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MODELING OF PROPAGATION OF ALLERGENIC PLANT POLLEN IN AN ATMOSPHERIC BOUNDARY LAYER USING HIGH-PERFORMANCE CALCULATIONS IN CLUSTER SYSTEM

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The quasi-two-dimensional model of impurity propagation early designed elsewhere is modified for treating transporting of allergenic plant pollen from spreaded forested areas in vicinity of a large city. The model includes consideration of mesoscale hydrothermodynamical processes in the lower atmosphere with account for the thermal nonuniformity of the underlying surface in the urban and suburban environs. The boundary conditions and the model coefficients are determined using the parametrization method. Some results of numerical calculations are presented. The calculations were performed using parallelized algorithms on the cluster supercomputer of the Vyatka State University. They show that, due to the action of an inhomogeneous horizontal temperature gradient in the lower atmosphere, vortex flows can be formed above populated areas.

Keywords: high-performance calculations; transfer of impurity; atmo- spheric boundary layer; allergenic plant pollen.

1. Introduction

Pollen grains contained in the atmosphere have the ability to cause allergic diseases. An increase in the number of pollen allergy diseases in the second half of the 20th century led to growth of interest of the atmospheric transfer of pollen around the world. 2018 was called by World Health Organization (WHO) to be the year of the allergy pandemic. The prevalence (30-60 Percent of the population) of allergic diseases (every third inhabitant of the planet suffers from allergic rhinitis and every tenth of bronchial asthma) turned allergies into a global medical and social problem. The percentage of people suffering from allergies (mainly among the young people) is significantly higher in highly developed countries than in developing ones.

The problem of allergic diseases spreading among children is very acute. Table 1 presents WHO data on allergic diseases (AD).

Table 1. The distribution of AD in various countries over the past 30 years, percents

Country	**Children**	**Adults**
Russia	2–4	1–6
Norway	12	10
Sweden	5	—
Switzerland	—	17
Italy	3–6	8
Finland	6	14
Germany	10	9–19
Great Britain	12	11
Portugal	—	7
USA	11	19
Ukraine	3–5	8–10

First of all, the inaccuracy of the data is due to significant divergence between the registered cases and the actual ones. So, if one relies on official information, the cases of allergic diseases in our country does not exceed 1.5 Percent, while according to the Institute of Immunology of Russia this figure reaches 30 Percent. Judging by the number of visits to medical institutions, no more than 0.4 Percent of the population suffers from allergic rhinitis, and only every 100 Russians suffer from asthma.

Until now, scientists can not come to a consensus on the true causes of allergies. However, it is known that almost anything can cause a reaction. And even such a common phenomenon as hay fever (an allergy to pollen of plants) is specific in each region of our country. Plant pollen is a strong allergen: sensitization to it is registered in 30-75 Percent of cases.

Therefore in the center of Russia allergic persons most often suffer when trees and cereals bloom; the residents of the Krasnodar and Stavropol Territories are most affected by ragweed; about 90 Percent of the population sneezes of wormwood in the Amur Region. In the Urals one in five complains about poor health when the first vegetation appears, in Vladivostok about 11 thousand people with allergies ask for medical help annually.

The following diagrams (Fig. 1, Fig. 2) show the dynamics of allergic diseases in the Kirov region for three population groups: children, teenagers and adults.

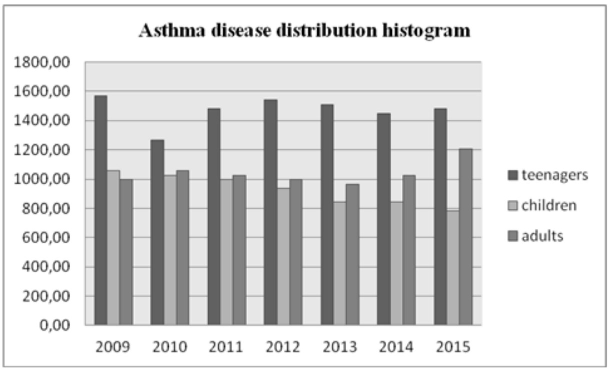

Fig. 1. Dynamics of asthma prevalence and asthmatic status among teenagers, children, adults of Kirov region for 2009-2015 (per 100 thousand of the corresponding population).

