EVALUATION OF THE EFFECT OF CLIMATIC METEOROLOGICAL CONDITIONS ON THE PATTERN OF AEROSOL DISTRIBUTION IN THE SIBERIAN REGION

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Received January 8, 1998

A system for mathematical modeling of atmospheric processes is described and possible source regions of air masses that influence the aerosol distribution in the Novosibirsk region are preliminary evaluated by the method of tracing backward trajectories from climatic meteorological data. An algorithm based on the Lagrange method is used to calculate the backward trajectories. The trajectories so obtained are close to average trajectories for the same period and can be used to evaluate source regions of air masses typical of each month that influence the Novosibirsk region.

INTRODUCTION

In the history of evolution of human society there were always many problems from the solution of which the material well-being of the people and their stable progress depended. In particular, the stable progress of the society should take into account not only the quality of the environment, but also its climatic changes. In their turn, changes in the chemical composition of air and underlying surface caused by natural factors and industrial man's activity affect these characteristics of the environment. Evaluation and consideration of the effect of atmospheric aerosols, which depends not only on aerosol concentration, color, and vertical distribution, but also on sizes of aerosol particles, is rather complex problem. Additional problems arise in connection with the transport (including long-range transport) of atmospheric pollutants.

An integrated approach including monitoring of the atmospheric state and atmospheric aerosols and development of systems for mathematical modeling of atmospheric processes and spread of pollutants is necessary for evaluation of the environmental effect of natural and anthropogenic factors.[1,2] In so doing, direct modeling and solution of inverse problems, in particular, tracing of backward trajectories from real meteorological data, are necessary for evaluation of the factors that influence regional ecology. In addition, investigations should be based on carefully designed computing experiment.[3]

This paper is devoted to the investigation of algorithms for evaluation of the effect of climatic meteorological conditions on the spread of aerosols in the Siberian region by the method of tracing of backward trajectories from climatic meteorological data.

SYSTEM FOR MATHEMATICAL MODELING AND DATABASE

An integrated system for mathematical modeling of atmospheric processes was basically developed at the Institute of Computing Technologies of the Siberian Branch of the Russian Academy of Sciences and described elsewhere.[4–9] The main components of this system are the following:

1. The atmospheric model with 15 vertical levels (up to a barometric height of 10 mbar); the domain of solution 7500×6300 km; the method for solving corresponding finite-difference equations based on the splitting and normal vertical mode methods.

2. The scheme of meteorological data analysis representing the box variant of three-dimensional multielemental method of optimal interpolation.

3. The model of transport of gas and aerosol pollutants, because the solution is based on the splitting method with the use of monotonic schemes.

4. The visualization block to display contour lines and vector fields in different cartographycal (stereographical, Merkatorial, rectangular, and orthographycal) projections.

The integrated system for mathematical modeling of atmospheric processes and ecological monitoring of the Siberian region is being developed now as part of the Project Aerosols of Siberia to solve problems of environmental protection and expert evaluation of anthropogenic effect.[11–12]

Measurements of meteorological fields and gas and aerosol pollutants are of great importance for this system. Algorithms for processing of these data should be developed to reconstruct overall pattern of pollution distribution from measurements at separate sites.

0235-6880/98/06 487-05 $02.00

A review of modern systems for meteorological data assimilation, that allow one to obtain spatiotemporal distribution of meteorological fields and main databases from the results of observations with the use of hydrothermodynamic models of the atmosphere was done in Refs. 8 and 13. From the review it follows that at present the meteorological database described in Ref. 4 is most complete. It was prepared as part of the joint project of the National Center of Environmental Prediction (NCEP) and the National Center of Atmospheric Research (NCAR) of the USA. The database includes data of observations and fields of meteorological parameters for the whole globe recorded in 1957–1996 and analyzed with the use of simplified (to save the data processing time) algorithms (only steps of discretization of horizontal variables were halved) of the version of the system for real-time data assimilation NCEP, which was used in January, 1995, namely:

– integrated control over the observational data,

– scheme of data analysis by the spectral method of statistical interpolation that does not require additional initiation,

– T62 (with equivalent horizontal resolution of 210 km) spectral model of the atmosphere with 28 vertical levels.

