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Dynamical effects of ionospheric conductivity on the formation of polar cap arcs

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Abstract. By using a magnetosphere-ionosphere (M-I) coupling model of polar cap arcs [*Zhu et al.*, 1993], a systematic model study of the effects of ionospheric background conductivity on the formation of polar cap arcs has been conducted. The variations of the ionospheric background conductivity in the model study cover typical ionospheric conditions, including solar minimum, solar maximum, winter, and summer. The simulation results clearly indicate that the ionospheric background conductivity can dynamically affect the mesoscale features of polar cap arcs through a nonlinear M-I coupling process associated with the arcs.

1. Introduction

Polar cap arcs are the auroral arcs occurring in the polar cap or in the regions poleward of the auroral oval. The lengths of these arcs can be from 100 km up to the size of the whole polar cap and are aligned parallel to the Sun-Earth direction [*Davis*, 1960; *Frank et al.*, 1986]. In contrast with the arcs in the auroral oval region, which have a good correlation to a southward interplanetary magnetic field (IMF), polar cap arcs are mainly observed during periods of northward IMF and quiet magnetic conditions [*Berkey et al.*, 1976; *Lassen and Danielsen*, 1978]. The observational study of polar cap arcs started as early as 1916 when *Mawson* [1916] was published and evolved from the morphological studies using single ground-based instrument in the early time to the more recent studies of electrodynamical mesoscale features and magnetosphere-ionosphere (M-I) coupling aspects of the arcs using multiple ground-based and space-based instruments in a series of observational campaigns (for the details of polar cap arcs observations, the readers are referred to a review paper by *Zhu et al.* [1997]).

Compared with the observations, theoretical studies of polar cap arcs, especially the quantitative theoretical studies, are still in their early stages. Most theoretical models of polar cap arcs [e.g., *Burke et al.*, 1982; *Chiu*, 1989] are either qualitative, semiquantitative, or steady state models. These models mainly deal with the global static patterns of polar cap arcs and their mapping to the magnetospheric configuration. Therefore they were unable to study dynamical mesoscale features and M-I coupling effects that have characterized the most recent observations of polar cap arcs. In contrast, the Utah State University Theory Group developed a time-dependent quantitative model of polar cap arcs [*Zhu et al.*, 1993] in which the electrodynamics of polar cap arcs is treated self-consistently in the frame of the coupled M-I system. Because of the nature of this M-I coupling model, it can not only conduct quantitative theoretical study of dynamical features and M-I coupling effects of polar cap arcs by using typical and generalized theoretical inputs, but also perform quantitative model-observation comparison by directly using observational data as the inputs. Several theoretical predictions of the M-I coupling model of polar cap arcs have been qualitatively and/or quantitatively confirmed by recent observations or through direct model-observation comparison studies [*Obara et al.*, 1996; *Zhu et al.*, 1996].

2. Theoretical Model and Motivation of Present Study

The present model study of the ionospheric conductivity effects on the formation of polar cap arcs was conducted by using the time-dependent M-I coupling model [*Zhu et al.*, 1993] mentioned in the preceding section. The mathematical formulation of the model will not be discussed in this paper, and the

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interested readers are referred to *Zhu et al.* [1993]. In the following, we only briefly summarize the physical scenario of the model.

The model proposes that development of polar cap arcs starts with a magnetospheric plasma shear flow moving earthward along either open or closed magnetic field lines and that the shear flow is carried by Alfvén waves. The significance of the assumed initial magnetospheric shear flow in the model has been discussed by *Zhu et al.* [1993] and is not repeated here. The downward propagating Alfvén waves are partially reflected from the ionosphere and then bounce back and forth between the ionosphere and magnetosphere. The nature of the wave reflections depends on the conditions both in the ionosphere and magnetosphere. The propagating Alfvén waves carry both upward and downward field-aligned currents. The precipitating electrons associated with upward field-aligned currents enhance the conductivity in the ionosphere, and the modified ionospheric conductivity launches secondary Alfvén waves toward the magnetosphere. The upward propagating Alfvén waves, which consist of the reflected waves and the secondary Alfvén waves launched by the temporal change of the ionospheric conductivity, carry the ionospheric information back to the magnetosphere, thus reflecting the active ionospheric role in the dynamics of polar cap arcs. The whole process is transient, during which all physical quantities in the ionosphere change self-consistently in time, and subsequently, polar cap arcs develop. Because of the finite conductivity in the ionosphere, the temporal variation of the Alfvén waves in the coupled M-I system diminishes with time, and the M-I system, as well as the development of polar cap arcs, approaches an asymptotic steady state after several Alfvén wave bouncing periods.

