APPLICATION OF NUMERICAL MODELS FOR FORECASTING OF EMERGENCY AND ECOLOGICALLY UNFAVORABLE SITUATIONS IN THE ATMOSPHERE

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Received February 12, 1998

This paper discusses the problems on organization and application of numerical models of the atmosphere hydrothermodynamics and pollution transfer in order to study and forecast ecologically unfavorable and emergency situations in the climatic system of towns and industrial regions with respect to modes of natural and anthropogenic pollution transfer and accumulation in the atmosphere.

1. INTRODUCTION

The problem on quality and forecasting capabilities of the mesoscale models of atmosphere hydrothermodynamics and pollution becomes very significant, when they must be used for solution of real environmental problems associated with ecological safety of population and natural complexes. Currently this problem is especially actuate in connection with the increased risk of technogenic emergencies in practically all branches of economy in Russia and CIS.

Models of such class are characterized by high space-time resolution, and for correct calculations they require a large bulk of actual information about current state of the climatic system. That is why they usually work well for evaluation of situations in the scenario mode, when there is a significant degree of freedom in selection of input data and no time deficit.

The main point in work in emergency and extremal situations and in a specific region is fast and adequate initialization of the models and generation of a forecast. In this case, time is the determining factor in taking a decision on evaluation of the extent of action and measure to relief its negative consequences. This means that the models should be initialed and the forecast should be generated faster than "real time" of situation evolution. Initialization is made by actual information about state of the atmosphere. In real conditions, even in normal situations, not to mention about emergencies, it is practically impossible to obtain a set of measurement data sufficient for formation of 3D-initial fields of state functions with the spatial resolution required by the model. Such technical capabilities are simply absent.

This paper proposes the way to solve such problems with minimal set of observation data as a basic model for forecasting fields of meteoelements and pollutant concentration, we use the model of dynamics and pollution of the atmosphere of industrial regions.[1,2]

2. STATEMENT OF THE PROBLEM

Main equations of the model are the following[2]:

$$\frac{\partial U}{\partial t} + \Lambda(U) - lV = -\pi_s\left[\frac{\partial H}{\partial x} + \frac{\sigma RT}{\Phi}\frac{\partial \pi_s}{\partial x}\right]; \qquad (1)$$

$$\frac{\partial V}{\partial t} + \Lambda(V) + lU = -\pi_s\left[\frac{\partial H}{\partial y} + \frac{\sigma RT}{\Phi}\frac{\partial \pi_s}{\partial y}\right]; \qquad (2)$$

$$\frac{\partial \tilde{T}}{\partial t} + \Lambda(\tilde{T}) - \frac{RT\tau}{c_p(\sigma + p_{\mathrm{T}}/\pi_s)} = \frac{\pi_s Q_T}{c_p}; \qquad (3)$$

$$\frac{\partial \pi_s}{\partial t} + \int_0^1\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right)\mathrm{d}\sigma = 0; \qquad (4)$$

$$\frac{\partial H}{\partial \sigma} + \frac{\pi_s RT}{\Phi} = 0; \qquad (5)$$

$$\frac{\partial(\pi_s c)}{\partial t} + \Lambda(\pi_s c) = Q_c. \qquad (6)$$

Here,

$$\sigma = (p - p_{\mathrm{T}})/\pi_s; \quad \pi_s = p_s - p_{\mathrm{T}}; \quad \Phi = \sigma\pi_s + p_{\mathrm{T}},$$

where p is pressure; p_{T} and p_{s} are pressure at the top of air mass and at Earth's surface; u, v, and $\dot{\sigma}$ are components of the velocity vector $\mathbf{u}$ in the direction of coordinates x, y, and σ, respectively; t is time; $U = \pi_s u$; $V = \pi_s v$; $\tau = \mathrm{d}p/\mathrm{d}t$ is vertical velocity in

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isobaric coordinates; H is geopotential; T is temperature; $\tilde{T} = \pi_s T$ $c = \{c_i\ (i = \overline{1, k})\}$ is pollutant concentration; k is the number of different substances; Q_T and Q_c are heat and pollution sources; R is universal gas constant; c_p is specific heat capacity; l is the Coriolis parameter; $\Lambda(\pi_s\varphi)$ is advectively diffusion operator. In the transfer operator for Eq. (6), the rate of gravitation sedimentation or lift of pollutant particles was additionally taken into account in the vertical velocity.

