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Coupled-Model Numerical Simulation of Ground Magnetic Fields during the Total Solar Eclipse of 22 July 2009

by

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Abstract

It has been uncertain whether geomagnetic variations are associated with solar eclipses. The uncertainty may be derived from the lack of a reliable numerical model for yielding geomagnetic signatures associated with localized and temporary decreases in ionospheric conductivities occurring during a solar eclipse. We used a newly developed coupled numerical model (Atmospheric Global Circulation model coupled with an ionospheric dynamo model and an ionospheric plasma circulation model) to conduct numerical studies of geomagnetic signatures during the 2009 total solar eclipse. The simulation successfully reproduced the geomagnetic Z-component variations observed at Kanoya Geomagnetic Observatory (KNY). It is noteworthy that this is the first work in the world to use a realistic numerical model to confirm definite geomagnetic variations caused by a solar eclipse.

1. Introduction

It is well-known that electric currents in the ionosphere cause diurnal geomagnetic variations. During the daytime, the ionospheric plasma population is enhanced when ultraviolet radiation from the Sun ionizes the molecules of the atmosphere. The temperature of the atmosphere which rises at this time as the energy of the ultraviolet rays ionizes the molecules is converted to kinetic energy. Conversely, the temperatures fall during the nighttime as there is no heat source. This day-night asymmetry in temperature creates a wind in the ionosphere which drags the positively ionized component of the atmosphere and causes an electric current to flow. The magnetic field variations caused by this electric current are observed on the ground as “solar daily variations on quiet days” (*Sq*). *Sq* exhibits similar feature at places of similar latitudes; the closer the place is to the Equator, the greater the variation.

In an ionospheric region where a solar eclipse interrupts the radiation from the Sun, a rapid decrease in radiative heating of the atmosphere generates an area of low temperatures in the neutral atmosphere. The neutral wind may be excited during this process, and the atmospheric circulation in the lower thermosphere (ionosphere) changes. In addition, localized temperature fluctuations may excite atmospheric fluctuation, such as fluctuations in gravitational waves. At the same time, the electron density decreases in the ionosphere due to the rapid decrease in solar radiation. Fluctuations in the *Sq* current are believed to occur during a solar eclipse as a result of these electric current and neutral wind fluctuations in the lower thermosphere.Resultantly, these fluctuationsaffect magnetic fields on the ground.

The effects of solar eclipses on geomagnetic fields, however, have remained unclear to date, including their existence. During the solar eclipse of 11 August 1999, the zone of totality passed in Europe.Then, several studies investigated geomagnetic fluctuations in Europe where numerous geomagnetic observatories are located. Korte et al. (2001), for example, reported that the solar eclipse affected ionospheric conductivity but had no effect on the magnetic fields observed on the ground. On the other hand, Hvoždara and Prigancová (2002) reported that the eclipse did affect the magnetic fields observed on the ground.

In this paper, we present the magnetic field fluctuations which we observed at our geomagnetic observatories, observation stations, and unmanned observation sites during the solar eclipse of 22 July 2009. We also present the results of a simulation of magnetic fields during the eclipse using a coupled model to demonstrate how they correspond to the observed fluctuations of the magnetic fields.

2. Ground magnetic fields observed during the solar eclipse

During the solar eclipse of 22 July 2009, totality was observed in the area including Yaku-shima, the Tokara Islands, and Amami-Oshima, with a partial eclipse over most of Japan. The maximum eclipse was 96.6% at Kanoya Geomagnetic Observatory and 98.3% at Chichijima's continuous observation site, providing a valuable opportunity to observe the effects of a solar eclipse on geomagnetic fields using a fluxgate magnetometer to obtain per-second data for three components.

The eclipse reached its peak at 22 July 01:50 UTC, with the center of the eclipse located near lat 30°N, long 125°E.

Fig. 1 shows variations in the geomagnetic field components H, Z, and D which were recorded at Kanoya between 21 July 2009 12:00 UTC and 22 July 2009 12:00 UTC. At Kanoya, the eclipse reached its peak at around 22 July 02:00 UTC, corresponding to Z-component variations of about 20 nT. It should be noted that the occurrence of a magnetic storm made it difficult to isolate the effect of the solar eclipse from the data recorded from around 04:00 UTC onward.

