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Impact of Various Sources of Disturbances on the Atmospheric Electric Field and the Lower Ionosphere †

Valentina Antonova *, Vadim Lutsenko, Galina Gordiyenko and Sergey Kryukov

Institute of the Ionosphere, JSC National Center for Space Research and Technology, Almaty 050020, Kazakhstan
* Correspondence: valanta@rambler.ru

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Abstract: The possible impact of solar activity on the atmospheric electric field, thunderstorm activity and lower ionosphere was investigated. The investigation was based on the electric field measurements and ionospheric observations at Alma-Ata (Kazakhstan). The investigation showed a decrease in the atmospheric electric field (~40 ÷ 50 V/m) under "fair" weather conditions, fluctuations under magnetic storms, and anomalous changes before and during significant and weak earthquakes. The study indicated a tendency for thunderstorm appearance with a 1–2-day delay after the impact of CME or HSS events on the Earth's magnetosphere. Noticeable changes in the lower ionosphere during these periods were found.

Keywords: thunderstorm activity; atmospheric electric field; earthquakes; effects in the ionosphere

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1. Introduction

The study of the interaction of dynamic processes occurring in different layers of the Earth's atmosphere and ionosphere is one of the most important fundamental problems of the physics of near-Earth space. Thus, interest in the problems of atmospheric electricity does not weaken. First of all, this is due to the understanding of the atmospheric electric field as an important environmental factor that is closely interconnected with other components in the Earth's atmosphere/ionosphere system [1] and affects human life. Ground-based data, in combination with satellite observations, will lead to a better understanding of the fundamental questions about the relationship between processes in the lower atmosphere–ionosphere region and to an understanding of the factors that control them. To date, not all processes in the atmosphere–ionosphere system are understood, especially their interrelation, which leads to the need for further research.

In the results of the analysis of data on the change in the electric field strength (E) in the atmosphere (as a measure of thunderstorm activity), it was previously shown [2,3] that approximately two days after the passage of an active region through the central meridian of the Sun, global thunderstorm activity on Earth is at a maximum. The authors concluded that the influence of the active region on thunderstorm activity acts through the high-speed solar wind emanating from this region. An increase in the number of lightning discharges, as well as an increase in thunderstorm days, which was observed by the authors of [4], coincided with an increase in the flux of solar energetic particles (SEPs) that were not recorded on the Earth's surface but penetrated to tropospheric heights and, as the authors of [3] suggest, under appropriate weather conditions, could initiate lightning discharges.

The purpose of this work was to (1) study the features of the manifestations of various sources of disturbances in the atmospheric electric field at the Tien-Shan high-mountain experimental complex of the Institute of the Ionosphere (Kazakhstan) and (2) study the relationship between the solar and thunderstorm activity using data of the registration of thunderstorm events at the complex.

2. Data and Methods

The experimental complex for measuring atmospheric electric fields, namely, "ELIS-TS", was installed at the high-mountain Tien-Shan station (3340 m above sea level, 43°02′ N, 76°56′ E). The complex consists of two detectors: a detector of the quasistatic electric field and a detector of the high-frequency component of the electric field. The detector of the atmospheric electric field is an electrostatic fluxmeter ("field mill") that was designed to measure the vertical component *Ez* in the range of ±50 kV/m with a sensitivity of 10 V/m. The detector of the high-frequency component dE/dt registers a return lightning stroke in the range of +/−600 V/m and, at the moment of the lightning discharge, generates a control signal, i.e., a trigger, for a complex of installations that measures various geophysical parameters. Both measuring systems can work in two modes: "slow" and "fast". The "slow" mode is intended for recording the measured parameters of the atmosphere in "fair weather" conditions and in the absence of lightning discharges (time resolution 0.05 s). The "fast" mode (time resolution 50 µs) is triggered by the trigger system due to a signal that comes from a sensor that measures dE/dt when a thunderstorm front approaches. The primary viewing of the results of measurements of the atmospheric electric field is carried out using the IDL program, which allows for a view of the recorded information with different time resolutions, draws preliminary conclusions, and determines the time of occurrence and duration of thunderstorm events.

