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A finite-difference model of atmosphere (ECSib) for climatic investigations*

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The climate and variability of the large-scale Nortern Hemisphere winter and summer tropospheric circulation are studied and some atmospheric statistics is presented.

Introduction

The atmospheric model ECSib is the Novosibirsk version of European Center forecasting model. The formulation of the parameterizations of subgrid scale processes resembles the one in the European Center version [4, 5, 6], while the dynamical part was mainly developed in Novosibirsk [7, 3]. The experience of leading specialist of European Center and Institute of Mathematics of Russian Academy of Sciences were considered in this work, we also took into account the availability of technical possibilities.

The focus of the current work (first phase of the simulation climate project) is on evaluating against available observations the model generated long term time average of monthly mean circulation during summer and winter.

1. The model and the experiment design

There are 15 levels in the vertical which are defined on σ – surfaces in troposphere and low stratosphere. The dynamical terms and physical processes are calculated on Arakawa C – grid which yields a horizontal resolution of $5^\circ \times 4^\circ$ (Figure 1).

Spatial-difference scheme gives the second order approximation and exhibits the potential enstrophy conservation law at the eddy advection by the horizontal velocity (in barotropic atmosphere [1, 2]). The special choice approximation of hydrostatic equation allows to construct vertical an angular momentum conserving scheme. The possibility of long-time integration is provided with conservation of some global invariants in finite-defference form, which exists in differential formulation of the task. Therefore in the

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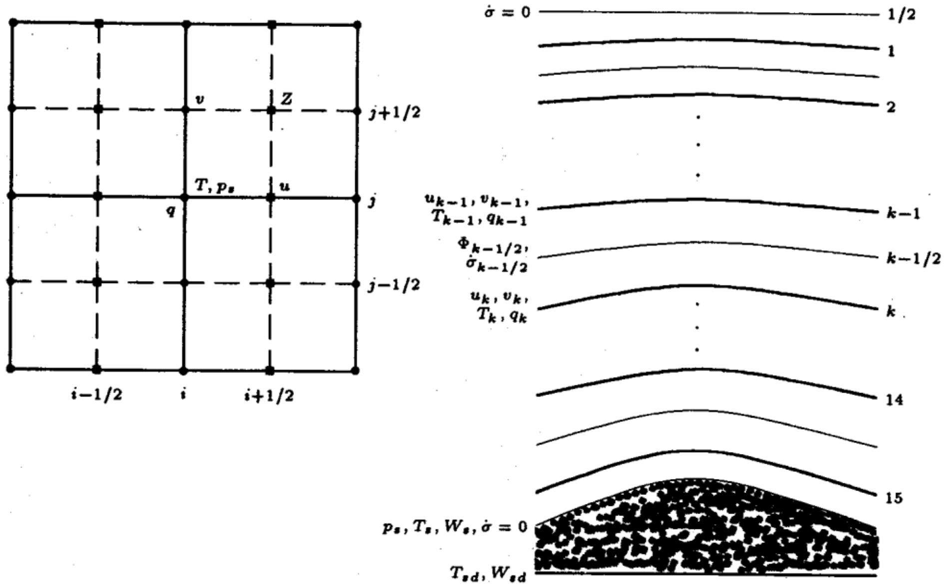

Figure 1. The finite-difference grid and horizontal and vertical distribution of variable

statistical sense they allow to approach discrete model dynamics to the continuous atmospheric dynamics. The basis of integration algorithms construction is the semi-implicit scheme with respect to linear part of dynamical operator, the explicit scheme with respect to "slow" physical processes and the implicit scheme with respect to "fast" physical processes (e.g. vertical diffusion). The semi-implicit time integration schemes widely used in numerical production and general circulation models, belong to the class of central time-differencies schemes and go back to G. Marchuk and A. Robert works.

The physical parameterizations are the following:

- **A nonlinear fourth-order horizontal diffusion operator** applied to velocities and temperature.
- **Processes of planetary boundary layer.** The calculation of surface fluxes is based on the Monin–Obukhov similarity theory, where wind and temperature profiles depend on outer parameters and on surface moment and heat fluxes. Equation used in the model for moment, sensible heat and moisture fluxes are different for stably and unstably stratificated surface level. Surface roughness height Z_0 over the sea is calculated with the help of ratio in accordance with Charnok $Z_0 = 0.032\frac{u_*^2}{g}$. Over the land Z_0 is assumed to depend on vegetation amount, urbanization and subgrid topography. Over the ice is taken as 0.0015 m.

