Space Weather Study Using the HF Radar in King Salmon, Alaska

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Earth orbiting and geostationary satellites often suffered from damages caused by space storms, of which energy is produced by the interaction between the solar wind and magnetosphere. In particular, the energy transmission to the inner magnetosphere and low latitude ionosphere is a critical issue in the space weather study. To monitor the electromagnetic energy coming into the magnetosphere and ionosphere, we built an HF radar in King Salmon, Alaska, and operated it as a part of the SuperDARN radar network. Combining with magnetometer data from the low latitude and equator, we revealed new aspects of the energy transmission to the equatorial ionosphere. Here we report the radar system and initial results basing on the radar and magnetometer observations.

Keywords
Space weather, Satellite anomaly, Magnetosphere, Ionosphere, HF radar, Magnetometer

1 Introduction

On October 24, 2003, the Earth Observation Satellite *Midori* was exposed to a heavy shower of auroral electrons, and the ensuing electrostatic charge, discharge, and resultant fire led to the failure of the satellite. Similarly, increases in the high-energy radiation in space near the Earth have caused temporary loss of functions in broadcasting and meteorological satellites, resulting in interruptions in communications and in the transmission of cloud coverage data. Moreover, anomalous increases in ionospheric electrons caused by magnetic storms are known to cause GPS positioning errors. These and other high-tech systems that use satellites are vulnerable to variations in the space environment and are easily damaged. In response to this vulnerability, studies on space weather forecasting are forming an increasing focus at a variety of universities and research institutes, including NICT. These trends are also seen in the US and Europe, and sessions on (or principally dealing with) space weather are always included in both domestic and foreign academic meetings relating to the geophysics and space sciences.

NICT began its globally pioneering studies of space weather forecasting in 1988, when the organization was known as the Communications Research Laboratory (Kikuchi, 1988). The goal of the research project launched was to transform the propagation disturbance warning system, which had been operated by the NICT (CRL) for several decades, into a forecasting system for electromagnetic field and radiation particle variations in space, in response to evolving demands in an era of space-based endeavors. In the 1990s, the US also embarked on space weather studies as a national project, and in recent years, the European Space Agency (ESA) has started similar activities; the movement has thus become a global trend. The CAWSES (Climate and Weather of the Sun-Earth System) project, a five-year initiative from 2004 to 2008, is one of a number of joint international space weather projects. The global increase in interest in space weather studies is a reflection of how space has changed, from a once-mysterious territory into an environment of human activity densely populated by operational satellites, including the first forays in to commercial space travel.

A system for space weather forecasting must in principle ensure the safety of space applications, but at present, the system has yet to be developed to a degree sufficient for practical application. Although immediately afterward it was determined that the *Midori* satellite accident was caused by auroral electrons (Kikuchi, Latest Space News, http://www.universe-s.com/news/2003/1125_j.html), the mechanism of the sudden commencement of auroral substorms remains unknown. Generally, an influx of electromagnetic energy or plasma carried by solar winds is required for the development of space storms, and in particular, it is known that the influx of electromagnetic energy is closely associated with the generation of auroral substorms, magnetic storms, and high-energy electrons in the radiation belt. Thus, monitoring of this influx of energy and plasma, and resolution of the mechanism of influx forms a major research theme. With the aim of monitoring the influx of electromagnetic energy, by 1998 NICT had installed magnetometers on the magnetic equator in Yap and in the low-latitude region of Okinawa, in addition to construction of an HF radar in King Salmon, Alaska, completed in July 2001. This radar has the same functions as those deployed under the international SuperDARN project (Greenwald et al., 1998), and the data will be shared by the international community to promote space weather studies worldwide.

2 Observation of the Ionospheric electric field using the HF radar and magnetometers

2.1 The King Salmon radar

The HF radar transmits HF radio waves in the 8～20 MHz frequency range obliquely upward, and receives the waves that are reflected back by the irregular structures of ionospheric electron density distributed along geomagnetic field lines having scales on the order of half-wavelengths, thus measuring the Doppler frequency of the reflected waves. The data is used to measure the velocity of plasma motion. Figure 1 shows the field of view of the 10 radar units deployed in the north polar region. The King Salmon radar is located on the westernmost end of the radar network, and covers the eastern Siberian region, previously an area fully outside of any similar radar coverage. Furthermore, since its field of view connects with that of the Hokkaido HF radar operated by the Solar-Terrestrial Environment Laboratory of Nagoya University (since December 2006), the King Salmon radar permits observation of ionospheric plasma motion from the polar region to the middle latitudes. As a result, this unique radar pair can monitor the influx of electromagnetic energy into the inner magnetosphere and low-latitude ionosphere.

