On mechanisms of aerosol layers formation in the stratosphere in the periods of increased magnetic activity

V.V. Bychkov,** V.N. Marichev,* G.G. Matvienko,* B.M. Shevtsov**

*Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk

**Institute of Cosmophysical Researches and Radio Wave Propagation, Far Eastern Branch of the Russian Academy of Sciences, Paratunka, Kamchatka Region

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The paper describes some results of lidar observations obtained at the Institute of Atmospheric Optics SB RAS in January–March 1996–2000. We have considered the role of geophysical processes, accompanying the magnitospheric perturbations, in the formation of layers with increased values of the aerosol scattering in the altitude range from 35 to 50 km. Basic characteristics of the atmosphere at 50 km altitude are considered as well as the role of water vapor and conditions of condensation in the stratopause. A mechanism is discussed accelerating the condensation due to supplementary ionization occurring under conditions of increased magnetic activity.

The data of lidar observations performed in March 1988 and 1989 over Tomsk were analyzed in Ref. 1. Description of the experiment and method of statistical processing are given in that paper. Based on data of March 1988 a significant correlation of the stratospheric aerosol content with the daily mean index of geomagnetic activity Kp was revealed and its dynamics was investigated. In March 1989 no correlation was detected.

The present paper analyzes a larger array of data compiled during January–March period in 1996 to 2000. In other seasons over Tomsk the aerosol layers at these altitudes were not observed. Figure 1 shows data obtained over the period from January to March in 1998.

Analysis of lidar data shows that, on the whole, the growth of layer intensity from January to March is observed. At the altitude range from 30 to 45 km the correlation coefficients between aerosol density, averaged over 5-km thick layers, with the indices of geomagnetic activity Kp and Dst, the particle density of solar wind, its velocity, and pressure were calculated. The calculations have shown high correlation between the stratospheric aerosol density (of the order of 0.8) in the 40–45 km altitudes with all the above-listed geophysical parameters for January 1998 and its absence for observations in February and March of 1998. Now we consider the possible causes of such contradictory results.

The atmospheric ion composition at 50 km altitudes

Main peculiarities of the lower part of the *D* layer of the ionosphere at 50 km altitude are taken from Ref. 2, where basic positively charged components are cluster ions, proton-hydrate complexes $H^+(H_2O)_3$ and $H^+(H_2O)_4$ with roughly equal content of the order of 10^3 cm^{-3}. The dominating negative ion in this region is the NO_3 ion with a small, about 6–8%, admixture of CO_3. The approximate equality of the total concentration of charged particles for night and daytime conditions is typical for the altitude of 50 km. Variations in the night conditions are mainly observed as a decrease of CO_3 content, which is not dominating at this altitude. This peculiarity of the ionosphere can easily be understood if we take into account that the main ionization source at 50 km altitude is the cosmic rays, which intensity is stable and does not vary during a day.

The influence of temperature and humidity on the content of charged particles at 50 km altitudes and higher was investigated in the same Ref. 2. In the calculations the water concentration profile was given, which decreased exponentially from 10^{11} cm^{-3} of H_2O particles at 50 km altitude to zero at 120 km altitude. To elucidate the influence of water content on the value of ion concentration, the calculations were made with “dry” mesosphere, in which the water vapor content was understated by 20 times. It was shown that the reasonable variations of temperature profile in the mesosphere did not affect the concentration values at 50 km altitude, whereas the water content decrease could significantly, by several times, decrease the content of complex $H^+(H_2O)_3$ and by one order of magnitude decrease the content of $H^+(H_2O)_4$. It should be noted that in photochemical reactions at the altitudes higher than 50 km the sum rate of losses of water molecules is higher than the rate of their formation in other reactions and the value of ion concentration at 50 km altitude is largely determined by the processes of water vapor transfer from lower layers.

A question on the water content in the stratosphere has been so far a subject of discussions, and the data of different authors in this field differ greatly. Based on the measurements of radiation absorption in the line L_α, performed using satellites of Interkosmos series in the period from 1972 to 1974,[3] in winter the water vapor content in the atmosphere can exceed the summer values by 2 or 3 orders of magnitude. According to other data the water content in the atmosphere is $(2–4)\cdot 10^{-6}$ and does not change up to the mesospheric altitudes.[4] The data are also available on the water content that in spring is higher than in winter by 2 or 3 times.

