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THE INFLUENCE OF CONDUCTIVITIES
CONSISTENT WITH FIELD-ALIGNED
CURRENTS ON HIGH-LATITUDE
CONVECTION PATTERNS

L.G. Blomberg and G.T. Marklund

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Department of Plasma Physics
The Royal Institute of Technology
S-100 44 Stockholm, Sweden

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Department of Plasma Physics

The Royal Institute of Technology, Stockholm, Sweden

Abstract. The influence on the high-latitude ionospheric convection of conductivities associated with upward field-aligned currents is investigated. Potential patterns are calculated from a given distribution of field-aligned currents and a conductivity model. The resulting patterns are shown to be modified considerably by including a coupling term between the conductivity and the field-aligned current in the conductivity model. The clockwise rotation of the entire potential pattern is reduced when the conductivity enhancement coincides with the regions of upward field-aligned current. Also, the electric field within these regions turns out to be rather insensitive to changes in the magnitude of the current. In regions of downward current or when the current-dependent conductivity is excluded there is on the other hand an almost linear relationship between current and electric field. Although the particles producing the conductivity enhancement may not be the same as those carrying the major part of the field-aligned current it is clear from observations that there is a positive correlation between upward current and conductivity. Therefore, the simple relationship used in this study is believed to reflect rather well the principal features of the current-conductivity coupling, which is of importance to the modelling of ionospheric electrodynamics.

1. Introduction

The magnetosphere-ionosphere system, is a system of strong electrodynamic interaction. The conducting layers of the ionosphere often act as a load on the magnetospheric generators, but may for localized ionospheric regions also act as generators during substorms. Reliable models of the coupling between field-aligned currents, the ionospheric electric field and the ionospheric conductivity are important to the understanding of the characteristics of this system. In such models two of the quantities are specified and the third is calculated from these. They can for instance be used to calculate (average) global convection patterns by using a measured (average) distribution of field-aligned currents [e.g., Iijima and Potemra, 1976] and a conductivity model as input. Another possibility is to derive the field-aligned current from assumed potential and conductivity distributions. Numerous models of these kinds have been developed during the past decade [e.g., Nisbet *et al.*, 1978; Kamide and Matsushita, 1979a,b; Gizler *et al.*, 1979; Bleuler *et al.*, 1982]. The method of assuming a field-aligned current distribution and a conductivity model and from these calculate the potential distribution has also been used by several authors to investigate some principal features of the high-latitude electrodynamics, such as the typical clockwise rotation of the polar cap electric field [e.g., Nopper and Carovillano, 1979; Yasuhara *et al.*, 1983].

Since the field-aligned currents close in the auroral ionosphere and the ionospheric current and electric field are related through the conductivity tensor, the conductivity is a crucial parameter in models of this kind. (The importance of the conductivity model has been discussed by, e.g., Reiff [1984]). However, the models developed so far generally employ a conductivity distribution which is not consistent with the field-aligned current.

The downward field-aligned electron flow can for simplicity be split into two characteristic parts; one of low energy, responsible for a large part of the downward particle flux, and often also for a significant part of the net upward field-aligned current (cf. Section 4), and one of higher energy, more efficient in producing E-layer ionization. Although there is no simple relationship between these two parts, an enhancement of the upward field-aligned current is usually accompanied by an

enhancement of the ionization, showing a positive correlation between the field-aligned current and the conductivity. This correlation is most pronounced on the nightside of the ionosphere. To obtain a realistic global conductivity distribution it is considered important to take this interdependence between field-aligned current and ionospheric conductivity into account [e.g., Vickrey *et al.*, 1981; Robinson *et al.*, 1985].

