# The Effects of Magnetospheric Convection on Atmospheric Electric Fields in the Polar Cap

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With 7 figures

Astract

It is well-known that a potential difference of some 30 to 300 kV exists between the dawnside and the duskside boundaries of the polar cap ionosphere. This potential difference arises from interactions between the solar wind and the magnetosphere. In this paper we examine how the resulting ionospheric electric fields map down to the lower atmosphere. It is found that such fields map down to balloon altitudes of 30—40 km with little attenuation or distortion, in agreement with several previous authors' results. It is also found that the mapping efficiency is not significantly affected by conductivity changes during auroral and polar cap absorption events, provided that these changes occur over areas larger than the scale size of electric fields involved. These results generally support the ideas behind balloon measurements of ionospheric electric fields. It also appears possible to infer magnetospheric convection electric fields from simultaneous ground-based measurements of vertical atmospheric fields at suitably spaced stations in the polar cap.

## Introduction

It is well established that large-scale electric fields exist in the earth's magnetosphere as a result of its interactions with the solar wind rushing by at supersonic speeds. Electric fields are also known to be associated with magnetospheric substorms, a process by which the magnetosphere explosively releases its energy [see, for example, *Akasofu* and *Chapman* (1972)]. These electric fields play vital roles in magnetospheric dynamics and have been a topic of great interest in recent years. These fields are typically $10^{-1}$ V/m or less, and hence difficult to measure, but a number of techniques have recently become available to measure them directly or indirectly. They include probes flown on satellites (e.g. *Heppner*, 1972; *Gurnett* and *Frank*, 1973), rockets (e.g. *Mozer* and *Bruston*, 1967; *Aggson*, 1969), and balloons (e.g. *Mozer*, 1971; *Mozer* and *Manka*, 1971), artificial injection of ion clouds (e.g. *Haerendel* and *Lüst*, 1970; *Wescott* et al., 1970) and ground-based probing techniques such as incoherent scatter radars (e.g. *Banks* et al., 1973) and whistlers (e.g. *Carpenter* et al., 1972). As a result of intensive experimental efforts utilizing these techniques, a crude first-order picture of electric field distribution in the magnetosphere and ionosphere is emerging.

At ionospheric heights and above, electrical conductivity along the geomagnetic field is normally so high that the magnetic field lines can be regarded as equipotentials. Thus, any potential difference set up between field lines in the magnetosphere is carried virtually undiminished to the lower edge of the ionosphere. It is interesting to investigate how this affects the ionospheric potential with respect to the earth and fair-weather electric fields in the lower atmosphere. In this paper, we will only consider the effects of solar-wind induced electric fields at high latitudes. We will not consider substorm-associated electric fields that are more turbulent and penetrate to middle latitudes (e.g. *Carpenter* and *Park*, 1973). Another source of electric fields not discussed here is the dynamo action in the ionospheric E region. Their effects on the lower atmosphere have been considered by *Volland* (1972).

The solar wind sets up a large-scale circulation of plasma in the magnetosphere through frictional interaction (*Axford* and *Hines*, 1961) or through field line merging (*Dungey*, 1961). We need not be concerned about the interaction mechanism here, because both mechanisms give rise to essentially the same circulation pattern in the polar ionosphere [see, for example, *Axford* (1969)]. Fig. 1 is a noon-midnight cross section of the magnetosphere illustrating *Dungey*'s field line merging model. As the solar wind encounters the magnetosphere, the interplanetary magnetic field in which the solar wind is embedded merges with the geomagnetic field as shown. Where the field lines are merged, magnetospheric plasma is swept in the anti-sunward direction by the solar wind. This is accompanied by a counterflow in the sunward direction at lower latitudes. Fig. 2 shows how this circulation pattern will appear when we look down upon the north pole. The flow lines in the figure are also equipotential lines, since the plasma flows perpendicular to electric fields according to the relationship
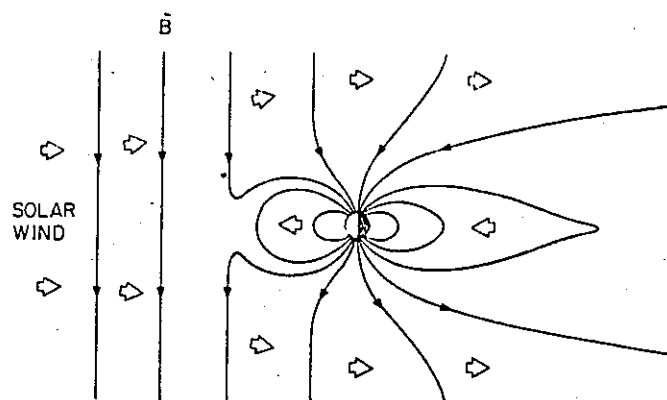
Fig. 3

