Numerical model of migration of the aerosol formed in forest fire zones

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Received January 4, 2003

The results of numerical modeling of local atmospheric circulation over a forest fire zone are considered. Two numerical models of the atmospheric boundary layer are used as the basic ones. One model has a detailed resolution along the horizontal, and there is a possibility of explicitly reproducing the ensemble of large convective vortices. The other model is hydrostatic and it is used for studying large-scale transfer of a smoke jet. The results of numerical experiments for a typical fire in middle latitudes are presented.

Introduction

Forest fires inflict a significant harm to human activity. First, they cause material losses because of breaking the structure or destruction of forest flora and fauna. Change of the atmospheric composition that is important to health occupies the second place. The latter factor is rarely an immediate threat to human health but it is undoubtedly injurious. Besides, forest fires often make up uncomfortable conditions in the regions that are far apart from the fire source that Muscovites experienced in 2002. Smoke from near Moscow fires reached Tomsk,[1] that is 3000 km far from the fire source. And finally, forest fires contribute significantly into aerosol composition of the atmosphere delivering water vapor condensation nuclei and coagulation nuclei for cloud particles influencing in that way processes of cloud and precipitation formation.[2]

According to Ref. 2, forest fire is a phenomenon of uncontrollable multistage burning in an open area covered with a forest, in the framework of which interrelated processes of convective and radiation energy transfer, heating, drying, and pyrolysis of combustible forest materials (CFM), as well as burning of gaseous and afterburning of condensed products of CFM pyrolysis occur. The forest fires are of the following types: surface, crown, miscellaneous, and ground (fires in peatbogs). In surface fires a litter (fallen twigs, needles, and leaves), soil cover (grass, moss, lichen), and shrubs burn out. In crown fire only CFL from the forest canopy burn out. In miscellaneous fire the CFL from down forest layer and the CFL from forest canopy burn out simultaneously. Ground forest fires are fires on peatbogs when a seat of fire is inside a peat stratum.

The territory covered by a fire usually has an oval form where open flame zone (fire front) forms outer line of this oval whereas the inner part consists of glowing CFMs. The surface temperature in the inner zone is from 50 to 250°C, the front advance speed depends on the fire type (surface or crown one) and varies from millimeters to meters per second.

From the viewpoint of simulations one can isolate the following problems in studying the forest fires[2,3]: (1) calculation of flame speed; (2) forecast of fire zone shape; (3) studying of the heat–mass transfer at front and in the inner zone; (4) general mathematical model for describing a fire as a whole. To solve the first three problems, strongly simplified mathematical statements are usually used that take into account the main physico-chemical factors when transforming multiphase medium (air, solid CFMs, liquid and gaseous pyrolysis products). The general mathematical model uses fluid thermodynamics equations that describe motion of air and combustion products accounting for chemical kinetics processes. Solution of such equations is very difficult both mathematically and technically therefore, even in the general case, serious simplifications are used when describing both pyrolysis and hydrodynamic aspects restricting oneself to consideration of 2D or axisymmetric flows. The forest fire models and detailed analysis of the solutions obtained are reviewed in detail in Refs. 2 and 3.

The aim of this work is to describe a local atmospheric circulation in the forest fire zone based on the eddy-resolved model of the atmospheric boundary layer (ABL). The flow characteristics calculated are used for solving a problem on spreading of solid combustion products (smoke particles) resulting from the forest fire. Influence of meteorological conditions on the smoke plume parameters and surface concentration of combustion products is studied as well.

Statement of the problem

The basic equations and method of turbulent closure of numerical eddy-resolved model for description of

0235-6880/03/05–06 439-04 $02.00

convective processes in ABL are presented in Ref. 4. Note that as the initial equations we used the equations of fluid thermodynamics for turbulent liquid written in Boussinesq approximation in Cartesian coordinates (x, y, z), where the z-axis is directed vertically. Let us discuss here only boundary conditions that bear peculiarities of the physical processes under consideration.

In the integration domain of 20×10 km in size, a fire zone Ω_R is separated out as a circle with the radius $R_{\text{eff}} = R_0 + \varpi_n t$ that expands with time. Here ϖ is a flame velocity perpendicular to the contour, t is time. The temperature of the fire zone Θ_R is considered to be constant. Let us set the ABL upper boundary at $z = H = 2$ km, and divide vertical domain into two layers: $0 \le z \le h$ and $h \le z \le H$, where h is the first from below calculated level of the model. We will describe the high-temperature processes in the lower layer parametrically moreover, we will determine the h value as well. A convective column[2] is always formed above the seat of a forest fire. This column is a stream of heated completely and incompletely burnt products (soot and ash particles in the form of smoke). The more heat is produced in combustion, the higher the convective column is.