Fig. 2 shows the geomagnetic Z-component variations which were observed at Memambetsu, Kakioka, Kanoya, and Chichijima observatories between 21 July 12:00 UTC and 22 July 12:00 UTC. While the geomagnetic signatures followed nearly the same pattern at the four observatories until about 22 July 01:00 UTC, the characteristic variations of the Z component which coincided with the eclipse were observed only at Kanoya and not at Chichijima where the maximum eclipse was larger than the one at Kanoya.

3. A simulation using a coupled ionosphere/neutral atmosphere model

In this section, we present the results of an analysis of the July 22 solar eclipse using a cou-

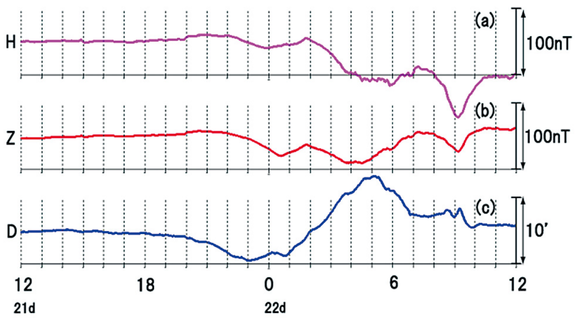

Fig. 1 Changes in the components of the geomagnetic field as observed at Kanoya between 21 July 12:00 UTC and 22 July 12:00 UTC in 2009.

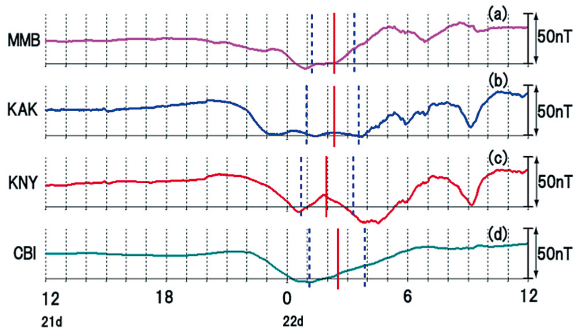

Fig. 2 Changes in the goemagnetic Z component observed at observatories between 21 July 12:00 UTC and 22 July 12:00 UTC in 2009. The traces (a), (b), (c), and (d) represent the values observed at Memambetsu, Kakioka, Kanoya, and Chichijima, respectively. Blue dotted lines indicate the start and the end of the eclipse at each site. Red lines indicate the time at which the eclipse reached a maximum.

pled ionosphere/neutral atmosphere model (hereafter called simply the "Coupled Model") to demonstrate how well the model reproduces the real phenomena. At the same time, we quantitatively evaluate the effects of a solar eclipse on geomagnetism.

The coupled model used in this study is not a single model designed to, for example, analyze the motions of the neutral atmosphere, ionosphere, and magnetosphere, separately. Instead it performs calculations using values derived by other models as the boundary conditions for each of the independently developed models. Our analysis used a neutral atmosphere model which was expanded to include the thermosphere (Miyoshi and Fujiwara, 2003) and an ionosphere model with a solver of the ionospheric electric field (dynamo model). A magnetosphere model was not included. The ionosphere model is a global model which was developed as a part of the real-time space weather simulation system (http://www2.nict.go.jp/y/y223/simulation/realtime/enter.html) to solve mass, momentum, and energy equations for several key ions and electrons. Calculations take into consideration ionization and deionization by photochemical reactions in addition to the processes of diffusion and convection. Horizontal grid intervals were 1 km latitudinally and 5 km longitudinally, and vertical intervals were 10 km up to an altitude of 600 km beyond which the intervals increased. The ionospheric electric field is also calculated by the dynamo model.The maximum altitude was 3000 km. Time resolution was 0.5 seconds. The details of this model have been published by Jin et al. (2011). Curto et al. (2006) used a model in an attempt to predict the effects of a solar eclipse on magnetic fields. They, however, tried to calculate magnetic fields by an equivalent electrical current system. We are the first in the world to have attempted to calculate ground magnetic fields using the coupled model consisting of a general circulation model of the neutral atmosphere and the ionosphere with a dynamo model.

