Mathematical model of the regional climate of Siberia

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A regional model of atmospheric dynamics is presented. The model is a component of the global climatic model ECSib [A.A. Fomenko and V.N. Krupchatnikov, Bull. Nov. Comp. Center, Num. Model Atmos., etc. **1**, 17–31 (1993); A.A. Fomenko, V.N. Krupchatnikov, and A.G. Yantzen, Bull. Nov. Com. Center, Num. Model Atmos. etc. **4**, 11–19 (1996)], has increased spatial resolution, and is designed to reproduce the climatic atmospheric characteristics on spatial scales not described by the global model. The model gives a more detailed account of processes of interaction with the underlying surface. The surface ground layer and active ground layer in the model allow for the presence of vegetative cover, a layer of snow on the surface, processes of heat and moisture exchange in the ground layer, processes of thawing of snow on the surface, uptake of moisture by the ground due to large-scale and convective precipitations, capture of precipitations by the vegetative cover, and effects of filtration of moisture into the ground [V.N. Krupchatnikov and A.G. Yantzen, *"Parametrization of Interaction Processes of the Atmosphere and Earth's Surface in the General Circulation Model (ECSib),"* Preprint No. 1013, Computational Center of RAS, Novosibirsk (1994)]. A series of results of numerical simulation of the climate of Siberia is presented.

1. Introduction

Global general circulation models (GGCM's), which are widely used to model climate, to study the effect of a number of external factors on climatic variations on various time scales, and to examine feedback of the underlying surface covered with ice, vegetation, etc., nevertheless have a number of limitations on their applicability. These limitations are due, first of all, to the inadequacy of description of subgrid physical processes (cloudiness, precipitations, turbulent fluxes in the boundary layer, etc.), which have a strong effect on mesoscale processes, second, to the rough resolution of the spatial grid and, third, to the rough account of peculiarities of the underlying surface (for the second reason, as a rule). An approach that allows one to exclude the last two factors is regional climate modeling. The spatial resolution in regional climate models is increased, enabling an explicit description of mesoscale phenomena, including those due to mesoscale features of the underlying surface of the region. As its boundary conditions, the model employs either results of a global analysis of actual observations or model data of the general circulation of the atmosphere obtained with the help of numerical models. The use of global analysis data is preferable since this eliminates large-scale modeling errors. Reference 4 was probably the first work that demonstrated the possibility and laid the groundwork of such an approach. The authors succeeded in showing how it is possible to improve the results of a simulation of regional climate for the example of the USA. The idea of a regional model was developed further in Ref. 5 and found wide application in studies of the regional climate of Europe[6,7] and the Arctic region.[8]

Primary attention is devoted in the present paper within the context of constructing a regional model of the dynamics of the atmosphere to improving the parametrization of the subgrid-scale physical processes, in particular, processes involved in the interaction of the atmosphere with the underlying surface. Such a formulation of the problem is motivated by interests connected with a study of the influence on the climate of special features of the Siberian landscape such as large forests, huge swamps, and tundra. A parametrization of the processes of interaction of the Earth's surface and the atmosphere is one of the most important aspects of the development of climate models. Surface conditions (boundary conditions), in and of themselves, determine to a significant degree the quasistationary state that one would want to obtain as a result of numerical simulation.

At present, there are quite a few works addressing this problem of devising parametrization schemes that do a sufficiently complete job of taking the most important aspects of the interaction into account, in particular Refs. 9–12.

The present paper presents a series of results of a numerical simulation of the dynamics of the atmosphere for the Siberian region based on a new parametrization scheme for surface processes developed at the Institute of Computational Mathematics and Mathematical Geophysics (Siberian Branch of the Russian Academy of Sciences),[3] which is a substantial improvement over the scheme used in earlier versions of the circulation model of the atmosphere and weather forecasting.[1,2]

2. Regional model of the atmosphere

The regional model of the atmosphere is a component part of the ECSib global climate model.[1]

Results of mathematical modeling of the climate based on the global model allow one to obtain an overall qualitatively accurate picture of the distribution of the main atmospheric characteristics.[2] However, because the global model has a horizontal spatial resolution of 5°×4°, it is not possible to study in detail the fine structure of regional features using this model. In light of this fact, we developed a regional model of the dynamics of the atmosphere which has a spatial resolution of 1.66°×1.25°, which at mid-latitudes gives an almost square grid cell with a horizontal resolution of around 130 km. The number and altitudes of the vertical levels coincide with the global model. The region of integration is a spherical rectangle 40°–146.6° longitude east and 40°–80° latitude north. The choice of the integration region was motivated by heightened interest in the Siberian region.

