Response of the Earth’s magnetosphere and ionosphere to solar wind driver and ionosphere load: Results of global MHD simulations

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Three-dimensional global magnetohydrodynamic simulations of the solar wind-magnetosphere-ionosphere system are carried out to explore the dependence of the magnetospheric reconnection voltage, the ionospheric transpolar potential, and the field aligned currents (FACs) on the solar wind driver and ionosphere load for the cases with pure southward interplanetary magnetic field (IMF). It is shown that the reconnection voltage and the transpolar potential increase monotonically with decreasing Pedersen conductance ($\Sigma_P$), increasing southward IMF strength ($B_s$) and solar wind speed ($v_{sw}$). Moreover, both of the region 1 and the region 2 FACs increase when $B_s$ and $v_{sw}$ increase, whereas the two currents behave differently in response to $\Sigma_P$. As $\Sigma_P$ increases, the region 1 FAC increases monotonically, but the region 2 FAC shows a non-monotonic response to the increase of $\Sigma_P$: it first increases in the range of $(0, 5)$ Siemens and then decreases for $\Sigma_P > 5$ Siemens.

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The solar wind-magnetosphere-ionosphere (SW-M-I) system is a multi-variable, multi-scale complex system [1], in which the solar wind serves as a driver and the ionosphere plays a role of load. It has been widely believed that magnetic reconnection (MR) between the geomagnetic and interplanetary fields on the dayside magnetopause leads to an efficient and rapid transfer of energy and momentum from the solar wind to the magnetosphere. The electrons may be temporarily trapped in the central reconnection region including electron diffusion region [2]. The MR takes place along the separatrix line, i.e., the MR line, which connects a pair of magnetic nulls lying on the magnetopause [3]. The total electric potential drop along the MR line (MR voltage) virtually represents the global MR rate [4, 5] so as to be an important parameter characterizing the SW-M-I coupling. The ionospheric transpolar potential, named as

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“cross polar cap potential” sometimes in the literature and defined as the difference between the positive and negative potential peaks in the ionosphere, was taken by some authors as a measure for the MR voltage [6], but actually they differ from each other because of the presence of parallel electric field along the geomagnetic field lines passing through the reconnection region [4, 5]. After all, the transpolar potential remains to be another coupling parameter, which is presently observable.

The significant progress has been made in the high latitude boundary/cusp region by the Cluster observation, such as the triple cusps due to temporal or spatial effect [7], a plasmoid-like structure without a core magnetic field [8], association of reverse convection with cusp proton aurora [9]. The high-latitude ionosphere serves as a monitoring screen for magnetospheric activities due to the magnetosphere-ionosphere (M-I) coupling. The coupling consists of a mapping of field aligned currents (FACs) from the magnetosphere to the ionosphere and a feedback of the ionospheric potential to the magnetosphere, which drives the magnetospheric plasma convection. The FAC generally consists of region 1 current on the poleward side and region 2 current on the equatorward side, and the two FAC currents flow in opposite sense [10]. The so-called northern $B_z$ (NBZ) current appears when the IMF is northward [11], but it does not exist on the condition of southward IMF [12]. A direct manifestation of the FACs is the aurora within the polar cap, so one may infer the global magnetospheric process from the morphology, intensity, and duration of the aurora. Therefore, a great attention has been paid to the investigation of the FACs.

The M-I system is jointly decided by various parameters such as the interplanetary magnetic field (IMF), the solar wind ram pressure, and the ionospheric conductance. When any of these parameters changes, the M-I system will accommodate itself and reach a new equilibrium. This results in a change of the MR voltage, the transpolar potential, and the FAC intensity. Note that here the ionosphere is not only a passive load for the M-I system, but plays a crucial role in the M-I coupling. It directly affects the transpolar potential and the FAC intensity, and exerts an indirect but important influence on the magnetosphere configuration, the magnetosheath flow, and the MR voltage [13-14]. Hence the effect of the ionospheric conductance must be included while studying the SW-M-I coupling. The governing equations and initial boundary conditions for this MHD model were given in detail by Hu et al. [5].

Global MHD simulation is a powerful tool for the study of the response of the M-I system to the solar wind driver and ionosphere load. As a matter of fact, it was used to study the dependence of the MR voltage and transpolar potential on the solar wind electric field and ionospheric Pedersen conductance [4, 5, 13, 14] and the paths of the FACs [12, 15, 16]. In particular, Guo et al. [16] found that more than 50% of the region 1 FAC may come from the bow shock under strong southward IMF conditions. To our knowledge, however, a systematic study of the dependence of the MR voltage, transpolar potential, and FAC intensity on the solar wind driver and ionospheric conductance is unavailable in the literature, and this paper will undertake such a task. All simulations in this study are made with the use of the PPMLR-MHD numerical scheme developed...
Table 1. Simulation case assortment of parametric studies of the ionospheric conductance $\Sigma_P$ and IMF $B_s$.

| Group | Case          | $v_{sw}$ (km/s) | $B_s$ (nT) | $\Sigma_P$ (S) |
|-------|---------------|-----------------|------------|----------------|
| 1     | A, B, C, D, E | 400             | 5          | 0.1, 1, 5, 10, 20 |
| 2     | A, B, C, D, E | 800             | 5          | 0.1, 1, 5, 10, 20 |
| 3     | F, G, H, I, J | 400             | 2, 5, 10, 15, 20 | 5         |
| 4     | F, G, H, I, J | 800             | 2, 5, 10, 15, 20 | 5         |

by Hu et al. [5, 17].