The effects of solar activity on the lower ionosphere and thunderstorm activity were studied according to the ground-based observations. The state of the lower ionosphere was estimated by studying the variations in the minimum reflection frequencies from the ionosphere (*fmin*) and the critical frequencies of the sporadic layer E (*foEs*), which were obtained via vertical radio sounding of the ionosphere at the Alma-Ata station (43.25° N, 76.92° E) during the considered thunderstorm events. Information about solar events (flares and their class), coronal mass ejections (SMEs), high-velocity solar wind streams (HSSs), their geoeffectiveness, and the date of their arrival at the Earth's magnetosphere boundary were obtained from weekly space weather surveys of the Space Weather Prediction Center (Space Weather Prediction Center) (ftp://ftp.swpc.noaa.gov/pub/warehouse/ (accessed on 1 January 2021)). The activity of the geomagnetic field was estimated according to the *Dst* index (http://wdc.kugi.kyoto-u.ac.jp/ (accessed on 1 January 2021)) in accordance with the generally accepted classifications: small ($-50 \leq Dst = -30$), moderate ($-100 \leq Dst = -50$), and big storms ($Dst < -100$).

3. Results and Discussion

3.1. Peculiarities of Regular Variations of the Atmospheric Electric Field

Variations in the atmospheric electric field due to regular, periodic sources of disturbances reflect its dynamics under "fair weather" conditions. The classic example of the global variation of the electric field is the unitary variation, which is characterized by the diurnal change in the magnitude of the electric field with a maximum around 19:00 UT, which is known as the Carnegie curve [5]. The dynamics of the atmospheric electric field under "fair weather" conditions was studied on the basis of 15-year measurements at the high-mountain Tien-Shan station. The daily course of the atmospheric electric field for the summer and winter periods is shown in Figure 1.

The absence of the Carnegie effect in the diurnal variation of the electric field at the high-mountain Tien-Shan station was established. We considered that the most probable explanation for this fact was the proximity to the thunderstorm source in the Himalayas. It is the mountain range of the Himalayas that plays the decisive role for our region. The maximum thunderstorm activity at the high-mountain cosmic-ray station occurs much earlier than in other regions at our latitude but is located lower in height. The local features of the location of the high-mountain station prevail over the global effects that affect the dynamics of the atmospheric electric field in this case.

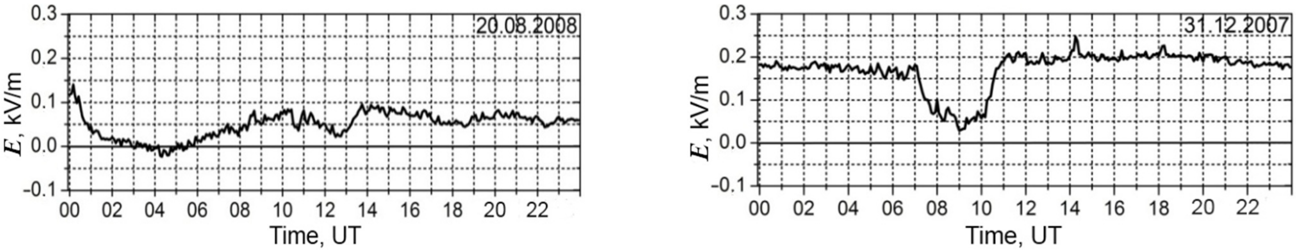

Figure 1. Diurnal variation in the electric field at the high-mountain Tien-Shan station under "fair weather" conditions in summer and winter.