Overall, the mathematical realization of the regional model differs very little from the global model. The specifics consist in the necessity of setting boundary conditions specifying how the regional model fits into the global model. As the boundary conditions, the regional model uses the values of the evolution variables at the boundaries of the region obtained from the global model by interpolation onto its finer grid. During integration the generation of "parasiticB short waves is possible as a result of spurious reflection at the boundary in the flux escape region. To solve this problem, Davies' relaxation method for incorporation of the boundary conditions is used.[13]

3. Parametrization of main physical processes

In contrast to the surface layer scheme used in previous versions of the model,[1,2] in the present model a new version of the parametrization of the active ground layer has been developed.[3] This variant of the model incorporates a sufficiently complete account of the physical factors for estimating the effects of the interaction of the atmosphere with the underlying surface. The given model of the active ground layer takes account of vegetative cover, the presence of snow on the ground, and processes in the upper ground layer. The model takes account of processes of thawing, decrease of surface moisture content due to filtration (downward percolation), the process of moisture runoff on the surface, uptake of moisture due to large-scale and convective precipitations, and precipitations in the form of snow, and finally capture of precipitations by vegetative cover. At each time step the ground surface temperature is calculated along with the temperature of four ground layers, the turbulent heat flux from the surface, the heat flux into the ground, the moisture-level of the surface, the moisture content of the surface layer, and the moisture flux from the surface.

The model utilizes a single-level representation of the vegetative cover, which is modeled as a film covering the ground. The moisture content of the surface layer is calculated in the model taking account of precipitation, evaporation, and thawing processes. The turbulent moisture flux is calculated from data on the moisture content of the surface and the adjacent calculational level. The model calculates the total uptake of moisture from the surface layer, consisting of the moisture flux from the snow-covered surface and turbulent moisture fluxes from vegetative cover, bare ground, and transpiration. The ground-level temperature and the depth of the snow cover are recalculated at each step taking into account the heat liberated by the thawing of snow. The moisture content of the surface layer, the moisture-level of the surface, the moisture runoff on the surface, and filtration of moisture into the ground are recalculated at each step taking into account precipitation and thawing processes.

The system ground–vegetation–atmosphere is represented schematically in Fig. 1.

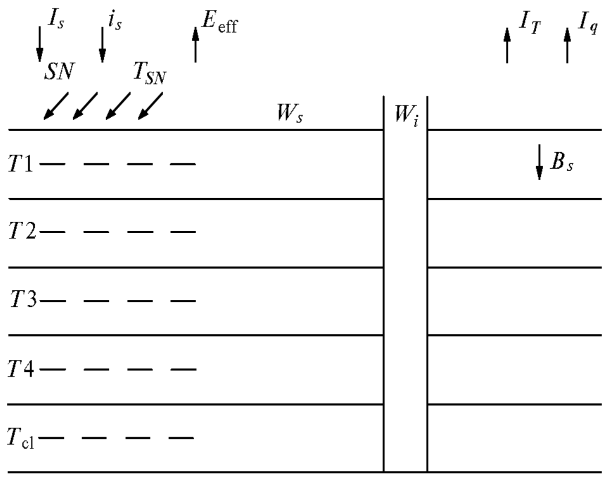


Fig. 1. Representational diagram of the system ground–vegetation–atmosphere for constructing a model of the interaction of the atmosphere with the active ground layer.

The external parameters (external *vis-a-vis* the given system) are the temperature and humidity of the air, the wind velocity, the precipitation rate, the direct (I_s) and scattered radiation (i_s), the back-radiation of the atmosphere (E_{eff}), and the temperature of the bottom calculational ground layer (T_{cl}).