In our analysis, we calculated the ionospheric electric current from the electrical field and ionospheric conductivity, and derived magnetic variations on the ground by applying the Biot-Savart law to the current.

3.1 Ionospheric conductivity

At altitudes of between 170 and 300 km, neutral molecules are actively ionized by extreme ultraviolet (EUV) radiation with wavelengths of less than 102.5 nm In our analysis, we assumed that the level of EUV radiation from the eclipsed Sun would decrease to 1% of the normal level, and we calculated changes in the atmospheric conductivity accordingly. We considered four ion species, (N^{2+}, NO^{+}, O^{+}, and O^{2+}) for our calculations. For each of these, the ion density values at 22 July 2009 01:50 UTC generated by the ionosphere model were assigned as the initial condition. For atomic weights, we used N=14.0067 and O=15.9994. For the electron density, we used the sum of the densities of the four positive ion species under conditions of charge neutrality. The value for the magnetic field is provided by the International Geomagnetic Reference Field (IGRF) model IGRF2000.0. Electron mass is 9.109×10^{-34} [kg], and elementary electric charge was 1.602×10^{-19} [C]. The collision frequency is adopted from Tohmatsu (1990).

Fig. 3 shows the vertical distributions of Pedersen (σ_1) and Hall (σ_2) conductivities, and Fig .4 shows the vertical distributions of longitudinal conductivity (σ_0). The vertical distributions in Fig. 3 and 4 indicate that both σ_1 and σ_2 decreased during the solar eclipse event to about 70% of the values when the Sun is not eclipsed. In addition, σ_0 was extremely high relative to σ_1 and σ_2. It should be noted that σ_0 is not used in our analysis from this point onward as we used $\sigma_0=\infty$ for the ionospheric dynamo calculation model in the coupled model. Furthermore, the peak altitude was higher and its value smaller in σ_1 compared σ_2. Since the area of high conductivities is limited to the altitudinal range between 130 and 160 km in this graph, we chose 150 km as a representative altitude. Fig. 5 to 8 show the distributions of σ_1 and σ_2 at that altitude. In order to show the effects of the solar eclipse, we illustrate differences of the conductivities from the normal condition without the solar eclipse. All values are presented in mho/m.

Fig. 6 and 8 indicate that the conductivities change due to the solar eclipse in an area with a radius of several hundred kilometers and a center at lat 30°N, long 125°E.

σ_1, σ_2, and σ_0 are explained briefly in the Appendix. For more detail, refer to Tohmatsu (1990).

3.2 Electric currents in the ionosphere

Fig. 9 and 10 show the distribution of electric fields at an altitude of 150 km which were used to determine the electrical currents in the ionosphere at 22 July 2009 01:48 UTC. The contours and vectors represent the vertical components and horizontal components, respectively. It should be noted that all Figures from this point onward are presented in the right-hand coordinate system which indicate south, east, and upward directions as positive.

Fig. 11 to 14 show the distribution of electrical currents which are perpendicular to, and those which are aligned to, the line of magnetic force at the 150-km altitude. The plasma density at 22 July 2009 01:50 UTC and electrical field at 22 July 2009 01:48 UTC are used for the calculation. The 2 minute-difference does not yield a substan-

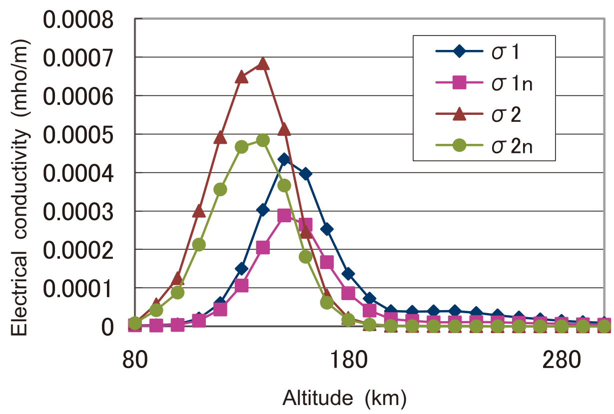

Fig. 3 Vertical distribution of σ_1 and σ_2 at lat 31°N, long 130°E at 22 July 2009 01:50 UTC. The appended symbol *n* means that the effects of the solar eclipse have been taken into consideration.