The antenna of the radar is a log-periodic

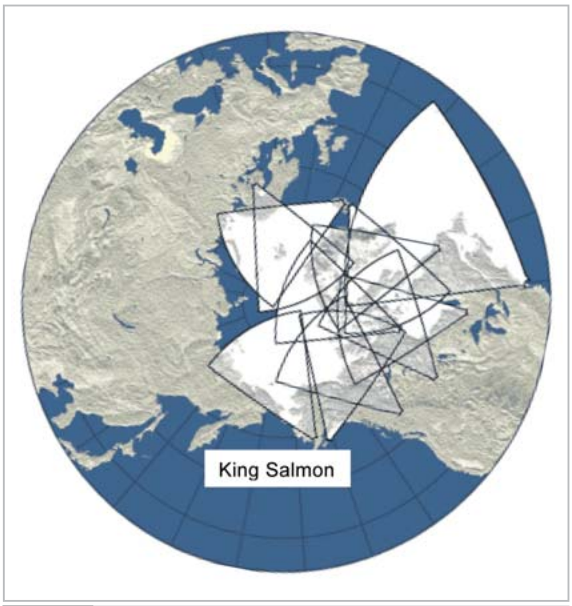

Fig.1 *The HF radar network in the north polar region*

SuperDARN. The King Salmon radar covers the eastern Siberian region north to Japan, and observation is coordinated with ionospheric and other observations based in Japan.

antenna performing continuous transmission and reception at frequencies of 8∼20 MHz, and the phased array consists of 16 antennas whose elements are stretched across 17 towers 15 meters high each and placed at 12 meter intervals (Fig. 2). The array observes the two-dimensional echo intensity and plasma velocity in the fan-shaped region with a radius of 3,000 km and an angle of view of 53°, by changing the phases among the 16 beams. A single sweep of the radar beam takes 7 seconds, and a single set of two-dimensional data is collected every 2 minutes (Fig. 3).

The velocity of the ionospheric plasma is determined by the ratio of the intensity of the electric field impressed along the magnetic field line from the magnetosphere to the ionosphere, and the geomagnetic field intensity. The direction of the plasma motion is perpendicular to the electric field and the geomagnetic field. Since the geomagnetic field is nearly vertical in the polar regions, the plasma motion is horizontal. When an irregular structure at half-wavelength scale is present in the ionospheric plasma, the incident radio wave to the ionosphere is reflected by this irregularity. The reflected wave is received by the same antenna that transmits the original radio wave, and the measured Doppler frequency is used to calculate the line of sight (LOS) velocity of the plasma motion. Figure 3 presents the plasma velocity inside a two-dimensional plane obtained by this method. The warm and cool colors indicate plasma motion heading away from and approaching the radar, respectively. Since a single radar unit can only measure the LOS plasma velocity, it is not possible to obtain 2-D velocity vectors. However, when two radar units are performing observations of the same region from different directions, 2-D velocity vectors may be calculated by synthesizing the LOS velocities. On the other hand, in cases such as the King Salmon radar, which is not part of a radar pair, the following method is utilized for determining the overall velocity vector distribution (Ruohoniemi and Baker, 1998). The stream function in the vector direction is assumed to be a sum of the series of the spherical harmonics, and the mean plasma convection pattern obtained in past observations is used together with the observed values to calculate the coefficients of the series to determine the overall velocity vector. Figure 4 shows the