Fluxes over the surface layer are calculated on the basis *l-theory*, where diffusion factors are defined in different ways for stable and unstable stratifications.

- **Cumulus convection.** The deep moisture convection parameterization scheme is based on Kuo's method. The main distinction of the used scheme from Kuo's parameterization is that not only convective clouds, generated by air rise from the earth surface, are considered, but also clouds being conceived at higher levels, where moisture convergence also can occur.

- **Scheme for stratiform clouds.** In the non-convective cloudiness parameterization scheme the condensation process occurs when specific humidity reaches the saturation value, but liquid water does not fall in the form precipitation until one of two conditions will be fulfilled. The first condition, *a fairly cold cloud top* is based on the mechanism which takes into account that ice nuclei generation goes more effectively when temperature is below some threshold temperature $T_c = 261.1$. The second condition, a fairly thick cloud is based on the fact that the rain drops coagulation increases when these drops number density increases. In this case criterion is that cloud water must exceed some value $q_{lc} = 0.0002$ m.

- **Surface processes.** At the land the thin soil layer is signed out with certain heat capacity, which exchanges heat and moisture with atmosphere and deep soil. The snow melting is considered each time when snow presents and land temperature exceeds ice melting temperature, while incoming energy goes to the snow melting. Moisture over the sea is equal to the saturation value at given temperature. Soil moisture and snow cover are calculated with account of precipitation, evaporation, melt water, runoff and moisture diffusion into soil.

- **Wave drag scheme.** This scheme computes the tendencies due to gravity wave drag following work by M. Miller and T. Palmer (1987). The wave drag modifies the horizontal components of the momentum equations, and termodynamics equation through dissipation. The parameterization scheme represents the momentum transports due to subgrid scale gravity waves exited by stably stratified flow over irregular topography.

- **Radiation scheme.** The solution of the radiative transfer equation to obtain the fluxes is very expensive, and we do it only twice a day at every grid point. The solution of the radiative transfer equation involves integration over angles, over vertical coordinate and over some intervals of spectrum. We suppose that we can separate the whole spectrum into two interval: short waves $(B_\nu(T) = 0)$ and long waves

($S_{0\nu} = 0$). In order to avoid a huge number of computations at different frequencies, we have to find how to determine optical depth τ_ν, single-scattering albedo ω and phase function (as J.-F. Geleyn, A. Hollingworth, 1979). The solution of the monochromatic equation being of exponential type, the problem comes from the nonlinear nature of the exponential functions, and we have to use spectrally averaged coefficients of absorbtion and scattering only when the coefficients have the same order of magnitude throughout the considered spectral interval. This is a case for cloud-aerosols absorbtion and scattering and Rayleigh scattering (for short waves) in some spectrum domains (3 for long waves, 2 for short waves) and we have grey effects except for gaseous absorbtion (CO_2, H_2O, O_3, NH_4, ...), because the coefficients strong depend on temperature and pressure. We, therefore, use empirical transmission functions for gases. First of all we make computation without any gaseous absorbtion, the resulting flux represents either the parallel flux or the upward or downward diffuse flux. After that we add each gase (CO_2, H_2O, O_3, NH_4, ...), with small absorbtion coefficient and finally we compute the real flux. We use interactive scheme of radiation with 3 layer clouds and convective tower predicted from relative humidity; clouds have fixed optical properties [10].

- **Seasonal cycle in solar radiation** was included and climatology monthly mean surface temperatures, computed from the so called AMIP-data set (Gates, 1992), were employed. The ozon distribution also varied on a monthly basis. The diurnal cycle was excluded from the simulation.

The model is described in detail in [2]. There are the global model and limited-area version of the one [7].

2. Model climatology and the data set of observations

The simulation consisted of 6-year integration performed with newly developed comprehensive finite-difference model.

Compared to the 10 year mean EC analysis the velocity of tropical easterly jet at 200 hPa is well represented by the model in long term mean, but westerly jets of the both hemisphere at 200 hPa are, however, weaker by 15 m/s, than analysed in Southern hemispere and by 5 m/s, than analysed in Nortern hemisphere.

The DJF and JJA climatology of the observed zonal mean velocity, precipitation rate, surface presure and surface temperature reasonable well simulated by the ECSib GCM model (Figures 2–5).

