THEORETICAL STUDY OF SOME PECULIARITIES IN THE SPREAD OF AN ADMIXTURE UNDER CONVECTIVE CONDITIONS

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Received February 4, 1998

A hydrodynamic model of the spread of an admixture is presented for the case of penetrating two-level convection (thermals below nonprecipitating cumuli). The following facts known from observations are explained qualitatively: turbidity of the convective lower 1-km *layer of the atmosphere and penetration of water drop coagulation and condensation nuclei into the cloud layer.*

INTRODUCTION

A study of regularities in the spread of an admixture under developed convection when admixture particles, including large ones, can penetrate to high altitudes due to considerable air velocity in thermals and clouds is of specific interest for some applied problems. The large particles may form coagulation nuclei for water drops and play a significant part in shower and hail formation.[1]

In addition, a large number of small salt crystals are detected in the troposphere. Water vapor is efficiently condensed on them, which is important for cloud formation.[2] These particles are most probably formed from small liquid drops that enter the air during storms and then evaporate.[3] The quickest rise of drops and crystal particles may occur under convection. Entering into high altitudes, crystal salt particles, for which the rate of gravitation sedimentation is about a millimeter per second, can exist a few days in air; they can be carried by wind at large distances.

To describe the spread of an admixture in the atmospheric boundary layer (ABL), including the convective boundary layer (CBL), the ABL models are usually used comprising the semiempirical equation of turbulent diffusion and some closure hypotheses.[3–5] In this case, irregular mesoscale processes in the CBL are parameterized as turbulent (subgrid). However, the solutions based on this approach do not describe many salient features of the CBL structure. This conclusion follows from observed data[3–6] and a series of theoretical investigations, in which the nonstationary penetrating convection[6–7] and cloud and precipitation formation are described in an explicit form using the so-called LES (Large Eddy Simulation) models,[8–11] in which eddies with dimensions more than 100 m are calculated on the basis of nonhydrostatic equations of thermodynamics, while smaller eddies are parameterized.

The spread of dust particles rised from the Earth's surface by "dry" convection (when the simulated ensemble consists of thermals) was studied in Ref. 12.

In this paper, the spread of the admixture is considered when the second convective layer consisting of nonprecipitating cumuli is located above the lower convective layer consisting of thermals. In addition, three mechanisms, rather than one as in Ref. 12, of admixture arrival at the atmosphere are considered:

1) the source of the admixture is a thin dusty layer of the atmosphere[12];

2) the admixture consists of small droplets that enter the air from the rough water surface.

Following Ref. 9 in describing the convective ensemble, we use the hydrothermodynamics equations

$$\frac{\partial \Omega}{\partial t} + (U + u)\,\frac{\partial \Omega}{\partial x} + w\,\frac{\partial \Omega}{\partial z} = \lambda\,\frac{\partial \upsilon}{\partial t} + \nu\,\frac{\partial^2 \Omega}{\partial x^2} + \nu\,\frac{\partial^2 \Omega}{\partial z^2}\,, \quad (1)$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = \Omega, \quad (2)$$

$$\frac{\partial A}{\partial t} + (U + u)\,\frac{\partial A}{\partial x} + w\,\frac{\partial A}{\partial z} = \alpha w + \nu\,\frac{\partial^2 A}{\partial x^2} + \nu\,\frac{\partial^2 A}{\partial z^2}\,, \quad (3)$$

$$\frac{\partial B}{\partial t} + (U + u)\,\frac{\partial B}{\partial x} + w\,\frac{\partial B}{\partial z} = \alpha_q\, w + \nu\,\frac{\partial^2 B}{\partial x^2} + \nu\,\frac{\partial^2 B}{\partial z^2}\,. \quad (4)$$

