Formation of circulation in the urban atmosphere at low rates of the background airflow

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Specific features of the formation of the air circulation over an urban area at low rate of the background airflow are discussed. The results of numerical experiments on modeling of the scenario of diurnal variation of the winter atmospheric circulation over Tomsk are presented.

Atmospheric circulation over a city and an industrial region as a whole is a result of interaction between a large-scale background airflow and local inhomogeneities of the terrain. Orographic, dynamic, and thermal inhomogeneities of different parts of a territory determine the type of atmospheric circulation. Usually, a city is a powerful heat island. If a region under study includes a large water basin, it may be both a heat island and a cold island depending on a season and time of a day.

Investigations show that there are the so-called critical rates of the background airflow, starting from which the effect of the surface on the circulation decreases sharply with the increasing flow rate. At a close-to-critical flow rate, the background airflow interacts with large heat and cold islands, and the resulting pattern is mostly similar for different cities. In this paper we consider the situations that the rate of the background airflow is quite low and the circulation is largely determined by properties of the underlying surface. In this case, the circulation is affected by the factors that are insignificant at high flow rates. As a result, circulations inherent in one particular city and atypical of others are formed. Peculiarities are caused, in particular, by the city geometry, the presence of suburbs, water pools, the type of surrounding forests and farmlands, etc. The cases of low rate of the background airflow are rather frequent on the territory of Siberia, and this is one of arguments in favor of practical significance of this study.

The numerical model used in the study includes equations of fluid dynamics and admixture transport in the atmosphere. Consider a system of complete equations of fluid dynamics of the atmosphere in the quasi-static approximation over an inhomogeneous surface. For a convenience of accounting for the landscape inhomogeneity, the model includes a vertical coordinate that follows the terrain:

$$\sigma = (p - p_T)/\pi_S,\ \pi_S \equiv p_S - p_T, \tag{1}$$

where p is pressure, p_T and p_S are the pressure at the air mass top and at the surface. The coordinates x and y are directed respectively to the east and to the north.

Let us write the main equations of the model.[1–3]

Flow equations:

$$\frac{\partial \pi_S u}{\partial t} + \tilde{L}(\pi_S u) - l\pi_S v = -\pi_S\left[\frac{\partial H}{\partial x} + \frac{\sigma R T}{\Phi}\frac{\partial \pi_S}{\partial x}\right], \tag{2}$$

$$\frac{\partial \pi_S v}{\partial t} + \tilde{L}(\pi_S v) + l\pi_S u = -\pi_S\left[\frac{\partial H}{\partial y} + \frac{\sigma R T}{\Phi}\frac{\partial \pi_S}{\partial y}\right], \tag{3}$$

where $\Phi \equiv \sigma\pi_S + p_T$.

Continuity equation:

$$\frac{\partial \pi_S}{\partial t} + L(\pi_S) = 0\ . \tag{4}$$

Here we use the following designations:

$$L(\pi_S\varphi) = \frac{\partial \pi_S \varphi u}{\partial x} + \frac{\partial \pi_S \varphi v}{\partial y} + \frac{\partial \pi_S \varphi \dot{\sigma}}{\partial x} \tag{5}$$

is the transport operator in the σ-coordinate system in the divergent form,

$$\tilde{L}(\pi_S\varphi) = L(\pi_S\varphi) + F_\varphi^{\mathrm{H}} + F_\varphi^{\mathrm{V}}\ , \tag{6}$$

where F_φ^{H} and F_φ^{V} are the operators of turbulent exchange of a substance φ in the horizontal and vertical directions; $\mathbf{u} = (u, v, \dot{\sigma})$ is the wind velocity vector, $u, v, \dot{\sigma}$ are the components of the wind velocity vector in the directions of the coordinates x, y, and σ, respectively, $\dot{\sigma} \equiv \frac{\mathrm{d}\sigma}{\mathrm{d}t}$; l is the Coriolis parameter; H is geopotential.

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Equation for pressure tendency

$$\frac{\partial \pi_S}{\partial t} + \int_0^1 \left[\frac{\partial \pi_S u}{\partial x} + \frac{\partial \pi_S v}{\partial y} \right] d\sigma = 0 \qquad (7)$$

can be obtained through integration of the continuity equation (4) over the vertical coordinate under the conditions $\dot{\sigma} = 0$ at $\sigma = 0$ ($p = p_T$) and $\sigma = 1$ ($p = p_S$).

