The Enhancement of High Energy Electron Fluxes and the Variation of the Atmospheric Electric Field in the Antarctic Region (Postprint)

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Abstract

High-energy electron precipitation in the high latitude regions enhances the ionization of the atmosphere, and subsequently increases the atmospheric conductivities and the vertical electric field of the atmosphere near the ground as well. The high-energy electron flux (HEEF) data measured by the Feng-Yun III meteorological satellite are analyzed together with the data of near-surface atmospheric vertical electric field measured at the Russian Vostok Station. Three HEEF enhancements are identified and show that when the HEEF increases to a certain level, the local atmospheric vertical electric field near the ground can increase substantially than usual. The time of the response of the electric field to the HEEF enhancement is about 3.7 to 4 days (delay time).

Full Text

Preamble

The Enhancement of High Energy Electron Fluxes and the Variation of the Atmospheric Electric Field in the Antarctic Region

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Abstract: High-energy electron precipitation in high-latitude regions enhances atmospheric ionization, which subsequently increases atmospheric conductivities and the vertical electric field near the ground. We analyzed high-energy electron flux (HEEF) data measured by the Feng-Yun III meteorological satellite together with near-surface atmospheric vertical electric field data from the Russian Vostok Station. Three HEEF enhancement events were identified, demonstrating that when HEEF increases to a certain level, the local atmospheric vertical electric field near the ground can increase substantially above normal values. The response time of the electric field to HEEF enhancement is approximately 3.7 to 4 days (delay time).

Keywords: high-energy electron flux (HEEF), polar precipitation, atmospheric electric field

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0. Introduction

Solar energetic particles have been demonstrated to affect the mesospheric electric field as well as the atmospheric vertical electric field near the ground. Solar proton events (SPE) can create measurable changes in the ground-level electric field (~5% change) [?]. One consequence of SPE incidence in the middle atmosphere is the generation of enhanced charged particle densities and a substantial increase in middle and upper atmospheric conductivities [?]. Holzworth and Reagan argued that atmospheric electric field changes occur because atmospheric conductivities have changed [?, ?]. Frank suggested that the interplanetary magnetic field could also alter the vertical atmospheric electric field [?].

A working model linking the ground to the atmosphere is the global electric circuit (GEC), which results from thunderstorm activities [?]. This model is illustrated in Fig. 1 [Figure 1: see original paper] [?]. Thunderstorms act as a voltage source, V, driving current upward from the ground through the upper atmosphere (h_R). The current path extends through the stratosphere and is completed via downward currents in the fair-weather atmosphere (l_{oc}) in regions well away from the storm [?].

The vertical electric field of the atmosphere near the ground is primarily determined by the current density J_z. Solar wind modulates the flow of current density in the GEC through many independent mechanisms [?, ?, ?], including (a) galactic cosmic rays [?, ?], for which many complex numerical simulations have been performed [?, ?], (b) relativistic electron precipitation [?, ?], and changes in ionospheric potential distribution due to magnetosphere-ionosphere coupling [?, ?, ?]. Farrell and Desch found that SPE can decrease J_z in the thunderstorm region, which subsequently increases E_z [?]. The conductivity equation is:

The conductivity near the ground remains constant, according to Ohm' s law:

If J_z increases, the vertical electric field of the atmosphere near the ground (E_z) increases absolutely.

Relativistic electron precipitation can effectively enhance stratospheric ionization by generating X-rays. With increased ionization in the stratosphere, the local resistance between the stratosphere and troposphere (R_{loc}) decreases, thereby increasing J_z. According to equation (2), the vertical electric field of the atmosphere near the ground is affected—it will increase. Weather in storm regions could also be influenced. The precipitation of relativistic electrons can excite X-rays in the atmosphere, which then increase ionization in the lower atmosphere [?, ?], as shown in Fig. 2 [Figure 2: see original paper].