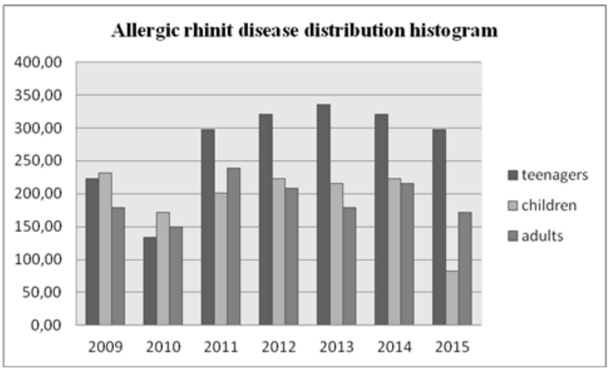

Fig. 2. Dynamics of allergic rhinitis prevalence among teenagers, children, adults of Kirov region for 2009-2015 (per 100 thousand of the corresponding population).

2. Morphology of a Pollen Allergy

Moreover, there are much fewer allergics among the villagers, while in Moscow every third suffers from hay fever, in Berlin - every fourth, in New York - every sixth. The reason is that allergies are caused not so much by the plants themselves as their pollen, which absorbs all the harmful emissions and polluting particles that are presented in catastrophic amounts in the air of the metropolis. A sharp increase in the number of AD occurs in April-May in conditions of central Russia, when the flowering of alder, birch, willow, maple and poplar begins. During this period, pollen calendars are formed for most large cities, patterns of pollen content of certain plant species in the atmosphere are investigated, the influence of meteorological factors is determined, a network of permanently operating stations for monitoring pollen is created . [3,4]

The most informative service for users is special sites, [3] however, these sites do not function regularly and not for all regions. The well-known information search engine Yandex publishes daily a map of the distribution of pollen emissions of various origin in the vicinity of large cities. Yandex.Pogoda forms a special map for those persons who are allergic to pollen. It shows the concentration of pollen of 15 common allergen plants (from ragweed to ash) in the air. The hazard level is indicated by color: yellow - low concentration, orange - medium, red - high. The gray color of the map indicates that dangerous plants in the region have not yet bloomed. The map covers the European part of Russia, Moldova, as well as certain regions of Belarus, Ukraine and Kazakhstan.

People who are allergic to pollen usually use plant flowering tables. They, however, provide only approximate data. Plants dont bloom strictly according to the calendar, but when appropriate conditions take place. The birch catkins began to intensively secrete pollen while a positive temperature is established it happens in different years at different times.

Flowering time also depends on the region: earlier in the south, later in the north. The map contains data for 15 common allergen plants: ragweed, birch, elm, oak, spruce, cereals, willow, maple, nettle, alder, hazel, wormwood, weed grass, pine and ash.

However, these distributions are not confirmed numerical parameters and can be considered as illustrative material of possible occurrences of aerosol pollen components. An important factor in assessing the degree of pollution of aerosol pollen is the knowledge of the physical parameters during the transfer of pollen. Data on the mass proportion of grains of various tree species and the procedure of measuring them are given in Ref. [5]. Table 2 shows the data on the distribution of masses of grains and the corresponding proportion of the main tree species for the European part of Russia.

One can see that the presented data are grouped by grain weight in three main groups: heavy (spruce, fir, pine), medium (linden, oak, maple, elm) and light (aspen, birch, alder, poplar, willow). Taking into account the presented data, attention should be paid to the fact that the mass of allergenic pollen grains has the greatest influence in the transfer processes and this is a group of light fractions. It is the group that represents the most dangerous impact on the development of AD in large cities.

The statement of the problem of the transfer of pollutants in the form of bioaerosol components involves the use of a sequence of mathematical models built on the principle of "from simple to complex." This sequence is determined by the choice of modeling scale.