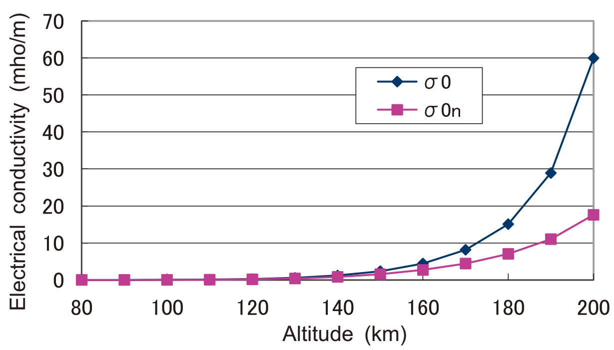

Fig. 4 Vertical distribution of σ_0 at lat 31°N, long 130°E at 22 July 2009 01:50 UTC. The appended symbol *n* means that the effects of the solar eclipse have been taken into consideration.

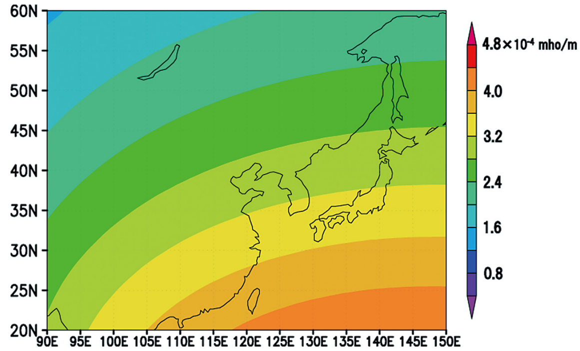

Fig. 5 σ_1 at altitude of 150km at 22 July 2009 01:50 UTC. The center of the eclipse is near lat 30°N, long 125°E.

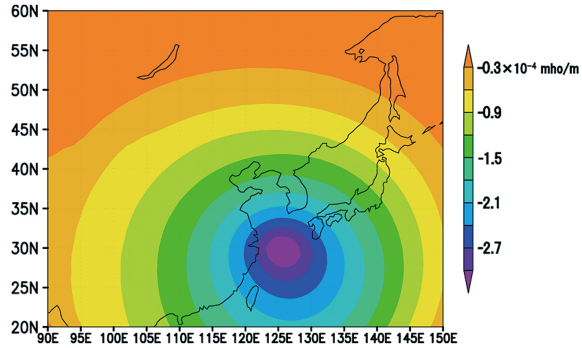

Fig. 6 σ_1 at altitude of 150km at 22 July 2009 01:50 UTC, determined by subtracting the value calculated without taking the effects of the solar eclipse into consideration from the value calculated by taking the effects into consideration. The center of the eclipse is near lat 30°N, long 125°E.

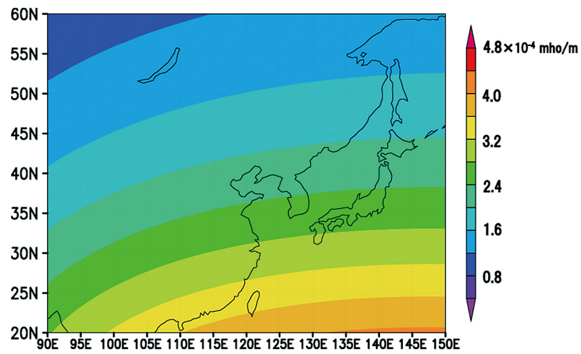

Fig. 7 σ_2 at altitude of 150km at 22 July 2009 01:50 UTC. The center of the eclipse is near lat 30°N, long 125°E.

tial effect on the results of our analysis because of the slow speed of tracking the totality zone. The electrical conductivities contributed more to the subsequent analytical results; therefore, all subsequent analytical results are deemed to be dated 22 July 2009 01:50 UTC.

With respect to the electrical currents perpendicular to the magnetic field line, a counterclockwise vortex which is known as *Sq*, is apparent in Fig. 11. The direction of the horizontal component changes depending on an altitude due to differences in the ratio of σ_2 to σ_1 at various altitudes. For example, the electrical current flows only in a direction parallel to the electrical field if σ_2 is 0.

