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Simulation of dust convective transfer of Zestafoni ferroalloy plant

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A B S T R A C T

Kinematics of aerosols propagation emitted into the atmosphere from aeration lanterns of gas-trapping units of workshops No. 1 and No. 4 of Georgian Manganese LLC is studied using numerical integration of the system of three-dimensional non-linear non-quazistatic equations of thermal convection and admixture transfer-diffusion in the atmosphere. It is obtained through modeling that a kinematics of dust propagation emitted into the atmosphere significantly differs from each other in cases of calm air and background motions. During calm air a dust propagation is caused by a wind velocity field generated as a result of thermal convection. At this time wind velocity convergence zone is formed in the vicinity of aeration lanterns. This zone is gradually getting smaller with height increase and turns into divergence zone in the upper part of the surface layer of the atmosphere. Ascending convective air and dust stream is obtained above each source. Vertical velocity formed as a result of convection process reaches 5 m/s. Horizontal components of wind velocity in divergence and convergence zones don't exceed 3 m/s. In case of background wind a dust is propagated as a result of both ordered (vented) horizontal and vertical streams, and small-scale vortex and diffusive motions. Advective, convective and turbulent dust diffusion under the influence of background motions forms the vertically inclined trail-like pollution zone. There is no place of vortex motion in the obtained zone.

Keywords: Atmosphere, Dust, Pollution, Simulation, Convection, Stationary sources

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Introduction

Modeling of atmospheric air anthropogenic polluton in the industrial centers, study of peculiarities of its spatial and time distribution is one of the topical problems related to human health and environment protection. Polluting sources are numerous, their origination sources [1], transformation kinematics and propagation dynamics [2] are diverse. Respectively, the mathematical models describing wide range of the problem from local one to global-scale processes are multifarious, as well [3-5]. One of the research directions is a propagation of polluting ingredients from separate sources at the territories of local scale. Mathematical systems describing local propagation of ingredients, use semi-empirical methods, stationary or non-stationary Gaussian models or rest on numerical integration of Navier-Stocks's nonstationary nonlinear nonstatic equations on the high-definition numerical grid.

Empirical system of atmosphere pollution estimation became widely used in Georgia and post-Soviet countries [6,7]. It is used for assessment of environment pollution extreme level, maximum permissible exhausts and common pattern of contamination and doesn't reflect the local features of pollutions caused by separate sources.

The goal of the presented work is the development of a numerical model of transfer-diffusion of substances emitted from separate sources (on a grid with high-definition (1-100m) ability) on the basis of thermal convection equations and study by its means of local peculiarities of dust propagation emitted in an orderly way into the atmosphere from Georgian Manganese LLC ferroalloy plant.

Research methods and ways of solution

System of equations of hydrothermodynamics, describing the propagation of meso-scale (≈1 km) atmospheric processes and agents emitted from separate sources into a dry atmosphere, can be written as follows [8, 9]:

$$\frac{du'}{dt} = -\frac{\bar{p}}{\bar{\rho}}\frac{\partial \varphi'}{\partial x} + l_z v' - l_y w' + \mu\Delta u' + \frac{\partial}{\partial z}\nu\frac{\partial u'}{\partial z},$$

$$\frac{dv'}{dt} = -\frac{\bar{p}}{\bar{\rho}}\frac{\partial \varphi'}{\partial y} - l_z u' + \mu\Delta v' + \frac{\partial}{\partial \zeta}\nu\frac{\partial v}{\partial \zeta},$$

$$\frac{dw'}{dt} = -\frac{\bar{p}}{\bar{\rho}}\frac{\partial \varphi'}{\partial z} + g\vartheta' + l_y u' + \mu\Delta w' + \frac{\partial}{\partial z}\nu\frac{\partial w'}{\partial z},$$

$$\frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} + \frac{\partial w'}{\partial \zeta} = 0,$$

$$\frac{d\vartheta'}{dt} + Sw = \mu\Delta\vartheta' + \frac{\partial}{\partial z}\nu\frac{\partial \vartheta'}{\partial z}$$

$$\frac{dC'}{dt} - w_c\frac{\partial C}{\partial z} = \mu\Delta C' + \frac{\partial}{\partial z}\nu\frac{\partial C'}{\partial z},$$

Operators $\frac{d}{dt} = \frac{\partial}{\partial t} + div(V\cdot),\ \Delta = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2},$

