An improved method to derive to equivalent current systems from global MHD simulations postprint

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Abstract

Derivation of equivalent current systems (ECS) from a global magnetospheric magnetohydrodynamics (MHD) model is very useful in studying magnetosphere-ionosphere coupling, ground induction effects, and space weather forecast. In this study we introduce an improved method to derive the ECS from a global MHD model, which takes account of the obliqueness of the magnetic field lines. By comparing the ECS derived from this improved method and the previous method, we find that the main characteristics of the ECS derived from the two methods are generally consistent with each other, but the eastward-westward component of the geomagnetic perturbation calculated from the ECS derived from the improved method is much stronger than that from the previous method. We then compare the geomagnetic perturbation as a function of the interplanetary magnetic field (IMF) clock angle calculated from the ECS derived from both methods with the observations. The comparison indicates that the improved method can improve the performance of the simulation. Furthermore, it is found that the incomplete counterbalance of the geomagnetic effect produced by the ionospheric poloidal current and field-aligned current (FAC) contributes to most of the eastward-westward component of geomagnetic perturbation.

Full Text

An Improved Method to Derive Equivalent Current Systems from Global MHD Simulations

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Abstract

Derivation of equivalent current systems (ECS) from a global magnetospheric MHD model is very useful in the study of magnetosphere-ionosphere coupling, ground induction effects, and space weather forecasting. In this study, we introduce an improved method to derive ECS from a global MHD model that takes into account the obliquity of magnetic field lines. By comparing the ECS derived from this improved method with those from the previous method, we find that the main characteristics are generally consistent between the two approaches. However, the eastward component of geomagnetic perturbation calculated from the ECS derived using the improved method is much stronger than that from the previous method. We then compare the peak values of geomagnetic perturbation as a function of interplanetary magnetic field (IMF) clock angle calculated from both methods with observations. The comparison indicates that the improved method enhances simulation performance. Furthermore, we find that the incomplete counterbalance of the geomagnetic effect produced by the ionospheric poloidal current and field-aligned current (FAC) contributes most of the eastward component of geomagnetic perturbation.

Key words: Equivalent current systems, global MHD model

Introduction

At the beginning of the twentieth century, the concept of equivalent current systems (ECS) was introduced to represent the time-varying configuration of large-scale magnetic perturbations [1]. These systems are determined by assuming that all currents responsible for magnetic disturbances flow in a thin shell of the ionosphere. Since they provide valuable information about ionospheric electrodynamics, ECS are widely used in studies of ionosphere-magnetosphere coupling and space weather. For ionosphere-magnetosphere coupling studies, ECS serve not only as the basis for the full solution of ionospheric electrodynamics [2], but under many circumstances provide a good approximation of ionospheric current behavior [3]. From a space weather perspective, ECS are of great interest because they are useful for studying geomagnetic induction phenomena that can cause problems for technological facilities on the ground. For example, Pulkkinen et al. [4] calculated geoelectric fields at some Baltic Electromagnetic Array Research (BEAR) sites from ECS determined using the method of spherical elementary current systems combined with the complex image method [5]. They compared their calculated results with measured electric fields and found generally good agreement. Using ECS derived from a global MHD model, Zhang et al. [6] simulated geomagnetically induced currents (GIC) flowing through a transformer at the Pirttikoski (PIR) substation in the Finnish high-voltage power system during a space weather event in 1999. They compared the modeled GIC with recorded values and found that the simulation reproduced the main features of the GIC signals for the event they investigated. ECS can also indicate where GIC hazards are most likely to occur, as the largest dB/dt spikes usually appear within large-scale electrojets where currents are strongest [7].

Global magnetohydrodynamics (MHD) simulations have played a significant role in space weather studies in recent decades. Despite rapid implementation of spaceborne and ground-based geospace environment monitoring projects, developing global models remains crucial for understanding observations of the magnetosphere-ionosphere coupling system in a global context and eventually for making accurate space weather predictions. Prediction of ECS from global MHD simulation models is significant for both magnetosphere-ionosphere coupling and space weather research. Wang et al. [8] reproduced ECS in the high-latitude region during two successive isolated substorms using the global PPMLR-MHD model [9]. In their work, ionospheric current was split into divergence-free toroidal current and curl-free poloidal current, with the toroidal current considered as the equivalent current based on Fukushima' s theorem [2, 10] for simplification. This theorem states that field-aligned current (FAC) and poloidal current together produce no ground magnetic signature under the assumption of radial geomagnetic field lines. When ionospheric conductance is uniform, the Hall current is divergence-free and the Pedersen current equals the poloidal current, so the geomagnetic variation produced by FAC and the Pedersen current cancel each other. Most modeling studies have adopted this assumption when calculating geomagnetic perturbations induced by current systems around Earth, using only the Hall or toroidal current in the calculations [7, 11, 12]. For rough estimation, this approach is appropriate. However, Earth' s magnetic field lines are not radial even in the auroral zone, so the ground magnetic signature produced by poloidal current and FAC cannot completely cancel each other in high-latitude regions [8, 11, 13]. In addition, the imperfect counterbalance of geomagnetic perturbation produced by poloidal current and FAC has never been shown or estimated, yet this effect may be necessary for more accurate requirements. Thus we introduce an improved method to derive ECS from a global MHD model that accounts for the obliquity of field lines. In other words, the improved method includes the effects of poloidal current and FAC on ECS in the simulation. We then conduct a comparison of ECS derived from this improved method and the previous one [8, 11] to quantitatively estimate the deviation and investigate the imperfect counterbalance effect of poloidal current and FAC.