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Fig. 1. A sketch illustrating *Dungey*'s (1961) model of solar wind-magnetosphere interaction
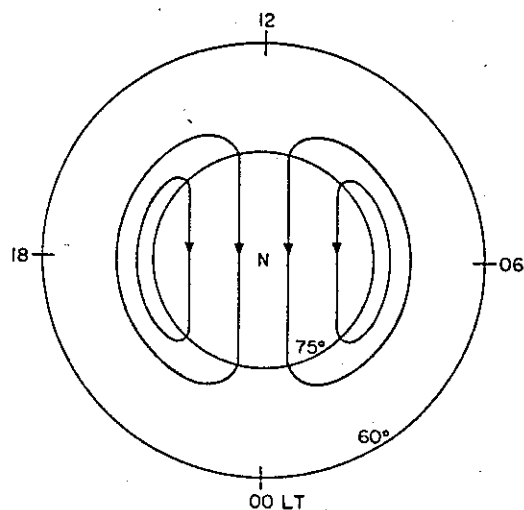


Fig. 2. A sketch of plasma flow pattern in the high-latitude ionosphere
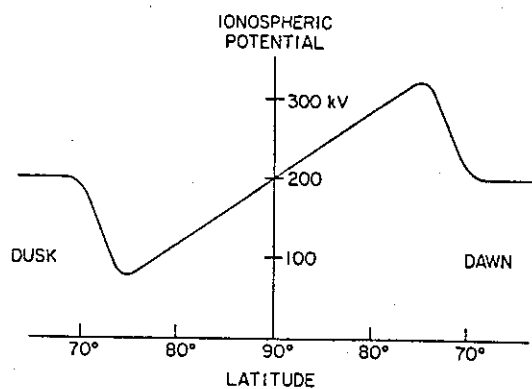


Fig. 3. A sketch of ionospheric potential distribution corresponding to the convection pattern illustrated in Fig. 2
(Earth potential $\equiv 0\ V$)

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$$v = \frac{E \times B}{B^2} \quad \text{where } B \text{ is the geomagnetic field.}$$

Associated with the circulation pattern of Fig. 2 is a dawn-to-dusk variation in the ionospheric potential as illustrated in Fig. 3. A total potential drop of 250 kV across the polar cap has been assumed in addition to an average ionospheric potential of 200 kV with respect to the earth. Electric field measurements by satellites flying over the polar cap show that such dawn-to-dusk potential difference may vary from ~30 kV to 300 kV depending upon the state of the magnetosphere and of the solar wind (*Heppner*, 1972; *Gurnett* and *Frank*, 1973). Given an ionospheric potential distribution as in Fig. 3, what electric fields are expected in the lower atmosphere? Before considering this question, we will first discuss the general problem of mapping ionospheric fields to lower altitudes.