The M-I coupling process of polar cap arcs described above is a time-dependent process, which more realistically describes the dynamics of polar cap arcs than the previous steady state models. As can be seen from the above, the development of polar cap arcs in the model is not a simple mapping of magnetospheric plasma structures to the ionosphere. Instead, it is determined by a time-dependent M-I coupling process in which the ionosphere plays an active role. This is in sharp contrast to the passive ionosphere adopted in the earlier models. The active role of the ionosphere in the formation of polar cap arcs is mainly represented by the upward propagating Alfvén waves, which can modify the convection and current patterns in the magnetospheric source regions and can also be partially reflected from the magnetosphere, depending on the source region conditions, thereby influencing the dynamical formation of polar cap arcs in the ionosphere. As mentioned above, the upward propagating Alfvén waves consist of reflected waves from the ionosphere and the secondary Alfvén waves launched by the temporal change of the ionospheric conductivity. The characteristics of these two kinds of waves can be influenced by the ionospheric background conditions, mainly the ionospheric background convection and background conductivity. Therefore the ionospheric background convection and conductivity can have nonlinear dynamical effects on the formation of polar cap arcs, according to the M-I coupling process of polar cap arcs described in the above.

In our previous work, we have systematically studied the dynamical effects of the ionospheric background convection on the formation of polar cap arcs [*Sojka et al.*, 1994]. In that work, various typical large-scale ionospheric convection patterns (two-cell, three-cell, four-cell, and distorted two-cell) reflecting the different IMF conditions were adopted, and their effects on the mesoscale features of the arcs were studied. The results indicated that the ionospheric background convection can significantly affect the dynamics of the arcs and the nonlinear M-I coupling processes associated with the arc formations. Specifically, it was found that the appearance of multiple polar cap arcs has a strong dependence on the magnitude of the large-scale background convection electric field (E). With the same initial magnetospheric driver, they found that the number of the arcs increased with an increase in the strength of the background convection, while the spacing between the arcs remained constant. This dependence is not a linear effect in which the polar cap arcs simply scale with the magnitude of the background convection. The degree of striation, or multiple character, of the arcs increases rapidly from a single arc for $E < 20$ mV m^{-1} to five arcs for 30 mV m^{-1} with the same magnetospheric driver. These results clearly indicate that the ionosphere plays an active role in the formation of polar cap arcs and that the ionosphere dynamically responds to the magnetospheric driver.

A natural extension of *Sojka et al.*'s [1994] work can be a study of the effects of ionospheric background conductivity on the formation of polar cap arcs. In the polar cap, the ionospheric background conductivity distributions can be significantly different due to the solar and seasonal variations. Since the formation of polar cap arcs is an M-I coupling process and the ionosphere can dynamically respond to a magnetospheric driver, significantly different ionospheric background conductivity distributions can lead to different dynamical and mesoscale features of polar cap arcs. To quantitatively explore the dynamical effects of these different conductivity distributions, we conducted a series of simulations using the M-I coupling model in which the variations of the ionospheric background conductivity cover typical ionospheric conditions, including solar minimum, solar maximum, winter, and summer. The simulation results indicate that for different ionospheric conductivity distributions due to the variation of solar and seasonal conditions, the dynamical features of polar cap arcs can be significantly different for the same typical magnetospheric driver.

3. Simulations and Results

The ionosphere is treated as a two-dimensional (2-D) slab with an integrated conductivity. The X axis measures the noon-midnight dimension and points to the dayside, and the Y axis measures the dawn-dusk dimension and points to the duskside. The magnetosphere is also treated as a 2-D plane that is used as a boundary for the reflection of Alfvén waves. The magnetosphere and ionosphere are connected by magnetic field lines which are assumed to be perpendicular to the ionosphere. The ionospheric simulation domain is 3000 km long in the X direction and 1000 km wide in the Y direction. The grid size is 30 km in the X direction and 10 km in the Y direction.

The selection of boundary conditions in the simulation is based on the following physical considerations: Polar cap arcs are mainly aligned in the noon-midnight direction. Typically, polar cap arcs can be tens to a few hundreds of kilometers wide and very much stretched (hundreds to a few thousands of kilometers) in the noon-midnight direction, sometimes even connected to both the dayside and nightside of the auroral oval. In the distant regions on the dawnside or duskside of polar cap arcs, the background ionosphere can be assumed undisturbed, and therefore we use a constant boundary condition for the dawnside and duskside boundaries in the simulation. On the noonside and midnightside boundaries, the situations are completely different. Not only can the elongated polar cap arcs reach or even go beyond the boundaries into the auroral oval, but also the large-scale convection which is mainly in the Sun-aligned direction can carry the disturbance associated with polar cap arcs through the boundaries.

