The influence of polar-cap convection on the geoelectric field at Vostok, Antarctica

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Abstract

Vertical geoelectric field measurements at Vostok, Antarctica (78.5°S, 107°E; corrected geomagnetic latitude, 83.4°S) made during 1998 are compared with both Weimer (1996) and IZMEM (1994) model calculations of the solar-wind-induced, polar-cap potential differences with respect to the station. By investigating the correlations between these parameters for individual UT hours, we confirm and extend the diurnal range over which significant correlations have been obtained. Nineteen individual UT hours are significantly correlated with the Weimer model predictions and nine with the IZMEM model predictions. Diurnal variation in the slopes of the linear regressions allows us to comment on each model, demonstrating that Antarctic polar plateau geoelectric field measurements can be used to investigate polar convection. Seasonal variations in the diurnal electric field variations at Vostok are compared with the Carnegie global electric circuit diurnal curves, after allowance is made for the solar-wind-induced, polar-cap potential difference patterns.

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1. Introduction

Wilson (1920) first introduced a hypothesis that global thunderstorm activity maintains an electric potential difference between the ionosphere and the surface of the Earth. Thunderstorm activity draws current upward to the ionosphere and is partially responsible (Williams and Heckman, 1993) for a time-varying potential difference of the order of 250 kV directed downward, between the ionosphere and the ground. Currents in the circuit are dispersed around the globe via the ionosphere and the magnetosphere, to return eventually to the ground. In fair-weather regions, a downward directed geoelectric field of ~100 – 200 Vm⁻¹ can be measured near the surface. The geoelectric field is responsive to variations in global current sources, including thunderstorm activity, on timescales of the order of 20 min (Bering et al., 1998). Bering et al. (1998), Tinsley (2000) and Rycroft et al. (2000) provide overviews of the development and present status of research in geoelectricity.

The global significance of geoelectric field measurements is more readily observable in regions where local diurnal variations of atmospheric conductivity are small—over oceans, in polar regions and at some mountain sites. Sites are judged as suitable for such studies if the average diurnal variation, in universal time (UT), is consistent with the
average fair-weather geoelectric field diurnal variation derived from measurements made during the voyages of the research ship Carnegie in the early decades of the last century (e.g. Reiter, 1992, p. 129). The Carnegie data set has reference status for historical reasons and because the measurements are made over the ocean where diurnal variations in conductivity are minimal. Vostok has been shown to be a suitable site for studies of the global electric circuit (Park, 1976a; Frank-Kamenetsky et al., 1999, 2001).

At high latitudes, the interaction of the solar wind and the Earth’s magnetic field imposes on the geoelectric field a variable dawn-to-dusk potential drop of between 20 and 150 kV. Large-scale (> 200 km) horizontal electric fields in the ionosphere map into the vertical component of the electric field near the Earth’s surface (Park, 1976b). Burns et al. (1998) show that the geoelectric field at Vostok is modulated by the $B_y$ component of the interplanetary magnetic field (IMF) during times when Vostok is magnetically linked to the dayside interaction region between the solar wind and the Earth’s magnetic field. Tinsley et al. (1998) compared variations of the surface electric field, $\Delta E_z$ (the observed electric field measurements at South Pole minus the Carnegie curve scaled to the average of $E_z$ for 4–6 and 14–16 UT h for each individual day) with variations in the calculated overhead ionospheric electric potential differences, $\Phi_{AV}$, inferred using the Hairston–Heelis model, (Hairston and Heelis, 1990). The authors found positive correlations with a slope of $\sim 0.7$ V m$^{-1}$/kV and correlation coefficients of $\sim 0.5$. Frank-Kamenetsky et al. (1999), using chart-scaled hourly data showed that the vertical electric field measured at Vostok (78.5°S, 107°E; corrected geomagnetic latitude, 83.4°S) was significantly correlated with IZMEM model (Papitashvili et al., 1994, 1995) calculated cross-polar-cap potential differences above the site, for six individual hours. Frank-Kamenetsky et al. (2001) introduced a modern Vostok data set and reported statistically significant linkages of the vertical electric field with the IMF components.