The following relations are valid within the clouds for $q > q_s$:

$$A = \vartheta - \left(\frac{L}{c_p}\right) v; \quad B = q_s + v,$$

$$v = \frac{B - Q_s + Q - Q_s\, bA}{1 + (L/c_p)\, Qb}\,,$$

$$q_s = Q_s \exp(b\vartheta), \qquad b = \frac{17.55}{\theta - 31.1}\,.$$

The relations

$A = \vartheta$; $B = q$; $v = 0$,

are valid beyond the clouds for $q < q_s$. Here, t is time; x and z are the horizontal and vertical coordinates; ψ is the stream function; $u = -\partial\psi/\partial z$ and $w = \partial\psi/\partial x$ are the convective vertical and horizontal components of the velocity; $U(z)$ is the background value of the velocity; $\Omega = \partial w/\partial x - \partial u/\partial z$ is the vorticity; ϑ, q, q_s are the convective deviations of the potential temperature, vapor mixing ratio (specific humidity), and saturation specific humidity from their background values $\Theta(z)$, $Q(z)$, $Q_s(z)$; v is the water (suspended in the air) mixing ratio of cloud (specific water content); $\alpha = -\dfrac{\partial\theta}{\partial z}$; $\alpha_q = -\dfrac{\partial Q}{\partial z}$; $\lambda = g/\theta$; g is the acceleration due to gravity; L is the evaporation heat; c_p is the specific heat of air at constant pressure; ν is the kinematic coefficient of turbulence.

By the unperturbed (background) state of the atmosphere we mean the atmosphere without convection, with a given constant wind $U = \text{const}$, given humidity field $Q(z)$, diurnal behavior of the potential temperature at the Earth's surface $\theta = \vartheta_0 + \vartheta_1 \sin(\omega t - \varphi)$ at $z = 0$ (here $\vartheta_0 = \text{const} > 0$ is the average daily temperature, ω is the angular rotation velocity of the Earth, $\varphi = \omega \cdot 6\,\text{h} = 1.57$), and standard value of the temperature gradient $\alpha_0 = -\partial\theta/\partial z = \text{const}$ at high altitudes. In this case, the solution of the thermal conduction equation $\partial\theta/\partial t = \nu\, \partial^2\theta/\partial z^2$ has the form

$$\theta = \vartheta_0 - \alpha_0 z + \vartheta_1 \exp\left(-z\sqrt{\frac{\omega}{2\nu}}\right) \times$$

$$\times \sin\left(\omega t - \varphi - z\sqrt{\frac{\omega}{2\nu}}\right). \quad (5)$$

We assume that at the lower and upper boundaries of the CBL for $z = 0$ and $z = H$

$$\psi = 0, \quad \Omega = 0, \quad A = 0, \quad B = 0. \quad (6)$$

Because the atmosphere is stably stratified in the upper part of the CBL, the convection decays as the upper boundary of the calculation domain $z = H$ is approached. At the side boundaries of the calculation domain $x = 0$ and $x = X$, we take the conditions of periodicity.

A series of heat pulses is taken as initial conditions. For this purpose, at the time $t = 0$ we assign random values of temperature deviation to every point of the calculation level immediately adjacent to the underlying surface. These deviations are set by a random-number generator from the interval -1°C to $+1$°C. In the presence of a layer with unstable stratification, the heat pulses cause the evolution of convection; otherwise, perturbations decay.

The model (1)–(6) permits us to study diurnal evolution of the convective ensemble, correctly reflects the main features of the CBL, and describes several types of convective motion[9]:

– the surface layer of steady flows with highly unstable air stratification;

– the mixed layer above it with height varying from a few tens of meters during morning hours to 1–2 km during afternoon hours;

– the thin inversion layer capping the convective ensemble from above;

– the two-level cloud convection, when thermals are in the mixed layer and the second convective layer consisting of nonprecipitating convective clouds is above the inversion.

