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Mathematical Modelling of Suspension Uplift by Wind Gusts

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Abstract
Introduction. The study of suspension uplift processes (e. g., particles of dust, sand, soil, etc.) by wind gusts in the surface layer is aimed at fundamentally understanding the mechanisms of wind erosion, dust storm formation, pollutant transport, and related phenomena. This area of scientific research has significant practical importance for combating desertification, erosion, drought, as well as for increasing crop yields and preserving natural ecosystems. Predicting these processes allows for the assessment and timely response to negative effects associated with them. The objective of this work is to propose and implement a mathematical model that enables numerical experiments with various scenarios of suspension uplift by wind gusts.
Materials and Methods. The paper presents a continuous mathematical model of multicomponent air medium motion in the atmospheric surface layer. The model accounts for factors such as turbulent mixing, variable density, Archimedes' force, tangential stress at media interfaces, etc. A distinctive feature of the mathematical model is the presence of suspension particles (their composition and aggregate state) in the air medium, as well as the influence of anthropogenic factors — suspension sources. The approach based on mathematical modelling aims to ensure the universality of the numerical implementation.
Results. The mathematical model has been implemented as a software package. Numerical experiments simulating the uplift of suspension by wind gusts in computational domains have been conducted.
Discussion. The results of this work can be in demand for a wide range of tasks related to human health protection, environmental safety, and land-use planning in arid and steppe regions of the country.
Conclusion. Further research by the authors may be directed towards modelling the movement of dust-laden air flows for natural landscapes containing forest plantations.

Keywords: wind gust, suspended matter, turbulent mixing, aerodynamics, mathematical model, numerical experiment

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Оригинальное эмпирическое исследование

Математическое моделирование подъема взвеси ветровыми порывами

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Аннотация
Введение. Изучение процесса подъема взвеси (например, частиц пыли, песка, почвы и др.) ветровыми порывами в приземном слое направлено на фундаментальное понимание механизмов ветровой эрозии, возникновения пыльных бурь, переноса загрязняющих веществ и др. Эта область научных исследований имеет важное практическое значение для борьбы с опустыниванием, эрозией, засухой, а также для повышения урожайности и сохранения природных экоси-

стем. Прогнозирование данных процессов позволяет оценивать и своевременно реагировать на негативные эффекты, связанные с данными процессами. Цель настоящей работы — предложить и реализовать математическую модель, которая позволит проводить численные эксперименты с различными сценариями подъема взвеси ветровыми порывами.
Материалы и методы. В работе представлена непрерывная математическая модель движения многокомпонентной воздушной среды в приземном слое атмосферы, которая учитывает такие факторы, как турбулентное перемешивание, переменную плотность, силу Архимеда, тангенциальное напряжение на границах раздела сред и др. Отличительной особенностью математической модели является присутствие в воздушной среде частиц взвеси (их состава и агрегатного состояния), а также влияние техногенных факторов — источников взвеси. Подход, основанный на математическом моделировании, призван обеспечить универсальность численной реализации.
Результаты исследования. Математическая модель реализована в виде комплекса программ. Проведены численные эксперименты, моделирующие подъем взвеси ветровыми порывами в расчетных областях.
Обсуждение. Результаты данной работы могут быть востребованы для широкого круга задач, связанных с охраной здоровья человека, экологической безопасностью и планированием природопользования в засушливых и степных регионах страны.
Заключение. Дальнейшие исследования авторов могут быть направлены на моделирование движения воздушного потока, содержащего пыль, для природных ландшафтов, содержащих лесонасаждения.

Ключевые слова: ветровой порыв, взвешенное вещество, турбулентное перемешивание, аэродинамика, математическая модель, численный эксперимент

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Introduction. The uplift of dust, sand, and other suspended particles in the lower atmospheric layers by wind gusts is a complex physical process. It depends on wind force (especially gusts), atmospheric turbulence, the physical characteristics of the particles, soil roughness and moisture, the presence of vegetation cover, and other factors. Upon reaching a critical (threshold) velocity, wind can "pick up" dust, sand, and fine soil particles and transport them over long distances, thereby destroying the upper fertile soil layer and causing wind erosion. One of the vivid manifestations of wind erosion is associated with the formation of dust storms.