The seasonal variation of the average diurnal curve is of interest for its relationship to variations in the global electric circuit generators (Adlerman and Williams, 1996; Israel, 1973, pp. 350–351). Frank-Kamenetsky et al. (2001) show a seasonal variation in the value of the geoelectric field at Vostok with a range of 40 V m$^{-1}$, maximum in August and minima in April and December. However, in determining the global circuit diurnal curve and its seasonal variation in polar regions the influence of the cross-polar-cap potential difference imposed by the interaction of the solar wind and the Earth’s magnetic field (Tinsley et al., 1998; Frank-Kamenetsky et al., 1999) can be significant and should be accounted for.

In this paper we start with the Vostok 1998 fair-weather days of geoelectric field measurements introduced by Frank-Kamenetsky et al. (2001) and compare the seasonal diurnal variations, after allowing for the influence of the cross-polar-cap potential difference inferred using the Weimer (1996) model, with the classic Carnegie seasonal curves (Reiter, 1992; Israel, 1973) and their recent re-evaluation (Adlerman and Williams, 1996). Hourly averaged ground-level, vertical electric field values are compared with both Weimer (1996) and IZMEM Papitashvili et al. (1994, 1995) model inferred potential differences above the site. The slope and significance of a linear regression with respect to the test of the null hypothesis that the slope is equal to zero, is determined separately for each UT h. We use these values to examine the models’ estimates of cross-polar-cap potential difference variations above Vostok as solar wind conditions vary, thus demonstrating that Antarctic polar plateau geoelectric field measurements can be used to investigate polar convection.

2. Instrumentation, data and ionospheric potential difference models

A rotating-dipole electric field mill was deployed at Vostok Station, Antarctica, in December 1997 under a cooperative agreement between Russian, Australian and American researchers. The electric field mill was mounted on a steel pole, approximately 1.5 m above the surface of the snow, upwind of the station’s main buildings. Electric field measurements are collected as 10-s samples and converted to hourly averages for this analysis. We commence with the 134 fair-weather days from Vostok 1998 as presented in Frank-Kamenetsky et al. (2001), which contains a more detailed description of the site and data.

Hourly averaged IMF components and solar wind speed data were obtained from the National Space Science Data Center (NSSDC) OMNIWeb database. These data are required inputs for the models we use to calculate the cross-polar-cap potential differences above Vostok. The OMNI database contains IMF and solar wind speeds obtained by the IMP8, Wind and ACE satellites. The IMP8 satellite is located within $\sim 12$ min of the Earth and is used as the primary dataset. Wind and ACE are located upstream of the Earth, at the L1 libration point. Position information and solar wind speeds from the respective satellites were used by King and Papitashvili (2001) to timeshift the IMF data to Earth. IMF data were available for 95% of the selected days.

Weimer and IZMEM-1994 models are used to calculate the cross-polar-cap potential difference above Vostok from the solar wind parameters and the station’s location. The Weimer model (Weimer, 1996) derives the ionospheric electric potential differences in the polar regions using IMF $B_x$, $B_y$ (not $B_z$) magnitudes, solar wind velocity, and dipole-tilt angle. The model is derived using a least error fit of ionospheric electric field measurements from DE-2 and coincident solar wind measurements from the ISEE-3 and IMP8 satellites. The IZMEM-1994 model (Papitashvili et al., 1994, 1995) uses IMF $B_z$, $B_y$, and $B_x$ components to infer the ionospheric electric potential differences in the polar regions. It is derived using a statistical regression
analysis of ground-based magnetometer data, collected in both northern and southern polar regions, and associated IMF data. A statistical model is used to calculate the ionospheric conductivities in both polar regions. The averaged ionospheric conductivity distribution is then used to compute the entire set of electrodynamic parameters resulting in an output which is UT independent. Separate derivations are made for the summer, winter and equinoctial seasons. The boundary conditions for both models are identical, the ionospheric electric potential difference is set to zero at 57° latitude.