Fig.2 *The antenna (top) and radar unit (bottom) installed at King Salmon*

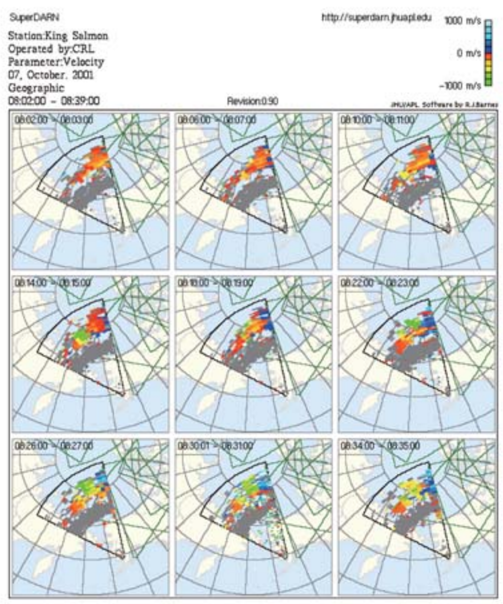

Fig.3 *LOS velocities of ionospheric plasma observed by the King Salmon radar*

Positive (cool colors) and negative values (warm colors) indicate motion heading toward and away from the radar, respectively.

vector diagram of the ionospheric plasma flow for the entire north polar region, which has been determined by including the King Salmon radar data (publicized by the John Hopkins University Applied Physics Laboratory at http://superdarn.jhuapl.edu/).

2.2 Low-latitude and equatorial magnetometer observation

The ionospheric plasma motion observed by the HF radar provides information on the ionospheric electric field, which induces electric currents in the ionospheric E region and causes variations in magnetic field intensities on the ground. Therefore, by applying the model for electric conductivity in the ionosphere, it should be possible to predict the electric current and the electric field in the ionosphere based on the magnetic field variations observed on the ground (Tsunomura and Araki, 1984). In the low to middle latitude regions presently lacking in radar coverage, magnetic field observations using magnetometers are particularly valuable. During the large-scale space storms that damage satellites, the ionospheric electric current flows into the low-to-middle latitude regions and the equatorial regions, triggering global magnetic field variations known as DP2 variations (Nishida et al., 1966; Kikuchi et al., 1996). DP2 variation has been historically used as an indicator for monitoring the influx of electromagnetic energy originating in the solar wind into the magnetosphere and the ionosphere, due to the good correlation of this variation with the Z component of the interplanetary magnetic field (IMF) (Nishida, 1968). In particular, the horizontal geomagnetic field at the magnetic equator creates a polarized electric field in the vertical direction due to the zonal electric field, and the Hall current induced as a result of the polarization effectively increases the electrical conductivity of the equatorial ionosphere by about one order of magnitude compared to the low-latitude ionosphere. Therefore, even weak electric fields that have propagated from the polar ionosphere can cause magnetic field variations with large amplitudes, and so the DP2 variation is used as data for detecting the global electric field (e.g., Kikuchi et al., 1996). To exploit this advantage, in 1998 NICT installed magnetometers at Yap (in the equatorial region) and in Okinawa (in the low-latitude region) to use as reference with respect to the equatorial magnetic field variations (Fig. 5).

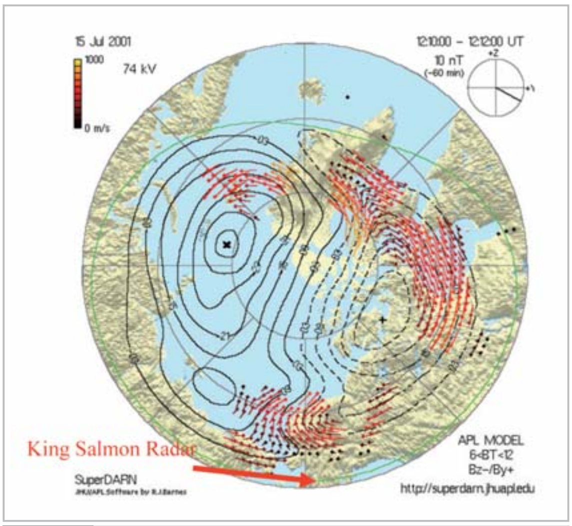

Fig.4 *Ionospheric plasma convection in the north polar region observed by the SuperDARN radar network*

The top and right areas of the plot correspond to the magnetic local times of 12 and 6 hour, respectively. Daytime and nighttime ionospheric plasma convection is observed simultaneously every 2 minutes.

