Numerical simulation of ionospheric convection with a global MHD simulation

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Abstract. A case study was conducted for simulated processes of magnetosphere-ionosphere (M-I) coupling process using a magnetohydrodynamic (MHD) simulation code developed by Tanaka (2010). We combined the MHD simulation and solar wind parameters derived from the ACE satellite, and compared the ionospheric \( E \times B \) plasma drift obtained from the global MHD simulation and that obtained from the SuperDARN HF Radar Network. The simulated plasma drift was not always reproducible under a southward interplanetary magnetic field (IMF) condition. We believe that the M-I boundary conditions in the global MHD simulation includes insufficient factors for the M-I coupling process.

1. Introduction

![Figure 1. A schematic diagram of the meridional magnetosphere noon-midnight section with the outer boundary (the solar wind) and the inner boundary (the ionosphere).](image)

The Earth’s magnetic field with north and south poles prevents the solar wind from directly hitting the Earth. The region where the Earth’s magnetic field deflecting the solar wind is
called “the magnetosphere”. The night-side magnetosphere is dragged out while the sunward side magnetosphere is compressed. Figure 1 shows a schematic diagram of the magnetosphere blasted by the solar wind. In this study, we use a magnetohydrodynamic (MHD) simulation of the magnetosphere-ionosphere coupling system, which enables us to examine the magnetospheric response to the solar wind.

MHD simulations have been developed to reproduce the magnetosphere from the early 1980’s [1,2], An increase in performance of computers in recent years allowed MHD calculations to employ minimum meshes and to reproduce magnetospheric phenomena [3,4]. Tanaka (2003) developed a high-resolution global MHD simulation that employs a finite volume (FV) total variation diminishing (TVD) scheme with an unstructured triangular grid system [5].

The global MHD model has been improved on the response of the Earth’s magnetosphere to variations in solar wind [6]. Thus, today, this model consists the magnetosphere-ionosphere coupling model and fetches solar wind parameters as an outer boundary condition of the magnetosphere model. As shown in Figure 1, the model sets one outer boundary at a distance of 20 times the radius of the Earth (20 \( R_E \); \( R_E \) denotes Earth radius) from the Earth’s center in the direction toward the sun. We use physical quantities associated with the solar wind as an outer boundary condition for the magnetosphere model. A second outer boundary is set at 200 \( R_E \) from the Earth’s center in the direction opposite the sun; the boundary condition is configured so that the gradients of all physical quantities vanish.

Meanwhile, the inner boundary of the magnetosphere lies 3 \( R_E \) from the center of the Earth. The system of MHD equation is solved in the magnetosphere. Physical quantities from the magnetosphere at the inner boundary are projected to the ionosphere along magnetic field lines. Ohm’s law is solved to match the divergence of the Pedersen and Hall currents with the field-aligned current (FAC) in the ionosphere. Physical quantities from the magnetosphere model and those from the ionosphere are interchanged with via some equations describing magnetosphere-ionosphere (M-I) interactions at the inner boundary (equations (1), (2), (3), and (4), as discussed in detail in Section 2). The equations include empirically determined parameters representing effects of the plasma pressure, temperature, and electric currents to the ionospheric electrical conductivity. Therefore, we expect the ionospheric conductivity and the ionospheric electric potential to vary depending on the empirically determined parameters.

To improve the existing model, we have to compare calculated and observed values of the conductivity and the electric potential of the ionosphere to estimate the optimal combinations of the empirically determined parameters. A realistic description of electromagnetic phenomena associated with auroras has become another task for this study.

In the present study, we reproduced the ionospheric potential by running the global MHD simulations while changing the empirically determined parameters. In particular, our discussion focuses on ionospheric electric potential variations in cases where the magnetic field of the solar wind is directed southward, a condition under which substorms — sudden releases of energy contained in the magnetosphere from solar wind — readily occur.

2. Magnetosphere-Ionosphere (M-I) Coupling Process
At the inner boundary of the magnetosphere, we compute the magnetic field structure and the electric current distribution of the magnetosphere, and then determine the ionospheric conductivity \( \sigma \) and potential distribution \( \Phi_I \) from the magnetic-field-aligned current, \( J_{\parallel} \). Then, we determine the background magnetic field \( \mathbf{B} \) and the momentum \( m \), followed by the potential distribution of the magnetosphere \( \Phi_M \) from \( \Phi_I \).