The IZMEM model has been recently modified by incorporating DMSP satellite measured potential differences with the ground-based magnetometer data (Papitashvili et al., 1999). We have chosen to use the IZMEM-1994 model to allow for comparison with an earlier Vostok analysis (Frank-Kamenetsky et al., 1999) and the distinct methods used to derive each of the models.

We use 104 of the 134 fair-weather days introduced by (Frank-Kamenetsky et al., 2001) for a comparison of the model calculated, solar-wind-induced potential differences above Vostok and the geoelectric field measurements. These are days for which all 24 hourly measurements of IMF and solar wind speed data are available, allowing both Weimer and IZMEM model calculations of the polar-cap potential difference above Vostok. IMP8 provided 46%, Wind 49% and ACE 0.3% of the IMF data. Solar wind speed data used come from only the IMP8 (45%) and Wind (50%) satellites. A total of 55 hours of interpolated solar wind speed data are used to extend the Weimer model predictions to 127 complete days. These are used for a seasonal analysis of the Vostok diurnal curves from which the influence of the polar-cap potential differences are subtracted.

3. Diurnal and seasonal variations

Fig. 1(a) shows the average UT variation for the Vostok site for the Northern Hemisphere (NH) winter (November, December, January, February; 44 days), NH summer (May, June, July, August; 33 days) and equinox (March, April and September, October; 50 days) and for all 127 fair-weather days in 1998 when complete hourly geoelectric field measurements and Weimer model calculated, potential differences above Vostok were available. Fig. 1(b) plots the average potential difference above Vostok calculated using the Weimer model, for the same days and seasonal splits. A typical standard error is plotted for each curve between 2 and 6 UT. Fig. 1(c) plots the estimated global circuit seasonal variations obtained by subtracting the polar-cap potential differences at the rate 0.71 V m⁻¹/kV (see text).

plotted in Fig. 1(c). Table 1 lists measurements of interest from the raw and corrected Vostok curves and the Carnegie equivalents. The time of the diurnal minimum and maximum and the mean and range are presented. The range is expressed as a percentage of the mean. Most of the Carnegie curve values are taken from Reiter (1992, p. 130) but the seasonal average values are calculated as averages of the monthly values determined by Adlerman and Williams (1996) in their reanalysis of the Carnegie data. The time of the maximum and minimum values are not altered by the process adopted to account for the influence of the variable cross-polar-cap potential difference, however, the range values are increased by between 7 and 9%. A NH summer maximum is apparent in the Vostok mean values, although the equinoctial mean is close to the high NH summer value, while the Carnegie equinoctial mean is close to the low NH winter value.
4. Solar variability influence on the geoelectric field

We seek to compare the vertical geoelectric field measured near the ground at Vostok with both Weimer and IZMEM model calculated cross-polar-cap potential differences above the site over 104 days in 1998. Vostok is at a magnetic latitude of 83.5°S and thus generally rotates daily well inside the peaks in the cross-polar-cap potential difference. Fig. 2 shows the average diurnal potential difference above Vostok for each UT hour, on a particular day, \( \bar{E}(d) \) is the average value for that day and \( \bar{E} \) is the average value across all days. The variation around an average value for each hour is determined as

\[
\Delta E_d(h) = E_d(h) - \bar{E}(h),
\]

where similar nomenclature has been used. This means that the electric field variations, \( \Delta E(d, h) \), are calculated as per the procedure adopted by Frank-Kamenetsky et al. (1999). While the potential difference variations are modified to ensure a zero level average across each day.

