Modeling the influence of the river on the wind pattern of Krasnoyarsk

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Abstract. The article analyzes the environmental situation in the city of Krasnoyarsk based on data of the Ministry of Natural Resources and the Ministry of Ecology and Environmental Management of the Krasnoyarsk Territory. The influence of the non-freezing Yenisei River on the movement of air masses over the city is considered based on numerical simulation. The obtained results demonstrate the ability to quickly simulate the wind pattern of the city, taking into account the heterogeneous nature of the terrain, heat transfer, wind load, and the influence of the river.

1. Introduction

According to the data presented in the report of the Ministry of Natural Resources [1], Krasnoyarsk is one of the environmentally unfavorable cities of Russia. Krasnoyarsk is the largest industrial center of Eastern Siberia, accommodating various industries, whose operations are accompanied by the release of pollutants into the atmosphere.

The city is also the largest transport hub in Eastern Siberia. The presence of the Trans-Siberian Railway, the freight route on the Yenisei River, a large airport, as well as highways of nationwide scale have led to a stable growth of motorization of the economy and the population in the last few years. In turn, it has a strong adverse impact on the overall environmental situation in Krasnoyarsk.

The deteriorating air quality is characterized by the level of pollution. In 2016, according to the observation data, 58 days were recorded in the “Black Sky” mode, i.e. a significant excess of the one-time maximum permissible concentrations of suspended solids and gases (carbon oxide, nitrogen dioxide, sulfur dioxide, hydrogen fluoride, etc.) [2]. In 2017, the nature of pollution in Krasnoyarsk did not change. According to the report [3], the atmosphere of the city received 190.7 thousand tons of pollutant emissions, of which 117.6 thousand tons were produced by stationary plants and 73.1 thousand tons – by mobile sources. For 2017, in the territory of Krasnoyarsk, the adverse meteorological conditions (AMC) of the first-class safety hazard were registered 11 times. The total number of the days with AMC amounted to 43.5.

The current environmental situation in the city was caused not only by the operation of industry and vehicles but also a specific feature of Krasnoyarsk, which is its geographical location. The city is located in the valley of the Eastern Sayan Mountains with non-freezing Yenisei River flowing...
throughout the entire city. The significant temperature difference between the non-freezing river and the surrounding space results in the local intensification of the air masses.

Specialists of the Kutataladze Institute of Thermophysics SB RAS carried out a simulation of this phenomenon [4]. The results of the numerical study showed that in the winter, upward airflow appears over the "warm" Yenisei, i.e. the airflow over the river rushes up, dragging the air from the right and left banks. However, at an altitude of about one kilometer, the upward air flow interacts with the inversion layer, which prevents air flow from moving further upwards. This results in the accumulation of harmful impurities over the city.

The urgent problem associated with ensuring a comfortable level of life-sustaining activity of the population is the solution to problems of forecasting and managing the air quality in the city that is possible if the understanding of dynamics of polluting substances distribution and accumulation in the atmospheric surface layer (formation and emergence of the "Black Sky" mode).

2. Mathematical model

The current development level of physical and chemical models, calculation methods, and computers allow advancing a mathematical model that uses airbrushing and meteorological features of the territory for possible forecasting and management of air quality.

Various methods and mathematical models, such as empirical, statistical, deterministic and their combinations, are used to calculate the dynamics of the atmosphere and the spread of harmful emissions. Special attention is paid to deterministic models, which are based on physical laws described by the complete spatial hydrodynamic equations.

The authors of the article are working on the implementation of the proposed model using the SigmaFlow software package [5]. The SigmaFlow complex [6] was created and is being developed in the Krasnoyarsk Branch of IT SB RAS and at the Department of Thermophysics, Siberian Federal University. It is designed to study a wide class of hydrodynamic and thermophysical processes, performing parallel computing on modern multicore processors and cluster systems. The software package includes modern turbulence models, models describing the transfer of fine inertial particles, as well as chemical reactions in a multicomponent medium.