\[
\nabla \cdot \sigma \nabla \Phi_I = G_m(\text{rot} \mathbf{B}_1 \cdot \mathbf{n}_b) = J_{\parallel},
\]

\[
\sigma = \sigma_{\text{EUV}} + k_2 \sigma_{\text{Diff}}(P, \rho) + k_3 \sigma_{\text{J}}(J_{\parallel}),
\]

where \( G_m \) is the gradient of the magnetic field, \( \sigma_{\text{EUV}} \) is the conductivity due to EUV radiation, \( \sigma_{\text{Diff}} \) is the diffusion conductivity, and \( \sigma_{\text{J}} \) is the current-induced conductivity.
\[ \Phi_M = \Phi_I - k_4 f_2(J_\parallel)|J_\parallel|, \]  
\[ m - (m \cdot n_b)n_b = -\rho \nabla \Phi_M \times B / B^2, \]

where \( B_1 \) is the variable component of magnetic field, \( G_m \) is a geometrical factor associated with the mapping along field lines from \( r = 3 \) \( R_E \) to \( r = 1 \) \( R_E \), and \( n_b \) is an outward unit vector along \( B \). Equation (1) indicates that \( J_\parallel \) from the ionosphere is a current flowing from the magnetosphere to the ionosphere that arises from excesses or deficiencies in the horizontal current flow in the ionosphere, while \( J_\parallel \) from the magnetosphere arises from shearing motion \((\text{rot} B_1 \cdot n_b)\) of the plasma in response to magnetic field variations.

Equation (2) indicates that several ionospheric conductivity components \( (\sigma_{EUV}, \sigma_{\text{Diff}}, \sigma_J) \) can increase the ionospheric conductivity \( \sigma \). \( \sigma_{EUV}, \sigma_{\text{Diff}}, \sigma_J \) mean a component due to extreme ultraviolet rays from the sun, a component due to diffuse auroras determined by the temperature and pressure of the magnetosphere, and a component due to discrete auroras determined by the upward-pointing \( J_\parallel \).

Equation (3) says that \( \Phi_I \), augmented by the Joule dissipation of currents along the field lines \((k_4 f_2(J_\parallel)|J_\parallel|)\), is reflected as \( \Phi_M \). Equation 4 is a rearrangement of Ohm’s law; in combining equations (1), (2), and (3), we have solved Ohm’s law to ensure that the divergence of the current flowing horizontally in the magnetosphere agrees with \( J_\parallel \).

Coefficients such as \( k_2, k_3, \) and \( k_4 \) in the equations above are scaling factors. \( f_2 \) takes the value 1 for upward-pointing \( J_\parallel \) and 0 for downward-pointing \( J_\parallel \). \( k_2, k_3, \) and \( k_4 \) are the empirically determined parameters representing effects of the plasma pressure, temperature, and electric currents to the ionospheric electrical conductivity.

Here, we focus on the electric potential in the ionosphere; we report the results of tests to assess the sensitivity of the global MHD simulation model to the empirically determined parameters.

### 3. Event Selection

Solar wind parameters, namely solar wind velocity, proton temperature, proton density and mean magnetic field in the solar wind, were used as an outer boundary condition. The solar magnetic field that spreads into interplanetary space is called Interplanetary Magnetic Field (IMF). The ACE satellite provides in-situ data of the solar wind parameters between Earth and Sun. For this study, we selected the interval that strong magnetospheric and ionospheric convections caused.

Figure 2 shows IMF on 11th September 2012 is directed to the southward and implies the ionospheric plasma convection is strong. Geomagnetic activity is evaluated using the geomagnetic auroral electrojet (AE) index [7], from the World Data Center for Geomagnetism, Kyoto (http://swdcwww.kugi.kyoto-u.ac.jp/). In this study, we used the AE index for the proxy of substorm activities and found that AE index on 11th September was low. Then the IMF Bz and the AE index indicate that strong magnetospheric and ionospheric convection caused, however, no auroras occurred in the interval.

Because the ACE satellite orbits at the Lagrangian point \( L_1 \), we can expect a time delay between the outer boundary and ACE data. To compare the ionospheric convection obtained from simulation data to actual observed values, we adjusted the time delay from the ACE satellite to the magnetopause.

In this paper, the x-axis points toward the Sun, the z-axis points north, and the y-axis is chosen to satisfy the right-handed system.

### 4. Simulation Results

The simulation started from a stationary state with solar wind parameters of the proton density, \( N = 3 \) /cc, the solar wind velocity, \( V_{SW} = 300 \) km/s, the y-component of IMF, \( B_Y = -1.6 \) nT,
Figure 2. Interplanetary Magnetic Field (IMF) corresponding to 11:00–14:00 Universal Time (UT) on 11th September 2012 (a part surrounded by a broken line), clearly showing a mainly southward magnetic field in the solar wind.

and the z-component of IMF, $B_z = -1.6$ nT. Subsequently, we used time series of solar wind parameters measured from the ACE satellite to simulate the ionospheric electric potential in the interval of 11:00–14:00 11th September 2012.