3.2. Peculiarities of Manifestations of Sporadic Disturbance Sources on the Dynamics of the Atmospheric Electric Field

Giant coronal mass ejections (CMEs) and high-velocity solar wind streams from coronal holes (HSSs) are the most geoeffective sporadic manifestations of solar activity. Their collision with the Earth's magnetosphere and atmosphere leads to magnetic and ionospheric storms, a Forbush decrease in the intensity of cosmic rays, and other phenomena. Forbush effects and magnetic storms are often considered inseparable from each other as a consequence of one source of disturbances. Contradictory results appear in studies of the impact of sporadic solar activity phenomena on geophysical parameters in connection with this [6]. However, the most significant difference between them is that the Forbush effect is determined by the conditions in the extended heliospheric region, while geomagnetic activity depends on the local situation near the Earth [7]. Our studies were carried out by taking into account features of manifestations of geoeffective sporadic phenomena of solar activity in the atmosphere and magnetosphere of the Earth: 1—large Forbush effects and large magnetic storms, 2—large Forbush effects and weak magnetic disturbance, and 3—large magnetic storms and Forbush effects of less 1%. Only periods of "good weather" were analyzed in this case. Both an increase and a decrease in the electric field were observed after the impact of powerful coronal mass ejections (CMEs) and were simultaneously accompanied by large magnetic storms and Forbush decrease in cosmic rays. It should be noted that the increases in the atmospheric electric field in these events were insignificant and rarer. Perhaps the increase was due to a lower background level the day before. An obvious decrease in the atmospheric electric field was observed after the impact of powerful coronal mass ejections on the near-Earth space, accompanied by a significant decrease in galactic cosmic rays (Forbush effect), but an insignificant magnetic disturbance. Values of the atmospheric electric field after a CME, accompanied by the large magnetic storm and the large Forbush effect (left panel), and after the CME, accompanied by the significant Forbush decrease and weak magnetic disturbance (right panel) are shown in Figure 2. The solid vertical line in the figures is the arrival of a CME or HSS into the Earth's orbit.

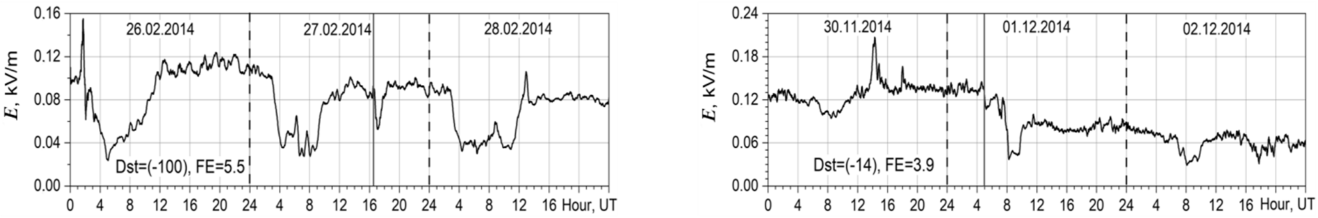

Figure 2. Values of the atmospheric electric field after the CME 27.02.2014 and 01.12.2014.

Galactic cosmic rays are the main source of ionization up to altitudes of 60 km. Near the Earth's surface, radioactive gases serve as an additional source of ionization; above 60 km, ultraviolet radiation dominates [8]. The high stability of the intensity of cosmic rays ensures relatively small variations in the electric field. During Forbush effects, the current in the Earth–ionosphere column decreases due to an increase in resistance due to a decrease in atmospheric ionization, which should lead to a decrease in *Ez* according to estimates [9]. Our results did not contradict the statements of the authors [8,9]; however, the relative contribution of radioactive gases to the ionization of the surface atmosphere needs to be clarified.

The values of the atmospheric electric field at the high-mountain station under the influence of the large geomagnetic storm *Dst* = −103 and under "fair weather" conditions for the 14 November 2012 event are shown in Figure 3 (left panel). The values of the electric field characteristic of "fair weather" conditions were not observed in this event, but significant field fluctuations were observed from 40 to 120 V/m. The results of calculations of the normalized power spectra of variations in the atmospheric electric field during magnetic storms (dashed-line curve) against the background of spectral estimates of the undisturbed atmosphere (solid line) are presented in the right panel of Figure 3. Spectral peaks exceeding the 95% confidence interval were observed in the minute ranges $10^{-3} \div 10^{-2}$ Hz and $10^{-2} \div 10^{-1}$ Hz.

