Polar cap index (PC) as a proxy for ionospheric electric field in the near-pole region.

O. A. Troshichev, and R. Yu. Lukianova

Arctic and Antarctic Research Institute, St Petersburg, Russia

V. O. Papitashvili[1]

Space Physics Research Laboratory, University of Michigan, Ann Arbor, Michigan, USA

F. J. Rich

Air Force Research Laboratory, Hanscom AFB, Massachusetts, USA

O. Rasmussen

Solar-Terrestrial Division, Danish Meteorological Institute, Copenhagen, Denmark

Abstract. The ion drift measurements made by a number of DMSP satellites during some intervals in 1991, 1997, and 1998 are utilized for estimation of the ionospheric electric fields over the near-pole region; these estimates are then compared with the Polar Cap (PC) magnetic activity index obtained from ground geomagnetic observations at Qaanaaq (former Thule, Greenland) and Vostok (Antarctica). The analysis shows that the polar cap electric field is primarily controlled by variations in the near-Earth's interplanetary electric field. The relationship between the polar cap ionospheric electric field and the PC-index can be approximated by a quadratic polynomial. The polar cap ionospheric electric field tends to saturate at the asymptote of ~45–50 mV/m when the PC index reaches large positive values (PC > 10); the residual electric field (for near-zero interplanetary electric field applied to the Earth's magnetosphere) is ~12 mV/m. It is concluded that the PC-index can serve as a proxy of the ionospheric electric fields in the near-pole region.

Introduction

Troshichev et al. [1979, 1988] introduced the PC index as an index for monitoring of geomagnetic activity over both the Northern and Southern polar caps caused by changes in the interplanetary magnetic field (IMF) and solar wind as they occur near the Earth's orbit. *Troshichev and Andrezen* [1985] showed that ground geomagnetic

disturbances measured at a single near-pole station highly correlate ($r > 0.8$) with the "merging electric field" [e.g., *Kan and Lee*, 1979] constantly applied to the Earth's magnetosphere:

$$E_m = v \cdot B_T \cdot sin^2(\theta/2) = v \cdot (B_y^2 + B_z^2)^{1/2} \cdot sin^2(\theta/2) \qquad (1)$$

where v is the solar wind velocity, B_y and B_z are the IMF azimuthal and vertical components, and θ is an angle between the geomagnetic field and the IMF total vector. The PC-index algorithm is based on a statistical analysis of the relationship between variations in E_m and magnetic perturbations ΔF at the near-pole station. However, the ionospheric electric field, not interplanetary electric field, is of prime interest for practical purposes. In principle, the ionospheric electric field could be derived from the merging electric field by mapping down along magnetic field lines with the use of the magnetic field lines convergence factor. To fulfill this operation we have to know the value of the merging electric field immediately at the magnetopause as well as the length reconnection line (where the IMF reconnects with the geomagnetic field) over the subsolar surface of magnetosphere. In the general case both these values are unknown and the merging electric field is calculated from the solar wind measurements made by spacecraft upstream of the bowshock. To avoid scaling in unused units of interplanetary electric field the PC index has been normalized per 1 mV/m of the interplanetary electric field to become dimensionless.

It is well known that the cross-polar cap voltage and distribution and strength of the electric field in the polar ionosphere can be regarded as key parameters characterizing the state of the magnetosphere. However, both these important parameters are difficult to monitor because our instrumental capabilities are limited. For example, we cannot identify with certainty the electric voltage or the electric field distribution in the near-pole region only from measurements from random spacecraft orbits crossing the polar cap under arbitrary angles. *Troshichev et al.* [1996]

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[1]Also at Solar-Terrestrial Division, Danish Meteorological Institute, Copenhagen, Denmark

have thoroughly analyzed the relationships between the cross-polar cap voltage (derived from the Akebono satellite particle and electric field measurements) and the PC index. Although values of the PC index were limited in range 0-6 the conclusion was drawn that the PC index could be utilized as a good indicator in monitoring this key ionospheric parameter.

