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Studying an effect of salt powder seeding used for precipitation enhancement from convective clouds

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Abstract

The experimental and theoretical studies of cloud microstructure modification with the "optimal" salt powder for obtaining additional precipitation amounts from convective clouds are performed. The results of experiments carried out in the cloud chamber at the conditions corresponding to the formation of convective clouds have shown that the introduction of the salt powder before a cloud medium is formed in the chamber results in the formation on the large-drop "tail" of additional large drops. In this case seeding with the salt powder leads to enlargement of the whole population of cloud drops and to a decrease of their total concentration as compared to the background cloud medium. These results are the positive factors for stimulating coagulation processes in clouds and for subsequent formation of precipitation in them. An overseeding effect, which is characterized by increased droplet concentration and decreased droplet size, was not observed even at high salt powder concentrations.

The results of numerical simulations have shown that the transformation of cloud drop spectra induced by the introduction of the salt powder results in more intense coagulation processes in clouds as compared to the case of cloud modification with hygroscopic particles with relatively narrow particle size distributions, the South African hygroscopic particles from flares being an example of such distributions. The calculation results obtained with a one-dimensional model of a warm convective cloud demonstrated that the effect of salt powder on clouds (total amounts of additional precipitation) is significantly higher than the effect caused by the use of hygroscopic particles with narrow particle size distributions at comparable consumptions of seeding agents. Here we show that seeding at rather low consumption rate of the salt powder precipitation can be obtained from otherwise non precipitating warm convective clouds.

1 Introduction

Operational hygroscopic cloud seeding aimed at rain enhancement has been conducted extensively in many countries, including India, USA, Saudi-Arabia, China, Thailand and other countries. The seeding practice with hygroscopic flares became fashionable after the reports of the apparent success of the South African (Mather et al., 1997) and Mexican (WMO, 2000; Bruintjes et al., 2001) experiments, and the simulations with theoretical support for the efficacy of the flares (Cooper et al., 1997). The operational practice has been to seed the updraft just below cloud base with one to two 1-kg hygroscopic flares that burn in about 4 minutes. This means a seeding rate of 0.25 to 0.5 kg/min or, with an air speed of 70 m/s, a rate of 0.015–0.03 kg/km of seeding path. This practice prevails even though demonstration of its efficacy is lacking. Furthermore, Segal et al. (2004) calculated the particle size distribution of hygroscopic aerosols that would accelerate the conversion of cloud water to rain drops for the least amount of salt mass, and showed that this was quite different from the particle size distribution that is produced by burning hygroscopic flares. Rosenfeld et al. (2010) followed this up and manufactured a salt powder that matched the optimal particle size distribution as calculated by Segal et al. (2004), and tested it against hygroscopic flares in actual cloud seeding experiments. The results of Rosenfeld et al. (2010) support the simulations of Segal et al. (2004) and show that to produce a microphysical seeding effect on the clouds that is detectable by cloud physics aircraft, a mass concentration greater by an order of magnitude than is presently practiced with hygroscopic flares has to be dispersed.

The paper presents the results of experimental and theoretical studies of cloud modification with the salt powder developed at the Hebrew University, Israel, for obtaining additional precipitation amounts from convective clouds. Experiments carried out in the cloud chamber of the Research and Production Association "Typhoon", Russia, under the conditions corresponding to the formation of convective clouds, as described in Sec. 2. The observed changes of the cloud microstructure at different seeding rates

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in the cloud chamber are given in Sect. 3. The conversion of cloud water into rain could not be fully documented even in this big cloud chamber due to sedimentation of the large cloud drops. The implication with respect to conversion of the cloud water to rainfall had to be assessed by a 1-dimensional cloud model, which replicated the observed initial spectra and extended the calculations through the formation of rain. This was done both for the salt powder and for other hygroscopic agents with narrow particles size distributions, as described in Sect. 4. The conclusions, given in Sect. 5, provide the particle size distribution and seeding rates that would result in the fastest conversion of cloud water to rainfall for a range of seeding rates of the hygroscopic seeding agents. It should be noted here that the fastest conversion of cloud water to rainfall does not always mean also the greatest amount of precipitation (Rosenfeld et al., 2008). Establishing the seeding effects on precipitation requires randomized seeding experiments in the natural atmospheric conditions accompanied by detailed microphysical measurements and model simulations.

2 The Big Cloud Chamber and its usage for measurements in aerosol and cloud media

Experimental studies of a salt powder seeding effect on a cloud medium were performed in the Big Cloud Chamber (BCC) of RPA "Typhoon". BCC is designed for modeling convective or stratified clouds and fogs of different origin under the conditions close to those in the real atmosphere. The chamber is a steel airtight cylinder of 18-m height and 15 m diameter. The chamber walls of 6-mm thickness are externally heat-insulated. The total volume of the chamber is 3200 m^3. A cloud medium is formed up to a height of 15 m. The technological compartment separated by a metallic grating is located above. A detailed description of the BCC and the methods of cloud media formation in it are presented in (Romanov and Zhukov, 2000).

The process of convective cloud medium formation in the BCC is made through air expansion. For this external air is pumped into the chamber. As a result the air pressure in it is increased to a certain level. The air pressure decrease is made by opening holes in the upper part of the chamber. The air discharge from the chamber through the holes of different cross sections makes it possible to regulate the rate of pressure decrease in the chamber, thus setting a certain velocity of air updraft in the atmosphere during the formation of a convective cloud. The program controlling pressure decreasing in the BCC makes it possible to realize a preset scenario of air mass updraft in the atmosphere with equivalent rates of 0.1–10 m/s. Air temperature, pressure, humidity and the chamber wall temperatures are basic parameters for setting thermodynamic conditions in the BCC. These parameters are continuously measured during the experiments in the BCC. For setting the conditions of cloud medium formation thermodynamic relationships and the known heat exchange coefficients for the BCC are used (Romanov and Zhukov, 2000).

In the efforts described in this paper the pressure decrease in the BCC was made from the initial value of 1300 hPa with the velocity of air mass updraft in the atmosphere of 1.2–1.3 m/s. Relative humidity of air in the chamber before the pressure drop is usually 90–96%. The air temperature is 22–25 °C. At such values of meteorological parameters a cloud medium in the BCC is formed in 2–3 min after the beginning of the pressure lowering. The air temperature decreases practically linearly until it becomes equal to that of the chamber walls. It usually makes 18–20 °C. This period lasts ≈12 min during which the equivalent velocity of air updraft decreases to ≈0.9 m/s. Just during this period the process of cloud medium formation in the BCC may be considered adequate to the process of convective cloud formation in the real atmosphere.