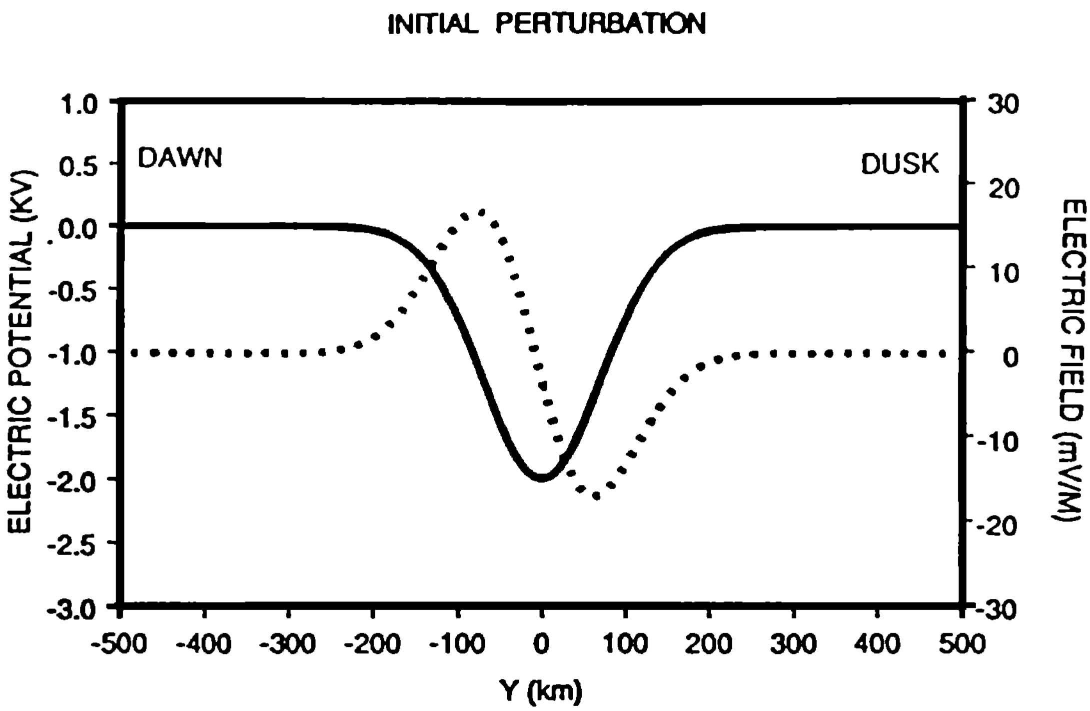

Figure 1. Potential distribution (solid line) in the dawn-dusk cross section associated with the initial magnetospheric shear flow and the corresponding electric field distribution (dashed line).

Accordingly, we use an open boundary condition for the noonside and midnightside boundaries, which allows plasma to freely flow through the boundaries.

Figure 1 shows the potential and electric field profiles of a typical magnetospheric shear flow which is carried by an earthward propagating Alfvén wave and was used as the initial magnetospheric driver for all the simulations in this study. The shear flow is uniform in the noon-midnight direction. Since the dynamical effects of large-scale ionospheric background convection have been systematically studied by *Sojka et al.* [1994], in this work we used a simple uniform antisunward convection (20 mV/m) as the ionospheric background convection in most of the simulations unless specifically mentioned.

To determine the ionospheric background conductivity distributions in the polar cap for various solar and seasonal conditions, we ran a quantitative ionospheric conductivity model developed by *Rasmussen et al.* [1988] first and produced global conductivity distributions for solar minimum, solar maximum, winter, and summer conditions. On the basis of these global distributions of the ionospheric conductivity, we then produced the background conductivity distributions in the polar cap simulation domain which were used as the inputs for the M-I coupling model.

The simulations started when the initial magnetospheric shear flow, which is carried by earthward propagating Alfvén waves, reached the

