Numerical Simulation of Convective Clouds Developing in the Extreme Conditions

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Abstract. Catastrophic natural and anthropogenic phenomena, such as large industrial explosions, volcanic eruptions, large forest fires, burning of oil and gas wells are accompanied by the formation of mature convective clouds containing a large amount of various products of burning and aerosol particles. These can considerably change atmospheric conditions in the region where the phenomenon takes place and also can exerts essential negative influence both upon the climate on the whole and upon the ecological situation in the nearest regions. The only mean of such convective flows and clouds investigation is numerical simulation. In this paper the numerical model of the convective cloud developing in the extreme conditions and the overview of the main results, obtained in the field of simulation of specific features of the evolution of such clouds depending upon various ambient conditions are presented.

1 Introduction

A role of clouds in evolution of atmospheric pollutant is quite significant. Cloud dynamics strongly modifies the distribution of pollutant through advection and more local eddy motions over the edges of the cloud. Cloud microphysics participates in pollutant evolution by means of condensation/evaporation and collection processes transferring them to the drops during precipitation formation and reinjecting back into the air by evaporation of droplets and raindrops. On the one hand, the processes in the clouds result in cleaning the atmosphere by wet removal of the pollution. On the other hand they are responsible for so called acid rains, damaging the material surfaces of aquatic and forest ecosystems. In addition, clouds participate actively in trace chemical redistribution, affect the global radiation budget and thus influence global background atmosphere.

Though clouds of all types contribute significantly to atmospheric processes, the case of the clouds developing in so called extreme conditions, such as volcano eruptions, explosions, large fires, when the upper boundary of the cloud can reach the tropopause level, is the most interesting one from the view point of pollutant delivering to the upper levels of troposphere. Besides, such clouds play an exclusively important role as pollutant converter and transport mean in various extreme situations when enormous amount of chemically active aerosol particles are being injected into the atmosphere.

Convective clouds are very complex natural objects, with a wide spectrum of interacting processes of different time/space scales (convective transport, microphysical interactions, chemical reactions, etc.). So practically the only mean of their investigation is numerical modeling. Besides due to the complexity of the reflecting processes such a model implementation will apparently demand essential computational facilities and the effective numerical algorithms including special techniques for supercomputer applications. Up to now there are a lot of models dealing with such flows simulation. In the most of them the main attention was paid to the dynamical aspects of the cloud development (see for example works of Andrustchenko [1] and Makhviladze [2]). However all this phenomena occur in moist atmosphere and this aspect influences greatly on main cloud evolution parameters and pollutant scavenging processes. There are some papers [3], [4] where the attention was paid to the microphysical characteristics investigation. But these models were based on Boussinesq approximation which is inapplicable to the flows with large variations of thermodynamic parameters and that is why they could not adequately simulate dynamical characteristics of such clouds. As a whole it could be stated that in each model only a few features of cloud processes interaction are being considered rigorously while the rest ones are treated approximately, with the use of strong simplifying assumptions and crude parameterizations. Thus, an urgent need does exist in a numerical model capable of representing properly all the essential interactions at least between dynamical and microphysical processes in convective clouds developing in extreme conditions.

This paper is dedicated to the description of the numerical model used for simulation of dynamical, turbulent, and microphysical processes in such clouds. Based on the developed model the specific features of the life cycle of the clouds depending upon various ambient conditions were investigated.

2 Model Description

The problem of simulation of the clouds, developing in extreme conditions, that is in the presence of the sources of high energy on the surface of the ground or in the atmosphere, results in simulation of a buoyant thermal rising in a stratified environment. Simulation is provided by the time-dependent, two-dimensional model, based upon the solution of equations, describing the axisymmetric turbulent flow of compressible two-phase two-component medium. This model is appropriate for the description of the flows with arbitrary vertical scales and temperature variations.

The system of the model equations contains the mass continuity equation, two equations of motion for radial and vertical compounds, thermodynamic equation and the equation of state.

