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Long-Term Evolution of the Occurrence Rate of Magnetospheric Electron Precipitation into the Earth's Atmosphere

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Abstract—Ionizing radiation fluxes in the Earth's atmosphere have been measured at the Lebedev Physical Institute since 1957. They allow the recording of X-ray radiation generated in the atmosphere by precipitating magnetospheric electrons with energies above 100 keV. The precipitation events are associated mainly with high-velocity solar wind fluxes and are often observed during the decaying phase of the 11-year solar cycle. They exhibit 27-day and seasonal repeatability and correlate with geomagnetic disturbances and fluxes of relativistic electrons in the outer radiation belt. More than 500 precipitation events have been recorded in Murmansk oblast since 1961 (McIlwain parameter $L \approx 5.5$). A long-term growing trend that does not correlate with the parameters of solar and geomagnetic activity has been observed in the occurrence rate of precipitation. Hypothetically, this trend could be due to the effect of ground-based VLF transmitters on the wave activity of the magnetosphere.

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INTRODUCTION

The precipitation of magnetosphere electrons into the Earth's atmosphere is one of the mechanisms that deplete the outer radiation belt of the Earth. Processes of the acceleration and loss of electrons in the belt are governed by solar activity. The energy of the solar wind enters the magnetosphere intensely against the background of the negative B_z component of the interplanetary magnetic field (IMF), which alters the configuration of the magnetosphere and its current systems, and amplifies the wave activity and wave–particle interactions. As a result, favorable conditions are created for competitive processes of the acceleration and loss of electrons. Despite efforts aimed at understanding these processes, including a series of specialized missions in near-Earth space (e.g., the Van Allen Probes [1] and MMS [2]) and with balloons in the atmosphere [3, 4], the relative roles of different physical mechanisms remain unclear. The part played by precipitating magnetospheric electrons in atmospheric chemical reactions responsible for the dynamics of the ozone content and changes in temperature in the stratosphere and mesosphere is also poorly understood (see, e.g., [5]).

Energetic electron precipitation (EEP) from the magnetosphere in Murmansk oblast (McIlwain parameter $L \approx 5.5$) have been recorded by the Lebedev Physical Institute since 1961. Measurements are made in the atmosphere using a radiosonde lifted by a meteorological balloon. The experimental technique was described in [6, 7] and allows us to register precipitating electrons with energies above 100 keV. Our set of data is the longest uniform array and enables us to study long-term variations in EEP occurrence rate.

CHARACTERISTICS OF MAGNETOSPHERIC ELECTRON PRECIPITATION

In this work, we summarize EEP properties established by analyzing the data from a catalog [7] of more than 500 EEP events registered since 1961. The precipitation is related to high-velocity solar wind fluxes and occurs mainly in the decaying phase of the 11-year solar cycle. The maximum EEP occurrence rate was observed in 1968, 1974, 1984, 1994, 2003, and 2015. An analysis performed using the superposed epoch technique revealed a stable relation between the emergence of EEP and the characteristics of interplanetary plasma, i.e., induction of the interplanetary magnetic field (IMF) B and its component B_z, solar wind velocity V, plasma density and temperature, dynamic pressure, and other characteristics, along with geomag-

Table 1. Results from our analysis using the superposed epoch approach. Zero days are dates of EEP records

Parameter	Effect	Shift relative to the zero day	Parameter	Effect	Shift relative to the zero day
B	Max	−1	Temperature	Max	0
B_z	Min	0	Dst	Min	0
V	Max	0	AE	Max	0
Density	Min	+1	$-V \times B_z$	Max	0
Pressure	Max	−1	El > 2 MeV	Max	+1

netic indices [8] and fluxes of relativistic electrons in the outer radiation belt [9]. The dates of EEP observations were used as zero days. In all of the above cases, the parameters exhibited an explicit effect (a minimum or a maximum) with a certain shift [10]. The results from this analysis are reflected in Table 1. The behavior of the interplanetary plasma parameters is typical of geomagnetic disturbances related to high-velocity solar wind fluxes and corotating interaction regions [11, 12]; similar relations were revealed in studying the dynamics of the outer radiation belt using the results from Van Allen Probe observations [13].