To specify the air temperature and speed in the convective column, let us use a simplified theory of one-dimensional atmospheric convective thermics over local heat source that is located on or near the underlying surface. According to Refs. 2 and 5, one can schematically present the air movement in the convective column in the following way. The air heated under the influence of a local heat source ascends forced by the buoyancy force and then cools under influence of adiabatic expansion and turbulent mixing with the cold air that enters the column through its lateral sides from the external space. One-dimensional theory of convective thermics[5] gives the following equations for the fire parameters:

$$\delta T = T_i - T_e = \delta_0 T \mathrm{e}^{-\alpha z} - \frac{\gamma_\mathrm{a} - \gamma}{\alpha}(1 - \mathrm{e}^{-\alpha z}), \quad (1)$$

$$W^2 = \frac{g}{\alpha^2 T_e}[2(\alpha\delta_0 T + \gamma_\mathrm{a} - \gamma)\mathrm{e}^{-\alpha z} - $$

$$-(2\alpha\delta_0 T + \gamma_\mathrm{a} - \gamma)\mathrm{e}^{-2\alpha z} - \gamma_\mathrm{a} + \gamma]; \quad (2)$$

$$\varphi = \varphi_0 \mathrm{e}^{-az}, \quad (3)$$

where δT is the mean deviation of temperature in thermics T_i from one in an undisturbed atmosphere T_e; $\delta T_0 = \delta T$ at $z = 0$; W is the mean thermic ascend speed; φ is the smoke particle concentration; z is the vertical coordinate; $\alpha = \frac{1}{M}\frac{\mathrm{d}M}{\mathrm{d}z}$ is the speed of cold air entrained into the thermic; M is the thermic weight; $\gamma = \text{const}$ is the temperature gradient of the polytropic atmosphere; γ_a is the temperature gradient of the adiabatic atmosphere.

Equations (1) and (2) were derived at $\alpha = \text{const}$. This case corresponds to thermic ascend in immobile atmosphere where the combustion products' weight is small as compared to the weight of heated air. Besides, Eqs. (1) and (2) do not account for influence of air drag and buoyancy force arising when thermic moves.

In calculations we consider that the fire zone Ω_R along with the territory burned out make up the inner part of the circle with variable radius R_{eff}. The temperature in the fire zone have been prescribed to be constant: when $x,y \in \Omega_R$, $z = 0$ $T_i = T_0 = \text{const}$. The entrainment speed is calculated by relation $\alpha = k/R_{\text{eff}}$, where k is the dimensionless coefficient accounting for fire type. The thermic radius increases with altitude as $R = R_{\text{eff}} + z\tan\theta$, where $\tan\theta \approx 0.2$ (Ref. 2).

In numerical calculations let us divide the atmosphere into two layers $z_1 \le z \le h$ and $z > h$. The h value we determine from Eq. (1) at $\delta T(h) = 30°\mathrm{C}$,

$$h = \frac{1}{\alpha}\ln\frac{\delta T_0\alpha + \gamma_\mathrm{a} - \gamma}{\delta T(h)\alpha + \gamma_\mathrm{a} - \gamma} \approx \frac{1}{\alpha}\ln\frac{\delta T_0}{\delta T(h)} = \frac{1}{\alpha}\ln\frac{\delta T_0}{30}. \quad (4)$$

Thus, accounting for the fire in the model is reduced to setting the following conditions at the lower calculation level:

$$K_z\frac{\partial u}{\partial z} = c_u \mid u \mid u, \quad K_z\frac{\partial v}{\partial z} = c_u \mid u \mid v, \quad w = W(h),$$

$$\Theta = \Theta_e + 30°\mathrm{C}, \; s = 1 \text{ at } x,y \in \Omega_R, \; z = h;$$

$$K_z\frac{\partial u}{\partial z} = c_u|u|u, \;\; K_z\frac{\partial v}{\partial z} = c_u|u|v, \; w = 0, \; \Theta = \Theta_e,$$

$$\frac{\partial s}{\partial z} = 0 \text{ at } x,y \notin \Omega_R, \; z = h, \quad (5)$$

where Θ is the temperature value at $z \ge h$; K_z is the vertical turbulent exchange coefficient; c_u is the drag coefficient calculated using surface layer model. At the upper boundary we set the conditions