As the total heat capacity of the BCC walls is by about 10 times greater than the total heat capacity of air in the chamber, the evolution of the cloud medium is more strongly affected by the processes of air heat exchange with the chamber walls. When the air temperature becomes lower than that of the wall, the wall heats the air. Despite the continuing lowering of air pressure the rate of air temperature change in the BCC decreases. The total cooling of the air in the BCC reaches ~8 °C by this time. During the experiment the wall chamber temperature changes very slowly (no more than by

1 °C). By 20 min after the cloud medium began to form the equivalent velocity of updraft drops to zero, the air temperature begins to rise and the cloud begins to evaporate. The total lifetime of the cloud in the BCC is 40–50 min.

For measurements of aerosol and cloud medium microstructure the BBC is equipped with the photoelectric particle analyzer developed at the RPA "Typhoon". These devices are based on measurements of light scattered from particles at an angle of 90°. The principle of operation of the analyzers is in the analysis of amplitudes of pulses of light scattered from single particles at their flight through the measuring volume. Optical formation of the measuring volume not causing changes in the microstructure of measured particle is used in the analyzers.

In the photoelectric meter of cloud drops (Romanov, 1991) an electric filament lamp is used as a light source. The light flux from the lamp is focused by a round lens on its axis. The light scattered from a drop in the lens focus is collected by the round lens and directed to the photodetector. The angle between the axes of the illuminating and the positive lenses makes 90°. The principle of drop sizes measurements is in the measurement of the intensity of light scattered by a drop and the use of the calculated dependences of scattered light intensity on a drop size. For this, the operating characteristic of the device is calculated. The operating characteristics of such devices are calculated with the Mie scattering theory for spherical particles (Heyder and Gebhart, 1979; Singh et al., 1982). The angular apertures of the light source and of the light detector are taken into consideration. The lamp radiation spectrum and the photodetector spectral sensitivity are also taken into account. The range of measured drop radii with this meter is within 1–50 µm. The number of drop size measuring channels is 360. The photoelectric meter is an analog of an airborne instrument used in studying cloud microstructure in the real atmosphere. It allows one to obtain cloud drop spectra at the time of data accumulation from 1 s at the medium flow rate through the measuring volume over 2.5 cm^3/s, which was driven through the probe by a fan located downstream of the measurement volume. During the measurements in the BCC the photoelectric meter was located near the bottom of the cloud chamber.

The same principle of drop size measurements, as that mentioned in the device described earlier, is used in the laser analyzer of particles (Kolomiets at al., 1989) for measurements of solid aerosol particles microstructure. A continuously operating laser at the 0.63 µm wavelength serves as a light source in the analyzer. Its main difference from the device described above is in the peculiarities of the optical formation of the measuring volume. High uniformity of illumination of the measuring volume is achieved in the laser analyzer because of the use of an annular laser beam and subsequent electronic processing of photoelectric pulses. The annular beam is formed from the initial laser beam with the help of a special lens (axicon) having one flat surface and the other one is conical in form. The light scattered by particles under study is collected with the elliptical mirror and sent onto a photodetector in the frames of the annular aperture in the scattering angles of 60°–120°. The operating characteristic of the laser analyzer is calculated with the account for the geometric peculiarities of its optical scheme. The laser analyzer makes it possible to measure particle size distributions within the particle radii of 0.1–5 µm. The number of particle size measurement channels is 120. The aerosol under study is supplied via a thin capillary into the region of laser beam focusing. The flow rate of air passing through the analyzer volume is 1 cm^3/s.

With the data of photoelectric analyzers calculated also are the integral parameters of size distribution functions such as concentrations and effective radii of the particles. The particle concentrations are determined from the frequency of pulses of light scattered from every particle. Both photoelectric analyzers are calibrated against round polysterol latex particles with the known sizes and the known light refraction index.

The experiments in the BCC on cloud medium modification by the salt powder were performed according to the following method. First a cloud medium on natural condensation nuclei was formed in the BCC, and during about 20 min measurements of the background cloud medium parameters were made. Then the pumping of the chamber up to the initial high pressure was repeated and salt particles were injected into it. The spraying of the salt powder from an airplane in the cloud was simulated by a pneumatic atomizing nozzle (like a spraying can). Then via the piping it was introduced into the BCC. With the help of fans the aerosol was uniformly mixed inside the chamber. At the moment of the beginning of pressure dropping the fans are switched off. The salt particles were introduced into the chamber at a relative humidity of about 96%. By this, the conditions of particles introduction into the subcloud layer of a convective cloud were simulated. Then, the process of lowering air pressure in the chamber was repeated, and the parameters of the cloud medium formed as a result of aerosol particles impact were measured. The modification effect was assessed from the results of comparing the parameters of the cloud medium with the corresponding parameters during the background experiment. During numerous experiments in the BCC it has been found that at repeated lowering of air pressure the parameters of the cloud medium remain practically the same, so the impact of salt particles with the use of the method developed is made under similar conditions of cloud medium formation as compared to the background experiment.

The agent under study is a specially prepared powder of NaCl with aerosol (SiO_2) used as an anticaking admixture (Lahav and Rosenfeld, 2005; Rosenfeld et al., 2010). The measurements of microstructure of the dry salt particles under this study were made in the BCC at the air relative humidity of about 40% with the laser analyzer of particles. After the salt powder was introduced into the chamber with the pneumatic atomizing nozzle the aerosol was uniformly mixed inside the chamber and measured there. The results of measurements of the dry particles size distribution function of the salt powder are shown in Fig. 1. Here also given are the spectra of background aerosol the mass concentration of which made 5×10^{-4} mg/m^3. The measurements were performed at a salt mass concentration of 0.4 mg/m^3. The spectra are obtained during the time of data accumulation of about 10 min. The spectrum of salt powder particles was obtained by subtraction of background aerosol spectrum from the aerosol spectrum in the BCC after the introduction of the salt powder. As is seen from the graphs, in the salt powder studied there is a considerable number of particles the sizes of which are smaller than the lower measurement limit of the laser analyzer (0.15 µm). These may be the particles of the anticaking admixture or the "fragments" of salt. The particles effective radius in the size range studied is 1.54 µm. As is seen from Fig. 1, there are also particles with the sizes exceeding the upper measurement limit of the laser analyzer (5 µm). To reveal the structure of these particles, aerosol particles sampling was made by their settling onto a glass substrate during the measurements in the BCC. Microscopic studies of the samples have shown that in the powder studied there exist large particles with the radii up to 10 µm. In this case, large particles with the sizes over 5 µm are mainly the salt particle conglomerates with finer particles that stuck to them. It should be noted here that the salt powder was tested three years after it was manufactured and held in closed plastic bags within cardboard boxes in a storage room, so that some clumping could take place during this long period.