(1)

where t – time, x, y and z – coordinates of axes directed to the east, north and upward vertically, p – pressure, ρ *- density, T – temperature, V – wind velocity vector, which components along x, y and z axes are u, v, and w.*

Meteorological figures are presented in the form of the sum of standard, background values and deviations from background values:

$$p = \bar{p} + \tilde{p} + p',\quad \rho = \bar{\rho} + \rho',\quad T = \bar{T} - \gamma z + \tilde{T} + T',$$

$$C = \tilde{C} + C',\ u = \tilde{u} + u',\ v = \tilde{v} + v',\ w = \tilde{w} + w'.$$

A line "¯" means that a physical value corresponds with standard atmosphere, undulating line "~" reflects a corresponding (background) value of large-scale atmospheric process, while dash line " ′ " shows that a physical value presents deviation from background value and characterizes local atmospheric processes, at that

$$\frac{p'}{\bar{p}} << 1,\ \tilde{\varphi} = \frac{\tilde{p}}{\bar{p}} << 1,\ \varphi' = \frac{p'}{\bar{p}} << 1\ \frac{\rho'}{\bar{\rho}} << 1,\ \tilde{\vartheta} = \frac{\tilde{T}}{\bar{T}} << 1,\ \vartheta' = \frac{T'}{\bar{T}} << 1.$$

$$\varphi' - \vartheta' = \frac{\rho'}{\bar{\rho}},\ \bar{p} = \bar{p}(z),\ S = (\gamma_a - \gamma)/\bar{T},\ \bar{T} = 300K.$$

γ_a is a dry-adiabatic gradient of temperature, γ – vertical gradient of background atmospheric temperature. μ and l_y are kinematic coefficients of horizontal and vertical turbulence, l_y and l_z – y and z components of Coriolis parameter.

The equation system is taken on the assumption that background wind velocities satisfy the geostrophic wind equations and we can neglect in the first approximation their horizontal and vertical changes in the local area: $\tilde{u} = const$, $\tilde{v} = const$, $\tilde{w} = 0$. The system (1) is defined in the time interval 0≤t≤T and spatial area $\omega\{0 \le x \le X\ 0 \le y \le Y\ 0 \le z \le Z\}$. Let's attach initial

$$u' = v' = w' = \vartheta' = C' = 0 \text{ when } (x,y,z) \notin \Omega_1 \text{ and } t = 0,$$
$$u' = v' = 0, w' = w_0, \vartheta' = \vartheta_0,\ C' = C_0 \text{ when } (x,y,z) \in \Omega_1 \text{ and } t = 0$$

(2)

$$(u', v', w', \vartheta', \varphi', C')_{x=0} = (u', v', w', \vartheta', \varphi', C')_{x=X},$$

$$(u', v', w', \vartheta', \varphi', C')_{y=0} = (u', v', w', \vartheta', \varphi', C')_{y=Y} \quad (3)$$

$$(u', v', w', C')_{z=0} = (u', v', \vartheta', \varphi', C')_{z=Z} = 0,$$

$$\vartheta' = \vartheta'_0,\ w' = w_0,\ C' = C_0\ (x,y,z) \text{ when } (x,y,z) \in \Omega_1,$$

to the system (1) Ω_1 where is the area of dust atmospheric emission; $\vartheta_0(x,y,z)$, $w_0(x,y,z)$ and $C_0(x,y,z)$ are the temperature analogue, emission rate and dust concentration of the gas discharged into the emission area, respectively.

The system of equations (1) with conditions (2) and (3) is integrated according to implicit and explicit numerical scheme [8,9]. They are implemented on the numerical grid consisting of 81x81x51 points. Grid steps along x and y axes are 20 m, along z axis – 10m, and time step is 0,2 s.

Integration domain sizes are 1600 m x 1600 m x 500 m. The main facilities of Georgian Manganese LLC, from which the ordered emission of solid aerosols into the atmosphere occurs, are placed in this area. Fugitive emission of aerosols is not considered during modeling process. Aerosols size is taken as 10 μ. Their deposition rate is w_c =0,01 m/s.

According to the data obtained from Georgian Manganese LLC, solid aerosols are emitted from two main facilities of the enterprise, namely, from aeration lanterns of waste treatment facilities of workshops No. 1 and No. 4 equipped with hose filters. Basic characteristic values of emitted manganese dioxide are given in Table.

