THE IMPORTANCE OF CONDUCTIVITY GRADIENTS IN GROUND-BASED FIELD-ALIGNED CURRENT STUDIES

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ABSTRACT

Magnetosphere-ionosphere coupling is achieved primarily through magnetic field-aligned currents. Such currents are difficult to measure directly and are usually inferred from satellite magnetometer recordings or from ground-based measurements of the divergence of ionospheric electric fields. The latter technique requires a knowledge of the ionospheric conductance distribution. Although it is possible to obtain the ionospheric electric field distribution over large spatial areas with good temporal resolution from coherent backscatter radars, these instruments cannot measure conductivity. Since the equation for computing field-aligned currents explicitly requires the gradient in conductance to be known, the use of statistically averaged models is excluded for case studies. If a dense enough array of magnetometers is available, these data may be used in combination with radar data to produce a measured conductance distribution within the overlapping fields of view. This has been done for data obtained in northern Scandinavia. Comparing field-aligned currents, computed with and without knowing the ionospheric conductance distribution, shows that gradients in conductance can not be ignored, even for quiet geomagnetic conditions.

INTRODUCTION

In this study, data is used from the Scandinavian Twin Auroral Radar Experiment (STARE) (Greenwald et al., 1978) for ionospheric plasma flows, the Scandinavian Magnetometer Array (SMA) (Küppers et al., 1979) for geomagnetic field disturbances, and an all-sky auroral TV imager, located at Skibotn in Norway (69.36^o N, 20.36^o E). STARE gives two-dimensional maps of the E-region plasma flow with good spatial (20 x 20 km) and temporal (10 sec) resolution over a large area (13.5-26.0^o E, 67.6-72.6^o N) when the ionospheric electric field exceeds a threshold of ~15 mV/m (cf. Kosch and Nielsen, 1995). Comparisons with incoherent scatter radar measurements show that the STARE plasma flows may be converted, with a non-linear correction, into equivalent ionospheric electric fields (Nielsen and Schlegel, 1985). The SMA consists of a two-dimensional array, giving equivalent current distributions, with a spacing of ~120 x 120 km within STARE's field of view, operating with 10 sec time resolution.

Since the ground magnetic field disturbance depends on the height-integrated horizontal ionospheric current density (**J**), and because the ionospheric electric field (**E**) is connected to **J** by Ohm's law via the Hall ($\mathbf{\Sigma_H}$) and Pedersen ($\mathbf{\Sigma_P}$) conductances, it is possible to estimate the two-dimensional conductance distribution of the ionosphere if the two-dimensional equivalent current ($\mathbf{J_{eq}}$) and **E** distributions are known (Baumjohann et al., 1981; Inhester et al., 1981; Opgenoorth et al., 1983a, 1983b). Inhester et al. (1992) showed that this was uniquely possible in many cases with an estimate of the Hall to Pedersen conductance ratio (α). Amm (1995) has implemented this concept, called the "method of characteristics" and has made it available for use in spherical

