Analysis of vortex structures formed in the winter in the atmosphere of Krasnoyarsk city

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Abstract. The article considers the influence of the relief, river, and urban development on the formation of vortex structures in the atmosphere and the spread of pollutants in the city of Krasnoyarsk in winter. The weak influence of urban development on the appearance of large vortex structures over the river is shown. However, in the ground layer, it significantly changes the flow pattern and determines the character of the distribution of pollutants.

1. Introduction
The city of Krasnoyarsk is one of the most polluted cities in Russia. The total number of days with unfavorable weather conditions in a year can be more than a month, most observed in winter. The cause is several factors: the geographical location of the city and its structure, the influence of industrial and energy-generating plants, and the heavy road traffic. Krasnoyarsk is located in a lowland between the hills on the left bank and the Torgashinsky Ridge on the right. When the wind direction is North, low-speed zones form. In those zones, pollutants can accumulate. Another essential feature of the city of Krasnoyarsk is the ice-free Yenisei River, which divides the city into two parts. It has a slightly varying water temperature throughout the year, about 4°C. Both of these factors lead to the formation of an atmospheric inversion layer in the city [1], which prevents the dispersion of pollutants from the city’s atmosphere. In the winter, the surface of the non-freezing and warm river generates an upward movement of heated air, which interacts with the incoming wind, forms complex vortex structures [2]. That affects the aerodynamics of air flows in the city and the spread of pollutants, accordingly. To understand the processes occurring in the atmosphere of the city of Krasnoyarsk, various research approaches are used: from measuring the state of the air in different parts of the city (stationary weather stations and mobile measuring instruments) to numerical experiments. This article presents the numerical study of the atmosphere of the city of Krasnoyarsk. Numerical methods for studying the atmosphere of cities depend on the size of the calculated area. Those can be divided into mesoscale (the calculation domain is several hundred kilometers), and microscale (the calculation domain is a city or individual districts of the city), modeling of individual buildings and adjacent territories [3]. Mesoscale models are based on the solution of nonstationary equations of atmospheric hydrodynamics and the parametrization of heat and moisture exchange processes between the earth and the atmosphere. Mesoscale models are usually used for weather forecasting or modeling large-scale atmospheric flows [4]. For smaller scales, computational fluid dynamics (CFD) methods are used based on the solution of the Navier-Stokes equation system [5]. Microscale models require a more detailed approach to preparing
the computational model. In this case, information is needed not only about the relief, but also about the shape of buildings and structures. That leads to the use of detailed computational grids and high computational costs, but allows taking into account the influence of micro factors on the formation of the urban atmosphere.

Previously, the authors developed and implemented a mathematical model for modeling aerodynamic and thermal processes occurring both in the atmosphere of the cities. The model implements the Reynolds—averaged Navier-Stokes equations for low-velocity flows with variable density, taking into account the lifting force. The energy conservation equation is written concerning the potential temperature. The air is considered an ideal gas. The k-ω SST [6] model was used to model the turbulent characteristics. The method of wall functions taking into account aerodynamic roughness was applied on solid surfaces [7]. The distribution of velocity, potential temperature, and turbulent characteristics for a stable atmosphere is set at the input boundary [8]. The unsteady simulation was performed. We neglect the influence of thermal stratification of the surface layer on the turbulent characteristics. The model was verified by comparison with laboratory experiments on the flow of urban development [9]. We used this model to simulate the atmosphere of the whole Krasnoyarsk city [10,11] and in one district of the city [12,13]. The works [10, 11] showed that the intensity of the vortices formed due to the interaction of the Yenisei River with atmospheric air significantly exceeds the vortices formed due to the relief. The works [12,13] showed that airflow disturbances caused by the flow around high-rise buildings could spread over considerable distances. It means each district affects the flow structure on a scale comparable to the scale of the city. In contrast to the works [12,13], which considered the influence of a single complex of buildings, in this work, we included about 40,000 buildings into the calculated domain of urban terrain to account for their effect on the formation of vortex structures and the spread of pollutants within the city.

2. Numerical technique.

2.1. Construction of the calculation grid

A method of construction of the calculation grid was developed based on the elevation map obtained from the digital elevation models (DEM). The DEM is constructed by the method of stereophotogrammetric processing of ultra-high-resolution images (WorldView 1 & 2), using the algorithm of The Surface Extraction with Triangulated Irregular Network-based on Search-space Minimization [14] (figure 1a). Using the bilinear height interpolation method, we determined the position of the first layer of grid nodes. The subsequent layers of the grid are built to a given height, with a given thickening to the surface (the minimum height of the first cell was ~0.3 m). The top layer of the domain should be flat. In this case, the horizontal step was equal to 30 m. To model buildings, cells that overlap with buildings by more than 20% were blocked. For more accurate localization of buildings, the cells intersecting with them were additionally split into four parts in the horizontal plane. A grid fragment is shown in Figure 1b. The service OpenStreetMap [15] provided information about the location of buildings and their height.

