21 Ruohoniemi, J. M. and K. B. Baker, "Large-scale imaging of high-latitude convection with Super Dual Auroral Radar Network HF radar observations", J. Geophys. Res., 103, 20797-20811, 1998
22 Ruohoniemi, J. M. and R. A. Greenwald, "The response of high latitude convection to a sudden southward IMF turning", Geophys. Res. Lett., 25, 2913-2916, 1998.
23 Saunders, M. A., M. P. Freeman, D. J. Southwood, S. W. H. Cowley, M. Lockwood, J. C. Samson, C. J. Farrugia, and T. J. Hughes, J. Geophys. Res., 97, 19373-19380, 1992.
24 Slinker, S. P., J.A. Fedder, J. M. Ruohoniemi, and J. G. Lyon, "Global MHD simulation of the magnetosphere for Novemver 24, 1996", J. Geophys. Res.,106, 361-380, 2001.
25 Song, P., D. L. DeZeeuw, T. I. Gombosi, C. P. T. Groth , and K. G. Powell, "A numerical study of solar wind - magnetosphere interaction for northaward interplanetary magnetic field", J. Geophys. Res.,104, 28361-28378, 1999.
26 Song, P., T. I. Gombosi, D. L. DeZeeuw, K. G. Powell , and C. P. T. Groth, "A model of solar wind-magnetosphere-ionosphere coupling for due northward IMF", Planet. Space Sci., 48, 29-39, 2000.
27 Southwood D. J. and M. G. Kivelson, "An approximate description of field-aligned currents in an planetary magnetic field", J. Geophys. Res., 96, 67-75, 1991.
28 Strangeway, R. J. and J. Raeder, "On the transition from collisionless to collisional magnetohydrodynamics", J. Geophys. Res., 106, 1955-1960, 2001.
29 Swift, D. W. and Gurnett, D. A., "Direct comparison between satellite electric field measurements and visual auroras", J. Geophys. Res., 78, 7306-7313.,1973
30 Tanaka, T., "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, 12057-12074, 1995.
31 Tanaka, T., "The state transition model of the substorm onset", J. Geophys. Res., 105, 21081-21096, 2000.

32 Todd, H. and S. W. H. Cowley, M. Lockwood, D. M. Wills , and H. Luhr, "Response time of the high-latitude dayside ionosphere to sudden changes in the north-south component of the IMF", Planet. Space Sci., Vol. 36, 1415-1428, 1988.

33 Weimer, D. R., "Models of high-latitude electric potentials derived with a least error fit of spherical harmonic coefficients", J. Geophys. Res.,100, 19595,1995.

34 Zmuda, A. J., J. C. Armstrong, and Heuring, F. T., "Characteristics of transverse magnetic disturbances observed at 1100 km in the auroral oval", J. Geophys. Res., 75, 4757-4762, 1970.

35 Zmuda, A. J., J. C. Armstrong, "The diurnal flow pattern of field-aligned currents", J. Geophys. Res., 79, 4611-4619, 1974.

***HASHIMOTO K. Kumiko**, Ph. D.*

Research Fellow, Space Weather Group, Applied Research and Standards Division

Physics of Magnetosphere and Ionosphere