The results are considered reasonable as the center line of the solar eclipse passes through the area centered at lat 30°N, long 125°E, and the Fig. showing conductivities (Fig. 6 and 8) indicate that the largest decrease in the plasma density was observed in this area. The strong effects of the solar eclipse are also evident in the area demarcated by latitudes 30-35°N and longitudes 95-100°E. The solar eclipse had the strongest effect on the electrical field in this area (Fig. 10). Furthermore, the effect of the known phenomenon in which large electric currents flow eastward near the Equator (equatorial electrojet) is also represented in the results.

The areas of lower electrical conductivity caused by the solar eclipse were different from the areas of modified electrical field. This may be due to the time it takes from the formation of a low-temperature area during a solar eclipse until the excitation of the neutral wind which creates the dynamo effect that affects the electric field.

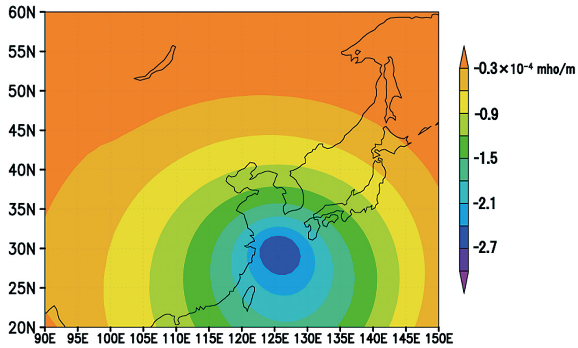

Fig. 8 σ_2 at altitude of 150km at 22 July 2009 01:50 UTC, determined by subtracting the value calculated without taking the effects of the solar eclipse into consideration from the value calculated by taking the effects into consideration. The center of the eclipse is near lat 30°N, long 125°E.

3.3 Variations in ground magnetic fields

Fig. 15 and 16 show the variations of the magnetic fields created by the electrical currents flowing through the ionosphere at an altitude between 80 and 300 km. The variations in the ground magnetic fields which are estimated from the distribu-

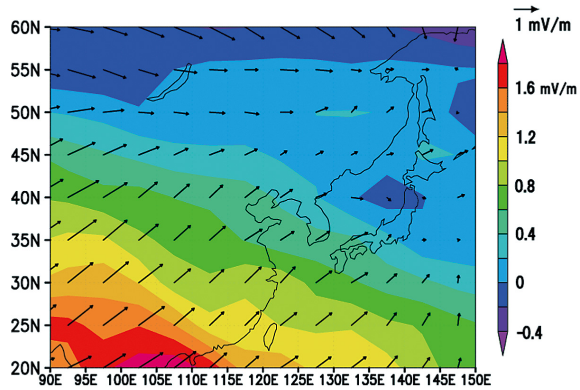

Fig. 9 Electric field at altitude of 150 km at 22 July 2009 01:48 UTC. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the vertical component with positive numbers indicating an upward direction. Arrows represent the horizontal component.

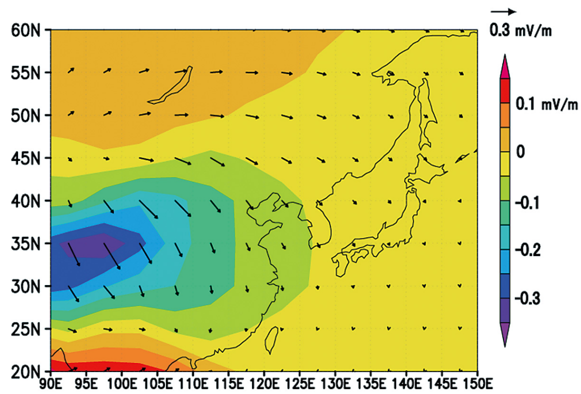

Fig.10 Electric field at altitude 150 km at 22 July 2009 01:48 UTC, determined by subtracting the value calculated without taking the effects of the solar eclipse into consideration from the value calculated by taking the effects into consideration. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the vertical component with positive numbers indicating the upward direction. Arrows represent the horizontal component.

tion of electrical currents presented in Fig. 11 are accurately reproduced in Fig. 15. Fig. 16 shows a considerable decrease in the value of the magnetic field in the area near Kyushu, Japan. Fig. 16 also shows that the vertical component reached its negative and positive peaks in the areas centered at lat 33°N, long 125°E and at lat 25°N, long 125°E, respectively. This may be due to a result of the solar eclipse significantly decreasing the horizontal electrical current flowing through the area between the two areas. It is also apparent that the peak at lat 33°N, long 125°E had a strong effect on the value of the magnetic field at Kanoya (lat 31°N, long 130°E) but very little at Kakioka (lat 36°N, long 140°E). These calculated results agree with the observations.