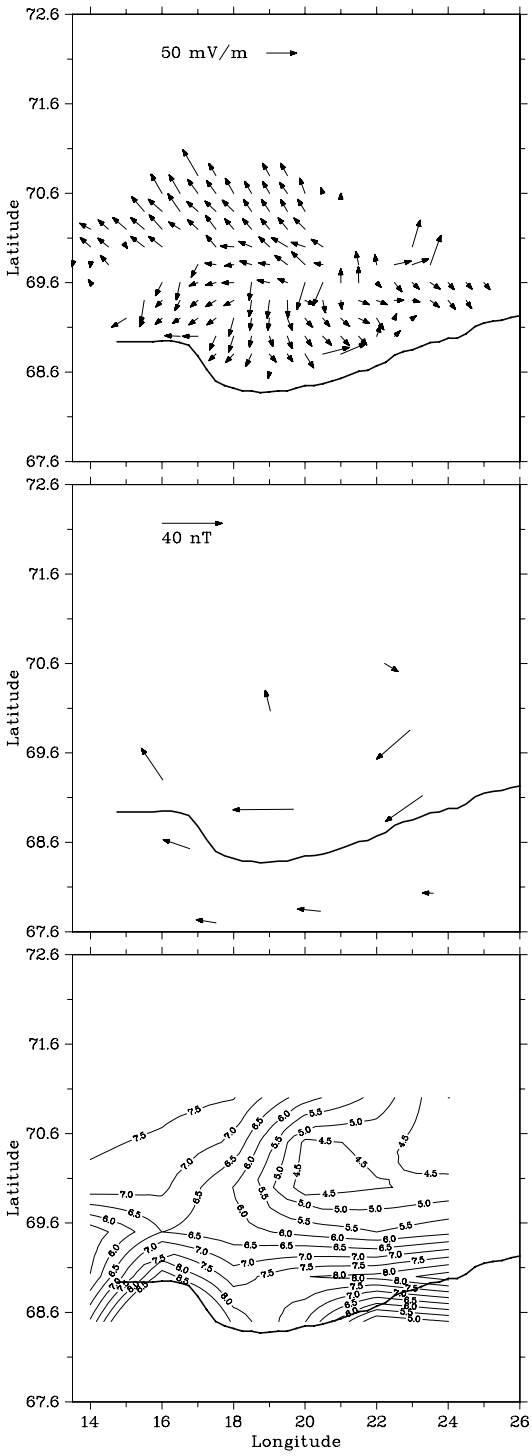

Fig. 1. STARE horizontal electric fields (top panel), SMA horizontal equivalent currents (middle panel), and the quantitative Hall conductance distribution (bottom panel) using the method of characteristics assuming α = 1.1.

coordinates (Amm, 1998). Only a rough estimate of α is needed, since the influence of the ratio on the final results is uncritical (Amm, 1995).

THEORY

We derive the equation for magnetic field-aligned currents (FACs) in the ionosphere to illustrate the importance of conductance gradients. Ohm's law in the ionosphere is:

$$\mathbf{J} = \Sigma_P \mathbf{E} + \Sigma_H (\hat{\mathbf{B}} \times \mathbf{E}) \qquad (1)$$

where **J** is the current vector, **E** the electric field vector, $\mathbf{\Sigma_P}$ and $\mathbf{\Sigma_H}$ are the Pedersen and Hall conductances, respectively, and $\hat{\mathbf{B}}$ is the unit vector in the direction of the earth's magnetic field. Assuming a vertical magnetic field with $\hat{\mathbf{B}}$ pointing along the Z-axis, $\hat{\mathbf{z}}$ being the unit vector pointing downwards, the FAC is given by:

$$J_{\|} = \text{div}\ \mathbf{J} = \text{div}\ (\Sigma_P \mathbf{E}) + \text{div}\ (\Sigma_H (\hat{\mathbf{z}} \times \mathbf{E})) \qquad (2)$$

Expanding Eq. 2,

$$J_{\|} = \Sigma_P\ \text{div}\ \mathbf{E} + \nabla\Sigma_P \bullet \mathbf{E} + \nabla\Sigma_H \bullet (\hat{\mathbf{z}} \times \mathbf{E}) + \Sigma_H\ \text{div}\ (\hat{\mathbf{z}} \times \mathbf{E}) \qquad (3)$$

The last term of Eq. 3 is zero because:

$$\text{div}\ (\hat{\mathbf{z}} \times \mathbf{E}) = \mathbf{E} \bullet \text{rot}(\hat{\mathbf{z}}) - \hat{\mathbf{z}} \bullet \text{rot}(\mathbf{E})$$

where $\mathbf{E} \bullet \text{rot}(\hat{\mathbf{z}}) = 0$ by definition and $\hat{\mathbf{z}} \bullet \text{rot}(\mathbf{E}) = 0$ since we assume that a curl-free potential electric field exists in the ionosphere. Hence:

$$J_{\|} = \Sigma_P\ \text{div}\ \mathbf{E} + \nabla\Sigma_P \bullet \mathbf{E} + \nabla\Sigma_H \bullet (\hat{\mathbf{z}} \times \mathbf{E}) \qquad (4)$$

The FAC current results from 3 terms, all of which depend on the electric field and conductance. Term 1 depends on the magnitude of the Pedersen conductance and on the divergence of the electric field, whereas terms 2 and 3 depend on the gradient of Pedersen and Hall conductance, respectively, as well as electric field strength. It is clear that assuming uniform conductances (i.e. dropping the last 2 terms of Eq. 4) may lead to considerable errors in computing FACs, since the terms relating to the conductance gradients are of the same order and can be of opposite sign to the first term in Eq. 4.