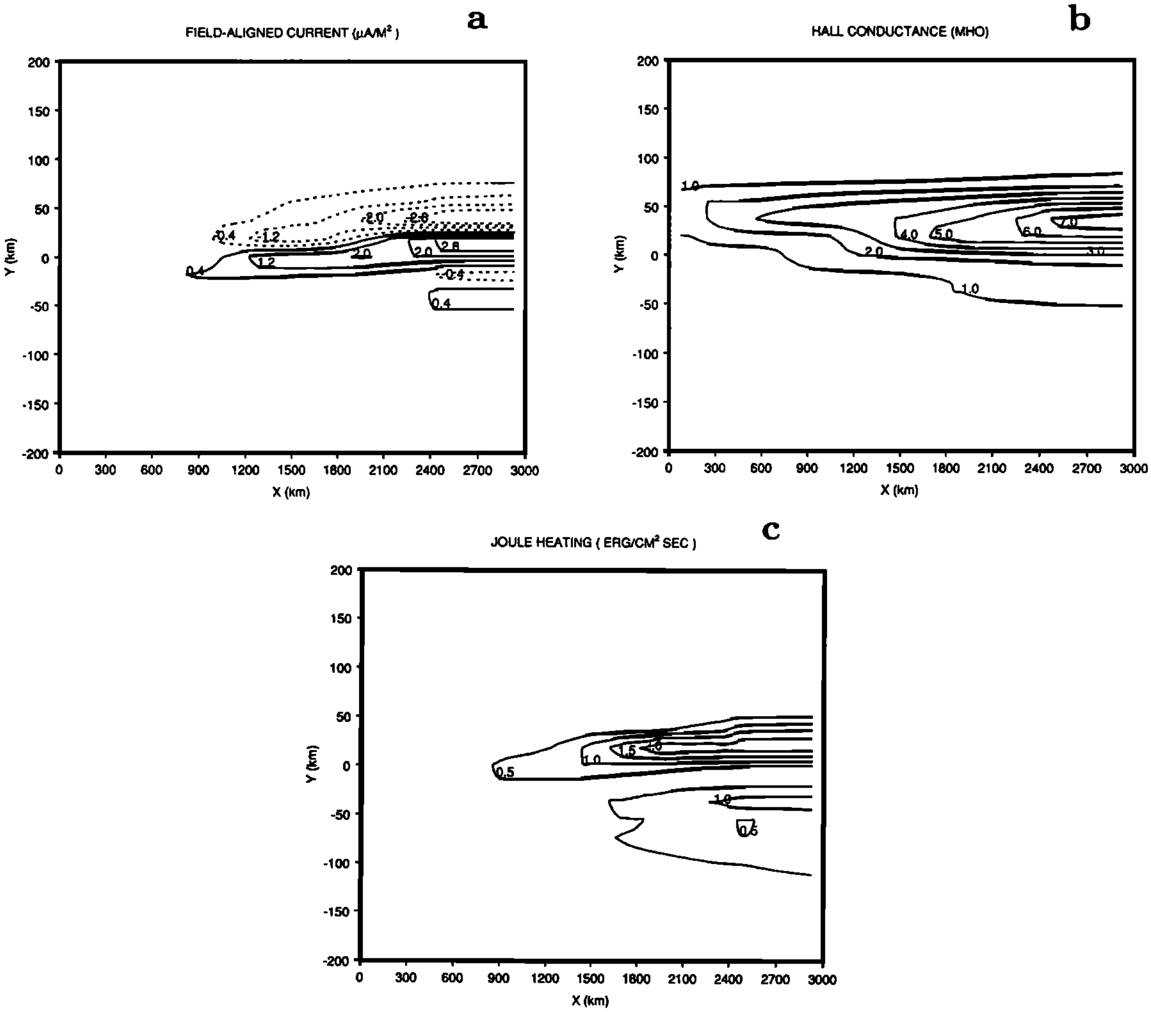

Figure 2. Distributions of (a) field-aligned currents, (b) Hall conductance, and (c) Joule heating rate at the asymptotic steady state for winter, solar minimum, and antisunward convection conditions. Solid lines in the field-aligned current plot denote downward currents and dashed lines denote upward currents.

ionosphere. This triggered the dynamical process of polar cap arcs in the simulations in which the Alfvén waves were partially reflected from the ionosphere, the conductivity changed in time due to precipitation associated with the shear flow, the ionospheric convection was modified, field-aligned currents and horizontal currents were enhanced, and the secondary Alfvén waves were launched from the ionosphere due to the temporal change of the conductivity. This is a time-dependent M-I coupling process which eventually approached an asymptotic state due to the finite conductivity in the ionosphere. In the present study, we focus on the asymptotic features of polar cap arcs to study how various ionospheric background conductivity affect the formation of the arcs.

3.1. Case 1: Winter, Solar Minimum, Antisunward Convection

The large-scale ionospheric convection for this case is a uniform antisunward convection with a magnitude of 20 mV m^{-1}. The distribution of background Hall conductivity is uniform in the dawn-dusk direction and linearly increases from 0.3 mho at the nightside polar cap to 0.8 mho at the dayside polar cap, which is based on the results of the ionospheric conductivity model mentioned in the above. The ratio of the background Hall conductance to the Pedersen conductance is 1. The magnetospheric driver is the shear convection flow shown in Figure 1.

Figure 2 shows the asymptotic features of the polar cap arcs for the winter and solar minimum conditions.

