The influence of landscape and urban development on modeling of transport of pollutants in Krasnoyarsk city

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Abstract. The paper presents the numerical simulation of the distribution of pollutants in winter in the atmosphere of Krasnoyarsk city. The source of the pollution is the suburban areas of the city of Krasnoyarsk, in which coal stove heating prevails. A micro-scale mathematical model based on the solution of the system of non-stationary Reynolds equations is used for modeling. The influence of various factors, such as elements of terrain and urban development, on the distribution of pollutants is studied in the paper.

1. Introduction
The problem of ecology in cities and urban agglomerations is one of the most actual for comfortable living of people. A striking example of a city with ecology problems is Krasnoyarsk, one of Russia's ten most polluted cities. Many factors have led to this situation, the main ones being: 1) the location of the city in a lowland between the hills on the left bank and the Torgashinsky ridge on the right bank. This causes problems with cleaning the city atmosphere by the wind. The wind has to be sufficiently strong and have a required direction. 2) The Yenisei River, which does not freeze in winter, conditions the formation of convective columns of air \cite{1}, which significantly affects the spread of pollutants. 3) Chaotic urban development with a predominance of high-rise buildings causes formation of stagnant zones and prevents wind cleaning of the city.

The most problematic period from the point of view of ecology in Krasnoyarsk is winter. The adverse weather conditions mode is most often declared in winter. It means that the level of air pollution in the city is above critical values, and this situation is called “black sky regime”. During this period seasonal sources of pollution are added to the constant ones (emissions from industrial enterprises and automobiles). A significant seasonal pollution is also associated with coal stove heating in the suburbs of Krasnoyarsk. The feature of the Krasnoyarsk agglomeration is the location of suburbs in its northern part, and the wind from this direction is least conducive to the purification of the city's atmosphere. In addition, there is often an inversion layer above the city during this period. It is due to a positive potential temperature gradient into the atmosphere, which also prevents the removal of pollutants from the city.

This paper presents the results of a numerical study of the influence of landscape and urban development on the distribution of pollutants under the least favorable scenario (winter, north wind direction, and positive potential temperature gradient) based on the micro-scale mathematical model of the atmosphere.
2. The micro-scale mathematical model of the atmosphere

A micro-scale mathematical model of the city’s atmosphere is implemented based on the SigmaFlow computational fluid dynamics software package developed at the Krasnoyarsk Branch of Kutateladze Institute of Thermophysics, Siberian Branch of the RAS, and at the Department of Thermophysics of Siberian Federal University [2].

The model is based on the Reynolds-averaged Navier-Stokes equations for incompressible flows with variable density. The system of equations includes:

- Mass conservation equation:
  \[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0, \]

- Momentum conservation equation [3]:
  \[ \frac{dU}{dt} = -\nabla P + g \cdot \rho_{\text{ref}} \cdot \left( \frac{\theta_{\text{ref}} - \theta}{\theta_{\text{ref}}} \right) + \nabla \left[ \mu \left( \nabla \mathbf{U} + \nabla \mathbf{U}^T \right) \right] + \nabla T, \]

- Energy conservation equation:
  \[ \rho C_p \frac{d\theta}{dt} = \nabla \cdot \left[ \left( \lambda + \frac{\mu C_p}{Pr} \right) \nabla \theta \right] + S_g, \]

where \( \mathbf{U} \) is the velocity; \( \rho \) is the density; \( \theta \) is the potential temperature; \( \theta_{\text{ref}} \) and \( \rho_{\text{ref}} \) are the potential temperature and density at height \( h \) following the initial and boundary distribution; \( P \) is the pressure; \( \mu \) is the viscosity; \( T \) is the Reynolds stress tensor; and \( S_g \) is the additional source term.

The Reynolds averaging of the Navier—Stokes equations (RANS) is used to model the turbulence of a nonstationary flow. The two-parameter \( k-\omega \) SST model is used to close the Reynolds equations [6].