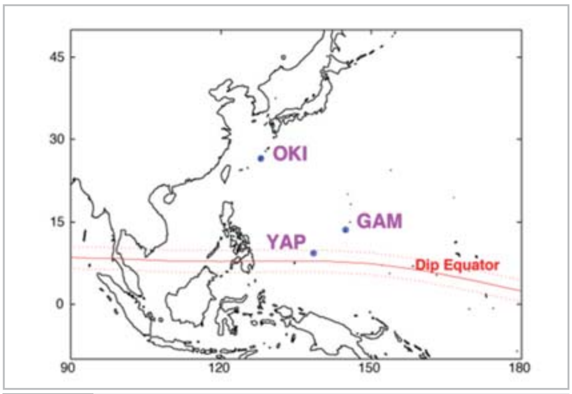

Fig.5 *Magnetometer stations in equatorial Yap and low-latitude Okinawa (OKI)*

Yap is located almost on the dip equator, and its abnormally large ionospheric electric conductivity results in large magnetic field variations induced by electric fields propagating from the polar ionosphere.

Araki (1977) discovered that the polar ionospheric electric field propagating at high speed into the equatorial region induces strong electric currents in the equatorial ionospheric E region based on the simultaneous occurrences of the preliminary reverse impulse of the magnetic Sudden Commencement (SC) in high-latitude and equatorial regions. The high-speed propagation of the polar electric field to low latitudes (the equator) has since been confirmed by direct observation of the low-latitude ionospheric electric field using the HF Doppler observation network of the former Radio Research Laboratory (Kikuchi, 1986), through observation of geomagnetic pulsations having minute-order cycles that increase at the equator (Motoba et al., 2002), and further by the confirmation of DP2 magnetic field variations having periods of several tens of minutes (Kikuchi et al., 1996). The mechanism that allows the nearly instantaneous propagation of the ionospheric electric field over a distance of approximately 8,000 km from the polar region to the equator has been explained by Kikuchi et al. (1978) and Kikuchi and Araki (1979) with the zero-order TM mode inside the waveguide consisting of the ground and the ionospheric E region. Although the TM0 mode waves are attenuated as they propagate due to the finite electrical conductivity of the ionosphere, the attenuation is less than 10 %, and so in comparison, the effect of the geometric attenuation caused by the small size of the electric field relative to the propagation distance is more significant. This attenuation reduces the electric field by at least 90 % at the equator, but as stated above, the abnormally large electrical conductivity of the ionosphere at the magnetic equator results in observable magnetic field variations.

2.3 Electric fields during magnetic storms

The penetration of the dawn-to-dusk electric field developing in the magnetosphere during magnetic storms is known to induce ring currents associated with magnetic storms. Such strong electric fields deep within the inner magnetosphere have in fact been observed by satellites during magnetic storms (Wygant et al., 1998; Shinbori et al., 2005). The electric field within the inner magnetosphere generates a large-scale electric current system during magnetic storms (Ebihara and Ejiri, et al., 2000; Burke et al., 1998), and it has been pointed out that this current system may possibly contribute to the generation of the radiation belt particles (Nishimura et al., 2007). Moreover, geomagnetic storm electric fields are known to propagate to the low-latitude and equatorial ionosphere, where they cause an increase in the number of ionospheric electrons and large resultant errors in GPS positioning (Maruyama et al., 2004; Tsurutani et al., 2004). Thus, these storm-generated electric fields represent a major research theme in the space weather forecasting field. An electric field penetrating into the low latitude and the equator has been directly observed by the Jicamarca incoherent scatter (IS) radar (Huang et al., 2005), and this field is also known to trigger DP2 magnetic field variations on the ground by inducing electric currents in the ionosphere in the middle-to-low latitudes (Wilson et al., 2001). In terms of the relationship between the ionospheric electric field and the inner magnetospheric electric field, Hashimoto et al. (2002) demonstrated that inner magnetosphere plasma convection is increased within minutes from an increase in the electric field in the polar ionosphere, leading the authors to propose a model in which the electric field propagates into the inner magnetosphere via the ionosphere.

If the magnetic storm electric field propagates into the inner magnetosphere via the ionosphere, then the King Salmon radar installed near the foot of the magnetic field lines of the inner magnetosphere should provide a powerful monitoring tool. Next, we will introduce some new findings on the DP2 electric field and the shielding electric field.