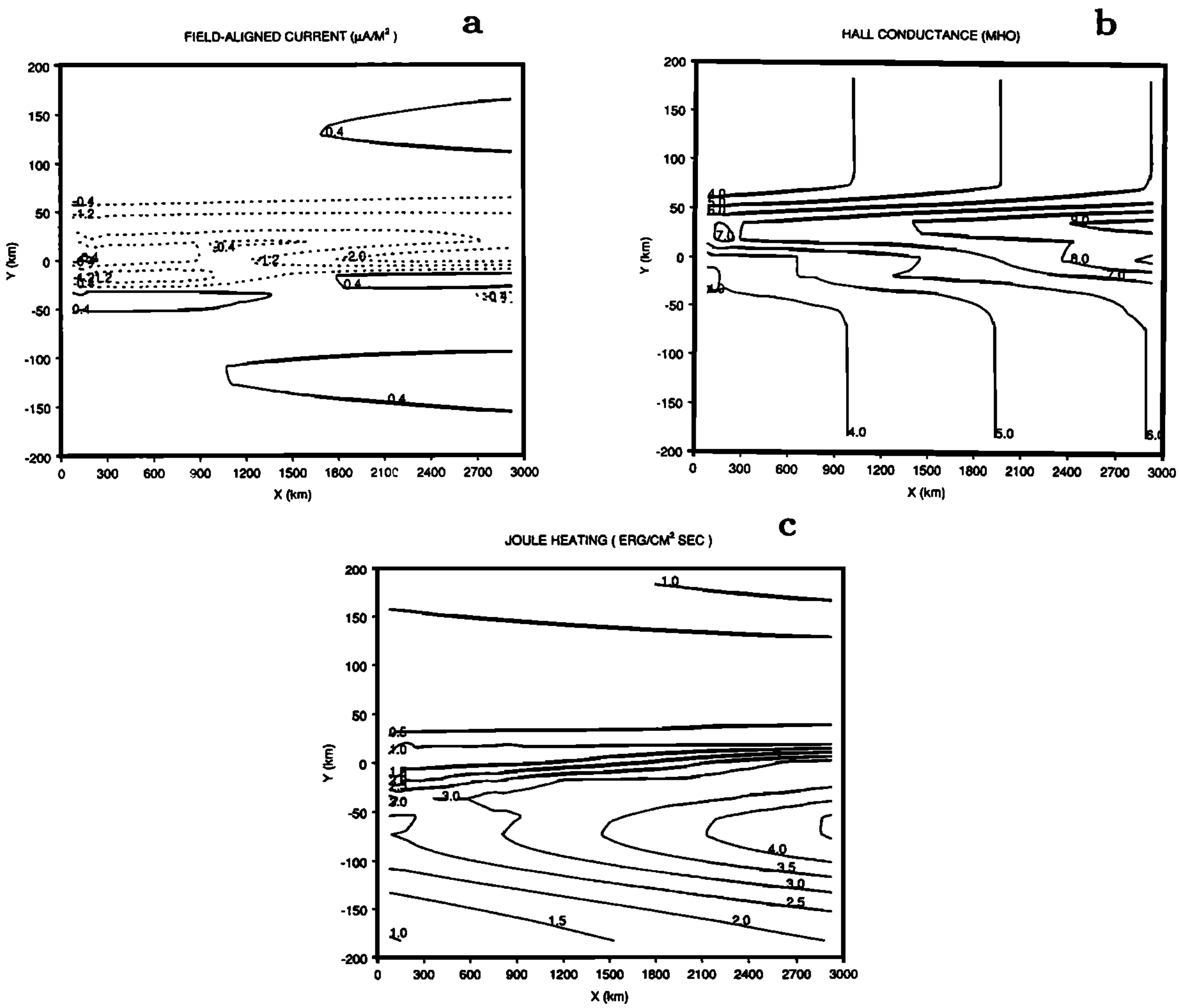

Figure 3. Distributions of (a) field-aligned currents, (b) Hall conductance, and (c) Joule heating rate, at the asymptotic steady state for summer, solar minimum, and antisunward convection conditions.

Figure 2a shows the field-aligned current distribution, in which the dashed lines denote upward field-aligned currents and the solid lines denote downward field-aligned currents. Please note that only a portion of the simulation domain is shown in this figure in order to display the detailed structures associated with the polar cap arcs. It can be seen that the polar cap arcs have multiple structures even though the initial magnetospheric shear flow has only a single precipitation channel in the center. This is consistent with the conclusions of *Zhu et al.* [1993] and indicates the nonlinear dynamical M-I coupling processes associated with the arcs. Even though the initial magnetospheric shear flow extends from the dayside boundary (X = 3000 km)to the nightside boundary (X = 0 km) of the ionospheric simulation domain, polar cap arcs only develop in the dayside regions where the ionospheric background conductivity is relatively higher. This indicates that in the regions where the ionospheric conductivity is extremely low, the magnetospheric currents associated with the initial shear flow simply cannot close in the ionosphere and the current flow is cut off in the M-I circuit. Therefore the dynamical M-I coupling process of polar cap arcs cannot start, and the development of the arcs is blocked. This result may imply that for solar minimum and winter conditions, the extended polar cap arcs stretching from the dayside to the nightside of the polar cap may not be common.