If we define a certain, rather small neighborhood of the impurity distribution

Table 2. Pollen graines parameters of various wood species

Wood species	**Mass of grains, ng**	**Percent in distribution**
Fir	82,4	0,06
Spruce	63,1	0,24
Pine	15,5	0,18
Linden, oak, maple, elm	10,7	0,02
Aspen	4	0,1
Birch	3,9	0,26
Alder	3,5	0,09
Poplar	3,5	0,03
Willow	2,5	0,02

region over a finite period of time, then it is quite reasonable to use simplified (including stationary) models that allow exact solutions. But it is necessary to take into account the complex dynamics of the velocity and temperature fields, surface inhomogeneity and boundary conditions in the case of problems with extended geometry or with sufficiently powerful pollutant sources, for example, when estimating emissions from large industrial enterprises. In Refs. [6,7], mesoscale models of the bioaerosol components transport are considered both for individual types of plant pollen (Ref. [6]) and in the aggregate of inert impurities (Ref. [7]). The equations of momentum, temperature, impurities and moisture transfer are used for calculations. In Ref. [8] the mesoscale model of the surface layer is used to calculate transfer of fungal mold and estimate its interaction with atmospheric flow moisture. This work presents a mesoscale quasi-two-dimensional model of the transfer of pollen grains of various fractions, which are the most common types of plant aerosol allergens: birch, alder, poplar, maple, willow on a micro- and mesoscale. [9] A finite-difference explicit calculation method was used for numerical implementation.

The construction of a parallel version of the calculation algorithm was based on the principle of geometric decomposition of the grid domain.

3. Math Model of Problem

We will consider the lower-atmosphere boundary layer restricting ourselves to mesoscale processes for which the layer height D and the horizontal scale L satisfy the relation is much less then 1. We will take the three-dimensional equations of the hydrothermodynamics of dry atmosphere in a rotating Cartesian coordinate system as the original equations [2]

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{\partial \Phi}{\partial x} + lv + A_M \Delta u + \frac{\partial}{\partial z} k_M \frac{\partial u}{\partial z} \qquad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{\partial \Phi}{\partial y} - lu + A_M \Delta v + \frac{\partial}{\partial z} k_M \frac{\partial v}{\partial z} \quad (2)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial \Phi}{\partial z} + \beta\theta + A_M \Delta w + \frac{\partial}{\partial z} k_M \frac{\partial w}{\partial z} \quad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (4)$$

$$\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y} + w\frac{\partial \theta}{\partial z} = A_T \Delta \theta + \frac{\partial}{\partial z} k_T \frac{\partial \theta}{\partial z} \quad (5)$$

$$\frac{\partial \varphi}{\partial t} + u\frac{\partial \varphi}{\partial x} + v\frac{\partial \varphi}{\partial y} + w\frac{\partial \varphi}{\partial z} + \sigma\varphi = A_S \Delta \varphi + k_S \frac{\partial^2 \varphi}{\partial z^2} \quad (6)$$

The initial and boundary conditions are as follows:

$$u = -c_g \sin(dd), \quad v = -c_g \cos(dd), \quad \theta = \theta_S, \quad \varphi = 0 \qquad t = 0 \quad (7)$$

$$\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = w = 0, \quad \frac{\partial \theta}{\partial z} = 0, \quad \frac{\partial \varphi}{\partial z} = 0 \qquad z = D \quad (8)$$

$$u = v = w = 0, \quad \frac{\partial \theta}{\partial z} = \gamma(\theta - \theta_S), \quad \frac{\partial \varphi}{\partial z} = \alpha\varphi - f_S \qquad z = 0 \quad (9)$$

In Eqs. (1–9) t is time, Δ is the Laplace operator, Ox, Oy, and Oz are the eastward, northward, and upward coordinate axes, (u, v, w) is the air flow velocity vector, $\Phi = RT_m p'/p$ is the geopotential fluctuation, where R is the specific gas constant and T_m is the mean air temperature in the layer, p is the atmospheric pressure, $p' = p - p_0$, where p is the potential pressure dependent only on the altitude, l is the Coriolis parameter, $\beta = \frac{g}{\theta}$ is the buoyancy parameter, $\theta = T\frac{p_0}{p}^{\frac{R}{C_p}}$ is the potential temperature, where T is the air temperature, p_0 is the atmospheric pressure near the ground, and C_p is the specific heat at a constant pressure; φ is the impurity concentration, σ is the impurity absorption coefficient in the atmosphere, θ_S is the air temperature at the roughness level of the underlying surface, c_g is the geostrophic wind velocity [11] at the upper free boundary of the atmospheric boundary layer, dd is the geostrophic wind azimuth, γ is the heat transfer coefficient, α is the coefficient of impurity absorption by the underlying surface, A_M,A_T, A_S, k_M, k_T, k_S are coefficients of gorizontal and vertical turbulent diffusion and $f_S = \sum_{i=1}^{m} f_i \delta(x - x_i)\delta(y - y_i)$ -intensity of sources of impurity, x_i and y_i are coordinates of sources, m - number of sources.

