Calculation of the ascent height of smoke aerosol entrained in cloud systems over a forest fire zone

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The numerical model of the atmospheric boundary layer with the possibility of directly describing coherent structures is presented. The model is used for calculation of the local atmospheric circulation over a forest fire zone. The theoretical aspects of smoke plume distribution and cloud formation are investigated. The ascent of smoke particles is estimated in a convection column generated by heating of the underlying surface under different meteorological conditions.

Introduction

Big forest fires are dangerous natural disasters causing considerable economical and ecological damage. The methods employed to control these fires are quite expensive and not always efficient. Often the attempts of artificial fire extinguishing on vast areas turn out unsuccessful and only precipitation extinguishes fires in the natural way.

At the same time, analysis of the data of the Earth sensing from space shows a marked decrease in the total amount of summer precipitation on the territory of possible forest fires. Thus, in Yakutiya in the forest fire period of 2002 there was no rain in the burning zone and its vicinities for an anomalously long time.[1] The mechanism of this phenomenon is unclear, but we can suppose that it is connected with the substantial emissions from the fires. For example, intense heat flows cause alteration of the cloud dynamics, which blocks the processes of precipitation formation. On the other hand, the leading role can play the emission of the smoke aerosol, rather than the heat fluxes. The smoke aerosol affects microphysical transitions in the cloud–rain systems as a generator of a large number of condensation nuclei (sublimation).

One of the possible ways of this effect is the following. Large masses of smoke particles lifted to high (up to several kilometers) altitudes cause rapid crystallization of the excess vapor in the upper part of clouds. The fine crystals produced are not involved in the zone of precipitation formation because of the low deposition rate, and this results in a decrease of the amount of rainwater.

In connection with the above-said, it seems important to study the regularities of the formation of local atmospheric circulation generated by the emission of heat and smoke during the fire and to determine the extent of its effect on the processes of cloud formation. In particular, it is necessary to estimate the volumes of smoke aerosol inflow into the cloud layers and to study the qualitative vertical distribution of the admixture emitted from the surface fire.

The problem of vertical aerosol transport in the unstable stratification of the atmospheric boundary layer (ABL) was studied in Ref. 2 based on the eddy-resolution model. For reproducing the convective ensemble, the conditions of periodicity at the side boundaries were specified in Ref. 2, and this does not allow the results obtained in that paper to be extended to real situations. In Ref. 3, a fire was considered as a local phenomenon within the framework of the mesoscale nonhydrostatic model of the ABL, but the turbulent closure used is based on the two-parameter, b, ε-model including no restrictions on the maximum scale of turbulence, which follow from the traditional LES (Large Eddy Simulation) method of the derivation of the initial equations.[4]

Within the approach used in Ref. 3, difficulties arise in calculation of the convective mode at the unstable stratification of the ABL. Therefore the configuration of the smoke plume in Ref. 3 has a regular toroid-like structure about a single vertical jet, which is characteristic of the problem statements within the framework of K-models of the closure.[5] Experimentally, it was found that the convective column over the fire might consist of several powerful jets of fluctuating character with irregular spatiotemporal dynamics.[6]

The task of this work was to formulate an eddy-resolving model of the ABL suitable for reproduction of both the convective ensemble and local phenomena in the stratified atmosphere based on the approaches accepted in LES methodology. The model is used to describe the ABL dynamics in the forest fire zone and to study the dispersal of the fire products and formation of the convective cloudiness.

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Formulation of the problem

The system of equations making the basis of the eddy-resolving model of the ABL is derived by applying the box-type spatial filter[4] to the Navier–Stokes equations for an incompressible liquid. Then the unperturbed steadily stratified background with the temperature Θ, pressure P, and density ρ fields is introduced, and simplifications of deep convection[7] are used. As a result, the inelastic[7] system of equations in the Cartesian coordinates (x, y, z) will have the following form (the axis z is directed vertically upwards)

