

SELF-CONSISTENT NUMERICAL MODELING OF THE GLOBAL WIND SYSTEM AND HEAT REGIME OF THE LOWER AND MIDDLE ATMOSPHERE

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Abstract. The regional non-hydrostatic mathematical model of the wind system of the Earth's lower atmosphere, developed earlier in the Polar Geophysical Institute, is improved by enlarging the three-dimensional simulation domain, with the new version of the mathematical model becoming global. In the new version of the mathematical model, the internal energy equation for the atmospheric gas is written by using a relaxation approach. The finite-difference method is applied for solving the system of governing equations. The new version of the mathematical model produces three-dimensional time-dependent global distributions of the gas dynamic parameters of the lower and middle atmosphere of the Earth. Thus, self-consistent numerical modeling of the global wind system and heat regime of the Earth's lower and middle atmosphere is allowed by the new version of the mathematical model.

Introduction

Earlier, in the Polar Geophysical Institute, two non-hydrostatic mathematical models of the wind system in the Earth's atmosphere have been developed. The first model is the non-hydrostatic model of the global neutral wind system in the Earth's atmosphere which has been described in the papers of *Mingalev I. and Mingalev V.* [2005] and *Mingalev et al.* [2007]. This model enables to calculate three-dimensional global distributions of the zonal, meridional, and vertical components of the neutral wind and neutral gas density over the height range from the ground to 120 km, with whatever restrictions on the vertical transport of the neutral gas being absent. The characteristic feature of this model is that the internal energy equation for the atmospheric gas is not included in the system of governing equations. Instead, the global temperature field is supposed to be a given distribution, i.e. the input parameter of the model, and obtained from one of the existing empirical models. This model has been utilized in order to simulate the global circulation of the middle atmosphere for various geophysical conditions [*Mingalev et al.*, 2014a and references therein].

The second mathematical model is a regional mathematical model of the wind system of the lower atmosphere which has been described in the paper of *Belotserkovskii et al.*, [2006], with the internal energy equation for the atmospheric gas being included in the system of governing equations. The model produces three-dimensional distributions of the atmospheric parameters in the height range from 0 to 15 km over a limited region of the Earth's surface. The mechanisms responsible for the formation of large-scale vortices in the Earth's troposphere, in particular cyclones and anticyclones, have been investigated with the help of this model [*Mingalev et al.*, 2014b and references therein].

The purpose of the present work is an improvement of the latter mathematical model by enlarging the three-dimensional simulation domain, with the new version of the mathematical model becoming global.

Mathematical model

In the present paper, the new version of the mathematical model of the wind system of the Earth's lower and middle atmosphere is described. It may be noticed that this new version of the mathematical model can be considered as a combination of two mathematical models pointed out in the previous Section. In the new version of the mathematical model, the atmospheric gas is considered as a mixture of air and water vapor, in which two types of precipitating water (namely, water microdrops and ice microparticles) can exist. The system of governing equations contains the equations of continuity for air and for the total water content in all phase states, momentum equations for the zonal, meridional, and vertical components of the air velocity, and energy equation.

In the new version of the mathematical model, the internal energy equation for the atmospheric gas is written by using a relaxation approach, in which a heating / cooling rate of the atmospheric gas in various chemical-radiational processes is supposed to be straightly proportional to the difference between the real temperature of the atmospheric gas and an equilibrium temperature of the atmospheric gas. The latter equilibrium temperature may be given by utilizing the global temperature field, obtained from one of the existing empirical models, for example, from the NRLMSISE-00 empirical model [*Picone et al.*, 2002].

Furthermore, the mathematical model is non-hydrostatic, that is the model does not include the pressure coordinate equations of atmospheric dynamic meteorology, in particular, the hydrostatic equation. Instead, the vertical component of the atmospheric gas velocity is obtained by means of a numerical solution of the appropriate momentum equation, with whatever simplifications of this equation being absent. Thus, three components of the air

velocity are obtained by means of a numerical solution of the generalized Navier-Stokes equation, with the effect of the turbulence on the mean flow being taken into account by utilizing an empirical subgrid-scale parameterization similarly to the global circulation model of the Earth's atmosphere developed earlier in the PGI [Mingalev I. and Mingalev V., 2005; Mingalev et al., 2007].

