Intensification of the Cowling current in the global MHD simulation model

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[1] We examine the effects of the ionospheric conductance on the intensification of the westward electrojet current in the ionosphere based on the piecewise parabolic method with a Lagrangian remap (PPMLR) global MHD simulation model. The ionospheric conductance is empirically linked to the plasma pressure in the plasma sheet. The simulation results are consistent with observations: When the Pedersen and Hall conductances are small, the ionospheric current shows a two-cell pattern; when the conductances increase and the ratio $\Sigma_H/\Sigma_P \geq 2$, an intense westward electrojet appears in the midnight sector. This intense westward electrojet is the Cowling current driven by the induced southward electric field due to the blockage of the northward Hall current from closure in the equatorial plasma sheet. The simulation shows the development of the Cowling electrojet is essential to the intensification of the westward electrojet in the ionosphere.


1. Introduction

[2] Baumjohann [1983] showed that an intense westward electrojet would appear in the midnight sector, and its magnitude is much greater than the preexisting two-cell currents. The increasing of this westward electrojet is usually taken as a signature of the substorm expansion phase.

[3] Kamide et al. [1996] pointed out that this intense westward electrojet in the midnight and early morning region is essentially conductance-dominated. That is, the magnitude of the electrojet is mainly controlled by the conductance, comparing to the electric field. The highly enhancement of the conductance, including the Hall conductance during the substorm expansion phase results in the high magnitude of the westward electrojet in the midnight sector. This scenario is also supported by an equivalent current model [Nakai and Kamide, 2005]. In their model, the westward electrojet is largely intensified when the Pedersen and Hall conductance increase to 20 S and 60 S from their initial value, and 90% of the westward electrojet is Hall current.

[4] Kan [2007] showed that the intensification of the westward electrojet is caused by the blockage of the northward Hall current($I_{WH}$) driven by the westward electric field. The blockage is due to the lack of the radial current in the midnight sector of the equatorial plasma sheet. A southward polarization electric field is induced by the blockage of the northward Hall current, which drives a southward Pedersen current($I_{SP}$) to cancel the northward Hall current. Here, a blockage parameter($\alpha$) is defined to express the extent of current blocking:

$$\alpha = I_{SP}/I_{WH} = E_S/(E_W * R)$$  (1)

where the parameter $R = \Sigma_H/\Sigma_P$ is the ratio of the Hall to Pedersen conductance. Thus the westward electrojet consists of the westward Pedersen ($I_{WP}$) current driven by the westward E field and the westward Hall current ($I_{WH}$) driven by the induced southward polarization E field, and it is usually called the Cowling electrojet($I_C$). The resulting westward Cowling electrojet can be written as

$$I_C = I_{WH} + I_{WP} = \Sigma_H E_S + \Sigma_P E_W = [1 + \alpha * R^2] * \Sigma_P E_W$$  (2)

From equation (2), the westward Cowling electrojet is highly sensitive to the Hall-to-Pedersen conductance ratio $R$.

[5] Observations have already shown both the nightside Pedersen and Hall conductance, and thus the ratio $R$, would change significantly from the substorm growth phase to the expansion phase [Lester et al., 1996; Aikio and Kaila, 1996; Gjerloev and Hoffman, 2000]. During the growth phase, $\Sigma_H$ and $\Sigma_P$ are less than 10 S and the ratio $R$ is close to 1. Both the Pedersen and Hall conductances increase at the end of the growth phase or the onset of the expansion phase, while the ratio $R$ reaches 2 or more. The typical peak value of the conductance will be tens of siemens. For example, Lester et al. [1996] showed the maximum $\Sigma_P$ and $\Sigma_H$ are 34 S and 71 S, respectively, and Gjerloev and Hoffman [2000] showed...
Based on an empirical conductance model from observations, this paper focuses on the effects of the conductance on the formation of the westward Cowling current in the ionosphere by using global MHD simulations. It is organized as follows: we describe the numerical simulation model in section 2, present the model results in section 3, and discuss and conclude it in section 4.