The top panel in Fig. 6 shows the three magnetic field components recorded in Okinawa from December 14-15, 2006. The H component begins to increase rapidly at

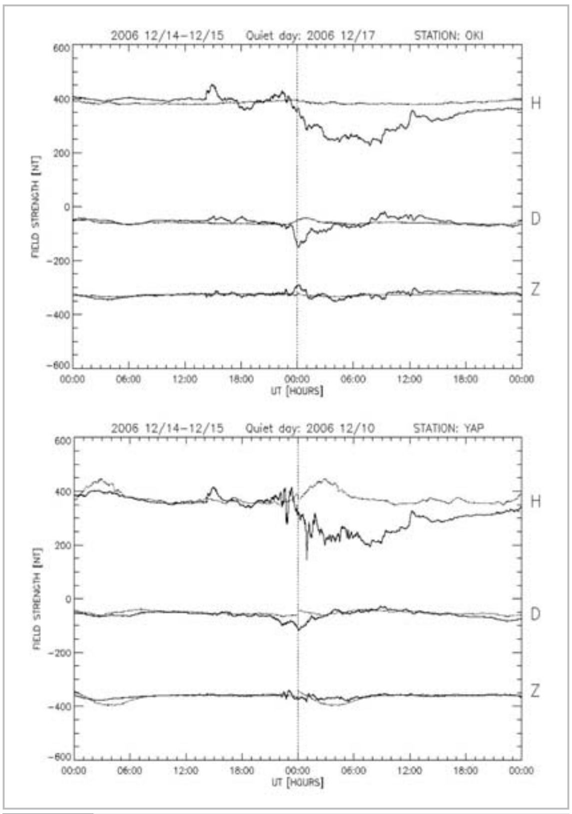

Fig.6 *Three magnetic field components recorded at Okinawa (top) and Yap (bottom) from Dec. 14-15, 2006, during which a magnetic storm was observed. The dashed line shows the magnetic field variation observed during a quiescent period on Dec. 10*

1410 UT on December 14, and the magnetic field begins to decrease at 2230 UT. The first rapid onset of an increase in the magnetic field is referred to as the SSC (Storm Sudden Commencement). The SSC is caused by the Chapman-Ferraro current, which is generated in the front of the magnetosphere when the solar wind shock collides with the magnetosphere. The subsequent decrease of the magnetic field is caused by the westward ring current, which develops in the magnetosphere at a distance of approximately four times the radius of the Earth. The ring current develops as a result of the electric field penetration into the magnetosphere. Since Okinawa is located at a position that is unaffected by the strong electric current in the magnetic equatorial ionosphere and the strong electric currents in the polar ionosphere, the magnetic field variations in Okinawa may be considered to reflect the effects of the magnetospheric electric currents.

The bottom panel in Fig. 6 shows the three magnetic field components recorded at equatorial Yap during the same period. The main difference from the magnetic field variations observed at Okinawa is seen in the periodic oscillations displaying 30 minute periods that develop around 2230 UT. These magnetic field variations are DP2 variations induced by the electric currents that flow in the magnetic equatorial ionosphere. To extract the components of these variations, it is necessary to correct for the diurnal variations in the magnetic field at both stations during quiescent periods and then to subtract the variations observed at Okinawa from those observed at Yap. Figure 7 shows the DP2 magnetic field variations obtained by the above method. The equatorial DP2 current repeats a cycle of increase and decrease in a period of approximately 30 minutes beginning at 22 UT, and displays a decreasing trend from 2320 UT.

Kikuchi et al. (1996) have shown that the DP2 magnetic field variations oscillating in 40 minute periods are caused by the propagation of the polar ionospheric electric field to the equatorial ionosphere at the speed of light. However, these variations may ultimately be traced back to the magnetospheric electric field variations caused by the periodic variations in the IMF N-S component (Nishida et al., 1966; Nishida, 1968). The ACE satellite has in fact observed an actual IMF variation directly associated with a DP2 variation event. Figure 7 shows that the DP2 variation is composed of positive and negative magnetic field variations induced by the eastward and westward electric currents, respectively. Analysis of the EISCAT radar data by Kikuchi et al. (1996) has shown a strong correlation between the DP2 variation and the convection electric field in the polar ionosphere, but the electric field that causes the negative variation observed in Fig. 7 is inverse to the convection electric field. This electric field requires further elucidation.