Figure 1 gives the approximation of background aerosol particles spectrum made by the Junge spectrum

$$f(r) = 0.005r^{-\nu}, \tag{1}$$

where $\nu = 5$. The spectrum of salt particles, as is seen from Fig. 1, is rather well approximated by the distribution like

$$f(r) = 1.7r^{-1.5}\exp(-(r/r_o)^2), \tag{2}$$

where r_o = 5 µm.

For comparison, the particle size distribution of the South African hygroscopic flares (Cooper et al., 1997) is given in Fig. 1 at a mass concentration equal to the salt powder concentration of 0.4 mg/m^3. Figure 1 reveals that the South African flares contain a very high number of particles with r<1 µm as compared to the salt powder. At the same time the particles with r>1 µm are much less in number.

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3 BCC measurements of salt seeding effects on cloud microstructure

The evolution of the cloud drop size spectra obtained with the use of a photoelectric meter in the BCC is shown in Fig. 2. Here presented are typical cloud drop spectra determined at different time steps after the formation of a cloud medium during the background experiments. The time starts from the moment of the cloud medium formation. At the chosen mode of air pressure lowering a cloud medium with the drop concentration from 1300 to 1550 cm^{-3} is formed. The liquid water content of the medium grows linearly with time and by 12 min it becomes equal to 0.8 g/m^3. The largest drops in the background experiments reached the radii of 12 µm.

Figure 3 gives the results of cloud drop spectrum measurements at different time steps at the introduction of 3.5 g of the salt powder into the BCC. When distributed over the BCC volume of 3200 m^3 it constitutes a mass concentration of 1.1 mg/m^3. The modal size of the cloud drops that formed in the BCC appear to be nucleated on the background condensation nuclei. The temporal character of variation of this spectrum range does not practically differ from the behavior of spectra obtained during the background experiment. From the graphs in Fig. 3 it is seen that the introduction of such an amount of salt particles manifests itself only in the large-drop fraction of the cloud drop spectrum. A "tail" of large drops that formed on the added salt particles appeared on the drop size distribution that was measured already at the first 2 minutes after cloud formation. In the spectra measured after 4 min of the cloud medium existence the large-drop "tail" of the distribution appears to be truncated due to gravitation-induced sedimentation of the largest drops onto the BCC floor. Actually, the terminal sedimentation rate of drops with the radii of, for example, 30 µm, is equal to 11 cm/s. At the height of the BCC working volume of 15 meters all the drops of such sizes formed at this level fall onto the floor of the BCC during 2.5 min. The duration of the settling process of drops with radii of 20 µm takes about 5 min. It is clear that the life-time of such drops formed at the lower levels of the BCC is much shorter. This causes a sharp decrease of the observed number of drops with radii larger than 20 µm. The effective radius of drops calculated over the spectra increased in this case by 5% as compared to the background experiment, and the largest registered drops reached radii of 16 µm.

The evolution of cloud medium spectra at the introduction of 16 g of salt particles with the mass concentration of 5 mg/m^3 is shown in Fig. 4. Here the bimodal character of the cloud drop spectrum is seen distinctly. In this case the cloud droplets formed on the background aerosol particles are smaller in size as compared to the background experiment. This effect is explained by a decrease of water vapor supersaturation in the cloud medium at the introduction of the given amount of salt particles. As a result, a slower growth of drops formed on the background aerosol occurs. The fraction of large cloud drops formed on the salt particles is here significantly greater than in the previous case. The drop effective radius at the introduction of 16 g of salt powder increased as compared to the background experiment by 20%. The largest drops attained radii of 20 µm.

At the introduction into the BCC of a rather great amount of salt particles (31 g, with the mass concentration of 9.7 mg/m^3), as is seen from Fig. 5, practically all the cloud drops are formed on salt particles. The fine-droplet spectrum fraction, that appeared due to the background condensation nuclei, does not manifest itself. The effective radius of drops increased in this case as compared to the background experiment by 1.35 times, and the largest drops registered reached the radii of 22 µm. The cloud drop concentration here decreased by 2.5 times. An example of changes in the integral parameters of cloud medium microstructure during the background experiment and in the experiment in the BCC with the introduction of 3.5 g of salt particles is presented in Fig. 6. The time count begins at the moment of the cloud medium formation. As one can see from the data presented, the introduction of the salt powder results in the formation of larger cloud drops and their lower concentrations as compared to the background experiment. The cloud medium liquid water contents are practically the same in both experiments. The experimental results have shown that at an increase of the mass of the particles introduced, the modification effect becomes stronger.

The results of measuring the cloud medium integral parameters at different masses of particles introduced are given in Table 1. Table 1 contains the salt particle mass concentrations at different masses of salt powder introduced, and cloud drop concentrations at the introduction of particles (N) and in the background experiment (N_F). Table 1 gives averaged data obtained during the experiment in 4–5 min. after the cloud medium formation in the chamber, i.e. after the process of nuclei activation ended and the cloud medium parameters are stabilized. It contains also the values of a relative dispersion of cloud drop spectra at the introduction of particles (S) and in the background experiment (S_F) calculated from the measured spectra with the formula $S = \sqrt{(r_2/r_1)^2 - 1}$, where r_1 and r_2 are the mean and mean-root-square radii of drops, respectively. The values of S are calculated for the 12th minute of the cloud medium existence.

A necessary condition for obtaining a positive effect at modification by hygroscopic particles (precipitation enhancement) is an increase of cloud drop sizes at the introduction of particles (Drofa, 2006), as far as the enlargement of cloud drops is the major factor stimulating gravitational coagulation in clouds and subsequent precipitation formation. Changes of cloud drop sizes were estimated by us during modification experiments over the changes of their concentrations against the drop concentrations in the background experiment. Under similar conditions of performing these experiments (the same liquid water contents of cloud media) the relationship $N_F/N = (r/r_F)^3$ is valid, where r and r_F, N and N_F are the effective radii of drops, their concentrations at modification and in the background experiment correspondingly. It means that the value of N_F/N characterizes the changes of cloud drop sizes under modification. It is easily measured experimentally. In such a way the values of r/r_F given in the Table 1 were obtained.

The effect of modification can be considered positive at $N_F/N>1$ (i.e. when the drop become larger). As one can see from the data given in the Table, the necessary condition for obtaining a positive effect of modification with the salt powder under study in our experiments is met – at the introduction of salt particles a decrease of cloud drop concentration and the drop growth are observed. With increasing weight concentration of salt particles introduced, this effect of modification increases practically linearly. The introduction of a great amount of salt particles does not result in “overseeding” at which the concentration of drops increases and instead of their enlargement the drops become smaller.

