THE GROUND-LEVEL ATMOSPHERIC CURRENT RESPONSE TO A MAGNETIC SUBSTORM

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ABSTRACT

We have analysed air-earth vertical currents (AECs) measured at Esrange, northern Sweden, using a long-wire antenna during 35 geomagnetic substorms. Using superposed epoch analysis we compared the AEC variation during the 3 hours before and after the time of the magnetic X-component minimum with that for 35 days under quiet geomagnetic conditions. We have obtained a clear decrease with time of AEC for both quiet and disturbed data sets during the whole interval under consideration. This corresponds well to the classical behaviour of fair-weather current and electric field around midnight due to changing global thunderstorm activity. We also found that, for the substorm group, the AECs are larger than that for quiet conditions during about 2 hours before the time of geomagnetic X-component minimum. This increase is rather small compared to the background daily variation. The significance of the result was confirmed using statistical analysis. The large-scale ionospheric electric field, enhanced during substorms, can map efficiently to the ground and might be responsible for the AEC increase. We have been able to find support for this interpretation in ionospheric electric fields measured using STARE. We present also modelling results for mapping the electric field from the ionosphere to the ground.

INTRODUCTION

The global atmospheric electric circuit is a complex electrical system. Thunderstorms occurring in the tropics produce upward currents from the ground to the ionosphere. These are spread all over the globe and returned to the ground through the fair weather regions. Thunderstorms maintain the potential difference between the ground and the ionosphere at about 250 kV (Roble and Tzur, 1986). The ionospheric potential drop of ca.100 kV across the polar cap which results from the coupling between the solar wind and Earth's magnetosphere is also important. It can give 20-25% difference in electric field magnitude for high and middle latitudes. Park (1976) estimated this effect theoretically. Recently Tinsley et al. (1998) and Frank-Kamenetsky et al. (1999) reported a correlation between South Pole ground-level electric field and overhead ionospheric electric potential.

However, the distribution of the ionospheric electric field can be changed during magnetospheric substorms, which are rather common phenomena at high latitudes. These might reasonably be expected to modify the local atmospheric electric circuit. The problem is how to extract a small effect due to a substorm against a background of large variability in air-earth atmospheric current (AEC) caused by other reasons. These are variations in local wind, cloudiness, cell-structured convection, mechanical vibration of the antenna and other instrumental and recording factors (Tammet, 1991). We use for this a superposed epoch analysis for AEC. The goal of this paper is to determine the effect of geomagnetic substorms on AEC, to explain the observed phenomena, to test the explanation using STARE data on ionospheric electric field, and finally, to use an analytical model for mapping electric field from the ionosphere to the ground to estimate the probable effect.

EXPERIMENTAL RESULTS

Observations of the fair weather current were made using a long wire antenna (length 100 m, diameter of about 2 mm) located near the top of a hill at Esrange (67°N, 21°E), Sweden. It collects the atmospheric vertical currents flowing above it from an effective area of about 200 m^2 (Tammet et al., 1996), and the current data were recorded every 1 minute.

As key times (t=0) for superposed epoch analysis we used the times when the north-south component of the geomagnetic field detected by the Kiruna magnetometer (35 km west of Esrange) reached a minimum during the substorm. We included only substorms occurring near local midnight and with magnetic variations exceeding 300 nT. In addition, we restricted the events to single magnetic bays, i.e. there were no new substorm intensifications for at least the next 2.5 hours. We summed up the values of AECs for all substorm events during an interval of 3 hours before and 3 hours after the key time. Before summing, the AECs show substantial scattering in the data values. Since the substorm intensity can vary from one event to another, we chose to normalise our currents before

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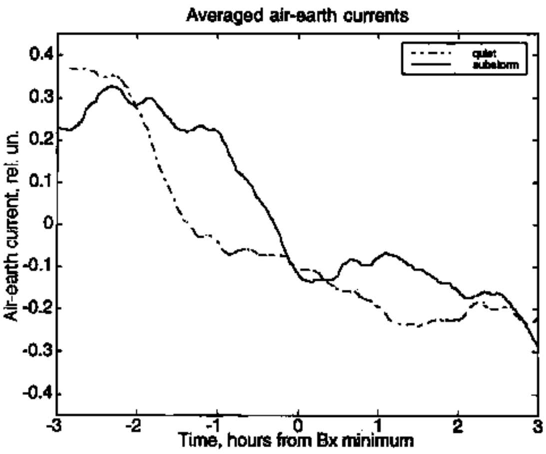

