NUMERICAL MODELING OF BACKGROUND ATMOSPHERIC PROCESSES AND THE PROBLEM OF AEROSOL TRANSPORT IN SIBERIAN REGION

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The structure and the state of the art of the system MAP for modeling of atmospheric processes and pollutant transport in Siberian region, being developed at the Institute of Computer Technology of the Siberian Branch of the Russian Academy of Sciences (ICT SB RAS) and intended to expertize meteorological conditions and emissions of pollutants into the atmosphere from observational data, are described in the present paper.

I. INTRODUCTION

The project "Aerosols of Siberia" is aimed at the study of patterns of aerosol transformation and transport in Siberia region.[1]

A powerful means of investigation of these processes is a computer experiment,2 which is taken to mean the sequence of operations including an analysis of examined process, construction of its mathematical model, software development, calculation, and analysis of obtained results. One of the most attractive features of the computer experiment as a means of investigating the atmospheric processes is not only the possibility of modeling of scenarios for prescribed states of the environment, but also its perfect safety for people and environment itself. At the same time, the computer experiment calls for the complex software to solve the above-enumerated problems, in particular, to describe the background processes in the atmosphere and to select or to create the bases of meteorological data and concentration and composition of the atmospheric aerosol.

A brief review of the advanced meteorological data bases (already available and being developed now) required for the computer experiment is done in the present paper. The construction and the state of the art of the system MAP for modeling of the atmospheric processes and regional pollutant transport, being developed at the ICT SB RAS and intended to expertize meteorological conditions and emissions of pollutants into the atmosphere from observational data with the help of computer experiment, are also described in the paper.

2. METEOROLOGICAL INFORMATION

To run the computer experiment, it is very important to create and to archive data bases or to provide access to them.

The meteorological information can be tentatively divided into routine and research. Data of synoptic (recorded every three hours), aerological (recorded every six and predominantly twelve hours), and continuous satellite sensing are collected at leading World Forecast Centers in about two hours. These data provide a basis for a large body of meteorological data bases of the second (observational data) and third (affixed to the nodes of a latitude–longitude grid) hierarchical levels. The data of the First GARP Global Experiment[3,4] (FGGE) and more extensive and refined bases of reprocessed data, being created now in the European Medium–Range Forecast Center and under the joint Project of the National Environment Center and the National Center for Atmospheric Research of the U.S.A. with the help of systems of meteorological data assimilation,[5] are most suitable for research and expertise. A review of modern systems and techniques for meteorological data assimilation was done in Ref. 6.

3. SYSTEM MAP

The system MAP for modeling of the atmospheric processes and description of pollutant transport in the region, being developed at the ICT SB RAS and intended to expertize,[7,8] includes the following main units:

– scheme for numerical analysis of the data of meteorological observations to reconstruct the initial fields at the nodes of a grid;

– initialization scheme intended to reduce the amplitudes of high–frequency gravity waves or to make them stationary;

– atmospheric model described by the hydrothermodynamic equations;

– model of pollutant transport;

– unit for visualization of the results of the computer experiment.

This structure of the system allowed us to expertize the anthropogenic impact on the atmosphere and the distribution and spread of the aerosol in the atmosphere on a local scale in Siberian region.

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3.1. Description of the units of the system MAP

3.1.1. Analysis

Box option of the method of a three-dimensional multicomponent optimal interpolation[9] is implemented in the scheme for numerical analysis. Prognostic fields and covariation functions of forecast errors for the given atmospheric model and observational data are used as *a priori* information.

Let us denote the vector of observational data by **D**, the vector of prognostic meteorological parameters by **F**, and the rms forecast error by E_{f}. Then the analyzed meteorological parameters at the nodes of the grid A_k can be found from the formula

$$\frac{A_k - \mathbf{F}_k}{E_k} = \sum_{i=1}^{N} w_i \frac{\mathbf{D}_i - \mathbf{F}_i}{E_{\mathrm{f}}} ,$$

where the subscript k indicates the serial number of the grid node and i is the serial number of observation.

In what follows the interpolation method is linear. It specifies the procedure for determining the vector $\mathbf{W} = \{w_i\}$ from the condition of minimization of the mean-square error of the analysis in a statistical sense, that is,

$$\min \overline{(A_k - I_k)^2} ,$$

where I_k is the true value of the meteorological parameter at the kth node and $\overline{(\cdot)}$ denotes the operator of above-indicated averaging.

To determine the weighting coefficients, we must solve a system of normal equations

$$M\boldsymbol{W} = \mathbf{H}.$$

To calculate the elements of the matrix l and the vector **m**, the correlation between the observation errors and between the forecast errors as well as their rms errors is required.

3.1.2. Atmospheric model

Modeling of the predicted state of the atmosphere is based on its hydrothermodynamic model. The efficient five-level atmospheric model for Siberian region, constructed by G.I. Marchuk using the separation technique, was further implemented under his supervision. This model has been used in the regional routine prognostic system for years. To introduce this model in the system being developed, it was refined not only to extend the vertical limits of integration, but also to improve the quality of prediction.[10]

Adiabatic atmospheric model in the coordinate system (. , *3*, p) most suitable for the separation technique (this model was selected for its simplicity) is described by the following system of hydrothermodynamical equations:

$$u_t + \frac{1}{2}\,[uu_x + (uu)_x + vu_y + (vu)_y + \tau u_p + (\tau u)_p] - fv = -gz_x ;$$

$$v_t + \frac{1}{2}\,[uv_x + (uv)_x + vv_y + (vv)_y + \tau v_p + (\tau v)_p] + fu = -gz_y ;$$

$$T = -(gp/R)\, z_p ;$$

$$u_x + v_y + \tau_p = 0;$$

$$T_t + \frac{1}{2}[uT_x + (uT)_x + vT_y + (vT)_y] + \tau\,(\gamma_a - \gamma) RT^*/(gp) = 0.$$