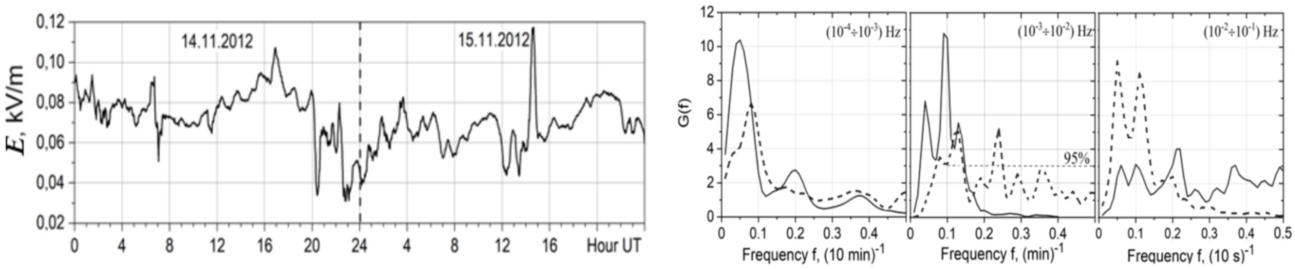

Figure 3. The values of the atmospheric electric field under the impact of the large geomagnetic storm (**left** panel) and power spectra of variations in the atmospheric electric field during magnetic storms (**right** panel, dashed-line curve).

3.3. Investigation of the Statistical Relationship between Thunderstorm Activity and Processes on the Sun

In general, 125 cases of thunderstorm events were recorded in the investigated period; of these, 55 cases were characterized by the appearance of negative discharges, 30 cases by the appearance of positive discharges, and 40 cases by the appearance of mixed discharges. The results of a joint analysis of the geomagnetic, solar, and thunderstorm activity showed that there was a tendency for thunderstorm activity to appear during periods of increased geomagnetic activity (geomagnetic storms), with the highest probability in the recovery phase when returning to the level of a quiet geomagnetic field, as well as during the impact of geoeffective coronal mass ejections (CMEs) on the Earth's magnetosphere and high-velocity solar wind streams (HSSs) observed during the considered periods. It was found that 21 out of 30 events of lightning activity with positive discharges, 39 out of 55 events with negative discharges, and 24 out of 40 events with mixed discharges were accompanied or preceded by the CME and HSS effects (see an example in Figure 4). In this figure, the symbols "↑", "▼", and "♦" indicate the dates of thunderstorm events with positive, negative, and mixed discharges, respectively; powerful events are highlighted in red. The horizontal arrows in the figures mark the time intervals when the Earth was under the influence of the effects of CMEs and HSSs, where the length of the each arrow indicates the duration of greatest impact.

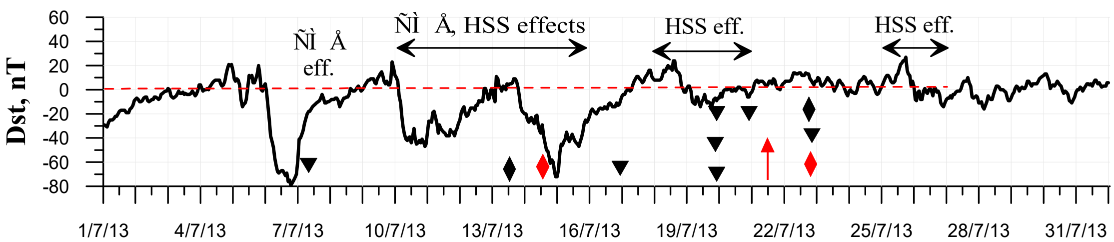

Figure 4. Variations of the Dst index and the occurrence of thunderstorm activity in July 2013.

As a result, it was found that in no less than 70% of cases, thunderstorm activity was observed during periods of impact on the Earth's magnetosphere by CMEs and HSSs, which suggested that the increase in thunderstorm activity occurred under the influence of high-speed flows of energetic particles of the solar wind (protons and electrons). Figure 5 shows the frequency of occurrence of the thunderstorm events as a function of time delay between an observed thunderstorm and the arrival of geoeffective CMEs and HSSs to the Earth. One can see that thunderstorm activity was usually most likely to increase during or 1–2 days after the arrival of geoeffective CMEs and HSSs to the Earth.