We will consider an $L \times L$ area. The geostrophic wind velocity c_g above the atmospheric boundary layer and its direction, as well as the boundary layer height D, are assumed to be known. The horizontal wind velocity fields are calculated from the formulae [11] $u = -c_g \sin(dd)$ and $v = -c_g \cos(dd)$, where $dd = 0$ corresponds to the north wind and $dd = \pi/2$ to the east wind. The wind can also be preassigned as the layer-average velocity field (mean across the layer). At the lateral boundaries it is assumed that

$$\frac{\partial \mathbf{v}}{\partial n} = 0, \quad \frac{\partial \theta}{\partial n} = 0, \quad \frac{\partial \varphi}{\partial n} = 0 \quad (10)$$

n is vector of external normal. For math modelling of the impurity transport from a ground source we will introduce a quasi-twodimensional model based on the locally-equilibrium approach. This technique was presented in Refs. [9,10,12,13]. Restricting our consideration to mesoscale processes we will assume that $t \gg t_r$ where t is the characteristic time of equilibrium states and t_r is the time of air flow relaxation to the equilibrium state when the external conditions are varied. We will introduce the dimensionless variable $\zeta = z/D$, denote the layer-average quantity as

$$\langle g \rangle = \int_0^1 g(t, x, y, \zeta)\, d\zeta \tag{11}$$

and integrate Eqs. (1–6) using the boundary conditions Eqs. (7–10). Then, with account for the condition of air incompressibility in the lower atmosphere we obtain

$$\frac{\partial \langle u \rangle}{\partial t} + \frac{\partial \langle uu \rangle}{\partial x} + \frac{\partial \langle uv \rangle}{\partial y} = -\frac{\partial \langle \Phi \rangle}{\partial x} + l\langle v \rangle + A_M \Delta \langle u \rangle + \frac{k_M}{D^2} \frac{\partial u}{\partial \zeta}\Big|_{\zeta=0}^{\zeta=1} \tag{12}$$

$$\frac{\partial \langle v \rangle}{\partial t} + \frac{\partial \langle uv \rangle}{\partial x} + \frac{\partial \langle vv \rangle}{\partial y} = -\frac{\partial \langle \Phi \rangle}{\partial y} - l\langle u \rangle + A_M \Delta \langle v \rangle + \frac{k_M}{D^2} \frac{\partial v}{\partial \zeta}\Big|_{\zeta=0}^{\zeta=1} \tag{13}$$

$$\frac{\partial \langle \theta \rangle}{\partial t} + \frac{\partial \langle u\theta \rangle}{\partial x} + \frac{\partial \langle v\theta \rangle}{\partial y} = A_T \Delta \langle \theta \rangle - \frac{\gamma k_T}{D} (\theta|_{\zeta=0} - \theta_S) \tag{14}$$

$$\frac{\partial \langle \varphi \rangle}{\partial t} + \frac{\partial \langle u\varphi \rangle}{\partial x} + \frac{\partial \langle v\varphi \rangle}{\partial y} + \sigma \langle \varphi \rangle = A_S \Delta \langle \varphi \rangle - \frac{k_S}{D} (\alpha\varphi|_{\zeta=0} - f_S) \tag{15}$$

To close the system of equations Eqs. (12–15) it is necessary to express $\langle uu \rangle$, $\langle uv \rangle$, $\langle vv \rangle$, $\langle u\theta \rangle$, $\langle v\theta \rangle$, $\langle u\varphi \rangle$, $\langle v\varphi \rangle$, $\frac{\partial u}{\partial \zeta}\Big|_{\zeta=0}^{\zeta=1}$ $\langle v\varphi \rangle$, $\frac{\partial v}{\partial \zeta}\Big|_{\zeta=0}^{\zeta=1}$, $\theta|_{\zeta=0}$, and $\varphi|_{\zeta=0}$ in terms of the layer-average impurity concentration $\langle \varphi \rangle$ and the mean velocity $\langle u \rangle$ and $\langle v \rangle$ and temperature $\langle \theta \rangle$ fields. For this purpose we will use the exact solution of the original problem which can be obtained for a linear air temperature distribution at the roughnesslevel of the underlying surface. We will seek the solution in the form: $u = u(\zeta)$, $v = v(\zeta)$, $w = 0$, $\theta = \theta_S + \theta(\zeta)$, and $\varphi = \varphi(\zeta)$. Then problem Eqs. (1–6, 8–10) becomes a linear boundary value problem for ordinary differential equations with constant coefficients. Its solution gives the following representation for the velocity