Figure 3 shows the simulation results for the interval of 11:00–14:00 11th September 2012. From left to right, the panels show contour maps in a time sequence of UT = 12:19, 12:49 and 13:22 UT. The top row shows the northern hemisphere and the bottom row shows the southern hemisphere. The color contours are representing the electric potential. Thick (thin) contours show positive (negative) electric potential. Each panel is seen from above the North Pole. Noon is to the top and dusk to the left.

In the case of intense ionospheric convection driving, it is well known from previous work that the IMF $B_Y$ introduces dawn-dusk asymmetries in the ionospheric convection pattern ([8], and references therein). In the Northern Hemisphere ionosphere, it was found that a round cell is formed at dawn and a crescent cell at dusk under a negative IMF $B_Y$ condition [9]. The results shown in Figure 3 coincides with many of the above earlier studies.

The global network of Super Dual Auroral Radar Network (SuperDARN) radars measures the plasma drift in the ionosphere in the auroral and polar regions [10]. We compared the ionospheric plasma drift estimated from the global MHD simulation and that observed from SuperDARN radars.

In this paper, we present procedures for deriving the plasma drift from the global MHD simulation. We can get the calculated ionospheric potential from the left panel of Figure 4 and the location where we can get SuperDARN radar data from the right panel of Figure 4. Then we can get the plasma drift from the center panel of Figure 5 and the plasma motion in the line-of-sight direction (LOS) from the right panel of Figure 5.

The left panel of Figure 4 shows calculated ionospheric potential with color contours. The
Figure 3. Overview of simulation results for the interval of 11:00–14:00 11th September 2012. The top row shows the northern hemisphere and the bottom row shows the southern hemisphere. The color contours are representing the electric potential. Thick (thin) contours show positive (negative) electric potential. From left to right panels, the panels show snapshots of contour maps at UT = 12:19, 12:49 and 13:22 UT. Each panel is seen from above the North Pole. Noon is to the top and dusk to the left.

The right panel of Figure 4 contains the plasma motion in the line-of-sight direction (LOSV) of the radar beams. From the calculated ionospheric potential and the magnetic field model, we calculated $\mathbf{E} \times \mathbf{B}$ plasma drifts and regarded them as plasma convections in the ionosphere. Arrows in the left panel of Figure 4 means the reproduced ionospheric convection.

Figure 5 shows the results at 11:12 UT 11th September 2012 in the northern hemisphere. The panels are in the same format as Figure 4. The simulated ionospheric convection velocities are projected to the center panel as the plasma motion at the point where we can get SuperDARN radar data (shown as arrows). Then we can calculate LOSVs of the radar beams from the simulated ionospheric convection. Arrows in the right panel mean the calculated LOSVs of the radial beams (shown as arrows).

Herewith we can compare the observed and calculated LOSVs at the point where we can get radar data. Figure 6 shows the time variation of the calculated and observed LOSVs at the King Salmon radar site. The horizontal axis is time and the vertical axis is the distance from the radar site. The observed LOSVs are shown in the left panels, and the calculated LOSVs are shown in the right panels. From top to bottom rows show the LOSVs from beam 5, 6, 7, and 8, respectively.

From the results of the observed LOSVs, we found that fast ($> 700$ m/s) westward flows appeared near the radar site at 11:30 to 12:30 UT. The regions where the fast flows appeared
**Figure 4.** The left panel shows the simulated ionospheric potential (shown as color contours) and the ionospheric convection (shown as arrows). The right panel shows the plasma motion in the line-of-sight direction (LOSV) of the radar beams derived from the Ionospheric scatter echoes observed by SuperDARN radars. This figure shows the results at 11:52 UT 11th September 2012 in the north hemisphere. Strings consists three characters mean radar name (**cve**: Christmas Valley East, **pyk**: Pykkvibaer, and **ksr**: King Salmon).

**Figure 5.** This figure shows the results at 11:12 UT 11th September 2012 in the north hemisphere. These panels are in the same format as Figure 4. The center panel contains the plasma motion (shown as arrows) at the point that we can get SuperDARN radar data. The right panel contains the plasma motion in the line-of-sight direction (shown as arrows) of the radar beams. Strings consists three characters mean radar name (**cve**: Christmas Valley East, **fhe**: Fort Hays East, and **fhw**: Fort Hays West).
Figure 6. This figure shows the time variation of the calculated and observed LOSVs at the King Salmon radar site. The horizontal axis is time and the vertical axis is the distance from the radar site. The observed LOSVs are shown in the left panels, and the calculated LOSVs are shown in the right panels. From top to bottom rows show the LOSVs from beam 5, 6, 7, and 8, respectively.

correspond to the blue regions in the right panel of Figure 4. From the data in Figure 4, it can be seen that the fast flows expand to lower latitudes ($60^\circ \sim 70^\circ$). Satellites often show significant westward convections in the dusk subauroral region. The rapid westward stream is distinguished with the two-cell convection pattern as shown in Figure 3. This kind of events is called Sub Aurora Polarization Stream (SAPS) [11]. We think that this significant fluctuation was caused by SAPS. On the other hand from the calculated LOSVs, we could not found such fluctuations in the same region and in the same time interval.