In Fig. 1, relativistic electrons enhance stratospheric ionization by generating X-rays. With enhanced ionization in the stratosphere, the local resistance between the stratosphere and troposphere (R_{loc}) decreases, and then J_z increases. Subsequently, the vertical electric field of the atmosphere near the ground would be affected, the electric field would increase, and weather in storm regions will be affected. According to the Gauss equation, $\rho = \varepsilon_0 \nabla \cdot E_z(z)$, where ρ represents the space charge generated by the electric field gradient. The electric field gradient changes the distribution of charge in clouds, affects cloud microphysics, and then changes weather and climate parameters [?, ?, ?], such as atmospheric vortices [?, ?, ?, ?], cloud cover [?, ?], and atmospheric transparency [?, ?].

1. Data Presentation

We used and analyzed HEEF data measured by the Feng-Yun III satellite in 2012 and vertical electric field of the atmosphere near the ground measured at the Russian Vostok Station ($78°06'S, 106°E$). We selected HEEF data during periods when the satellite flew over the Russian Vostok Station (the satellite passed through longitudes between $100°E$ and $115°E$, latitudes between $70°S$ and $90°S$, as seen in Fig. 3 [Figure 3: see original paper]). The satellite passed through this region nearly 2190 times in 2012, and we used a data-fitting method to study the tendency of these HEEF data. Three HEEF enhancement events were identified, with only one showing strong enhancement (Event 1 illustrated in Fig. 4 [Figure 4: see original paper], Event 2 in Fig. 5 [Figure 5: see original paper], and Event 3 in Fig. 6 [Figure 6: see original paper]).

Fig. 3 shows the position of the Russian Vostok Station and the HEEF data selection region during satellite overpasses (longitude between $100°E$ and $115°E$, latitude between $70°S$ and $90°S$). In Figs. 4 to 6, the top four panels show HEEF at different energy channels: (a) 0.15–0.35 MeV, (b) 0.35–0.65 MeV, (c) 0.65–1.2 MeV, and (d) 1.2–2.0 MeV. The black dashed lines represent the HEEF trend using the data-fitting method, and the red vertical lines on the left and right sides indicate the approximate times when HEEF begins to increase and when the electric field begins to enhance, respectively. Panel 'e' shows the vertical electric field of the atmosphere near the ground. Panels 'f' to 'h' represent solar wind parameters: (f) interplanetary magnetic field component, (g) solar wind velocity, and (h) solar wind kinetic pressure—these parameters come from ACE (Advanced Composition Explorer, USA). Panels 'i' to 'j' represent geomagnetic activity parameters: (i) Dst index and (j) AE index from Kyoto (downloaded from: http://omniweb.gsfc.nasa.gov/form/omni_min.html).

Figs. 4 and 5 show that when HEEF increases to a certain level, the vertical electric field of the atmosphere near the ground will increase substantially. The delay time for the electric field to begin increasing after HEEF enhancement is about 3.7 to 4 days.

Event 1 (Fig. 4): During the period from January 19 to January 31, an interplanetary disturbance from the sun occurred on January 22. B_z varied from +20 nT to -10 nT, solar wind speed varied from 300 km/s to 450 km/s, and plasma pressure enhanced from 2 nPa to 17 nPa. Afterwards, a geomagnetic storm generated near the time indicated by the left red dashed line, with Dst about -40 nT and AE index about 500 nT. These geomagnetic storms led to HEEF enhancement. Event 1 occurred in the interval between the two red dashed lines. HEEF began to increase at the time indicated by the left red dashed line. After HEEF declined to pre-enhancement levels, the electric field began to increase substantially at the time indicated by the right dashed line. There were two electric field enhancements in this event: the first lasted about 12.5 hours, and the second lasted about 15.3 hours. The time between the two red dashed lines was about 3.7 days.