In order to reflect the fundamental physics of the SW-M-I system, two simplified assumptions are made: (1) the IMF is pure southward, and (2) the ionospheric Pedersen conductance is uniform and the Hall conductance vanishes. Three adjustable parameters are chosen in the following numerical examples: the solar wind speed $v_{sw}$ and the southward IMF $B_s$, which describe the solar wind driver, and the Pedersen conductance $\Sigma_P$, which characterizes the ionosphere load. All other solar wind parameters are fixed, including the number density $n = 5 \text{ cm}^{-3}$ and temperature $T = 0.91 \times 10^5 \text{ K}$. The corresponding adjustable parameters of numerical examples are listed in the Table 1 being divided into four groups: 1 and 2 for different values of $\Sigma_P$, and 3 and 4 for different values of $B_s$. Groups 1 and 2 differ in $v_{sw}$, so do Groups 3 and 4. The MR voltage, the transpolar potential, and the total region 1 and 2 current intensities, $I_1$ and $I_2$, are calculated for each example in order to examine their dependence on $\Sigma_P$, $B_s$, and $v_{sw}$. The calculation of these quantities are straightforward except for the MR voltage, which is evaluated with the use of the method proposed by Hu et al. [5].

The responses of the MR voltage, transpolar potential, region 1 FAC $I_1$, and region 2 FAC $I_2$ to $\Sigma_P$, $B_s$ and $v_{sw}$ are shown in Fig. 1. As seen from the left column of Fig. 1, the MR voltage and the transpolar potential [Fig. 1(a)] decrease monotonically with increasing $\Sigma_P$. The MR voltage is always larger than the transpolar potential and the two become approximately identical for very small $\Sigma_P$ or $I_1$, the same conclusion as reached by Hu et al. [5]. The region 1 current intensity $I_1$ increases monotonically with increasing $\Sigma_P$ [Fig. 1(b)] as expected, whereas the region 2 current $I_2$ exhibits a non-monotonic response to the increase of $\Sigma_P$ [Fig. 1(c)]; it first increases in the range of (0, 5) S and then decreases as $\Sigma_P$ exceeds 5 S. Two competing factors may be responsible for such a behavior of $I_2$. On the one hand, the enhancement of $\Sigma_P$ favors an increase of $I_2$ as it does for $I_1$; on the other hand, the weakening of the MR voltage caused by the enhancement of $\Sigma_P$ reduces the magnetospheric plasma convection and the associated convective electric field, which in turn leads to a decrease of $I_2$. The former factor dominates if $\Sigma_P$ is small, whereas the latter becomes dominant if $\Sigma_P$ exceeds a certain
Figure 1. The responses of the MR voltage and transpolar potential (a, d), region 1 FAC intensity $I_1$ (b, e), and region 2 FAC intensity $I_2$ (c, f) as functions of the Pedersen conductance $\Sigma_P$ in column A (Groups 1 & 2) and the southward IMF $B_s$ in column B (Groups 3 & 4). Numerical results are drawn in solid for Groups 1 and 3 with the solar wind speed $v_{sw} = 400 \text{ km s}^{-1}$ and in dashed for Groups 2 and 4 with $v_{sw} = 400 \text{ km s}^{-1}$. The thick and thin lines in (a, d) denote the MR voltage and transpolar potential, respectively.

critical value, 5 S for the present cases. Therefore, $I_2$ exhibits a non-monotonic response to $\Sigma_P$ as illustrated in Fig. 1(c).

The response of the MR voltage, the transpolar potential, $I_1$ and $I_2$ to the southward IMF $B_s$ and solar wind speed $v_{sw}$ is simpler: all of them increase monotonically when $B_s$
and \( v_{sw} \) increase. The two adjustable parameters, \( B_s \) and \( v_{sw} \), characterize the solar wind driver. The stronger the driver is, the larger the MR voltage, the transpolar potential, and the region 1 and 2 FACs will be.

From the results obtained we may reach the following conclusions. (1) The ionosphere is not only a passive load, but also has a subtle effect on the SW-M-I system. An increase of the ionospheric Pedersen conductance \( \Sigma_p \) leads to a decrease of the magnetospheric reconnection voltage and the ionospheric transpolar potential, and an increase of the region 1 FAC. (2) The region 2 FAC shows a non-monotonic response to \( \Sigma_p \), consisting an initial increase followed by a subsequent decrease with increasing \( \Sigma_p \). Two competing factors, a positive effect by the increase of \( \Sigma_p \) and a negative one by the reduction of the MR voltage and the associated weakening of the magnetospheric plasma convection, produce such a behavior of the region 2 current. (3) All of the magnetospheric reconnection voltage, the ionospheric transpolar potential, and the region 1 and 2 currents become larger under stronger solar wind conditions, characterized by a larger solar wind ram pressure and a stronger southward IMF.

Uniform Pedersen and zero Hall conductances are taken for the ionosphere in this study for simplicity. In reality, the Hall conductance does not vanish, and both of the Pedersen and Hall conductances are non-uniform in space, fluctuating in time, and closely related to the solar radiation intensities and solar wind conditions \([13]\). While the present simulation model needs to be refined to incorporate a more sophisticated treatment of the ionospheric conductances, we argue that this will not substantially change the basic conclusions reached above. Another issue worth mentioning is that MHD simulations of the SW-M-I coupling generally produce weak region 2 current \([11, 12]\). The contribution made by particle drift to this current is important but essentially ignored in the MHD simulations. Nevertheless, the MHD effect contributes to the region 2 current, too, and this effect is properly reflected by our preliminary simulations.

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