Table. *Basic characteristic parameters of dust emitted into the atmosphere and of its sources*

N	Height H (m)	Area S (m^2)	Gas-and-dust mixture temperature, T_0' (°C)	Emission rate W_0 (m/s)	Concentration C_0 (mg/m^3)
Workshop No. 1	22	110	50	1	1,8
Workshop No. 4	42	440	31-63	1	5,4

Analysis of obtained results

Kinematics of dust emission into the atmosphere from two main sources of the ordered emission (workshops No. 1 and No. 4) of Georgian Manganese LLC (ferroalloy plant, Zestafoni) is studied through numerical experiments. Modeling was made for two meteorological situations: calm air and north-west wind, when wind velocity increases from 0 to 10 m/s, at 500 m height from the ground. In case of this direction a dust propagation emitted from both sources along one straight line and superposition of concentrations take place. Numerical modeling is conducted from the beginning of dust emission into the atmosphere to establishment of its quazi-stationary distribution – roughly within 0.5 hour.

Experiment I. Spatial distribution of dust concentration obtained through calculations during background calm air, when thermal convection is the main mechanism of dust propagationis is shown in Fig. 1 and 2. Concentration isolines are shown in the units of maximum permissible concentration (MPC = 0.5 mg/m^3). It is seen from this figure that after emission from gas-cleaning systems a dust is propagated in the atmosphere in the form of two vertical cylindrical streams independent from each other.

The basic dust mass (with concentration >0.1MPC) is distributed in the narrow area, which is getting wider and unites (gets together) approx. at 200-350 m height. Cylindrical column spread angle varies within the limits of 5-45°. At the higher levels a dust pollution cloud is of "mushroom"-like shape that is caused by origination of vertical vortex in the process of convection.

Concentration > 3 MPC is obtained directly above the emission site in 100-meter column. Concentration value 0.01-0.1 MPC is obtained at the significant territory of modeling area, at 10, 50m from the Earth surface and higher., We got low dust concentration 0.5-0.01 MPC close to the Earth surface, within 10 meters, around the waste treatment facilities of the workshop No. 1. In the vicinity of relatively higher waste treatment facilities of the workshop No. 4, dust concentration 0.1-0.01 MPC is obtained at substantially smaller area.

Spatial pattern of concentrations obtained through calculations is formed by velocity distribution peculiar for thermal convection (Fig. 2 and 3).

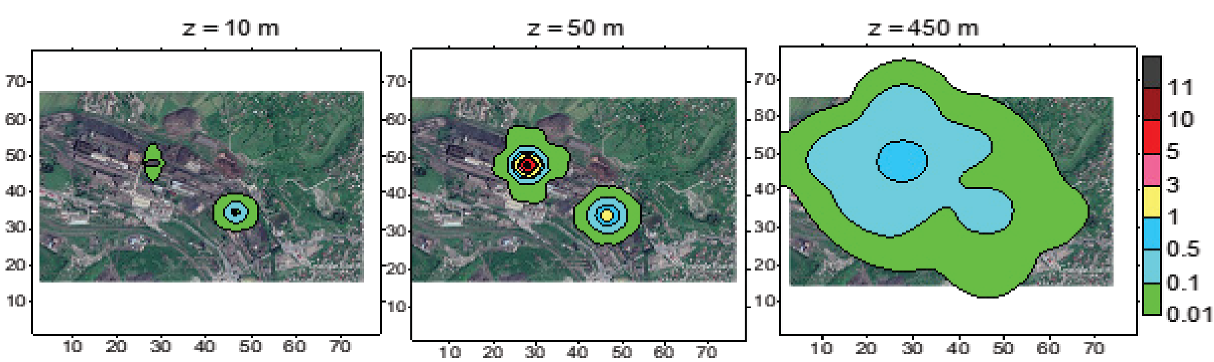

Fig. 1. *Dust concentration isolines in the atmosphere during calm air at 10, 50 and 450 m altitudes*

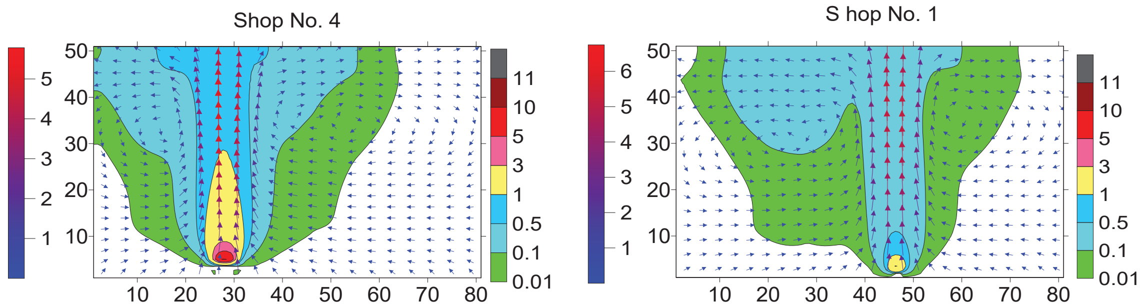

Fig. 2. *Dust concentration isolines and wind velocity vector projections in XOZ planes passing through treatment facilities*

