Estimation of the effect of coarse smoke particles on the process of precipitation formation

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Numerical estimates have been obtained that the smoke aerosol, produced by forest fires, can reduce precipitation. The phase composition of clouds with supercooled tops, which produce the most intense precipitation in the mid-latitudes, is very sensitive to the presence of aerosol particles with the size larger than 1 μm. The intrusion of coarse smoke aerosol is accompanied by fast crystallization of water droplets in the upper part of a cloud. Such clouds produce much less intense precipitation.

Introduction

Forest fires exert thermal and dynamic effects on the ambient atmosphere, as well as pollute the atmosphere with gaseous, liquid, and solid combustion products. The thermal and dynamic effects on the processes of cloud and precipitation formation is limited to a local area above the fire zone, while the smoke plume of a large forest fire can be as long as 100 km [Ref. 1]. In 2002 in Saha Republic (Yakutiya), mass fires covered the area of $0.7 \cdot 10^6$ km^2. This situation was accompanied by smoking of the territory more than $2 \cdot 10^3$ km long, and the smoked area was larger than 10^6 km^2 [Ref. 1]. The aerosol, produced by mass fires, can enter the cloud layer[2–4] and affect the processes of cloud and precipitation formation on the territories of a regional scale.

Condensed particles of a smoke aerosol produce the main effect on the processes of precipitation formation, and therefore the influence of gases and other combustion products is not considered in this paper. Taking into account the dynamics of particle microstructure at different stages of smoke formation and the following evolution, the smoke aerosol particles with the size up to 2 μm have long lifetime and, consequently, are transported in plumes to long distances. These particles can be separated into three fractions: fine fraction with the particle median radius $0.03 < r < 0.06$ μm, medium fraction with $0.3 < r < 0.6$ μm, and coarse fraction with $1.0 < r < 1.5$ μm [Ref. 5], which affect differently the cloud and precipitation formation. Smoke particles generally serve condensation nuclei for water vapor, while particles of the medium and coarse aerosol serve also coagulation nuclei for water droplets. The increase in the rate of vapor condensation and water droplet coagulation depends on the chemical composition of aerosol, its hygroscopic property, and many other factors.

These processes lead to intensification of the formation of fine rain fraction in "warm" clouds, not including the ice fraction. In the mid-latitudes in summer, the shower clouds with the vertical size from 5 to 10 km are responsible for the main mass of precipitation. The top of such clouds lies in the supercooled part of the atmosphere. Under ordinary conditions, it consists of water vapor, water droplets, ice crystals, snow and small hail.[6] The airborne observations and experimental data[6,7] indicate that ice crystals are observed near the edge of clouds at the altitudes, where the air temperature is below −12°C. Ice crystals are formed of vapor and water droplets in the presence of a sufficient amount of solid aerosol with $r > 1.0$ μm [Refs. 6 and 7], whose fractions serve crystallization nuclei, which leads to slower precipitation formation processes[7] (showers in the mid-latitudes precipitate from clouds, whose top consists of vapor, water and ice particles).

The mechanism of fire influence on the clouds and precipitation formation is quite complicated and not completely studied yet. Consider the influence of the coarse aerosol on the processes of precipitation formation. According to statistical data, in the second half of year 2002 summer the amount of precipitation in Eastern Siberia was anomalously low. This can be likely explained by the slower processes of precipitation formation under the effect of the smoke aerosol, generated in mass forest fires in Yakutiya in summer of 2002.

The data of laboratory experiments, conducted in a thermal vacuum chamber,[6,7] indicate that about 100 particles of the coarse aerosol per 1 m^3 of air is sufficient to provide for the crystallization of the

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most part of the droplet fraction at $T \le -12$°C. Thus, to estimate the probable effect of the smoke aerosol on the processes of precipitation formation, it is necessary to address the following questions:

– are there enough coarse aerosol particles in the smoke of a forest fire;

– can such particles be transported to the middle troposphere, where the processes of precipitation formation proceed;

– is the residence time of the coarse aerosol particles in the middle troposphere sufficient to affect the processes of precipitation formation.