Figure 2b shows the asymptotic Hall conductance associated with the arcs. It can be seen that in the

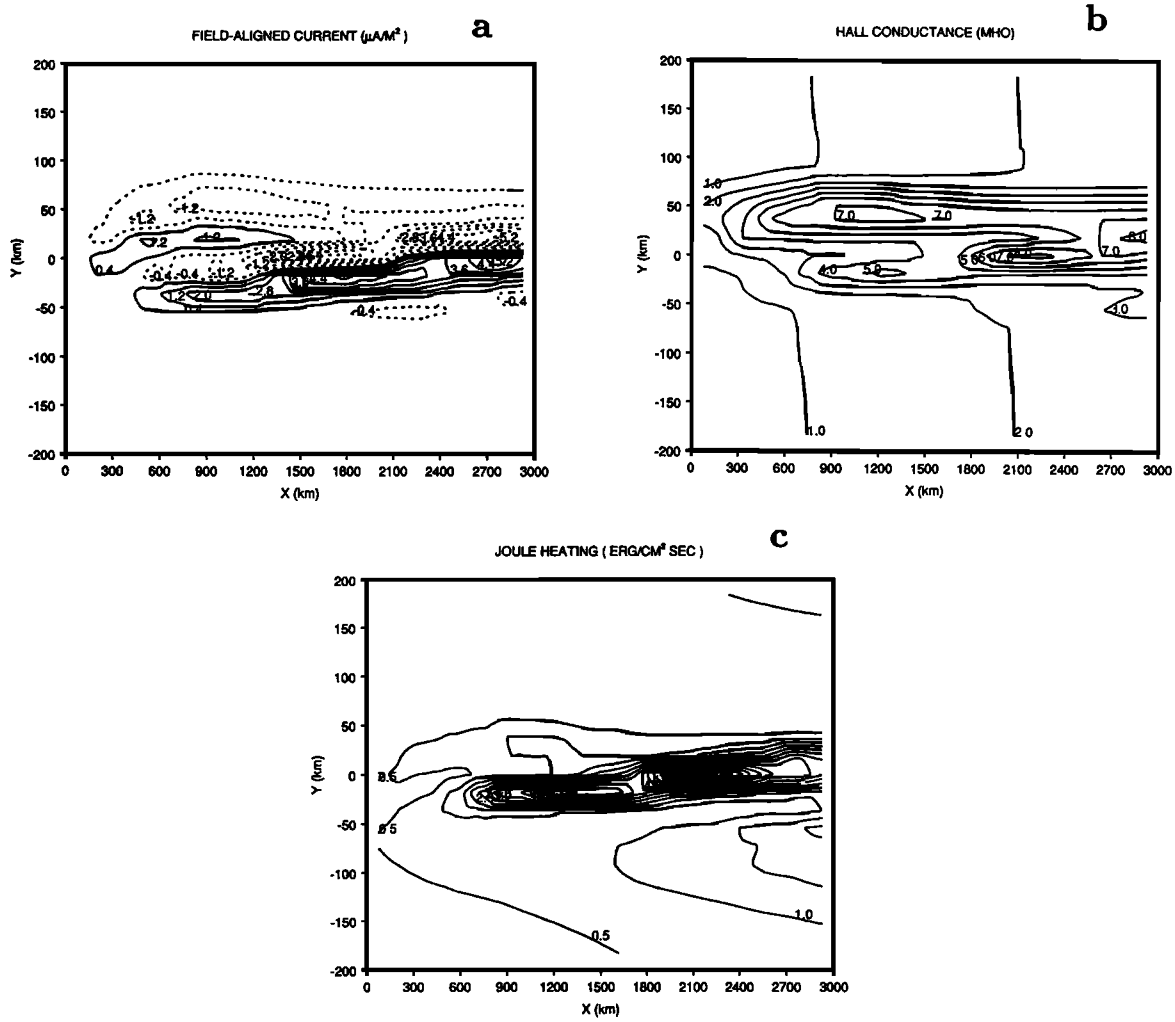

Figure 4. Distributions of (a) field-aligned currents, (b) Hall conductance, and (c) Joule heating rate, at the asymptotic steady state for winter, solar maximum, and antisunward convection conditions.

regions of polar cap arcs, the conductance has been elevated by a factor of almost 10 from the background level for this specific case. Figure 2c shows the Joule heating rate distribution. Strongest Joule heating is not colocated with the strongest upward field-aligned currents, where the arcs locate. This is because the precipitation associated with the upward field-aligned currents enhances the conductance, thereby reducing the electric field in these regions.