The problem is solved in the space-time area D_t with the boundary conditions: $\dot{\sigma} = 0$ at $\sigma = 0.1$ and $H = gh(x, y)$ at $\sigma = 1$, where g is free fall acceleration; $h(x, y)$ is terrain of the Earth's surface. At the side and top boundaries of the area D_t, the corresponding state functions are assumed having background values. At the bottom boundary, conditions are given for fluxes of angular momentum, heat, and pollutants within the framework of the parametrization model of the surface layer[1] with regard for stratification of the atmosphere and diurnal behavior of the underlying surface in dependence on the land tenure categories.

3. ESTIMATION OF THE BACKGROUND STATE OF THE ATMOSPHERE

To describe the fields of meteoelements within the framework of the local and mesoscale models, the principle of decomposition by process scales[1] is usually used. In accordance with this principle, the state functions are presented as a sum $\varphi = \Phi + \varphi'$, where Φ is the background value of the state function, which is considered as a given one, and φ' is the sought deviation from the background value.

Let the background functions have characteristic space-time scales greater than the corresponding scales for deviation functions φ'. At this approach, processes can be considered as quasi-stationary, and their time dependence can be set parametrically in description. Such decomposition to some degree simplifies the problem with statement of the initial conditions and conditions at the top and side boundaries of the area, because in this case the conditions are stated for deviations or their derivatives, and the background values of state functions calculated from current information can be taken as the initial conditions.

Having assumed the quasi-stationary character of the background behavior, for calculation of velocity vector components of the background flow let us use the stationary model of atmosphere dynamics over the inhomogeneous Earth's surface

$$\mathbf{u}\ \mathrm{grad}\ u - l(v - v_g) - \nu \frac{\partial^2 u}{\partial z^2} = 0\ ; \qquad (7)$$

$$\mathbf{u}\ \mathrm{grad}\ v + l(u - u_g) - \nu \frac{\partial^2 u}{\partial z^2} = 0\ ; \qquad (8)$$

$$\mathrm{div}\ \mathbf{u} = 0; \qquad (9)$$

$$\frac{\partial p}{\partial z} + g\rho = 0, \quad p = \rho RT\ , \qquad (10)$$

where u, v, and w are components of the velocity vector $\mathbf{u}$ in the coordinate system (x, y, z); ρ is density; u_g and v_g are components of the velocity vector of the geostrophic wind. For the boundary layer, the following relationship is taken

$$\frac{\partial}{\partial z}|u + iw| = \frac{u_*}{\varkappa}\left(\frac{1}{z} + \frac{a}{L}\right), \qquad (11)$$

where i is imaginary unit; u_* is friction speed; $\varkappa$ is the Karman constant; a is an empirical constant; L is the Monin-Obukhov scale.

To close the model given by Eqs. (7)–(11), we use the following boundary conditions:

$$u = v = w = 0 \ \text{ at } z = h(x, y);$$

$$u = u_g,\ v = v_g,\ p = p_\phi \ \text{ at } z = h_b;$$

$$u + iv = A\partial/\partial z(u + iv) \ \text{ at } \ z = h(x, y) + h_s,$$

where h_s is the height of the surface layer; h_b is the top boundary corresponding to p_T; p_ϕ is the background value of pressure; A is the constant. In horizontal variables, all functions are assumed sufficiently smooth and limited.

If the values of parameters ν and l are constant in space, solution to Eqs. (7)–(9) and (11) with these boundary conditions can be found analytically.[3] Thus, we can calculate the background values of wind field $\mathbf{u}$ in the area D_t with regard for inhomogeneous terrain. Some input parameters are used here: $\{u_g, v_g, \nu, a, L, h_s, h_b, h(x, y)\}$.

The velocity of the geostrophic wind at the height $z = h_b$ is given by the measurement results. It is assumed parametrically dependent on time. At relatively large horizontal size of the area D_t, the velocity $\{u_g, v_g\}$ can depend on (x, y). In this case, the area is divided, by the horizontal, into a set of sub-areas with step parameters $\{u_g, v_g, \nu\}$, and wind velocity components are calculated for every sub-area. If necessary, background values of pressure and density fields are calculated from the observation data on pressure p_ϕ at the height h_b and the data on temperature using Eq. (10).