Microphysical processes are parameterized by Kessler's scheme and deal with the liquid phase only. Condensed water substance is classified into two compounds: cloud droplets (cloud water) and raindrops (precipitation water), between which the following transitions were taken into account: autoconversion (formation of the rain drops by the coalescence of cloud droplets with each other), accretion (coalescence of rain and cloud droplets) and evaporation of rain drops. It was accepted that condensed water appears each time when the partial vapor pressure exceeds its saturated value for a given temperature.

Modified k-e model taking into account the buoyancy and streamline curvature effects was used for the description of turbulence processes.

For the numerical solution the alternative direction scheme was employed. A special procedure of monotonization [4] was used to avoid the solution oscillations occurring when using the second order schemes for advective terms approximations. This procedure is especially valuable when calculating such processes as condensation. A moving grid algorithm generation was used in order to adjust the boundaries of the calculation domain to the increasing size of the thermal. The system of equations of the moist turbulent convection is described in detail in [5] – [8].

4 Simulation Results

A wide set of numerical experiments conducted with the different values of initial and atmospheric parameters showed that evolution of the dynamical and microphysical cloud characteristics depends upon atmospheric conditions, initial thermal moisture content and the value of the initial buoyancy storage of the thermal *B:*

$$B = \int_V g \frac{(\rho_a - \rho)}{\rho_a} dV ,$$

where ρ_a and ρ are consequently air density in the environment and inside the thermal, g – acceleration of gravity, V – thermal volume.

At high values of the buoyancy storage caused either by the large initial excess temperature (more then 500K) or size of the thermal (radius R exceeds 100m), and at rather high values of the ambient relative humidity (more than 50%), the polluted thermal can easily reach the upper troposphere boundary, carrying all the captured aerosols or loosing some amount of them due to precipitation. The height of the upper level of the cloud is determined only by the value of the initial buoyancy storage. The processes of condensation of both the initial thermal moisture content and the atmospheric water vapor, penetrated inside the thermal, are observed. Precipitation formation is fully determined only by the values of the relative atmospheric humidity. If the relative humidity value is less than 50%, the amount of the condensed water appears to be not sufficient enough for precipitation formation.

At the low values of initial thermal buoyancy (this case is more close to the natural convective cloud development) cloud dynamical and microphysical characteristics are fully determined only by the values of the relative atmospheric humidity and not by the value of the initial buoyancy storage. At the large values of the relative atmospheric humidity (about 90% up to 5 km) thermal rising determine only the delivering of the air bubble to the condensation level. In this case cloud development occurs in the convective flow initiated and supported by the latent heat of the atmospheric water vapor condensation. Added buoyancy caused by water vapor condensation is able to increase the height of the cloud upper boundary considerably.

At lower values of atmospheric humidity process of condensation of initial thermal water content is not observed.

The results of the numerical experiments show that the evolution of the convective cloud developing in extreme conditions differs greatly from the evolution of the cloud developing in natural conditions. In the last case the thermal rising plays only the role of the trigger mechanism. Thermal only delivers warm moist air to the level of condensation, the cloud formation is provided by the latent heat of phase transition. Cloud evolution in natural conditions lasts longer than in extreme ones. At natural convection both dynamical and microphysical characteristics reach their maximum values later.

As an illustration we can consider the life cycle of thermal with radius R equals to 300 meters and initial temperature equals to 2000K, rising in the wet atmosphere. Distribution of the temperature outside the thermal corresponds to the parameters, defined using Standard Atmosphere Model. Relative humidity values at the level from 0 to 5,5 km are taken equal to 90%, at higher levels they decrease linearly up to 10% at height of 11 km and afterwards remain constant.

The simulation results confirm the well-known scenario of buoyant thermal development and convective transport in the atmosphere. The evolution of the thermals before reaching the level of condensation agrees with the well-studied phenomenon of buoyant thyroidal vortex formation. When rising, a thermal transforms into a toroidal vortex characterized by coincidence of the regions of maximum excess temperature and vorticity (Fig.1). The flow obtains typical “mushroom” form.