3.2. Case 2: Summer, Solar Minimum, Antisunward Convection

The large-scale ionospheric convection for this case is still an antisunward convection, which is the same as that in case 1. The ionospheric background conductivity distribution is uniform in the dawn-dusk direction and linearly increases from 3 mhos at the nightside polar cap to 6 mhos at the dayside polar cap, which is again based on the results of the ionospheric conductivity model [*Rasmussen et al.*, 1988]. The ratio of the background Hall to the Pedersen conductances is 1.5 for this case. The magnetospheric driver is still the shear convection flow shown in Figure 1.

Figure 3 shows the asymptotic features of the polar cap arcs for the summer and solar minimum conditions. As can be seen, now there is only a single arc developed. The developed arc is more smooth and wider than the arcs in case 1. This can be explained by the fact that the

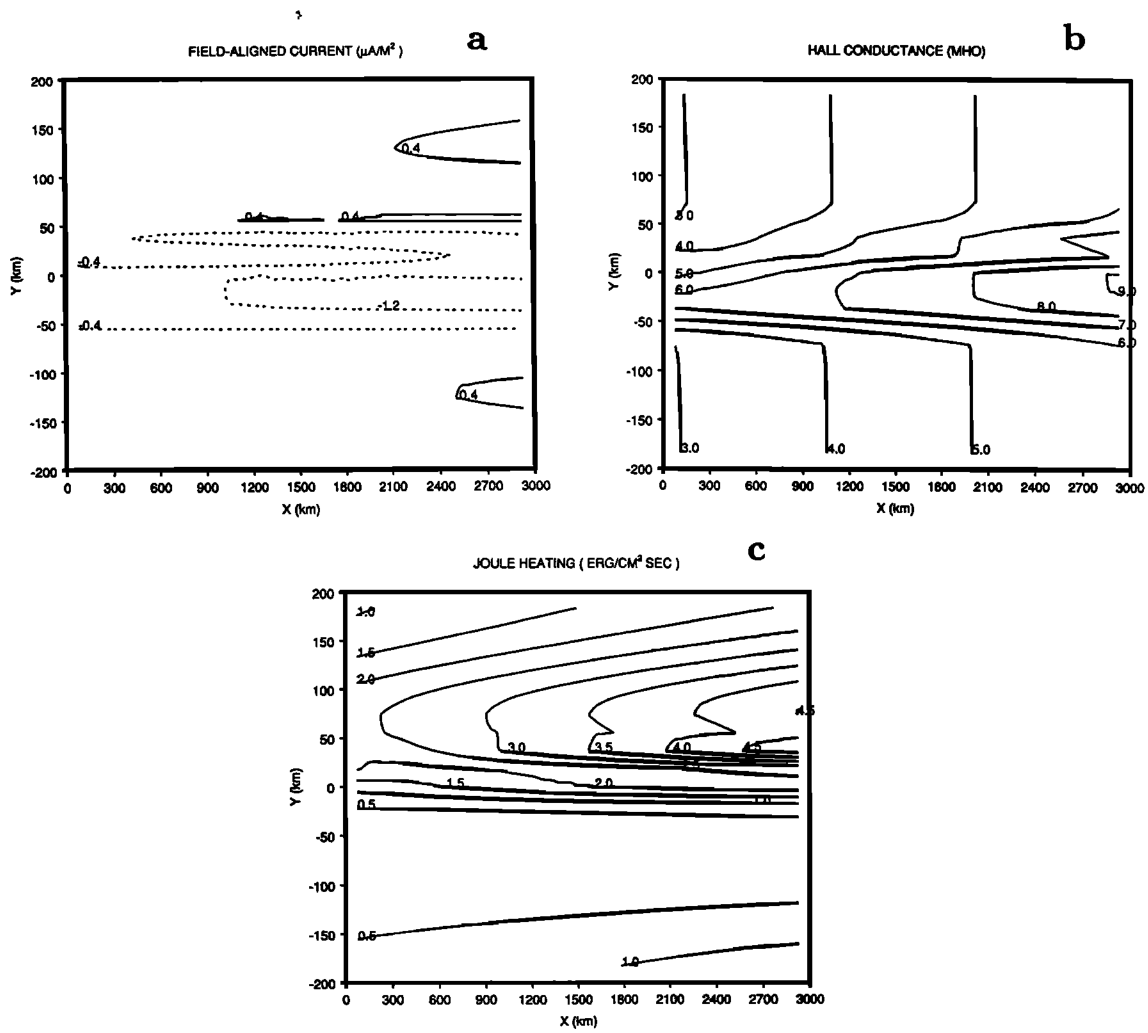

Figure 5. Distributions of (a) field-aligned currents, (b) Hall conductance, and (c) Joule heating rate, at the asymptotic steady state for the same solar and seasonal conditions as Figure 3, but with a sunward convection.

high ionospheric background conductance allows the magnetospheric current to be more freely closed in the ionosphere, which acts to smooth localized discrete structures and leads to wider arcs. In this case, the Hall conductance is enhanced by a factor of only 1.5 at the dayside and about 2 at the nightside. The Joule heating distribution in this case is more spread and less structured than that in the case of winter and solar minimum.