Equation for the vertical velocity in the σ-coordinate system

$$\dot{\sigma} = -\frac{1}{\pi_S} \int_0^{\sigma} \left[\frac{\partial \pi_S}{\partial t} + \frac{\partial \pi_S u}{\partial x} + \frac{\partial \pi_S v}{\partial y} \right] d\sigma , \qquad (8)$$

and $\frac{\partial \pi_S}{\partial t}$ can be excluded by use of Eq. (7).

Heat influx equation

$$\frac{\partial \pi_S T}{\partial T} + \tilde{L}(\pi_S T) - \frac{R T \tau}{c_p (\sigma + p_T / \pi_S)} = \frac{\pi_S Q}{c_p}, \qquad (9)$$

$$\tau = \frac{dp}{dt} = \pi_S \dot{\sigma} + \sigma \frac{d\pi_S}{dt}; \quad \frac{d\pi_S}{dt} = \frac{\partial \pi_S}{\partial t} + u \frac{\partial \pi_S}{\partial x} + v \frac{\partial \pi_S}{\partial y}, \qquad (10)$$

where T is temperature; c_p is the specific heat of dry air at constant pressure; Q are the heat sources.

Hydrostatic equation:

$$\frac{\partial H}{\partial \sigma} = -\frac{\pi_S R}{\Phi} T. \qquad (11)$$

Admixture transport equation

$$\frac{\partial \varphi}{\partial t} + \tilde{L}(\varphi) = f, \qquad (12)$$

where f is the function describing admixture sources; φ is the admixture concentration. Atmospheric admixtures in the general case are multicomponent mixtures. The number of components is specified as an input parameter of the model. The rate of gravitational sedimentation of the admixture is taken into account through addition of the corresponding value to the vertical component of the velocity vector.

For closure of the mathematical model, the initial and boundary conditions should be set. At the lower boundary the conditions are specified with the use of parametric models of the surface and boundary atmospheric layers; at the top of the air mass and at the side boundaries these are the conditions of transformation into the background processes. Discrete approximations are based on the variational principle in combination with the split method.[4,5] To approximate model equations at the transport stage, monotonic numerical schemes are used.[6,7]

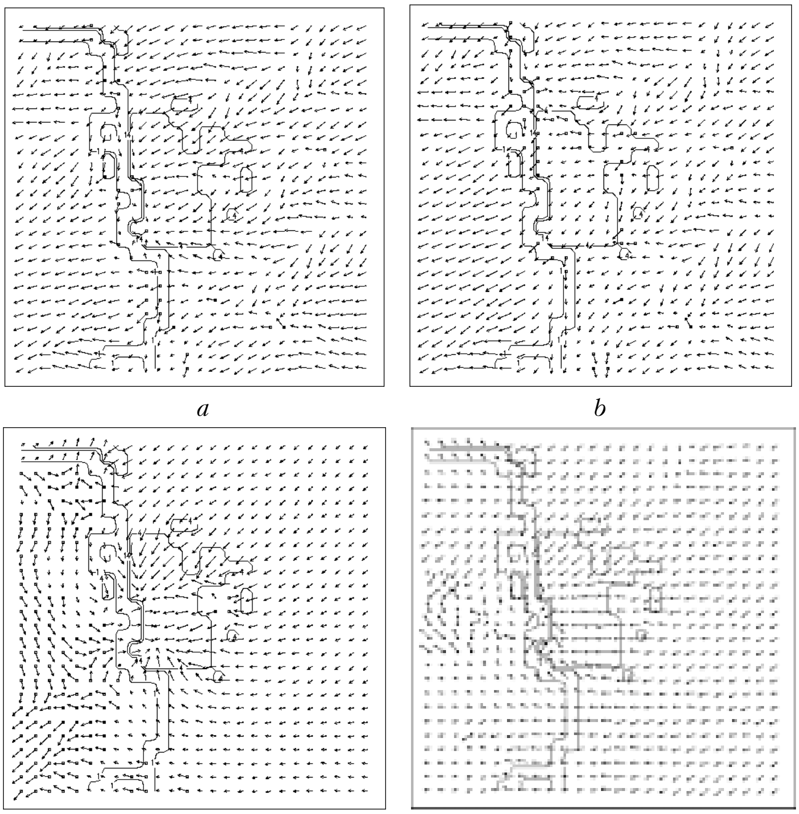
In the numerical experiments considered, Tomsk industrial region was used as a case study. The problem was solved on a 100 × 100 km area with Tomsk at its center. The top boundary of the air mass coincided with the 700 mbar isobaric surface. The horizontal step of the computational grid was 1 km, and 10 vertical levels were considered.