2. Simulation Method

In this study, we use the global MHD simulation code, developed by Hu et al. [2007], on the basis of an extension of the Lagrangian version of the piecewise parabolic method (piecewise parabolic method with a Lagrangian remap (PPMLR)) [Collela and Woodward, 1984] to solve the ideal MHD equations. The numerical mesh is a stretched cartesian coordinate system with the Earth center at the origin and the $x$, $y$ and $z$ axes pointing to the Sun, the dawn-dusk and the northward direction, respectively. The simulation box is taken to be $-300 R_E \leq x \leq 30 R_E, -150 R_E \leq y, z \leq 150 R_E$ with the smallest grid of $0.4 R_E$. An inner magnetosphere boundary is set at $r = 3 R_E$, and an electrostatic ionosphere is put at $r = 1.017 R_E$. Thus a magnetosphere-ionosphere coupling process is considered as follows: First, field-aligned currents are mapped from the inner boundary to the ionosphere, then an electrostatic equation is solved at the ionosphere

$$\nabla \cdot (\Sigma \cdot \nabla \Phi) = -J_\parallel \sin I$$  \hspace{1cm} (3)$$

where $\Sigma$ is the conductance tensor constructed by $\Sigma_P$ and $\Sigma_H$, $\Phi$ is the ionospheric potential, $J_\parallel$ is the field aligned current and $I$ denotes the inclination angle of the dipole field. At last, the calculated ionospheric potential is mapped back to the inner boundary to get the convection velocity. It is noted that these two mapping processes are along magnetic dipole field lines.

The conductance model used in the simulation is a crude first approximation from the observations, and it consists of two parts: the conductance distribution pattern and the conductance value. The general conductance pattern is empirically derived from ground magnetic disturbances [Ahn et al., 1998], but a Gaussian distribution is set in latitude direction to reduce the conductance to the background value at the polar and subauroral region, that is, $2 S$ for the Hall conductance and $1 S$ for the Pedersen conductance. Meanwhile, the oval conductance depends mainly on the plasma pressure in the near-Earth plasma sheet. Xing et al. [2010] find that substorm expansion onset is associated with an increase of plasma pressure in the radial distance between ~9 and 12 $R_E$ due to the particle energization, which may be related to the enhanced earthward convection driven by the near-Earth reconnection in the plasma sheet. So the maximum values of $\Sigma_P$ and $\Sigma_H$ are set to be ~6 S, and thus the ratio $R$ is ~1 without a near-Earth X line (NEXL). Once NEXL is formed, the maximum values of $\Sigma_P$ and $\Sigma_H$ are increased artificially to ~25 and 60 S in 10 min, but keep the original conductance distribution pattern. Thus, the ratio $R$ becomes larger than 2. Figure 1 shows the Pedersen and Hall conductance patterns in detail after the enhancement of the conductances.

In this study, we consider a southward turning of IMF $B_Z$ from 5 nT to $-5$ nT, which would result in dynamic

Figure 1. (a) The pattern of Pedersen conductance and (b) Hall conductance.
activities in the magnetotail and ionosphere, while other solar wind parameters keep constant: the solar wind speed is 400 km/s in x direction, the proton number density $5 \text{ cm}^{-3}$ and temperature $10^6 \text{ K}$. $T = 0 \text{ min}$ is the time when IMF discontinuity encountering the bow shock.

3. Simulation Results

[11] When the IMF discontinuity reaches the magnetopause, the magnetic flux is removed by the reconnection; thus, large-scale earthward convection starts to transport the magnetic flux from the distant tail slowly, and the plasma sheet is getting thinner. However, if this earthward convection cannot supply the magnetic flux to dayside magnetopause timely, a new near-Earth X line would form (in this run, it is at $t = \sim 56 \text{ min}$). Figure 2 depicts the earthward convection minutes before and after the formation of NEXL. The enhanced earthward convection would result in the increase of the thermal pressure. The conductance model used in this simulation is physically reasonable, though it is not self-consistent.

