MODELING OF MESOCLIMATE AND ATMOSPHERIC POLLUTION IN INDUSTRIAL REGIONS (TOMSK AS A CASE STUDY)

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We present mathematical models of atmospheric hydrothermodynamics and pollution transport in the atmosphere of industrial regions. The model examples of mesoclimate and dispersal of air pollution for typical situations in the Tomsk industrial region are given.

1. INTRODUCTION

The necessity of studying changes in hydrothermodynamic processes, as well as the need in evaluating ecological future of industrial regions initiate constructing mathematical models of these processes.[1,2] Spread of pollution in the atmosphere of a large city and, in general case, an industrial region takes place against the background of atmospheric circulation. Air mass circulation is the result of interaction of large-scale atmospheric motions with local inhomogeneities of the underlying surface of warmer (as compared to environment) city, temperature difference between land and water reservoirs, as well as temperature contrasts between different areas of the underlying surface. When modeling processes of such a scale, one should take into account the anthropogenic factors artificial sources of heat, moisture, pollutants, and changes in the Earth's surface parameters over large areas.

To take into account the effect of the underlying surface and to describe air flows in the surface layer more accurately within the framework of the models considered, corresponding parametrizations are introduced. To describe inhomogeneities of the underlying surface itself, the concepts of land exploration categories are used. For every category, individual estimations of the Earth's surface parameters are set both in their natural form and allowing for their anthropogenic changes.

2. BASIC SYSTEM OF EQUATIONS

Our numerical model is based on the system of equations of hydrothermodynamics and pollution transport in the atmosphere. Let us consider a system of complete equations of atmospheric hydrothermodynamics in the quasistatic approximation above inhomogeneous Earth surface. For a convenience of allowance for surface relief, the model uses vertical coordinate that describes the relief

$$\sigma = (p - p_t)/\pi_s, \quad \pi_s \equiv p_s - p_t , \tag{1}$$

where p is pressure; p_t and p_s are the pressure values at air mass top and the Earth's surface. Coordinates x and y are directed to east and north, respectively.

Let us write basic equations of the model.[2,3] The equations of motion

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

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

where $\Phi \equiv \sigma \pi_s + p_t$.

The equation of continuity

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

Here we use the following designations:

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

is the transfer operator in σ-coordinate system in the divergent form;

$$\tilde{\mathcal{L}}(\pi_s \varphi) = \mathcal{L}(\pi_s \varphi) + F_\varphi^{\mathrm{H}} + F_\varphi^{\mathrm{B}} , \tag{6}$$

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

The equation for pressure tendency $\pi_s \equiv p_s - p_t$:

$$\frac{\partial \pi_s}{\partial t} + \int\limits_0^1 \left[\frac{\partial \pi_s u}{\partial x} + \frac{\partial \pi_s v}{\partial y}\right] d\sigma = 0. \tag{7}$$

This equation is obtained by integrating the continuity equation (4) over the vertical coordinate under conditions: $\dot{\sigma} = 0$ at $\sigma = 0$ $(p = p_t)$ and $\sigma = 1$ $(p = p_s)$.

The equation for vertical velocity in the σ-coordinate system is

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

the parameter $\frac{\partial \pi_s}{\partial t}$ can be removed from this equation using Eq. (7).

The equation of heat influx is

$$\frac{\partial \pi_s T}{\partial t} + \tilde{\mathcal{L}}(\pi_s T) - \frac{RT\tau}{c_p\,(\sigma + p_t/\pi_s)} = \frac{\pi_s Q}{c_p}, \qquad (9)$$

$$\tau = \frac{dp}{dt}; \quad \tau = \pi_s \dot{\sigma} + \sigma \frac{d\pi_s}{dt};$$

$$\frac{d\pi_s}{dt} = \frac{\partial \pi_s}{\partial t} + u\frac{\partial \pi_s}{\partial x} + v\frac{\partial \pi_s}{\partial y}, \qquad (10)$$

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

The equations of hydrostatics is as follows:

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

The equation of the admixture transfer is

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

where f is the function describing the pollution sources; φ is the pollutant concentration. In the general case, pollutants in the atmosphere are multicomponent mixtures. The number of components is set as an input model parameter.

The rates of pollutant sedimentation due to gravitation are taken into account by adding corresponding values to vertical velocity components.