In the remainder of this paper, we first introduce the global MHD simulation model and the improved ECS derivation method, then compare ECS derived from the improved and previous methods, and finally present conclusions and summary.

1.1 Global MHD Model

The global PPMLR-MHD simulation model [9] is the numerical model used in this study. The PPMLR-MHD code solves ideal MHD equations for the solar wind-magnetosphere-ionosphere coupling system. The coupling process between magnetosphere and ionosphere has been described in detail by Wang et al. [8]; here we provide only a brief description. An inner magnetosphere boundary is set at r = 3 RE, and an electrostatic ionosphere is set at r = 1.017 RE. A magnetosphere-ionosphere electrostatic coupling model is embedded between the inner boundary and ionosphere to drive inner boundary convection. From the inner boundary, FAC are mapped along Earth' s dipole magnetic field lines to the ionosphere where they serve as source terms for a two-dimensional Poisson equation for electric potential. Once the potential is obtained, it is mapped back to the inner boundary to calculate convection velocity. To calculate the conductance tensor of the ionosphere, two models are applied together. For contributions from solar EUV radiation, we use a model in which conductance depends on solar flux F10.7 and solar zenith angle [14]. For the auroral region, we use the model developed by Ahn et al. [15], in which conductance is empirically derived from geomagnetic disturbance. The Hall and Pedersen conductance over the dark polar cap region and subauroral region are given to be constants 2.0 S and

1.2 The Previous Method to Derive ECS

In previous studies [8, 11], the total height-integrated ionospheric current was split into two parts: the divergence-free toroidal current and the curl-free poloidal current . Taking Fukushima' s theorem [2, 10] and neglecting the influence of magnetosphere current for the high-latitude region, the toroidal current is considered as the equivalent current.

1.3 The Improved Method to Derive ECS

To account for the influence of and FAC in ECS, we first define fictitious magnetometer sites at ground grid points spaced every 1° in latitude and 1 hour in magnetic local time. We then calculate magnetic variations at each site produced by the current system represented by , , and FAC using Biot-Savart' s law.

Between the inner boundary and the ionosphere in the MHD model exists a data gap region, in which FAC is mapped from the inner magnetosphere boundary along Earth' s dipole magnetic field lines to the ionosphere as mentioned in Section 1.1. This region exists outside the consideration of numerical computation in a global MHD simulation model. To obtain current information in this region, we utilize correlation to calculate at any point of the region along a field line from the current at the inner boundary, TPJJJ JdJ=constantBJ where represent the FAC and magnetic field magnitude at any position of the gap region along a field line.

Geomagnetic perturbation at any fictitious station is calculated by integrating the ionospheric toroidal and poloidal currents above 60° magnetic latitude and the gap region FAC using Biot-Savart' s law. Finally, we input these geomagnetic perturbations into a geomagnetic inversion algorithm to derive ECS in the ionosphere at radius r = 1.017 RE. The inversion algorithm is based on the principle that in the lower atmosphere where electric current flow is negligible, magnetic variation can be expressed in terms of a magnetic potential Φ, and the equivalent current is related to the external portion of Φ by straightforward mathematical relations [16]. This method for deriving ECS also formed the basis of the famous KRM algorithm (see Kamide et al. [2] for details).

2.1 Comparison of the ECS with the Previous Method

We run the model under fixed solar wind and interplanetary magnetic field (IMF) conditions, with IMF set to -10 nT, solar wind speed at 450 km/s, plasma density N fixed at 7.5 cm ^{3}, plasma temperature T at 10 T, and other parameters , , , set to 0. The simulation reaches a quasi-steady state, and the magnetosphere and ionosphere currents under this state are used to derive ECS.