[12] Since the ionospheric conductance changes significantly when the NEXL is formed, the ionospheric current evolves from the two-cell pattern to the state of an intense westward electrojet existing in the midnight region. Figure 3 shows this two current patterns at $t = 47 \text{ min}$ and $77 \text{ min}$, respectively. In Figure 3a, a weak eastward electrojet appears in the afternoon sector between $70^\circ$ and $75^\circ$ latitude, and meanwhile, a westward electrojet grows at morning sector. At this time, the intensity of these two electrojet is nearly equal which is less than 0.2A/m. The background field aligned current is relatively weak. When the ionospheric conductances are enhanced, the westward electrojet expands both latitudinally and longitudinally, and flows across the midnight region. The intensity of the electrojet increases dramatically, which peaks at the late midnight region,

Figure 2. The convection pattern in the equatorial plane (top) before and (bottom) after the formation of NEXL. The background contour is Z component of the magnetic field, and the red line indicates the location of reconnection.

Figure 3. The ionospheric current vectors at (a) $t = 47 \text{ min}$ and (b) $t = 77 \text{ min}$. Dotted circles show latitudes of $60^\circ$, $70^\circ$, and $80^\circ$. The background contour shows the FAC distribution, with warm colors for downward FAC and cool colors for upward FAC.
reaching 0.8A/m. The field aligned current extends to the nightside region, and grows in intensity, too.

[13] Figure 4 illustrates how the westward electrojet intensifies in the midnight meridian which shows changes of the total region 1 field-aligned current, the maximum Pedersen and Hall conductance, the maximum electric field and the total westward current and its components from the top to the bottom panels, respectively. For simplicity, the total region 1 field-aligned current is integrated from all upward current in the dusk sector and the westward current is between 61° and 71° latitude. The first response of the nightside ionosphere to the IMF discontinuity is at ∼12 min shown by the appearance of the westward electric field and current. The response time also accords with Yu and Ridley [2009]. However, before the formation of NEXL (the vertical solid line), the southward electric field is very small, which means the blockage effect is not obvious. Thus the westward electrojet is weak and mainly consists of the Pedersen current. When the ionospheric conductance increases (the vertical dotted line), the southward electric field has to develop to cancel the northward Hall current generated by the westward electric field, and its value is larger than the westward electric field. Since the Hall conductance is at least two times of the Pedersen conductance, the westward Hall current becomes the main part of the westward current. The former weak westward current intensifies to be the Cowling current. In this simulation run, the total current is around 0.6 MA, and the westward Hall current dominate the Cowling current by contributing more than 80% of the total current. Correspondingly, the total amount the region 1 FAC increases from ∼0.8 MA to ∼1.8 MA, which is in accordance with the result in Figure 3.

[14] The ratio of $I_C/I_{WP}$ shown in Figure 4 is >5 when the ionospheric conductance is increased, which indicate the blockage is noticeable according to equation (2). Figure 5 shows the current blockage in details. The fact that the ionospheric current in latitude direction must be blocked is due to the lack of radial current in the midnight sector of the near-Earth plasma sheet from the current loop view [Kan, 2007]. Figure 5a shows the average radial current in the equatorial plane, which is similar to the observational evidence presented by Iijima et al. [1990]. The current vector in the midnight region is relatively small comparing with the premidnight and postmidnight sector, and thus the cur-

Figure 4. The ionospheric physical quantities since the IMF discontinuity encounters the bow shock. The total amount of region 1 FAC, the maximum value of the ionospheric conductance, the electric field and the total westward electrojet in the midnight ionosphere from the first panel. The solid and dotted vertical lines indicate the starting time of near-Earth reconnection and the increasing time of ionospheric conductances, respectively.
rent along the latitude direction in the midnight region is limited. Figure 5b shows the blockage parameter defined by equation (1). Once the conductance increases, which results in the intensification of the northward Hall current, the magnetic disturbance is relatively small, and then a sharp decrease of the perturbations at $t = 61$ min shows the sudden intensification of the westward electrojet intensity and the largest disturbance is around $65^\circ$ latitude, the location of the largest intensity of the Cowling current. Similarly, this current pattern evolution is also speculated by simulated AU/AL index as shown in Figure 6b: the AU/AL index retains small at the beginning, and AL index is rapidly depressed when ionospheric conductance is enhanced.

Figure 5. (a) The average radial current in the equatorial plane and (b) the contour of the blockage parameter in the midnight meridian in the ionosphere.