Thus, the new version of the mathematical model is based on numerical solving of non-simplified gas dynamic equations and produces three-dimensional time-dependent distributions of the wind components, temperature, air density, water vapor density, concentration of micro drops of water, and concentration of ice particles. The model takes into account heating / cooling of the air due to absorption / emission of infrared radiation, as well as due to phase transitions of water vapor to micro drops of water and ice particles. The finite-difference method is applied for solving the system of governing equations. The calculated parameters are determined on a uniform grid. The latitude and longitude steps are equal to 0.94° , and height step is equal to 200 m. The simulation domain is a layer surrounding the Earth globally. The planetary surface is assumed to be a smooth spheroid. The lower boundary is the Earth's surface, whereas, the upper boundary is the sphere lain at the altitude of 75 km over the equator sea level.

Simulation results

In the present study, simulations were performed for one concrete situation. The initial moment of the calculations has corresponded to 10.30 UT for 16 January that is for winter in the northern hemisphere. Simulations were performed for conditions corresponding to moderate solar activity ($F_{10.7} = 101$) and low geomagnetic activity ($K_p=1$). At the initial moment, the neutral gas density at the lower boundary and air temperature in all simulation domain were taken from the NRLMSISE-00 empirical model [Picone et al., 2002], moreover, all components of the neutral wind velocity were equal to zero. The variations of the atmospheric parameters with time were calculated during the period for about four hundreds of hours.

It turned out that the three-dimensional global distributions of the gas dynamic parameters of the lower and middle atmosphere, calculated with the help of the model, changed essentially after initial moment. Maximal absolute values of the horizontal and vertical components of the air velocity are larger at higher altitudes. The gas dynamic parameters, in particular the zonal, meridional, and vertical components of the air velocity, are changeable functions not only of latitude and longitude but also of altitude. The distribution of the vector of the horizontal component of the neutral wind velocity as function of longitude and latitude at the altitude of 50 km is shown in Fig. 1. It is seen that, at levels of the mesosphere, the horizontal wind velocity can achieve values of more than 70 m/s.

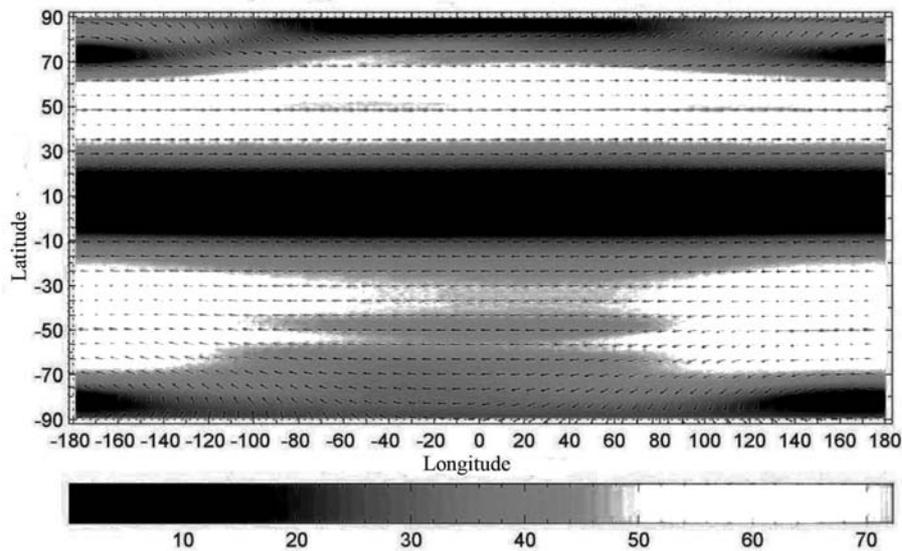


Figure 1. The distribution of the vector of the calculated horizontal component of the air velocity (m/s) as function of longitude and latitude at the altitude of 50 km, computed 412 hours after the beginning of calculations. The degree of shadowing of the figure indicates the module of the velocity in m/s.

The distribution of the neutral gas temperature as function of longitude and latitude at the altitude of 50 km is shown in Fig. 2. It can be seen that the neutral gas temperature in the southern hemisphere is larger than that in the northern hemisphere. This fact is not extraordinary because of, in January, winter is in the northern hemisphere, whereas, summer is in the southern hemisphere.