This paper deals with use of numerical models for forecasting fields of meteoelements in real time and, against their background, processes of pollution spread in the atmosphere in emergency situations accompanied with emission of toxic pollutants. In such situations, it is necessary to decide at least whether the system for observation over pollutant propagation should be set up or not. This system must allow the evaluation (depending on pollutant composition) of chemical, bacteriological, or radiological situation in order to organize necessary measures on prevention of possible negative consequences. The presence of forecast allows planning of these measures.

For certainty, we consider the case with relatively cold emission, i.e. when temperature increment in a medium-size cell of the grid area and for the time period Δt of model discretization is the value of the order of 1–5 K. This is the restriction of the considered basic model given by Eqs. (1)–(6). At higher rate of emergency heating of the atmosphere, it is necessary to use model in non-hydrostatic approximation.[1]

The model given by Eqs. (7)–(11) is functionally full and agrees with the basic model in physical content. Therefore, the background state obtained with this model gives good start conditions for the basic model and without shock effects usually appearing at initialization of models with incomplete observation data due to disagreed characteristic scales and model errors and real fields. Agreement procedures are very cumbersome and computationally expensive.

4. EXAMPLES OF TYPICAL SITUATIONS

Let us consider the examples of calculation of some situations, which usually occur in industrial regions with specific modes of pollutant spread and accumulation, caused by particular peculiarities of territories and objects situated there – the pollution sources. These situations become extremal, if pollutants "suddenly" prove to be highly toxic.

Experiment 1. Aim of this experiment is to estimate the influence of changes in temperature at the Earth's surface in the mode of diurnal behavior and the background wind velocity on the character of local circulation and pollutant spread in the atmosphere using the Novosibirsk region as an example. The set of stationary sources localized in the Berdsk city adjacent to the Novosibirsk water storage and situated 40 km to the south from the center of Novosibirsk and 15 km to the south from the Akademgorodok (the Scientific Center) plays the part of pollutant sources.

Considered are two scenarios with different value of the background flow velocity: scenario A – 5 m/s and scenario B – 7 m/s. In both versions, flow is south-west, the season is summer. The models were initialized by the above-described method. Figure 1 presents the 2D cross sections of calculated pollutant concentration 50 m above the terrain for 09:00 a.m. and 09:00 p.m. LT.

In both scenarios, at night time pollutants spread mainly in the low layers of the atmosphere, what is caused by inversion establishing at this time as a result of cooling of the underlying surface. At night the temperature of the water storage is higher than the temperature of adjacent land. In the vicinity of the source, direction of the breeze wind coincides with that of the background wind. That is why the directions of pollutant motion in scenarios A and B are close (Figs. 1*a* and *c*).

In this case, significant is the fact that at weak background wind (Fig. 1*a*) and consequently bad refreshing pollutant concentration in the source vicinity is far higher than at stronger wind (Fig. 1*c*). As seen in Fig. 1*a*, in scenario A the local maximum of concentration is formed at the north-east outskirts of Akademgorodok. In scenario B, this effect is not so pronounced, and the local maximum is shifted to the north from the Scientific center.

In daytime, the pollutant propagates in both vertical and horizontal direction. The breeze wind direction is opposite to that of the background wind. In scenario A, the background wind velocity is low, and the pollutant practically does not propagate to the Berdsk cove shore opposite to the source (Fig. 1*B*). In scenario B, the background flow already can overcome the mass of cold air over the cove, and the pollutant comes to the territory of Akademgorodok. Since the later acts as an island of heat both in daytime and at night, the badly refreshed zone accumulating the pollutant arises at its leeward outskirts.

These scenarios show that, even in relatively comfort conditions with moderate background refreshing of the atmosphere, the zone of pollution accumulation arise due to local peculiarities of terrain and temperature contrasts of the type "water – land – city," what results in ecologically unfavorable situations. We specially consider here only remote sources, in order to demonstrate the characteristic scales of pollution processes. Local sources significantly enhance the pattern of pollution, especially in the low atmosphere. It should be noted that sanitary zones are usually taken 0.2–1.5 km wide around a source.

