Influence of Convection on the Exchange of Aerosol Emissions between the Ground Surface and the Atmosphere

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Abstract

On the basis of analysis of calculations by a hydrodynamic model of atmospheric convective ensemble (LES), various mechanisms of cloud and precipitation formation processes are discussed. The influence of convection on the vertical transportation of aerosols has been studied. Advantages of LES in application to theoretical studies of vertical transport of aerosols in the atmosphere are demonstrated.

INTRODUCTION

It is well known that in summer it is the ground surface that is the source of the major part of primary aerosol. It is the dust and sand from the territories deprived of vegetation, particles of salt formed from the evaporated drops of water from the surface of water bodies, products of combustion of organic fuel *etc*. Like the aerosols from the ground surface, hothouse gases such as the hothouse vapor, carbon dioxide, methane *etc*. come to the atmosphere. Given a stable stratification, almost the whole aerosol emitted from the ground surface remains in the ground surface layer several tens of meters thick. However, when there is a convective instability typical of summer season, conditions are created for a vertical transport of aerosol up to a height of 1–2 km, and with convective cloudiness the aerosol can penetrate up to the upper boundary of the troposphere. Having got to such an altitude, the aerosol can be transported over thousands kilometers from the discharge source. Besides, under conditions of convection, the velocity of vertical transfer of aerosols greatly increases, which is explained by the property of the atmospheric convection to form relatively large quasi-ordered structures – thermal conditions and cumuli with a size of up to several kilometers and the velocity of vertical rise of up to 10 m/s. Such structures are referred to as coherent. Let us note that modern models of turbulent diffusion, both statistical and hydrodynamic ones, do not describe the formation of coherent structures and therefore cannot explain many peculiarities of aerosol diffusion under convection conditions. LES (Large Eddy Simulation) – the approach in which so-called large eddies (perturbations with a size of more than 100 m) are solved explicitly with the help of appropriate thermohydrodynamic equations and smaller perturbations are parametrized as subnet turbulence [1–3] – is free from these drawbacks.

The goal of the present paper consists in discussing the physical statement of the problem that can be solved on the basis of LES approach, and in comparing the results of calculations obtained with the help of the eddy-solving model developed by us [1] with the results of observations and with some data known from LES publications [2, 3]. In addition, an attempt is made to demonstrate the possibilities of models [4, 5] for studying single (typical) scripts of exchange of aerosols and gaseous admixtures between the ground surface and the atmosphere taking into account the vertical transport of admixtures under the conditions of developed convection.

PHYSICAL FORMULATION OF THE PROBLEM

The calculation region represents a parallelepiped with horizontal dimensions of 20 km and the height of 10 km which depends on the thickness of the convection layer. The lower layer is a land or water surface which temperature is calculated taking into account the supply of short-wave solar radiation and long-wave back radiation. Higher, there is a layer of 100 m thick in which the processes are described parametrically on the basis of similitude theory. Above it, the convective layer is situated. On the upper border of the convective layer, boundary conditions are set which ensure linkage with the regime in free atmosphere.

The mathematical statement of the task is presented in [1]. The initial differential equations describe the ordered transport and the turbulent diffusion of air, steam, aerosols, heat and water drops. Liquid moisture is represented by two fractions: cloudy drops suspended in the air and heavy drops falling out as rain. The equations in a simple form take into account the vapor condensation and enlargement of drops due to coagulation, evaporation of cloud and rain particles.

The physical cause of convection is the heating of the ground surface during the daytime. Convection is a stochastic ensemble consisting either only of thermics or of thermics and cumuli. The convection characteristics depend on the intensity of heating and on the initial distribution of average profiles of temperature, humidity and wind. Below, the most typical convection regimes obtained in modeling in [1, 6, 7] are going to be described.

