Peculiarities in the formation of a pollutant concentration field in the atmosphere over an industrial region in the absence of pollution sources on its territory

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Received January 18, 1999

A three-dimensional model of pollutant transfer is considered. Zones of increased and decreased volume concentration are formed in the case of transport of pollutants through the boundary and in the absence of pollutant sources in the areas. Novosibirsk industrial region has been chosen as an object for numerical experiments.

The investigation of qualitative characteristics of the atmosphere of large industrial centers and surrounding territories using numerical simulation methods is based on the creation of models describing the processes of pollutant propagation in the atmosphere. The formation of pollutant concentration field occurs against the background of atmospheric circulation due to the interaction of large-scale motion of air masses with orographic and thermal inhomogeneities of the Earth's surface. In this case the presence of a large city and, as a rule, of a large-scale water object, which may be presented as a warm or cold island depending on the season and time of the day, increases greatly the influence of the underlying surface on the wind field formation and, hence, on the pollutant spread. It is evident that the space-time distribution of the pollutant sources and their emission power are also among the basic factors determining the formation of the pollutant concentration field.

The effect of sources, located on the territory of an industrial region, on the air quality was discussed in the literature.[1,2] In this paper an attempt is made to study the influence of external remote sources of pollution.

1. Mathematical model

Now we consider a three-dimensional equation of a pollution transfer with the allowance for turbulent diffusion written as Cartesian coordinates ($\mathbf{x} = (x, y, z)$):

$$\frac{\partial \varphi}{\partial t} + \frac{\partial u\varphi}{\partial x} + \frac{\partial v\varphi}{\partial y} + \frac{\partial w\varphi}{\partial z} - \frac{\partial}{\partial x} k_x \frac{\partial \varphi}{\partial x} - \frac{\partial}{\partial y} k_y \frac{\partial \varphi}{\partial y} - \frac{\partial}{\partial z} k_z \frac{\partial \varphi}{\partial z} = f. \qquad (1)$$

Here $\varphi = \varphi(\mathbf{x}, t)$ is the volume pollution concentration; u, v, w are the components of the pollution velocity vector $\mathbf{u}$; k_x, k_y, k_z are the turbulence coefficients; $f = f(\mathbf{x}, t)$ is the function of pollution sources (u, v, w, k_x, k_y, k_z are assumed to be known).

Let the problem (1) be solved in the range Ω with the boundary Γ. The initial conditions of the problem are as follows:

$$\varphi(\mathbf{x}, 0) = \varphi_0(\mathbf{x}). \qquad (2)$$

The boundary conditions are

$$\begin{cases} \varphi\big|_{\mathbf{x}\in\Gamma} = g(\mathbf{x}, t), \text{ if } \mathbf{u}_n(\mathbf{x}, t) \text{ is directed inward } \Omega, \\ \dfrac{\partial \varphi}{\partial n}\Big|_{\mathbf{x}\in\Gamma} = 0 \quad \text{in other case.} \end{cases} \qquad (3)$$

Here $\mathbf{u}_n$ is the component of the velocity vector $\mathbf{u}$ normal to Γ.

Since we consider the process of pollution transfer in the atmosphere, which is not an incompressible medium, the divergence of the velocity vector is not equal to zero:

$$\text{div } \mathbf{u} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \neq 0. \qquad (4)$$

Let us consider a specific statement of the problem. It can be assumed that the lack of internal pollution sources ($f \equiv 0$ in (1)) within Ω takes place. The pollution arrives to the area only through the boundary Γ.

Assume that

$$\varphi_0(\mathbf{x}) \equiv g(\mathbf{x}, t) \equiv \psi \equiv \text{const}. \qquad (5)$$

This means that at the initial time moment everywhere over the region the pollution concentration was constant and was equal to the concentration of a pollutant coming continuously to the area through its boundary. This may be interpreted as follows: the pollutant that reaches the area boundary from a remote source has already dispersed to a certain degree.