To make the mathematical model closed, initial and boundary conditions should be set. At the low boundary the conditions are set using parametrized models of the surface and boundary atmospheric layers; at the upper boundary and at lateral boundaries these conditions are set using the conditions of coming to «background» processes.[2]

Discrete approximations are based on the variation principle in combination with the splitting method.[3] Following the method of splitting into physical processes,[4] let us separate out two stages: 1) transfer with turbulent exchange and 2) dynamic matching of fields of meteoelements. At the stage of transfer, monotonic numerical schemes[5–7] are used for approximation of the advective-diffusion operators of the type (6).

The experience of using the splitting method for solving the problems of geophysical hydrothermodynamics shows that the problem of field dynamic matching is most complicated and cumbersome stage of splitting. The relation between spatiotemporal scales of the phenomena at the modeling stage of matching is such that for their correct reproduction one needs to use implicit or explicit-implicit schemes. This happens because the operator of matching the pressure gradient and wind field in spatial variables without the account for turbulent exchange is antisymmetric, while two-layer schemes for problems with antisymmetric "spatial" operators are unstable in time.

To solve the problem, at the stage of matching, the explicit-implicit direct algorithm is used that provides for energy balance if the approximation conditions hold true and, as a consequence, make calculations stable independently of the temperature stratification of the atmosphere.[8]

3. SCENARIOS OF MODELING THE MESOCLIMATE AND THE QUALITY OF THE ATMOSPHERE

When modeling the atmospheric processes of mesoregional scale one needs to know the value of the function of state at the initial moment in time. In addition, continuous flow of information about the "background" state of the atmosphere, i.e. the data on large-scale processes, are needed. Without this information it is problematic to set correctly the initial conditions at lateral boundaries of the region. Usually, the initial data and data on background processes are either absent or irregular in space and time. Therefore it is a serious problem to initialize models or to make them closed by boundary conditions at limited territories when solving problems in real-time mode. Our main goal is to study the conditions of mesoclimate formation. In this case it is convenient to work within the framework of a scenario approach. This approach requires formation of a set of atmospheric circulation scenarios, and, naturally, of a special interest in this case is modeling of scenarios corresponding to most frequent meteorological situations and evaluation, on their basis, of anthropogenic impact on the objects under study. This also would allow revealing of areas most unfavorable, from the ecological point of view, for new industrial enterprises.

To evaluate the intensity and configuration of the areas affected by anthropogenic sources, we used the functions of functional sensitivity determining mean values of pollutant concentration in subareas of the region for certain time intervals.

Detailed description of the set of models, information-modeling system, and examples of the forecast-expert scenarios made on their basis are given in Refs. 9 and 10. Their analysis shows that evaluation of the atmospheric quality and ecological future of industrial centers should be done taking into account the fact that town is a part of a climatic system of the industrial region as a whole. As a result of interaction of local structure of the town heat islands, inhomogeneities of the underlying surface of the surrounding territory with the air inflow, a complex system of atmospheric circulation is formed involving ascending air flows over overheated areas of the underlying surface and, what is characteristic, backward flows. Therefore assessment of ecological situations and planning of nature-protection measures in the vicinity of "island of heat" with techniques based on the use of "wind rose" will not be adequate to actual state.

To study the peculiarities of mesoclimate formation in Tomsk region and to model the structure of atmospheric circulation in the vicinity of Tomsk in a more detail, the boundaries of the so-called Tomsk industrial region and Tomsk region were determined.

Since in Siberia the underlying surface is sufficiently homogeneous over vast areas and large industrial centers are far from each other, we supposed that local factors of both natural and anthropogenic origin play a decisive role in formation of atmospheric circulation and air quality in Siberian industrial regions. Such an assumption allows the size of modeling domain to be significantly decreased. Below by the Tomsk region we mean the 100×100 km area, and by the Tomsk industrial region the 50×50 km area. The centers of these areas coincide with the center of Tomsk. The height of the free upper boundary of air mass coincides with the 700 Mbar isobaric surface. The first calculated level coincides with the height of the free upper boundary of the air mass. In our calculations, the height of the surface layer was taken 50 m over the relief level of the underlying surface. The surface characteristics are presented by parametric division of the following categories: water surface, coniferous forest, deciduous forest, mixed forest, city building, country building, field, marshes.