$$M(\zeta) = f_1(\zeta)\langle M \rangle - 2 f_2(\zeta) U \tag{16}$$

where

$$f_1 = \frac{1}{1 - \tanh(\lambda)/\lambda} \Big[1 - \frac{\cosh(\lambda(\zeta))}{\cosh(\lambda)} \Big], \tag{17}$$

$$f_2 = f_1(\zeta) \Big[\frac{\cosh(\lambda) - 1}{\lambda^2 \cosh(\lambda)} \Big] - \frac{\sinh(\lambda\zeta)}{\lambda \cosh(\lambda)} + \zeta. \tag{18}$$

The mean values of these function $\langle f_1 \rangle = 1$ and $\langle f_2 \rangle = 0$. Here, $\lambda = (1+i)/\sqrt{2Ek}$ is a parameter dependent on the Ekman number $Ek = k_M/lD^2$, $M(\zeta) = u(\zeta) +$

$iv(\zeta)$, $U = u_x + iv_y$, $U_x = -\beta D \frac{\partial\langle\theta\rangle}{\partial y}$, $U_y = \beta D \frac{\partial\langle\theta\rangle}{\partial x}$, $i = \sqrt{-1}$. The subscripts denote the partial derivatives with respect to x and y, respectively. We will assume that the potential temperature $\theta = \langle\theta\rangle$.

$$\varphi = \langle\varphi\rangle + \frac{f_S D}{\alpha D \cosh(S) + S \sinh(S)} \Big[\cosh(S(1-\zeta)) - \frac{\sinh(S)}{S}\Big], \tag{19}$$

where $S^2 = (\sigma D^2)/k_S$ is dimensionless parameter.

In Refs. [7,8] similar solutions are called locally-equilibrium. Assuming that, provided conditions Eq. (1) and Eq. (12) are fulfilled, formulae Eq. (16)–(21) fairly adequately (asymptotically correctly in the small parameter δ_1) describe the structure of a thermally nonuniform mesoscale air flow at each point of the layer and at each moment of time Ref. [13], we will use these conditions as the closing relations of system Eqs. (12–15). Applying the curl operation to Eq. (12) and Eq. (13) we arrive at an evolutionary equation for the vorticity

$$\omega(t, x, y) = \frac{\partial\langle v\rangle}{\partial x} - \frac{\partial\langle u\rangle}{\partial y} \tag{20}$$

Bearing in mind that the layer-average velocity is divergence-free,

$$\frac{\partial\langle u\rangle}{\partial x} + \frac{\partial\langle v\rangle}{\partial y} = 0,$$

we will introduce the stream function $\psi(t, x, y)$, such that

$$\langle u\rangle = -\frac{\partial\psi}{\partial y}, \quad \langle v\rangle = -\frac{\partial\psi}{\partial x} \tag{21}$$

$$\frac{\partial\omega}{\partial t} + k_1\{\psi,\omega\} + k_3 Rt[\{\theta,\omega\} + \{\psi,\Delta\theta\}] - k_5 Rt^2\{\theta,\Delta\theta\} = \frac{1}{Re}\Delta\omega - \mu(k_7\omega - k_8 Rt\Delta\theta) \tag{22}$$

$$\Delta\psi = \omega \tag{23}$$

$$\frac{\partial\theta}{\partial t} + \{\psi,\theta\} = \frac{1}{Pe}\Delta\theta - \bar{q}(\theta - \bar{\theta}_S) \tag{24}$$

$$\frac{\partial\varphi}{\partial t} + \{\psi,\varphi\} = \frac{1}{Pe_S}\Delta\varphi - \bar{\sigma}\varphi + A\sum_{i=1}^{m} \bar{f}_i \delta(x - x_i)\delta(y - y_i) \tag{25}$$

We will take the quantities L, c_g, L/c_g,$\theta_0 = \max\theta_S$, and φ_{MPC} (maximum permissible impurity concentration) as the length, velocity, time, temperature, and impurity concentration scales. Then in terms of the vorticity ω, the stream function ψ, the layer-average potential temperature taken in the units of the stream function, $\theta_*(t, x, y) = (\beta d)/(2l)\langle\theta\rangle$, and the layer -average concentration $\varphi_*(t, x, y) = \langle\varphi\rangle\varphi_{MPC}$ (for the brevity in what follows the symbols "*" will be omitted) the equation of the model describing the mesoscale processes in the lower atmosphere can be brought into the following dimensionless form.