With this aim in mind, the SuperDARN

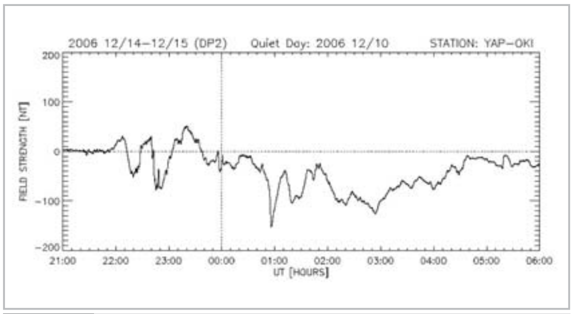

Fig.7 DP2 magnetic field variations induced by equatorial ionospheric currents obtained by subtracting the magnetic field variations observed at Okinawa from those observed at Yap

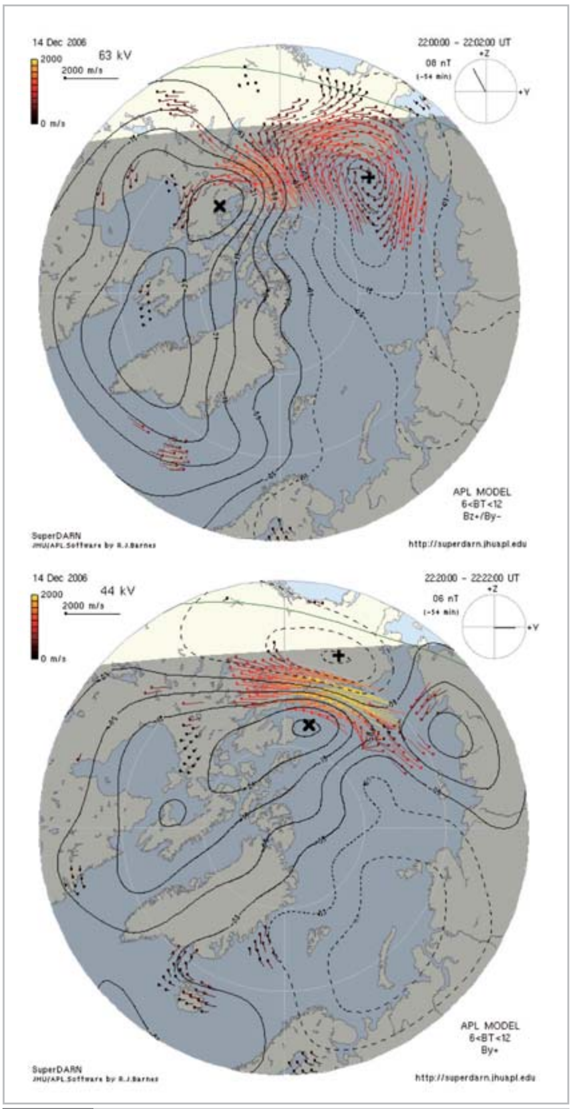

Fig.8 Twin-vortex ionospheric convection pattern corresponding to positive magnetic field variation in the equator at 2200 UT (top) and a deformed pattern corresponding to negative variation at 2220 UT (bottom)

The clockwise convection cell on the morning side, believed to cause the negative magnetic field variation, was observed by the King Salmon radar.