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+\frac{w}{\rho}\frac{\partial \rho u}{\partial z}=-\frac{\partial \pi}{\partial x}+fv-\frac{\partial \tau_{xx}}{\partial x}-\frac{\partial \tau_{xy}}{\partial y}-\frac{\partial \tau_{xz}}{\partial z},$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+\frac{w}{\rho}\frac{\partial \rho v}{\partial z}=-\frac{\partial \pi}{\partial y}-fu-\frac{\partial \tau_{yx}}{\partial x}-\frac{\partial \tau_{yy}}{\partial y}-\frac{\partial \tau_{yz}}{\partial z},$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+\frac{w}{\rho}\frac{\partial \rho w}{\partial z}=$$
$$=-\frac{\partial \pi}{\partial z}+\lambda\theta-\frac{\partial \tau_{zx}}{\partial x}-\frac{\partial \tau_{zy}}{\partial y}-\frac{\partial \tau_{zz}}{\partial z}, \qquad (1)$$

$$\frac{\partial \theta}{\partial t}+u\frac{\partial \theta}{\partial x}+v\frac{\partial \theta}{\partial y}+w\frac{\partial \theta}{\partial z}+\Theta_z w=-\frac{\partial \chi_x}{\partial x}-\frac{\partial \chi_y}{\partial y}-\frac{\partial \chi_z}{\partial z}+\frac{L}{\rho c_p}\Phi,$$

$$\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=0,$$

where u, v, and w are the wind velocity components; π is the analog of pressure; θ are perturbations of the potential temperature; f is the Coriolis parameter; τ_{ij} are the components of the tensor of turbulent stresses of the sub-grid scales; Φ is the rate of phase transitions of moisture; L is the latent heat of condensation. In accordance with the LES approach,[4] it is assumed that τ_{ij} can be approximated by the equations similar to molecular transport:

$$\tau_{ij}=-K\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right),\ \chi_i=-K_\theta\frac{\partial \theta}{\partial x_i}, \qquad (2)$$

where K, K_θ are the coefficients of turbulent viscosity and temperature conductivity. For calculating K the following equation is used[8]:

$$K=cl\sqrt{b}, \qquad (3)$$

where l is the length scale proportional to the step of the spatial grid; c is the universal constant; b is the kinetic energy of irresolvable scales, which satisfies the following balance equation:

$$\frac{\partial b}{\partial t}+u\frac{\partial b}{\partial x}+v\frac{\partial b}{\partial y}+\frac{w}{\rho}\frac{\partial \rho b}{\partial z}= \qquad (4)$$
$$=K(u_z^2+v_z^2)-K\lambda(\Theta_z+\theta_z)+0.61gKq_z+\mathrm{Diff}-\varepsilon,$$

where λ is the buoyancy parameter. The parameter ε in Eq. (4) describes the dissipation rate of sub-grid energy and is parameterized according to the Kolmogorov hypotheses through b and l, while the term Diff characterizes the diffusion processes.

The system of equations of the moisture and precipitation transport is considered together with the equations of fluid thermodynamics (1) and includes the equations for the water vapor q, suspended droplet q_c and a crystal q_i moisture, wet precipitation q_r, and snow q_s. For a quantitative description of Φ in Eq. (1), the model[9] based on the Kessler parameterization[7] is used.

Let us now formulate the boundary conditions for Eqs. (1) and (4). At the side boundaries of the considered parallelepiped $(0, L_x)\times(0, L_y)\times(h, H)$, where L_x, L_y are the dimensions in the horizontal directions; h is the thickness of the surface layer; H is the top boundary of the ABL, assume

$$\frac{\partial u}{\partial x}=\frac{\partial v}{\partial x}=\frac{\partial w}{\partial x}=\frac{\partial \theta}{\partial x}=\frac{\partial b}{\partial x}=0 \text{ at } x=0,\ x=L_x;$$
$$\frac{\partial u}{\partial y}=\frac{\partial v}{\partial y}=\frac{\partial w}{\partial y}=\frac{\partial \theta}{\partial y}=\frac{\partial b}{\partial y}=0 \text{ at } y=0,\ y=L_y. \qquad (5)$$

At the bottom boundary coinciding with the top boundary of the surface layer, specify the following conditions:

$$K\frac{\partial u}{\partial z}=c_u|\mathbf{u}|u,\ K\frac{\partial v}{\partial z}=c_u|\mathbf{u}|v,\ w=0,$$
$$K_\theta\frac{\partial \Theta}{\partial z}=c_\theta|\mathbf{u}|(\Theta_0-\Theta) \text{ at } z=h, \qquad (6)$$

where c_u is the coefficient of resistance; $\Theta_0(x, y, t)$ is the preset distribution of the surface temperature. At the top boundary of the ABL, the following conditions are set:

$$u=u_G;\ v=v_G;\ p=0;\ \frac{\partial \Theta}{\partial z}=0 \text{ at } z=H, \qquad (7)$$

where u_G, v_G are the components of the geostrophic velocity. The initial fields are assumed zero. The profile of the relative humidity was set as a linear function taking the value 0.9 at the bottom boundary of the ABL and decreasing to 0.4 at the level $z = H$. The value of the humidity at the bottom boundary was kept unchanged during the entire computational period. The model of transport and diffusion of the smoke aerosol applied in the following calculations was formulated in Ref. 3.