RESULTS OF CALCULATIONS AND THEIR COMPARISON WITH OBSERVATION DATA

Penetrating convection in serene weather

Convection without clouds takes place in the atmosphere with a low steam content and at the initial stage of evolution of all the types of convective ensembles. At “dry” convection, the thickness of the convective layer increases to 2.00−4.00 p.m. local time, whereupon a gradual damping of convective activity and destruction of the mixing layer begins. The thickness of the convective layer at the stage of maximal development amounts to 0.5−2 km and depends on the average temperature of the underlying surface, on the time of sunshine and on the amplitude of the circadian time course of temperature. The results of comparison of calculations for different LES models for “dry” convection are presented in Fig. 1 in terms of heat flow profiles. Designations in the Figure coincide with those used in [2] (z_{i0} is the height of the mixing layer, $\langle w\theta\rangle$ is the heat flow averaged

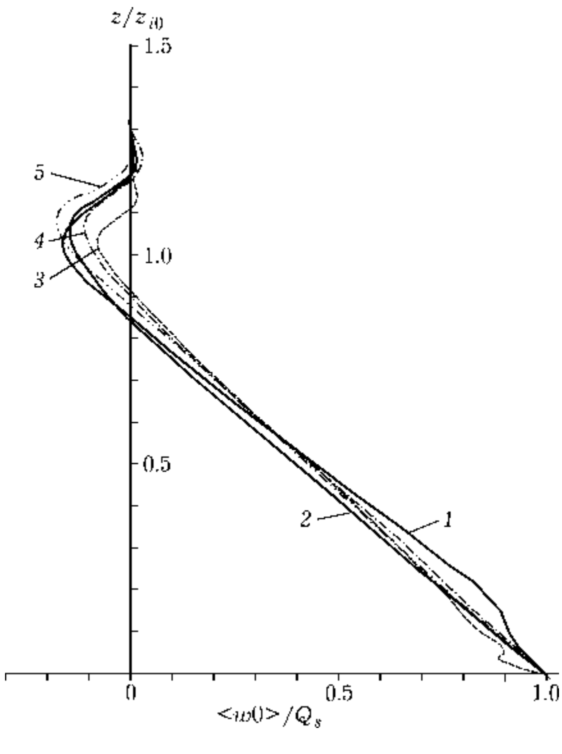

Fig. 1. Vertical distribution of normalized heat flow in the model [1] (*1*) and in four LES models according to the data of [2] (*2–5*).

along the horizontal, Q_s is the surface heat flow). Note the closeness of integral characteristics of the models, by which one can judge about the representativeness of the authors model [1].

Single-layer cloudy convection

At a high relative humidity at an altitude of several hundred meters, development of cumuli begins. A typical picture of single-layer convection is presented in Fig. 2, where isolines of the vertical component of velocity are represented, solid lines corresponding to ascending flows and the dashed line designating descending motions.

The bold line indicates calculated cloud contours, *i. e.* regions in which liquid moisture is present. One can see that the horizontal dimensions of the clouds do not exceed 1 km, and the vertical ones are by about 2 times smaller. All the clouds are situated in the upper part of thermics.

The presented convection is of single-layer type. Under real conditions, single-layer cloudy convection is formed above the surface of tropical ocean characterized by high values of temperature with a small circadian change and an elevated steam content. It is noteworthy that in convection above tropical ocean the major part of the steam and the condensed moisture are supplied to the atmosphere from the ground surface. Observations and calculations demonstrate that as a result of convective exchange, a mixing layer about 1 km thick is formed in the atmosphere, where the relative humidity is close to saturating one. Above the mixing layer there is a thin inversion layer above which the relative humidity is much lower than the saturating one. Such a convection type is typical of immense territories situated over tropical and subtropical ocean. It makes a considerable contribution to the circulation of water on the scale of the whole planet, and it is not ruled out that a considerable part of precipitation falling out in Siberia has been formed as a result of convection above the tropical Atlantic.

In this way, the adequacy of description of heat-mass exchange processes between water and air, as well as taking into account the convective mixing in the lower atmosphere, greatly predetermine the success in using models of general circulation of the atmosphere and the plausibility of the theory of climate. For this reason, a rather large number of LES for single-layer cloudy con-