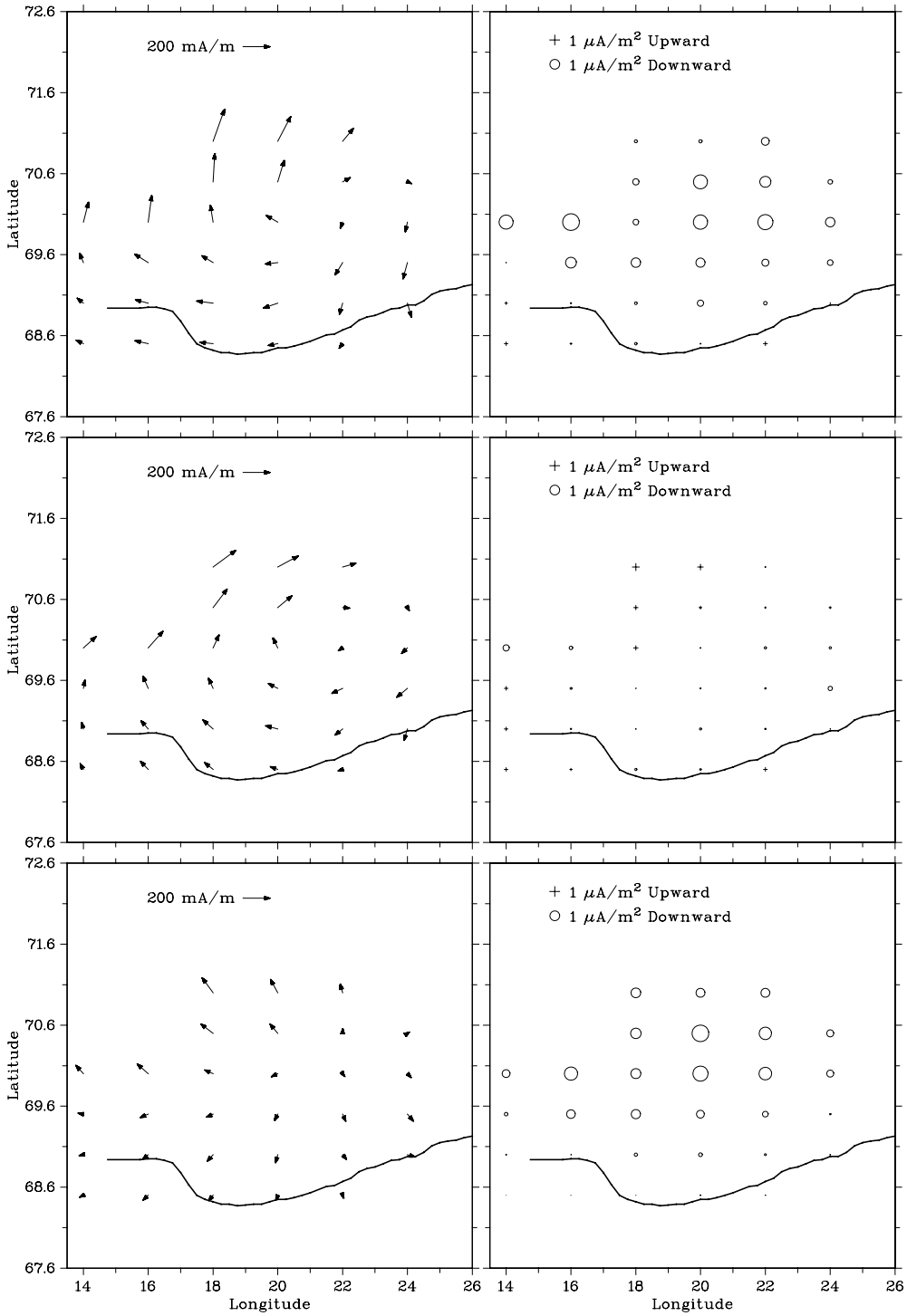

Fig. 2. The complete quantitative currents for 21:35 UT on 15 January 1980 using the method of characteristics. Total horizontal current (top left panel), Hall currents (middle left panel), Pedersen currents (bottom left panel), total field-aligned current (top right panel), field-aligned currents due to Hall currents (middle right panel), and field aligned currents due to Pedersen currents (bottom right panel) are shown.