The problem is solved using the finite differences in the variables x, y, z, and t; the numerical algorithm is based on a version of the "predictor–corrector" splitting method and application of the implicit schemes. The approximation of the transport operators is based on the quasimonotonic scheme with the control function. The spatial resolution for the 10 × 10 km area was $\Delta x = 80$ m, $\Delta z = 20$ m, and the time step was taken equal to 15 s.

Calculated results

The described model was used for a comparative analysis of the admixture and cloud fields during fire and in the absence of a fire, in the dry and humid atmosphere. The fire was simulated as an extending (with time) thermal source in a bounded area by specifying local overheating of the surface by 70°C with respect to the periphery temperature. Calm conditions with $u_G = v_G = 0$ were considered.

As a control result, we will use the calculated ABL characteristics obtained in Ref. 3 in simulating the circulation over fire in the dry stable stratified atmosphere. Curve *1* in Fig. 1 shows the temporal variation of the total kinetic energy $E = \langle \rho(u^2 + v^2 + w^2) \rangle$ normalized to $E_{max} = 3.5 \cdot 10^9$ J (angular brackets here denote spatial integration). In this experiment, the characteristic value of w in the convective column over the heat source amounted to 2 to 3 m/s, the mean ascent height of 1% concentration of the admixture is equal to 1200 m.

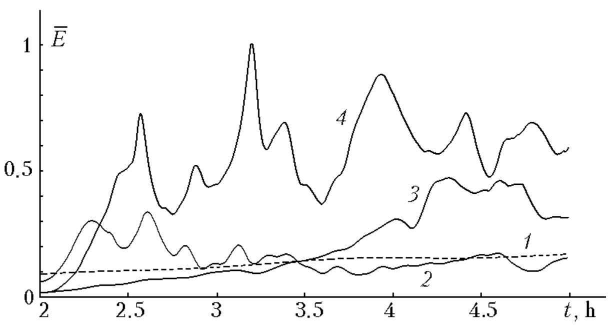

Fig. 1. The dynamics of the normalized kinetic energy in the versions of calculation of circulation in the ABL during fire under conditions of stable stratification in the dry (curve *1*) and humid (curve *2*) atmosphere and at the diurnal dynamics of temperature without fire (curve *3*) and with a fire (curve *4*).

In the experiment 2, the stable stratification was set as well, but the consideration of phase transitions of moisture was additionally introduced. The calculated results are shown by curve *2* in Fig. 1. In the model time interval of 2 to 3 h, the formation of a single cloud with the maximum water content of 0.6 g/kg, its separation from the surface source, and fast ascend to the top cloud boundary are observed. The instant of separation is illustrated in Fig. 2, which also shows the temperature isoline field at $t = 2$ h 20 min (dotted line shows the cloud contour).

The isolines are drawn with the step of 0.5°C; the unshaded area corresponds to zero deviations of θ. Note that the cloud has its own internal structure and consists of several powerful warm ($\theta > 0$) jets with the characteristic speed of 3 to 5 m/s. At the same time, the upper part of the cloud (marked by the minus sign in Fig. 2) turns out to be colder than the ambient air due to the processes of adiabatic cooling in the stable atmosphere. This structure of the cumulus clouds is well known and described in the literature.[10] The maximum concentration of the admixture in the cloud achieves 10% of the surface values.

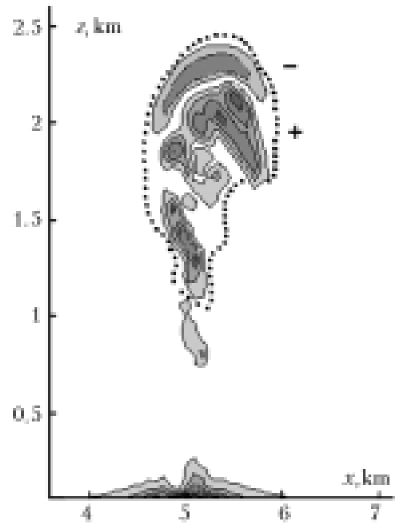

Fig. 2. The field of temperature perturbations at cloud separation from the fire site. The dotted line shows the cloud contour.