Proceeding from this, we chose the base for meteorological data archives for the Siberian region. Further this meteorological data archive is called re-analysis. We note that some meteorological centers also have such archives. So, the European Center of Medium-Range Weather Forecast (ECMWF) realized[15] the project ERA (ECMWF Re-Analysis) on the creation of the archive of meteorological data recorded in 1979–1993 with the use of the special version of the ECMWF system for real-time data assimilation, which includes:

– scheme of meteorological data analysis (by the method of optimal interpolation) with a 6-h data sampling interval,

– nonadiabatic scheme of nonlinear initiation (5 vertical modes),

– T106 atmospheric spectral prognostic model with 31 vertical levels.

In addition, re-analysis of meteorological data is carried out at the Data Assimilation Office (DAO) of the NASA Goddard Space Flight Center, where many-year (March 1980–February 1995) archive of atmospheric data with a horizontal resolution of 2° along meridian and 2.5° along parallel (91×144) and 18 vertical levels (barometric heights 1000–20 mbar) is being prepared for climatic investigations including chemistry of the troposphere.[16]

The first re-analysis data and plans for further research work were discussed at the First International Conference on Re-Analysis in the framework of the Global Program for Climatic Change.[17]

The database including all these components is being created now with the use of the concept of integrated processing of meteorological and aerosol data and accumulated experience in the development of meteorological data assimilation system.[9] It is important to note that the system is being developed; not only its main blocks are being modified and improved, but also it is extended to include the database Aerosols of Siberia being developed in collaboration with the scientists of the Institute of Chemical Kinetics and Combustion of the SB RAS[11] and the works devoted to direct and inverse modeling of the spread of pollutants.

METHODS OF TRACING THE BACKWARD TRAJECTORIES

Evaluation of the source regions of air masses that influence the state of the environment in the examined region is an important problem. To solve it, we traced the backward trajectories from the actual and climatic meteorological data for Novosibirsk. The data from the above-mentioned re-analysis archive averaged for each month over the period 1982–1994 were used as climatic meteorological information. The trajectories traced from these data were used to evaluate mean-climatic source regions of air masses typical of each month that influence Novosibirsk.

The backward trajectories were traced on the basis of analysis of synoptic maps by the methods of mathematical modeling from the data of numerical (objective) analysis. The first method based on an analysis of synoptic maps, in addition to advantages, has some disadvantages caused by the fact that the backward trajectories of air mass transport are reconstructed rather than the trajectories of particles. The velocity of particles (especially its vertical component) differs from the velocity of air flow.

Thus, in Ref. 18 the 6-day backward trajectories were traced from the synoptic maps for a barometric height of 850 mbar to identify the large source regions of air masses that enter the atmosphere of Russian Arctic (archipelago Severnaya Zemlya and Vrangel' island) for two spring months (March and April) from the data of 10-year observations (1981–1990). However, the backward trajectories of the atmospheric aerosol are the curves in the three-dimensional rather than in the two-dimensional space and hence do not coincide with trajectories reported in the above-mentioned paper.

For this reason, the second method was used in this paper, namely, the Lagrange method of tracing the backward trajectories of the atmospheric aerosol.[19–21]

Let us briefly describe the algorithm used for calculation of the backward trajectories. Let (λ, θ, p) be the three-dimensional coordinates of the point in the spherical system of coordinates, where λ is the longitude, θ is the latitude, and p is the air pressure. Then the equation for the change of coordinates with time has the form

$$\frac{d\lambda}{dt} = \frac{U(\lambda, \theta, p, t)}{r \cos\theta}, \quad (1)$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{V(\lambda,\ \theta,\ p, t)}{r}\ , \qquad (2)$$

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \mathrm{W}(\lambda,\ \theta,\ p,\ t)\ . \qquad (3)$$