The present work is part of a larger study with the aim to develop methods to derive “instantaneous” pictures of the auroral electrodynamics on a global scale from satellite measurements. The numerical model used to calculate the potential is essentially the same as the one used by Marklund *et al.* [1987a,b], who reported the first results from this larger study. (A detailed description of the model is found in Blomberg and Marklund [1988].) One important feature in the conductivity model used by Marklund *et al.* [1987a,b] was the coupling term between field-aligned current and conductivity. In the present paper we investigate the influence of this term on the high-latitude ionospheric convection patterns. Since our major aim is to clarify the principal effects of such an additional coupling term, we have for convenience used a somewhat idealized current model. The method to obtain “instantaneous” global potential distributions is illustrated by Marklund *et al.* [1987a], using as input a field-aligned current distribution inferred from and calibrated against Viking satellite data, and Marklund *et al.* [1987b] using input data calibrated against Viking as well as DMSP/F7 satellite data.

Although it is still an open question whether the magnetospheric source of the ionospheric convection electric field is best described by a constant current or a constant voltage generator, we have chosen in this study to treat the field-aligned current as the driving term for several reasons. Since the field-aligned current (as a first approximation) is confined to a limited region of the ionosphere (the auroral oval) it is relatively easy to find illustrative current distributions for this kind of study. Furthermore, using the current as input also implies that the conductivity distribution can be determined from input data. This approach is also believed to be the most suitable one for studies of the instantaneous electrodynamical behaviour of the magnetosphere-ionosphere system.

The model is described briefly in Section 2. Potential patterns for a symmetrical current distribution and currents enhanced in various ways are presented in Section 3. In Section 4, the assumptions and results are discussed in some detail.

2. Model

The calculation of the potential distribution has been performed using spherical (surface) coordinates, where the θ -coordinate corresponds to magnetic colatitude and the ϕ -coordinate is related to magnetic local time (MLT).

The basic equation relating the height-integrated ionospheric (horizontal) current ($\mathbf{J}_0$) to the ionospheric electric field ($\mathbf{E}_0$) can be written

$$\mathbf{J}_0 = \boldsymbol{\Sigma} \cdot (\mathbf{E}_0 + \mathbf{v}_n \times \mathbf{B}) \quad (1)$$

where $\mathbf{E}_0 + \mathbf{v}_n \times \mathbf{B}$ is the electric field in the frame of the neutral wind, $\mathbf{v}_n$. The electric field will be presented in the frame where $\mathbf{v}_n = 0$ (i.e., $\mathbf{J}_0 = \boldsymbol{\Sigma} \cdot \mathbf{E}_0$). This can be approximately identified with an Earth-fixed (corotating) frame. $\boldsymbol{\Sigma}$ is the height-integrated horizontal conductivity tensor

$$\boldsymbol{\Sigma} = \begin{bmatrix} \Sigma_{\theta\theta} & \Sigma_{\theta\phi} \\ \Sigma_{\phi\theta} & \Sigma_{\phi\phi} \end{bmatrix} \quad (2)$$

whose components (except close to the magnetic equator) are given by

$$\Sigma_{\theta\theta} = \Sigma_P / \sin^2 I \quad (3a)$$

$$\Sigma_{\theta\phi} = -\Sigma_{\phi\theta} = \Sigma_H / \sin I \quad (3b)$$

$$\Sigma_{\phi\phi} = \Sigma_P \quad (3c)$$

where I is the inclination of the geomagnetic field ($\mathbf{B}$), (approximated by a dipole in this study), and Σ_P and Σ_H are the height-integrated Pedersen and Hall conductivities respectively.

In a steady-state situation the total current (ionospheric and field-aligned) should be divergence-free. Denoting by $j_{\parallel}$ the field-aligned current flowing into the ionosphere this can be expressed as

$$\nabla \cdot \mathbf{J}_0 = j_{\parallel} \cdot \sin I \quad (4)$$

(1), (4) and the introduction of the electrostatic potential Φ , ($\mathbf{E}_0 = -\nabla\Phi$) yield:

$$\nabla \cdot (\Sigma \nabla \Phi) = -j_{\parallel} \cdot \sin I \quad (5)$$

This equation forms the basis for solving (numerically) for the electrostatic potential once the field-aligned current and the conductivity are specified.

The boundary condition used in the calculation was that $\Phi(\theta = 90^\circ, \phi) = 0$; i.e., the magnetic equator is an equipotential surface.