Let us try to answer these questions.

In the literature, there are quite voluminous experimental data on the emission coefficient and the disperse composition of smoke aerosols, generated during the burning of wood and other forest combustibles (FCs). From the estimates presented in Refs. 8, 9, and other papers, it follows that the aerosol emission coefficient of the FC burning varies from 1 to 5%. In Ref. 10 it is shown that the number concentration of particles with radii of 0.4 to 1.4 μm in the wood smoke is rather high (up to 10^4 cm^{-3}) and the contribution of these particles to the total volume amounts to about 60%. The information about the changes in the volume contribution of three subfractions for wood smoke aerosols of the pyrolysis origin is summarized in Table 1.[5]

Table 1. Volume contributions of three subfractions of the wood smoke aerosol under different conditions of smoke formation and the following transformation in time

Particle fraction	Median radius of particles, μm	Contribution of fractions to aerosol volume, %		
		Weak smoke	Dense smoke	Settled dense smoke
Fine	0.03–0.06	95–98	1–2	2–3
Medium	0.3–0.6	2–5	3–5	18–20
Coarse	1.0–1.5	–	90–95	75–80

It follows from the Table that as the smoke density increases, coarse smoke particles are formed.

The influence of different factors on the microstructure of wood smokes was studied in Ref. 10. Pyrolysis of a wood sample having a mass of 380 mg was carried out in a small aerosol chamber with a volume of 0.1 m^3 (10^5 cm^3). Parts of a cedar branch, covered with bark, were used as samples. The experiments have shown that the number concentration of the smoke aerosol of medium fraction ($0.4 < r < 1.4$ μm) for 8 min of measurements decreased from 12 300 to 700 cm^{-3}. This decrease is explained by aerosol deposition on the chamber walls. The total number of particles with $0.4 < r < 1.4$ μm in the aerosol chamber was $\approx 10^9$.

Let us estimate which part of the burned wood mass n comes to formation of the coarse aerosol $1 < r < 1.4$ μm, using the equation

$$n = \frac{m_1}{m} = \frac{(4/3)\pi r_c^3 \rho v n_1 N}{m}, \qquad (1)$$

where $m = 0.38$ is the burned wood mass, in g; m_1 is the coarse aerosol mass; $r_c \approx (1\ \mu m + 1.4\ \mu m)/2 = 1.2 \cdot 10^{-4}$ cm is the mean radius of coarse aerosol particles; $\rho = 1.5$ g/cm^3 is the mean density of the smoke particulate matter; $v = 10^5$ cm^3 is the chamber volume[10]; $n_1 \approx 0.5$ is the coarse aerosol subfraction in the fraction of particles with the radius $0.4 < r < 1.4$ μm; $N = 12\ 300$ cm^{-3} is the number concentration of the medium and coarse aerosol; $\pi = 3.14$. Substituting these values into Eq. (1), we obtain $n = 1.75 \cdot 10^{-2}$. Thus, during the pyrolysis of wood of small branches of conifers, about 1.75% of burned matter transforms into the coarse aerosol. Since the mass of aerosol deposited on the chamber walls was ignored, the estimates obtained in Refs. 5 and 8–10 by different methods approximately coincide.

Estimate now the deposition time of aerosol particles with $1 \le r \le 2$ μm. According to calculated data, the rate of gravitational sedimentation by the Stokes equation at the particle density of 1.5 g/cm^3 is $5.27 \cdot 10^{-5}$ m/s for particles of 1 μm radius and $1.95 \cdot 10^{-4}$ m/s for particles having radius of 2 μm.

Particles with $r = 1$ μm for 1 day descend roughly by 4 m, while particles with $r = 2$ μm descend by 16 m. Thus, particles of such size lifted by a convective flow to the height of several hundred of meters can reside in air for several tens of days and can be transported in smoke plumes to hundreds and thousands kilometers from a fire site.