Figure 1. Normalised and running averaged air-earth currents obtained using superposed epoch analysis for the interval from 3 hours before to 3 hours after the time of the geomagnetic X-component minimum. Dashed line for 35 cases under quiet geomagnetic conditions, solid line for 35 cases during magnetic substorms.

analysis to the values at key times. For comparison we repeated the same procedure for both substorm and non-substorm groups, each of them consisting of 35 events, occurring between September 1998 and March 1999. In Figure 1 the results of the superposed epoch analysis for air-earth currents both under quiet conditions and during the substorms are shown. To suppress the great variability of currents we have made a running average of currents over 65 minutes. A decrease of AECs during the whole interval is clear seen for both cases. This is most likely due to daily variations of global thunderstorm activity, the main generator of atmospheric current. There is another feature: the disturbed "substorm" current is larger than the undisturbed one during approximately 2 hours before the time of the magnetic X-component minimum. At later times, both currents show similar behaviour.

As AECs have strong random fluctuations, and the difference between AECs corresponding to substorm and quiet conditions is not large, we need to test the reliability of the results using statistical methods. For this we have introduced 3 indices characterising a mean value of AECs, their fluctuation level and the shape of curves in Figure 1. From physical consideration these indices should change due to substorms. The hypothesis that substorms don't affect the values of the selected indices was tested using the Van der Warden X-test. It was rejected for all 3 indices that allow us to proceed with interpretation of the substorm effect on AEC.

INTERPRETATION OF THE RESULTS

The ionospheric electric potential pattern has a two-cell structure (e.g. Weimer, 1999), with positive potential for the dawn cell and negative for the dusk cell. The transition region between the cells at auroral latitudes corresponds roughly to the Harang discontinuity region for ionospheric currents. It is located in the local midnight sector. When mapping electric field from the ionosphere to the ground, we obtain that northward electric field corresponding to the negative dusk cell converts to upward vertical electric field near ground and should thus lead to a decrease of fair-weather current. And vice versa, southward electric field of the positive dawn cell maps to the ground as downward and should produce an enhancement of AEC. During substorms occurring near local midnight, enhanced convection is usually observed, implying enhanced electric field also.

By superposed epoch analysis we obtained that the AEC is increased during the interval roughly corresponding to the growth and expansion phase, compared to the recovery phase. If our site is close to the longitude of substorm onset, we would expect it to lie under the dusk convection cell during the substorm growth phase. An enhanced convection in this cell would map to increased upward vertical electric field at the ground and reduced AEC.

The possible explanation is that our site might rather often be far east from the onset region but we can still detect the depression of the magnetic X-component if we are not too far from the westward auroral electrojet. In this case we might have enhanced southward electric field overhead our site even during substorm growth and onset phase, which could lead to the observed increase of vertical downward atmospheric current.

To check this we have analysed ionospheric electric field data derived from STARE measurements of electron drift velocity in the E-region (Zi and Nielsen, 1982). Unfortunately, the data are available only over Tromso, that is about 300 km N-W from Kiruna. Moreover, we are limited to 15 events with substorms and 9 events for quiet conditions because the STARE technique allows measurements only when the field exceeding 15 mV/m. Because the data were rather scarce for undisturbed conditions, we averaged the ionospheric electric field over all 9 events. In Fig. 2 the distribution of averaged electric field vectors during the 3-hour interval before local midnight is shown. Absence of data indicates that the E field was below the STARE threshold. We have no possibility here to discuss the E field behaviour in detail. We note only that the electric field reverses its direction from northward to southward first near 2135 UT. However after 2150 UT the E field vector turns to the north again briefly, and becomes mostly southward after 2220 UT. Figure 3 is similar to Figure 2, but for one selected substorm on November 6, 1998. We have chosen this event among the 15 available because of a very clear substorm pattern of electric field. The minimum in the geomagnetic X-component occurred at 2235 UT. We have also estimated substorm onset times using information on