Linear regressions are calculated of \( \Delta E_d(h) \) against \( \Delta \phi_d(h) \) for each UT hour for both the Weimer and IZMEM calculated cross-polar-cap potential differences above Vostok. Fig. 3 shows the results for both models for the hour from 12 to 13 UT (hereafter 12.5 UT). Considerable noise is apparent in the \( \Delta E_d(h) \) values and expected due to hour-to-hour variability in the global electric circuit and local meteorological influences on the ground-level atmospheric conductivity which should not be correlated with

<table>
<thead>
<tr>
<th>N.H. Winter</th>
<th>Equinox</th>
<th>N.H. summer</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vostok Raw EF Time of min. (UT h)</td>
<td>3.5</td>
<td>3.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Time of max. (UT h)</td>
<td>18.5</td>
<td>19.5</td>
<td>20.5</td>
</tr>
<tr>
<td>Range (%)</td>
<td>42</td>
<td>28</td>
<td>19</td>
</tr>
<tr>
<td>Mean (Vm(^{-1}))</td>
<td>166</td>
<td>183</td>
<td>182</td>
</tr>
<tr>
<td>Vostok minus ( \phi ) Time of min (UT h)</td>
<td>3.5</td>
<td>3.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Time of max. (UT h)</td>
<td>18.5</td>
<td>19.5</td>
<td>20.5</td>
</tr>
<tr>
<td>Range (%)</td>
<td>51</td>
<td>35</td>
<td>27</td>
</tr>
<tr>
<td>Mean (Vm(^{-1}))</td>
<td>170</td>
<td>187</td>
<td>189</td>
</tr>
<tr>
<td>Carnegie Time of min. (UT h)</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Time of max. (UT h)</td>
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<td>19.5</td>
<td>20.5</td>
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<tr>
<td>Range (%)</td>
<td>40</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Mean (Vm(^{-1}))</td>
<td>125</td>
<td>125</td>
<td>147</td>
</tr>
</tbody>
</table>

*Calculated from Adlerman and Williams (1996).
Fig. 2. Average Weimer and IZMEM model calculated polar-cap potential differences above Vostok for the 104 days analysed. Standard errors are also plotted.

Fig. 3. Variations in the geoelectric field compared with variations in the calculated polar-cap potential difference for 12.5 UT, for both (a) Weimer and (b) IZMEM model predictions.

\[ \Delta E \sim 0.87 \times \Delta \phi \]
\[ \rho = 0.43 \]

\[ \Delta E \sim 0.67 \times \Delta \phi \]
\[ \rho = 0.29 \]

Fig. 4. The slope of the straight line fit for the variation in the scaled geoelectric field values, \( \Delta E_s \), and variation in the Weimer modelled polar-cap potential differences above Vostok, \( \Delta \phi \), for each UT hour; and the probability that the association is due to chance. Local noon at Vostok occurs at \( \sim 5 \) UT and local magnetic noon at \( \sim 13 \) UT.

\[ \text{Slope (Vm}^{-1}/\text{kV}) \]
\[ \text{Chance Probability} \]

If an average potential difference of \( \sim 250 \) kV generates an average vertical electric field near ground level at \( \Delta \phi(d, h) \). However, the Weimer and IZMEM linear regressions are both significant in the sense that the linear regression of \( \Delta E_s \) and \( \Delta \phi \) has a slope significantly different from zero and the probability of the linear regression relationship occurring by chance is less than 0.001% and 0.4%, respectively. We describe as significant, those UT hours for which there is a less than 5% probability that the linear relationship between \( \Delta E_s \) and \( \Delta \phi \) occurred by chance. Fig. 4 shows the slope of the linear regression (\( \text{Vm}^{-1}/\text{kV} \)) and the probability that \( \Delta E_s \) and \( \Delta \phi \) are associated by chance for each UT hour, for the Weimer model data. Fig. 5 shows similar results for the IZMEM model. Standard errors are plotted on the slope values in both Figs. 4 and 5.
Vostok of 177 V m$^{-1}$, then the expected slope of the correlation is $\sim 0.71$ V m$^{-1}$/kV. For the Weimer model, the slope obtained from combining all data is 0.76 V m$^{-1}$/kV. The linear regressions show significant association of the $\Delta E_s$ and $\Delta \phi$ values for 19 individual hours. The $\Delta E_s$ and $\Delta \phi$ values are generally significantly associated across the magnetic daylight hours (magnetic noon $\sim 13$ UT) and near magnetic midnight. The hours for which the chance probability of $\Delta E_s$ and $\Delta \phi$ being associated is greater than 5% are limited to a few hours either side of magnetic midnight and one almost-significant hour (14.5 UT) near magnetic noon. The average slope across those hours for which significant associations between $\Delta E_s$ and $\Delta \phi$ were obtained using the Weimer model is a relatively high value of 0.90 V m$^{-1}$/kV.