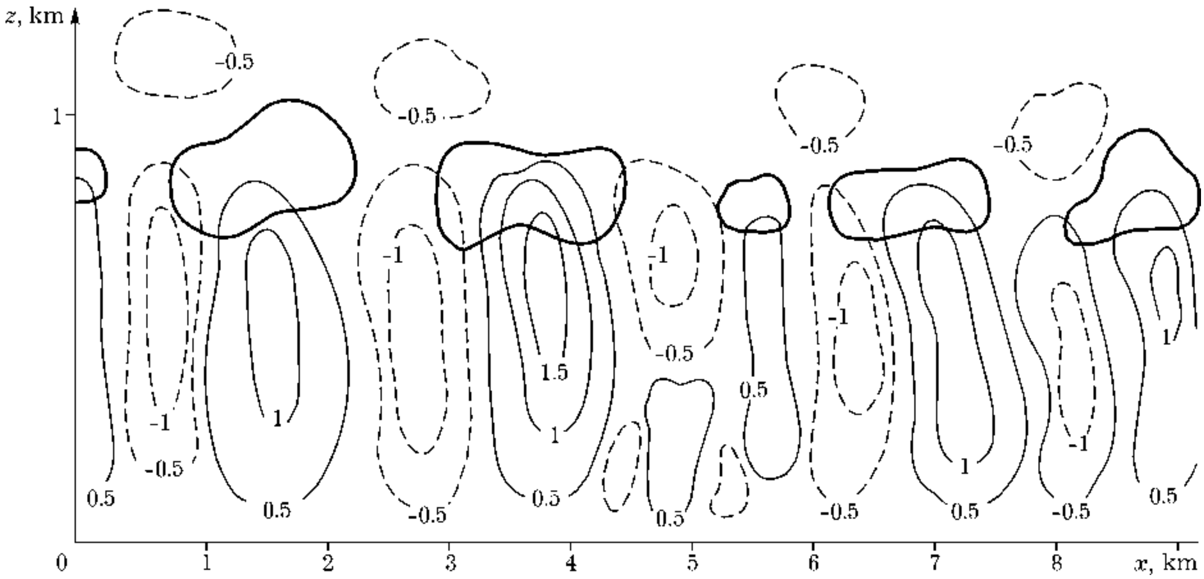

Fig. 2. Isolines of vertical velocity at single-layer convection. Bold line: the outlines of clouds, thin line: ascending flows, dashed line: descending flows.

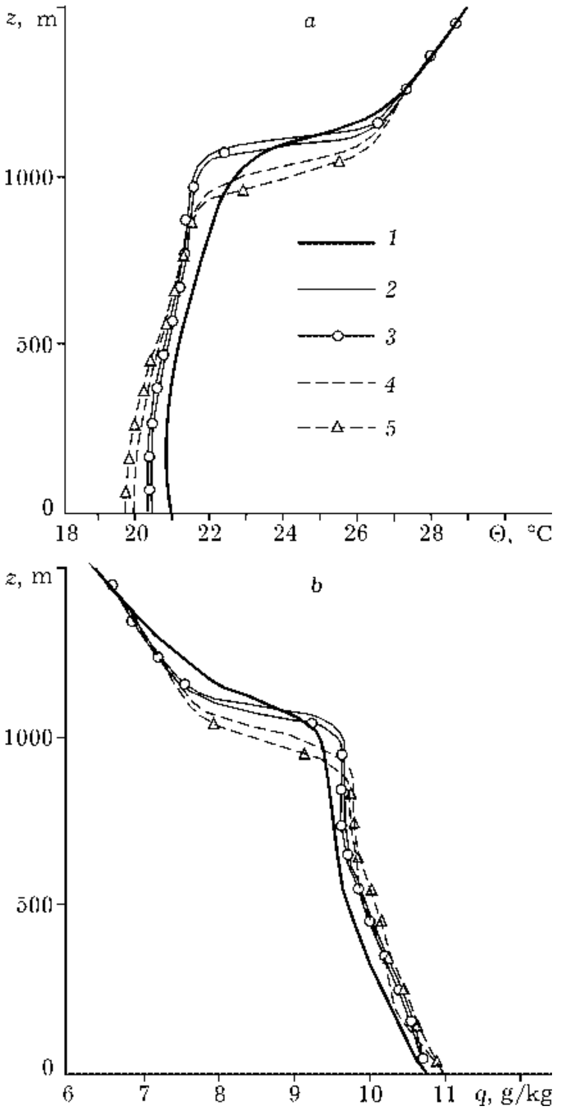

Fig. 3. Vertical profiles of equivalent potential temperature Θ (*a*) and water content *q* (*b*) in model [1] (*1*) and in LES modes by the data of [3] (*2–5*).

vection has been developed nowadays. They include also the model [1] which reproduces satisfactorily this type of convection, although it somewhat understates the rate of formation of the rain fraction. This may be explained by the fact that in the model parametrization of precipitation formation processes corresponding to continental but not oceanic conditions is used. Comparison of calculated temperature and water-impounding profiles obtained in different models, and their comparison with observation data are presented in Fig. 3. Data of observations and results of numerical modeling presented in Fig. 3 are borrowed from [3].