At the input boundary, the distribution of the velocity, potential temperature, and turbulent characteristics (\( \varepsilon \) is the dissipation and \( \kappa \) is the turbulent kinetic energy) for a stable atmosphere is set as follows [4]:

\[ u(h) = \frac{u_*}{K} \left( \ln \left( \frac{h}{h_0} \right) + 4.7 \cdot \xi \right), \quad \varepsilon(h) = \frac{u_*^3}{K \cdot h} (1 + 4 \cdot \xi), \]

\[ k(h) = \frac{u_*^2}{C_m} \sqrt{\frac{1 + 5 \cdot \xi}{1 + 4 \cdot \xi}}, \quad \theta(h) = c \cdot h + \theta(h_0), \]

where \( h \) is the height; \( h_0 \) is the height where velocity is set; \( u_* \) is the component of velocity normal to the input boundary; \( c \) is the shear rate; \( c = \Delta h/\Delta \theta \) is the potential temperature rise factor; \( K \) and \( C_m \) are the constants, and \( \xi = \frac{h}{L} \), where \( L \) is the Obukhov scale [5].

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The surface layer of the atmosphere is a non-stationary flow of air with volumetric forces and forced convection, which develops in conditions of a complex landscape. It leads to the formation of large coherent structures in the turbulent flow, in which it is possible to distinguish large-scale vortex structures with a certain degree of determinism. These non-stationary long-wave structures have significant turbulent kinetic energy and a sufficiently long life cycle. One way to model large-scale vortex structures is to solve the nonstationary Reynolds equations (URANS method).

A relatively coarse grid is used for modeling the surface atmospheric layer by URANS method. It means that we do not perform direct modeling up to the wall and have to use wall functions. The
method of wall functions involves modeling the wall layer, i.e. the introduction of a sub-model defining the behavior of the flow near the wall. In this paper, to describe the dynamic and thermal wall layer, we use the mixed wall functions based on a seamless combination of standard wall functions and asymptotics for a viscous sublayer [7, 8].

The diffusion-inertial model of the motion of low-inertia particles [9] is used to model the transport of solid particles of smaller sizes. This model is a simplification of the two-liquid model of dispersed flows. In this case, the particle velocities are assumed to deviate slightly from the carrier phase velocity, and the transport equations of the dispersed phase are reduced to a single convective-diffusion equation for the impurity concentration. The diffusion-inertial model allows predicting the distribution of a fine impurity in turbulent flows, with account for some inertial transport mechanisms: the action of mass forces and transport due to the deviation of particle trajectories from the gas flow lines during their curvature and due to the flow unsteadiness.

The approach to the description of the dispersed phase is associated with the introduction of a set of continuums, each referring to a specific phase of the mixture. The values related to the solid dispersed and carrier liquid phases are indicated by the lower indices p and f, respectively. Non-Brownian particles are assumed to be spheres with a constant diameter \( d_p \) and a constant density \( \rho_p \). The volume concentration of the particles \( \phi \) characterizes the fraction of the volume occupied by the dispersed phase. Since the volume concentration of the dispersed phase is not very high the influence of the particles on the carrier gas phase may be neglected. There are no processes of clumping, crushing of particles, and collisions between particles.

Various cartographic data were used to construct the computational domain. The source of information on the natural terrain was the data from the digital terrain model of the SRTM satellite radar survey (Shuttle radar topographic mission) of the US National Aeronautics and Space Administration (NASA). Data from the OpenStreetMap [10] project served to account for urban buildings. The discretization of the computational domain was performed based on an unstructured non-orthogonal hexagonal grid.

3. Problem statements

There is a need to perform numerical simulations and analyze the results of the distribution of pollutants in the city in winter, depending on the landscape (terrain and river) and urban development (buildings). The wind blows from the north and the environmental situation in the city worsens because products of coal stove heating from the suburbs transfer to the city (Figure 1). This scenario is one of the implemented variants of the “black sky” regime. The spread of pollutants is modeled by the transfer of soot particles with a diameter of 10 microns. To research the impact of the landscape and urban development, a series of simulations are carried out. In each variant of simulation, different factors are consistently added: the landscape of the location of the city with a non-freezing river (variant 1), urban development (variant 2), and heat generation of the city (variant 3).