Dust storms, combined with strong winds in southern Russia (primarily in the Rostov, Volgograd, and Astrakhan regions, Krasnodar and Stavropol territories), are caused by a combination of the following factors: intense heat, which dries out the soil; wind intensification up to 12–15 m/s, which lifts and transports dust and sand particles; vast expanses of plowed land not covered by vegetation. Seasonally, dust storms occur in early spring and early autumn (their greatest intensity is observed in the second half of the year, specifically in September and October), which is associated with low atmospheric precipitation, soil moisture loss, and a high degree of land plowing. The main and long-term cause is the disappearance of protective forest belts that could restrain the wind, as well as the influx of hot air masses from neighboring desert regions, such as Kalmykia. Here, in zones with semi-desert and desert landscapes, conditions are created for the transport of dust-sand and aerosol material to neighboring regions. The scale and cyclicity of these phenomena have increased in recent years.

In this context, predicting the processes of air mass movement containing dust and fine sand particles, and identifying areas at high risk of wind erosion, becomes relevant. Therefore, the experience of Russian and foreign researchers and their teams, who have applied both fundamental physical models (Euler-Lagrange, Discrete Phase Model — DPM) and modern software packages (ANSYS Fluent, COMSOL, etc.), is interesting and useful [1–5]. The vast majority of research focuses on specific regions and territories, which is related to specific meteorological conditions, local data on topography and soil types, unique dust sources, etc. For Southern Russia, studies on this topic are reflected in the works of scientists from the Southern Mathematical Institute of the Vladikavkaz Scientific Center of the Russian Academy of Sciences, Southern Federal University, Don State Technical University, and others [6–10].

The authors propose for consideration a mathematical model that will allow conducting numerical experiments with various scenarios of dust-laden airflow movement. The work emphasizes modeling the turbulence of the airflow caused by the wind structure, which contributes to the uplift of suspended matter particles from the earth›s surface and is the main cause of dust storm formation. The mathematical model has been implemented as a software package. Numerical experiments have been conducted, simulating wind gusts in the lower atmospheric layers with the uplift and transport of suspension by ascending turbulent flows in computational domains.

Materials and Methods

Mathematical Model of Suspension Propagation in the Atmospheric Surface Layer. The authors consider a comprehensive mathematical model describing the processes of air medium motion and suspension propagation within it, which includes [9, 10]:

– a model of multicomponent air medium motion (defining the velocity field of the air medium), accounting for turbulent exchange, variable density, and the dependence of air medium density on pressure,

– a model of suspension propagation in the air medium, accounting for the phase transition of water from liquid to gaseous state and vice versa, and substance transport,

– a pressure calculation model, accounting for medium compressibility, suspension sources associated with the phase transition of water from liquid to gaseous state and vice versa, as well as turbulent mixing of the multicomponent air medium.

Let us formulate the equations of the multicomponent air medium motion model in the coordinate system $Ox_1x_2x_3$:

– motion equation (Navier-Stokes equations):

$$\frac{dv_j}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + div\left(\mu grad\left(v_j\right)\right) - g_i; \tag{1}$$

– substance transport equation:

$$\frac{\partial \rho}{\partial t} + div\left(\rho\vec{v}\right) = div\left(\mu grad\left(\rho\right)\right) + I_\rho; \tag{2}$$

– equation of state:

$$P = \sum_i \frac{\rho_i}{M_i} RT; \tag{3}$$

– impurity transport equation:

$$\frac{d\varphi_i}{dt} = div\left(\mu grad\left(\varphi_i\right)\right) + I_\varphi; \tag{4}$$

– turbulence model equation:

$$v_{SGS} = \left(C_S \Delta\right)^2 S. \tag{5}$$

In equations (1–5), the following notations are used: t is the temporal variable; v_j ($j = 1, 2, 3$) are the components of the air medium velocity vector $\vec{v}$; p is the pressure; μ is the turbulent exchange coefficient; ρ is the density of the air medium; ρ_i is the density of the i-th phase ($i = 0$ — air, 1 — water in gaseous state, 2 — gas at the source, 3 — water in liquid state, 4 — soot); φ_i are the volume fractions of the i-th phase; I is a function describing the distribution and power of suspension sources; R is the universal gas constant, M is the molar mass, T is the temperature of the gas phase.