Double-layer cloudy convection

Under continental conditions of middle latitudes characterized by a strong circadian changes of temperature and a low air humidity in lower layers, clouds can detach themselves from the maternal thermics and form a second convective desk. Cloudy nuclei in this case are much larger than the thermics. If the vertical size of clouds exceeds 1 km, then they may give precipitation. In Fig. 4, a picture of a typical cloud ensemble is shown which second desk consists of nonrainy clouds with the power of about 2 km containing suspended large-drop rainy moisture (under real conditions, such clouds have a dark color).

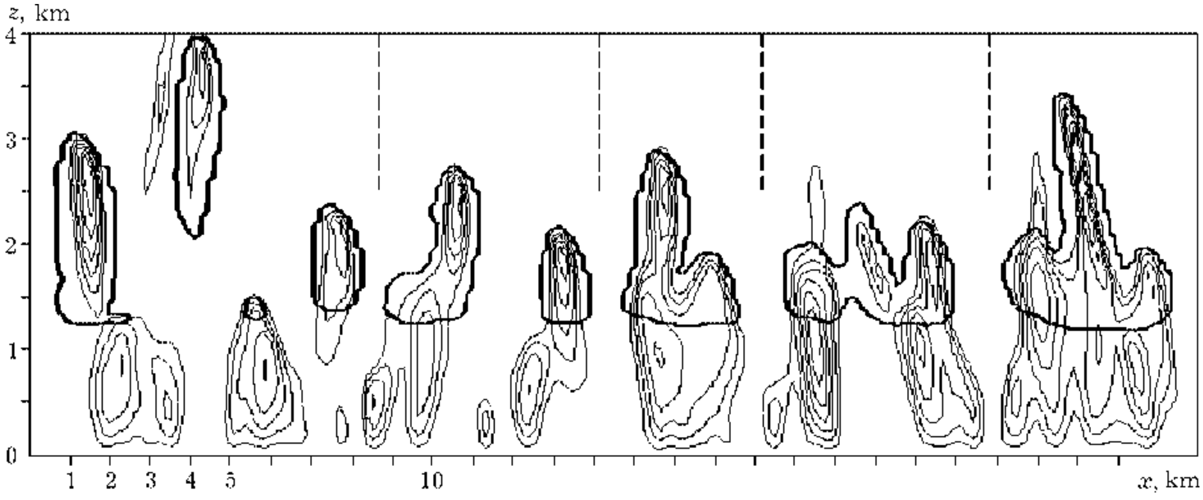

Fig. 4. Double-layer convection.