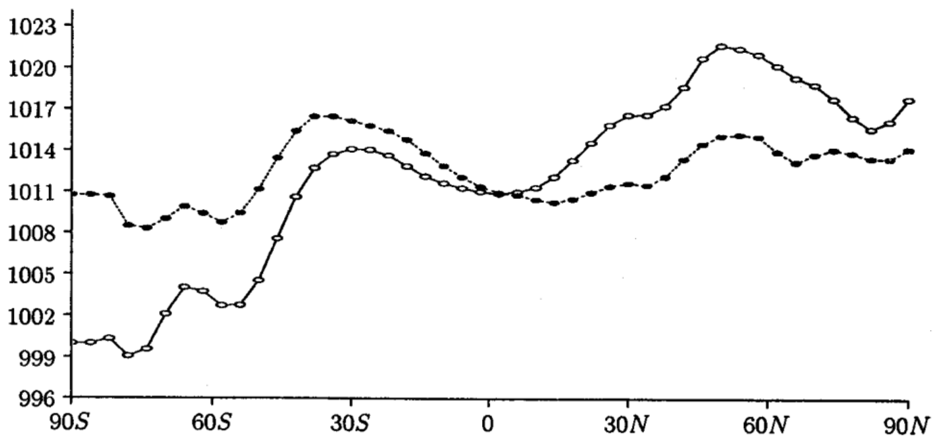

Figure 2. Zonally averaged mean DJF (solid line) and JJA (short dash line) surface level pressure

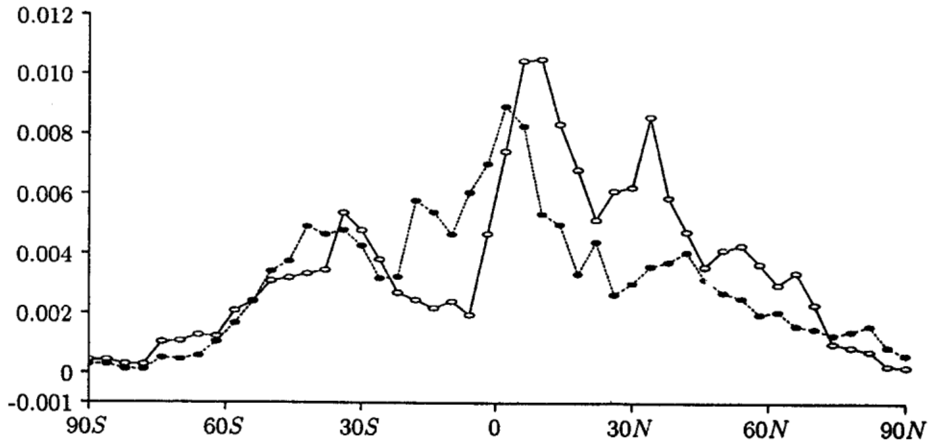

Figure 3. Zonally averaged mean DJF (solid line) and JJA (short dash line) precipitation rate

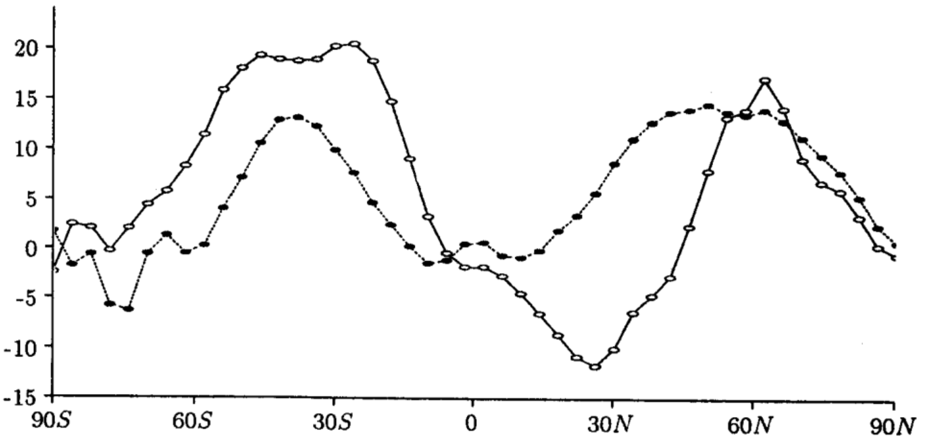

Figure 4. Zonally averaged mean DJF (solid line) zonal JJA (short dash line) wind at 200 hPa