5. Summary
For global MHD simulations, we chose the data assimilation target to be the plasma convection velocity in the ionosphere. In our simulation model, we use solar wind parameters from the ACE satellite as outer boundary conditions. We reproduced the ionospheric electrical potential and calculated the ionospheric $\mathbf{E} \times \mathbf{B}$ plasma drift to compare the ionosphere plasma convection velocity obtained from simulation data with actual observed values. The observed values were the observed Doppler shift of ionospheric scatter echoes from the SuperDARN radar network. We reproduced the plasma motion in the line-of-sight direction (LOSV) of the radar beams at the point where SuperDARN radar data were obtained.

The results of our analysis revealed that the reproduced dawn-dusk asymmetries in the
ionospheric convection pattern coincide with many of the above earlier studies. However, significant fluctuations due to SAPS were not seen in the reproduced LOSVs while measured data values showed LOSVs. It seems possible that the M-I coupling model currently used in global MHD simulations may not be capturing the effects of polarization fields on ionospheric convections or magnetospheric convections. We confirmed the need to design a M-I coupling model that incorporates more realistic processes of interaction between the magnetosphere and ionosphere. One accomplishment of this study is the establishment of an environment for reproducing observed values from global MHD simulation data and comparing observed and calculated values. In future work, we will attempt to establish data assimilation methods that make use of more massive volumes of data, including not only the SuperDARN radar data but also data on field-aligned currents (FACs) measured by the AMPERE satellite.

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References
[1] Lyon J, Brecht S H, Fedder J A and Palmadesso P 1980 Geophys. Res. Lett. 7 721
[2] Ogino T 1986 J. Geophys. Res. 91 6791
[3] Fedder J A and Lyon J G 1995 J. Geophys. Res. 100 3623
[4] Tanaka T 1995 J. Geophys. Res. 100 12057
[5] Tanaka T 2003 Space Plasma Simulation Lecture Notes in Physics 615 275
[6] Tanaka T, Nakamizo A, Yoshikawa A, Fujita S, Shimagawa H, Shimazu H, Kikuchi T and Hashimoto K K 2010 J. of Geophys. Res. 115 A05220
[7] Rostoker G 1972 Rev. Geophys. 10 935
[8] Haaland S E, Runov A and Forsyth C 2017 Dawn-dusk asymmetries in planetary plasma environments (Hoboken, NJ: John Wiley)
[9] Lockwood M 1991 Modelling the high-latitude ionosphere Proceedings IEE Colloquium on 'National Radio Propagation Programme' 10 (London, UK: IEE)
[10] Greenwald R A, Baker K B, Dudeney J R, Pinnock M, Jones T B, Thomas E C, Villain J P, Cerisier J C, Senior C, Hanuise C, Hunsucker R D, Sofko G, Koehler J, Nielsen R, Pellinen R, Walker A D M, Sato N and Yamagishi H, 1995 Space Sci. Rev. 71 761
[11] Erickson P J, Matsui H, Foster J C, Torbert R B, Ergun R E, Ergun, Kholyaintsev Yu V, Lindqvist PA, Argall M R, Farrugia C J, Paulson K W, Strangway R J and Magnes W 2016 Geophys. Res. Lett. 43 7294
[12] Yatagai A, Tanaka , Abe S, Shinbori A, Yagi M, UeNo S, Koyama Y, Umemura N, Nosé M, Hori T, Sato Y, Hashiguchi N O, Kaneda N and IUGONET project team 2014 Data Sci. J. 13 PDA37
[13] Hayashi H, Koyama Y, Hori T, Tanaka Y, Abe S, Shinbori A, Kagitani M, Kouno T, Yoshida D, UeNo S, Kaneda N, Yoneda M, Umemura N, Tadokoro H, Motoba T and IUGONET project team 2013 Data Sci. J. 12 WDS179
[14] Abe S, Umemura N, Koyama Y, Tanaka Y, Yagi M, Yatagai A, Shinbori A, UeNo S, Sato Y and Kaneda N 2014 Earth, Planets and Space 66 133
[15] Tanaka Y, Shinbori A, Hori T, Koyama Y, Abe S, Umemura N, Sato Y, Yagi M, Ueno S, Yatagai A, Ogawa Y and Miyoshi Y 2013 Adv. Polar Sci. 24 231