Let us represent Eqs. (1)–(3) in the finite-difference form

$$\lambda^{n+1} - \lambda^{n} = $$
$$= \tau U(\lambda^{n+1/2},\ \theta^{n+1/2},\ p^{n+1/2},\ t^{n+1/2}) / (r \cos\theta^{n}), \qquad (4)$$

$$\theta^{n+1} - \theta^{n} = \tau V(\lambda^{n+1/2},\ \theta^{n+1/2},\ p^{n+1/2},\ t^{n+1/2}) / r, \qquad (5)$$

$$p^{n+1} - p^{n} = \tau W(\lambda^{n+1/2},\ \theta^{n+1/2},\ p^{n+1/2},\ t^{n+1/2}), \qquad (6)$$

where τ is the digitization step. From Eqs. (4)–(6), the equations for calculating the quantities $(\lambda^n,\ \theta^n,\ p^n)$ from $(\lambda^{n+1},\ \theta^{n+1},\ p^{n+1})$ follow:

$$\lambda^{n} = \lambda^{n+1} -$$
$$- \tau U\left(\frac{\lambda^{n} + \lambda^{n+1}}{2},\ \frac{\theta^{n} + \theta^{n+1}}{2},\ \frac{p^{n} + p^{n+1}}{2},\ t^{n} + \frac{\tau}{2}\right) /$$
$$\left(r \cos \frac{\theta^{n} + \theta^{n+1}}{2V}\right), \qquad (7)$$

$$\theta^{n} = \theta^{n+1} -$$
$$- \tau V\left(\frac{\lambda^{n} + \lambda^{n+1}}{2},\ \frac{\theta^{n} + \theta^{n+1}}{2},\ \frac{p^{n} + p^{n+1}}{2},\ t^{n} + \frac{\tau}{2}\right) / r, \qquad (8)$$

$$p^{n} = p^{n+1} -$$
$$- \tau W\left(\frac{\lambda^{n} + \lambda^{n+1}}{2},\ \frac{\theta^{n} + \theta^{n+1}}{2},\ \frac{p^{n} + p^{n+1}}{2},\ t^{n} + \frac{\tau}{2}\right). \qquad (9)$$

The parameters U, V, and W were taken from the climatic meteorological data of the re-analysis archive. Implicit Eqs. (7)–(9) were solved by the method of direct iteration. The values of the parameters U, V, and W at the point $(\lambda^{n+1/2},\ \theta^{n+1/2},\ p^{n+1/2})$ were calculated by the method of cubic bispline interpolation; the linear interpolation over $\ln(p)$ was carried out for the vertical coordinate. The backward trajectories were calculated for the preceding period of 10 days from τ = 1 hour.

POSSIBLE PATTERN OF THE SPREAD OF AEROSOLS IN THE SIBERIAN REGION

The backward trajectories were calculated from the climatic data by the algorithm described in the previous section. The data averaged over the calendar months for the period 1982–1994 are meant by the climatic data. The trajectories obtained from these data were close to average trajectories for the same period. They were used to evaluate the source regions of air masses typical of each month that influence Novosibirsk.

The backward trajectories traced from the climatic data for January–April (*a*), May–August (*b*), and September–December (*c*), respectively, are shown in Fig. 1. The figures denote months. The backward trajectories for July 1981–1994 are shown in Fig. 1*d*. The figures indicate years.