For the IZMEM model, the linear regression slope obtained from combining data from all hours is only 0.33 V m$^{-1}$/kV. Significant associations of $\Delta E_s$ and $\Delta \phi$ are obtained for only nine individual hours ranging across the interval from five hours before local noon ($\sim 5$ UT) to four hours after magnetic noon. The average slope across those hours for which significant associations between $\Delta E_s$ and $\Delta \phi$ were obtained using the IZMEM model is 0.56 V m$^{-1}$/kV.

The correlation coefficient, $\rho$, of the $\Delta E_s$ and $\Delta \phi$ values for 12.5 UT is also shown in Figs. 3(a) and (b). The average coefficient of determination, $\rho^2$, across the hours for which the $\Delta E_s$ and $\Delta \phi$ values are significantly associated using the Weimer model is 0.14. The value similarly obtained using the IZMEM model is 0.08. The coefficient of determination, $\rho^2$, indicates the proportion of variance that $\Delta E_s$ and $\Delta \phi$ have in common, however, because of the scaling inherent in $\Delta E_s$ and $\Delta \phi$, this is not a direct measure of how much variation in the ground-level, vertical electric field measurements is related to the variation in the cross-polar-cap potential differences above the site.

5. Discussion

Diurnal and seasonal variations of the Vostok geoelectric field curves generally show features compatible with the reported variations of the Carnegie curves. Consistent features include the shift to later UT times of the maximum between NH winter and summer months, the general seasonal constancy of the timing of the diurnal minimum (with the exception of the NH summer curve which minimises an hour later at 4.5 UT) and the range of the total data set. As such, the Vostok site again demonstrates its suitability for studies of the global electric circuit (Park, 1976a; Frank-Kamenetsky et al. 1999, 2001).

The range of the diurnal curves, expressed as a percentage of the mean, increases by between 7 and 9% when the cross-polar-cap potential difference contribution is subtracted. The increase in the range of the Vostok diurnal curve from 28% of the mean value to 37% of the mean value, thus matching the value for the Carnegie data set, is the most apparent improvement made by allowing for the cross-polar-cap potential differences above the site. The time of the minima and maxima are found not to vary. This is due to the fortuitous temporal alignment of the average cross-polar-cap potential difference diurnal curve with the Carnegie curve, and is assisted by the relatively low magnitude of the cross-polar-cap potential differences above this high magnetic latitude site. The Weimer model maximum potential difference above Vostok occurs at 5.5 UT and the minimum at 18.5 UT. These are close to the inverse of the average global geoelectric field diurnal variation which has an annual maximum at 19.5 UT and a minimum at 3.5 UT. For polar cap sites it is necessary to account for this additional influence when discussing diurnal and seasonal variations of the geoelectric field in reference to the global circuit. The average diurnal range of the cross-polar-cap potential differences above other polar-cap sites may be larger than at Vostok (this is generally true for sites with magnetic latitudes greater than $\sim 60^\circ$ and less than the magnetic latitude of Vostok, $\sim 83.5^\circ$) and the temporal alignment may be such that the minimum and maximum of the diurnal geoelectric field curves are altered by the required corrections.

The annual variation in the magnitude of the electric-field at Vostok, which peaks in the NH summer (MJJJA) and minimises in the NH winter (NDJF) is consistent with the annual variation in global thunderstorm activity. Global thunderstorm activity should be stronger in the NH summer as thunderstorm activity is principally a summer, landmass phenomena. The Carnegie oceanic measurements were, however, initially reported to show a NH winter peak in magnitude (see for example Israel, 1973, pp. 364–366).
This discrepancy was resolved by Adlerman and Williams (1996) who reanalysed the Carnegie data and found the expected NH summer maximum.