The Region 1 and Region 2 field-aligned currents in this idealistic model were taken to be located at 70° to 74° and at 66° to 70° magnetic latitude, respectively, in reasonable agreement with the measured average location and extent, reported by Iijima and Potemra [1976]. The observed offset of these regions towards the nightside has been neglected. The longitudinal distribution of the currents was specified at 72° and 68° respectively and the shape is shown in Figure 1. In this study different ratios between the peak values for the respective regions as well as for the dawn and dusk sides will be used (cf. Figures 3–4). The latitudinal variation follows a parabola in each region (Figure 2).

The conductivities are represented by

$$\Sigma_P = \sqrt{\Sigma_{0P}^2 + \Sigma_{gP}^2 + \Sigma_{UVP}^2 + \Sigma_{j_{\parallel}P}^2} \quad (6a)$$

$$\Sigma_H = \sqrt{\Sigma_{0H}^2 + \Sigma_{gH}^2 + \Sigma_{UVH}^2 + \Sigma_{j_{\parallel}H}^2} \quad (6b)$$

The root-sum-square relation is employed since the various processes giving rise to the conductivity take place roughly within the same altitude range, and hence, as discussed by, e.g., Wallis and Budzinski [1981] and Reiff [1984], addition of the ionization rates (proportional to n_e^2) gives a far more accurate estimate of the total conductivity (proportional to n_e) than a direct summation of the different conductivity contributions.

Σ_0 is a background term having a constant low value, representing the contribution from cosmic radiation and galactic EUV.

Σ_g represents an average auroral zone background conductivity given by

$$\Sigma_g = \Sigma_{g0} \cdot \exp\left(-\frac{(\theta - \theta_0)^2}{\theta_{g0}^2}\right) \quad (7)$$

Here $\theta_0 = 20^\circ$ (70° magnetic latitude) and $\theta_{g0} = 4^\circ$ for both the Pedersen and Hall component.

Σ_{UV} describes the part of the conductivities which is produced by solar EUV-radiation. It is given here by

$$\Sigma_{UV} = \alpha \cdot \sqrt{\cos \chi} \quad (8)$$

where χ is the solar zenith angle.

$\Sigma_{j_{\parallel}}$ represents the conductivity enhancement produced by precipitating electrons associated with upward field-aligned currents as discussed above (Section 1). The total ionization produced by these electrons is determined primarily by their energy flux. In the present study the relation between current and conductivity has been taken as

$$\Sigma_{j_{\parallel}} = \begin{cases} k(MLT) \cdot |j_{\parallel}|, & \text{for } j_{\parallel} \text{ upward} \\ 0, & \text{for } j_{\parallel} \text{ downward} \end{cases} \quad (9)$$

The proportionality factor $k(MLT)$ has a lower value on the dayside than on the nightside to account for the fact that the energy spectrum of the downward field-aligned electron flow is softer on the dayside. In the mid-dawn and mid-dusk sectors there is a smooth transition between the high nightside and the low dayside values. Upflowing particles usually have thermal energies and thus deplete rather than enhance the ionospheric ionization. This effect is, however, negligible in the E-layer [cf. Block and Fälthammar, 1968] where the ionization contributes significantly to the conductivity. Although downward currents may contribute to the ionospheric ionization through precipitation of protons associated with the diffuse aurora, the contribution by protons to the total precipitated particle energy is estimated to be at most 10 to 20 per cent [Hultqvist, 1973]. Some ionization may also be produced by precipitating electrons within the regions of downward current. These contributions are accounted for by the auroral zone background term Σ_g .

3. Results

For each of a series of different field-aligned current distributions, the electric potential distribution has been calculated using the conductivity model described

above but with two different sets of parameter values. For the first case the coupling term between the field-aligned current and the conductivity, $\Sigma_{j_{\parallel}}$, has been set to zero, so that the auroral oval is represented simply by the azimuthally symmetrical gaussian shaped term Σ_g . For the second case the current-conductivity coupling has been taken into account. The peak value of Σ_g is in this latter case, however, reduced so that in regions of upward current the major contribution to the conductivity comes from $\Sigma_{j_{\parallel}}$. In this case Σ_g accounts for the diffuse auroral contribution rather than represents an auroral zone average conductivity (as in the former case).