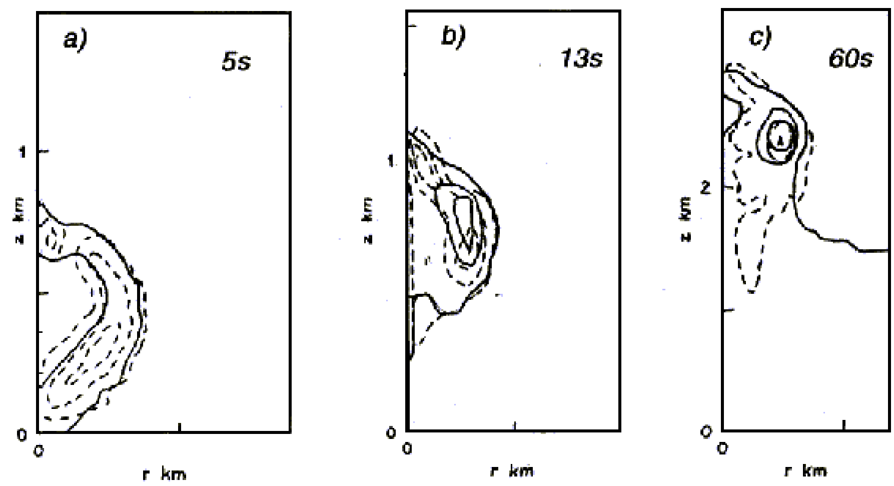

Fig.1 Temperature (solid lines) and vorticity (dashed lines) fields at the stage of the initial thermal rising; a) T = 300K, 1700K, rotV = 0.05, 0.45, 0.9 1/sec; b)) T = 310K, 710K, 1110K, rotV = 0.12, 0.47, 0.82 1/sec; T = 278K, 303K, 328K, rotV = 0.03, 0.38, 0.73 1/sec

The structure is preserved until the end of the rise; the temperature in the vortex core only gradually decreases. By the 3-5 min of rise, the air-cooling results in the updraft near the symmetry axis, changing into the downdraft movement. The thermal ascend rate slows down, and the thermal enlarges only in horizontal dimensions.

While further penetration into the colder atmospheric levels, water vapor condensation takes place in the updraft. This process characterizes thermal transformation into the convective cloud. Condensation starts near the symmetry axis, spreading afterwards to the vortex region. Cloud water field evolution is presented on Fig.2, where vorticity isolines are shown for the comparison.