Figure 1 [Figure 1: see original paper] shows ECS for the northern hemisphere derived from both methods. Figure 1(a) displays ECS from the improved method, while Figure 1(b) shows ECS from the previous method. Each pattern is centered on the northern magnetic pole with circles drawn every 10° in magnetic latitude to the outer boundary of 60°. Equivalent current vectors are plotted at grid points every 1° in latitude and 1 hour in magnetic local time. The two patterns are generally consistent with each other. Under southward IMF, the westward electrojet located in the midnight and dawn sectors is much more intense than the eastward electrojet in the dusk sector. Both westward and eastward electrojets mainly distribute between 60° and 70° magnetic latitude. However, discrepancies exist: the peak values of westward and eastward currents derived from method (a) are smaller than those from method (b). The maximum westward current intensity is 1.01 A/m in Figure 1(a), while the value is 1.26 A/m in Figure 1(b); the maximum eastward current intensity is 0.31 A/m versus 0.36 A/m. Additionally, the center of the westward current is located at somewhat higher latitude in Figure 1(a) than in Figure 1(b). These discrepancies are mainly attributed to the smoothing effect of the interpolation used in the inversion algorithm of the improved method.

Figure 1. ECS derived from (a) the improved method and (b) the previous method. Red vectors denote westward current, and blue vectors represent eastward current. Vector length indicates current intensity, with the same scale adopted for both patterns. Peak values of westward and eastward current are given in the bottom corner of each pattern, with eastward specified as positive.

We also calculate the total westward current intensity flowing through magnetic local time meridians on the nightside from both results and show the curves in Figure 2 [Figure 2: see original paper]. The change tendency of the curves agrees well, with total westward current intensity reaching maximum at local time 2-3. The deviation between the two results is small, with an average deviation of 4.42% over these 13 local times.

Figure 2. Total westward current intensity flowing through each magnetic local time meridian on the nightside derived from both methods. Red triangles rep-

resent results from the improved method, and black triangles represent results from the previous method.

2.2 Comparison of the Geomagnetic Perturbation

ECS represent large-scale geomagnetic perturbation on the ground. To compare geomagnetic variation represented by ECS derived from both methods, we calculate geomagnetic perturbation from the two ECS shown in Figure 1 using Biot-Savart' s law and then make comparisons. Patterns of the three geomagnetic variation components are shown in Figure 3 [Figure 3: see original paper], with Figures 3(a) and 3(b) showing results calculated from ECS derived using the improved and previous methods, respectively. The patterns of northward and downward components derived from the improved method are similar to those from the previous method, with peak value locations identical. For the northward component, the maximum southward perturbation appears at about 65° latitude and 3 MLT, and the maximum northward perturbation appears at about 65° latitude and 15 MLT for both methods. For the downward component, positive and negative peak values are both located on the dawn side, with the latitude of the positive peak higher than that of the negative peak. A relatively notable difference is that for the northward component, perturbation above 80° latitude in Figure 3(a) is stronger than in Figure 3(b). However, the deviation is significant for the eastward component: although the distribution regions of positive and negative perturbation are similar, the intensities are much larger in Figure 3(a) than in Figure 3(b). We attribute this difference mainly to the imperfect counterbalance of the geomagnetic effect produced by ionospheric poloidal current and FAC. Figure 4 [Figure 4: see original paper] shows patterns of total horizontal geomagnetic perturbation calculated from both ECS. We find the two patterns are similar, with perturbation over regions higher than 80° latitude somewhat stronger in Figure 4(a) than in Figure 4(b), mainly due to stronger northward and eastward components of geomagnetic perturbation above 80° latitude derived from the improved method.

We list peak values of the three geomagnetic perturbation components and peak values of the horizontal component in Table 1 for further comparison. According to Table 1, the largest deviation appears for westward and eastward geomagnetic perturbation, with peak values from the improved method about three times those obtained from the previous method. The deviation for the horizontal component is smallest at -2.11%. ECS obtained from the improved method can represent much stronger eastward component of geomagnetic perturbation. However, one should note that the northward component is always the dominant perturbation, while the eastward component is relatively weaker.

Figure 3. Geomagnetic perturbations represented by ECS. The first and second rows show three components calculated from ECS derived using (a) the improved method and (b) the previous method. Perturbation intensity is characterized by the color bar. Northward, eastward, and downward components are specified as positive, with peak values indicated at the bottom corners of each pattern.

Figure 4. Horizontal geomagnetic perturbation calculated from ECS derived using (a) the improved method and (b) the previous method. Maximum and minimum perturbation values are given in the bottom corners of each polar plot, with intensity characterized by the color bar.

Table 1. Comparison of peak values of geomagnetic perturbations.