Differences between the Vostok and Carnegie diurnal curves point to some of the uncertainties associated with using ground-level geoelectric field measurements to investigate the global circuit. The mean Carnegie equinoctial value is similar to the mean Carnegie NH winter value, while the mean equinoctial Vostok value is similar to the mean Vostok NH summer value. This is a significant distinction in terms of the annual variations. Although vertical electric fields are relatively easy to measure, these measurements are inversely proportional to the local conductivity. Seasonal variations in the local conductivity may influence the magnitudes of our seasonal geoelectric field measurements.

The range of the corrected Vostok NH winter diurnal curve, 51% of the mean value, is also excessive when compared to the associated Carnegie value of 40%. Average diurnal variations in conductivity at the site may influence such range measurements. The Weimer cross-polar-cap potential differences are not significantly correlated with the scaled Vostok geoelectric field over the interval from 2.5 to 4.5 UT. This may effect the diurnal range results as the model may not be accurately indicating the cross-polar-cap potential difference above Vostok around the time of the diurnal minimum. Alternately, it may indicate that the geoelectric field values are influenced by a conductivity variation around local noon (∼5 UT). Contrary to the alternate argument, the IZMEM model values are significantly correlated at 3.5 UT. Inconsistencies between the data sets, at the levels indicated, are presently unresolvable.

The conductivity of the ground-to-ionosphere path is dominantly controlled by ionisation by cosmic rays. Cosmic ray ionisation of the atmosphere varies on a wide-range of time scales, locations and altitudes. Time-scale variations include solar cycle variations of ∼20% in ground-level nucleonic intensities, Forbusch Decreases associated with coronal mass ejections result in ground level nucleonic intensity reductions of generally less than 5% over intervals of 2-3 days and average annual diurnal variations of less than 0.3% (Pomerantz and Duggal, 1974). Cosmic ray ionisation has a latitudinal dependence, with the Earth’s magnetic field shielding the atmosphere more effectively in equatorial regions. At magnetic latitudes higher than ∼60°, the near vertical magnetic field provides an ineffective shield to cosmic radiation and atmospheric ionisation is approximately uniform in the high-latitude regions (Hays and Roble, 1979). Energetic particles of solar origin may increase the ionisation of the upper regions of the ground-to-ionosphere path in the polar regions, causing polar-cap absorption events. Tinsley (2000) presents a model of the global electric circuit with variable separate resistances assigned to high and mid-latitudes and to the tropospheric and stratospheric parts of the circuit. Cosmic rays can alter the resistances in such a model circuit somewhat independently, depending on the type of event. Even if atmospheric conductivity is a passive component in the global circuit, cosmic rays variations will influence ground-level geoelectric field measurements with the effect varying at different sites and being event specific.

Considering the magnitude of the cosmic ray variations discussed above, significant solar cycle variations in ground-level electric field magnitudes are expected, and the influence of Forbusch Decreases can be found by careful time-alignment and the summing of events (Reiter, 1992, pp. 409–419) but diurnal and seasonal influences within a year-long data set are likely to be minor.

We have examined ground-level neutron intensities at Mawson (67.6°S, 63°E; corrected geomagnetic latitude, 70.2°S) for the Vostok ‘fair-weather’, days in 1998. The Mawson neutron data provides 97% hourly coverage. The average neutron intensities, relative to the yearly average, are +0.7% for the NH winter, +0.3% for the equinoctial months and −1.5% for the NH summer days. While it is not certain whether these variations in high-latitude ionisation would increase the ground-level geoelectric field measurements at Vostok (that depends principally on the associated relative variations at mid-latitudes), they are insufficient to account for the discrepancies between the Vostok and Carnegie seasonal magnitudes.

Complete 24-h Mawson neutron intensities are available for only 125 of the 134 days. For these 125 days the average diurnal range is only 0.6%, with minimal variation from this value for the seasonal splits (NH winter, 0.6%; equinoctial months, 0.7%; NH summer, 0.7%). Variations of these magnitudes will have an insignificant influence on the Vostok seasonal diurnal geoelectric field ranges.