Method

In this paper we show results of examination of the relationship between the PC index and the ionospheric electric fields observed in the polar region by the DMSP satellites. We mainly selected the orbits that crossed the near-pole region (above 85° corrected geomagnetic latitude) in approximately the dawn-dusk direction. We assumed that the selected orbits crossed near the foci of the normal 2 ionospheric convection cells, as well as the trans-polar portion of the convection where the potential reverses its sign. The following method to calculate average electric fields over the near-pole region has been developed: first, we fixed the potential values at the entry and exit points of the trajectory at the CGM latitude ±85°; second, we calculated geometric distance between these two points along the great circle arc crossing the near-polar area; and third, the average near-polar electric field was determined as the electrostatic potential difference between the fixed points divided by the geometric distance.

To test the method we examined dependence of the potential values on appropriate geometric distances and obtained the following relationship $\Delta\Phi(kV)=$ -35.6 + 3.9 size (deg). Troshichev et al. [1996] have been used DMSP data to derive relationship between the cross-polar-cap potential drop and size of the polar cap, the boundaries of the polar cap being determined as the plasma convection reversal in the polar cap. Analysis of Troshichev et al. [1996] has yielded relationship $\Delta\Phi(kV) =$ -44.32 + 3.2 size (deg) for total case. One can see that fixation of the potential values at the entry and exit points of the trajectory at the CGM latitude ±85° ensures approximately the same dependence of the potential drop on distance as in case of more rigorous treatment of the cross-polar-cap potential drop. Therefore the method used by us for determination of electric field in the polar cap can be regarded as warrant.

We selected data from the DMSP electrostatic potential database for 1991, 1997, and 1998 for days when the PC-index reached large (PC > 5) and low (PC < 0) values. In total, 450 trajectories of the DMSP crossings of the northern and southern near-pole regions are analyzed. Because we used the PC-index derived independently from a single near-pole station (Thule, Greenland, and Vostok, Antarctica), we obtained two independent sets for comparisons over the northern and southern polar regions.

Statistical relationships between the polar cap electric fields and PC index

The average electric fields (along the great circle arc discussed above) obtained from the DMSP potential data

Ionospheric electric field -DMSP
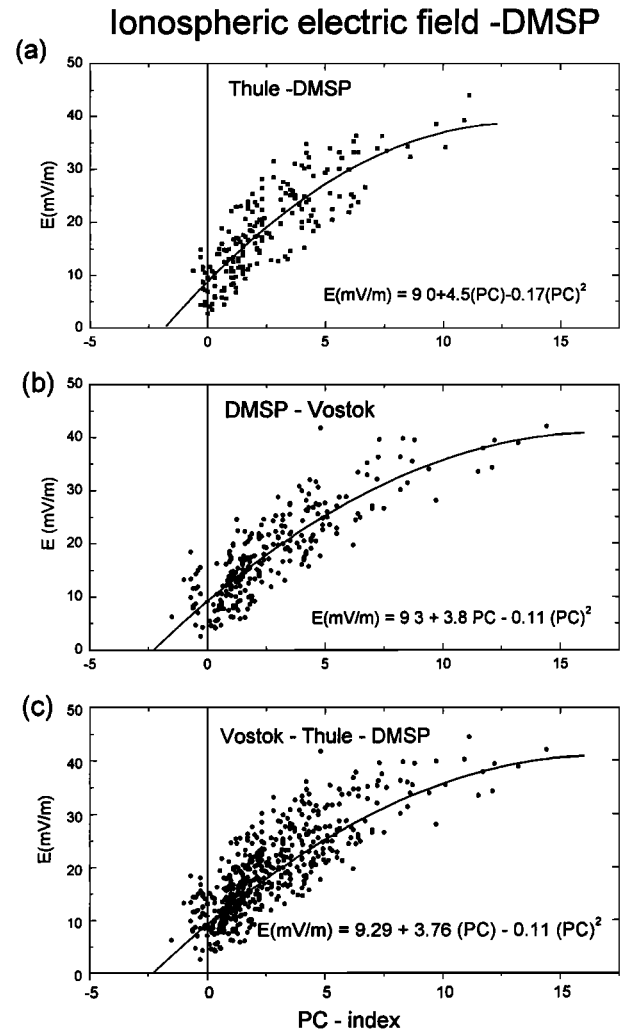
Figure 1. (a) The northern polar cap electric field vs the PC index from Thule, (b) the southern polar cap electric field vs the PC index from Vostok, and (c) relationship between values of the polar cap electric field and the PC index for the combined DMSP data set and the corresponding polynomial fit (solid line).