The measurement results of a relative dispersion of drop spectra given in Table 1 show that the introduction of salt particles in the cloud medium causes the spectrum broadening as compared to the background cloud medium. This effect increases with increasing the particle mass. The effect is a positive factor at cloud medium modification for precipitation enhancement as far as the greater the difference in drop sizes in the cloud medium, the more efficient the coagulation processes of cloud drops and precipitation formation are. As has been mentioned earlier, the drop spectra obtained in the BCC are “truncated” in the large-drop-spectrum range because of the settling of drops onto the BCC floor. It is most probable that in real clouds broadening of cloud drop spectra may be considerably larger than in the experiment.

The value of N_F/N can serve as an estimate of the efficiency of cloud modification with hygroscopic particles having relatively narrow particle size distributions (Drofa, 2006). At the introduction of such particles into the subcloud layer governing in the stimulation of coagulation processes in a cloud is the increase of the whole population of cloud drops. The more the value of N_F/N is realized in the cloud base, the greater will be the amount of additional precipitation at modification. A characteristic property of modification by particles with narrow drop size distributions is that the positive effect of modification is realized only at an optimal concentration of such particles. An example of the use of such particles is the modification of convective clouds by pyrotechnic flares developed in South Africa (Mather et al., 1997). Their particle size distribution is given in Fig. 1. When such flares were used, the positive meaningful modification effect was obtained in several projects aimed at obtaining additional precipitation amounts from convective clouds. Using the method proposed in (Drofa, 2006) with the known data on particle size distribution, physical and chemical characteristics of pyrotechnic flares for typical atmospheric conditions, it is possible to obtain a maximum value of

N_F/N =1.42. This value is achieved at a certain concentration of particles introduced (300–500 cm^{-3}). The mass concentration of the substance contained in pyrotechnic flares makes ≈0.05 mg/m^3. At higher or lower concentrations the value of N_F/N decreases. When mass concentrations of particles introduced make over 0.14 mg/m^3, an effect of "overseeding" appears, i.e. at the introduction of particles the drop concentration in the cloud increases and their mean size decreases. This is the cause of decreasing intensity of precipitation formation in the cloud at "overseeding".

4 Simulations of the seeding effects

To overcome the effect of truncation of the drop size distribution by sedimentation and to assess the efficiency of hygroscopic agents with rather wide particle size distribution functions (one of them is the salt powder under study), simulation studies are needed. In this paper we shall theoretically study the efficiency of cloud modification by the salt powder with the use of a one-dimensional convective cloud model developed by Drofa, (2008, 2010). This numerical model of a warm convective cloud allows one to study a spatiotemporal scheme of cloud formation and development and to analyze the evolution of cloud microstructure and precipitation in response to the introduction of hygroscopic particles.

The 1-dimensional numerical model describes the evolution of a cloud medium in the central part of an axisymmetric warm convective cloud at a preset variable with height velocity of an air updraft forming the cloud. The equation system is used for temperature and air pressure changes and for water vapor supersaturation at air mass lifting. Entrainment of heat and water vapor into a lifting air parcel from the environment is accounted for parametrically (as in Pruppacher and Klett, 1997). The value of the entrainment coefficient is taken inversely proportional to the altitude above the cloud base. Adjustment of parameters characterizing entrainment gives a possibility to achieve a complete matching of vertical profiles of cloud parameters obtained in the model with the parameters of continental clouds in the real atmospheric conditions

(Mazin and Shmeter, 1983; Shmeter, 1987).

The vertical profile of vertical air velocity is prescribed in the numerical model and does not change between the stages of cloud development. To describe the air updraft velocity vertical profile a universal function considering basic regularities of air vertical fluxes in continental convective clouds (Shmeter, 1987) is applied. The velocity of an air updraft at the cloud base is set to 1.5 m/s. It increases proportionally to altitude in the lower half of the cloud. Maximum velocity is achieved at the half cloud height. It is proportional to the cloud thickness. At a cloud thickness of 4 km it reaches about 5 m/s. In the cloud upper half the updraft velocity drops gradually to zero. The altitude at which the updraft velocity is equal to zero is determined by the cloud thickness.

Limitation of growth of the convective cloud upwards occurs due to the existence in the atmosphere of a barrier layer with isothermality and inversion of air temperatures. The height of this layer above the cloud base determines the height of maximum liquid water content in the cloud. In the numerical model, the atmospheric barrier layer is simulated by the introduction at a certain level above the cloud base of water vapor sub-saturation, as far as low air relative humidity has a governing role in the cloud medium evolution. The altitude of the barrier layer above the cloud base is preset at the level of 0.8 of the cloud thickness. This corresponds to the parameters of moderate convective clouds observed in real atmospheric conditions. Above this level the cloud top is formed, where fine cloud droplets evaporate and the large drops precipitate into the lower cloud layers.

In the given numerical model it is assumed that the activation of condensation nuclei takes place in the cloud base. At a further lifting of the cloud medium only the process of drop condensation growth/evaporation occurs. New cloud drops do not form. The initial stage of cloud medium microstructure formation is described by the equation of drop condensation growth. With the use of the initial conditions of the air mass state and the parameters of condensation nuclei (atmospheric and/or additionally introduced), the size distribution function of drops originated at the cloud base is calculated according to the method used in (Drofa, 2006). Further evolution of the size distribution function is calculated with the use of the kinetic equation. The model contains a precise description of warm rain microphysics. The processes of drop condensation growth/evaporation, coagulation, breakup of drops and their sedimentation are considered. For a numeric solution of the kinetic equation a fixed grid of cloud drop sizes in the radius range of 1–2500 µm (396 points) with a non-uniform step in radii was used. Sedimentation of drops and precipitation are computed from the difference of terminal falling velocities of drops of different radii and the rate of the air mass updraft. For this determined is the number of drops that fell from the given cloud layer and those that entered this layer from the above level during a certain period of time.

With the data obtained during model simulation calculated are the spatiotemporal structure of meteorological parameters and integral characteristics of the cloud drop size distribution function – the drop number concentration, cloud liquid water content and the cloud drop effective radius. The liquid water contents of large drops with the radii $r > 200$ µm characterizing precipitation are computed as well. Total amounts of precipitation are calculated at the level of the lower cloud boundary. It should be said that owing to the fairly simplified description of the dynamic structure of the cloud development, dynamic responses of the clouds to the modified precipitation are not considered in the model. The results of calculated precipitation in this model should be regarded as relative estimates. They can be used only for comparison of the efficiencies of the tested hygroscopic cloud seeding methods.