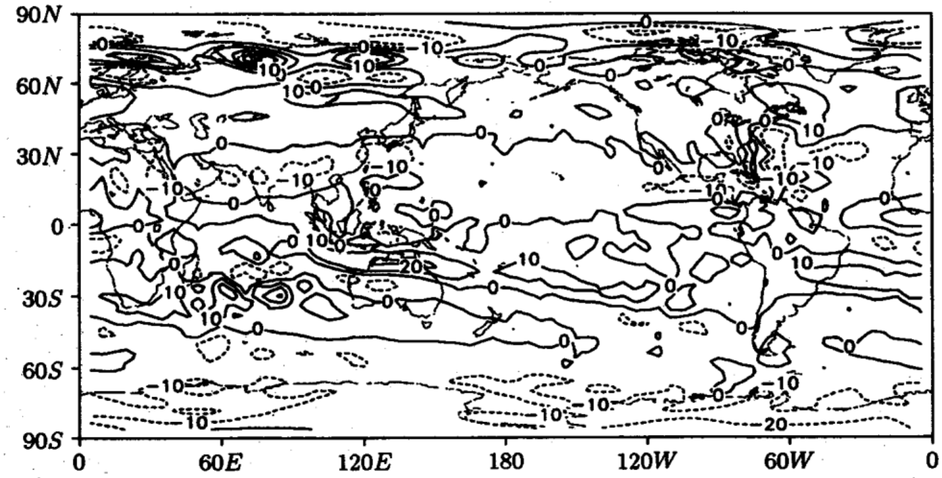

Figure 5. DJF relative vorticity at 200 hPa

The wind observations were obtained from 10-year data set of EC.

3. The impact of small gas components on radiation budget

Small gas components (SGC), which are always present in small quantities in the atmosphere, actively absorb the infra-red radiation. We refer ozone O_3, carbon dioxide CO_2, methane CH_4, nitrons oxide N_2O to SGC. Also, to these gases we can refer water vapor H_2O. Methane CH_4, carbon-containing component, is formed near the Earth's surface and gradually goes upwards to the heights where it is oxided thus becoming a source of carbon oxide and formaldehyde oxide. CH_4 is not formed by the chemical way in the atmosphere. Its sources are the biosphere and the lithosphere. In present, concentration of CH_4 is 1.7 cm/m, it is well mixed in the troposphere. However, above the tropopause its content rapidly decreases due to oxidation and participation in reactions with other gases. The volume of methane slowly increases by 1.2–1.5 per cent from year to year. Nitrous oxide N_2O is formed in the soil, more intensively, at higher temperatures and when applying fertilizers. The content of N_2O in the troposphere is about 0.31 cm/m^3 and increases by 0.3% per year. The absorption of the infra-red radiation by CH_4 and N_2O occurs within the domain 7.25–8.15 mkm.

In addition to CO_2 which is most spread and important greenhouse gas, here we consider methane and nitrous oxide and assess the effect of CH_4 and N_2O on the infra-red radiation as compared to CO_2 following by [9].

The penetration function $T_i(p, p')$ depends on three parameters $\bar{S}_i/\sigma_i$, γ_i/σ_i

$$T_i(p,p') = \exp\left[-\frac{\bar{S}_i u}{\sigma_i}\left(1+\frac{\bar{S}_i u}{\pi' \gamma_{L_i}}\right)^{-1/2}\right], \qquad (1)$$

where $\bar{S}_i$ is the mean intensity of the line, π is the mean spectral distance between the lines, σ_i is a semi-width of the Lorentz profile, u is the content of the absorbing substance. Parameters $\bar{S}_i/\sigma_i$, γ_i/σ_i are taken from (C.D. Rodger, C.D. Walshaw, 1966), the data for CH_4 and N_2O from (E.V. Rozanov, Yu.M. Timofeev, V.A. Frolkis, 1981) being added to them. In overlapping absorption bands of different gases the function of the mixture penetration is determined by the law of multiplication. The absorption function of H_2O in the area of the window continuum is described by relation

$$T(p,p') = \exp\{[-k_1\Phi_1(\theta)p + k_2\Phi_2(\theta)e]u\}, \qquad (2)$$

where $k_1 = 0.1^{-1}$ cm^{2}atm^{-1}, $k_2 = 20^{-1}$ cm^{2}atm^{-1} (at $\theta_o = 263°$K),

$$\Phi_1 = (263/\theta)^{-1.5}, \qquad \Phi_2 = (263/\theta)^{6.5}, \qquad (3)$$

e is saturation vapour pressure, u is the quantity H_2O (g/g).