Studying the sequence of events related to EEP led to the most probable scenario of their occurrence [14, 15]. The arrival of a high-velocity solar wind flux at the Earth's orbit against the background of a negative B_z means a substantial flow of the solar wind's energy into the magnetosphere. A geomagnetic storm is the result. A high-velocity flux always brings disturbances to the magnetosphere when the solar wind velocity is high, lengthening the storm recovery phase. The inflow of new energy, the violation of the magnetic field's configuration, the change in currents, and the amplification of magnetosphere plasma convection and instabilities initiate wave activity in the magnetosphere and amplify processes of wave–particle interaction, thereby accelerating and scattering electrons of the belt. Precipitation begins with the onset of a magnetic storm and continues during the recovery phase. About 40% of the observed EEP occurred in series with durations shorter than 10 days. Although this sequence of events is fairly typical and coincides with commonly accepted concepts, influx of energy into the magnetosphere happens permanently, resulting in substorm activity and eventually the acceleration and loss of electrons [16].

LONG-TERM EVOLUTION OF EEP OCCURRENCE RATE

The frequency of radiosonde launches was not constant during an experiment. Annual values of the number of EEP events were normalized to study the time behavior of EEP occurrence rate: $N_{in} = N_{io}N_{94f}/N_{if}$, where N_{in} and N_{io} are the normalized and actually recorded numbers of EEP events in the i-th year and N_{94f} and N_{if} are the total number of flights of radiosondes that reached an altitude of 26.5 km (20 g cm^{-2}) in 1994 and the i-th year, respectively. The altitude of 26.5 km was chosen because only 5% of all EEP events were observed below it. Normalization was performed to 1994, since the number of observed EEP was greatest that year. Days when solar protons precipitated into the stratosphere were excluded from consideration.

The normalized series of EEP occurrence retained the dependence on the phase of the solar cycle (maxima on the decaying phase) but unexpectedly revealed a growing trend in the EEP occurrence rate (Fig. 1a). The number of EEP events in every maximum since the 1960s has grown. The behavior of the annual values of different parameters that, as was shown using the superposed epoch approach, accompany EEP events is shown in Figs. 1b–1f by curves with different symbols; the lines without symbols are the results from smoothing over 11 points. The higher occurrence rate of EEP events before 1990 can be explained by an increase in solar activity; starting with the 22nd cycle, however, solar activity has diminished (Fig. 1b). This trend is reflected in the behavior of the *Dst* and *AE* magnetospheric indices (Figs. 1d, 1e). The best correlation is observed between the occurrence rate of EEP events and the solar wind velocity. Although local maxima of the number of EEP events coincide with those of the solar wind velocity, the smoothed values of V display virtually no trend at least until the mid-2000s, with a subsequent drop (Fig. 1c).

The discrepancy between the signs of trends of most parameters and the EEP trend was especially clear in the early 1990s. We therefore analyzed the properties of observed EEP events separately for 1961–1991 and 1992–2017. Our analysis using the superposed epoch approach was performed for the second time, the distribution of EEP events relative to the onset of a geomagnetic storm (*Dst* minimum) was verified, and the 27-day and seasonal repeatability were checked. All EEP properties before and after 1991 were similar. Under the conditions of the experiment, nothing changed that might have