![Figure 1. To build a grid: a) a map of the heights of the relief of the Krasnoyarsk, b) a fragment of the grid.](image)
As a result, a grid was constructed in a rectangular area with a cells number of about 16 million. The direction of the airflow is along with one of the sides of the rectangle. We choose the height of the calculated domain from the condition of minimizing air disturbances that reach the upper limit. In this case, it is equal to 2.5 km

2.2. Boundary and initial conditions

We set special boundary conditions for velocity and temperature on the selected surfaces: the ground, the buildings, the river, the input boundary - the northern side of the computational domain, the output boundary, the side boundaries, and the upper boundary.

Adiabatic conditions are chosen for the ground surface. The heat flux associated with the heat release was set on the building's surfaces. The river's surface was set in the form of a distributed velocity field obtained by modeling a two-dimensional task about the flow of the river. The surface temperature of the river was set to 4°C. The distribution of velocity (on 10 meters above of ground \( v = 2 \text{ m/s} \)), potential temperature (-20°C at the ground), and turbulent characteristics for a stable atmosphere are given at the input boundary. The distribution of the potential temperature over the height was assumed to be linear with a positive gradient of 10°C/km. Such boundary conditions simulated the actual situation when unfavorable weather conditions occurred in the winter of 2019. Calculations were carried out for the winter when the ambient air temperature is significantly lower than the river temperature, leading to a powerful convective column. As the initial conditions, the zero velocity in the calculated region and the conditions of a stable atmosphere in terms of temperature were set.

A more detailed description of the mathematical model used for the calculations is presented in the article [10].

3. The results

This article presents the results of numerical modeling of three variants, which considered the influence of the city on the formation of the flow structure near the Yenisei River. In the first variant, only the natural relief was taken into account. In the second, urban buildings were added, and in the third, the heat flow from buildings equal to 40 W/m² was added. Figure 2 (isosurface of the vertical component of velocity \( w = 1 \text{ m/s} \)) shows the formation of upward convective flow for all three variants. The updraft consists of a set of convective columns, which form depends partly on the topography and shape of the river. The feature of the eastern part of the city area is the closest location of the Torgashinsky Ridge to the river and the location of the narrowest and fastest section of the river. The largest convective columns are formed in this area, especially for the first and third variants (Figure 2). The highest density of vortex structures is observed here, respectively (Figure 3).

The presence of urban buildings leads to a decrease in the velocity in the near-surface region (Figure 2b), which leads to a reduction in the intensity of convective columns and vortices (Figures 2, 3). On the other hand, the buildings themselves are generators of vortices, only much less intense than the river (Figure 4).
Let us consider the impact of the river and urban development on the spread of polluting particles (10μm). The source of particles is the combustion products from suburbs with stove heating (see figure 5a). Qualitatively, the calculation result was estimated by the particle deposition area. The larger the area, the lower the particle deposition rate and their local concentration. For the first variant, the largest area of distribution of soot particles is observed, also on another side of the river (figure 5b). Part of the particles is elevated into the upper layer of the atmosphere by an ascending convective flow and is dispersed there. With the account of urban buildings, the particle deposition area reduces due to a decrease in the velocity in the surface area and the formation of vortex structures behind the buildings (Figure 5c). When a heat source adds, the velocity near the ground increases, but the deposition of the area of the pollution particles decreases (Figure 5d). This leads to a higher concentration of pollutants near their sources falling in the far distance. This can be due to more intensive vorticity in the city.

**Figure 2.** The upward flow consists of a set of convective columns (isosurface vertical component of velocity - w = 1 m/s) to three variants: a) first, b) second, c) third.

**Figure 3.** Lambda-2 on surface 200m above the river to three variants: a) first, b) second, c) third.
Figure 4. Isosurface of $\lambda_2 = -0.0005 \text{ s}^{-1}$ to three variants: a) first, b) second, c) third.

Figure 5. Result of modeling pollutant distribution: a) source of pollutant a) first variant, b) second, c) third.
4. Conclusion
The paper was the first to investigate the influence of urban development on the structure of airflow and the spread of combustion products from suburbs with stove heating in the atmosphere of the city of Krasnoyarsk in winter, taking into account the ice-free Yenisei River. An ice-free river in winter significantly intensifies the movement of air masses. The interaction of the relief, even free of the urban development, with the river causes large-scale vortex structures between the river and the Torgashinsky ridge, which is consistent with the works of other authors [2]. The presence of urban development leads to a significant decrease in the average wind speed and the creation of numerous local vortex zones at the height of buildings. This contributes to an increase in the deposition rate of harmful impurities, resulting in reducing the transfer of polluting particles across the river to the right riverbank. Accounting for heat release from buildings leads to an increase in atmospheric temperature in the surface layer of about 20°C, local intensification of air movement near buildings, and an urban heat island formation. The heat island contributes to the dispersion of pollutants in the upper part of the city's atmosphere. Thus, it was shown that urban development determines the nature of the airflow at low altitudes (of the order of the height of the building), both in the city itself and above the riverbed. As a result, it affects the spread of polluting particles.

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