An example of computation of the initial stage of the cloud medium microstructure formation at the introduction of the salt powder into the subcloud layer of the convective cloud according to the method used in (Drofa, 2006) is shown in Fig. 7. Here presented are the calculation results of cloud drop spectrum evolution with time for the conditions typical of continental convective clouds. The physical and chemical properties of the aerosol correspond to mean characteristics of atmospheric aerosol of continental origin (Drofa, 2006). The Junge distribution (1) was used as an initial distribution of aerosol particles being atmospheric condensation nuclei at $\nu = 4$. The velocity of air mass updraft is accepted as $V = 1.5$ m/s. The initial temperature of air is 10 °C. The pressure is 900 hPa. To describe the salt particles size distribution the function like (2) was used. It corresponds to experimentally measured spectra of dry salt powder particles. The sizes of salt particles were accounted for within the range of radii from 0.01 to 10 µm. The mass concentration of the particles introduced was taken equal to 1 mg/ m^3. At such a concentration, as is seen from Fig. 7, the effect of salt particles reveals itself only in the large drop "tail" of cloud drop distribution range without changes in the spectrum of drops formed on atmospheric condensation nuclei. The same character of cloud drop spectrum variations is observed in experimentally obtained spectra measured in the BCC at a very similar concentration of the salt powder introduced (see Fig. 3).

The calculation results of drop spectra in the convective cloud after 120 s at the introduction of different amounts of the salt powder into the subcloud layer are presented in Fig. 8. The atmospheric conditions are the same as in the case mentioned above. As it is seen from Fig. 8, at a small mass concentration of the powder, the introduction of such particles results only in the growth of the large-cloud drop fraction. This drop fraction is growing with increasing mass of the powder introduced. The shape of the drop spectrum formed on the background aerosol particles does not change at their mass concentration of the particles up to 1 mg/m^3.

At the concentrations of the salt powder higher than 1 mg/m^3 a decrease of the number of drops formed on atmospheric condensation nuclei occurs. This effect is also observed in the experimental data obtained at high concentrations of the salt powder (see Figs. 4 and 5). The effect is explained, as it has been mentioned earlier, by the fact that the introduction of larger amounts of salt particles decreases the supersaturation of water vapor. This causes a slower growth of drops formed on the background aerosol particles.

The evolution of the cloud drop size spectrum at the introduction of hygroscopic particles with a very narrow particle size distribution into the convective cloud sublayer is given as an example in Fig. 8 as well. In this case, the particles of NaCl with an effective radius of 1 µm and a relative dispersion of the drop size spectrum $S = 0.3$ are introduced. The number concentration of the particles introduced makes 120 cm^{-3} (an optimal concentration of particles of the given sizes). The particle mass concentration is 1.1 mg/m^3. As is seen from Fig. 8, the result of the introduction of such particles is in the formation of a bimodal cloud drop spectrum. The large drop mode is governed by the growth of drops formed on salt particles. The small drop mode is formed on the background aerosol particles. Further, the bimodal character of the cloud drop spectrum is maintained in the quasi-equilibrium state.

The studies of the modification effect induced by such particles have shown (Segal et al., 2004, 2007; Drofa, 2006) that at the introduction of salt particles, due to decreasing water vapor supersaturation in the cloud, the number of atmospheric nuclei is activated (i.e. they turn into cloud drops) to a lesser degree than in the background cloud. As a result, the total concentration of cloud drops formed on the background and additional nuclei appears less than in the case when additional condensation nuclei are absent. Average sizes of cloud drops at the introduction of particles become greater. Due to this a positive effect of modification by hygroscopic particles with narrow drop size distributions is attained, because the enlargement of cloud drops is the major factor stimulating gravitation-induced coagulation in clouds and subsequent precipitation formation. One should pay attention to the fact that the cloud drops formed on atmospheric aerosol particles are smaller in size as compared to those in the background cloud. It means that in this case the impact of salt particles leads to changes in the conditions of cloud drop formation on atmospheric condensation nuclei.

Modification made by the salt powder does not result in such changes even at rather high mass concentrations of the powder introduced. The number of cloud drops formed on background aerosol particles changes little here. As the analysis of the results of numerical simulations demonstrate, the modification by the salt powder causes a higher intensification of coagulation processes in the cloud than at the modification by hygroscopic particles with narrow size distributions. This can be explained by the fact that at the modification by the salt powder the drop spectrum is broadened only towards the large-drop fraction where coagulation is more efficient.

The data obtained at the initial stage of condensation (Fig. 8) are used as starting data for calculations of evolution of cloud medium microstructure with the one-dimensional numerical model of a convective cloud (Drofa, 2010). The calculation results for precipitation obtained with the model for clouds of different thicknesses at modification by different amounts of salt particles are shown in Fig. 9. The introduction of particles into the 60, 120 or 240 m subcloud layer is made at the 10th min. from the beginning of the cloud formation. The data given in the same figure for clouds without modification demonstrate that the significant precipitation quantities calculated with this model fall out from convective clouds with thicknesses over 3.5 km. This result is in agreement with the data of experimental studies of clouds in real atmospheric conditions (Mazin and Shmeter, 1983).

The results of numerical simulations show that the effect of modifying clouds with hygroscopic particles significantly depends on the cloud vertical thickness – the more the thickness, the greater the precipitation amounts are. The calculation data on the effect of the South African pyrotechnic flares particles show that significant additional precipitation amounts are observed only at modifying clouds with the thicknesses over 4 km. The calculations are made for the case of particles introduction into the layer with the thickness of 240 m at a mass concentration of particles of 0.05 mg/m^3 and the consumption of 12 kg of the agent per 1 km^2 of the seeded area. The use of smaller amounts of such particles does not lead to a discernible positive modification effect. The result presented is in agreement with the data of field experiments aimed at cloud modification with such particles (Mather et al., 1997; WMO, 2000; Bruintjes et al., 2001). In these experiments at comparable with the above-mentioned agent consumptions a 10–15% precipitation enhancement from the clouds of 6-km thicknesses was obtained.

Modeling was made for different mass concentrations of the salt powder with 0.01, 0.05, 0.1 and 0.2 mg/m^3. The results of numerical simulations demonstrated that the effect of modification by the salt powder is determined by the total amount of the powder introduced into subcloud layer. This means that at the introduction of the powder with the concentration of, for example, 0.1 mg/m^3 into the 120-m layer the same precipitation amount is observed as at the introduction of the powder with the concentration of 0.2 mg/m^3 into the 60-m layer. The amount of the agent at the given mass concentration is determined by the thickness of the layer into which the agent is introduced. So, at the introduction of the powder with the particle mass concentration of 0.1 mg/m^3 into the 120-m layer the consumption of the agent is 12 kg per 1 km^2 of the seeding area. At changing the layer thickness where the agent is introduced the agent consumption changes proportionally with the thickness of the layer.