To perform scenario calculations, the data bank was compiled for the whole region that contains information required to set the input parameters of the model, the land types were mapped, and the arrays of values of relief height above the sea level were constructed with different degree of discretization.

Figure 1 shows the mapped scheme of Tomsk industrial region at which only two of eight categories of land are shown (water and city building), boundaries of Tomsk region are shown, as well as the settlements.

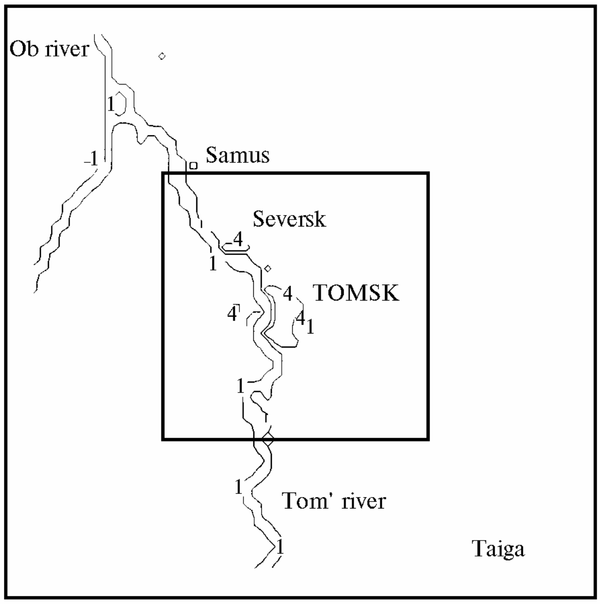

FIG. 1. Tomsk industrial region. 100×100 km *area: 1— water reservoir boundary; 4 — boundary of city regions.*

As an example, we present the results of modeling the scenario corresponding to day time in summer at the background west wind the speed of which was taken to be 5 m/s. Such direction and speed of background air flow are typical for summer season. In addition, this scenario is interesting by the fact that the air inflow is under strong influence from the underlying surface inhomogeneity.

Figure 2 shows the structure of atmospheric circulation in the Tomsk industrial region at a height of 50 m over the surface. Arrow length at this figure is proportional to the wind speed at the grid nodes. Squares are for the nodes in which the wind speed is less than the maximum value for this region by an order of magnitude.

Character of air mass motion in the central part of the region is mainly determined by the interaction between city "island of heat" and running-on background air flow. Behind the city the vortex cell is formed with a relatively weak counter flow. In the low layer over the city, wind becomes stronger due to breeze effect caused by the influence of temperature contrasts between the river Tom', neighbouring territories, and the city. This favors city ventilation from windward side. At the same time, behind the city, in the area of counter currents, the conditions are formed favorable for accumulation of pollutants transported by the wind from the city and other territories being in the zone of vortex flow formation. On the whole, in the leeward part of the area, air mass motion becomes slower and circulation cells are formed.

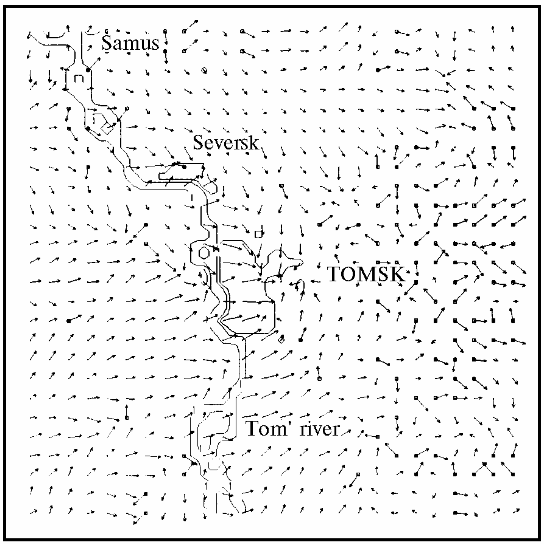

FIG. 2. Tomsk industrial region. Structure of atmospheric circulation. Horizontal section at 50 m *over the surface.*

Figure 3 shows the field of pollutant concentration at the height of 50 m over the surface from a stationary point surface of a unit power, situated 25 km north-west of Tomsk. The extreme isoline corresponds to 0.1 % of maximum concentration in the area, while the succeeding ones correspond to 1, 10, 20, 30 %, etc., respectively. One can see that the pollution cloud spreads against the background of air circulation and covers the city of Seversk and Tomsk. From the view point of ecological safety, this situation is interesting because here the mechanism of entraining pollutants to the zone affected by the island of heat manifests itself although the west background flow should transport pollutants away from these cities.

