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Effect of Precipitating Energetic Particles on the Ozone Layer and Climate

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Abstract—The mechanisms of the influence of various energetic particles on the atmosphere and their consideration by modern models are discussed. The types of energetic particles considered are galactic cosmic rays, auroral electrons, solar protons, and electrons precipitating into the atmosphere from outer radiation belt. The effects of these particles on the ozone layer and climate are illustrated using observational data and model calculations. The influence of galactic cosmic rays is noticeable only in the troposphere at southern latitudes, whereas a strong but short-term destruction of ozone by episodic solar protons have no effect at climatic time scales. Thus, the main influence on the long-term ozone layer variability is exerted by energetic electrons. Changing ozone contents lead to changing heating rates, temperature, and structure of stratospheric circulation, which in turn affects wave processes and climate. Simulation of these processes requires the use of complex numerical models that include all necessary processes and their interaction in the atmosphere from the surface to the upper thermosphere.

Keywords: energetic particles, climate, ozone, numerical simulations
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INTRODUCTION

The Earth's atmosphere is constantly bombarded by various precipitating energetic particles (PEPs). Their effect on the atmosphere has been studied for many years, but it has only recently been suggested that PEPs may significantly affect the ozone layer and climate [1, 2]. Energetic particles can be differentiated depending on their origin, energy spectrum, geographic location of direct impact, and connection with the solar activity cycle. The properties of the main types of precipitated energetic particles are presented in Table 1. Various energetic particles have been discussed in detail in an extensive review [3]. The precipitating energetic particles lose energy ionizing neutral molecules (mostly N_2 and O_2) in the middle atmosphere. Ionization initiates the chemical transformation of neutral constituents leading to reactive hydrogen ($HO_x = H + OH + HO_2$) and nitrogen oxides ($NO_x = N + NO + NO_2$) formation. These gas constituents may play a significant role in several cycles of catalytic ozone destruction. For example, the catalytic ozone destruction caused by hydrogen oxides is important in the mesosphere, while nitrogen oxides play an important role in the stratosphere. Two important catalytic cycles are given below:

$$\begin{array}{l} OH + O_3 \rightarrow HO_2 + O_2, \\ \underline{HO_2 + O \rightarrow OH + O_2} \\ \text{Summary: } O_3 + O \rightarrow 2O_2; \end{array}$$

$$\begin{array}{l} NO + O_3 \rightarrow NO_2 + O_2, \\ \underline{NO_2 + O \rightarrow NO + O_2} \\ \text{Summary: } O_3 + O \rightarrow 2O_2. \end{array}$$

The fate of radicals formed by energetic particles depends on their lifetime. The effects of the short-lived HO_x are very local and are observed only immediately after the event in the region where the particles lose energy. At the same time, the more stable NO_x can be carried by air currents, and its effects are observed in regions distant from the immediate impact region at later times. This chain of processes is an indirect effect of PEPs [4].

EFFECT OF ENERGETIC PARTICLES ON THE OZONE LAYER

The processes listed in the Introduction are most pronounced after a strong solar proton event (SPE). Figure 1 shows the changes in ozone after SPEs in

Table 1. Characteristics of different types of precipitating energetic particles

Type	Source	Energy range	Maximum impact height, km	Maximum impact region	Event duration	Shift related with the maximum solar activity	Maximum ionization values (number of ion pairs/(cm^3 s)
Auroral electrons	Solar wind, magnetosphere	<30 keV	110	Auroral zone, about 70° of geomagnetic latitude	Constantly	2–3 years	30000
Medium-energy electrons	Solar wind, radiation belts	30–300 keV	80	Subauroral zone, 55°–75° of geomagnetic latitude	Several days	2–3 years	5000
Relativistic electrons		300 keV–2 MeV	60		Up to several hours	2–3 years	10000
Solar protons	Coronal mass ejections	Up to 2 GeV	40	From 60° to 90° of geomagnetic latitude	Several days	In phase	30000
Galactic cosmic rays	Supernovas	Up to 10^{18} eV	15	Magnetic poles	Constantly	In anthyphase	500

October 2003 measured by MIPAS on board the ENVISAT satellite [5]. A significant (up to 80%) short-term ozone depletion in the mesosphere during the two main events is associated with the production of hydrogen radicals formed by solar protons. The low ozone zone in the upper stratosphere is visible until the end of November 2003 and is caused by nitrogen oxides produced during main events [5] and carried down by atmospheric winds. The significant destruction of ozone after a strong SPE has minor consequences for long-term average levels of stratospheric ozone or the surface climate, because strong SPEs are very rare. There have been only about 10 strong SPEs in the last 15 years.