As is seen from Fig. 9, seeding with salt powders results in a significant increase of precipitation amounts as compared to cloud modification by fine particles of the South African pyrotechnic flares. At the consumption of 2.4 kg/km^{2}of the salt powder the precipitation amounts falling from the clouds with the thicknesses over 4 km are greater than at cloud modification with the pyrotechnic flares (at the consumption of pyrotechnic particles of 12 kg/km^2).

The modification effect obtained in case of a salt powder is also significantly higher than that achieved with larger salt particles with narrow particle size distributions. Fig. 9 gives the calculation results for precipitation at seeding with salt particles with effective radii of 1 µm at optimal mass concentration 1.1 mg/m^3. The cloud drop spectrum at the initial stage of condensation at seeding by these particles is shown in Fig. 8. The consumption of the agent per 1 km^2 of the seeding area for such particles, when they are introduced into the 60-m subcloud layer, makes 64 kg. From Fig. 8 it is seen that at seeding with such particles the modification effect appears almost the same as in case of using the salt powder with its consumption of 12 kg/km^2. It means that the consumption of the salt powder is by 5 times less than that of the salt particles with the radii of 1 µm.

The calculation results demonstrated that in case of cloud seeding with salt powders at their consumption of 24 kg/km^2, additional precipitation amounts may be obtained from clouds with $2.5<H<3.5$ km. Such clouds are not giving significant precipitation under natural conditions. Maximum effect of modification – the greatest precipitation amounts – is realized at the consumption of 48 kg/km^2 of the salt powder (the upper curve in Fig. 9). Here, as the analysis of numerical simulation results shows, when precipitation falls down, an insignificant number of cloud drops remains in the cloud. Practically, almost all of the cloud water transforms into rain drops. Therefore, a further increase in consumption of the agent (over 48 kg/km^2) does not lead to a significant additional precipitation enhancement.

5 Conclusions

The results of experiments carried out in the cloud chamber at the conditions corresponding to the formation of convective clouds have shown that:

- The introduction of the salt powder before a cloud medium is formed results in the formation on the large-drop "tail" and in the broadening of drop size spectrum. This result is a positive factor for stimulating coagulation processes in clouds and for subsequent formation of precipitation in them.
- No impact is observed on the fine-droplet spectrum fraction formed on background condensation nuclei even at moderate amounts of the powder introduced.
- Seeding with the salt powder leads also to enlargement of the whole population of cloud drops and to a decrease of their total concentration as compared to the background cloud medium. With the introduction of increasing mass concentration of salt particles, this effect increases practically linearly. This factor also leads to a positive modification effect for stimulating the conversion of cloud water into rain drops.
- At the introduction of very high concentration of the powder no "overseeding" is observed, i.e., increase of drop concentration along with reduction of their size is not observed.

The results of numerical simulations of cloud medium formation at the initial stage of condensation have shown that:

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- The introduction of the salt powder into the convective subcloud layer leads to the appearance of a large-drop "tail" in the cloud drop size distribution. The shape of the spectrum in the large-drop region is determined by the salt powder particles spectrum.

- The shape of the spectrum of drops formed on background condensation nuclei does not change at rather high concentrations of the powder introduced. This means that the introduction of the salt powder does not change much the conditions of the formation of cloud drops on the background aerosol particles, except for at very high mass concentration. This result is confirmed by the experimental data obtained in the cloud chamber.

- As the analysis of numerical simulation results shows, the transformation of cloud drop spectra induced by the introduction of the salt powder results in much more intense coagulation processes in clouds as compared to the case of cloud modification with particles from hygroscopic flare at the same mass concentration.

- The salt powder results also in much more intense coagulation also with respect to hygroscopic particles having 1- µm very narrow particle size distribution of the same mass concentration.

The calculated rainfall amounts of the numerical simulations with a 1-dimensional numerical model of a warm convective cloud have shown that:

- The effect of the salt powder on clouds (total amounts of additional rain) is significantly higher than that caused by the use of hygroscopic flares at comparable consumptions of seeding agents (of the order of 10 kg/km^2).

- At the consumptions of the salt powders over 20 kg/km^2 rainfall can be obtained from otherwise no-precipitating clouds with thicknesses of $2.5<H<3.5$ km. At the consumptions of about 50 kg/km^2 of the powder the maximum effect of modification – maximum precipitation amounts – is realized. A further increase of the amounts of the salt powder introduced into a cloud does not result in significant additional precipitation amounts. Owing to a fairly simplified description of cloud development in the present 1-dimentional model, the consumptions of the salt powders indicated above should be regarded as estimates. For more accurate calculations it is necessary to use more realistic 2 or 3-dimensional cloud model with full ice microphysics and dynamic feedbacks to the precipitation forming processes.

In summary, the experimental data and the results of numerical simulations presented demonstrate the great promises arising from the use of the salt powder studied for obtaining additional precipitation amounts from convective clouds when accelerating the coagulation results in additional rainfall on the ground. Thus it is proposed to recommend using this salt powder in the seeding experiments in the natural atmospheric conditions.

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Table 1. Measurement results of cloud medium parameters in the experiments of introduction of salt powder particles into the cloud chamber.

N	Salt mass (g)	Mass concentration (mg/m^3)	N_F (cm^{-3})	N (cm^{-3})	N_F/N	r/r_F	S_F	S
1	1.0	0.31	1380	1370	1.00	1.00	0.285	0.287
2	3.5	1.1	1400	1220	1.15	1.05	0.283	0.289
3	11	3.4	1290	820	1.57	1.16	0.286	0.320
4	16	5.0	1300	710	1.83	1.22	0.276	0.326
5	21	6.6	1340	680	1.97	1.25	0.290	0.334
6	31	9.7	1560	630	2.48	1.35	0.284	0.367
7	35	10.9	1430	490	2.92	1.43	0.290	0.391