To simplify computational calculations for the discrete analogues of the model equations, a transition from 3D to 2D equations is performed. Consider the 3D convection-diffusion-reaction equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial\left(\rho v_1\right)}{\partial x_1} + \frac{\partial\left(\rho v_2\right)}{\partial x_2} + \frac{\partial\left(\rho v_3\right)}{\partial x_3} = \frac{\partial}{\partial x_1}\left(\mu\frac{\partial \rho}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\left(\mu\frac{\partial \rho}{\partial x_2}\right) + \frac{\partial}{\partial x_3}\left(\mu\frac{\partial \rho}{\partial x_3}\right) + I_\rho. \tag{6}$$

Equation (6) is supplemented with corresponding boundary conditions [9].

As a result of transformations, we obtain:

$$\varepsilon\frac{\partial \rho}{\partial t} + \frac{\partial\left(\varepsilon\rho v_1\right)}{\partial x_1} + \frac{\partial\left(\varepsilon\rho v_3\right)}{\partial x_3} = \frac{\partial}{\partial x_1}\left(\mu\varepsilon\frac{\partial \rho}{\partial x_1}\right) + \frac{\partial}{\partial x_3}\left(\mu\varepsilon\frac{\partial \rho}{\partial x_3}\right) - \frac{\tau}{\rho}\bigg|_{x_2(a)}^{x_2(b)} + \varepsilon I_\rho, \tag{7}$$

where ε is a parameter describing the relative volume of the computational domain free from plants.

Two-Dimensional Mathematical Model of Atmospheric Surface Layer Aerodynamics. Let us further assume $x_1 = x$, $x_2 = y$, $x_3 = z$, and for the components of the air medium velocity vector $\vec{v}$ — $v_1 = u$, $v_2 = v$, $v_3 = w$.

Consider the basic equations of air medium dynamics:

– system of Navier-Stokes equations:

$$\begin{aligned} &\varepsilon u'_t + u\varepsilon u'_x + v\varepsilon u'_z = -\frac{1}{\rho}\left(\varepsilon P\right)'_x + \left(\mu\varepsilon u'_x\right)'_x + \left(\mu\varepsilon u'_z\right)'_z + \varepsilon f_x, \\ &\varepsilon w'_t + u\varepsilon w'_x + w\varepsilon w'_z = -\frac{1}{\rho}\left(\varepsilon P\right)'_z + \left(\mu\varepsilon v'_x\right)'_x + \left(\mu\varepsilon w'_z\right)'_z + \varepsilon f_z; \end{aligned} \tag{8}$$

– continuity equation:

$$\varepsilon\rho'_t + \left(\varepsilon\rho u\right)'_x + \left(\varepsilon\rho w\right)'_z = \left(\varepsilon\mu\rho'_x\right)'_x + \left(\varepsilon\mu\rho'_z\right)'_z + \varepsilon I_\rho; \tag{9}$$

– equation of state:

$$P = \sum_i \frac{\rho_i}{M_i} RT, \tag{10}$$

where ε is a parameter describing the relative volume of the modeled area free from plants.

Assuming the air medium is initially at rest, the initial conditions are:

$$u = 0,\ w = 0,\ P = P_a,$$

where $\vec{v} = \{u, w\}$, P_a is atmospheric pressure.

The system of equations (8)–(10) is considered under the following boundary conditions:

– on an impermeable boundary:

$$\rho_w \eta u'_n = \tau_{x,b}(t),\ \rho_w \eta v'_n = \tau_{z,b}(t),\ \overline{V}_n = 0, P'_n = 0,\ P'_n = 0;$$

– on lateral permeable boundaries:

$$u'_n = 0,\ w'_n = 0,\ P'_n = 0;$$

– on the source:

$$u = U,\ w = W,\ P'_n = 0,$$

where P is the pressure; U, W are the components of the velocity vector at the source; τ_x, τ_z are the components of tangential shear stress.

Splitting Schemes for Physical Processes in Solving Aerodynamic Problems. According to the pressure correction method, the original hydrodynamic model is split into three subproblems [11–14].

The first subproblem is represented by the convection-diffusion-reaction equation, based on which the components of the velocity field at an intermediate time layer are calculated:

$$\begin{gathered}
\varepsilon\frac{\tilde{u} - u}{h_t} + u\varepsilon\bar{u}'_x + w\varepsilon\bar{u}'_z = \left(\mu\varepsilon\bar{u}'_x\right)'_x + \left(\mu\varepsilon\bar{u}'_z\right)'_z, \\
\varepsilon\frac{\tilde{w} - w}{h_t} + u\varepsilon\bar{w}'_x + w\varepsilon\bar{w}'_z = \left(\mu\varepsilon\bar{w}'_x\right)'_x + \left(\mu\varepsilon\bar{w}'_z\right)'_z.
\end{gathered} \tag{11}$$

For the temporal approximation of the convection-diffusion-reaction equation, weighted schemes are used. Here $\bar{u} = \sigma\tilde{u} + (1-\sigma)u$; $\sigma \in [0,1]$ is the scheme weight.