These consequences can be produced by precipitating medium-energy electrons and relativistic elec-

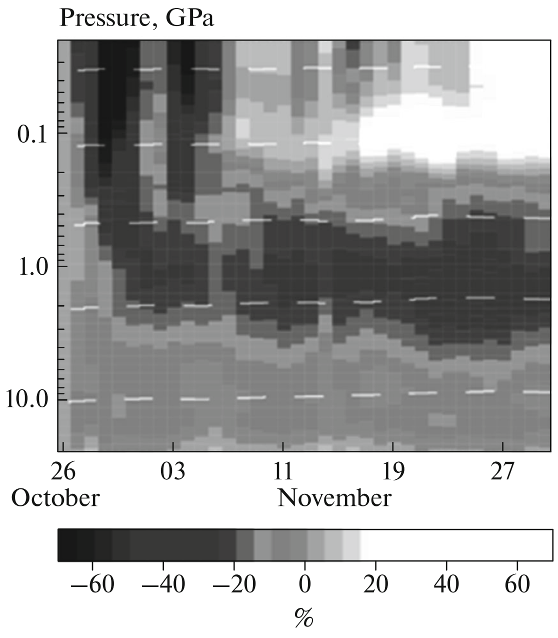

Fig. 1. Deviation (in %) of ozone concentrations averaged over the latitude belt 70°–90° N from the values for October 26, 2003, according to the MIPAS satellite. The figure is taken from [5].

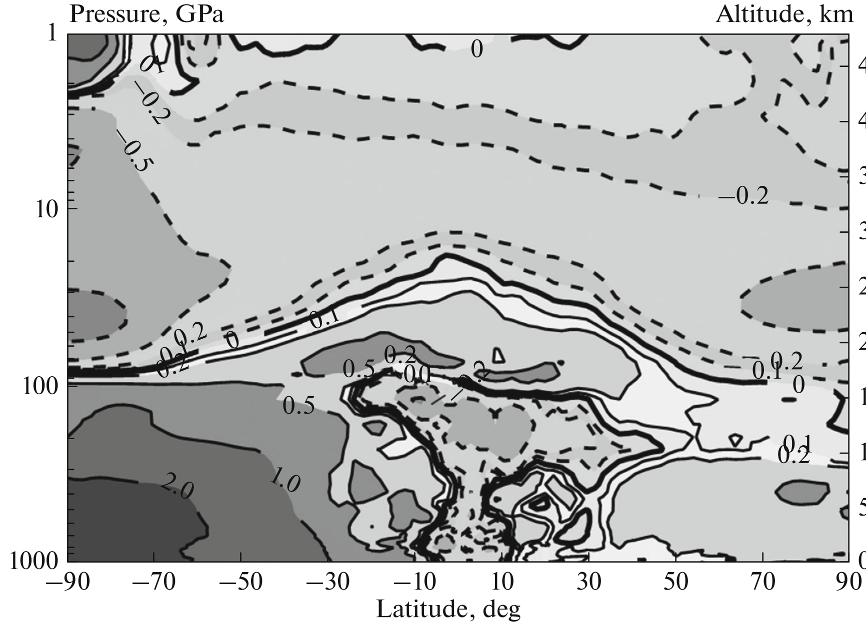

Fig. 2. Changes in the average annual ozone concentration in the WACCM-SD model caused by the influence of GCRs. The figure is taken from [7].

trons from the outer radiation belt. These events occur more often and can potentially affect the ozone layer and climate. However, a lower signal-to-noise ratio and insufficient knowledge of the energy spectrum of the particles do not always make it possible to clearly explain the destruction of ozone [6]. The effect of auroral electrons and galactic cosmic rays (GCRs) on the ozone layer differs from the effects of SPE and high-energy electrons. The lower thermosphere, in which auroral electrons have a direct influence, contain practically no water vapour, so the production of HO_x has no effect; only the production and transport of NO_x to the stratosphere affects the ozone layer [4]. The effect of GCRs is mainly limited to the lower polar atmosphere, where their effect on the ionization rate is most pronounced. In this region, the additional formation of NO_x can lead to reduction or increases in the ozone concentration, caused by so-called photochemical smog reactions [7], which mask the signal from GCRs. These processes are more pronounced in the model results, since in this case it is possible to detect relatively weak destruction or formation of ozone by comparing numerical experiments with the presence or absence of GCRs. The effect of GCRs on ozone has recently been analyzed using the modern chemical and climatic model WACCM-SD [7]. Figure 2 shows that GCRs, as a rule, destroy ozone in the stratosphere but increase its concentration in the troposphere. This effect is more pronounced in the Southern Hemisphere, where the additional NO_x produced by GCRs are more effective catalysts for ozone production. However, even in this case, the increase in ozone concentration does not exceed 4%.