The physical process via which large-scale features in the cross-polar-cap potential differences influence ground-level, vertical electric field measurements is well established (Park, 1976b; Hays and Roble, 1979). Experimental difficulty arises in confirming a statistically significant linkage amongst the noise. At ground level, meteorological conditions can significantly influence the atmospheric conductivity and thus the geoelectric field measurements (see, for example, Burns et al., 1995; Frank-Kamenetsky et al., 1999). Variability in global thunderstorm intensity is another significant source of noise when making this comparison. The values ΔEs and Δφ are introduced to remove the day-to-day variability in both these sources of noise.

The difficulty of establishing statistically significant linkages between ΔEs and Δφ is indicated by the low values of the coefficient of determination, ρ2, presented at the end of Section 4. Conversely, 1 − ρ2, is indicative of the amount of un-attributed variation. As a significant proportion of this is likely due to site-specific meteorological variability influencing local atmospheric conductivity, it is difficult to assign a physically useful interpretation to the low ρ2 values.

If average diurnal variations in conductivity at a site are not significant, a fact established for the Vostok site to the extent that the Vostok and Carnegie diurnal curves are similar, then the slopes of the linear regressions between ΔEs and Δφ should be constant for all hours. For these Vostok
measurements, this constant value is $\sim 0.71 \, \text{Vm}^{-1}/\text{kV}$, as previously introduced. By using two models and determining the chance probability of $\Delta E_s$ and $\Delta \phi$ being associated for individual UT hours, we can consider whether the variations obtained relate to difficulties of determining the polar-cap potential differences from solar wind data (the aim of both models) or the methods used to derive the models. The diurnal variation of the slope of the linear regression between $\Delta E_s$ and $\Delta \phi$ when these values are significantly associated can be compared to $0.71 \, \text{Vm}^{-1}/\text{kV}$ to determine how appropriately the two models respond to solar-wind-induced variations in the potential difference above Vostok.

Frank-Kamenetsky et al. (1999) used the IZMEM model to investigate the cross-polar-cap potential difference influence on geoelectric field measurements for 36 fair-weather days at Vostok from 1979. They adopt an analysis procedure similar to that presented here, and found significant associations for six individual UT h. Using the Weimer model and a modern digital data set we have found significant associations for 19 individual UT h. The improvement appears to be principally due to the change of model, as the same IZMEM model tested against the modern data set was significantly associated for only nine individual UT h.

The hours for which the Weimer polar-cap potential differences were not significantly associated were dominantly located either side of magnetic midnight ($\sim 1$ UT). The polar-cap potential differences are magnetic coordinate associated phenomena and a degree of magnetic symmetry is understandable. However, the post-magnetic midnight interval of non-significant associations (2.5–4.5 UT) is broader than the pre-midnight interval (22.5 and 23.5 UT; see Fig. 4) and may be additionally related to local conductivity variations around local noon as previously discussed. Both the Weimer and IZMEM models seek to determine the polar-cap potential difference pattern from solar wind parameters. The solar ionosphere directly linked to the dayside magnetosphere may be more predictable from solar wind parameters whereas nightside activity may be less directly related due to storage and release mechanisms associated with the magnetotail. It is thus interesting that three significantly associated Weimer-model UT hours, 23.5 to 1.5 UT, extend across magnetic midnight. The chance probability of the associations of $\Delta E_s$ and $\Delta \phi$ values for these particular hours while less than 5% are, however, larger than for most of the dayside hours, possibly reflecting this less direct association.

The nine significantly associated, IZMEM model, UT hours occur in the range from 0.5 to 16.5 UT. The six significantly associated, IZMEM model, UT hours in the analysis of Frank-Kamenetsky et al. (1999) are covered in the range 3.5–14.5 UT. The results of the two analyses are similar if some allowance is made for the larger modern data set. The 1994-version of the IZMEM model used in both these investigations derives polar-cap potential difference patterns from ground-based magnetic measurements and an E-region conductivity model. The magnetic signature of an imposed polar-cap potential difference is larger and thus more readily distinguished when there is significant ionisation in the altitude range that ionospheric currents flow (120–160 km). The two principal sources of ionisation at these altitudes are solar EUV electromagnetic radiation and charged particle precipitation. At the magnetic latitude of Vostok, charged particle precipitation will be generally centred on magnetic noon. The ease of discerning the ground magnetic signal of the polar potential difference pattern may be a contributing factor to the hours for which $\Delta E_s$ and $\Delta \phi$ are significantly associated, extending only slightly beyond the interval between local noon ($\sim 5$ UT) and magnetic noon ($\sim 13$ UT).