4. Discussion

The coupled model has indicated that the decrease in plasma density during a solar eclipse leads to both a decrease in the ionospheric conductivity in the area and a decrease in electrical cur-

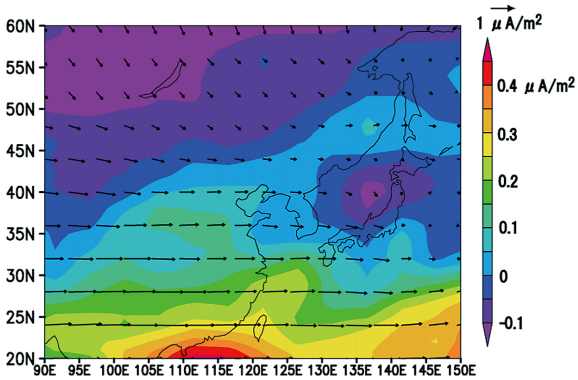

Fig.11 Electric current perpendicular to the magnetic field line at 22 July 2009 01:50 UTC. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the vertical component with positive numbers indicating the upward direction. Arrows indicate the horizontal component.

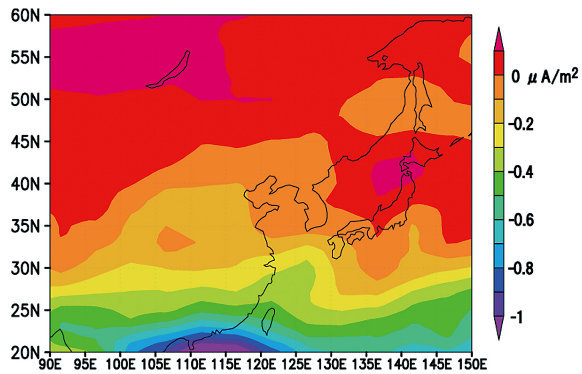

Fig.13 Field-aligned Electric current at 22 July 2009 01:50 UTC. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the values with positive numbers indicating the alignment with the line of magnetic force.

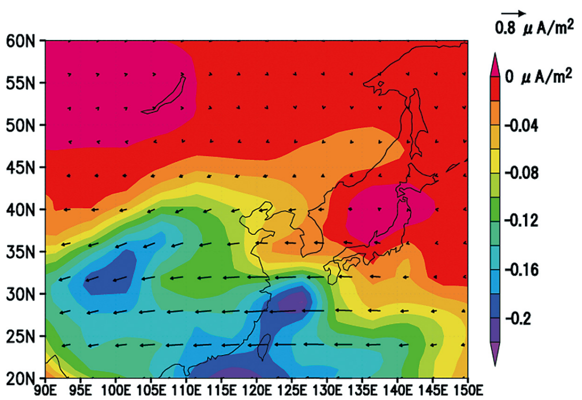

Fig.12 Electric current perpendicular to the magnetic field line at 22 July 2009 01:50 UTC, determined by subtracting the value calculated without taking the effects of the solar eclipse into consideration from the value calculated by taking the effects into consideration. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the vertical component with positive numbers indicating the upward direction. Arrows indicate the horizontal components.