Figure 6. (a) The magnetic disturbance at 0000 MLT and (b) the simulated AU/AL index.
Meanwhile, the magnetotail is very active. The magnetic field lines are stretched tailward and the $B_Z$ component reduces first, which results in the formation of NEXL at $t = 56$ min (shown in Figure 7a). Then earthward moving magnetic flux piles up, and dipolarization occurs. It is noted that the dipolarization front moves from $X = -7.8 \, R_E$ to $X = -10.6 \, R_E$, indicating the moving direction is tailward. Corresponding to this magnetic field change, the cross-tail current first increases during the thinning process, and then it is largely disrupted at $X = -10 \, R_E$. Figure 7c shows the total amount of the cross-tail current in the box at $-13 \leq x \leq -7 \, R_E$, $|z| \leq 1.5 \, R_E$, and cross-tail current undergoes an increasing-decreasing process. During the decreasing process, the cross-tail current reduces from 2.05 to 1.2 MA, about a 40% reduction. However, since the conductance model is not self-consistent in our simulation, the causal relationship of the M-I coupling process will not be further discussed here.

4. Discussion and Summary

Using a relatively simple ionospheric conductance model, our MHD model successfully produces the intensification of the Cowling current in an IMF $B_Z$ southward turning case. In this study, the formation of NEXL is taken as a signature of the enhancement of the ionospheric conductance. Figure 4 demonstrates the westward electrojet increases slowly before the NEXL forms, and is mainly the Pedersen current. Once the ionospheric conductance is enhanced, the westward electrojet rapidly intensifies into Cowling current, and over 80% of this current is composed by the Hall current. The dominance of the Hall current is caused by the blockage of current in the latitude direction, which would produce a southward electric field, too [Kan, 2007]. The total amount of the Cowling current is estimated to be around 0.6 MA, producing the AE index of 500 nT. The model results are not unusual for a moderate substorm [Kamide and Akasofu, 1974] and agree well with the empirical estimations [Akasofu, 2003].

For a comparative study, we run another case which retains the ionospheric conductance unchanged all the time even after the NEXL is formed. The result indicates the ionospheric current remains the two-cell pattern. Figure 8a shows the current pattern at $t = 77$ min when NEXL is formed, which is still similar to that in Figure 3a. Figure 8b illustrates this westward current qualitatively in the same format as in Figure 4. The amount of the total westward current is no more than 0.15 MA, and it is mainly composed by the Pedersen current rather than Hall current. As would be expected, the blockage effect is not significant. The blockage...
parameter is less than 0.5, as shown in Figure 8c. This implies that the ionospheric conductance is an indispensable factor in controlling the westward electrojet, which accords with previous observations [Kamide et al., 1996].

However, there are several improvements which could be made in the future work. First, the present study sets the ionospheric conductance empirically, and a self-consistent ionospheric conductance model is needed to capture the magnetosphere-ionosphere coupling process. Second, the ionospheric current dominated by ionospheric conductances does not mean the electric field can be ignored. It is found that the $E_S$ increases significantly to 30–40 mV/m during substorm expansion phases [Sun et al., 2008], while it is 20 mV/m at most in our simulation. This may limit the total amount of the Cowling current. Third, the model result shows the cross-tail current would reduce when the westward electrojet intensifies into the Cowling current, but the detailed current circuit has not been analyzed for the nonself-consistency of the conductance.

In general, the enhancement of the ionospheric conductance, particularly the Hall conductance results in the current blockage in the midnight region, and thus it is an important precondition for the intensification of the Cowling current. Moreover, the ionospheric conductance is linked to

Figure 8. Results from the comparative case without the enhancement of ionospheric conductances: (a) the ionospheric current at $t = 77$ min after near-Earth reconnection; (b) the ionospheric physical quantities, which are in the same format as in Figure 4; and (c) the blockage parameter in the midnight meridian.
the conditions in the magnetotail, and the current blockage is attributed to the lack of the radial current in the near-Earth plasma sheet. Thus, the Cowling current intensification should be treated as a magnetosphere-ionosphere coupling process.

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