## Downward Mapping of Ionospheric Electric Fields

### Conductivity Profile

At high latitudes conductivities are greatly influenced by precipitating energetic particles associated with geophysical disturbances such as aurora and polar cap absorption. Fig. 4 shows model conductivity profiles representing undisturbed nighttime conditions and polar cap absorption (PCA) events. These models were constructed in consultation with *T. Watt* (private communication, 1974), who has been measuring electron densities above ~50 km altitude using an incoherent scatter radar at Chatanika, Alaska. At lower altitudes we lack experimental data and therefore must rely on "best guesses". We assume that the conductivities are identical to the middle latitude values below 15 km (see our companion paper) and fill in the region between 15 km and 50 km with smooth curves. Comparing these with corresponding middle latitude models in our companion paper, it appears that at high latitudes the conductivities are significantly enhanced by background precipitation even during geophysically "quiet" times.
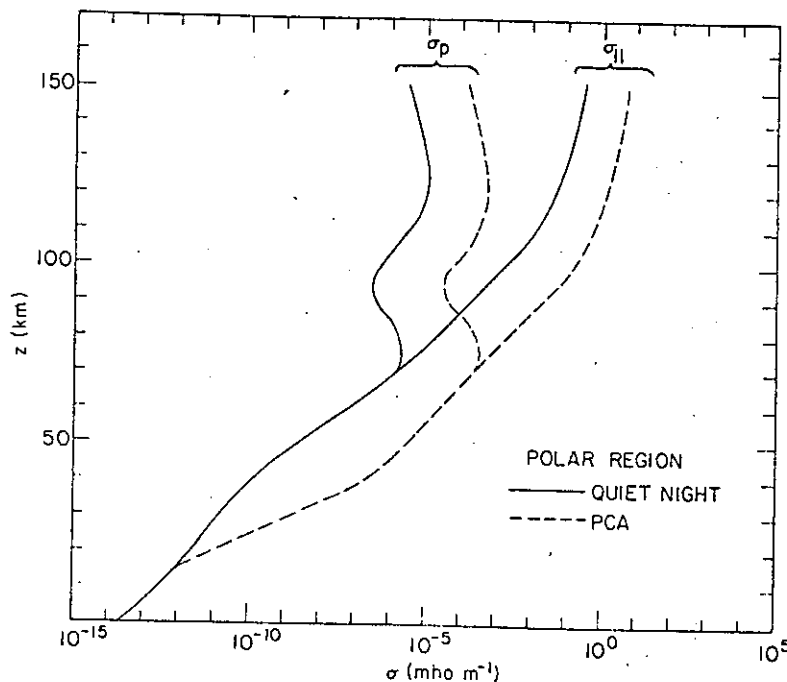


Fig. 4. Conductivity profiles representing quiet night and polar cap absorption conditions in the polar region

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### Mapping Factor

We use similar procedures as in the third section of our companion paper to calculate the mapping factor, defined as the ratio of horizontal electric field $E_H$ at the altitude of interest to the assumed horizontal field at the source altitude of 150 km. We will only consider time-independent fields with spatial variations of the form $E_H = E_0 \cos(k_x x) \cos(k_y y)$. We use 160 homogeneous layers to approximate the anisotropic region between 70 km and 450 km, while the isotropic region below 70 km is divided into three layers with exponentially varying conductivity. The basic equations and their solutions for both regions are given in our companion paper. Eqs. [5] and [7] of that paper apply here as well except that the *Bessel* function $J_0(kr)$ must be replaced by $\cos(k_x x) \cos(k_y y)$ because of the coordinate system change. The boundary conditions are also similar, but in the present case we specify the potential at 150 km as the uppermost boundary condition.
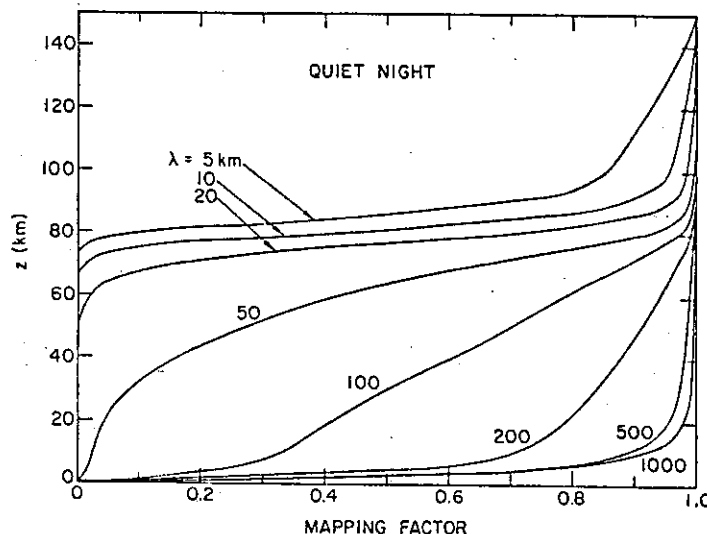