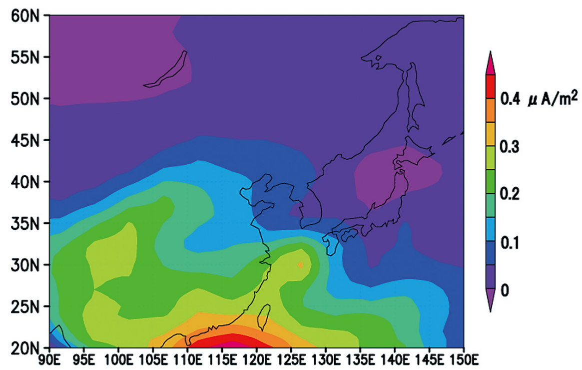

Fig.14 Field-aligned Electric current at 22 July 2009 01:50 UTC, determined by subtracting the value calculated without taking the effects of the solar eclipse into consideration from the value calculated by taking the effects into consideration. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the values with positive numbers indicating the alignment with the line of magnetic force.

rents that flow through the area, thereby changing the magnetic field observed on the ground. The model yielded results which agreed with the observation that the vertical component of the ground magnetic field decreased at Kanoya in particular but not at Kakioka. This result has confirmed that the model reproduced the actual phenomena accurately and demonstrated that a solar eclipse affects the magnetic field on the ground.

The simulation, however, indicated that

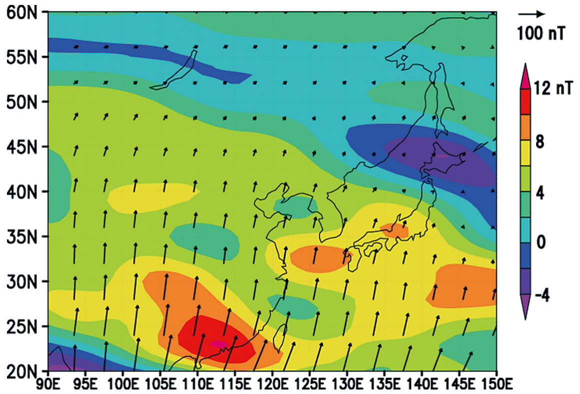

Fig.15 Changes in the ground magnetic field at 22 July 2009 01:50 UTC. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the vertical component with positive numbers indicating the upward direction. Arrows represent the horizontal component.

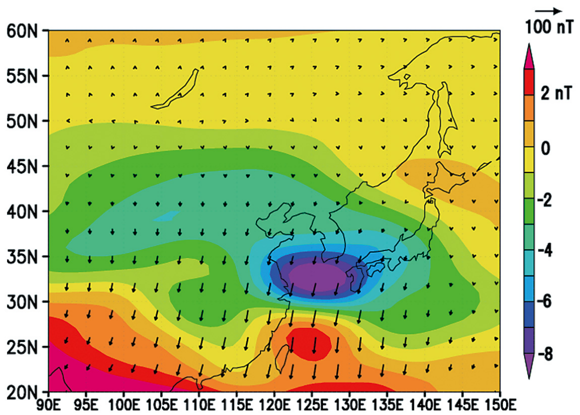

Fig.16 Changes in the ground magnetic field at 22 July 2009 01:50 UTC, determined by subtracting the value calculated without taking the effects of the solar eclipse into consideration from the value calculated by taking the effects into consideration. The center of the eclipse is near lat 30°N, long 125°E. Isopleths represent the vertical component with positive numbers indicating the upward direction. Arrows represent the horizontal component.

changes were greater in the horizontal component than in the vertical component, which contradicts the observation results. While it is possible that a solar eclipse has no effect on the horizontal component of the ground magnetic field, the cause for the contradiction may lie in the coupled model.

Theoretically, the field-aligned currentsin the northern and southern hemispheres must be symmetrical. In other words, the value of the field-aligned current should be zero at the magnetic equator. It is not, however, the case in our calculation. The problem may lie in the calculation for low latitudes. It is also possible that the models within the coupled model are not insufficiently linked, or that the calculations do not take into consideration field-aligned currents at an altitude of 300 km or higher.

The simulated effect by the solar eclipse appears to be too great compared with the observed eones. This may indicate that the decrease in plasma density due to the solar eclipse is too great. The reasons for this may be that we assumed the decrease in EUV during the solar eclipse to be 99%, which might have been excessive, and we did not consider underground electrical currents.

Our simulation did not extend to the time at which Chichijima entered the eclipse region. In addition, the effect of the solar eclipse was not observed at the conjugate point in the geomagnetic field at which the lines of magnetic force are connected. The reproduction of these events and improvements of problems in the model remain as tasks for the future.