The difference in the number of hours of significant associations between $\Delta E_s$ and $\Delta \phi$ for the Weimer and IZMEM model analyses may indicate advantages of the Weimer model inputs over those of the IZMEM model. Both models use IMF $B_z$, as solar wind input parameters, but the Weimer model uses solar wind speed as a third parameter rather than IMF $B_z$ (IZMEM). The Weimer model has a continuously variable seasonal parameter, the dipole tilt angle, whereas IZMEM allows for broad seasonal variations via splitting data into summer, winter and equinox intervals. Satellite measured ionospheric electric fields are more direct measurements of polar convection than ground-based magnetometer measurements that require interpretation via an E-region conductivity model. This may specifically explain the Weimer model’s better performance on the nightside for the Vostok site. The IZMEM model has been recently upgraded by incorporating satellite measurements of ionospheric electric fields into a new derivation (Papitashvili et al., 1999).

The diurnal variation of the slope of the linear regression between $\Delta E_s$ and $\Delta \phi$ indicates how appropriately the two models respond to solar wind induced variations in the potential difference above Vostok. The variation of the Weimer model potential difference above Vostok as the solar wind varies is too small between 5.5 and 8.5 UT (average slope $\sim 1.3 \, \text{Vm}^{-1}/\text{kV}$) and between 18.5 and 20.5 UT (average slope $\sim 1.1 \, \text{Vm}^{-1}/\text{kV}$) and consistent with ground level measurements of the vertical geoelectric field across the other hours for which significant associations are obtained (23.5–1.5 UT, 9.5–13.5 UT, 15.5–17.5 UT and 21.5 UT; average slope $\sim 0.71 \, \text{Vm}^{-1}/\text{kV}$; see Fig. 4). Variation of the IZMEM model potential difference above Vostok as the solar wind varies is consistent with ground level measurements of the vertical electric field between 11.5–14.5 UT, and 16.5 UT (average value $\sim 0.68 \, \text{Vm}^{-1}/\text{kV}$) and too large across other hours for which significant associations are obtained (0.5, 3.5, 5.5 and 6.5 UT; average slope $\sim 0.41 \, \text{Vm}^{-1}/\text{kV}$; see Fig. 5).

6. Conclusions

When examining geoelectric field measurements collected at high-latitude sites for evidence of the global
circuit, it is necessary to first remove the influence of the polar-cap convection.

- We have demonstrated a method of making this correction by using the Weimer model to calculate and remove the influence of the cross-polar-cap potential differences above Vostok.
- The most significant improvement for the high magnetic latitude site of Vostok (83.4°S) is the increase in the range of the diurnal curve, making it equivalent to the appropriate Carnegie value.
- The annual variation in the magnitude of the geoelectric field at Vostok, with a peak magnitude in the NH summer and a minimum in the NH winter is consistent with the annual variation in global thunderstorm activity.

An array of geoelectric field instrumentation on the Antarctic plateau has been proposed by previous authors as a passive method of inferring the instantaneous polar-cap convection pattern independent of any E-region ionisation. Byrne et al. (1991); Bering et al. (1991); Byrne et al. (1993); Tinsley et al. (1998). Our analysis supports the feasibility of this project by using single-site geoelectric field measurements to investigate and compare two polar convection models derived from solar wind parameters.

- The Weimer model (significant associations of $\Delta E_y$ and $\Delta \phi$ for 19 separate hours) better represents the variations in the cross-polar-cap potential difference above Vostok due to solar wind fluctuations than IZMEM-1994 (significant associations of $\Delta E_y$ and $\Delta \phi$ for 9 separate hours).

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