By the initiative of IAO SB RAS, a scenario of the diurnal behavior of atmospheric circulation in the area studied was simulated. As the input information, meteorological data were used for February 10–11 of 2001 that were kindly presented at our disposal by the IAO staff. During this period, weak background airflow (up to 5 m/s) was observed. The amplitude of the diurnal behavior of the surface air temperature was 10–12° depending on an observation site.

The minimum nighttime and maximum daytime temperatures were, respectively, −25 − 27 and −13 − 15°C. The results of simulation are given with the interval of 6 h. Figure 1 shows the horizontal structure of atmospheric circulation at the height of 50 m above the ground surface in the vicinity of Tomsk (25×25 km). River Tom and city boundaries are schematically shown as well. The squares mark the grid nodes with low (as compared with maximum) wind. The mean wind velocity in the vicinity of Tomsk at this height was equal to 1–3 m/s in daytime. Figure 2 shows the direction of the vertical airflows at the height of 100 m: upward (vertical dashes) and downward (horizontal dashes).

As can be seen from the figures, the structure of the wind field is a result of the interaction between rather weak background airflow with the heat island of the city. Temperature contrasts of the surface parts, depending on their usage, have a significant effect on this structure. The circulation changes during a day. As an example, let us consider the part lying between the central part of Tomsk and Akademgorodok situated to the east from the city downtown area. Downward airflows and low wind velocities are observed here for 24 hours. In the presence of pollution sources, this can favor pollutant accumulation and formation of the high pollutant concentration.[8]

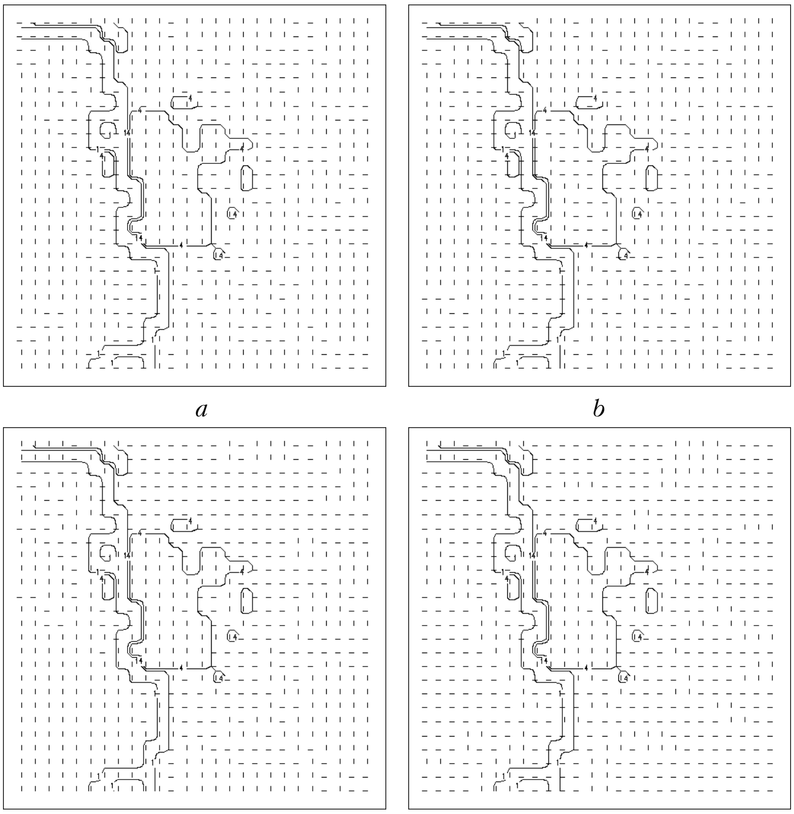
Analysis of the results obtained suggests that the pollutant accumulated spreads against the background airflow, which prevails in the area of simulation. As a result, the increased pollutant concentrations may be episodically observed during a day in Akademgorodok. The decrease in the pollutant concentration can be caused by better “ventilation” of Akademgorodok at some periods.



a *b*

c *d*

Fig. 1. Horizontal structure of atmospheric circulation: 03:00 (*a*), 09:00 (*b*), 15:00 (*c*), and 21:00 L.T. (*d*).



a *b*

c *d*

Fig. 2. Direction of vertical airflows: 03:00 (*a*), 09:00 (*b*), 15:00 (*c*), and 21:00 L.T. (*d*).

Acknowledgments

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