RESULTS

The data examined here were obtained at 21:35 UT on 15 January 1980. Geomagnetic conditions were quiet with Kp = 1^+ and ΣKp = 12^- on this day. The geophysical details of this event have been studied by Kosch et al. (1998). Given the geomagnetic activity level, the most realistic Hall to Pedersen conductance ratio is taken to be α = 1.1 (cf. Schlegel, 1988).

Figure 1 shows the STARE electric field pattern (top panel), SMA equivalent current distribution (middle panel), and the quantitative Hall conductance (lower panel) resulting from the method of characteristics. The lower border of an auroral arc which was present, projected at 100 km altitude, is also shown. For the analysis, gaps in the STARE data, due to the backscatter threshold, are filled by interpolation: An algorithm that implicitly preserves a curl-free electric field is used based on a curl-free elementary vector system (Amm, 1997). The Pedersen conductance will have exactly the same distribution as the Hall conductance but is reduced in magnitude by a factor of 1.1 due to the value of α assumed above. The conductance distribution reproduces the auroral arc rather well, giving confidence in its derivation. The minimum in conductance, centered on 70.1^o latitude and 21° longitude corresponds closely to the center of the horizontal current vortex (middle panel) and the region of strongly diverging electric fields (top panel). The result shows that even under very quiet geomagnetic conditions, auroral preciptation can still produce significant conductivity gradients.

Figure 2 gives the real (not equivalent) currents extracted by the method of characteristics. Shown is the total horizontal current (top left panel), Hall currents (middle left panel), Pedersen currents (bottom left panel), total FAC (top right panel), FACs due to Hall currents (middle right panel), and FACs due to Pedersen currents (bottom right panel). The lower border of the auroral arc is also shown. The horizontal current vortex is predominately a Hall current. However, the FACs result mostly from the divergence of Pedersen currents. Possible sources of error in the analysis method include incomplete data coverage, regions in which the solution of the differential equations used to compute Σ_H are non-unique, and the estimate of α. For this event, the data coverage by both the radar and magnetometers is excellent, there are no areas in which the solution for Σ_H is non-unique, and the estimate of α is well facilitated by the very low geomagnetic activity (cf. Schlegel, 1998). Hence, the error for the FACs is estimated to be 5% at most (cf. Amm, 1995).

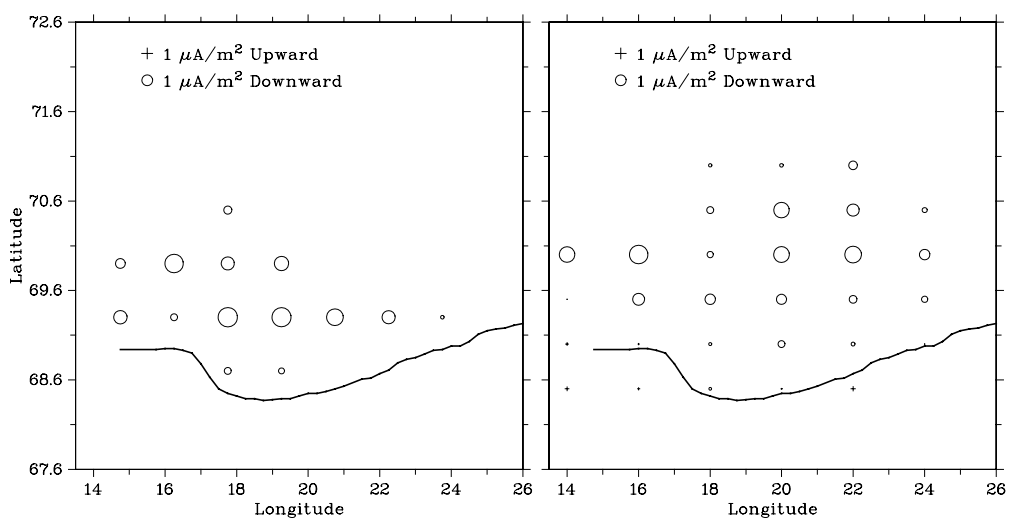

Fig. 3. Total field-aligned current ignoring (left panel) and including (right panel) conductance gradients.