Formulation of the physical problem

Consider the case of a mass fire, when the number of fire seats is large. After a sufficiently long time after burning at hot and dry weather, the aerosol is uniformly distributed in the mixing layer except for local areas above the seats of fire.[3] Let us estimate the concentration of the coarse aerosol in the mixing layer for mass fires of 2002 in Yakutiya, taken as examples. We will take into account only the aerosol emitted into the atmosphere on August 14, 2002. The estimates obtained in Ref. 1 show that about $24.1 \cdot 10^9$ kg CO_2, $6.3 \cdot 10^9$ kg CO, and $0.37 \cdot 10^9$ kg CH_4 were emitted for this period. Since all carbon and hydrogen in these gases were produced from wood, we can obtain from these data only strongly underestimated amount of the burned biomass by calculating the mass of the gaseous elements (using their molar mass). It is $\approx 9.66 \cdot 10^9$ kg or less than 10^{10} kg.

Assume that for 1 day the aerosol has spread over an area of 1000×1000 km and was uniformly distributed over the 1-km thick layer. Determine the concentration of smoke aerosol particles, produced in burning of 10^{10} kg biomass, in the mixing layer. According to our estimates, 1.75% of this mass, that is, $m_c = 1.75 \cdot 10^8$ kg, comes to formation of the coarse smoke aerosol. Since it follows from Ref. 10 that the burning of $m = 0.38$ g biomass produces

$N = 12\,300 \cdot 10^5 = 1.23 \cdot 10^9$ particles, the burning of $m_c = 1.75 \cdot 10^8$ kg produces $N_c = (1/m)m_cN = 5.66 \cdot 10^{20}$ particles with $r \geq 1.0$ μm. Distributing uniformly these particles over a $1000 \times 1000 \times 1$ km $= 10^{15}$ m^3 volume, we obtain the concentration $N_{mix} = 5.66 \cdot 10^5$ m^{-3} in the mixing layer.

Determine the conditions, under which the aerosol from the mixing layer penetrates into the free atmosphere. At intense fires, a convective plume above the burning zone and clearly seen due to high concentration of large smoke particles, can penetrate into the free atmosphere.[2–4] In addition, because of the rather high humidity of the air the most powerful thermics, forming the mixing layer, reach the condensation level and give rise to cumulus, cumulonimbus, and shower clouds. Thus, at a sufficiently high moisture content a two-level convection arises, which consists of thermics in the mixing layer and the upper-lying layer of convective clouds of different types.[11,12] The coarse aerosol from the fire zone comes to the mixing layer, where its concentration is almost constant. During the cloud formation, an insufficient part of aerosol enters the cloud layer. Reaching the level above the isotherm of −12°C, the aerosol affects the phase transitions in the vapor–ice–liquid water system (Fig. 1). Naturally, these clouds contain the aerosol, penetrating from the mixing layer and affecting the processes of cloud and precipitation formation. The total amount of such an aerosol is not large and, according to the estimates presented in Ref. 3, does not exceed 1% of its concentration in the mixing layer: $N_{cl} = 0.01N_{mix} = 5.66 \cdot 10^3$ m^{-3}. Thus, the particles with $r \geq 1.0$ μm, emitted for only 1 day of mass fires in Yakutiya, can be sufficient to affect the phase transitions in the vapor–liquid water–ice system in the supercooled part of convective clouds.

Mathematical formulation of the problem

It is assumed that the aerosol particles with $r \geq 1.0$ μm and the given constant concentration are already contained in the supercooled part of clouds. In the "warm" part of clouds and in the free space, the smoke aerosol behaves as a passive admixture.

As the initial equations, we took the equations of deep convection[13] with the parametric consideration of the processes of cloud and precipitation formation.[14] These equations, the boundary and the initial conditions, as well as the method of solution can be found in Ref. 15.

The grid of 512×32 nodes in a horizontal plane of each of the 100 levels along vertical over the region of $80 \times 10 \times 10$ km allows one to explicitly resolve the coherent structures (thermics and convective clouds) in a stochastic convective-cloud ensemble.