Here, in Eqs. (22–25):

$$\{\psi,\omega\} = \frac{\partial\psi}{\partial x}\frac{\partial\omega}{\partial y} - \frac{\partial\psi}{\partial y}\frac{\partial\omega}{\partial x}$$

- is the Jacobian operator;

$$Rt = \frac{\beta D\theta_0}{2lc_g L}$$

- is the counterpart of the thermal Rossby number [12];

$$Re = \frac{c_g L}{A_T}$$

-is the Reynolds number;

$$\mu = \frac{lc_g}{L}$$

- is the dimensionless coefficient of the friction on the underlying surface,

$$Pe = \frac{c_g L}{A_T}$$

- is the Peclet number;

$$\bar{q} = qc_g/L$$

- is the dimensionless coefficient of cooling, where $q = \gamma_* k_T/D$;

$$Pe_S = \frac{c_g L}{A_S}$$

- is the solutal Peclet number;
$\bar{\sigma} = \sigma_1 L/c_g$ - is the dimensionless impurity absorption coefficient, where $\sigma_1 = \sigma + \alpha * k_S/D$;

$$\bar{f}'_S = \frac{f'_S k_S L}{\varphi_{MPC} c_g D};$$

$$A = 1 - \frac{\alpha D}{\alpha D \cosh(S) + S\sinh(S)}\Big(\cosh(S) - \frac{\sinh(S)}{S}\Big);$$

and $k_1 = \Re(\langle f_1 f_1\rangle)$, $k_3 = \Re(\langle f_1 f_2\rangle)$, $k_5 = \Re(\langle f_2 f_2\rangle)$, $k_7 = \Re(f'_1)$, $k_8 = \Re(f'_2)$ are the Ekman - number - dependent coefficients (here, $\Re$ is the real part of a number). In the case under consideration Ek= 1 and these coefficients are as follows: k1 = 1.199, k3 = 0.00077, k5 = 0.0005909, k7 = 3.0057, and k8 = 0.000952. In terms of the vorticity ω, the stream function ψ, and the reduced, layer-average potential temperature the initial and boundary conditions are brought into the form:

$$t = 0 : \psi = y\sin(dd) - x\cos(dd), \omega = 0, \theta = \theta_S, \phi = 0. \qquad (26)$$

$$\frac{\partial\psi}{\partial n} = 0, \omega = 0, \frac{\partial\theta}{\partial n} = 0, \frac{\partial\phi}{\partial n} = 0. \qquad (27)$$

4. Results of Modelling

The parallel computational algorithm was realized in the Intel Fortran 12 in Intel Cluster Studio Package for Linux , installed on the Vyatka State University HPC Enigma X000 cluster supercomputer. The calculations were carried out on the basis of the system of equations Eqs. (22–25) with the initial and boundary conditions Eqs. (26–27). The explicit difference scheme [16] was used on a 1000×1000 grid. In accordance with the theory of Monin and Obukhov [2,3,17], the coefficients of vertical and horizontal turbulent viscosity, thermal conductivity, and diffusion for mesoscale turbulent processes in the lower atmosphere were assumed the same, namely, $k_M, T, S = lD^2$, where $D = 400m$ and $A_M, T, S = 400m^2/s$.

In the reference frame chosen the westward wind was blowing from left to right. The wind velocity c_g was varied from 1 to 10 m/s. In most of calculations the velocity was 2-5 m/s; in this case, the temperature inhomogeneity effect on the wind flow in the vicinity of a heat source is most clearly expressed. The interaction between aerosol impurity and the underlying surface was taken into account on the basis of the information on the nonuniformities of the temperature and absorption coefficient distributions taken from the map of land utilization of the computation domain. The air temperature θ_S varied from 18° C outside populated areas to 23° C in the city of Kirov. A minimum temperature was observable at the north boundary of the area. The coefficient of impurity absorption by the underlying surface was taken to be $\alpha = 0.0139m^{-1}$ outside populated areas and $\alpha = 0.00139m^{-1}$ on their territories. A point impurity source was located on the underlying surface, at the center of the region under consideration (within the city territory). In the calculations it was also taken that $l = 1.2410^{-4}s^{-1}$, $\sigma = 5.6710^{-8}s^{-1}$, $\gamma = 0.2510^{-3}m^{-1}$, $f_S = 0.999610^{-7}kg/m^4$, and $\varphi_{MPC} = 0.510^{-7}kg/m^3$.