It is evident that in view of Eq. (4) even under condition (5) $\phi(x, t) = \text{const}$ is not a solution to Eq. (1) ($\phi \equiv \text{const}$ is not a solution in the general case as well).

Thus, in this region the areas of enhanced and lower pollution concentration are formed, whose space-time distribution is governed by the velocity field structure.

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2. Numerical experiments

The Novosibirsk industrial region (Fig. 1) was considered as an object for a research in the numerical experiments.

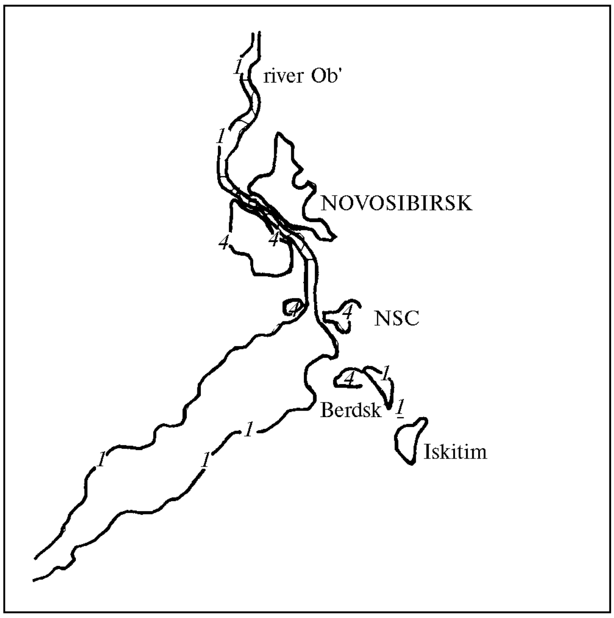

Fig. 1. The Novosibirsk industrial region: boundary of the city territory (*4*); boundary of water objects (*1*).

The components of the velocity vector and the turbulence coefficients were calculated using the model of atmospheric dynamics presented in Refs. 1 and 2, therefore as vertical coordinate in the model of pollution transfer we used the coordinate $\sigma = (p - p_s)/(p_s - p_T)$. Here p is the pressure, p_s, p_T are the pressure values at the low and upper boundaries of air mass. All considerations in Sect. 2 concerning this problem in Cartesian coordinates remain valid in this case too.

For digitization of the advective terms of the transfer equation the monotonic balance numerical schemes with nonlinear renormalization of advective fluxes were used.[3] The operators of turbulent exchange were approximated over space by the three-point schemes of the second order of accuracy. The integration of the problem was performed with the use of the two-cycle method of splitting.[4,5]

The primary goal of this study is to determine the character of pollutant transport under conditions of atmospheric circulation over the city. Therefore the impurity is considered as a passive tracer and the pollutant concentrations are given and calculated in relative units. According to conditions (3) and (5) the concentration of a pollutant coming through the boundary was assumed to be equal to unity.

In conducting the numerical experiments, the consideration of meteorological situations typical for a definite season is of great interest. This is caused by the fact that during a season the orographic and dynamic characteristics of underlying surface vary only slightly and its temperature varies only within the range of diurnal behavior.[6] In calculating the components of the velocity vector and turbulence coefficients in the model of atmospheric dynamics, the temperature of underlying surface was set according to diurnal variation as a periodic function taking into account the categories of land use and season.

As an example we give the fragments of scenario of modeling the atmospheric circulation and pollutant transport for the fall season assuming southwest background flux (Figs. 2–5). The velocity of the background flux of air masses was given in the model being equal to 10 m/s at a level of 700 hPa.