were compared with the PC index independently for the northern (number of orbits n = 190) and southern (n = 250) hemispheres. In this study we were able to deal with sufficiently high values of the PC index: up to 15. The correlation results are shown in Figure 1(a,b) and the corresponding polynomial fits for two hemispheres appear to be very close:

$$E\ (mV/m) = 9.00 + 4.50{\cdot}PC - 0.17\ PC^{\ 2}\quad \text{for Thule}\quad (2)$$

$$E\ (mV/m) = 9.30 + 3.80\ PC - 0.11{\cdot}PC^{\ 2}\quad \text{for Vostok}\quad (3)$$

Figure 1c shows the polynomial fit (solid line) for the combined data set (northern and southern hemispheres):

$$E\ (mV/m) = 9.29 + 3.76\ PC - 0.11\ PC^{\ 2}\qquad\qquad (4)$$

This expression is valid for electric field measured at orbit of DMSP spacecraft (h ≈ 840 km). Owing to the convergence of magnetic field lines the electric field would be

dependent on altitude. To derive ionospheric electric field (at altitude about 110 km), we have to take into account the magnetic field convergence factor. Since the distance between geomagnetic field lines is related to the distance R from the center of the earth times 3/2, the magnetic convergence factor is about 1.7 would be taken in going from h=840 km to h=110 km. Just this factor would be used while calculating the ionospheric electric field with use expression (4).

Figure 2 shows the distribution of electric fields over the near-polar cap vs. AE indices for three specific cases: (a) over the northern hemisphere, (b) over the southern hemisphere, and (c) for the combined set of data. One can see that there are no relationships between the substorm activity in the auroral zone and the electric fields over the near-pole region; that definitely implies that the polar cap electric fields are primarily controlled by variations in the near-Earth's interplanetary electric field (i.e., the "directly-driven" processes), but not the "loading-unloading" processes in the auroral zone.

Ionospheric electric field - DMSP
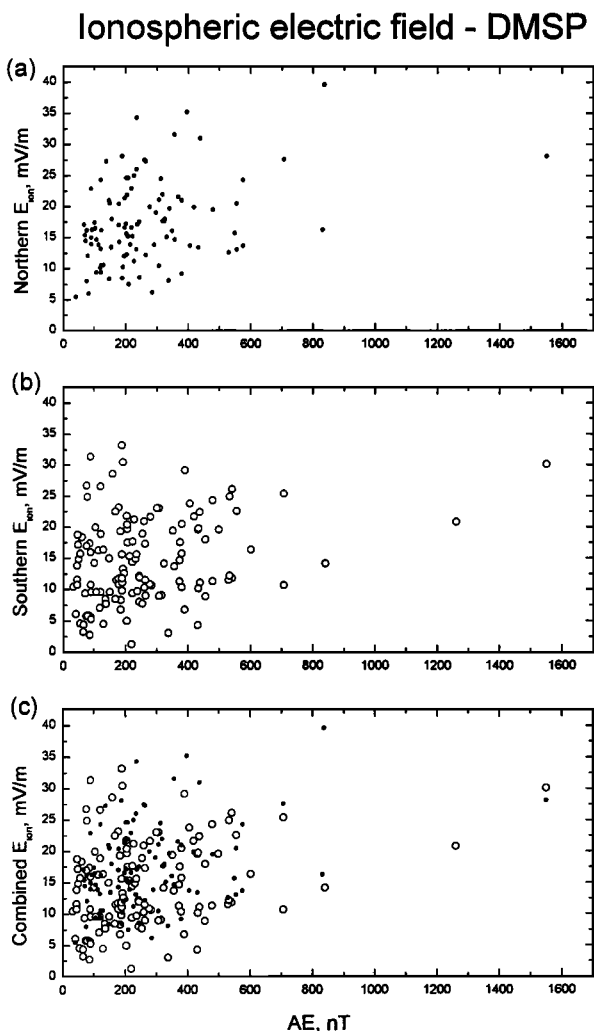
Figure 2. Distribution of electric fields over (a) the northern polar cap, and (b) the southern polar cap vs the AE index, and (c) relationship between the polar cap electric field and the AE index for combined set of data.