To describe the spread of the admixture, we use the following equation[2,12]:

$$\frac{\partial s}{\partial t} + (U + u)\frac{\partial s}{\partial x} + (w - w_0(r))\frac{\partial s}{\partial z} = \nu\, \Delta s\,. \quad (7)$$

Here, s is admixture concentration; $w_0(r)$ is sedimentation rate of admixture particles with radius r; $\Delta = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2}$.

1. COMPARISON BETWEEN THE CONVECTIVE AND DIFFUSION REGIMES OF THE SPREAD OF DUST PARTICLES IN THE ABL

First, let us consider the case in which the source of the admixtures is a thin dusty atmosphere layer adjacent to the Earth's surface.[12] Following Refs. 12 and 13, for $z = 0$ we have

$$\nu\frac{\partial s}{\partial z} = -f = \text{const}\ (f > 0). \quad (8)$$

In addition, we assume that the admixture is absent at high altitudes, and for $z = H$

$$s = 0. \quad (9)$$

At the side boundaries of the calculation domain $x = 0$ and $x = X$, we take the periodicity conditions.

The exact standard solution of Eqs. (7)–(9) with $u = w = 0$ is taken as the initial condition: for $t = 0$

$$s = \frac{f}{w_0}\exp\left(-\frac{w_0}{\nu}z\right). \quad (10)$$

We recall that the initial moment corresponds to 09:00 h, local time. Calculations were performed for the values $U = 0$, $\theta_0 = 20$°q, $\theta_1 = 4$°q, $\nu = 5\ \text{m}^2 \cdot \text{s}^{-1}$. The relative humidity was assumed linearly decreasing from 0.7 at $z = 0$ to 0.3 at $z = H$.

The convection was simulated in the domain $0 < x < L = 5$ km, $0 < z < H = 3$ km.

The spread of the admixture was studied for the period between 09:00 and 21:00 h. We recall that the

LES model (1)–(6) is two-dimensional. The spread of the admixture is also two-dimensional in character. For more details about the grid domain and method of solving, see Ref. 12.

Let us briefly dwell on the results of calculations. The concentration of the dust particles

$$\overline{s} = \frac{1}{t_0 L} \int_t^{t+t_0} \int_0^L s \, dx \, dt' \quad (t_0 = 1 \text{ h})$$

averaged from $x = 0$ to $x = L$ and from $t' = t$ to $t' = t + t_0$ is maximum near the surface, quickly decreases with altitude, and becomes less by about an order of magnitude at altitudes of 15–50 m. The thickness of the very dusty lower layer is the larger, the lower is the admixture particle fall velocity. Above the layer, up to the upper boundary of the mixed layer, the average concentration is almost constant; then it quickly decreases. The number of particles in the CBL is approximately inversely proportional to their fall velocity.[12]

Thus, the net effect of the ensemble of thermals is similar to shaking of a jar filled with the liquid containing small heavy particles of an admixture. The mixed layer height varies from several tens of meters during morning hours to 1.2 km at noon. Approximately at this time the most intense thermals reach the condensation level and give rise to the second convective layer consisting of nonprecipitating convective clouds. An insignificant amount of admixture penetrates into the cloud layer.

At the initial stage, almost all the admixture entering the cloud layer is contained in clouds. Then the admixture gradually spreads over the cloud layer. With the decay of convection after noon, the admixture slowly settles on the Earth's surface. Qualitative measure of the difference between the convective and purely diffusive regimes of the spread of the admixture is illustrated by Table I, in which the following designations are taken: t_h is day time; h_1 is the height of the upper boundary of the mixed layer; h_2 is the height of the upper boundary of the cloud layer; w_1 is the maximum velocity of upward motions in thermals; w_2 is the velocity of upward motions in clouds; n_1 is the number of thermals in the mixed layer; n_2 is the number of clouds in the cloudy layer; l_1, l_2, and l_3 are the ratios of average admixture concentration in the mixed layer to the maximum concentrations in the diffusion layer for $w_0 = 0.02$, 0.1, and 0.5 m/s, respectively; m_1, m_2, and m_3 are the ratios of the maximum admixture concentrations in the cloud layer to those in the diffusion layer for $w_0 = 0.02$, 0.1, and 0.5 m/s, respectively; N is the ratio of the total admixture mass to the mass of the admixture in the diffusion layer.