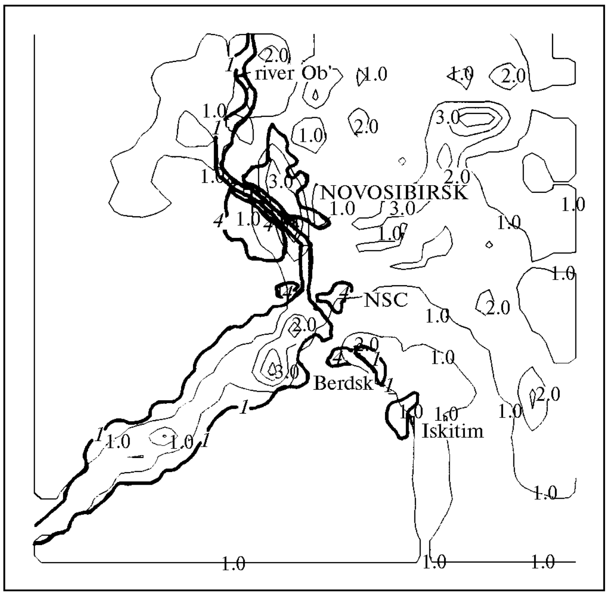

Fig. 2. The field of pollutant concentration (50 m above the level of relief) in the region at the southwest background flux (10 m/s). Fall, 6:00 LT.

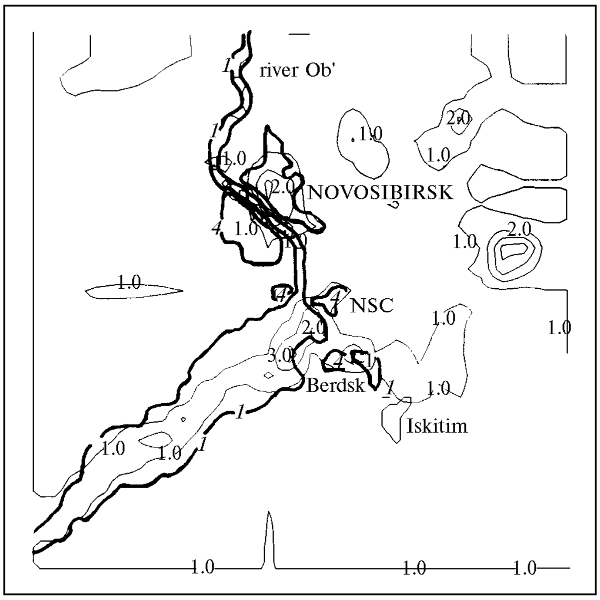

Fig. 3. The same as in Fig. 2, but for 15:00 LT.

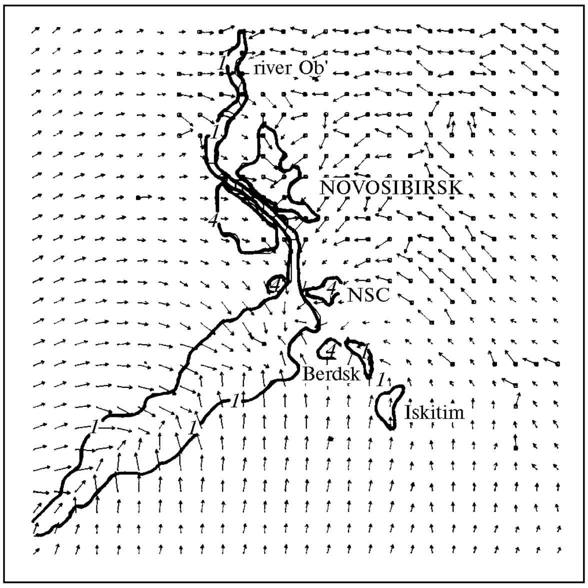

Fig. 4. Horizontal structure of the wind field (50 m above the relief level) under the same conditions as in Fig. 2.