Figure 3 shows the FACs computed using term 1 of Eq. 4 only (left panel) and using all terms from Eq. 4 (right panel). The left panel is derived from the STARE electric fields (Figure 1) and assuming a uniform Σ_P = 4. For a fair comparison, the electric field spatial resolution has been averaged down to 60 km. The right panel was derived by Kosch et al. (2000) and is identical to Figure 2, right top panel. Again, the lower border of the auroral arc is also shown. The geophysical relationship between the auroral arc and the downward FACs has been discussed in

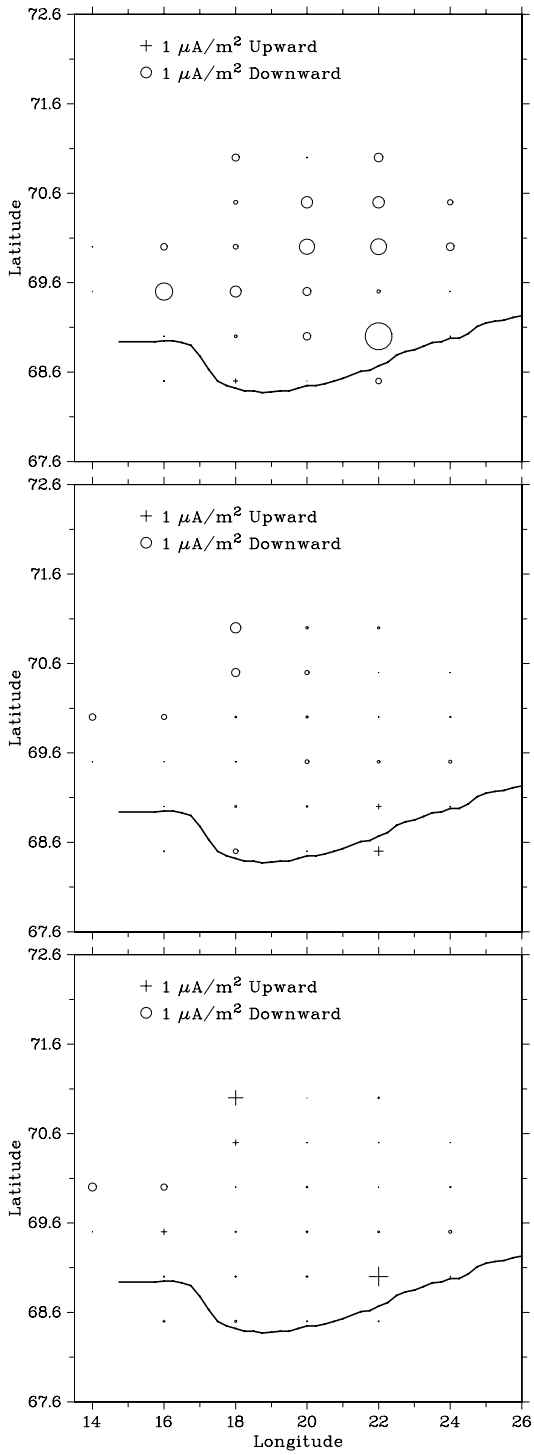

Fig. 4. The quantitative field-aligned current (FAC) components using the method of characteristics. The FAC from term 1 (top panel), term 2 (middle panel), and term 3 (bottom panel) of Eq. 4 are shown.

detail by Kosch et al. (1998, 2000). Here we concentrate on the conductance distribution (see Figure 1, bottom panel). Clearly, including the conductance gradient has significantly changed the spatial distribution of the FACs. The conductance gradients result in a spatial broadening of the FACs away from the arc. This will always be a natural consequence of auroral precipitation.

Figure 4 shows the various terms of Eq. 4 which result in the total FAC (Figure 3, right panel). Terms 1, 2 and 3 of Eq. 4 correspond to the top, middle and bottom panels of Figure 4, respectively. The lower border of the auroral arc is shown. In this case study, the downward current region results predominantly from the diverging horizontal Pedersen currents (Term 1, Eq. 4). However, especially the gradient in Pedersen conductance (Figure 4, middle panel and Term 2 of Eq. 4) is responsible for broadening of the FAC distribution.

CONCLUSIONS

We show that conductance gradients must be taken into account when computing magnetic field-aligned currents (FACs). This is especially true for auroral studies as particle precipitation will always result in conductance gradients. In this case study, the conductance gradients do not significantly alter the magnitudes of the FACs. However, a very significant spatial redistribution occurs which can affect the interpretation of geophysical events, even for quiet geomagnetic conditions.

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