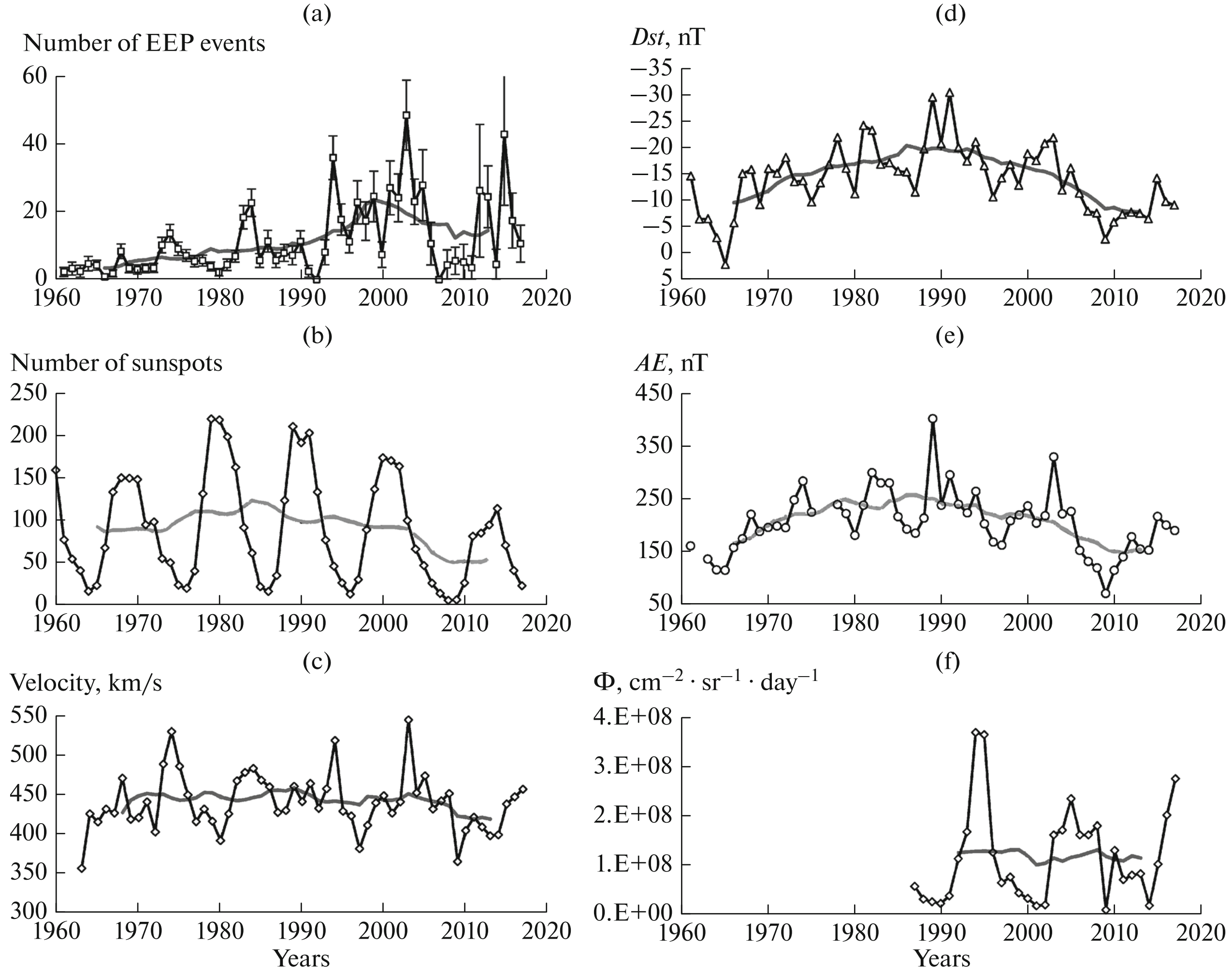

Fig. 1. Time behavior: (a) number of EEP events; (b) number of sunspots; (c) solar wind velocity; (d) *Dst* index; (e) *AE* index; and (f) fluence of electrons with energies above 2 MeV in geostationary orbit. The curves with symbols represent the annual values of the parameters; grey curves without symbols are values smoothed by 11 points.

affected the ratio of the number of radiosonde flights with observed EEP events to the total number of radiosonde flights.

We observed EEP events whose characteristics did not differ from those measured in other experiments (e.g., [2, 13]). The identical characteristics of events lead us to believe that the EEP time series was uniform. At the same time, we observed a growing trend in EEP occurrence from 1961 at least to the mid-2000s. The growth seemed to cease in the later period, but it is difficult to draw definite conclusions because the reduced number of flights resulted in substantial errors of measurement (Fig. 1a). None of solar and geomagnetic activity parameters displayed the trend we observed in EEP occurrence rate. A possible hypothesis is the effect of ground-based radio transmitters on EEP. There is a network of ground-based radio transmitters that operate in the VLF band. This band includes natural magnetospheric waves which interact intensely with particles, followed by the breaking of adiabatic invariants [17]. Radiation of ground-based transmitters can penetrate into the magnetosphere and affect EEP in regions near the transmitters [18–20]. There are transmitters of this type in Murmansk oblast [21]. The number of such transmitters used for naval communications could grow. In addition, the radiation of powerful HF stands developed for active influence on the ionosphere [17] penetrates into the magnetosphere and serves as a trigger (source) of other waves (VLF in particular).

It should be noted that the available information about EEP events initiated by transmitters refers to comparatively low latitudes and nighttime. However, dynamic wave processes in the magnetosphere are so complicated that we cannot exclude the possibility of anthropogenic radiation affecting the EEP events observed by our group.

CONCLUSIONS

The uniform series of magnetospheric electron precipitation events with electron energies of >100 keV recorded in the polar atmosphere displayed a growing trend from 1960s to mid-2000s. No similar trends were observed in accompanying interplanetary and magnetosphere processes. It is hypothesized that the increase in the number of precipitation events was associated with the growing activity of ground-based radio transmitters.

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