The relationship between variations of the atmospheric electric field in the southern polar region and thunderstorm activity

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Abstract

Observations of the atmospheric, near-surface vertical electric field component $E_z$ have been carried out at the Russian–Antarctic station, Vostok, since 1998 under the framework of a cooperative Russian–Australian project. Only data satisfying “fair weather” conditions are selected for the subsequent analyses. Behavior of $E_z$ field at Vostok station is compared with thunderstorm occurrence determined from a network of ELF magnetic field measurements in April 1998 and with simultaneous VLF emission measurements at Halley Bay (Antarctica). We find no correlation between the 5 min averages of $E_z$ and the lightning flashes intensity or between $E_z$ and VLF emissions, although significant correlation between $E_z$ and VLF emissions is observed in particular cases. The same statistical results have been obtained from a comparison of hourly averaged values. Moreover, even the mean diurnal variation of electric field derived for 10 fine weather days in April 1998 turned out to be inconsistent with the mean diurnal variation of the lightning flashes for the same days. Reasons of these inconsistencies are discussed.

Keywords: Atmospheric electric field; Southern polar region; Thunderstorm activity

1. Introduction

Long-standing measurements of electric parameters at the ground level are indicative of a vertical electric field of intensity about 100 V/m and electric current of intensity about $2 \times 10^{-2}$ A/m$^2$. Electric fields have also been observed in the stratosphere (Markson, 1977). The theory explaining the existence of the electric field put forward by Wilson (1920) included the global electric circuit with the charging currents in the thunderstorm areas and discharging currents at all other sites. The main experimental support of this theory is the fact that the universal daily variation of the electric field measured over the ocean regions (“Carnegie curve”) is consistent with the daily change of the total area occupied by thunderstorms over the Earth (Alderman and Williams, 1996; Bering et al., 1998). A quasi-static model of global atmospheric electricity, with thunderstorm clouds as generators of the electric field, has been developed by Hays and Roble (1979). The near-surface electrical environment can be significantly influenced by the cross-polar cap voltage controlling the high-latitude ionospheric electric fields (Markson, 1978; Roble and Hays, 1978). Indeed, measurements of the near-surface atmospheric electric field on the high-altitude, dry Antarctic plateau shows some influence of the interplanetary magnetic field (IMF) on the variations of $E_z$ (Park, 1976; Frank-Kamenetsky, 1983; Tinsley et al., 1998; Burns et al., 1995; Frank-Kamenetsky et al., 2000). The contribution of global cloud-to-ground lightning activity to the atmospheric electric field in Antarctic has been examined by Fullekrug et al. (1999).
The hourly recordings of the atmospheric electric field on the surface of the Earth at South Pole and simultaneous ELF magnetic field measurements from 10 to 135 Hz have been used for analysis. Results of the analysis of Fullekrug et al. (1999), show that the mean diurnal variation of the ELF magnetic field and the atmospheric electric field exhibit a remarkable similarity in shape and phase. In this paper we present a similar analysis of measurements of the ground electric field at the Antarctic station Vostok, simultaneous VLF emissions at Halley Bay stations and the triangulated lightning flashes available for April 1998.

2. Instrumentation, data, method of the analysis

A rotating dipole, electric field mill, produced in the Australian Antarctic Division is used at Vostok station, Antarctica, to register the atmospheric electric field. In our analysis we use 5 min averaged data of the electric field, $E_z$, derived from 10 s measurements. Only observations taken in conditions of “fair weather” have been used; that is during the absence of a strong wind, falling or drifting snow, clouds, and of any electric field “pollution” from the station power plant (see Frank-Kamenetsky et al., 2001). The accuracy of the $E_z$ measurements was 1 V/m. The flash occurrence was determined from a network of electromagnetic field measurements, described by Fullekrug and Constable (2000) with accuracy up to microsecond. To examine the influence of lightning flashes on the global electric circuit, we divided all the data on lightning flashes into two parts according to their sign. Thereafter the 5 min averaged charge was determined as the 5 min summation divided by a number of corresponding flashes in the 5 min range. The currents associated with negative or positive lightning flashes would charge or discharge the global electric circuit, respectively. VLF emissions from at the British station, Halley Bay, Antarctica have been examined in range from 0.5 to 10.2 kHz. A comparative analysis of the variations in the near-surface electric field at Vostok, the lightning flash occurrence, and VLF emissions has been undertaken for 10 days in April 1998 (10–19) corresponding to the days of fair weather conditions at Vostok with available data about lightning flashes. In addition, the relationship between the amplitude of the VLF emission at Halley Bay and the intensity of the electric field at Vostok has been examined for all months of 1998.