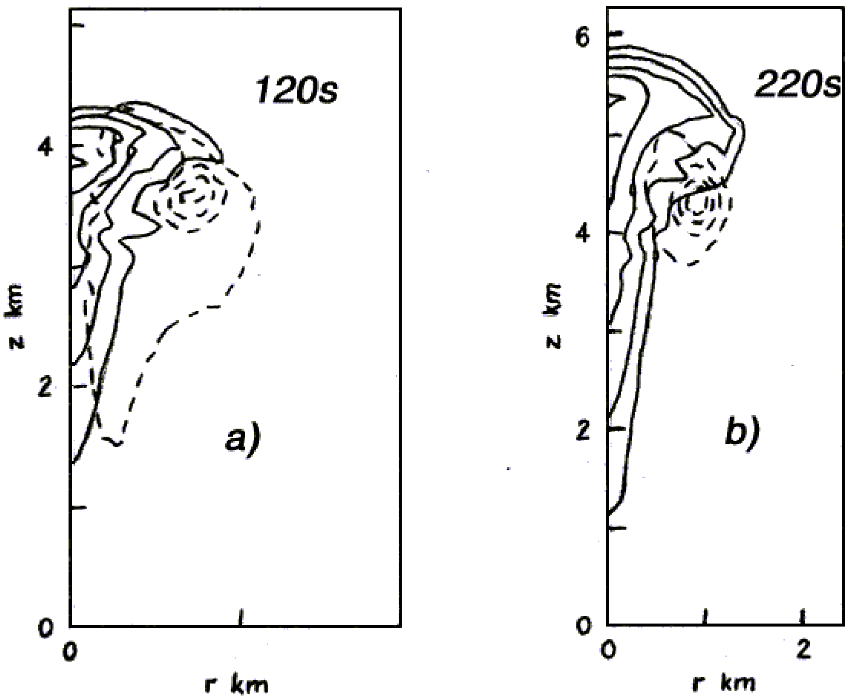

Fig.2 Cloud water (dashed lines) and vorticity (dashed lines) field evolution. 120 seconds: qc = 0.1, 0.3, 0.6, 0.9, 1.2 g/m^3, rotV = 0.01,0.11,0.21,0.31 1/sec; 220 seconds: qc = 0.1, 0.3, 0.6, 0.9, 1.2 g/m^3, rotV = 0.02,0.06,0.10,0.14 1/sec

Further thermal evolution essentially depends upon the ambient atmospheric conditions. If the atmospheric air humidity is sufficiently high, the development of convective flow supported by the latent heat of condensation takes place. In the regions of high water content the formation of raindrops begins. At the first stage of their appearance precipitation particles are hold by vertical movement, then they begin to fall and soon reach the ground.

Fig.3 illustrates the influence of the atmospheric relative humidity f to the thermal rising and further cloud evolution. At $f = 50\%$, condensation takes place only in the region of the thermal, while at higher relative humidity levels water vapor condensates both in the thermal and convective updraft near its axis.

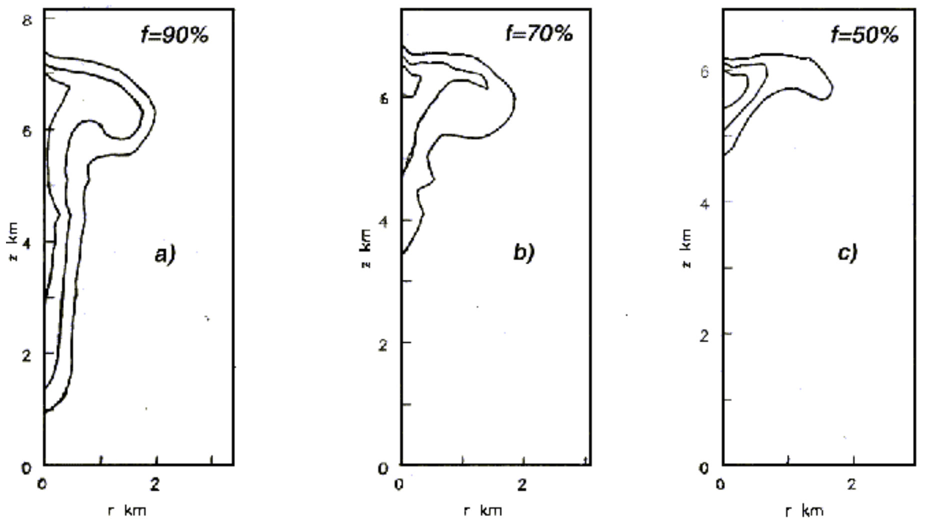

Fig.3 Cloud water fields at t = 400 s for different values of the atmospheric relative humidity ***f***

4 Conclusions

Time-dependent, two dimensional model, based upon the solution of equations, describing the axisymmetric turbulent flow of compressible two-phase two-component medium was used for simulation of dynamical, and microphysical processes in the clouds developing in extreme conditions, such as industrial explosions, volcanic eruptions, large forest fires, burning of oil and gas wells. A wide set of numerical experiments conducted with the different values of initial and atmospheric parameters showed that evolution of the dynamical and microphysical cloud characteristics depends upon the value of initial buoyancy storage of the thermal, initial thermal water content and ambient atmospheric conditions. At high values of the buoyancy storage caused by a large initial excess temperature or size of the thermal and at rather high values of the ambient relative humidity (more than 50%), the polluted thermal can easily reach the upper troposphere boundary, carrying all the captured aerosols or loosing some amount of them due to precipitation.

The model can be incorporated into the operational regional or global climate models for online forecasting of the pollutant propagation in the certain area and possible prevention of undesirable effects of catastrophic phenomenon frequently accompanied by the convective cloud development.

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