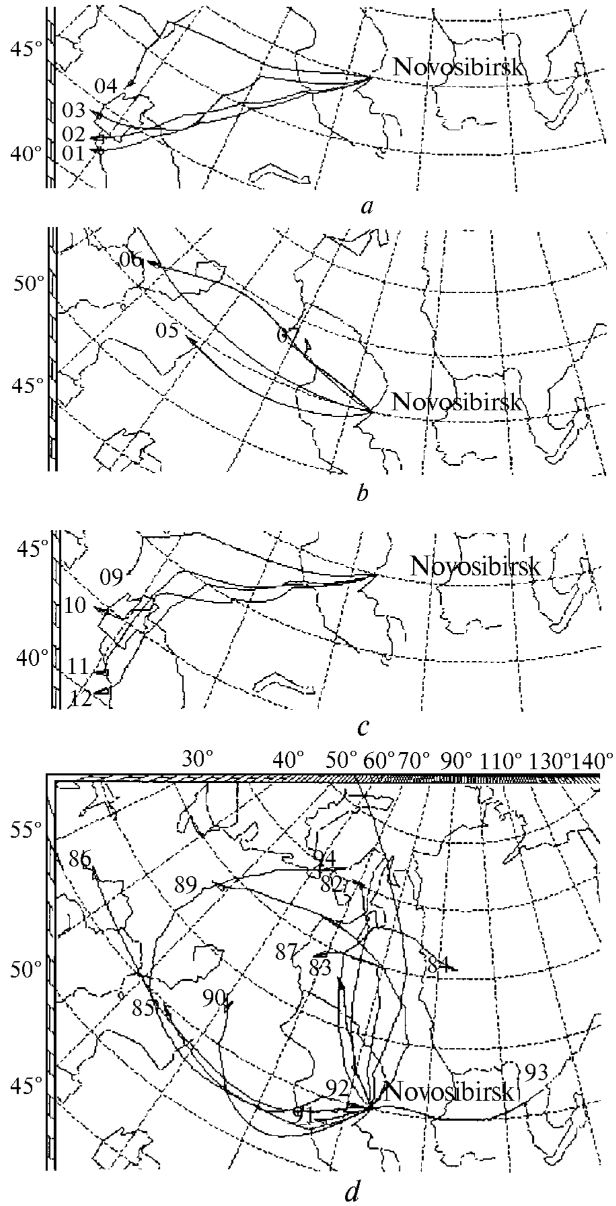

FIG. 1. Backward trajectories in 1982–1994.

The climatic fields of the vertical wind velocity component for a barometer height of 850 mbar are shown in Figs. 2 and 3. We note that Fig. 1 was displayed using the visualization means[5] developed at the Institute of Computing Technologies of the SB RAS. Figures 2 and 3 were displayed using the visualization system GrADS developed by B. Doty from the Center of Ocean–Land–Atmosphere Studies, Calverton, MD, USA, included into NCEP/NCAR Re-Analysis Climatology AMS CD–ROM.[14]

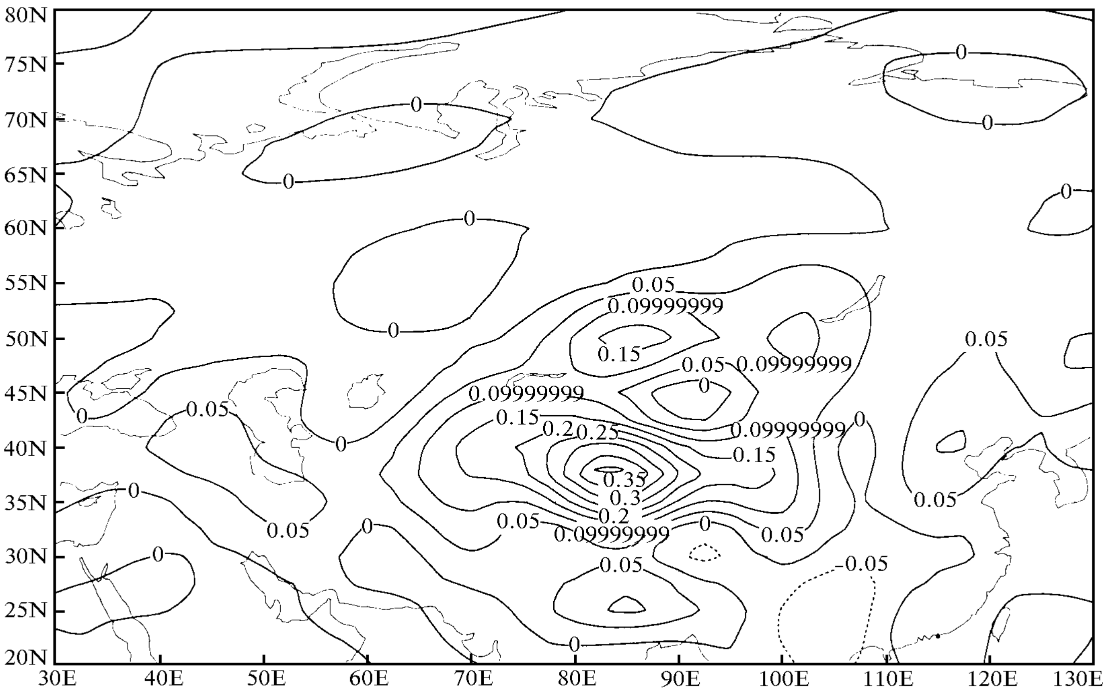

FIG. 2. Climatic values of the vertical wind velocity component (in January).