The model[15] was used for the comparative analysis of the amount and distribution of precipitations in the presence of different concentrations of admixtures in the atmosphere. The appearance of clouds was simulated by specifying the overheating T_h in a local zone of the space R, having the dimensions of 10×10 km along x and y, respectively, at $z = h$ [Ref. 15].

Calculated results

We have performed calculations for 1.5 h of the process. The results have shown that the overheating leads to formation (in few minutes) of a convective ensemble, which initially consists only of thermics. Then, when most "powerful" thermics reach the condensation level, convective clouds begin to form.

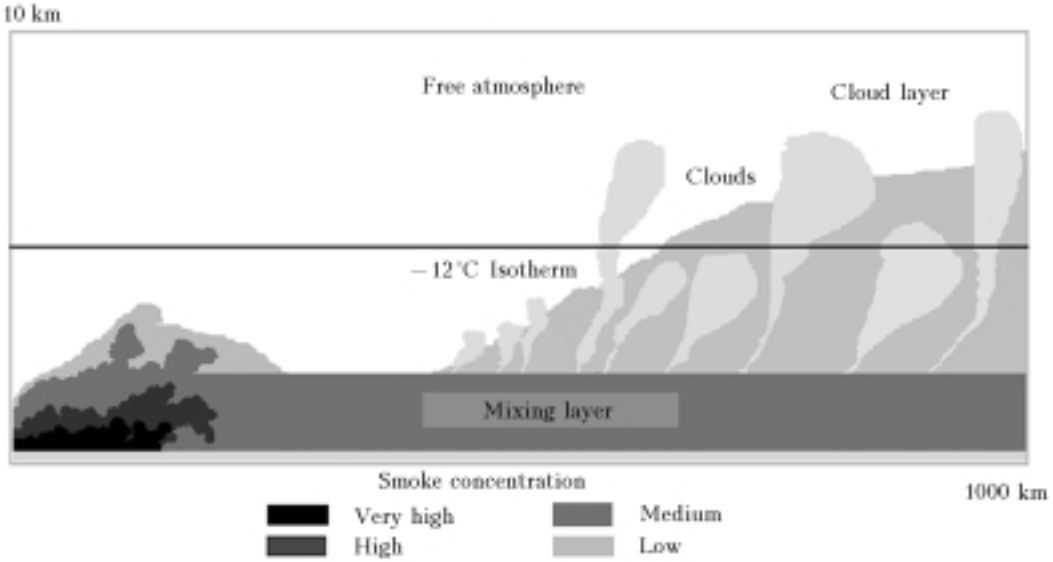

Fig. 1. Scheme, explaining the penetration of smoke aerosol into the cloud layer.