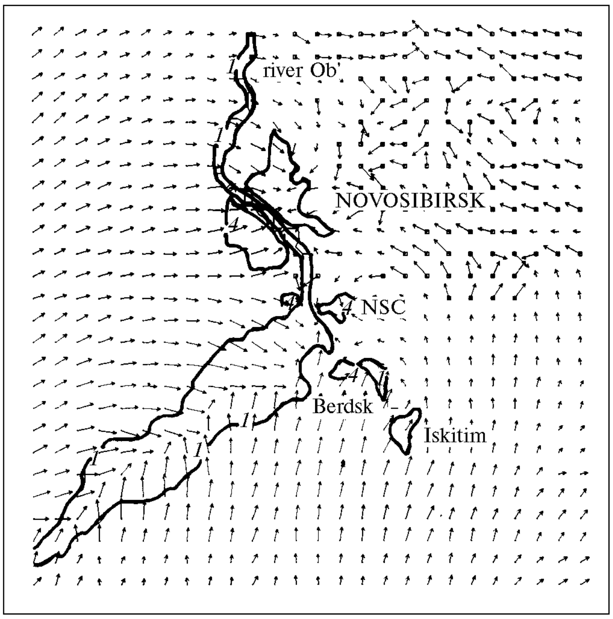

Fig. 5. The same as in Fig. 4, but for 15:00 local time.

In calculations we used a 26×26 horizontal grids with a step of 4 km at 10 vertical levels. The model, the technique, the calculation procedure, and organization of simulation scenarios have been described in detail in the literature.[1,2] The above literature describes the two-dimensional horizontal plans of the calculated fields of state function at 50 m height above the relief level. Figures 2 and 3 show the field of pollutant concentration in relative units at 6:00 and 15:00 local time, and Figures 4 and 5 show the horizontal field of wind velocity. At points of small velocity the arrows are mapped as squares.

Both at night-and day-time the Novosibirsk water reservoir is a high-power heat island, however, the temperature contrast between water and dry land increases at night-time. The urban territory is also warmer than the surroundings. The interaction of the background flux with the underlying surface results in the formation of a complex structure of atmospheric circulation. In this region the badly ventilated areas are formed in the leeward zones of heat islands that, in its turn, contributes to the creation of inhomogeneities of the concentration field. The concentration maxima are observed both in the leeward zones of local heat islands and in the leeward zone of the high-power heat island created by Novosibirsk and the Novosibirsk water reservoir.

3. Conclusion

Analysis of the results of numerical experiments shows that with at such formulation of the transfer model even at homogeneous initial and boundary conditions and in the absence of pollution sources within the territory of the region, there appear inhomogeneities in the pollutant concentration field due to the peculiarities of local atmospheric circulation. This means that different areas of the region will have different load of anthropogenic pollution. The position of areas of minimal and maximal concentrations is determined first by the characteristics of underlying surface and the presence of orographic inhomogeneities. The influence of the direction of background flux should be taken into account at velocities larger than 4 or 5 m/s and increases with the velocity growth. Under real conditions the air quality depends on the intensity of pollutant emission by the sources located within the territory of the region and on the pollution flux across the boundary of the region, i.e., on the distant sources. And only the joint use of models of atmospheric dynamics and the pollutant transport with the results of the observation experiments has made it possible to discover the regularities in pollutant distribution and specific properties of their manifestation under specific meteorological conditions.

Acknowledgments

The work has been supported by the Russian Foundation for Basic Research (Projects No. 97–05–6511 and 98–05–65318) and Integration Grant of SB RAS–97 No. 30.

References

1. V.V. Penenko, M.G. Korotkov, Atmos. Oceanic Opt. **10**, No. 6, 365–369 (1997).
2. V.V. Penenko, M.G. Korotkov, Atmos. Oceanic Opt. **11**, No. 6, 492–496 (1998).
3. A.A. Bott, Mon. Wea. Rev. **117**, 1006–1015 (1989).
4. G.I. Marchuk, *Numerical Solution of Problems of Dynamics of the Atmosphere and the Ocean* (Gidrometeoizdat, Leningrad, 1974), 304 pp.
5. V.V. Penenko, *Methods of Numerical Simulation of Atmospheric Processes* (Gidrometeoizdat, Leningrad, 1981), 352 pp.
6. L.T. Matveev, *Manual of General Meteorology. Atmospheric Physics* (Gidrometeoizdat, Leningrad, 1984), 752 pp.