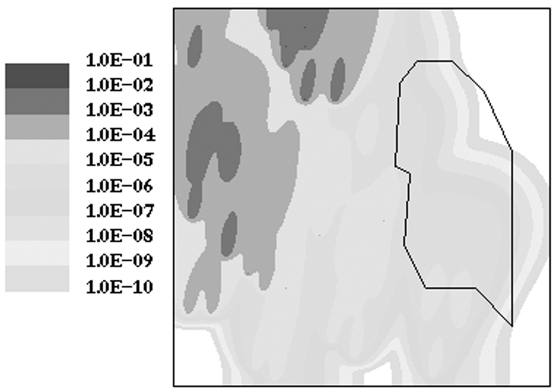

Fig. 3. The 20-km zone near Kirov city, wind from south

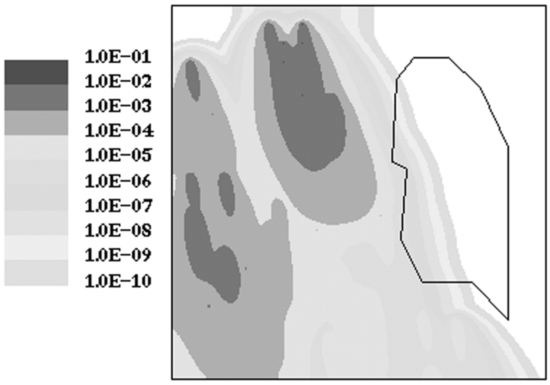

Fig. 4. The 20-km zone near Kirov city, wind from north

The results of calculations of pollen concentration distribution with some wind directions are presented on Fig. 3 – Fig. 4.

References

1. Pukhlik BM, *Pollinoz [In Russian]*, Vinnitsa, 2017.
2. Golovko VV, Kutsenogiy PK, Kirov EI, Istomin VL, Ryzhakov VA, Pollen components of atmospheric aerosols the neighborhood of Novosibirsk [In Russian], *Optic of Atmosphere and Ocean*, **6**: 645–649, 1998.
3. Starchenko AV, Modelling of transfer of aerosol impurity in the city scale, *II International conference "Climatology and Glatiology of Siberia"*, Tomsk, 2015.
4. Belov PN, Shcherbakov AYu, Numerical Modeling of the Diurnal Course of Meteorological Elements in a Large City, *Meteorol. Gidrol.*, **7**: 45, 1983.
5. Penenko VV, Aloyan AE, *Models and Methods for the Problems of Environmental Control [in Russian]*, Nauka, Novosibirsk, 1985.
6. Aloyan AE, *Dynamics and Kinematics of Gas Impurities and Aerosols in the Atmosphere. A Textbook [in Russian]*, Russian Academy of Sciences, Inst. Comput. Math., Moscow, 2002.
7. Kibel IA, Hydrodynamic Short-Term Forecasts in the Problems of Meteorology, *Tr. Gidrometeotsentr SSSR*, 48, 3, 1970.
8. Veltishcheva NS, Three-Dimensional Nonhydrostatic Model Describing Circulation over an Urban Heat Island, *Tr. Gidrometeotsentr SSSR*, 219, 66, 1979.
9. Tarnopolskii AG, Shnaidman VA, Modeling the Atmospheric Boundary Layer for an Urban Built-up Area and a Suburban Zone, *Meteorol. Gidrol.* **1**: 41, 1991.
10. Aristov SN, Frik PG, *Dynamics of Large-Scale Flows in Thin Fluid Layers, Preprint [in Russian]*, Ural Division of the Russian Academy of Sciences, Inst. of Continuum Mechanics, Perm, Russia, 1987.
11. Aristov SM, Frik PG, Large-Scale Turbulence in a Thin Layer of Nonisothermal Rotating Fluid, *Fluid Dynamics*, **23**(4): 522, 1988.
12. Shvarts KG, Shklyaev VA, Modeling Impurity Transport Processes in the Free At-

mosphere on the Basis of a Quasi-Three-DimensionalModel, *Meteorol. Gidrol.*, **8**: 44, 2000.