Fig. 5. Mapping factors for horizontal ionospheric electric fields with selected values of spatial wavelength

Fig. 5 shows the mapping factor as a function of altitude for the quiet night conductivity model. The effective wavelength, $\lambda$, is defined by

$$\lambda = \frac{2\pi}{\sqrt{k_x^2 + k_y^2}}.$$

It is evident in Fig. 5 that electric fields with $\lambda > 200$ km map down to the lower atmosphere with little reduction in magnitude, whereas smaller scale fields are attenuated rapidly. Similar results have been obtained by *Kellogg* and *Weed* (1969), *Mozer* (1971), *Boström* et al. (1973), and *Chiu* (1974). Because electric fields map more efficiently in the direction of decreasing conductivity, the mapping factors we obtain here are many orders of magnitude larger than the corresponding factors for upward mapping case in our companion paper. This fact has been used to good advantage in many balloon experiments to infer ionospheric electric fields from measurements made at 30—40 km altitudes (*Mozer* and *Serlin*, 1969; *Mozer* and *Manka*, 1971).

### Effects of Conductivity Anisotropy

We show in our companion paper that conductivity anisotropy is extremely important in calculating upward propagating electric fields above ~80 km. To find out how anisotropy affects downward mapping, we repeated the calculations of Fig. 5 with $\sigma_P$ made equal to $\sigma_{\parallel}$. The results are shown by solid curves in Fig. 6a. The dashed curves are reproduced from Fig. 5 for reference. The effects of ani-

sotropy is to decrease attenuation at large altitudes where the geomagnetic field lines approach equipotentials. Thus, for large scale ($\lambda \gtrsim 100$ km) electric fields, the effective source altitude is lowered to $\sim 80$ km, where $\sigma_H/\sigma_p \gtrsim 10$. This is better illustrated in Fig. 6b. The solid curve was obtained by placing the source at 80 km and using isotropic conductivities. This agrees well with the dashed curve (reproduced from Fig. 5) which assumes the source at 150 km but includes anisotropy above 70 km.
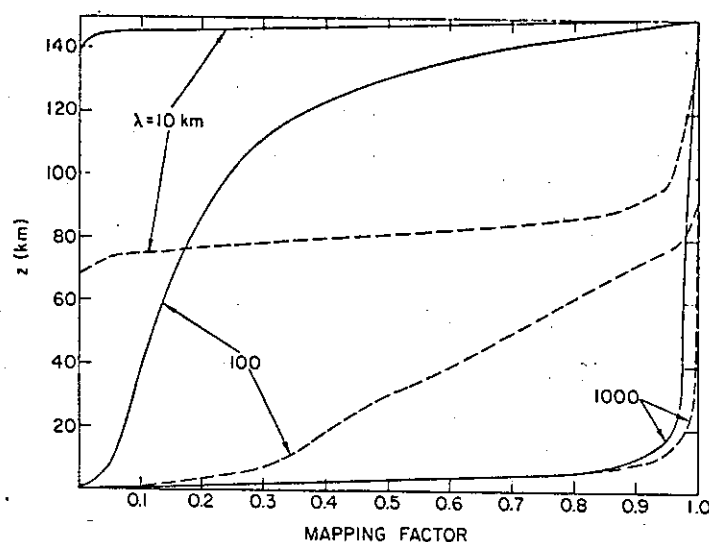
Fig. 6a. Mapping factors for horizontal ionospheric electric fields with (dashed curves, reproduced from Fig. 5) and without (solid curves) the conductivity anisotropy introduced by the geomagnetic field
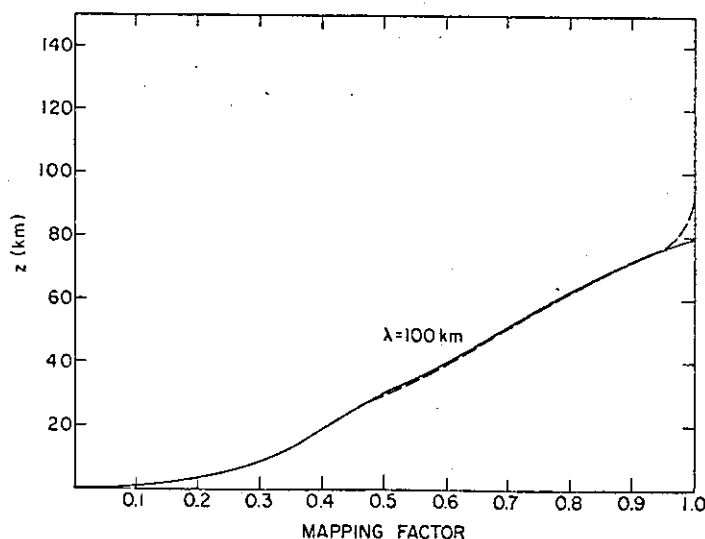
Fig. 7. Mapp