Discussion

The knowledge of electric fields over the polar caps is important in characterizing the state of the magnetosphere and the polar ionosphere. The fields can be close to zero under the extremely quiet conditions, but they might sharply increase up to tens (or even hundred) millivolts per meter during periods of magnetic storms. Also, the polar cap electric fields largely determine ionospheric convection patterns over the entire high latitude region; therefore, they are important for modeling a variety of magnetosphere processes. However, realistic monitoring of the electric fields over the near-pole region by the spacecraft remains a serious problem because of the random distribution of the satellite orbits over the entire the polar cap. On the other hand, our analysis shows that electric fields over both the northern and southern near-pole regions can be monitored with confidence by using the PC index (derived from the corresponding near-pole magnetic observatories) as a proxy in accordance with Equations 2 - 4. At present, the 1-min PC index is derived from geomagnetic observations at Vostok (Antarctica) and available on-line (http://www.aari.nw.ru).

We note that the relationships between the PC index and the polar cap electric fields show some sort of "saturation" effect for high levels of magnetic activity. Indeed, as seen in Figure 1, the polar cap ionospheric electric field tends to saturate at the asymptote of ~45–50 mV/m when the PC index reaches large positive values (PC > 10). The residual electric field (for near-zero interplanetary electric field applied to the Earth's magnetosphere) is ~12 mV/m deduced from the value of the electric field when the PC is about 0.5. This value of the PC index has been taken as a threshold since the IMF B_z component turns from southward to northward when PC is in the range between 0 and 1. The electric field of magnitude 12 mV/m effectively builds the cross-polar potential drop of 33 kV over the polar cap with diameter of 25° (12 mV/m x 2750 km ≈ 33 kV).

The existence of "residual potential" (or the "residual electric fields") related to the quasi-viscous interaction of the solar wind with the magnetosphere has already been noted in many experimental and theoretical studies [e.g., *Reiff et al.*, 1981; *Troshichev*, 1982; *Doyle and Burke*, 1983; *Wygant et al.*, 1983; *Cowley*, 1984; *Mozer*, 1984; *Reiff and Luhmann*, 1986, etc.]. However, various analyses produced quite different values of that "residual": from 20 kV [*Wygant et al.*, 1983] to 35 kV [*Reiff et al.*, 1981; *Papitashvili et al.*, 1999]. Our analysis agrees with the maximum estimate of the residual electric field or potential drop, but it is possible that this estimate is valid only for the near-pole region, i.e. within the 85° latitude circle.

Conclusions

The analysis of average electric fields over the near-pole region obtained from DMSP satellite data shows clearly that the intensity of these fields is primarily controlled by the interplanetary electric field penetrating into

the magnetosphere. These electric fields can be realistically monitored for various IMF conditions with confidence by using the corresponding PC index, that is, derived from the northern (Thule) or southern (Vostok) near-pole station. The relationships between the polar cap electric fields and the PC index are better fitted by the quadratic polynomials, which suggest the effect of saturation of the near-pole electric fields at ~45–50 mV/m for high magnetic activity (PC > 6) and "residual electric fields" of ~12 mV/m when PC = 0-1. We conclude that the PC index can effectively serve as a proxy of the ionospheric electric fields over the near-pole region.

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O. A. Troshichev, R. Yu. Lukianova, Arctic and Antarctic Research Institute, 38 Bering Str., St. Petersburg, 199397, Russia (e-mail: olegtro@aari.nw.ru)

V. O. Papitashvili, Space Physics Research Laboratory, University of Michigan, Ann Arbor, Michigan, USA (e-mail: papita@umich.edu)

F. J. Rich, Air Force Research Laboratory, Hanscom AFB, Massachusetts, USA (e-mail: rich@plh.af mil)

O. Rasmussen, Solar-Terrestrial Division, Danish Meteorological Institute, Copenhagen, Denmark (e-mail: or@dmi dk)