Event 2 (Fig. 5): During the period from May 15 to May 24, a geomagnetic storm generated near the time indicated by the left red dashed line, with B_z about -5 nT, solar wind speed about 380 km/s, plasma pressure about 1 nPa, Dst about -20 nT, and AE index about 1000 nT. These geomagnetic activities led to the following HEEF enhancement. The ground electric field had some fluctuations between May 15 and May 17, which might have been caused by other factors (for example, winds). Event 2 occurred in the interval between the two red dashed lines. The electric field hardly changed during the HEEF enhancement and decline but began to increase after the time indicated by the right red dashed line. The enhancement lasted about 10.7 hours. The time between the two red dashed lines was about 4 days.

Event 3 (Fig. 6): During the period from August 24 to September 11, the ground electric field fluctuated before HEEF began to increase between August 25 and August 30, which may have been caused by other factors. Near the time indicated by the left red dashed line, B_z was about -4 nT, solar wind velocity about 340 km/s, plasma pressure about 1 nPa, Dst about -20 nT, and AE index about 400 nT. Geomagnetic activities generated near the time indicated by the left red dashed line led to HEEF enhancement, but it did not enhance obviously. Afterwards, HEEF declined to pre-enhancement levels, and the ground electric field did not change.

As shown in Fig. 4, Event 1 is more representative and obvious. Before the right red dashed line, the electric field remained almost unchanged at about 120 V/m, with no other factors affecting it. After about 3.7 days from when HEEF began to enhance, the electric field began to increase substantially. The peak value of the first enhancement was about 1200 V/m and lasted about 12.3 hours; the peak value of the second enhancement was about 1400 V/m and lasted about 15.3 hours. Afterwards, the electric field declined to pre-enhancement levels. Fig. 5 shows that there were some enhancements before HEEF began to increase, which might have been caused by other factors, probably wind (wind data checked from: http://www.wunderground.com/history/station/89606/2012/4/26/MonthlyHistory.html). However, the electric field remained almost unchanged during HEEF changes and started to increase at the time indicated by the left red dashed line. The enhancement lasted about 10.7 hours, and then the electric field declined to pre-enhancement levels.

While there were some HEEF enhancements in Event 3 (seen in Fig. 6), the electric field showed no fluctuations. This may be because HEEF did not increase to a level sufficient to cause electric field enhancement. We also consider that HEEF may not be the only factor causing electric field enhancement. Nevertheless, if HEEF increases to a certain level (flux is high, nearly 10^4 in the data analysis), the electric field can enhance substantially. It generally takes about 3.7 to 4 days for the electric field to enhance following HEEF enhancement.

Based on the transport path of high-energy electrons shown in Fig. 1, the following physical processes can be understood: High-energy electron fluxes first enhance in Earth' s radiation belts during magnetic storms. After plasma waves in space diffuse these high-energy electrons into the loss cone for atmospheric loss, the precipitation produces X-rays. Furthermore, X-ray emissions increase ionization of the middle-upper atmosphere at high-latitude regions, decrease local resistance R_{loc}, increase current density J_z, and then result in substantial increase of the vertical electric field of the atmosphere near the ground.

2. Discussion and Conclusion

We adopted HEEF data measured by the Feng-Yun III satellite and vertical electric field of the atmosphere near the ground measured at the Russian Vostok station ($78^\circ 06' S, 106^\circ E$) for analysis. We investigated the potential influence of HEEF enhancement on the vertical atmospheric electric field near the ground for three identified HEEF enhancements. By comparing them with the vertical electric field of the atmosphere near the ground, we found that while HEEF enhancement may not be the only factor causing electric field increase, if HEEF increases to a certain level, the electric field can enhance substantially. The delay time for the electric field to begin increasing after HEEF enhancement is about 3.7 to 4 days.

It takes some time for electrons to diffuse and decay. The Feng-Yun III satellite is a low-altitude satellite. The lifetime of high-energy electrons at low altitude has been modeled by Tu et al. [2010], and their case study showed that the lifetime of electrons was less than 10 days but longer than 1 day for almost all energy electrons [?]. In another paper, Li et al. [2001] found that the average electron lifetime is approximately 2.67 days at geostationary orbit [?]. The high-energy electrons in Event 1 enhanced around January 23. After about 2 days, the electrons began to precipitate. It might take about 1 or 2 days for the precipitated electrons to arrive in the atmosphere and then affect local conductivity. Therefore, according to data analysis, the time from HEEF enhancement to ground electric field fluctuations is about 3.7 to 4 days (delay time).