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Fig. 6b. Mapping factors as in Fig. 6a except that in the isotropic case (solid curve) the source altitude is lowered to 80 km

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Since the effective source is at $\simeq 80$ km for ionospheric fields with $\lambda \gtrsim 100$ km, conductivity changes above that altitude are not expected to influence mapping factors. It turns out that even during PCA events which cause large conductivity enhancements at much lower altitudes, the mapping factors remain relatively unaffected. Fig. 7 compares mapping factors calculated for quiet night and PCA conductivity profiles of Fig. 4.
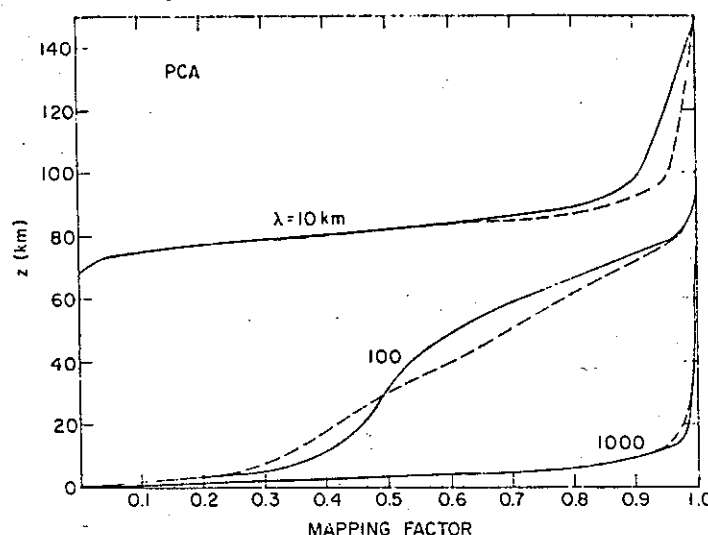


Fig. 7. Mapping factors for quiet nighttime condition (dashed curves, reproduced from Fig. 5) and for polar cap absorption condition (solid curves)

During auroral activity, conductivities become comparable to the PCA values above ~100 km. Although auroral x-rays are known to penetrate to balloon altitudes, they are not expected to compete with PCA's in increasing conductivities there. Thus we conclude that conductivity modulations by geophysical disturbances do not significantly change downward mapping of large-scale ($\lambda \gtrsim 100$ km) ionospheric electric fields, provided that such modulations occur over areas much larger than the scale size of electric fields involved.

We assumed no horizontal conductivity variations in our analysis. If there are small scale conductivity irregularities at low altitudes, as might be the case when discrete auroral forms are present, then electric field distortions due to such irregularities must be considered. At present no experimental data are available on conductivity structures in the polar atmosphere.