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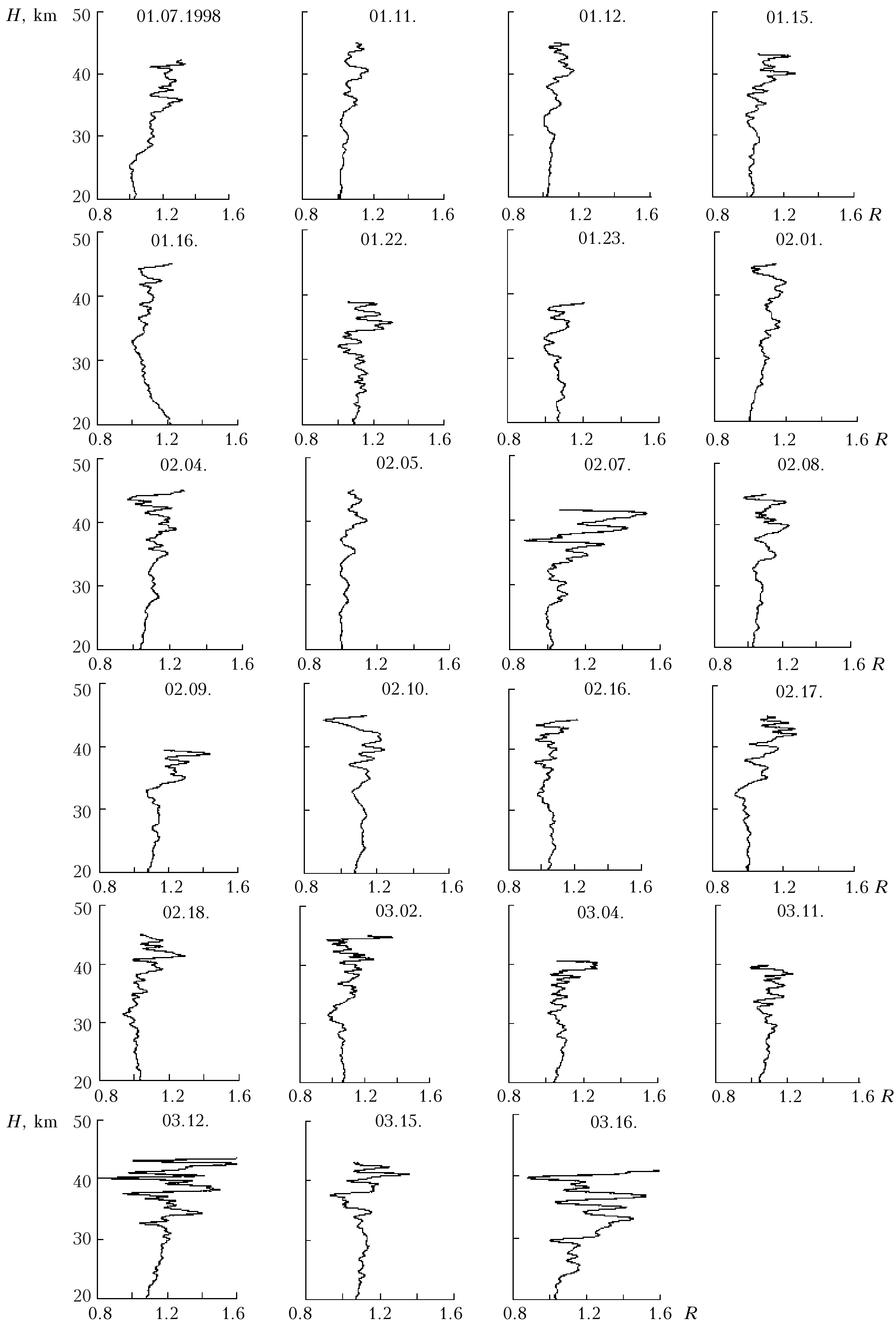

Fig. 1. Altitude profiles of relative aerosol density (aerosol scattering ratio R) in January–March of 1998. Date of observation is shown in each diagram.