3.3. Case 3: Winter, Solar Maximum, Antisunward Convection

The ionospheric conditions and magnetospheric driver for this case are the same as those for case 1, except the solar condition which is solar maximum here instead of solar minimum as in case 1. According to the results of the conductivity model, now the ionospheric background Hall conductance linearly increases from 0.4 mho at the nightside polar cap to 2.6 mhos at the dayside polar cap, which mimics the winter and solar maximum conditions.

Figure 4 shows the asymptotic features of the arcs for winter and solar maximum conditions. One of the interesting features of the arcs in this case is that there is neither a simple single smooth arc nor typical multiple arcs. It starts with a single arc at the dayside and gradually changes to an arc with multiple structures. At the far end of the nightside regions, the dynamical process of polar cap arcs is blocked, and no arc developed. Bearing in mind the results of case 1 and 2 discussed above, it is not hard to understand these spatial features of polar cap arcs. It is the ionospheric background conductance that plays an active role in the M-I coupling process of the formation of polar cap arcs. A high conductance favors the appearance of a single arc, while a low conductance favors the appearance of multiple arcs, and an extremely low conductance may block the dynamical development of the arcs. Specifically, the favorable range of Hall conductivity for multiple arcs is from 0.5 mho to 1.5 mhos. Below 0.5 mho there will be no observable arc, and above 1.5 mhos there will be just a single smooth arc.

Another interesting feature for the case of winter and solar maximum is strong Joule heating associated with polar cap arc processes. For this case, the maximum Joule heating rate goes beyond 7 ergs cm^{-2} s^{-1}. Again, the strongest Joule heating regions are not collocated with the arcs, but instead are located at the edge of the polar cap arcs.

We also ran the case of summer and solar maximum with antisunward convection (not shown here). A wide and smooth single arc was developed in the simulation. Hall conductance and Joule heating distributions are also not structured.

3.4. Case 4: Summer, Solar Minimum, Sunward Convection

When studying the effects of seasonal and solar conditions on the features of polar cap arcs, the influence of large-scale ionospheric background convection cannot be completely excluded. This is because the plasma convective effect can modify the conductivity enhancement caused by the polar cap arc precipitation, thereby modifying the features of the arcs.

Figure 5 shows the results of the case in which the seasonal and solar conditions are the same as those in case 2, but a sunward convection is used instead of an antisunward convection. By comparing the features of polar cap arcs shown in Figure 5 with those in Figure 3, it can be seen that the effect of a sunward convection is actually to reduce the intensity of polar cap arcs. The effect of the large-scale convection on the enhancement of conductivity, and thereby on the formation of polar cap arcs, can be explained in the following: For an antisunward convection, enhanced electron populations are convected antisunward into regions of reduced conductivity and so enhance the conductivity effect on the M-I coupling process of the arcs. In contrast, a sunward convection moves the same enhanced electron populations into regions of larger conductivity, thereby reducing its effect on the M-I coupling process. It can also be seen from the comparison that a sunward convection tends to reduce the spatial gradients of both the conductance and Joule heating rate.

4. Summary and Conclusions

By using an M-I coupling model of polar cap arcs [*Zhu et al.*, 1993], in which the electrodynamics of polar cap arcs is treated self-consistently in the frame of the coupled M-I system and the active role of the ionosphere is specifically stressed, we conducted a systematic model study of the effects of ionospheric background conductivity on the formation of polar cap arcs. The main results can be summarized as follows:

1. The ionospheric background conductivity can dynamically affect the formation of polar cap arcs through the associated M-I coupling processes.

2. A very low conductivity can block the formation of the arcs, high conductivity conditions favor the appearance of a single arc, and the favorable range of

Hall conductivity for multiple arcs is from 0.5 mho to 1.5 mhos.

3. The model predicts that for winter and solar minimum, extended polar cap arcs crossing the whole polar cap should not be common. Typically, polar cap arcs are narrower and more structured for winter and wider and less structured for summer.

4. In the precipitation regions of polar cap arcs, conductivity can be enhanced by a factor of more than 10 for winter and solar minimum conditions and by a factor of 1.5-2 for summer and solar maximum.

5. Winter and solar maximum conditions favor the appearance of polar cap arcs with strong Joule heating. For all seasonal and solar conditions, strong Joule heating regions are not colocated with polar cap arcs and always center at the edge of the arcs.

6. A sunward convection tends to reduce the intensity of the arcs.

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