Peak values	Improved Method	Previous Method	Deviation (a-b)/b×100%
Northward			
Southward			
Eastward			
Westward			
Horizontal			
Downward			
Upward			

2.3 Comparison with the Observations

Since ECS represent large-scale geomagnetic perturbation, comparing modeled ECS with observations is equivalent to comparing geomagnetic perturbation derived from simulation with observations. To compare both simulation results with observations, we run the model for seven additional cases. Together with the case used in Section 2.1, these form a case group investigating how ECS vary with IMF clock angle in the simulation. Here, zero clock angle is defined in the direction of positive Z with $= 0$, and the angle increases as IMF rotates clockwise in the GSM Y-Z plane. For the eight runs, the clock angle changes from 0° to 360° in 45° increments, the transverse IMF magnitude ($= \sqrt{\ {}^{2} + {}^{2}}$) is fixed at 10 nT, solar wind velocity , plasma density N, and temperature T are the same as in Section 2.1, and , , are set to 0.

Weimer et al. [17] mapped geomagnetic perturbation as a function of IMF and solar wind conditions using spherical harmonics fits. The geomagnetic data they used were collected from 104 geomagnetic observatories located above 40° geomagnetic latitude in the northern hemisphere during 1998-2001. Under similar solar wind and IMF conditions, we compare geomagnetic perturbation patterns with Figures 9 [Figure 9: see original paper], 10, and 11 of Weimer et al.' s work and find that patterns derived from simulation are similar to observational results. For the statistical results, IMF is 10 nT, is 450 km/s, and average plasma density N in the database approximates 7.5 cm ^{3}, matching the simulations. Comparison of peak geomagnetic perturbation values derived from both simulation methods with observations is shown in Figure 5 [Figure 5: see original paper]. Figure 5 shows how peak geomagnetic perturbation values vary with IMF clock angle . We see from Figure 5(a) that the two simulation curves nearly coincide for the northward component of ground geomagnetic perturbation, with very small deviations, and they match statistical results well.

Figure 5(c) shows that for the downward component, deviations between the two simulation results remain very small, and they reproduce the variation tendency of statistical observations. For the eastward component, deviations are much larger. Figure 5(b) shows that results derived from the improved simulation method (denoted by red lines) are much closer to statistical perturbation intensities, while results from the previous method are too small to represent the eastward component. This indicates that applying the improved method enhances simulation results, and ECS derived from the improved method can represent more realistic eastward component of geomagnetic perturbation. It also confirms that incomplete counterbalance of the geomagnetic effect produced by and FAC contributes most of the eastward component of geomagnetic perturbation.

Figure 5. Peak values of geomagnetic perturbations as a function of IMF clock angle . The three graphs show (a) northward, (b) eastward, and (c) downward components. Triangle and square symbols represent peak values of positive and negative perturbation, respectively. Black lines indicate statistical results, red lines indicate results calculated from ECS derived using the improved method, and green lines indicate results from the previous method.

3. Conclusion and Summary

In this study, we introduce an improved method to derive ECS from a global MHD model. Besides toroidal current, the method accounts for the influence of ionospheric poloidal currents and FAC on ECS. The basic pattern of ECS derived from the improved method is consistent with that from the previous method. Comparing geomagnetic perturbation represented by ECS derived from both methods, we find that for northward and downward components the results are consistent with small deviation. However, for the eastward component, the improved method produces much stronger perturbation than the previous method. We attribute this deviation to imperfect counterbalance of geomagnetic effects between ionospheric poloidal current and FAC. To verify which result is more realistic, we finally compare peak geomagnetic perturbation values from both simulation results with observations. The comparison indicates that northward and downward components of geomagnetic perturbation derived from both simulation methods are very close to each other and reproduce the variation tendency of observations. The eastward component of geomagnetic perturbation derived from the improved method is much closer to statistical results than that from the previous method, implying that ECS derived from the improved method is more accurate. However, it should be kept in mind that the northward component of geomagnetic perturbation is always the dominating component, implying that ECS derived from both methods are effective, but the improved method is desirable for more accurate requirements. For example, when simulating GICs flowing in long conductor systems, both northward and eastward components of geomagnetic variation are important [6].

In summary, the improved method can enhance simulation performance, while both methods for deriving ECS are effective for rough estimation. When more accurate requirements exist, the incomplete counterbalance of poloidal current and FAC effects should be considered, and the improved method can be applied for such studies. Additionally, we find that incomplete counterbalance of the geomagnetic effect produced by ionospheric poloidal current and FAC contributes most of the eastward component of geomagnetic perturbation.

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Note: Figure translations are in progress. See original paper for figures.