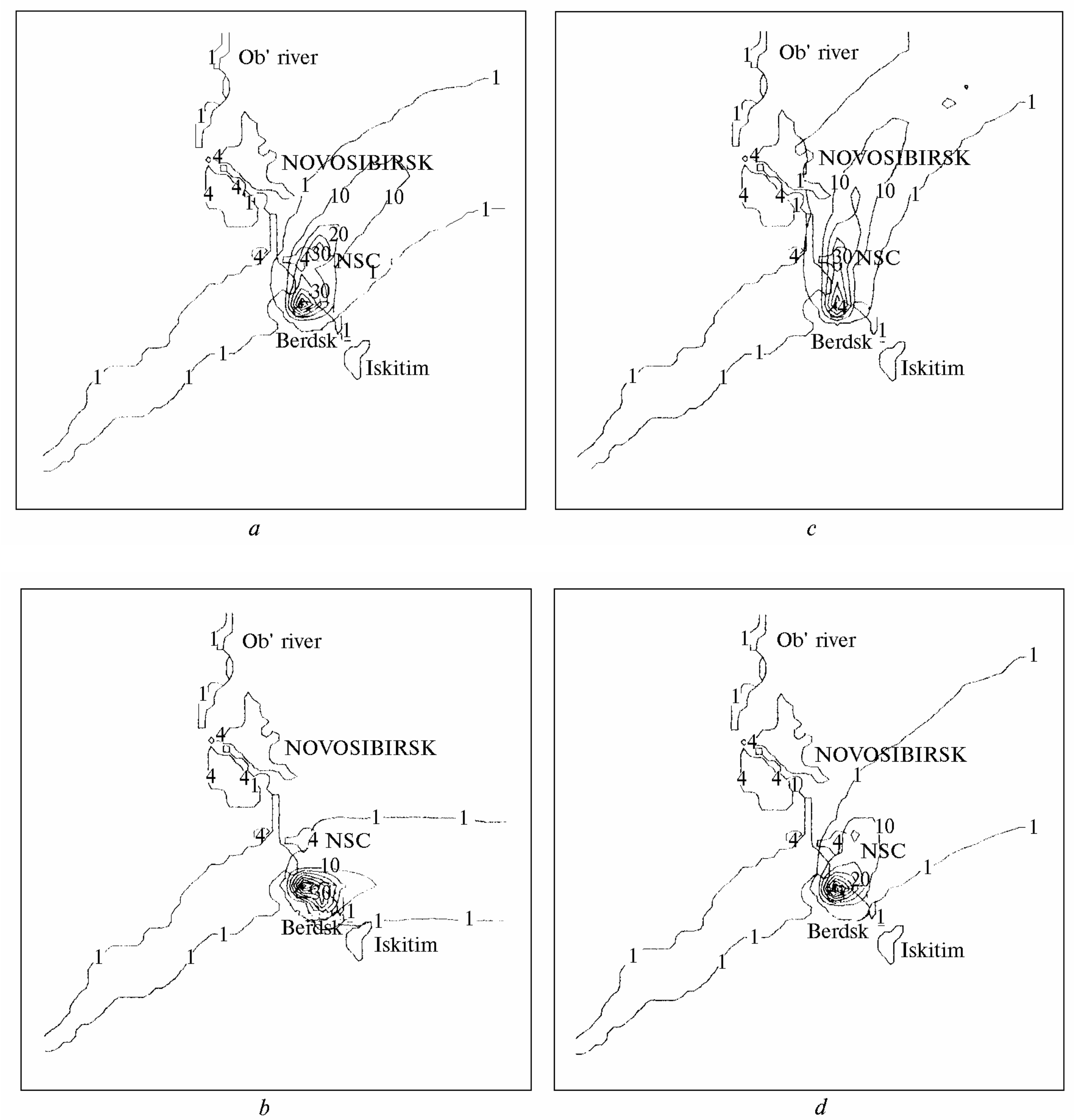

FIG. 1. Diurnal behavior of fields of pollutant concentration in the atmosphere of Novosibirsk city caused by pollution sources in Berdsk city (summer season, south-west background flow, 2D cross sections 50 m *above the terrain, local time):* 09.00 a.m. *(a),* 21:00 *(b),* 09:00 *(c), and* 21:00 *(d) at background wind of* 7 m/s.

Experiment 2. The aim of this experiment was to reproduce situations connected with formation of mesoscale atmospheric circulation in the Tomsk region and pollutant spread at emergency emission of radio nuclides from the radiochemical plant in Seversk. Input data for calculation were set from the available actual information for April 6–13, 1993.