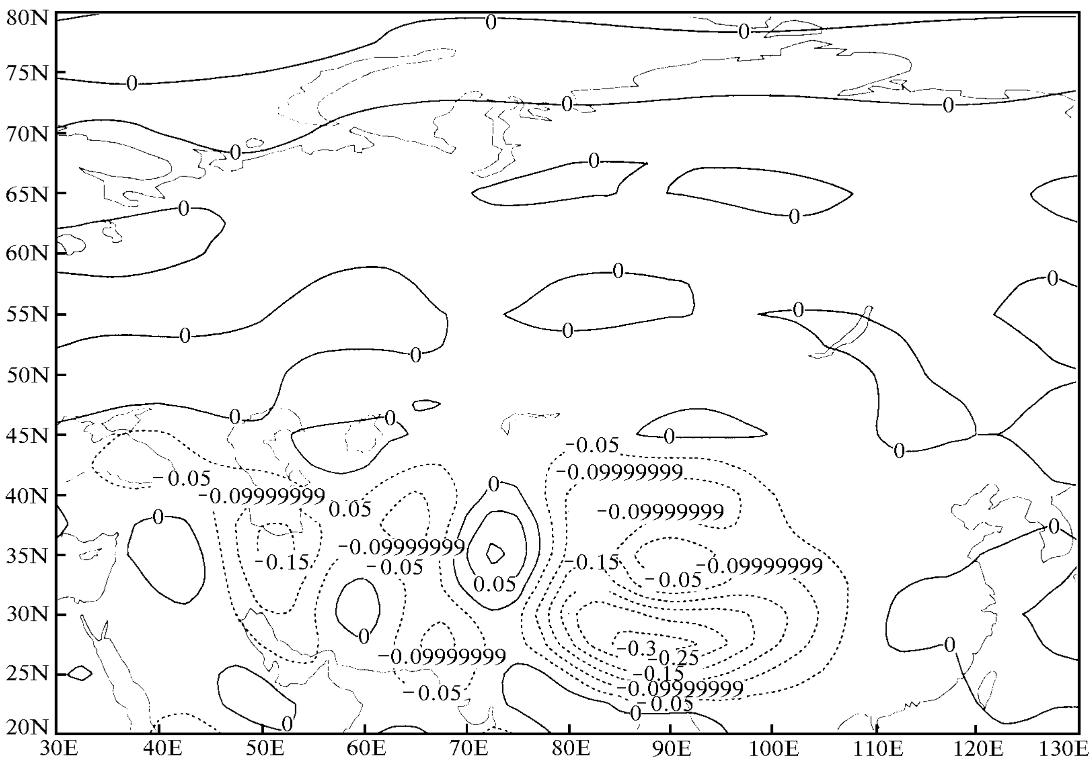

FIG. 3. Climatic values of the vertical wind velocity component (in July).

As can be seen from Fig. 1, the transport of air masses from south-west to the north-east was typical of the first and third periods; in this case, all trajectories pass through the Aral region. The west-east transport of air masses was typical of the second period. It should be noted that in winter (see Fig. 2) ascending air masses were observed in the Aral region and descending in the Novosibirsk region. In summer (see Fig. 3) ascending air masses were observed in Eastern European part of Russia and descending in the Novosibirsk region.

Thus, the established source regions of air masses that influence the Novosibirsk region are well correlated with the vertical motion of air masses.

CONCLUSION

The system for mathematical modeling of atmospheric processes has been considered and the source regions of air masses that influence the aerosol distribution in the Novosibirsk region has been preliminary evaluated. Further the technique for tracing the backward trajectories considering velocities of sedimentation of particles having different sizes and mechanism of turbulent mixing will be studied in more detail. In addition to calculations with climatic data, we plan to do calculations with actual meteorological data.

ACKNOWLEDGMENTS

We would like to acknowledge Prof. K.P. Kutsenogii (from the Institute of Chemical Kinetics and Combustion of the Siberian Branch of the Russian Academy of Sciences) for useful discussion of the paper and Director of the NCEP Center of Environmental Modeling Dr. E. Kalnai for kindly provided material on re-analysis and CD-ROM with climatic data.

This work was supported in part by the Russian Foundation for Basic Researches (Grant No. 95-05-15581).

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