The potential distribution resulting from a symmetrical field-aligned current distribution (Figure 3a), for which the Region 1 (poleward) to Region 2 (equatorward) current ratio is 3:1, and an azimuthally symmetrical conductivity (i.e., unrelated to the current), is shown in Figure 3b. It is presented in a magnetic latitude - local time system. The polar cap electric field is rotated approximately 3 hours (45°) clockwise from the dawn-dusk direction. Apart from this rotation the potential pattern is highly symmetrical, with the morning and evening cells being of equal size. The potential distribution obtained using the same field-aligned current as above, but the conductivity model including $\Sigma_{j_{\parallel}}$, is presented in Figure 3c. The rotation of the polar cap electric field is here reduced to about 1.5 hour (22°). The zero potential curve (connected to the equatorial boundary) is slightly shifted towards dusk. The magnitude of the potential maximum on the morningside (related to a downward Region 1 current) exceeds the potential minimum on the eveningside (related to an upward Region 1 current) by about 50 per cent. In other words, the electric field in the morning cell is on the average significantly stronger than the field in the evening cell, which was not the case when the coupling term was excluded.

The potential patterns computed from a symmetrical field-aligned current where the Region 1 to Region 2 current ratio is 3:2 (Figure 3d), are shown in Figure 3e ($\Sigma_{j_{\parallel}}$ excluded) and Figure 3f ($\Sigma_{j_{\parallel}}$ included). For this current model the polar cap electric field is more rotated than before. Using the symmetrical conductivity model a clockwise rotation of about 4 hours is obtained. The potential pattern is,

as for the previous current model, symmetrical with equal morning and evening cells. When using the current-related conductivity, the polar cap field rotation is reduced to approximately 3 hours. The potential maximum exceeds the minimum by 25 per cent and the east-west electric field in the auroral zone is significantly stronger on the dawnside than on the duskside. Thus, as in the previous example the electric field within the morning cell is stronger than the evening cell field.

Figure 4a shows a field-aligned current where the Region 1 to Region 2 ratio is 5:2 and the eveningside Region 1 current exceeds the morningside one by 50 per cent. The potential pattern obtained by neglecting $\Sigma_{j\parallel}$ is shown in Figure 4b. The polar cap electric field is rotated clockwise approximately 3 hours. As expected the evening cell is dominating. The potential pattern derived from this current distribution when $\Sigma_{j\parallel}$ is included in the conductivity is presented in Figure 4c. Here, the polar cap field is seen to be less rotated, about 2 hours. The polar cap potential drop has increased some 40 per cent. Furthermore, the east-west electric field in the auroral zone is significantly stronger on the morning- than on the eveningside, as opposed to the field obtained using the azimuthally symmetrical conductivity.

The field-aligned current shown in Figure 4d is similar to the one used in the previous example, except that in this case the Region 1 morningside current exceeds the Region 1 eveningside current by 50 per cent. This current distribution was used to calculate the potential patterns presented in Figure 4e ($\Sigma_{j\parallel}$ excluded) and Figure 4f ($\Sigma_{j\parallel}$ included). In this case the polar cap rotation is almost the same as above. However, the polar cap potential drop is about 80 per cent higher when using the current-related conductivity, in contrast to the previous case where the increase was merely 40 per cent. For both conductivity models the east-west auroral zone electric field is strongest on the morningside, also contrasting the previous case.

4. Discussion

Realistic models of the coupling between field-aligned currents and the ionospheric electric field distribution are needed for a more complete understanding of the characteristics of the auroral electrodynamics on a global scale, as well as the

magnetosphere-ionosphere interaction. A central parameter in these models is the ionospheric conductivity. Discrete aurora has been found to appear mostly within the regions of upward field-aligned current, while the diffuse aurora is often found to be connected with regions of downward current [e.g., Kamide and Akasofu, 1976]. Furthermore the conductivity has been observed to peak in regions of discrete auroral activity [e.g., Marklund *et al.*, 1983], indicating a close relationship between ionospheric conductivity and upward field-aligned current. However, the models developed so far generally neglect this relationship between current and conductivity, with a few exceptions [e.g., Mishin *et al.*, 1986; Marklund *et al.*, 1987a,b]. In this study we have concentrated on the principal effects of taking this relationship into account, which is seen to cause significant modifications to the ionospheric convection patterns.