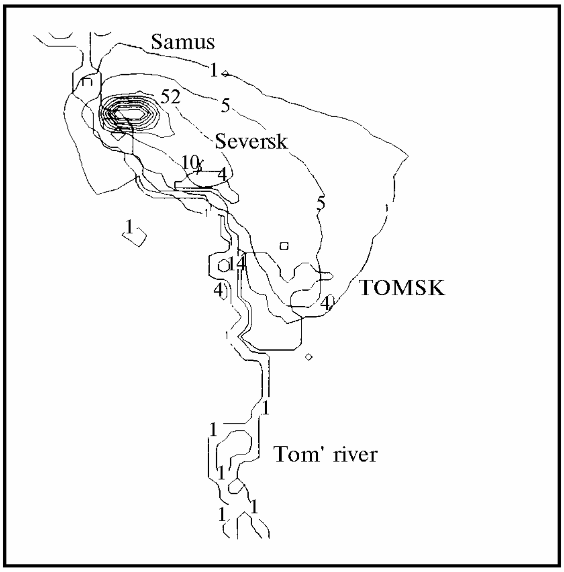

FIG. 3. Tomsk industrial region. Field of pollutant concentration. Horizontal section at 50 m over the surface.

Figure 4 shows the function of influence of the pollution sources on the quality of the atmosphere in the populated areas.

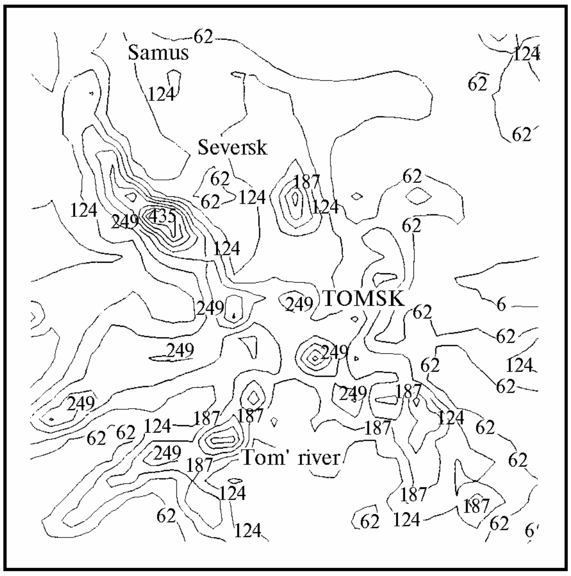

FIG. 4. Tomsk industrial region. Function of influence for populated areas of the region. Horizontal section at 50 m *over the surface.*

The functional estimated is the pollutant concentration averaged in time and over the populated areas of the region with the weight conditionally allowing for difference in population density. Thus, for example, the weight of concentration measurements at every point of the region for city territories is twice as high as that for country settlements. Selection of weighing function and measures for functional calculation is done in accordance with the goal the research. In this case, the experiment is methodical, and functional was constructed by the principle of "protected zones". Therefore the function of influence also is the superposition of functions for separate zones. From the information side, the function of influence characterizes relative contributions of sources to the functional estimated, and, as a consequence, that the greater it is at a point, the greater is the contribution from the pollution source situated at this point to the functional. Placement of pollution sources in the vicinity of maxima is most favorable from the ecological point of view.

4. CONCLUSION

Analysis of the scenario modeling results confirms our thesis that for ecological planning and forecasting it is insufficient to use some simplified methods, that are usually used in practice for solving problems of the environmental protection. It is necessary to take into account specific features of the regions and their potential in formation of ecologically unfavorable situations.

Our experience suggests that socially acceptable assessments of ecological future can be obtained only using sufficiently complete, in their physical content, mathematical models allowing for interaction between the hydrothermodynamic, chemical and biospheric the processes in the climatic system of towns and industrial regions at different anthropogenic impact. One of the basic models of this class is described in this paper. With such an approach to the problem of nature-protection forecasting, situations with "unexpected" manifestations of ecological catastrophes will be excluded.

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