It is seen from the figures that the emitted warm gas-and-dust mass causes development of thermal convection. Formation of a powerful vertical stream is peculiar for it. Clearly defined convergent zone is formed in the 350m thick stream layer, and intensification of vertical motion and dust transfer to the upper layer take place. Above 350 m air convergent stream gradually turns into divergent one, vertical velocity is getting smaller, wind is increased in horizontal direction and dust horizontal diffusion process is getting more intense. In the middle part of the modeling horizontal and vertical vortexes of wind velocity are formed, the unity of which creates a complex pattern of spatial annular stream. The maximum value of wind velocity 6 m/s is obtained in the convectional vertical stream.

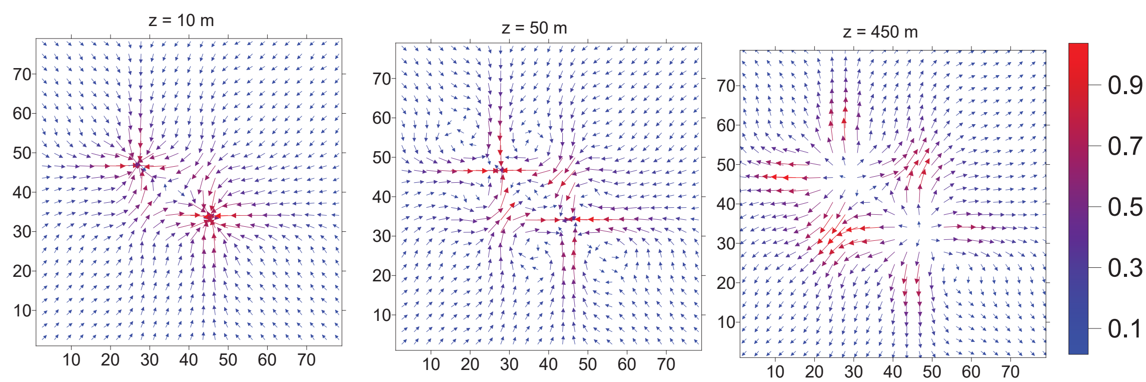

Fig. 3. *Dust concentration isolines and wind velocity vector projections in XOZ planes passing through treatment facilities*

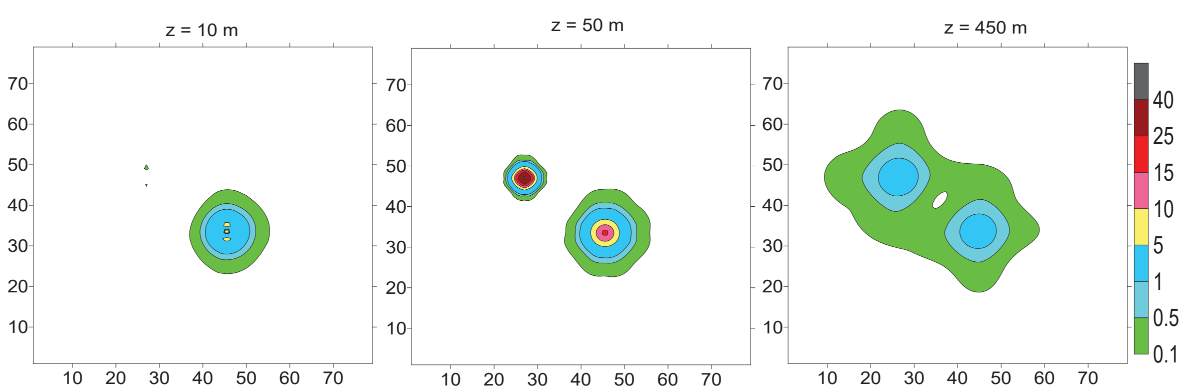

Fig. 3. *Temperature perturbation field at 10, 50 and 450 m altitudes resulted from convection*