Let us describe the boundary conditions for system (11):

– on an impermeable boundary:

$$\rho_w \eta u'_n = \tau_{x,b}(t),\ \rho_w \eta v'_n = \tau_{z,b}(t);$$

– on lateral permeable boundaries:

$$u'_n = 0,\ w'_n = 0;$$

– on the source:

$$u = U,\ w = W,\ P'_n = 0.$$

The second subproblem allows for the calculation of the pressure distribution

$$\left(\varepsilon P'_x\right)'_x + \left(\varepsilon P'_z\right)'_z = \varepsilon\frac{\hat{\rho} - \rho}{h_t^2} + \frac{\left(\bar{\rho}\varepsilon\tilde{u}\right)'_x}{h_t} + \frac{\left(\bar{\rho}\varepsilon\tilde{w}\right)'_z}{h_t}$$

or

$$\varepsilon\frac{\hat{P} - P}{h_t} + \left(\varepsilon\bar{P}\tilde{u}\right)'_x + \left(\varepsilon\bar{P}\tilde{w}\right)'_z = kh_t\left(\left(\varepsilon\bar{P}'_x\right)'_x + \left(\varepsilon\bar{P}'_z\right)'_z\right),\ k = \frac{RT}{\mathrm{M}}. \tag{12}$$

The third subproblem allows for the determination of the velocity distribution at the new time level using explicit formulas:

$$\varepsilon\frac{\hat{u} - \tilde{u}}{h_t} = -\frac{1}{\rho}\left(\varepsilon\bar{P}\right)'_x,\ \varepsilon\frac{\hat{w} - \tilde{w}}{h_t} = -\frac{1}{\rho}\left(\varepsilon\bar{P}\right)'_z, \tag{13}$$

where h_t is the step in the temporal coordinate; u is the velocity field value at the previous time level; $\tilde{u}$ is the velocity field value at the intermediate time level; $\hat{u}$ is the value at the current time level.

Multiplying the system of equations (13) by $h_t\rho$ and differentiating with respect to the variables *x, y, z* respectively, we obtain:

$$\left(\varepsilon\rho\hat{u}\right)'_x = \left(\varepsilon\rho\tilde{u}\right)'_x - \varepsilon h_t P''_{xx},\ \left(\varepsilon\rho\hat{w}\right)'_z = \left(\varepsilon\rho\tilde{w}\right)'_z - \varepsilon h_t P''_{zz}. \tag{14}$$

Using expressions (14) to transform equation (9), we get:

$$\varepsilon\rho'_t + \left(\varepsilon\rho\tilde{u}\right)'_x - \varepsilon h_t P''_{xx} + \left(\varepsilon\rho\tilde{w}\right)'_z - \varepsilon h_t P''_{zz} = \left(\varepsilon\mu\rho'_x\right)'_x + \left(\varepsilon\mu\rho'_z\right)'_z + \varepsilon I_\rho. \tag{15}$$

Taking into account the equation of state, expression (15) takes the form:

$$\varepsilon\frac{\rho}{P}\frac{\partial P}{\partial t} = \varepsilon h_t P''_{xx} + \varepsilon h_t P''_{zz} - \left(\varepsilon\rho\tilde{u}\right)'_x - \left(\varepsilon\rho\tilde{w}\right)'_z + \left(\varepsilon\mu\rho'_x\right)'_x + \left(\varepsilon\mu\rho'_z\right)'_z + \varepsilon I_\rho. \tag{16}$$

The pressure field is computed based on equation (16). It should be noted that the pressure calculation accounts for medium compressibility, thermal expansion, substance sources associated with the phase transition of water from liquid to gaseous state and vice versa, as well as turbulent mixing of the multicomponent air medium.

The construction of finite-difference schemes approximating the considered equations (16) has been performed on hydrodynamic grids using methods described in works [15, 16] and is not presented in this article.

Results. Based on the developed algorithms, a software package was created for the numerical simulation of suspension uplift by wind gusts in a multicomponent air medium. A series of numerical experiments was conducted.