$$u = u_G, \;\; v = v_G, \;\; \frac{\partial w}{\partial z} = 0, \;\; \frac{\partial\Theta}{\partial z} = \gamma_\mathrm{a} - \gamma,$$

$$\frac{\partial s}{\partial z} = 0 \text{ at } z = H, \quad (6)$$

where u, v, w are the wind velocity components along x, y, and z axes; $s = \varphi/\varphi(h)$. We also demand that at the lateral sides derivatives of the velocity, temperature, and concentration with respect to normal to the boundary are zero. As the initial condition, we took horizontally homogeneous stationary solution of the problem without fire, i.e., at $R = 0$ $\Theta = \Theta_e + (\gamma_\mathrm{a} - \gamma)\, z$.

The finite-difference grid containing 256×128×100 nodes has been introduced in the integration domain, time step was 10 s. The value ϖ_n has been taken equal to 0.2 m/s.

The main purpose of calculations was to study hydrodynamic structure of the flow over the fire and to analyze smoke plume characteristics near the underlying surface at different wind strength. Figure 1 demonstrates transformation of an admixture cloud with time under calm weather conditions.

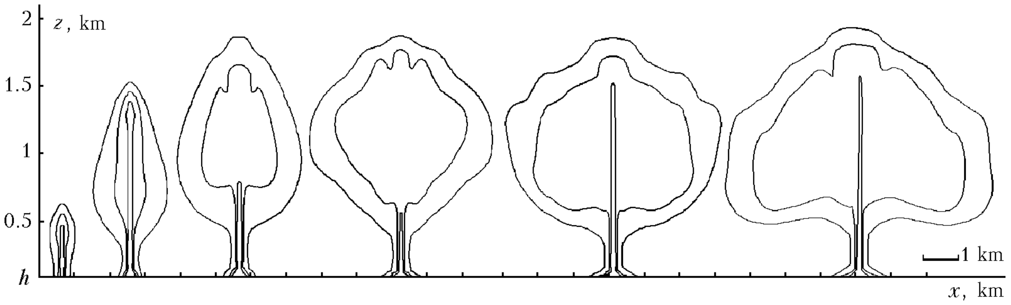

Fig. 1. Isolines of normalized concentration field s in the (x, z) plane at sequential time moments aliquot to 20 min. Outer line corresponds to s value equal to 0.01, middle and inner ones correspond to 0.1 and 0.2, respectively.

It is seen from Fig. 1 that a convective column is formed over the geometric center of the fire zone. This column is a powerful vertical stream that is visually seen because of high smoke concentration. The characteristic velocity of the ascending current is 5–7 m/s. The stream temperature, except for the very low part, weekly differs from the ambient air temperature. Over 2-hour period the stream top reaches almost 2-km altitude but its horizontal size is practically invariable (about 600 m in diameter). As the vertical motions develop, in the upper part of the stream an entrained layer is formed, where vertical motions decay and horizontal flow divergence is generated due to the spreading. The combustion products released are lifted up, where stream spreading results in formation of smoke plume in the middle part of ABL, which horizontal sizes increase with time. A mushroom-shaped structure of the concentration field is formed.

Bypassing descending currents on the periphery cause slow settling of the cloud that is clearly seen in Fig. 1 at $t = 2$ h. Sedimentation rate of the admixture particles is small as compared with air mass velocities and it is of no importance at the time intervals considered. Note that the convection pattern presented is in a good agreement with the observation data on the behavior of flows and admixture spreading over powerful heat sources at very weak winds. In particular, it gives a pattern of the latest stage of nuclear explosion cloud evolution.

The calculated results presented in Fig. 1 correspond to the crown fire of a medium strength. For more powerful fire, where burning zone exceeds 10 km^2, under calm weather conditions, one powerful convective stream and a number of more week floating thermics located on the combustion zone periphery appear over relatively vast heated territories. At the altitudes of 100–300 m these thermics either decay or merge with the stream. For surface fires with a low flame velocity the qualitative pattern of circulation over the fire zone does not change but its strength significantly decreases. Thus, maximum air ascend speed in convective stream does not exceed 2–3 m/s depending on the fire strength.

An admixture spreading pattern essentially changes in the case of ground (peatbog) forest fire. Since burning occurs under soil where access for oxygen is limited, the surface temperature is relatively low. The area included in the ground fire is much larger than that of open forest fires, and it has more complicated configuration that is hard to identify by means of ground-based measurements. Thus, ground fires are characterized by emission of immense smoke amounts into the atmosphere (due to incomplete peat combustion) and relatively low heat emission that mostly is heating the soil.