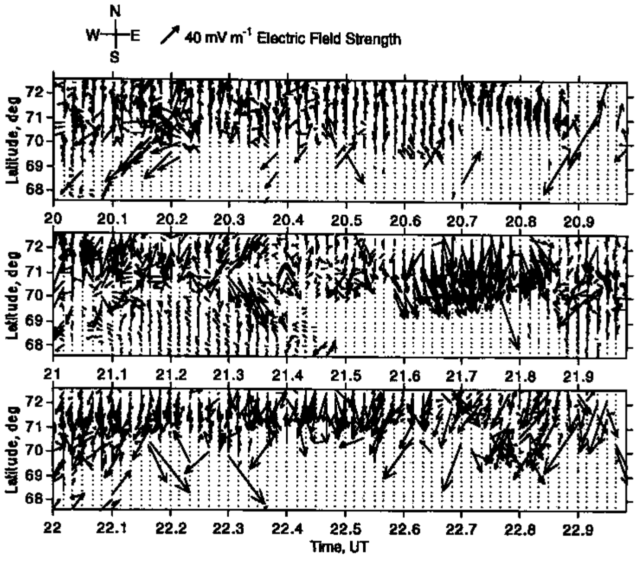

Figure 2. Latitude-time distribution of the E-region ionospheric electric field derived from STARE data and averaged over 9 quiet days. The data were integrated over 1 minute in time and over 18°-20° in longitude.

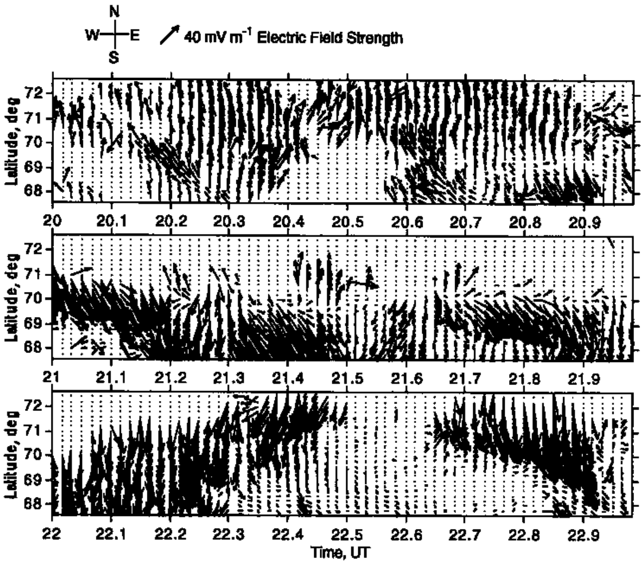

Figure 3. The same as in Figure 2 but for the substorm on November 6, 1998.

Pi2 pulsations recorded by the Kiruna magnetometer - the onset was at 2218 UT. However the electric field turned from near northward to southward direction, at least for the lowest latitude (67.6°), at 2045 UT, approximately 1.5 hour before the onset time. We can conclude that during this period enhanced southward ionospheric electric field could increase fair weather current flowing downward from the ionosphere to the ground. We believe it is very likely that the electric field distribution pattern at Kiruna's latitude (67°) shows the same behaviour. This implies that ionospheric electric field could be responsible for the AEC increase during the growth and expansion phases of substorms. We should note that similar behaviour in the E field is observed in 11 out of 15 events that have been analysed. It might mean that for most of the substorm events considered, our site rather often was far east from the onset region. In this case we might have enhanced southward electric field overhead our site even during substorm growth and onset phase, which could lead to the observed increase of vertical downward atmospheric current.

MODELLING

Now we will consider theoretically the problem of mapping horizontal electric field from the ionospheric level to the ground. This problem is not new, there are a lot of papers (Boström and Fahleson, 1974; Dejnakarintra et al., 1985), in which the problem was solved numerically under different conditions and initial parameters. We restrict our analysis to the electrostatic case as in Park (1976) but find a new analytical solution.

We search for a solution of the following equation for the electric-field potential φ:

$$\mathrm{div}(\sigma \cdot \mathrm{grad}\varphi) = 0$$

where σ is an atmospheric conductivity which increases exponentially with height with characteristic scale L_σ.