The combined effect of auroral electrons, SPEs, and GCRs on ozone was investigated using the SOCOL chemical and climatic model [8]. Figure 3 illustrates the response of the zonal average ozone content (in %) to GCRs, SPEs, and auroral electrons. The most pronounced (up to 10%) reduction in ozone was found in the polar average atmosphere above 10 hPa in the cold season, but some ozone depletion (up to 4%) persists even before the summer season. The effects of GCRs are similar in magnitude and location to the results reported [7] and are notable and statistically significant.

EFFECT OF ENERGETIC PARTICLES ON CLIMATE

Ozone depletion can lead to changes in cooling and heating rates caused by the absorption and emission of solar and IR radiation. During the polar night, the IR radiation component is more important. Calculations using reference radiation models show that a 10% reduction in ozone in the upper stratosphere is sufficient to provide additional cooling equal to 0.25 K/day within the circumpolar vortex. This cooling increases the temperature gradient between the polar and tropical regions, which leads to the acceleration of the polar night jet, the heating of the tropical lower stratosphere, the shift of the Hadley cell and the shift of the North Atlantic oscillation to the positive phase [9, 10]. The changes in surface temperature related to this are characterized by pronounced warming, which is observed in Scandinavia, central Russia, and North America. This phenomenon was identified using

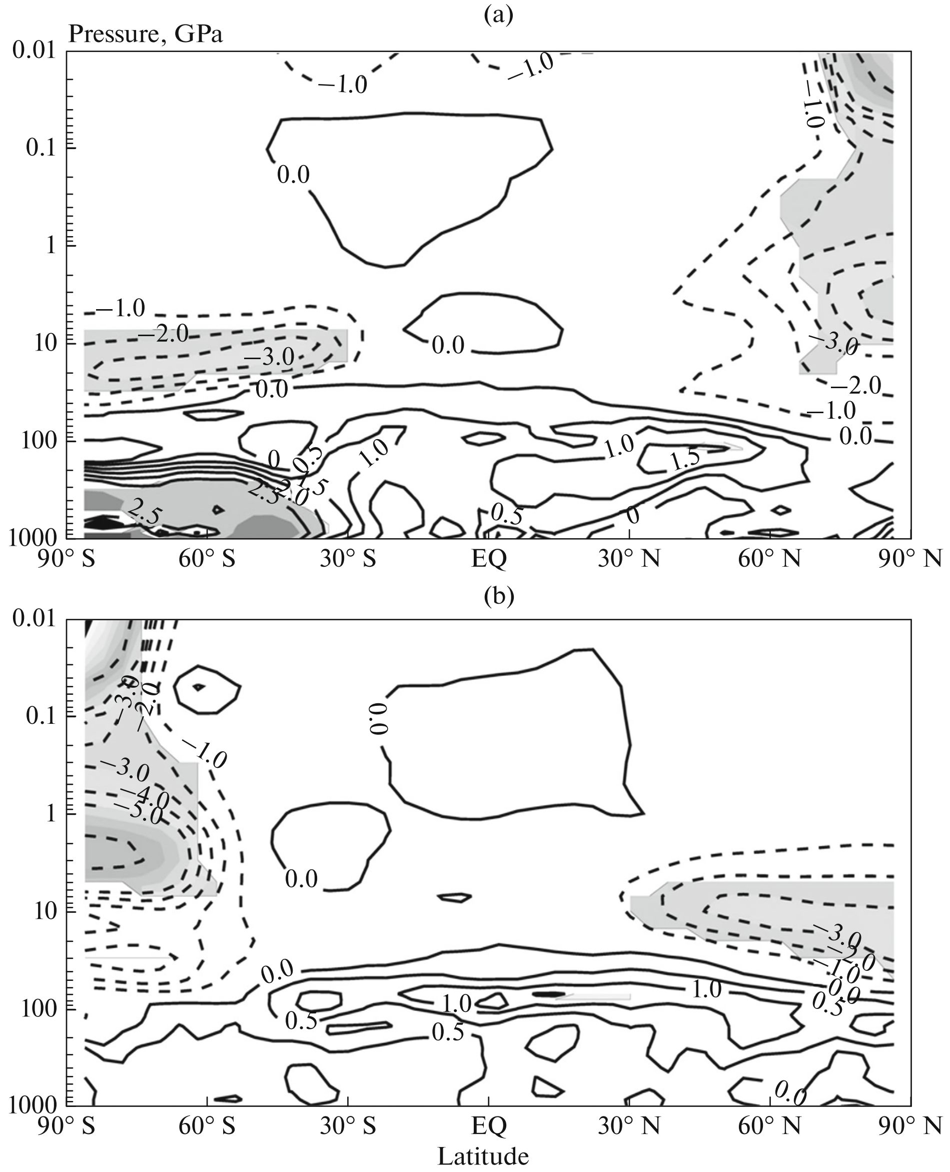

Fig. 3. Calculated changes in ozone concentration (in %) caused by the influence of GCRs, SPEs, and auroral electrons for the periods of (a) December–February and (b) June–August. The results are averaged over all years from 1960 to 2005. Positive and negative values are shown by solid and dashed lines, respectively. Areas where the significance of changes exceeds 90% are shaded.

meteorological reanalysis data [2] by comparing the surface temperature distributions during the winter in northern latitudes between periods with high and low geomagnetic activities. An analogous distribution of changes in the temperature of the surface is shown in Fig. 4, which was obtained from experiments with chemistry–climate models [1, 8] and can be explained by the effect of NO_x produced by the HEPs.