It is well known from numerous observations that the global atmospheric circulation can contain sometimes so called circumpolar vortices. In the global neutral wind system, these vortices are the largest scale inhomogeneities which are formed at heights of the stratosphere and mesosphere in the periods close to summer and winter solstices. It is know that, in the northern hemisphere, the circumpolar anticyclone arises under summer conditions, whereas, the circumpolar cyclone arises under winter conditions. In the southern hemisphere, the circumpolar cyclone arises under winter conditions, whereas, the circumpolar anticyclone arises under summer conditions.

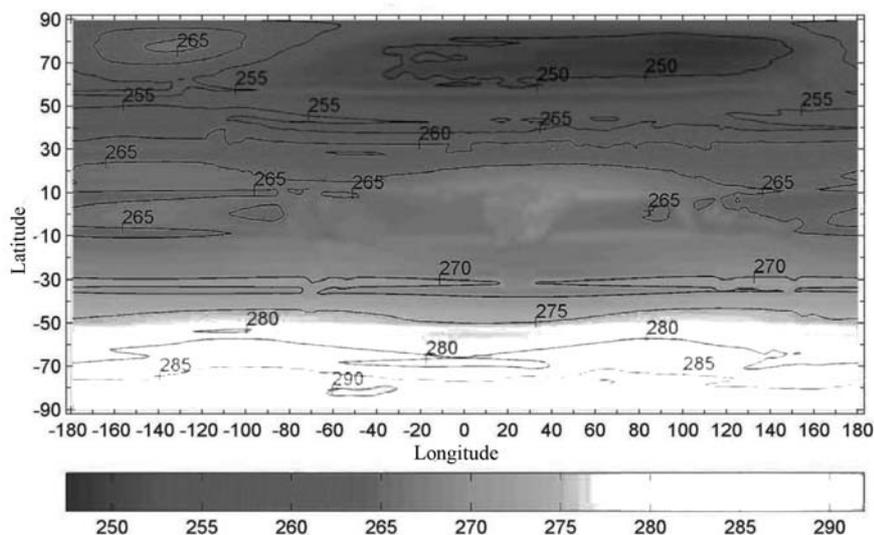


Figure 2. The distribution of the neutral gas temperature, computed 412 hours after the beginning of calculations, as function of longitude and latitude at the altitude of 50 km. The degree of shadowing of the figure indicates the temperature in K.

Let us compare these experimental data with the simulation results, obtained in the present study for January conditions. It can be seen from Fig. 1 that a circumpolar cyclone is formed in the northern hemisphere in the winter period (the motion of the neutral gas is primarily eastward), simultaneously, a circumpolar anticyclone is formed in the southern hemisphere in the summer period (the motion of the neutral gas is primarily westward). It can be noticed that the centers of the northern cyclone and southern anticyclone are displaced from the poles a little. Thus, the circumpolar vortices of the northern and southern hemispheres, calculated in the present study, correspond well to the global circulation of the stratosphere and mesosphere, obtained from observations for January conditions. The results of simulation indicate that, in the course of time, the global distributions of the gas dynamic parameters of the lower and middle atmosphere of the Earth acquire a tendency to fluctuate, with the period of the fluctuations being close to one day. Thus, daily variations of the gas dynamic parameters, conditioned by the rotation of the Earth around its axis, may be reproduced by the new version of the mathematical model of the global wind system and heat regime of the Earth's lower and middle atmosphere.

Conclusion

The new version of the mathematical model of the Earth's lower and middle atmosphere has been described which enables to calculate the global wind system and heat regime at levels of the troposphere, stratosphere, and mesosphere. The system of governing equations contains the equations of continuity for air and for the total water content in all phase states, momentum equations for the zonal, meridional, and vertical components of the air velocity, and internal energy equation. The new version of the mathematical model is non-hydrostatic. The internal energy equation for the atmospheric gas is written by using a relaxation approach. The new version of the mathematical model produces three-dimensional time-dependent global distributions of the gas dynamic parameters of the lower and middle atmosphere in the layer surrounding the Earth globally and stretching from the ground up to the altitude of 75 km. The time evolution of the global distributions of the gas dynamic parameters has been simulated during the January period for about four hundreds of hours. The new version of the mathematical model can reproduce daily variations of the gas dynamic parameters, conditioned by the rotation of the Earth around its axis. The results of simulation have reproduced the circumpolar vortices of the northern and southern hemispheres which are well known from observations.

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