As boundary conditions we use, at the ionospheric level z_0 , a potential disturbance in the form of a plane wave with a characteristic scale of ionospheric potential perturbation L, and vanishing potential on the ground. We obtain a solution in the form:

$$\varphi = \varphi_0 \frac{\sinh(z\sqrt{\beta^2 + k^2})}{\sinh(z_0\sqrt{\beta^2 + k^2})} \exp(\beta(z - z_0)) \cdot \exp(ikx)$$

Here $\beta=(2L_\sigma)^{-1}$ and $k=2\pi/L$ is a wave number.

Using STARE data on the electric field for the magnetically quiet situation, and for the substorm on November 11, 1998, we estimated (for one latitude) an amplitude of substorm variation in north-south electric field component for the interval 2045 UT - 2235 UT as being about 100 mV/m. Then, with the help of the above analytical solution we get a magnitude of AEC disturbance due to the substorm as a function of L and atmospheric conductivity parameters. Assuming the potential difference Φ_i between the ionosphere (z_0=100 km) and the ground being equal to 280 kV (Roble and Tzur, 1986) and using an exponential law for atmospheric conductivity, we obtain an expression for undisturbed AEC magnitude at the ground. In Fig.4 we present the AEC disturbance due to the substorm, normalised by AEC undisturbed value versus characteristic scale of ionospheric potential L. Three values of conductivity scale L_σ are considered. The

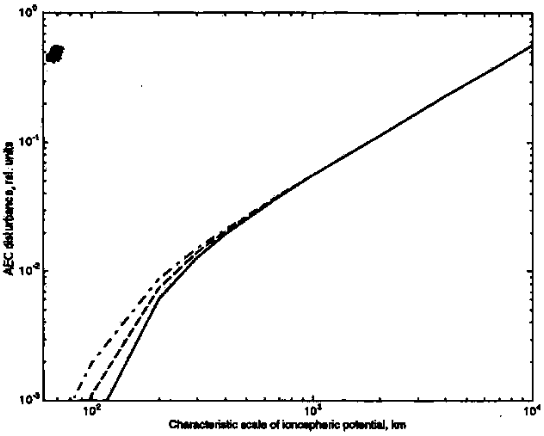

Figure 4. AEC disturbance due to a substorm normalised by the undisturbed value and calculated for $L_\sigma = 3$ km (dashed-dotted line), 5 km (dashed line) and 8 km (solid line) as a function of the characteristic scale of the ionospheric potential.

influence of this parameter is important only for ionospheric disturbances on scales less than 300 km, but then the effect in current is rather small. This effect becomes essential (more than 10% of the undisturbed value) if there is ionospheric electric field disturbance on the scale of 2000 km or more. Assuming, for the substorm under consideration, that the disturbance lasted for 2 hours, yields a characteristic scale of about 1300 km, and an effect in AEC of about 7%. All estimates seem to be realistic for the common substorm situation.

SUMMARY

We have considered the effect of substorms on air-earth current measured near the ground. Using AEC data from a long-wire antenna and Kiruna magnetic data we have performed a superposed epoch analysis for 35 substorms and 35 quiet intervals. We obtained that during about 2 hours before the time of geomagnetic X-component minimum (key time), the AEC increases compared with the level under quiet conditions. A statistical test was used to prove or reject the suggested hypothesis that substorm doesn't influence AEC. The test showed that AEC mean value, the relative fluctuations of the AEC and shape of AEC versus time curve do change significantly for substorm conditions. To find a reasonable interpretation of these results we analysed the behaviour of ionospheric electric field derived from STARE data. We found that for 11 substorm events out of the 15 available, enhanced ionospheric electric field with a southward direction was observed for about 1.5-2 hours before the key times. Mapping these fields to the ground can give an increase of downward AECs. This might be the explanation of the effect we found in AEC if, for most of the 35 substorm events under consideration, the substorm onset region was localised far east from our observation point. We also obtained an analytical solution for the problem of mapping the ionospheric electric field to the ground and applied it to the real substorm situation. The values obtained for the AEC effect and for parameters of ionospheric disturbances during substorms are realistic and close to those observed.

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