3. Results of the analysis

Fig. 1 shows, as an example, the behavior of the electric field (1 min data) and lightning flashes (original data and with 5-point smoothing) on April 16. One can see the general inconsistency in the running of these two parameters. The inconsistency does not seem to be surprising if we take into account the quite different resolution of data presented in Fig. 1. That is way in our further analysis we compared variations of the 5 min averaged intensity for positive and negative lightning flashes with the 5 min averaged values of electric field observed at Vostok station. Fig. 2(a) and (b) show the behavior of electric field and positive and negative lightning flashes on April 10 and 11, 1998. These two days are characterized by an obvious tendency for an increase (Fig. 2(a)) or decrease (Fig. 2(b)) of electric field during a day. The same lack of correlation between the 5 min averaged values of electric field and electric current is typical of the other 10 examined days.

We also calculated the mean diurnal variation of the electric field at Vostok station for the 10 days with fine weather and the corresponding diurnal variation of the lightning flashes intensity. Fig. 3 shows the mean diurnal variation for intensity of the positive and negative flashes and for the atmospheric electric field. One can see that intensity of positive and negative flashes slowly decrease from 00 UT to 10 LIT, after that time they start to increase, reach a maximum (positive flashes at 16–18 UT, negative flashes at 18–20 UT), then their intensities slowly decrease. The total intensity is negative and close to zero before 07 UT and positive after this time with a maximum value at 14 UT. The mean diurnal electric field variation at Vostok is shown on lower panel of Fig. 3 along with the curve of polynomial smoothing of order 5. One can see that the mean diurnal electric field variation at Vostok is not consistent with either the diurnal variation for the positive flashes or the diurnal variation of the total lightning intensity.
Correlation between VLF emissions registered at Halley Bay and the electric field variations turned out to be extremely unstable: the coefficients of correlation between the intensity of $E_z$ and VLF amplitude vary from day to day ranging from 0 to ±0.9, and there is no regularity in their changes. Fig. 4 shows changes of the hourly atmospheric electric field at Vostok station, intensity of positive lightning flashes and amplitude of VLF emission (9.3 kHz) at Halley Bay for April 12–13, 1998.

Fig. 2. Variations of the 5 min averaged values of electric field observed at Vostok station and the 5 min averaged intensity for positive and negative lightning flashes in cases of April 10 (a) and April 11 (b), 1998.

Fig. 3. The mean diurnal variation of intensity for the positive, negative, total lightning flashes and atmospheric electric field.

Fig. 4. Changes in the hourly values of the atmospheric electric field at Vostok station, intensity of positive lightning flashes, and amplitude of VLF emission (9.3 kHz) at Halley Bay for April 12–13, 1998.
VLF emission (9.3 kHz) at Halley Bay for April 12–13, 1998. One can see rather good correlation between the lightning flashes and VLF emission: the intensity of both varies almost synchronously over these two days, reaching maxima and minima at the same time. By contrast, the $E_z$ intensity runs irrespective of variations in lightning flashes and VLF emissions. The same regularity takes place for other days of April 1998: the mean correlation between the positive thunderstorm flashes and the amplitude of the VLF emissions remains around $R = 0.6$, whereas the correlation between the thunderstorm flashes and $E_z$ intensity as well as between the VLF emissions and $E_z$ did not exceed a value of $R = 0.2$. Therefore, the atmospheric electric field at Vostok station does not seem to be influenced by lightning flashes at low latitudes.