Motion kinematics shows that a dust propagation in the central part of the modeling area occurs resulting from convective, advective, vortex processes and turbulent diffusion. The contribution of convective transfer and vertical turbulent diffusion in the vertical plane is roughly the same. In the horizontal plane a vortex turbulent diffusion prevails compared to an advective transfer. Gas emitted from waste treatment facilities changes atmosphere temperature in the vertical cylindrical area located near to the source (Fig. 4). Temperature change is minimal close to the earth and maximal in the vicinity of aeration lanterns. Warm air column penetrates through the space up to its upper limit. At the 450 m height a maximum value of ambient temperature perturbation reaches 5°C.

Experiment 2. Dust propagation emitted into the atmosphere from workshops No. 1 and No. 4 of the plant is modeled in case of north-west wind.

In Fig. 5 and 6 there is shown the dust concentration distribution at 10, 50 and 450 m altitudes. It is seen from the figures that a dust is transferred in south-east direction. In addition to the transfer, dust stream is getting wider and takes different shapes. Near the earth surface a pollution zone is located in the vicinity of aeration lanterns. Concentration value is small there and varies within a range of 0.01-0.5 MPC. Roughly at the 300 m distance from emission site, at 450 m height concentration reaches 0.5 MPC. At 50 m height a pollution cloud is of rectangular-like shape. Concentration maximums are located directly in the vicinity of emission site and are getting smaller both in the background wind direction and its perpendicular direction. The pattern different from classic dust propagation [11] is obtained in the central part of its stream at 50 m height, where a total concentration value created by both sources is equal to zero. The achieved effect is caused by the local ascendant motion generated during convective dust transfer (Fig. 6 and 7).

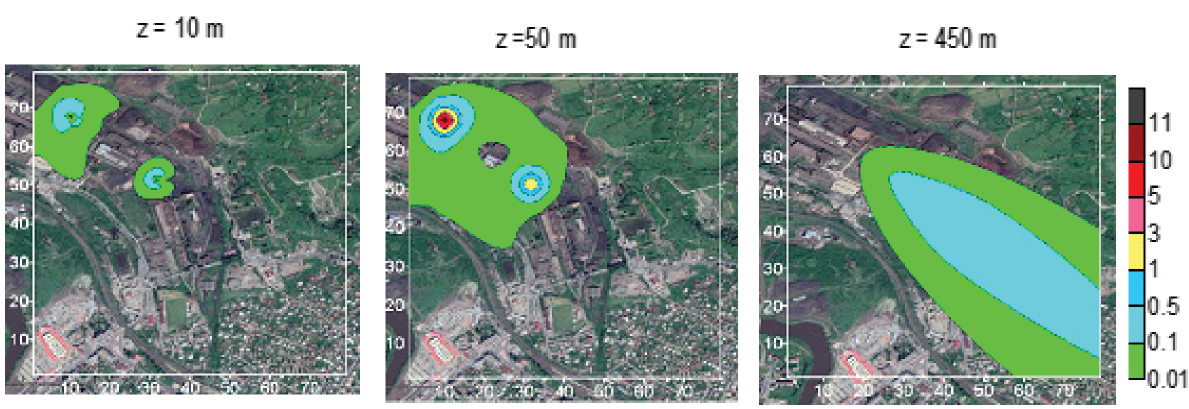

Fig. 5. *Dust atmospheric concentration isolines in the XOY plane at 10, 50 and 450m altitudes during background north-east wind*

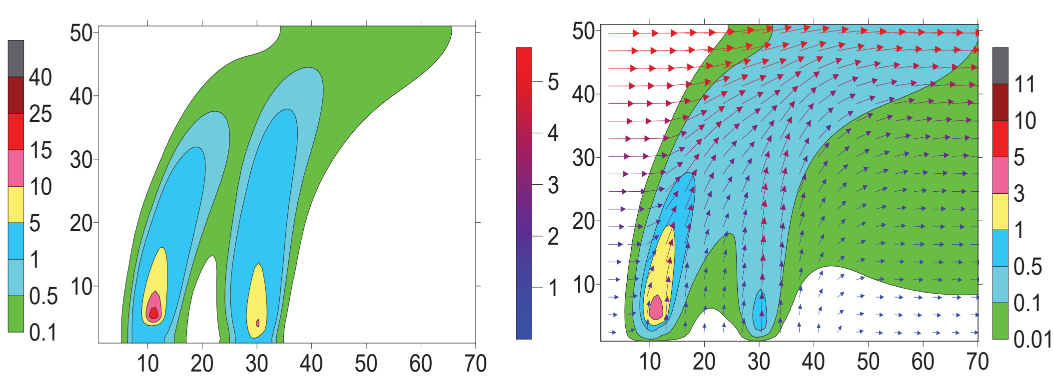

Fig. 6. *Distribution of temperature perturbation and dust concentration isolines, and wind velocity vector distribution along the vertical XOZ section directed along the background wind and passing through aeration lanterns of workshops No. 1 and No. 4*