Temperature and condensation

Charged particles can be condensation nuclei for atmospheric water vapor in the absence of saturation.[5] This is derived from the fact that the equilibrium water vapor pressure above the surface of a charged drop is less than above an uncharged one. From data given in Fig. 1 it is evident that the maximum values of aerosol density (relative to the air density) are observed in the altitude range from 40 to 50 km. In addition, the condensation can be caused, apart from the increase of the presence of water and ionization sources, by a favorable temperature conditions. The altitude range being studied is the stratopause, whose standard mean value of temperature is 270 K. At the stratospheric warmings, higher temperatures about 290 to 300°C were observed. Thus, from the point of view of a possibility of the existence of water in gaseous state, the altitude range under study can play a decisive role.

A critical parameter for water condensation is the pressure of saturated vapor. With the rise of temperature this pressure increases, i.e., the stratopause layer is capable of accumulating without condensation a greater amount of water per unit volume, than the upper or lower layers. So, the ionization increases with the increase of water content due to constantly running photochemical processes. The ionization increase in this layer is favorable for condensation. Thus, the existence of supplementary ionization sources for water condensation and the formation of aerosol layers in the stratopause in principle is not necessary. It is obvious that there exists a self-regulating system preventing water drift to the mesosphere, where it disappears because of dissociation and further photochemical transformations. The conditions, where the correlation between aerosol density and geomagnetic activity is lacking, do not call for an explanation, since this is normal state of the atmosphere; the conditions under which the correlation occurs do.

An additional argument in favor of a hypothesis on the role of water in the formation of aerosol layers at the stratopause altitudes is the correspondence of data given in the Ref. 1 on the mean seasonal profiles of aerosol concentration and their variances to the data on seasonal variations of water content in the stratosphere. Besides, the coagulation of aerosol particles formed on positive and negative ions and their motion to the Earth under the gravity force to the atmospheric regions with low temperatures[1] are the material for the formation of noctilucent clouds of Type 1: NAT (Nitric Acid Trihydrate Clouds, http:/www. Meteors.de/psc/pscl.html).

Ionization

In the first place, the relation of aerosol content to geomagnetic activity should be considered in the additional ionization produced by magnitospheric perturbations at 40–50 km altitudes that favors water vapor condensation. Because the observations were made at nighttime over Tomsk, the sources related to the X-ray radiation will not be considered. In Ref. 6 the effect of geomagnetic activity on the mesospheric temperature was studied. Based on the correlation analysis of the temperature data at Churchill station and the index of geomagnetic activity Kp it was shown that the correlation exists, and it is higher at daytime than at nighttime; the effect decreases toward the mid-latitudes and it is not extended to the altitudes below 60 km. The absence of the effect of temperature rise in the mesopause region at 50 km altitude was simulated in Ref. 2.

As to additional ionization sources, e.g., by solar cosmic rays (SCR) at the power of several tens of MeV, then at geomagnetic latitude of Tomsk, being equal to 46° ($L = 2.5$), they can occur only during very strong geomagnetic storms. Really, during strong geomagnetic storms the shift of penetration boundary of solar protons, sometimes down to the latitude of 45°, were detected.[7] Thus Reference 8 described the effects in the mid-latitude ionosphere related to the magnetic storm on October 28–30, 2003. In that paper, based on the analysis of the phase shift of the VLW-signals (Very-Long Waves) of the phase radio navigation system Alpha, the increase of electron concentration at night was determined not only in the *D* layer in different cases by 5 to 30 times, but also in the underlayer *C*. The authors explain such a decrease of concentration by a shower of high-energy particles from the Van Allen radiation belt.

Reference 9 describes the profiles of ion formation rate in the atmosphere in the events of proton showers. The profiles of ion formation rate for electrons are given, for example, in Ref. 10. One can readily see that "ideal" from the viewpoint of a possibility of production of ionization at 40–60 km altitudes will be protons of 20–50 MeV energy and the electrons of more than 300 keV energy.