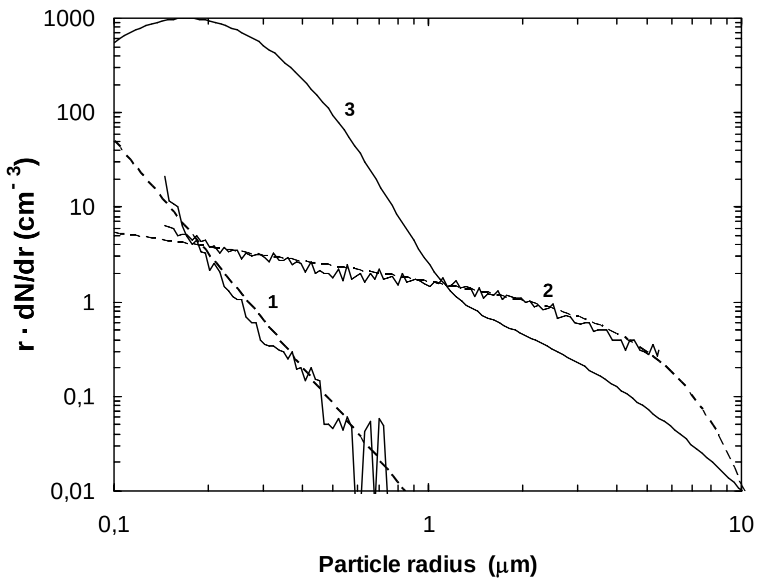

Fig. 1. Observed background aerosol particles spectrum in the BCC at a mass concentration of 5×10^{-4} mg/m^3 (1), the spectrum of dry salt particles (2) and the spectrum of the South African hygroscopic flares particles (3) both at the same mass concentration 0.4 mg/m^3. Dashed lines refer to the approximation made by functions (1, 2).

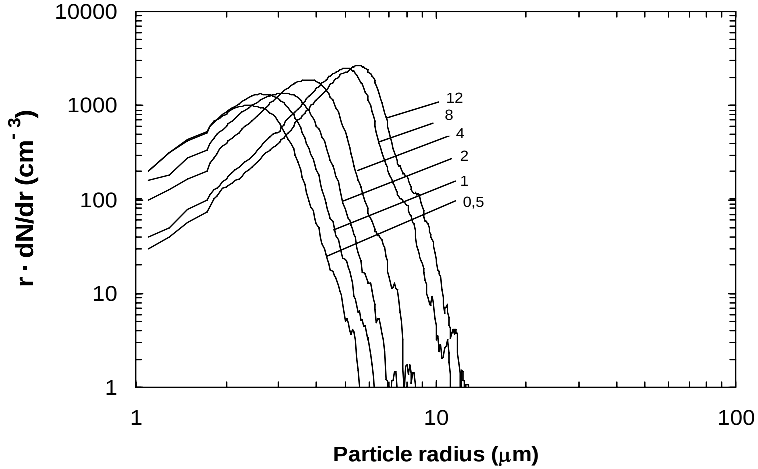

Fig. 2. Observed evolution of cloud drop spectrum in the background experiment (numbers at the curves – time (min.) after the cloud medium formation).

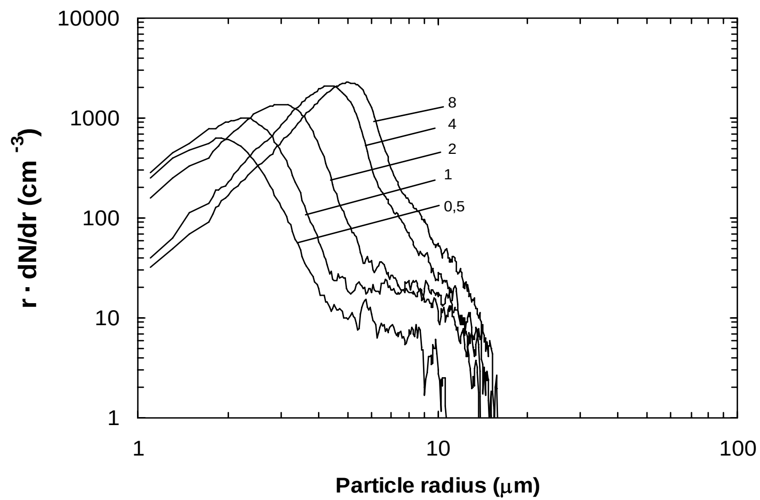

Fig. 3. Observed evolution of cloud drop spectrum at introduction of salt powder into the BCC with the mass concentration of 1.1 mg/m^3 (numbers at the curves – time (min.) after the beginning of cloud medium formation).

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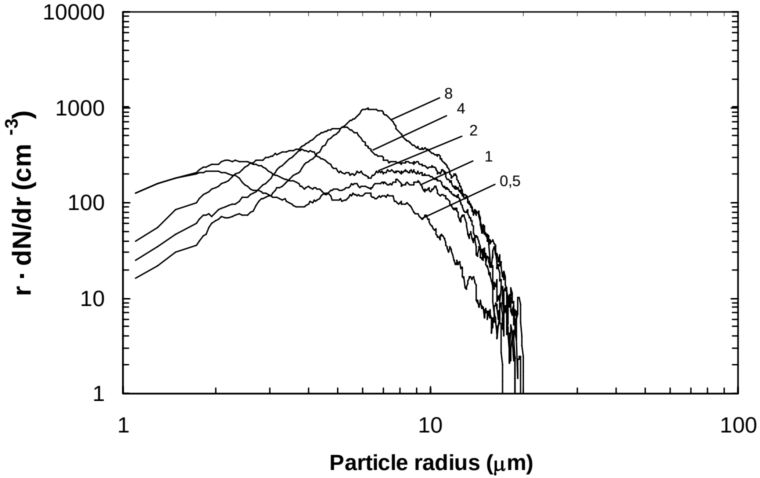

Fig. 4. Observed evolution of cloud drop spectra at the introduction of salt powder into the BCC with the mass concentration of 5 mg/m^3 (numbers at the curves – time (min.) after the beginning of cloud medium formation).

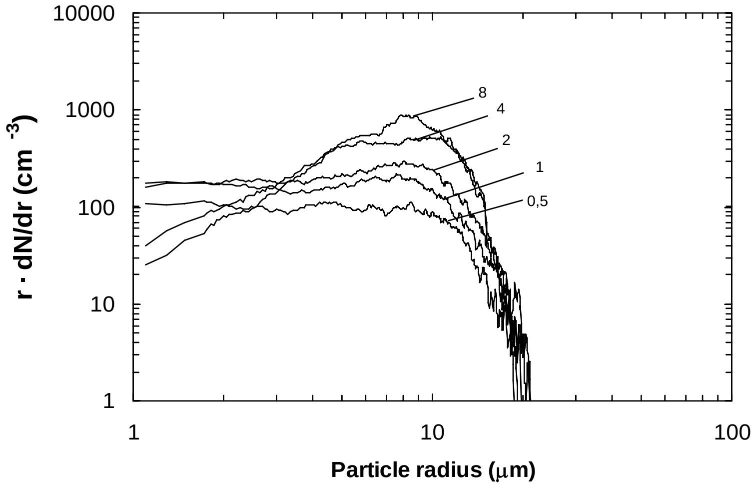

Fig. 5. Observed evolution of cloud drop spectra at the introduction of salt powder into the BCC with the mass concentration of 9.7 mg/m^3 (numbers at the curves – time (min.) after the beginning of cloud medium formation.