As discussed above (Section 1) the energy spectrum of the downgoing electrons can be thought of as split into two characteristic parts. One is of high energy, responsible for the aurora and ionization production at E-layer heights, contributing considerably to the height-integrated ionospheric conductivity. The other is of lower energy and produces ionization mainly at higher altitudes and thus gives less contribution to the height-integrated conductivity. These low-energy electrons may, however, carry a large fraction of the field-aligned current.

If the electrons have been accelerated by a magnetic field-aligned potential drop so that the primary particles are of high energy, the low-energy part of the spectrum may arise from (upgoing) secondary (or tertiary, etc.) and backscattered electrons, which are reflected and forced to precipitate by the parallel electric field, as proposed in the model by Evans [1974]. In this case the low-energy electrons do not carry any net field-aligned current (or a small downward current arising from upgoing electrons having sufficient parallel energy to overcome the potential barrier presented by the parallel electric field) and hence, the particles carrying the current are the same as those producing the ionization. Observations indicate, however, that the downcoming flux usually exceeds the upgoing flux at low energies significantly [cf. e.g., Whalen and Daly, 1979]. Thus, the low-energy particles seem to carry a net upward current which may account for a sizeable fraction of the total

field-aligned current.

From rocket observations in the vicinity of auroral activity, Lyons *et al.* [1979] found that when a field-aligned acceleration voltage (V) could be inferred from the electron spectra, the net downward electron energy flux generally varied as V^2 while the net upward field-aligned current was generally proportional to V . The same relations were obtained (for all relevant values of V) in the model by Fridman and Lemaire [1980]. Since Σ_P is roughly proportional to the square-root of the electron energy flux (cf. e.g., Harel *et al.* [1981]) the relations above imply a direct proportionality between Σ_P and $j_{\parallel}$.

Although an exact picture of the precipitation mechanisms is not at hand at present, observations reveal that an enhancement of the upward field-aligned current is usually accompanied by an enhancement of the E-layer ionization, indicating an intimate coupling between the current and the ionospheric conductivity. This justifies the simple relationship between Σ_P and $j_{\parallel}$ used in this study, regardless of the actual acceleration process.

The values of the various conductivity parameters were chosen in the following way: The coupling factors between current and conductivity (k) were chosen to be consistent with the currents and conductivities calculated from magnetometer and particle flux data obtained on the Viking and DMSP/F7 satellites [cf. Marklund *et al.*, 1987b]. The values used for α were the same as those used by, e.g., Vickrey *et al.* [1981]. In this study we have, however, assumed a mid-winter solar declination, in order to minimize the polar cap conductivity noon-midnight gradient which is known to squeeze the convection streamlines towards dawn [Atkinson and Hutchison, 1978]. Finally, Σ_0 and Σ_{g0} were chosen so that a realistic average field-aligned current distribution should give a total conductivity which is in reasonable large-scale agreement with empirical models of the high-latitude conductivity [e.g., Wallis and Budzinski, 1981]. As pointed out by, e.g., Reiff [1984] empirical conductivity models based on satellite data must be used with care. Since they require at least six months of data for global coverage, they represent smeared out averages reflecting the continuously changing location of the aurora (and field-aligned currents) rather than a typical instantaneous conductiv-

ity distribution. However, they are considered adequate for the present purpose of determining values for the coefficients of the background terms in the expression for the total conductivity.