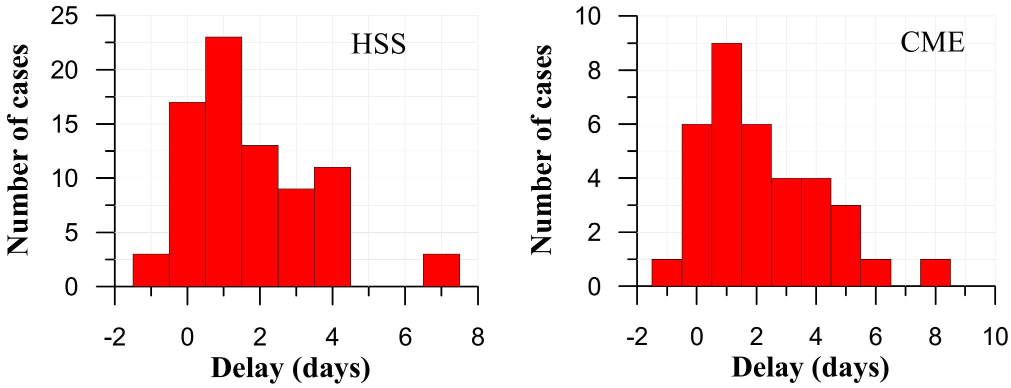

Figure 5. Lightning occurrence as a function of time delay between an observed thunderstorm and the arrival of geoeffective HSSs (**left** panel) and CMEs (**right** panel) to the Earth.

Of course, it should be said that certain meteorological conditions are necessary for the formation of lightning discharges and thunderstorm activity in general, which is not always the case. Therefore, there are many (about a quarter of all cases considered) examples when, in the presence of CMEs and HSSs, little or no thunderstorm activity was observed. Conversely, a number of cases were identified when thunderstorm activity was observed in a quiet geomagnetic field, e.g., when CMEs and HSSs events are not observed or these events are not geoeffective (not shown here). In these cases, an increase in the values of *fmin* and intensification of the sporadic layer Es were observed, which indicated an increase in the level of absorption of radio waves in the D-region of the ionosphere and the level of electron density at altitudes of 100–120 km (not shown here).

4. Conclusions

There is no Carnegie effect was found in the diurnal variations of the electric field at the high-mountain Tien-Shan station.

A decrease in the atmospheric electric field was observed after the impact of powerful coronal mass ejections on the near-Earth space, accompanied by a significant decrease in galactic cosmic rays (Forbush effect).

Atmospheric electric field fluctuations ($40 \div 120$ V/m) in the range of $10^{-3} \div 10^{-1}$ Hz were observed under the impact of large geomagnetic storms.

In at least 70% of cases, thunderstorm activity was observed during periods of impact on the Earth's magnetosphere by CMEs and HSSs, and this suggested that the increase in thunderstorm activity occurred during the arrival of high-speed streams of energetic particles of solar wind.

There was a tendency for thunderstorms to appear with a 1–2-day delay after the impact of CME or HSS events on the Earth's magnetosphere, which is in agreement with the findings of [1,2].

There were noticeable changes in the state of the lower ionosphere during these periods, an increase in the critical frequencies of the sporadic layer E up to 8–10 MHz, and short-term bursts of *fmin* values.

Future data analysis and observational efforts are needed to understand the thunderstorm initiation due to solar activity.

Author Contributions: V.A. conceived, designed, and performed the evaluation; wrote Sections 3.1 and 3.2; and corrected the manuscript. G.G. guided the current research work related to the ionosphere, prepared the tables and figures, and wrote Section 3.3 of the manuscript. V.L. and S.K. guided the measurement collection, collected the data related to the atmosphere, and prepared the tables and figures. All authors have read and agreed to the published version of the manuscript.

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