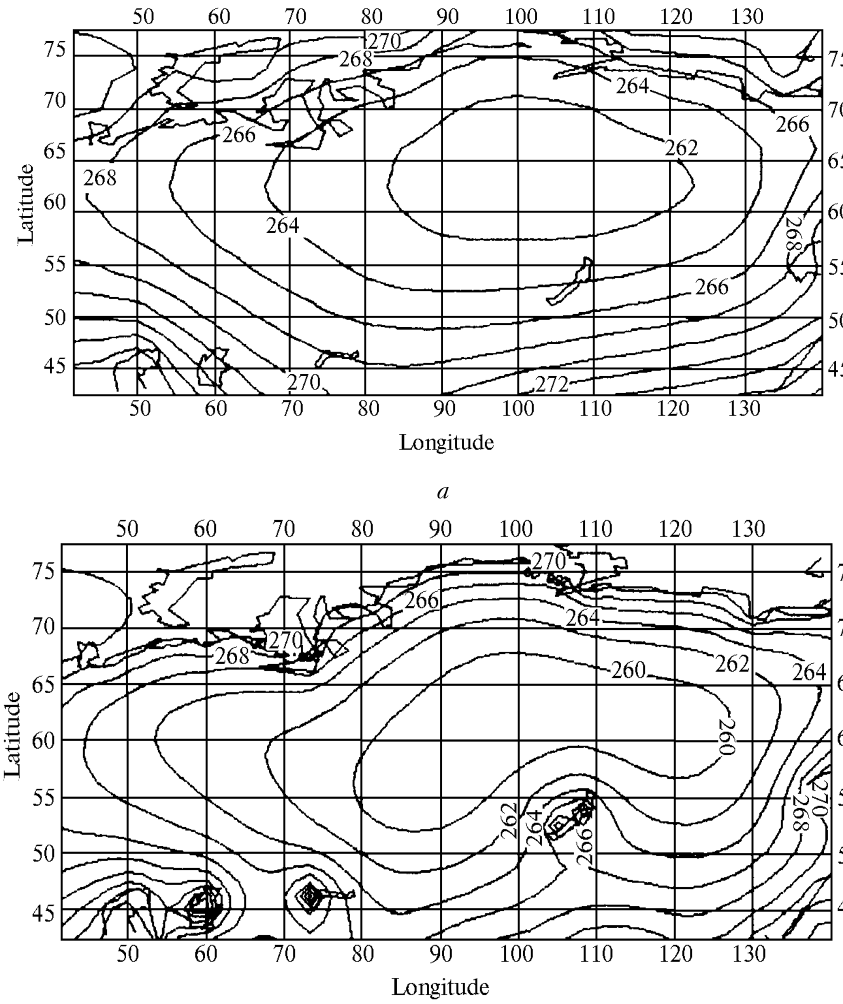
The model is described in more detail in Ref. 3 in the form of mathematical formulas and their realization.

4. Results of mathematical simulation

An experiment investigating the sensitivity of the regional model of the atmosphere to the new parametrization scheme of the interaction with the underlying surface was performed. The order of this experiment was as follows. First we obtained the quasi-equilibrium climatic state of the atmosphere based on a 10-year integration of the global model allowing for the annual variation of the solar radiation. During the integration the zenith angle of the Sun varied as a function of the day of the year. The diurnal variation of the solar radiation was not taken into account. The input parameters were the monthly average climatic values of the ocean surface temperature, obtained from AMIR data, the distribution of ice cover, the monthly average values of the temperature and moisture content of the ground at depth. The height of the topography, characteristic for the adopted spatial resolution, and the roughness parameter of the surface were fixed in the model, where the latter depended on the type of underlying surface, urbanization, and the topography. The values of the albedo of the underlying surface depended on the characteristics of the underlying surface and varied in time as they varied.

On the basis of the state obtained at the last year of the integration period we calculated the evolution of the climate for one year using the regional model in combination with the global model with the new parametrization scheme. All external parameters for the regional model were taken with allowance for the increased spatial resolution. Results of the simulation are shown in Figs. 2–5.

The spatial distribution of calculated characteristics such as the ground-level temperature, ground-level pressure, precipitations, shows that increasing the spatial resolution and using the improved parametrization of the processes of interaction of the atmosphere with the underlying surface allows one to obtain a more detailed picture, in which regional peculiarities are clearly manifested. In particular, in the regional model, islands of heat above a water surface during winter months (Baikal, Balkhash, Aral) are clearly manifested. This is not observed in the global model since the given formations are not described by the spatial resolution used in it (Fig. 2). Naturally, this had an effect on the ground-level pressure, which was decreased above regions in which water basins (on the regional scale) were located. This in turn altered the overall picture of the ground-level pressure (Fig. 3).



b

Fig. 2. Distribution of the mean ground-level temperature (K) for February calculated in the global model (*a*) and in the regional model (*b*).