Calculations show that in the case of ground fires, up to several tens of thermics filled with smoke and warm air are formed instead of one convective stream depending on the burning area. These thermics ascend up to several hundreds meters. All this is in a good agreement with the observation data.[2]

In experiments where geostrophic wind was nonzero, components u_G and v_G were chosen, accounting for Eckmann turn, in such a way that surface wind was directed along x axis. The presence of horizontal transfer changes qualitatively convection pattern and influences the admixture spreading that is demonstrated in Fig. 2.

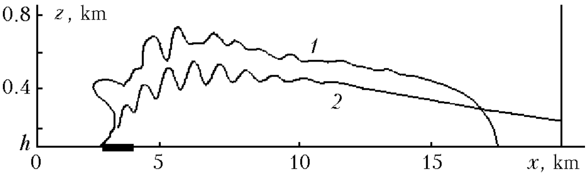

Fig. 2. Isolines of s field on (x, z) plane, bounding the 1-% level of blackening with smoke at wind velocity of 5 and 10 m/s (curves *1*, *2*). Fire zone is marked on x axis.

Instead of a relatively narrow vertically elongated convective stream there appears a system of floating thermics that move along the wind and damp outward from the fire center. Figure 3 illustrates such a flow.

The admixture cloud does not spread higher than 500–600 m and elongated along the wind over a distance of 10–20 km from the fire seat. The upper boundary of the smoke cloud has a specific wavy structure that represents a large-eddy structure of the flow. The admixture fall-out zone has a shape of a flame elongated along the wind velocity. According to observations, such a pattern of convection and admixture spreading in fires is more typical than at calm weather conditions; as a rule it is exactly the external wind that causes evolution of an a accidental inflammation into great fire.

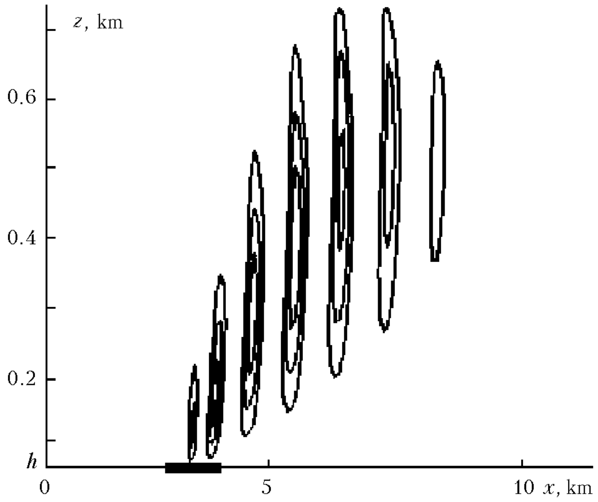

Fig. 3. Configuration of domains with $w > 0.5$ m/s on (x, z) plane at wind speed of 10 m/s, $t = 2$ h. Internal isolines were made with the step $\Delta w = 0.5$ m/s.

At wind speed higher than 10 m/s the admixture cloud has been spread for a distance of hundreds kilometers from the emission source. In this case the model suggested has been used only to preset local parameters of the concentration field, whereas the large-scale transfer has been studied with the use of hydrostatic model[6] with the horizontal grid step of 10 km. In the case with ground fires with large amount of smoke emitted and large duration even at a moderate wind quite sufficient smoke concentrations spread for distances of 1000 km from the fire seat in several tens of hours.

Relatively rare, but the most dangerous, miscellaneous fire accompanied by eddy atmospheric circulation (like a fire storm[2]) stands apart from the theory considered. Seemingly special external conditions should be preset for such eddies to appear, for example, as a flux with a large shear.

Conclusion

The calculations made demonstrate applicability of the eddy-resolved modeling for solving applied problems arising in strong natural or technogenic fires. An essential theory refinement can be made when taking into account interference of processes inside the burning zone and processes in the convective column located above this zone where transformation of solid, liquid, and gaseous pyrolysis products is different in principle. Account for these transformations is important for the theory refinement. Besides, in our opinion, study of pyrolysis products evolution and its connection to processes of cloud and precipitation formation is promising.

Acknowledgments

This work was performed at the support of the Russian Foundation for Basic Research, Projects No. 03–05–65279 and No. 03–05–96825.

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