TABLE I. Comparison between the convective and diffusion regimes of the spread of dust particles in the boundary layer.

t_h	09	11	13	15	17	19	21
h_1	–	760	960	1100	–	–	–
h_2	–	–	1230	2700	2900	–	–
w_1	–	3.2	2.1	0.6	–	–	–
w_2	–	–	4.2	3.1	1.2	0.6	–
n_1	–	9	8	6	–	–	–
n_2	–	–	3	2	2	–	–
l_1	–	0.6	0.6	0.6	0.5	0.3	–
l_2	–	0.4	0.4	0.4	0.2	0.1	–
l_3	–	0.1	0.1	0.1	0.1	–	–
m_1	–	–	0.009	0.007	0.005	0.003	0.002
m_2	–	–	0.006	0.004	0.002	0.001	0.001
m_3	–	–	0.001	0.001	–	–	–
N	1	1.7	3.8	4.3	4.1	2.3	1.3

2. COMPARISON BETWEEN THE CONVECTIVE AND DIFFUSION REGIMES OF THE SPREAD OF SALT WATER SPRAY IN THE ABL

Let us consider the case in which the admixture rises from the water surface due to wind. Following Ref. 3, we assume that for the spray of salt water at $z = 0$

$$\log s_0 = -PV^2/(V^2 + 172), \tag{11}$$

where V is mean velocity of wind-driven waves, $P = \text{const}$.

TABLE II. Comparison between the convective and diffusion regimes of the spread of the salt-water spray in the boundary layer.

t_h	09	11	13	15	17	19	21
h_1	–	580	720	900	–	–	–
h_2	–	–	1080	1720	2200	–	–
w_1	–	2.3	1.2	0.4	–	–	–
w_2	–	–	3.3	2.4	0.8	0.3	–
n_1	–	9	8	6	–	–	–
n_2	–	–	3	2	2	–	–
l_2	–	0.4	0.4	0.4	0.2	0.1	–
m_2	–	–	0.007	0.007	0.006	0.004	0.002
N	1	1.5	3.1	3.6	3.1	2.0	1.3

In addition, we assume that a storm has just passed ($U = 0$, there is no convection under storm conditions) and the water surface is much warmer than the air in the ABL.

The exact stationary solution to problems (7) and (11) for $u = \omega = 0$ and $t = 0$

$$s = s_0 \exp(-w_0 z/\nu) \tag{12}$$

is taken as the initial condition. Calculations were performed with $w_0 = 0.1$ m·s^{-1} and $\theta_1 = 2$°C. The relative humidity was taken decreasing from 1 at $z = 0$ to 0.3 at $z = H$. The rest boundary conditions and values of the parameters were the same as in the case considered above. Formulation of the problems clearly demonstrates that the peculiarities in the spread of the dust particles and salt water spray are connected with the difference in the external parameters. Therefore, general regularities are similar for the both cases (Table II).

CONCLUSION

As follows from the results obtained, convection conditions influence the optical characteristics of the lower 1-km layer of the atmosphere and lead to its considerable turbidity. This is also supported by observed data.[4] In addition, observations support the theoretical conclusions about the presence of the mixing layer in the vertical profile of the admixture concentration and its temporal behavior near the Earth's surface as a function of the convection intensity,[4] about penetration of water vapor coagulation[1] and condensation nuclei into the cloud layer.[2]

Because it is very expensive to obtain the data about the spread of the admixture in the real atmosphere, the proposed approach can be useful in developing parametrization procedures for processes of admixture transfer and transformation under conditions of dry or moist convection.

ACKNOWLEDGMENT

This work was supported in part by the Russian Foundation for Basic Researches, project No. 96–05–66104.

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