Figure 2 shows a graphical representation of monthly variation for January–March 1998 of Dst index (mean curve), in which the time of detection at 35–50 km altitudes of layers with an increased value of the aerosol scattering coefficient is indicated by a rectangle. The upper diagram shows the flux of protons with the energy more than 1 MeV, the bottom diagram shows the electron flux with the energy more than 2 MeV.

The fluxes were recorded from a geostationary GOES-8 satellite. Any relationship between the time of appearance of aerosol layers and the values of Dst index is not visually observed.

Figure 2 shows the agreement between the time of layer observation and the time of increase above the background level of the integral proton and electron fluxes together or separately. A significant correlation between aerosol density and the particle flux value is not observed. The time agreement is practically complete, for all available data from 1996 to 2000.

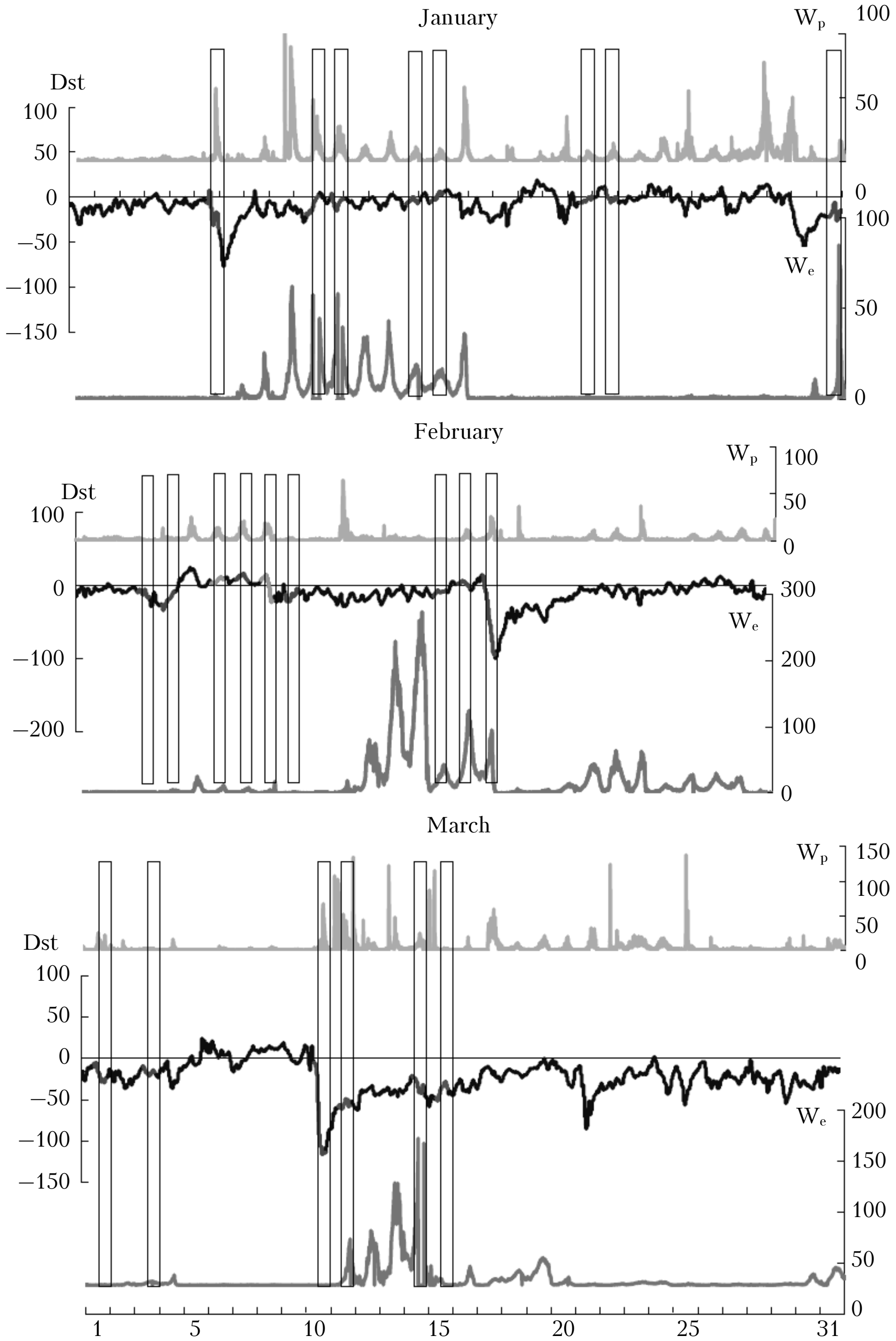

Fig. 2. Monthly behavior of the Dst index, of proton flux density W_p, and electron flux density $W_e/100$. Nighttime, when the stratospheric aerosol layers were observed, is denoted by rectangles.

Taking into account the fact that data for obtaining the scattering profile have been compiled during the whole nighttime, one can speak in favor of the correlation in time accurate to several hours. Over the entire observational period (82 profiles) we would pointout some (no more than 5–10) cases of appearance of aerosol layers in the absence of excess of particle fluxes over the background level, including calm geomagnetic situation.

Based on data shown in Fig. 2, from the energy estimations one can assume that fluxes of high-energy particles recorded at nighttime while moving toward the Earth under the action of electric field of convection arrive in the region of capture and further, as a result of diffusion across drift shells, though only partially, penetrate to the L-shells of the order of 2.5. In this case, for example, the protons, as a result of such a transfer and adiabatic acceleration, increase their energy by $(L_1/L_2)^3 = (6.6/2.5)^3 \simeq$ $\simeq 18$ times. Taking into account that the initial flux energy is more than 1 MeV, the proton energy would become sufficient to make ionization at the altitudes being considered in the case of penetration of any part of protons to the ionosphere. This assumption does not agree with the theory of radiation belts. In Ref. 11 the plot of velocity ($V = 1.5 \cdot 10^{-7} L^9$) is given of the forward front of a diffusion wave in units $R_E/24$ hrs, where R_E is the Earth's radius. These velocities even by the order of magnitude do not correspond to the velocity necessary for particle transfer from $L = 6.6$ to $L = 2.5$ during the observation time. Nevertheless, the experimental data are available on synchronous increases of particle fluxes obtained from geostationary and low-orbiting satellites. Note that from 1996 to 2000 in 90% of cases these fluxes were recorded with the use of USA satellites. Possible connection between particle flux variations at the heights of the geostationary satellite on the night side of magnetosphere and the principle mechanism of particle escape from the Earth radiation belt – cyclotron instability of plasma – must be studied. The fact that the variation of the particle flux at the satellite orbit means a variation of the ring current and the magnetic field of the Earth must be taken into account as well. However, this problem calls for further investigation.

The second possible mechanism is the penetration of particles of the appropriate energies existing in $L = 2.5$ of the Earth's radiation belt from the tail of pitch-angular distribution of particles at variations of the magnetic field. For the effect to take place at 50 km no larger particle fluxes are needed taking into account the value of the rate of constantly existing basic ionization source by cosmic rays of about one pair of ions per second.

The possibility of observing correlation of indices of geomagnetic activity with the aerosol concentration in some periods and its lack in other periods can be explained. In the latter cases more powerful aerosol layers were observed, whose density could be determined by not only condensation nuclei available, but also by an excess in the initial material, i.e., water vapor. In this case, there appears the so-called state of supersaturation, and the correlation with magnetic activity can disappear.

Conclusions

From the consideration of lidar data acquired during 1998 a conclusion can be drawn about the appearance of aerosol layers at the stratopause altitude both in connection with the rise of geomagnetic activity and regardless of it. The possible mechanisms of aerosol layers formation in both cases are proposed. Based on analysis of main characteristics of the lower ionosphere at 50 km altitude a conclusion has been drawn on a special role of water in the stratopause.

The mechanism has been substantiated, according to which at deficient water content the formation of aerosol layers can be accelerated with the increase of geomagnetic activity due to the rise in ionization and the appearance of supplementary condensation nuclei. With the increase in water vapor content the aerosol formation process was monitored by the growth of ionization due to the participation of water vapor in the ionospheric photochemical reactions, and the relation to the parameters of geomagnetic activity decreases in this case.

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