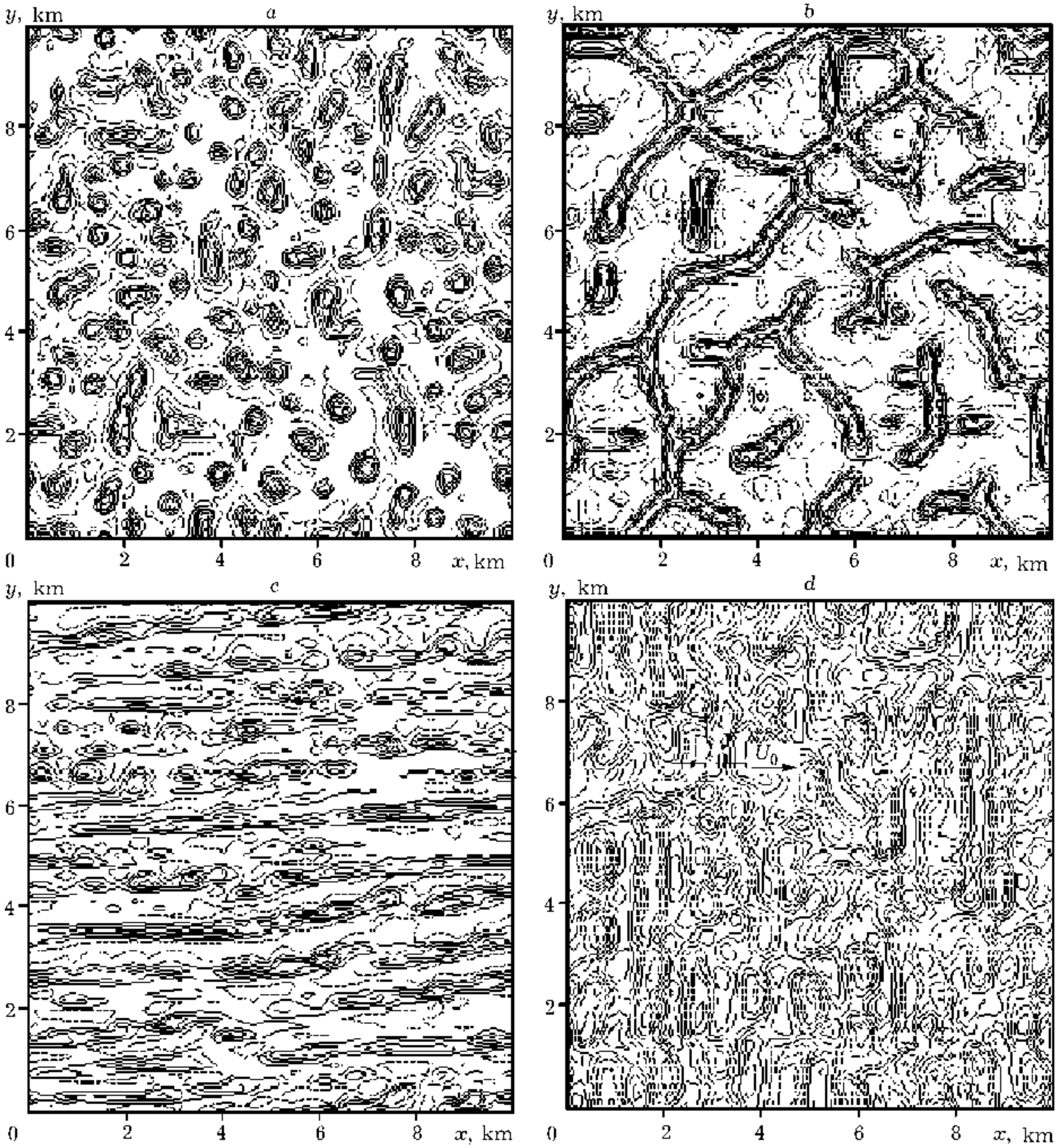

Fig. 5. Horizontal section of a field of vertical velocity at the height of 500 m: a – chaotic positioning of convective nuclei; b – hexagonal structures at a weak wind; c – convective paths oriented along the velocity vector; d – transversal structures at a strong wind shift.

Formation of supernuclei

In nature, thermics and convective clouds often form larger quasi-ordered conglomerates called supernuclei with a long lifetime. The model [1] describes the majority of the observed supernuclei types, which is demonstrated in Fig. 5.

A comparative analysis of calculated and measured distributions of cloud nuclei and supernuclei can be made by Fig. 6.

Exchange of arid aerosol between the land and the atmosphere

A study of mass exchange between the ground surface and the atmosphere has been carried out in [4]. The source of aerosol was an ground surface covered by small dust particles. Fig. 7 illustrates the horizontal distribution of admixture concentration at the altitude of 300 m.

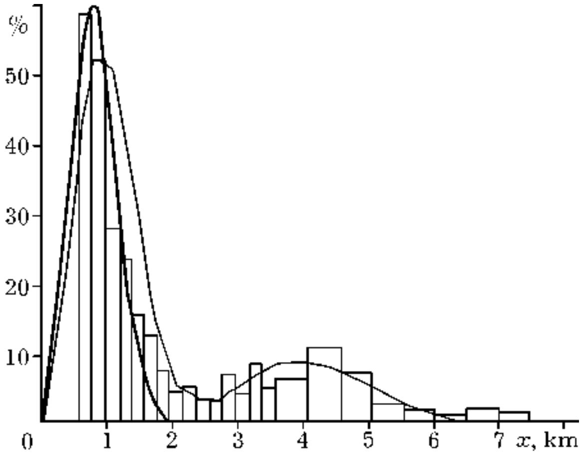

Fig. 6. Occurrence frequency of cloud sizes across the diameter. Rectangles designate measurement data [10], the bold line stands for the calculated distribution at a chaotic positioning of clouds; the thin line indicates the calculated distribution in the system with supernuclei. The left maximum corresponds to small clouds, the right one to convective supernuclei.