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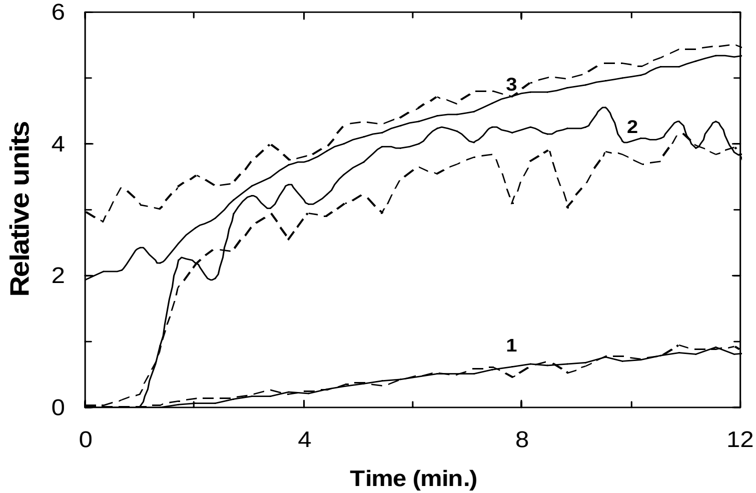

Fig. 6. Observed changes with time of cloud medium liquid water content (1, g/m^3), concentration (2, 300 cm^{-3}) and effective radius of cloud drops (3, µm) in the background experiment (solid curves) and at the introduction of salt powder with the mass concentration of 1.1 mg/m^3 (dashed curves).

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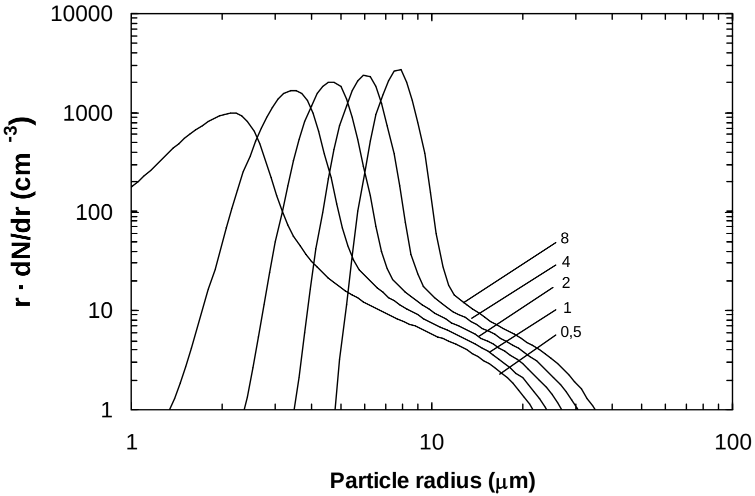

Fig. 7. Evolution of simulated cloud drop spectrum at the introduction of salt powder with the mass concentration of 1 mg/m^3 (the numbers at the curves – time (min.) after the beginning of the cloud medium formation).

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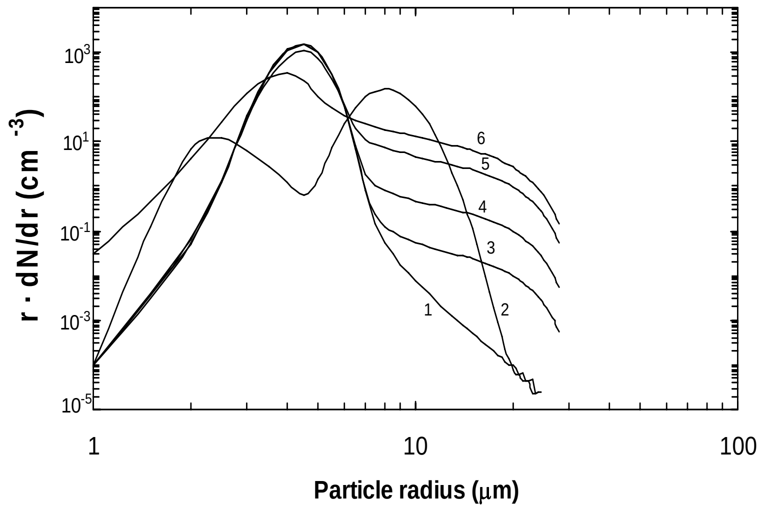

Fig. 8. Simulated drop spectrum in the background cloud (1), at the introduction of salt particles with the radius of 1 µm with the mass concentrations of 1.1 mg/m^3 (2) and at the introduction of salt powder with the mass concentrations of 0.01, 0.1, 1 and 5 mg/m^3 (curves 3–6, correspondingly).

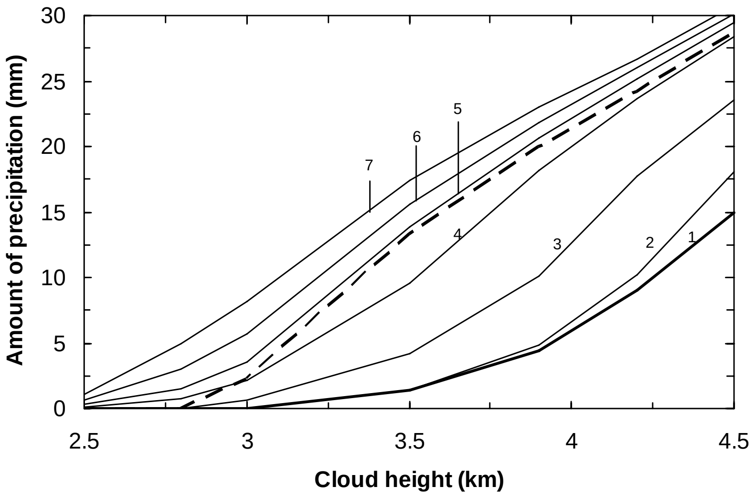

Fig. 9. Simulated total amount of precipitations, defined as $r > 200\,\mu m$, from clouds of different thicknesses without the introduction of particles (1), with the 12 kg/km^2 particles of the South African flares consumed (2), with 2.4, 6, 12, 24, 48 kg/km^2 of the salt powder (curves 3–7, respectively). Dashed lines refer to the introduction of 64 kg/km^2 of salt particles with the radii of 1 µm. The precipitation is calculated at the level of cloud base.

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