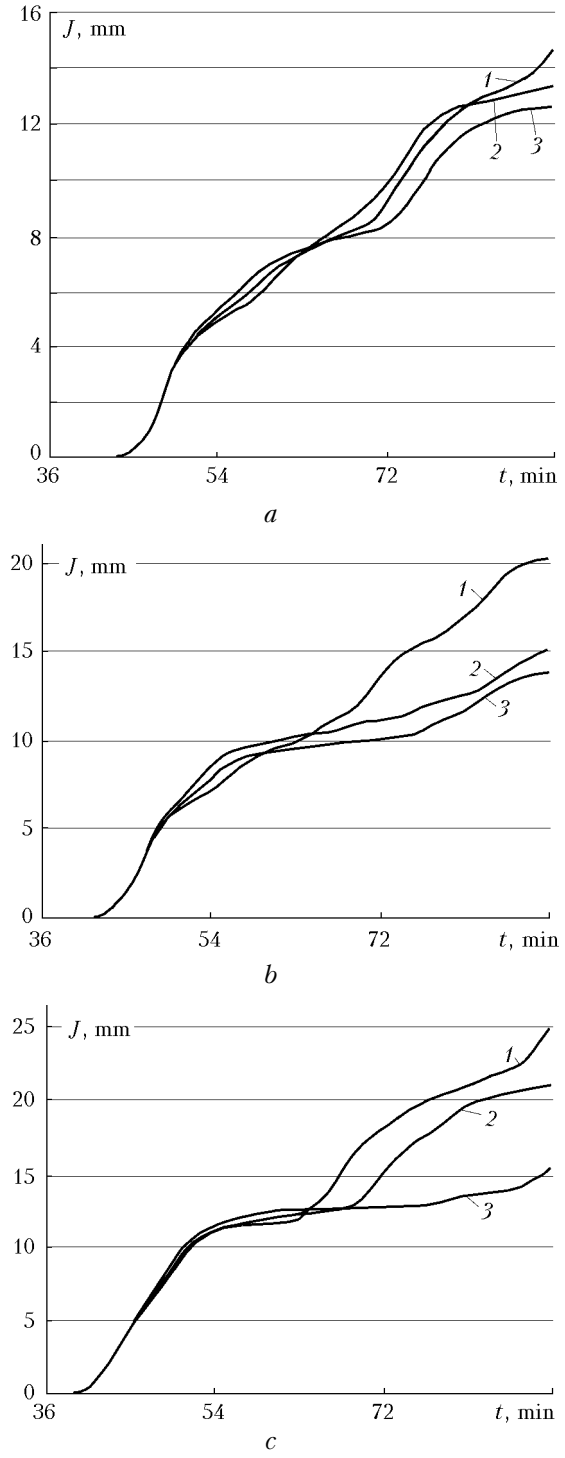

Fig. 2. Influence of aerosol on the precipitation amount at different time at the overheating temperature T_h = 5°C (*a*), 7°C (*b*), and 9°C (*c*). *J* is the precipitation amount at the level $z = h$; *t* is time; aerosol is absent (*1*); the aerosol concentration is 100 m^{-3} (*2*); the aerosol concentration is 800 m^{-3} (*3*).

The vertical dimensions of the clouds increase, and 20–30 min later they begin to precipitate. The intensity of precipitation depends significantly on the altitude of the top edge of clouds H_{cl}, which is about 4 km at T_h = 5°C, about 5 km at 7°C, and about 6 km at 9°C. The precipitation amount (in mm) at different time for these values of overheating is shown in Fig. 2. It can be seen from this figure that, in the absence of admixtures in clouds, the precipitation amount was 15 mm in the first case, 20 mm in the second case, and 25 mm in the third case. The introduction of large admixture particles in all the three cases leads to a decrease of the precipitation amount. In the first case, 100 particles per 1 m^3 appeared to be sufficient to decrease the precipitation by 10%. In the second and third cases, the same concentration of particles decreased the precipitation amount by 20%.

The numerical experiments suggest that if a cloud has a supercooled top (just such clouds produce intense precipitation) then the introduction of aerosol particles with the size larger than 1 μm decreases the precipitation. The intrusion of the coarse aerosol is accompanied by fast crystallization of water droplets in the upper part of the cloud. Such clouds give much less intense precipitation, than the clouds, whose tops are a mixture of ice crystals, snow, and rain droplets.

Conclusions

The results obtained by numerical simulation with the use of the described theoretical approach and with regard for the experimental data available, indicate that the smoke aerosol, produced in forest fires, can actually decrease the amount of precipitation in the mid-latitudes. This effect is not usually observed during mass fires in tropical forests. In this geographic zone, showers are produced by "warm" clouds, and therefore all thermal and dynamic factors, as well as all forms of aerosol, favor the intensification of precipitation. Fires in tropical forests are almost always accompanied by showers and thunderstorms.

A more detailed study of the weather and climatic effect (forcing) of mass forest fires in the mid-latitudes needs for further combined investigations with regard for numerous chemical, photochemical, microphysical, thermal, and dynamic factors responsible for the effects of aerosol on the weather and climate.

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