One can see that regions of elevated concentration of admixtures are localized in ascending zones of convective structures. This result is confirmed by measurements carried out by members of the IFA in 1986 in near desert of Kalmykia [8]. In on-location data and in calculations, the characteristic scale of regions of elevated admixture concentration is approximately equal, and the extreme concentration values are alsoconsistent wich each other. The vertical profile of the admixture concentration averaged over the horizontal has a maximum near the land surface, decreases rapidly in the layer of constant flows and is almost unchanged in the convective mixing layer. Let us note that the turbidity of the whole convective layer is a well-known fact. The concentration of aerosol particles in the convective layer is approximately inversely proportional to the eigenvelosities of descent of particles [6], which is also confirmed by measurements. A small part of aerosol gets into the second convective desk where the admixture particles serve as coagulation nuclei for raindrops and as crystallization nuclei in hail formation [5, 6].

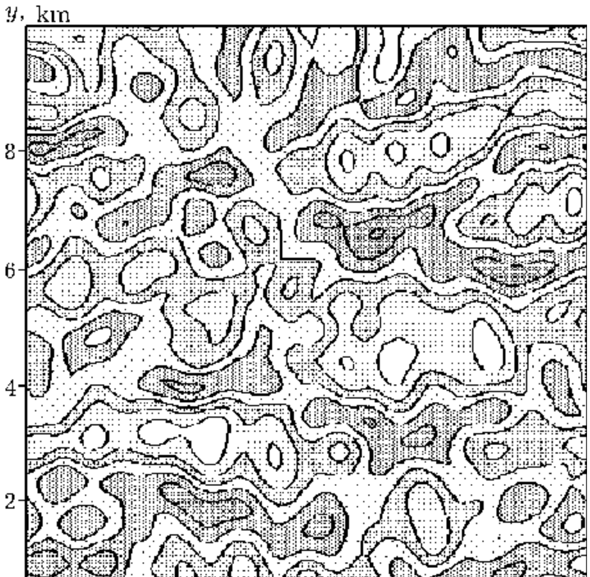

Fig. 7. Distribution of arid aerosol concentration at the altitude of 300 m.

Washing of arid aerosol

It is noteworthy that convection is not only a very efficient mechanism of vertical transfer of contaminating admixtures, but at the same time can influence the air purification processes. In [9] it is demonstrated that a rain of moderate intensity purifies the atmosphere from arid aerosol within 15–20 min, which is confirmed by observation data.

Exchange of aerosol between the ocean and the atmosphere

The mechanism of aerosol supply from the ocean surface to the atmosphere very important for the climate of the planet. In strong wind, due to breakdown of waves, foam is formed consisting of an enormous number of air bubbles which, bursting, supply to the atmosphere a great number of water drops. Under the conditions of stable stratification, the major part of these drops returns to the water; however, convection creates conditions for carrying out water particles to the lower and middle troposphere. The drop moisture is rapidly evaporated and a large number of salt particles turns out to be present in the atmosphere. These particles are the main source of steam condensation nuclei in cloud and precipitation formation. This mechanism of aerosol supply to the atmosphere has been studied in [5]. The qualitative pattern of distribution of "sea" aerosol is analogous to those of distribution of arid aerosol.

CONCLUSION

Under the conditions of developed convection, the eddy-resolving approach has undoubted advantages over the traditional diffusion and statistical approaches when calculating the vertical transport of aerosol. Models [1, 6] are represented here as a hydrodynamic basis serving for solution of the problems of monitoring and for the forecast of aerosol contamination of the atmosphere boundary layer. Thus, taking into account the chemical transformation of admixtures permits extending the circle of considered tasks due to description of acidic rains, diffusion of dangerous contamination from the sources within the city borders and solving also different tasks of close transport. In application to the Siberian region, the most important tasks are of convective transport of aerosols over industrial zones, forest fires, the tasks of vertical transport of hothouse gases which sources are the swamps of taiga, tundra and forest-tundra of Siberia.

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