Experiments were made with the distribution data according to the temperature, specific humidity, pressure, ozone from [9]. The volume content of $[CO_2]$, $[CH_4]$ and $[N_2O]$ is given constant. To estimate the influence of SGC upon the long-wave radiation the following variants have been considered:

- gas components are absent;
- with the presence of $[H_2O]$, $[CO_2]$, $[CH_4]$, $[N_2O]$;
- with the presence of $[H_2O]+[CO_2]$;
- with the presence of $[H_2O]+[CO_2]+[CH_4]$;
- with the presence of $[H_2O]+[CO_2]+[CH_4]+[N_2O]$;
- with the presence of $[H_2O]+[CO_2]+[2CH_4]+[N_2O]$;
- with the presence of $[H_2O]+[CO_2]+[CH_4]+[2N_2O]$,

where $[a]$ denotes the volume content of quantity a.

The table shows that introduction of $[CH_4]$ and $[N_2O]$ results in the decrease of decooling in the troposphere by 0.02° per day. The doubling of $[CH_4]$ concentration results in the decrease of the decooling below 549 mbar by 0.02° per day. From considerations stated above it follows that in the simulation problems of possible variations of the climate of the atmosphere, including the areas of higher $[CH_4]$ and $[N_2O]$ concentrations, the latter should be taken into consideration in the radiational block of the general circulation model.

Infra-red cooling rate $\partial T/\partial t$ for individual components and their variations

p	$[H_2O]$	$[CO_2]$	$[CH_4]$	$[N_2O]$	$[H_2O]+[CO_2]$	$[H_2O]+[CO_2]+[CH_4]+[N_2O]$	$[H_2O]+[CO_2]+[CH_4]+[N_2O]$
2.27	−0.3	−1.15	−0	0	−1.47	−1.473	−1.479
18.70	−0.4	−1.20	−0	0	−1.56	−1.56	−1.589
52.50	−0.24	−0.70	0	0	−0.95	−0.95	−0.958
96.70	−0.21	−0.34	0.016	0.014	−0.56	−0.55	−0.554
156	−0.44	−0.05	0.042	0.022	−0.49	−0.46	−0.452
223	−1.12	−0.104	0.048	0.025	−1.23	−1.20	−1.195
297	−1.90	−0.177	0.037	0.020	−2.07	−2.06	−2.059
378	−2.04	−0.208	0.022	0	−2.19	−2.19	−2.195
458	−1.74	−0.217	0	−0	−1.84	−1.85	−1.850
542	−1.57	−0.202	−0.014	−0.030	−1.58	−1.59	−1.579
624	−1.48	−0.206	−0.038	−0.057	−1.41	−1.40	−1.390
703	−1.41	−0.198	−0.062	−0.085	−1.26	−1.24	−1.224
777	−1.45	−0.193	−0.086	−0.115	−1.23	−1.20	−1.187
844	−1.62	−0.196	−0.112	−0.144	−1.34	−1.30	−1.290
901	−1.87	−0.216	−0.144	−0.173	−1.56	−1.52	−1.503
947	−2.11	−0.238	−0.175	−0.198	−1.78	−1.73	−1.714
980	−2.48	−0.308	−0.218	−0.219	−2.16	−2.12	−2.106
998	−3.43	−0.518	−0.263	−0.232	−3.26	−3.22	−3.200

Conclusions

The climate of the atmosphere from a model simulation and from global observations have been examined. The simulation was performed with the new general circulation model integrated for 6-year. The DJF and JJA climatology of the observed zonal mean velocity, precipitation rate, surface presure and surface temperature reasonable well simulated by the ECSib GCM model.

The second phase of simulation climate project is now undertaken, inluding treatment of hydrological cycle over Siberia with a new parameterization scheme of the surface processes for the AGCM was developed that is based on the works by C. Blondin, H. Bottger (1987) and P.J. Sellers, et al. (1986). The given scheme takes into account the plant cover, the presence of snow on the land surface, processes in the top-soil layer. Account is taken of melting processes, decrease of moisture on the surface due to its filtration into the soil depth. The process of moisture outflow on the surface, moisture supply from large-scale and convective precipitation and that of snow, absorption of the precipitation by plants.

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