Figures 1 and 2 present the results of a numerical experiment simulating air medium motion under wind gusts. The model domain has dimensions of 30 m × 50 m. The input data are: air medium density 1.29 kg/m³; atmospheric pressure 100 kPa; wind gust speed 10 m/s, wind direction — from left to right. Computational grids with a step of 10 meters in each coordinate direction were used to solve the problem. The temporal step was 0.1 s, and the total simulation time interval was 100 s.

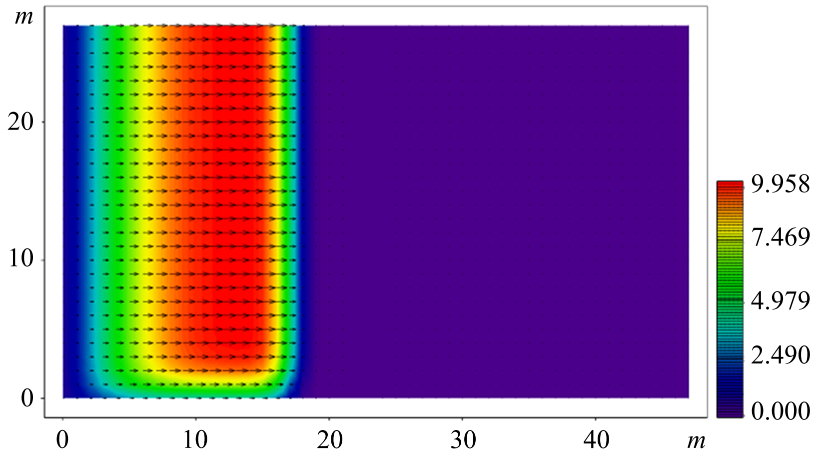

Fig. 1. Image of the initial simulation moment for calculating air medium velocity. Horizontal cross-section

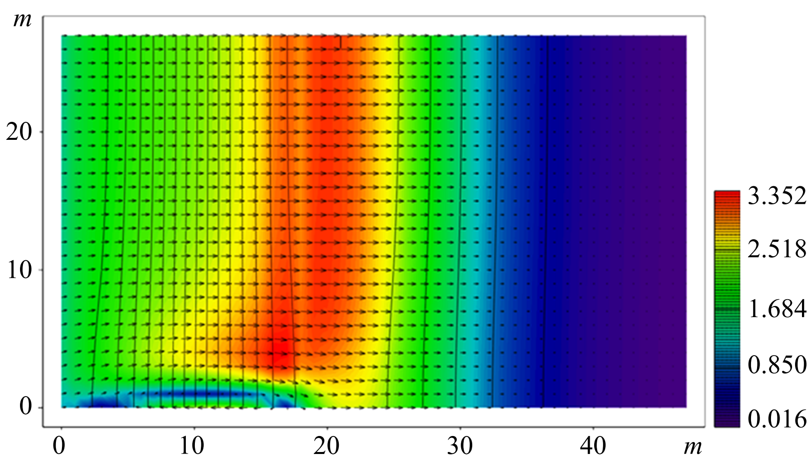

Fig. 2. Simulation result of air medium velocity. Horizontal cross-section

In Fig. 1 and 2, the intensity of air medium motion in m/s is represented according to the color palette. Fig. 2 demonstrates the presence of a vortex in its lower left part, which may be associated with the motion of a flow at different speeds at the interface between air layers, as well as with the terrain relief (vortex flows often arise due to the "repulsion" of air masses from the surface). The vortex nature of atmospheric flows is observed near the surface and gradually diminishes with height. This leads to the formation of a stable density gradient. The airflow in the surface layer becomes stably stratified, and the vortices weaken. As a result, the flow velocity increases.

Next, we present the results of modeling suspension uplift under wind gusts. The input data are: air medium density 1.29 kg/m³; emission density 1.4 kg/m³; ambient temperature 20 °C; air medium flow velocity 10 m/s; specific emission power 5 L/s. Computational grids with dimensions of 30 m × 50 m were used to solve the model problem. The steps in the spatial variables are 1 m, and the air medium velocity on the left boundary was set to 1 m/s. Weighted schemes were applied to solve the model problem, with the scheme weight set to 0.5. The temporal step was 0.1 s, and the total simulation time interval was 10 s.