The convection patterns presented in Figure 3 were obtained using symmetrical distributions of the field-aligned current. These current distributions are idealized, but they are reasonable first approximations (regarding the shape and relative magnitudes between Region 1 and 2) to an average quiet situation (Figure 3a) and an average disturbed situation (Figure 3d). The field-aligned current distributions used to calculate the convection patterns shown in Figure 4 were unsymmetrical with a non-zero net current. They were chosen to illustrate the effects of current-conductivity coupling rather than to represent any real geophysical situation.

Several earlier studies have found a clockwise rotation of the polar cap electric field (from the nominal dawn-dusk direction). Yasuhara *et al.* [1983] obtained such a rotation depending on the degree of auroral zone conductivity enhancement. Nopper and Carovillano [1979] demonstrated that as the Region 1 to Region 2 field-aligned current ratio decreases the field rotation will increase. In both these studies the conductivity distribution used to represent the auroral oval was azimuthally symmetrical.

Any ionospheric conductivity distribution has to account for contributions from discrete as well as diffuse auroral precipitation. Whereas the conductivity arising from the diffuse precipitation may be approximated by an azimuthally symmetrical expression, the contribution from discrete precipitation may not. When a current-conductivity coupling term is introduced in the conductivity model, the azimuthally symmetrical term might be retained, but its magnitude should of course be reduced since in this case it should account for the contribution from diffuse precipitation only.

One finding in the present study is that the gaussian-shaped azimuthally symmetrical auroral zone average conductivity seems to influence the electric field rotation more than the conductivity part coupled to the field-aligned current which represents active auroral precipitation. Hence, using an azimuthally symmetrical average conductivity, which underestimates the discrete part and overestimates

the diffuse part of the precipitation contribution, will result in an electric field whose rotation is also overestimated. Moreover, any kind of conductivity distribution which is inconsistent with the field-aligned current might lead to erroneous results concerning the orientation of the polar cap electric field.

Another result in the present study is the tendency for the convection cell related to a net downward current (the morning cell) to expand slightly and contain a stronger electric field, while the convection cell related to a net upward current (the evening cell) diminishes slightly and contains a weaker electric field, when the term $\Sigma_{j_{\parallel}}$, which couples the conductivity to the field-aligned current, is taken into account. Qualitatively this is easily understood. In all models of the field-aligned current used in this study the Region 1 current exceeds the Region 2 current considerably. Hence, the convection cells are controlled primarily by the Region 1 currents (and conductivities). The Region 1 current is downgoing on the morningside and upgoing on the eveningside. Thus, the morning convection cell is positive and since the conductivity is unaffected by the Region 1 current, the electric field depends linearly on the ionospheric current which is closely connected to the field-aligned current. On the other hand, the evening convection cell is negative and due to the field-aligned current – conductivity coupling the electric field is very insensitive to variations in the current. This is because an increase of the ionospheric current is accompanied by a corresponding enhancement of the conductivity.

5. Summary and conclusions

The influence on the high-latitude potential distribution of using a more realistic conductivity model which includes a current–conductivity coupling term, has been investigated. The main results of such a coupling are summarized below.

- 1) The clockwise rotation of the polar cap electric field is less pronounced.
- 2) Convection cells related to upward current contract slightly, while cells connected to downward current expand slightly.
- 3) The electric field is significantly weaker in regions of upward current than in regions of downward current.

- 4) There is an overall modification of the high-latitude convection pattern which is essential to the modelling of auroral electrodynamics and magnetosphere-ionosphere interaction.

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Fig. 1 Distribution of the field-aligned currents in magnetic local time (MLT).

Fig. 2 Latitudinal distribution of the field-aligned currents.

Fig. 3 Field-aligned currents (a,d) and potential distributions calculated from these currents, neglecting current-conductivity coupling (b,e) and including such coupling (c,f) for two different cases of symmetrical current distributions.

Fig. 4 Field-aligned currents (a,d) and potential distributions calculated from these currents, neglecting current-conductivity coupling (b,e) and including such coupling (c,f) for two different cases of non-symmetrical current distributions.

The Royal Institute of Technology, Department of Plasma Physics
S-100 44 Stockholm, Sweden

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Key words: Field-aligned currents, Ionospheric conductivities, Ionospheric convection, Ionospheric modelling