Approaching the level $z = H$, the cloud leaves the studied area. The total energy of the system decreases, and curve *2* in Fig. 1 shows the drop of $\bar{E}$ at $t = 2.5$ h. Then a series of clouds with the gradually decreasing depth is repeatedly generated, and the last cloud occupies the steady position over the fire zone, not lifting above the level of 1.2 km. This phenomenon is confirmed by observations – single steady clouds, slightly displaced down-wind, are quite frequent companions of the forest fires and can be clearly identified on space images.[11] Thus, consideration of the processes of cloud formation allows the ABL structure in the fire zone to be reconstructed quite adequately.

The numerical experiment 3 was conducted to check the efficiency of the model in description of the diurnal dynamics of temperature over the horizontally uniform surface. Random heat pulses with the amplitude up to 0.1°C were specified at the lower boundary as perturbing factors.

Heating the surface, a convective ensemble consisting of thermics and jets transporting heat and moisture upwards is developed in the low layers. At the condensation level, formation of cumulus clouds of low depth is observed; the number of clouds varies from two to six at different time. These are fair weather clouds[10] with the water content of about 0.5 g/kg and the height of formation about 1200 m. The calculated parameters of the convective cloud ensemble and its components fall within the range of the values observed in reality. Curve *3* in Fig. 1 illustrates the dynamics of the kinetic energy in this experiment.

In conclusion, let us calculate the circulation arising during a fire at unstable ABL stratification caused by the diurnal cycle. In this case, the convective ensemble is developed over entire area along with the localized vertical jet from the fire. This experiment is illustrated by the curve *4* in Fig. 1.

This process significantly differs from the case of a fire in the dry atmosphere considered in Ref. 3. The convective column grows without the formation of the diffusion zone; 80 min later, it reaches the condensation level, and then the development of the convective cloud begins at the top of the convective jet. Initially, this leads to formation of a local maximum in the vertical velocity (higher than 5 m/s) at the altitudes above 1 km and the fast increase of the vertical dimension of the convective column up to 3 km. The significant amount of the admixture (more than 1% of the maximum concentration) reaches these altitudes. Two and a half hours after the beginning of a fire, the cloud separates from the convective column and dies out due to condensation without the inflow of moisture and heat. The admixture contained in this cloud remains in the cloud layer, migrating later on due to the turbulent diffusion. Thirty minutes later, the jet rate increases again in the lower, dry part of the convective column, thus giving rise to a new cloud. Thus, convection over the fire zone generates the self-oscillation mode of the convective clouds development with their sequential generation, ascend, and dissipation or leaving the area studied. According to Fig. 1 (curve *4*), seven clouds have fully evolved during 5 h of the process.

The admixture concentration profile has the following shape. Just near the fire site the concentration is maximum, but it quickly decreases with height. Starting from the height of 1000 m, the concentration varies only slightly, that is, forms the mixed layer. The thickness of the zone of constant concentration increases with time, achieving the maximum height of 3 km. The admixture does not penetrate above 3.5 km. As the clouds go through the upper layers, the mean concentration in the cloud layer increases markedly, but the vertical profile of the concentration loses its regular character; it includes local peaks caused by the effect of different clouds.

Conclusions

The numerical eddy-resolving model for calculation of the fields of moisture and smoke aerosol in the zone of an extended forest fire has been presented. The strong effect of the phase transitions of moisture on the admixture transport into the cloud layers up to 3 km in height has been revealed. The processes of cloud formation have different character under stable and unstable stratification: in the former case a quasistationary cloud of small depth is formed over the fire, while in the latter one a pronounced cyclicity of cloud generation connected with the large depth and buoyancy of clouds is observed.

The increased moisture content, typical of cyclonic conditions, creates favorable conditions for penetration of the aerosol produced in the fire zone into the cloud layer. The great amount of this aerosol can markedly affect the evolution of the cyclonic cloudiness over the fire zone. At mass fires, this effect can grow to a regional scale.

Acknowledgments

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