It is seen from Fig. 6 and 7 that the development of thermal convection that is accompanied by warm gas-and-dust mass emission into the atmosphere, forms the horizontal convergent zone of wind velocity (Fig. 7) and powerful ascendant motion from the leeward side of emission (Fig. 6). Ascendant motion velocity significantly exceeds dust particle settling rate. As a result, at the distance more than 30 m from the source a dust convective transfer prevails over gravitational and turbulent depositions at the upper levels and it reduces near-the-ground pollution. In case of two sources, the combined action of two convective cells amplifies convective transfer effect and reduces dust settling on the underlying surface. As a result, an area of small dust concentration and area free of dust are formed near the ground.

In the upper layers baroclinic wind and established convective motions cause dust arc-shaped transfer in the vertical plane in the background motion direction.

In case of background wind, in contradistinction from calm air, local-scale horizontal and vertical vortexes don't generate. Respectively, a turbulent vortex dust diffusion has no place. A transfer is made as a result of convective and advective motions and gradient turbulent diffusion.

Conclusion

Carried-out numerical experiments revealed some peculiarities of dust local transfer that are not obtained when using wide-spread meso-scale and quazi-static models [2, 11]. In particular, they showed that thermal convection dynamics acts oppositely to turbulent diffusion and sedimentation processes, substantially reduces dust concentration in the vicinity of the source near to underlying surfaces of the atmosphere. In the vicinity of emission source the dust transfer from lower levels to higher ones and their subsequent advective propagation take place. Near the source and in the lower 300 m layer, during warm emissions and calm air situations, a dust vertical transfer is prevalent, while in the upper part – horizontal advective and turbulent transfers caused by divergent motion are dominant.

Dust concentration in the surface layers of the atmosphere is higher in case of baroclinic wind, than during background calm air. The mentioned effect is presumably caused by the increase in vertical turbulent transfer related to baroclinic motion.

It should be noted that obtained results are in qualitative agreement with the general, known from observation, results for emitted ingredients [12] (Fig.8) that can be used when performing a similar scientific research work taking into account the results of special experimental measurements.

Carried-out experiments showed that in order to specify the theory of dust local propagation it is necessary to investigate the number of issues, such as: impact of thermal and dynamic stratification, emission temperature and rate on convective and dust transfer processes etc.

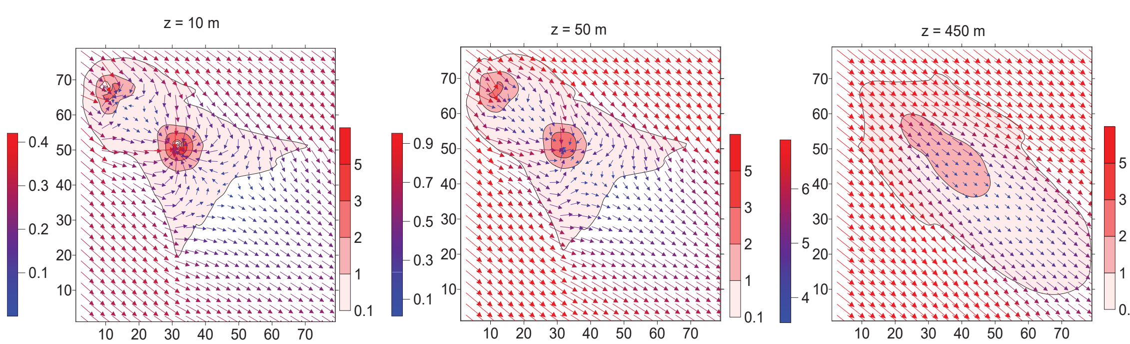

Fig. 7. *Distribution of wind velocity vertical component isolines and horizontal components at 10, 50 and 450 m altitudes*

Fig. 8. *Typical patterns of atmosphere pollution by separate sources*

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