Background flow was south-west with velocity of 7 m/s at the level of 700 mbar. The wind field is formed as a result of background flow interaction with orographic and thermal inhomogeneities of the underlying surface, its fragment is shown in Fig. 2*a*.

Pollutant propagates in such a way that the zone of increased pollution includes the settlement Georgievka, to the north-east from which the local maximum of concentration is formed (Fig. 2*B*). At the same time, the settlement Naumovka, which is situated at the background wind trajectory, proves to be out of the zone of maximum pollution. The modeling results were compared with the measurement results of radioactive pollution of the area from Ref. 4.

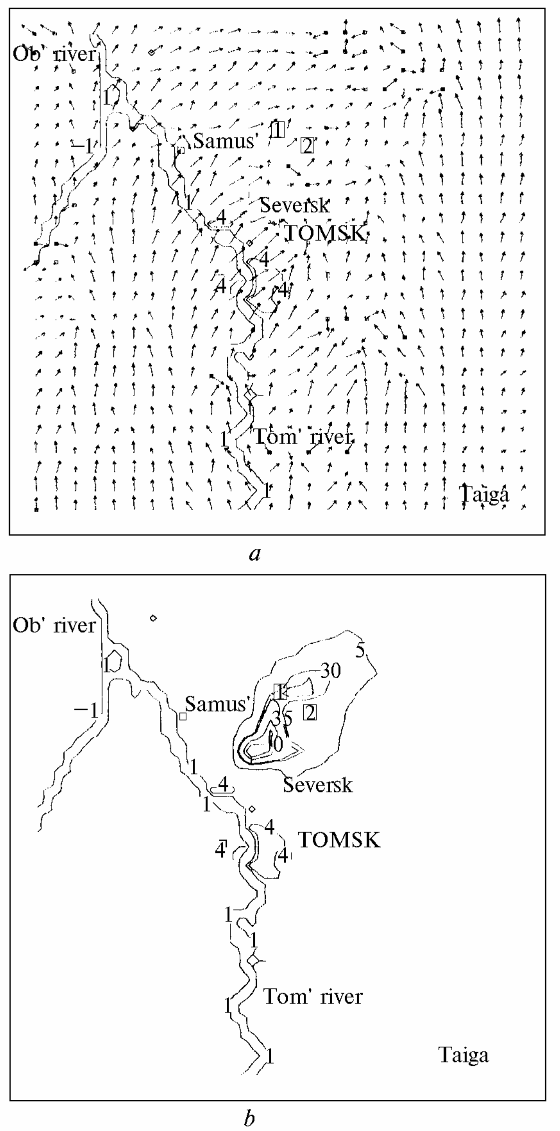

FIG. 2. Numerical experiment on modeling of pollution propagation from a point source (radiochemical plant in Seversk), Georgievka (1), Naumovka (2): horizontal structure of the atmospheric circulation 50 m *above the terrain, south-west background flow,* 7 m/s *(a); pollutant concentration field (b).*

Figure 2*B* shows the 2D cross section of the calculated field corresponding to the scheme of the zone of territory increased pollution with radio nuclides constructed in Ref. 4 from the measurement data. Note that concentration fields calculated by us agree with the scheme[4] in configuration and intensity of the zone of increased pollution. This agreement indicates the good potential capabilities, in reproduction and forecast of real situations, of the model and the presented method of fast initialization of models by the limited set of actual data.

CONCLUSION

The presented complex of models supplemented by the initialization procedure possesses high efficiency and mobilization readiness for use for calculation of extremal situations, because it require minimum actual information about background atmospheric processes. It should be noted that for successful estimation of extremal situation, the attention should be paid to obtaining of plausible information about pollution parameters.

ACKNOWLEDGMENT

This work was partially supported by the Russian Foundation for Basic Researches (Grant No. 97–05–96511) and the Integration Grant IG SB RAS–97 No. 30.

REFERENCES

1. V.V. Penenko and A.E. Aloyan, *Models and Methods for Problems of Environmental Protection*, (Nauka, Novosibirsk, 1985), 256 pp.
2. V.V. Penenko and M.G. Korotkov, Atmos. Oceanic Opt. **10**, No. 6, 365–369 (1997).
3. S.K. Kao, J. Appl. Meteor. **20**, No. 4, 386–390 (1981).
4. Yu.A. Israel et al, Meteorol. Gidrol., No. 6, 5–8 (1993).