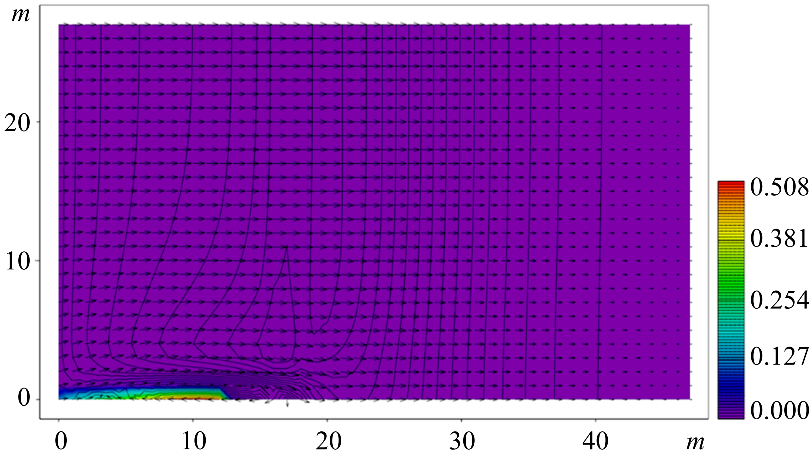

Fig. 3. Image of the initial simulation moment for calculating suspended matter concentration

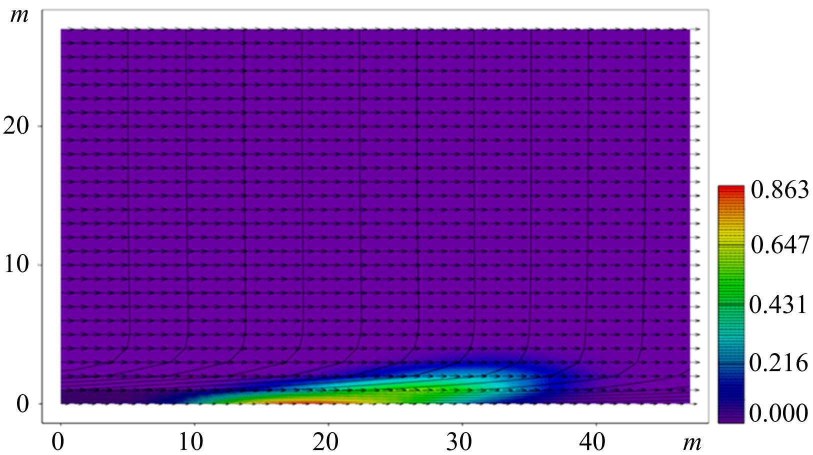

Fig. 4. Simulation results for calculating suspended matter concentration 10 seconds after the start of the simulation

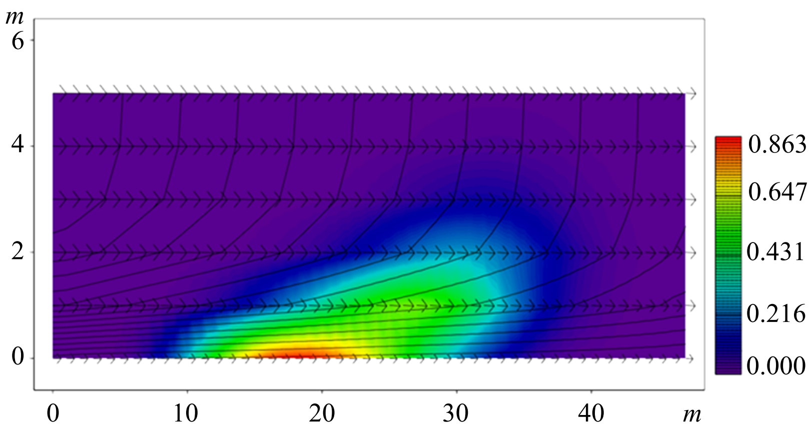

Fig. 5. Simulation results for calculating suspended matter concentration 10 seconds after the start of the simulation — zoom into the substance propagation zone

The color palette in Fig. 3–5 indicates the concentration of suspended matter in the atmospheric surface layer. The simulation results demonstrate the propagation of the impurity in the direction of air medium motion over tens of meters; the impurity uplift exceeded 5 m.

Discussion. The results of this work can be applied to a wide range of tasks related to human health protection, environmental safety, and land-use planning in arid and steppe regions of the country.

Conclusion. Further research by the authors may focus on modeling the movement of dust-laden airflows in natural landscapes containing forest plantations.

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