13. Shvarts KG, Shklyaev VA, Numerical Modeling of Mesoscale Vortex Structures near an Intense Hot Impurity Source in the Atmospheric Boundary Layer, *Vych. Mekh. Sploshnykh Sred*, **1**: 96, 2009.
14. Gill AE, *Atmosphere-Ocean Dynamics*, Acad. Press, San Diego & London, 1982.
15. Schwarz KG, *Mesa-Scale Flows over Large City,* eds. Branover H, Unger Y, Progress in Fluid Flow Research: Turbulence and Applied MHD, AIAA Progr. Ser. 182, p. 271, 1998.
16. Shvarts KG, *Models of Geophysical Hydrodynamics. A Textbook [in Russian]*, Perm Univ. Press, Perm, 2006.
17. Rychkov SL, Shatrov AV, Shvarts KG, Mathematical Modeling of Aerosol Transport in the Atmosphere, *Proc. All-Russian Sci. Conf. Environment and Stable Development of Regions: New Research Methods and Technologies. Vol. III. Modeling in the Environmental Control. General Ecology and Control of Biovariety [in Russian]*, Kazan, Russia, p. 84, 2009.
18. Shvarts KG, Shatrov AV, Simulation of Aerosol Impurity in a Ground Boundary Layer above Industrial Center, *Europ. Aerosol Conf. 2009*, Karlsruhe, Germany, Abstract T031AD1, 2009.
19. Naumovich TV, Rychkov SL, Shatrov AV, Shvarts KG, Software Complex for Modeling the Biotechnological Impurity Transport in the Ground Layer in the City of Kirov, *Proc. of the IV All-Russian Sci. Conf. on Math. Modeling of the Developing Economics and Ecology EKOMOD-2009 [in Russian]*, Kirov, Russia, p. 256, 2009.
20. Monin AS, *Theoretical Fundamentals of Geophysical Hydrodynamics [in Russian]*, Gidrometeoizdat, Leningrad, 1988.
21. Belov PN, Borisenkov EP, Panin BD, *Numerical Methods of Weather Forecast. [In Russin]*, Gidrometeoizdat, Leningrad, 1989.
22. Kutsenko BYa, Mukhin SP, Numerical Study of Local Atmospheric Processes on Inhomogeneity Underling Surface, *Meteorol. Gidrol.*, **10**: 29–36, 1991.
23. Alishaev DM, Dynamics of Two-dimensional Hydrodynamic Model of Baroclinic Atmosphere [in Russian], *Izv. AS USSR. Phys. Atm. and Ocean* **16**(2): 99-107, 1980.
24. Matveev LN, Soldatenko SA, Two-dimensional Hydrodynamic Model of Processes of Vortex Formation in Baroclinic Atmosphere [in Russian] , *Izv. AS USSR. Phys. Atm. and Ocean* **30**(4): 437-442, 1994.
25. Shvarts KG, Shklyaev VA, *Mathematical Modeling of Mesoscale and Largescale Processes of Transport in Baroclinic Atmosphere*, Institute of Computing Research, Moscow-Izhevsk, 2015.
26. Shatrov AV, Shvarts KG, Numerical Modeling of Mesoscale Atmospheric Impurity Transport Processes in the Environs of the City of Kirov, *Fluid Dynamics* **46**(2): 333–340, 2011.
27. Shvarts KG, Shklyaev VA, Numerical Modeling of Mesoscale Processes for Transport of Multicomponent Impurity from Peat Fire [in Russian], *Vych. Mekh. Sploshnykh Sred* **5**(3): 274–283, 2012. http://dx.doi.org/10.7242/1999-6691/2012.5.3.32
28. Shvarts KG, Shvarts YuA, Shklyaev VA, Two-dimensional Model of Mesoscale Processes in the Lower Atmosphere with Allowance for Ingomogeneity of Temperature and Air Humidity [in Russian], *Vych. Mekh. Sploshnykh Sred* **8**(3): 5–15, 2015. http://dx.doi.org/10.7242/1999-6691/2015.8.1.1