CONCLUSIONS

The results presented show that energetic particles can significantly influence the ozone layer and climate during the cold season and should be taken into account in models representing changes in climate. The correct consideration of energetic particles is particularly important for modeling the future ozone layer and climate in cases where the widely discussed decrease in solar activity is real [11]. This decrease in the solar magnetic activity can weaken the frequency and intensity of the precipitation of energetic particles and leads to an increase in ozone in the polar middle stratosphere and the cooling of the northern terrestrial masses in the cold season. This effect may partially compensate for the global warming caused by greenhouse gases, and its estimation is important for understanding the future of the climate. The study of these processes requires the use of new numerical models

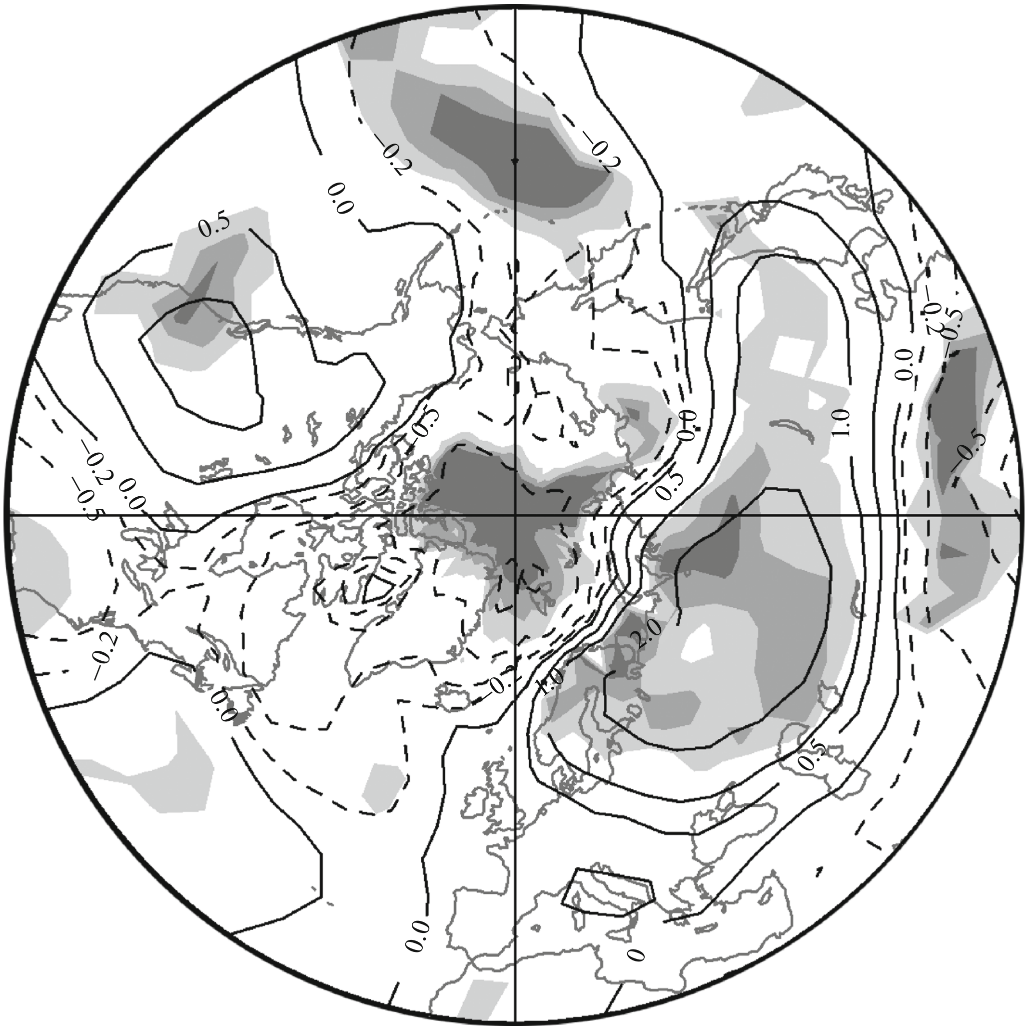

Fig. 4. Changes in surface temperature in the Northern Hemisphere in winter caused by the effect of energetic electrons [1].

including all the necessary physical and chemical mechanisms and their interaction in the atmosphere from the surface of the Earth to the upper thermosphere.

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