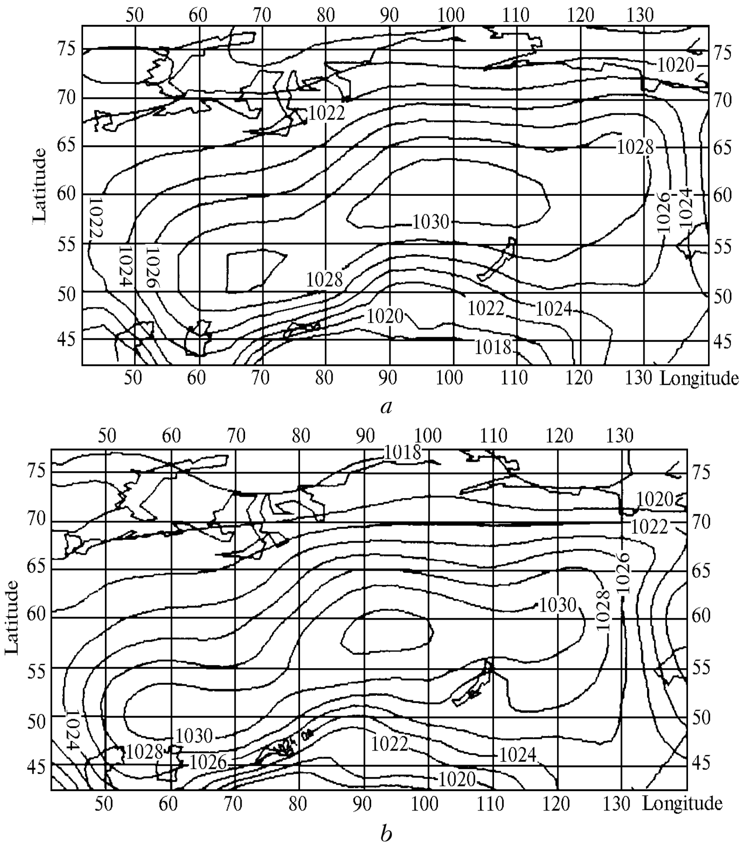


Fig. 3. Distribution of the mean ground-level pressure (hPa) for February calculated in the global model (*a*) and in the regional model (*b*).

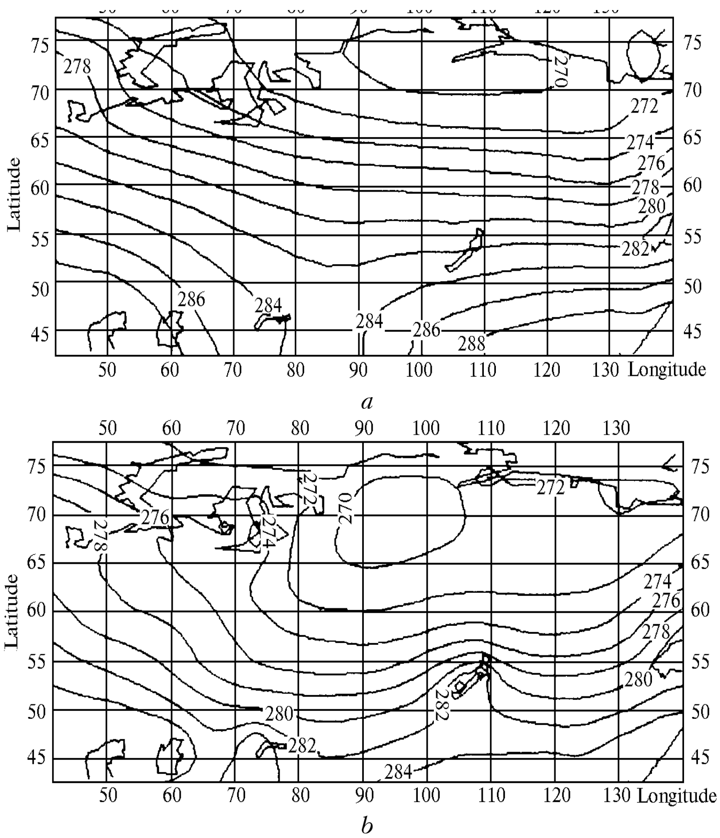


Fig. 4. Distribution of the mean ground-level temperature (K) for July calculated in the global model (*a*) and in the regional model (*b*).