radar network data has been analyzed, including King Salmon radar data, relating to the observation of plasma motion in the polar ionosphere. The top panel in Fig. 8 presents the plasma convection at 2200 UT at which a positive shift was observed in the equatorial magnetic field variation. A strong poleward plasma flow was observed at 12 hours magnetic local time (MLT) (top portion of plot), and a counter-clockwise convection cell was observed on the morning side (right side of plot) by the radars at King Salmon and elsewhere. This sort of convection pattern is consistent with the large-scale twin vortex convection pattern of the southward IMF, and indicates that the convection electric field has intensified in the direction from dawn to dusk. The penetration of this dawn-to-dusk electric field into the equatorial ionosphere is believed to drive the eastward electric current, which causes the positive magnetic field variation observed during daytime. In contrast, the bottom panel in Fig. 8 shows the plasma convection at 2220 UT, at which a negative shift was observed in the equatorial magnetic field. The 12 MLT plasma flow is converted from northward to westward, and the plasma flow that had been counter-clockwise in the morning side was observed to change to a clockwise flow by the King Salmon radar. This change in convection pattern signifies a reversal of the electric field from the dawn-to-dusk to the dusk-to-dawn direction. This reversal of the polar ionospheric electric field is believed to cause the change from a positive to a negative transition in the equatorial magnetic field variation. The reversal of the electric field suggests the development of a shielding electric field, the development of which may be observed directly using the HF radar. The development of the shielding electric field is associated with the decay of the magnetic storm, and this development also causes variations in the low-latitude ionosphere. Thus, HF radars that observe relatively low-latitude areas in the polar region (such as the radar at King Salmon) are expected to provide valuable data in the understanding and prediction of magnetic storm evolution.

3 Conclusions

In the era of an increasing range of human endeavors in space, the major obstacles to such activity are the high-energy particles and plasma that damage satellite equipment, in addition to the variations in electric and magnetic fields that trigger ionospheric disturbances. Among these variations, the electric field causes magnetic field variations and also contributes to an increase in the total electron content of the ionosphere (Maruyama et al., 2004; Tsurutani et al., 2004), as well as the generation of high-energy particles in the radiation belt (Lyons et al., 2005, Nishimura et al., 2007). One of the major themes of space weather forecasting is the establishment of an efficient method of observation with respect to this electric field. One effective method of enabling such observation involves direct observation within the magnetosphere by satellites such as the AKEBONO satellite (Shinbori et al., 2005). However, there are limits to such satellite observations, which provide data only from a single point. In contrast, by focusing on the tendency of the electric current to flow along magnetic field lines, the electric potential of the magnetosphere may be observed directly as the electric potential of the ionosphere. The usefulness of conducting observations of the ionospheric electric field using HF radars thus becomes clear. The King Salmon radar was installed in July 2001, and now forms a part of the SuperDARN radar network, together with other HF radars operated by the participating countries. On the other hand, since the transmission of electromagnetic energy is represented as a Poynting flux—a vector product of the electric and the magnetic fields—it is also important to observe the magnetic field as well as the electric field. In particular, observation of the magnetic field at the magnetic equator is an effective means of monitoring the penetration of the electric field to the low-latitude ionosphere and the inner magnetosphere.

The present paper compares the electric field of the equatorial ionosphere observed by the Yap and Okinawa magnetometers and the 2-D patterns of the polar electric field observed by the SuperDARN radar network, with particular focus on the King Salmon radar data. The results show that the eastward electric field, which triggers positive magnetic field variations on the morning side equator, corresponds to large-scale twin-vortex plasma convection in the polar ionosphere, while a new type of convection cell is formed in the low latitude side of the polar ionosphere involving negative magnetic field variations in the equator. These results were achieved thanks to the King Salmon radar, which covers the low-latitude areas in the polar region. The direction of the convection cell for twin-vortex convection is in the clockwise direction (opposite to the predicted counterclockwise motion), and indicates the presence of a shielding electric field that counters the convection electric field. Correlation analysis of the data from the Hokkaido HF radar (operated by the Solar-Terrestrial Environment Laboratory of Nagoya University) and the simulation results for magnetospheric ring currents should prove effective in an investigation of this phenomenon. The Hokkaido radar has in fact succeeded in observing the lower-latitude portion of the clockwise convection cell through observation of the middle latitude region immediately adjacent to the field of view of the King Salmon radar. Furthermore, the results of ring current simulation by Ebihara and Ejiri (2000) has revealed the development of region 2 field-aligned currents that form the shielding electric field, which confirms the association of the clockwise convection cell observed by the HF radar in the development of the shielding electric field. It is expected that a comprehensive analysis of the results of electric and magnetic field observations using HF radars and magnetometers, in addition to simulation results, will contribute greatly to the understanding of the electromagnetic energy transmission mechanism — a key factor in determining space weather.

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