Based on the physical model, our data presentation can be used to explain how HEEF affects the vertical electric field of the atmosphere near the ground. Event 1 (seen in Fig. 4) shows that HEEF is a major factor that can affect the electric field of the atmosphere (excluding the possibility of wind induction).

The region where high-energy electrons collide with the atmosphere and cause direct ionization is above 50 km; however, X-ray production causes ionization down to 20 km (seen in Fig. 2). High-energy electrons can affect J_z by modulating conductivity between about 20 km and 60 km [?]. Low-energy electrons between 1 keV and 10 keV cannot excite X-rays and make less contribution to modulating conductivity compared to high-energy electrons.

During storm time, high-energy electrons precipitating from the inner and outer radiation belts interact with the middle and lower atmosphere. On one hand, precipitated electrons affect ionization through direct ionization; on the other hand, they affect ionization indirectly through bremsstrahlung radiation [?]. High-energy electrons with initial energy E_{k1} collided with atomic nuclei, after which the electrons lost energy, their energy became E_{k2} and excited X-rays (seen in Fig. 7 [Figure 7: see original paper]). The X-rays reacted with molecules in the atmosphere as follows:

(4.1) $h\nu + O_2 \rightarrow O + O$
(4.2) $h\nu + O_2 \rightarrow O^+ + O + e^-$
(4.3) $h\nu + N_2 \rightarrow N + N$
(4.4) $h\nu + N_2 \rightarrow N^+ + N + e^-$

The processes in equations 4.2 and 4.4 lead to ionization enhancement. Conductivity is strongly modulated by high-energy electron precipitation, which accompanies high-energy electron density enhancements. High-energy electrons precipitating from the radiation belt with associated X-ray bremsstrahlung lead to enhanced ionization in the middle and upper atmosphere and consequently to chemical changes [?], affecting local conductivity in the stratosphere. Therefore, increases in electron and ion density caused by high-energy particle precipitation increase the local upper-layer atmospheric electrical conductivity [?].

HEEF and X-rays enhance stratospheric ionization, increase conductivity, decrease resistance (R_{loc}), then the ionosphere-earth current density J_z increases, afterwards leading to ground electric field enhancement. The schematic of this process is shown in Fig. 7 [Figure 7: see original paper].

Meteorological effects show correlations between changes in the vertical electric field of the atmosphere and cloud microstructure. The varied static electric field can affect the electro-scavenging process near droplets, air ions, and aerosol particles. Reconstruction of space charge in clouds due to precipitation-associated changes in the vertical electric field can lead to potential variations in cloud microstructure, which may subsequently affect ambient temperature evolution with consequences for weather and climate at different scales. Electric field variations might cause changes in space charge at cloud boundaries, and there may be several ways in which this affects cloud microphysics and produces correlated changes in weather and climate [?]. Generally, storms and substorms caused by solar activities result in HEEF enhancement. Then, high-energy electrons precipitating in the atmosphere excite X-rays through bremsstrahlung. Afterwards, the precipitated electrons and X-rays increase atmospheric ionization, leading to local conductivity increase. Finally, increased conductivity causes the electric field to enhance. Therefore, space weather could affect weather variation and global climate change under some conditions.

Our data presentation and analysis have demonstrated that HEEF could modulate the atmospheric vertical electric field. Meanwhile, we have obtained a better understanding of how GEC is influenced by high-energy particles. We have made qualitative attempts to explain how HEEF affects the vertical electric field of the atmosphere near the ground. Future work will involve quantitative study of the relationship between them and how weather and climate will respond if precipitation-associated vertical atmospheric electric field changes.

3. Acknowledge

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Note: Figure translations are in progress. See original paper for figures.