Figure 1. Computational domain and sources of pollutants.
The grid had 16,000,000 cells with a horizontal pitch of about 30m with additional partitioning at the locations near the buildings. The following parameters were set as the main weather conditions: the speed of the north wind of 2 m/s at a height of 10 m, the growth of the potential temperature at a height of $c = 0.01$ K/km, the temperature in the surface layer of $-20$°C, and the surface temperature of the river of 4°C. The heat output from urban development was 40 W/m² [11].

4. Results

The main features of the terrain in this scenario are: the wind is directed almost perpendicular to the riverbed and the mountain range (Torgashinsky Ridge) is located on the leeward side of the river. A significant temperature gradient between the water surface and the surrounding air is formed by a non-freezing river in winter. As a result, ascending air flows are formed and stretched horizontally along the wind direction. The interaction of the mountain range and the updrafts leads to the formation of large-scale vortex structures. Moreover, the size of zones of vortices formation depends on the distance of the riverbed to the mountains. The power of these vortices increases with a drop in the wind speed and a decrease in the potential temperature gradient over the height. The direct influence of the mountain range on the updrafts becomes noticeable only when the distance between the river and the mountains becomes comparable to the horizontal size of the updraft.

In the ground layer, four zones can be distinguished depending on velocity: the first is a high-speed zone located on the tops of mountains and hills; the second is an area with increased speed on the leeward side of the river and, to a lesser extent, on the windward side at relatively low wind speeds; the third is a low-speed zone located in the depressions between the tops of mountains and hills; the fourth, a low-speed zone located on the leeward side of the river in a low-speed vortex region formed by ascending air flows and a mountain range (Figures 2a, 3a). As a result all this determines the distribution of particles from pollution sources. Firstly, there is a deformation of the cloud of particles along the direction of the river flow. The particles do not propagate strictly in the direction of the wind but move slightly to the east. Secondly, the ascending air flows heated by the river partially carry the particles out of the surface layer.

![Figure 2](image-url)  
**Figure 2.** Distribution of the velocity magnitude in the surface layer, isosurface of the vertical velocity component $w = 1$ m/s: a) variant 1, b) variant 2, c) variant 3.
Urban development, on the contrary, leads to a significant decrease in the average wind velocity and the formation of numerous local vortex zones, but only at low heights. As a result, the intensity of the updrafts decreases, and their amount increases but with smaller sizes. This situation leads to an increase in the deposition rate of pollution, and their transfer across the river to the other bank is reduced (Figures 2b, 3b).

The influence of heat release from buildings leads to an increase in temperature in the surface layer, intensification of air movement at the height of urban development, and the formation of an urban heat island. Figure 4 shows that there is a 2°C increase in temperature in the surface area due to heat release from buildings. The right bank of the city warms up most strongly due to the wind direction.

The urban heat island, on the one hand, intensifies vortices near buildings, but on the other hand, slows down the high-velocity airflow over the city. A decrease in the velocity of the airflow over the city increases the intensity of the upward convective flows from the river (Figures 2c, 3c).

Changing the nature of the airflow in the city atmosphere leads to a deformation of the field of concentrations of pollutants. In the presence of an urban heat island the count of particles that are dispersed in the atmosphere increases, resulting in a lower concentration of pollutants in the ground layer.

**Conclusions**
The simulation has shown that the non-freezing river in winter significantly intensifies the movement of air masses. The interaction of the terrain and the river can lead to the formation of large-scale vortex structures between the river and the Torgashinsky ridge. Urban development, on the contrary, leads to a significant decrease in the average wind speed and the creation of numerous local vortex zones, but only at low altitudes. This contributes to an increase in the deposition rate of harmful impurities, in particular, because of this, their transfer across the river to the right bank is reduced. The influence of heat release from buildings leads to an increase in atmospheric temperature in the surface layer be ~2°C, local intensification of air movement in the locations of buildings, and the formation of an urban heat island, which contributes to the dispersion of pollutants in the upper part of the city atmosphere.

![Figure 3](image1)

**Figure 3.** On the left - distribution of particle concentration on in the surface layer, on the right - isosurface of the volume concentration of polluting particles: a) variant 1, b) variant 2, c) variant 3.
Figure 4. Comparison of the potential temperature distribution for the variants: a) variant 2, b) variant 3.

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