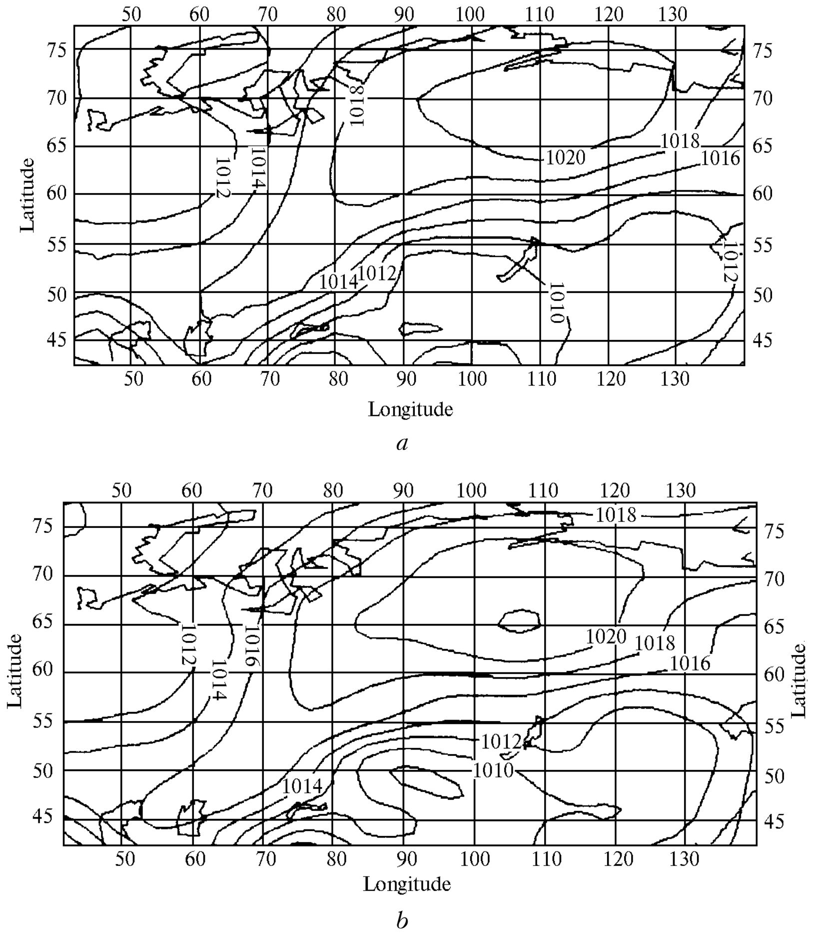


Fig. 5. Distribution of the mean ground-level pressure (hPa) for July calculated in the global model (*a*) and in the regional model (*b*).

In the summer months the picture is completely different since the contrast between the temperature of the water surfaces and the temperature of the dry land almost completely disappears (Fig. 4). Here the difference in the reproduction of the ground-level pressure is due mainly to dynamic factors (Fig. 5). Use of the regional model made it possible to obtain a finer structure of the distribution of precipitations, moisture content of the soil, and regular and latent heat fluxes on the surface, which it would be impossible to achieve without the help of the global model. This, in turn, is reflected in the dynamical characteristics near the surface, which reveal the emergence of mesoscale circulations.

5. Conclusion

The present version of the regional model of the atmosphere with an improved parametrization scheme for the active ground layer takes full account of the physical factors for estimating the effects of the interaction of the atmosphere with the underlying surface. The parametrization scheme for processes of heat and moisture transfer in the active ground layer takes into account their nonlinearity and nonstationarity, explicitly describes the functions of the vegetative cover, and describes in sufficient detail the hydrological cycle.

The results obtained by numerical simulation make it possible to obtain a finer picture of the regional structure of the distribution of the calculated characteristics. In addition, the new parametrization scheme makes it possible to reproduce a number of characteristics, which were not calculated in the global model, such as the temperature and moisture content of the ground, the moisture runoff and filtration of moisture into the ground.

Acknowledgments

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