Acknowledgements

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Appendix: Ionospheric Electric conductivities

There are three types of electric conductivity in the ionosphere: Hall conductivity (σ_2), Pedersen conductivity (σ_1), and longitudinal conductivity (σ_0). Of these, σ_0 is the field-aligned electric conductivity, and is the same as the conductivity when there is no magnetic field. Following is a brief explanation of σ_1 and σ_2 (Fig. 17):

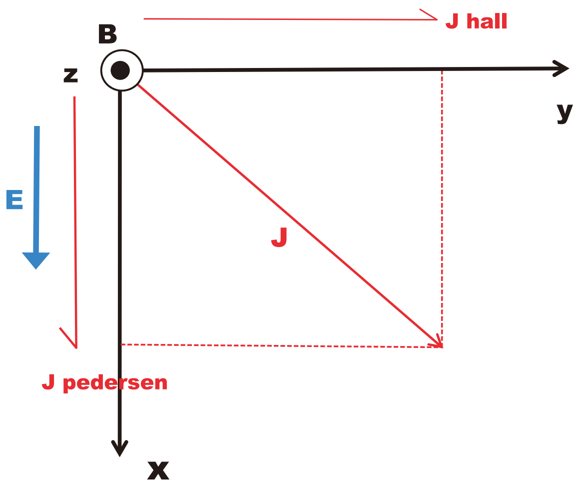

Fig.17 Direction of the electric current (J) in relation to the line of magnetic force (B) and electric field (E).

Equation (1) is an equation of motion when a particle of type k having mass m and electric charge q is moving at velocity v in the uniform magnetic field B.

$$m_k \frac{dv}{dt} = q_k (v \times B) \quad (1)$$

The solution of Equation (1) produces a spiraling motion (Larmor motion). The frequency of the motion given by Equation (2) is called the Larmor frequency, and the radius of the gyration given by Equation (3) is called the Larmor radius. According to this expression, the Larmor radius is dependent on velocity.

$$\Omega_k = \frac{q_k B}{m_k} \quad (2)$$

$$r_{Lk} = \frac{v}{|\Omega_k|} = \frac{m_k v}{|q_k| B} \quad (3)$$

When a charged particle is moving with Larmor motion through a magnetic field, it either accelerates or decelerates depending on the direction of its motion and the electrical field. The particle accelerates in a certain phase of its spiral motion as the direction of the motion coincides with that of the electrical field. After the half cycle, however, it is decelerated by the electric field as the direction of motion of the particle reverses. The Larmor radius becomes greater during the acceleration due to increased velocity, and smaller during the deceleration. As a result, the charged particle moves in a direction perpendicular to the electric and magnetic fields, which produces an electrical current. This current, which flows perpendicular to both the line of magnetic force and the electric field, is called a Hall current.

When the effect of collision is added to the motion of this charged particle, the collision causes ions to move along the direction of the electric field (Fig. 18). The electric current produced as a result of the collision, and which flows perpendicular to the line of magnetic force but along the direction of the electric field, is called a Pedersen current.

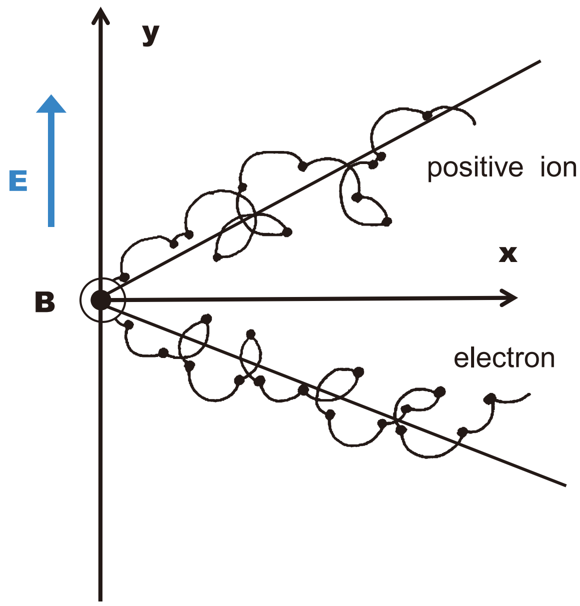

Fig.18 Drifts when a collision with neutral particles is present.