4. Discussion

Our results show that variations of the atmospheric near-surface electric field at Vostok station are not guided, or are only slightly influenced by positive or negative lightning flashes. The following hypotheses can be proposed to explain the indifference of the electric field at Vostok to lightning flashes: (1) the contribution of lightning flashes to the potential difference between the ionosphere and the Earth’s surface is not decisive factor for this difference; or (2) the influence of the magnetospheric electric field is more crucial for the near-pole region.

Indeed, the commonly accepted model of the global electric circuit includes the current generator operating in the thunderstorm clouds. This generator acts owing to the electrification typical of clouds: charge separation processes fill the upper portion of the thundercloud with pre-dominantly positive charge and the lower portion with negative charge. A conduction current flows from the positively charged top of the cloud toward the ionosphere and into the global circuit. Measurements by Gish and Wait (1950), Stergis et al. (1957), Vonnegut et al. (1966, 1973), Kasemir (1979) show that the total current flowing upward from thunderstorms areas is about 0.7 A per thunderstorm cell. These few data indicate that a positive current flowing toward the ionosphere is of sufficient magnitude to account for the fair-weather conduction current. The thunderstorm current generator is regarded as quasi-static, acting irrespective of lightning flashes. Indeed, Krider and Musser (1982) show that the average Maxwell current density is usually not affected by lightning discharges and varies slowly throughout the evolution of the thunderstorm. They infer that the cloud electrification processes are substantially independent of the electric field connected with lightning flashes. So, the Maxwell current represents an electric quality that is coupled directly to the meteorological structure of the storm.

Quasi-static models like those of Holzer and Saxon (1952) and Hays and Roble (1979) may describe the state of the electric field when the thunderstorm clouds are developed (or recovered), in absence of lightning flashes. A non-steady model is required to take into account the lightning generators. A model of thunderstorm electric currents including the conduction and displacement currents, associated with the charging mechanism, as well as intra-cloud and cloud-to-ground lightnings, has been developed by Driscoll et al. (1992). This research has demonstrated that the lower atmosphere’s time-averaged steady state electrical response to a simple bipolar thunderstorm is similar in magnitude to the atmosphere’s complete time-varying response, even when thunderstorm is producing a considerable amount of lightning. The problem of establishing a quasi-static electric field while accounting for the lightning generators, and the problem of changes in the electric state of the atmosphere under periodical current oscillations in the thunderstorm generators has been examined by Morozov (1992). Estimations made by Morozov (1992) show that input of the lightning generators in the total electric potential between ionosphere and Earth’s surface is small (~4%) in comparison with the regular thunderstorm generator.

The results of our analysis seem to be consistent with the results of the above examined model and experimental studies. Indeed, if the lightning input in the total potential difference between the Earth’s surface and ionosphere is small, the regular correlation between the lightning rate in the tropical zone and atmospheric electric field at the polar cap Vostok stations can be found only against the background of the extremely stable state of the global electric circuit. Meanwhile, the influence of the magnetospheric electric field and corresponding changes in the ionospheric cross-polar cap voltage turns out to be important within the polar cap. Indeed, the effects of the IMF variations are obvious in the behavior of the atmospheric electric field at the near-pole station Vostok, where statistical input of the magnetospheric electric field in the atmospheric electric field is about 10% in average, and can be much more in particular events (Frank-Kamenetsky et al., 2000).

5. Conclusions

- Comparison of the atmospheric electric field variations observed at Vostok station and the lightning flash intensity for 10 fine weather days in April 1998 does not show any significant correlation between the 5 min averaged values of electric field and flashes, as well as between the hourly averaged values. The mean diurnal variation of electric field over 10 days is inconsistent with the mean diurnal variation of the equivalent electric currents for the same days.
• Inconsistency between the global thunderstorm intensity and variations of the atmospheric electric field at Vostok station suggests that the electric field in the southern near-pole region is influenced by lightning flashes less effectively than by electrodynamics processes in the magnetosphere.

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References