Basic equations:

continuity equation

$$\frac{\partial \rho U_i}{\partial x_i} = 0$$

(1)

equation of motion

$$\bar{\rho} \left( \frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] - \bar{\rho} \frac{\partial \left( \dot{u}_i \dot{u}_j' \right)}{\partial x_j} - \left( \bar{\rho} - \rho_{ref} \right) g_i$$

(2)

energy conservation equation

$$\bar{\rho} \left( \frac{\partial \Theta}{\partial t} + U_j \frac{\partial \Theta}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial \Theta}{\partial x_j} \right) - \bar{\rho} \frac{\partial \left( \dot{\theta} \dot{u}_j' \right)}{\partial x_j} + S_\theta$$

(3)

where $\theta$ is the potential temperature; and $S_\theta$ is the additional source term.

The MSST model was used to simulate turbulence.
To discretize the equations, a control volume method was used along with a second-order approximation of accuracy of time and space.

The properties of the medium correspond to the properties of air, and the density is determined from the equation of state for an ideal gas. The velocity profile of the incoming flow at the boundary of the computational domain was given by the power law. The speed of the river was set at 4 m/s.

The parallelepiped was chosen as the computational domain. Its longitudinal 36.5 km long axis (x-axis) was directed along the Yenisei River, while the 20 km wide y-axis was directed perpendicularly, and the 1 km high z-axis was directed vertically. The calculation took into account the actual terrain of Krasnoyarsk city, as well as the presence and influence of the Yenisei River (figure 1).

![Figure 1. Computational domain under study.](image)

For the calculation, we used unstructured hexagonal grid 200x100x60 with the number of cells equal to 1.2 million, whose size in the horizontal plane was 200x200 meters. Vertically, the grid increased along with the height, i.e. the size at the earth was 1.3 m, while at a height of 1 km it was 20 m. Figure 2 shows a fragment of the calculated grid.

To adapt the atmospheric dynamics model over the city of Krasnoyarsk, the data of field observations were used.

3. Results

In this paper, we considered the influence of the non-freezing Yenisei River on the air masses moving in the winter period.

In the beginning, the air flow modeling was carried out for the varying wind intensity without regard for the heat transfer and the river flow. In this case, the flow structure was affected only by the orthographic factor. Further, the influence of the river flow without heat transfer was considered. In these calculations, natural convection was not taken into account, and the density was assumed to be constant. At the next stage, heat transfer was taken into account. The temperature of the underlying surface and the incoming flow was set at -20 °C, while the temperature of the river was 4°C.

Figure 2 shows the calculation results of the air flow for various options without (figure 2a) and with heat transfer (figure 2b). The figures show that taking into account the natural convection, the upward air flow is formed over the Yenisei River. This flow interacts with the incoming wind flow to form complex vortex structures. In the option without heat transfer, vortices are formed due to the flow separation from the relief, and they are significantly smaller in scale.

Visualization of vortex structures, using the $\lambda_2$ criterion, shows the location of vortex motion area (figure 3 a, b). As is obvious, for the option with account for heat transfer and river movement, large-
scale structures are formed over the river, which determines the local air dynamics. The nature and scale of the vortex are visualized by particle tracks in figure 4.

**Figure 2.** Vortex formation area, m/s
(a - without heat transfer; b - with heat transfer).

**Figure 3.** Vortex formation area
(a - without heat transfer; b - with heat transfer).
Figure 4. Vortex over the river visualized by particle trajectories.

Figure 5 shows the trajectory of massless particles with starting points from the areas of CHP-1 chimneys and the industrial site of KrAZ. The results of the simulation have shown that with a decrease in the incoming flow velocity, the influence of the Yenisei River increases, while with a decrease in the wind speed, the air is more intensively ejected from the city to the river area (figure 5).

Figure 5. Streamlines from the main pollution sources at different rates of incoming flow (a. 0.8 m/s; b. 2.5 m/s).
4. Conclusions
The first results of simulating the dynamics of the atmosphere over the city demonstrate the ability to quickly calculate the wind regime of the city, taking into account the heterogeneous nature of the terrain, environment, and heat transfer.

Further systematic studies will help to understand the mechanisms of transport, to study the features of the formation of local atmospheric circulations and accumulation of harmful impurities in the city atmosphere.

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