## Polar Cap Atmospheric Fields

We saw in the previous section that large-scale horizontal electric fields in the ionosphere map down to low altitudes quite efficiently. The mapping factor decreases with descreasing scale-size so that fine structures in ionospheric fields tend to get smeared out. However, gross features of polar cap ionospheric fields illustrated in Fig. 3 should map down to balloon altitudes of $30-40$ km without suffering significant distortion. As we approach the ground level, however, even large-scale fields get attenuated severely so that ground-based measurements of horizontal electric fields do not appear to be promising for the purpose of inferring ionospheric fields.

Since large-scale ionospheric fields are not shorted out by horizontal currents, it follows that vertical electric fields at low altitudes should faithfully follow the overhead ionospheric potential. For example, vertical electric fields should have the same dawn-to-dusk variation across the polar cap as the potential

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variation illustrated in Fig. 3. If measurements are made at a ground-based station, we expect diurnal variations with a dawn maximum and a dusk minimum. (Recall that magnetospheric convection pattern illustrated in Fig. 2 is fixed in the solar-magnetospheric coordinate system, with the earth rotating underneath it.) In addition, there will be universal time variations as both the size of the polar cap and the potential drop across it change with the changing state of the magnetosphere. Auroral effects on vertical atmospheric fields have been reported by several experimenters (*Olson*, 1971; *Freier*, 1961; *Lobodin* and *Paramonov*, 1972) but it is not clear whether they are related to the effects discussed here.

Because ground-based measurements are influenced by local meteorological conditions, it is difficult to infer ionospheric electric fields from measurements at a single station. However, if vertical fields are measured simultaneously at a latitudinal chain (or several chains) of stations, it should be possible to separate local and global effects by statistical means.

## Conclusions

Magnetospheric convection electric fields are expected to significantly affect fair-weather atmospheric electric fields in the polar region. Balloon measurements of horizontal electric fields have been successfully carried out and magnetospheric electric fields inferred from them. It appears that ground-based measurements of vertical electric fields can also be used to infer magnetospheric fields. In addition to the polar cap electric fields considered here, electric fields associated with magnetospheric substorms and the ionospheric dynamo may also have important implications for atmospheric electricity at middle and low latitudes.

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## Discussion

*Ruhnke*, Reston, Virginia, USA:

With the potentials which map down from the ionosphere in polar regions there are horizontal electric fields associated and also conduction currents. Can you give us any idea how the horizontal conduction current maps down in polar regions?

*Park*, Stanford, California, USA:

The conduction current is simply related to the electric field through the conductivity. So, the current mapping would be identical to electric field mapping except for multiplication factors due to conductivity profile.

*Kasemir*, Boulder, Colorado, USA:

In one of your slides (Fig. 3) you showed the potential difference in the ionosphere near the polar cap, and you said that the fields were mapped down to the ground. Could you give us the value of the vertical fields that we could measure at the ground? Let's say you are at the best place, at 70° or 75° latitude. What would be the difference between the dusk and dawn vertical fields at the ground?

*Park:*

In this particular case illustrated here, you would have more than a 3:1 difference in vertical electric fields measured at dawn and dusk.

*Kasemir:*

I would like to clarify this a little. The absolute value is important insofar as we have a superposition of the ordinary fair-weather field and the ionospheric field. The question would therefore be: can we detect the ionospheric field against a fair-weather field of, say, 50 V/m at the ground?

*Park:*

The potential pattern I showed does include the average ionospheric potential of 200 kV with respect to the earth. So the total vertical electric field you see at dawn and dusk would differ by a ratio of more than 3:1.

*Mühleisen*, Ravensburg, West-Germany:

I think we have continuous measurements of the potential gradient in Spitzbergen and other places at about 75 degrees. As I remember, no clear deviations from the global daily variation occur in these measurements. Do you have an explanation for this?

*Park:*

Of course, there are daily variations of the average ionospheric potential in addition to the dawn-to-dusk potential difference. The latter is also known to be quite variable so that if you look at the data from one station you may find a pattern dominated by the global daily variation depending upon the relationship between the universal time and the magnetic time at the station. If we want to look for the magnetospheric effects, I think we need simultaneous observations at multiple stations.

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