Its solution is reduced to a solution of the advection equations

$$\frac{1}{2}\,\varphi_t + \frac{1}{2}\,[u\varphi_x + (u\varphi)_x + v\varphi_y + (v\varphi)_y + A\varphi_p + (A\varphi)_p] = 0$$

sequentially for each interval $(t_n,\ t_{n+1/2})$ and of a system of the adaptation equations

$$\frac{1}{2}\,u_t - fv = -\,gz_x;$$

$$\frac{1}{2}\,v_t + fu = -\,gz_y;$$

$$T = -(gp/R)\, z_p ;$$

$$u_x + v_y + \tau_p = 0;$$

$$\frac{1}{2}\,T_t + \tau\,(\gamma_{\mathrm{a}} - \gamma)\, RT^*/(gp) = 0$$

for each interval $(t_{n+1/2},\ t_{n+1})$, where p is the pressure; , , v, and τ are the components of the wind vector U along the x, *3*, and p axes, respectively; z is the deviation of the isobaric surface altitude from its standard level; T is the deviation of the temperature from its standard value; T^* is the standard temperature; f is the Coriolis parameter; γ is the standard lapse rate of the temperature; γ_{a} is the adiabatic lapse rate of the temperature; R is the universal gas constant; g is the acceleration due to gravity; $\varphi = (u, v, T)^{\mathrm{T}}$, and 3×3 matrix $A = \mathrm{diag}(\tau, \tau, 0)$.

In its turn, a solution to the advection equation is obtained by the separation technique. A solution to the system of the adaptation equations is obtained by the biorthogonalization method in terms of the vertical modes.

3.1.3. Pollutant transport

The transport of pollutants in the atmosphere is described by the following equation:

$$\eta_t + \mathrm{div}(U\eta) + L\eta = D\eta + F.$$

Here, η is the concentration of the aerosol being transported by an air flow and U is the velocity vector of particles in the air, L is the operator describing local transformations of pollutants, $D\eta$ is the term describing diffusion, and F describes the aerosol source. The difference scheme for a solution of this equation must keep the solution positive. This means that we must use the monotonic difference scheme to solve the transport equation.

3.1.4. Visualization

By now the technology of construction of specific display processors intended to solve a wide class of visualization problems arising in modeling of the atmospheric processes and production process[12] has been developed drawing on the experience acquired from visualization of meteorological information.[11] This display processor, being a standalone, mobile, compact, and readily controllable system, with a corresponding user interface may be inserted into an automated software system to control the computer experiment or production process.

3.2. Verification of the units of the system MAP

1. A refined model of the atmosphere used in the system MAP has 15 levels (1000 – 10 hPa) and a horizontal grid of type D (after Arakava) with size 26×22 and a 300–km step centered on Novosibirsk. The coefficient of correlation between diurnal trends was improved, on average, by 20% for isobaric surfaces while the rms error was decreased by 12% and the accuracy of estimating the gradients of the $S1$ layer altitudes was decreased by 5% for this model.[10]

2. To estimate the quality and the functional capabilities of the system MAP, the meteorological data were assimilated[12,13] implementing an analysis–initialization–forecast cycle that harnesses practically all the units of the system MAP.

The employed assimilation subsystem comprised various options of examination, initialization, and forecast procedures in addition to the main menu to control the computer experiment. To run the numerical experiment, we used routine data of aerological and synoptic observations from March 30 to April 1, 1991 performed at the Russian Hydrometeorological Center.

To find the spatiotemporal distribution of fields of the meteorological parameters from March 30 to April 3, 1991 the data obtained for the basic synoptic periods 12 h apart were assimilated. The field forecasted for the 12-h period by the National Forecast Center of the U.S.A. was taken as the first approximation for an analysis on March 30, 1991. The further assimilation implemented the forecast–analysis–initialization cycle.

As shown in Ref. 12, qualitative character of time behavior of the estimated meteorological fields confirmed the efficiency of the system MAP for adequate description of large-scale meteorological processes.

3. Investigation[14] of the effect of different model correlation functions used to estimate the errors of the first approximation on the result of multicomponent numerical analysis demonstrated the efficiency of the correlation function represented by a series in the Bessel functions.

4. To select an efficient monotonic scheme, we have compared different monotonic schemes, accurate to the second order, which are widely used in meteorology, gas dynamics, and plasma physics.[12] Numerical experiments have shown that it makes sense to use the Bothe scheme to solve the equation of transport of the nonnegative characteristics. Selection of the second-order approximation is caused by the fact that the components of the wind vector are determined with the accuracy of the second order.

5. Using the visualization technology developed for the system MAP, we have developed the system AVIA–MAP (SAK95) for visualization of aviation prognostic maps proposed by the Regional Computer Center of Western Siberia (RCCWS). The system comprised a display processor, a user window interface, and a control program. Now the system SAK95 is passed to the RCCWS for testing.

4. CONCLUSION

Verification of individual units of the system MAP including its main subsystem, which allows the distribution of the meteorological fields to be obtained, has demonstrated its efficiency. Work is now underway toward the preparation and pursuance of the computer experiment on pollutant transport to investigate the methods of information assimilation with the use of the Calman filtration, to develop new methods of initialization, to construct refined models of the atmosphere (including higher spatial resolution), and to extend the functional capabilities of the visualization unit.

The system of modeling under development will allow various computer experiments to be conducted on modeling of scenarios for the atmosphere under stress impacts (volcanic eruptions, nuclear war, and so on), description of the spread of the aerosols, and adequate reconstruction the meteorological fields.

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