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THE IMPROVEMENT OF THE NUMERICAL MODEL OF THE GLOBAL WIND SYSTEM OF THE ATMOSPHERE BY TAKING INTO ACCOUNT THE RELIEF OF A PLANET

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Abstract. The non-hydrostatic mathematical model of the global wind system of the atmosphere, developed recently in the Polar Geophysical Institute, is improved by taking into account the relief of a planet. In the previous version of the mathematical model, the planetary surface was assumed to be a smooth spheroid. In the new version of the mathematical model, a planetary surface can contain mountains and depressions. A planetary surface is approximated by using one of the existing digital maps of the surface relief of a planet. The new version of the mathematical model is based on the numerical solution of the system of gas dynamic equations in the layer surrounding the Earth globally and stretching from the ground up to the altitude of 75 km, with the internal energy equation for the atmospheric gas being taken into account.

Introduction

During the last decade, in the Polar Geophysical Institute (PGI), two non-hydrostatic mathematical models of the wind system in the Earth's atmosphere have been developed. The first model enables to calculate three-dimensional global distributions of the zonal, meridional, and vertical components of the neutral wind and neutral gas density in the layer surrounding the Earth globally over the height range from the ground to 120 km. 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 mathematical model has been applied in order to investigate numerically how various geophysical conditions influence on the formation of the global wind system of the Earth's troposphere, stratosphere, mesosphere, and lower thermosphere [*Mingalev et al.*, 2014a and references therein].

The second mathematical model is a limited area mathematical model of the wind system of the lower atmosphere, 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. This regional model has been applied in order to investigate numerically the mechanisms responsible for the formation of large-scale vortices, in particular cyclones and anticyclones, in the Earth's troposphere [*Mingalev et al.*, 2014b and references therein].

Recently, the second mathematical model has been improved by enlarging the three-dimensional simulation domain [*Mingalev et al.*, 2015], with the new version of the second mathematical model having been become global. In the new version of the second mathematical model, the internal energy equation for the atmospheric gas is included in the system of governing equations and written by using a relaxation approach. This version of the mathematical model enables to calculate the global wind system and heat regime in the layer surrounding the Earth globally and stretching from the ground up to the altitude of 75 km, with the planetary surface being approximated by a smooth spheroid. It may be sawn that the new version of the second mathematical can be considered as a combination of the first and second mathematical models pointed out in the beginning of the present Section. This new version of the second mathematical model may be named as a self-consistent mathematical model of the global wind system and heat regime of the planet's atmosphere. It can be noted that analogous self-consistent mathematical models have been developed for simulations of the behavior of the atmospheres of Venus and Titan [*Mingalev et al.*, 2012; 2015].

The purpose of the present work is an improvement of the self-consistent mathematical model of the global wind system and heat regime of the Earth's atmosphere by taking into account the relief of a planet.

Mathematical model

In the present study, the new version of the self-consistent mathematical model of the global wind system and heat regime of the Earth's atmosphere is described. In the new version of the self-consistent 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 internal energy equation. The characteristic feature of the new version of the self-consistent mathematical model is that it 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 et al*., 2014a].

The another characteristic feature of the new version of the self-consistent mathematical model is that 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 with the help of the global temperature field, obtained from one of the existing empirical models, for example, from the NRLMSISE-00 empirical model [*Picone et al.,* 2002]. Incidentally, the relaxation approach may be applied for self-consistent numerical modeling of the global wind system and heat regime in the lower and middle atmosphere not only of the Earth but also of other planetary bodies, in particular, of Venus and Titan [*Mingalev et al*., 2012; 2015].

Thus, the new version of the self-consistent 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 0.47°, and height step is equal to 200 m. The system of gas dynamic equations is numerically solved in a simulation domain which is a layer surrounding the Earth globally. The lower boundary of this layer coincides with the Earth's surface which is approximated by an oblate spheroid, with the relief being taken into account. A planetary surface can contain mountains and depressions. This surface is approximated by using one of the existing digital maps of the surface relief of a planet. The upper boundary of the simulation domain is the sphere lying at the altitude of 75 km over the equator sea level. The complete details of the utilized finite-difference method and numerical schemes have been presented in the paper of *Mingalev et al*. [2010].

Simulation results

To demonstrate the ability of the self-consistent mathematical model of the global wind system and heat regime of the atmosphere, which takes into account the relief of a planet, to simulate global distributions of the gas dynamic parameters of the Earth's lower and middle atmosphere we have made calculations 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 (Kp = 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 17 days.

Simulation results indicated that, after initial moment, three-dimensional global distributions of the gas dynamic parameters of the lower and middle atmosphere, calculated with the help of the model, changed essentially. 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. Maximal absolute values of the horizontal and vertical components of the air velocity are larger at higher altitudes. To the latest moment of calculations, at levels of the mesosphere, the horizontal wind velocity has achieved values of more than 70 m/s, whereas, the vertical component of the air velocity has achieved values of more than 10 m/s. Maximal absolute values of the upward vertical wind component are more than the maximal module of the downward vertical wind component.

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 self-consistent mathematical model of the global wind system and heat regime of the atmosphere, which takes into account the relief of a planet.

The distribution of the vector of the horizontal component of the neutral wind velocity as a function of a longitude and latitude at the altitude of 0,6 km is shown in Fig. 1, with arrows being absent in the regions where the mountains are higher than 0,6 km. It is seen that, at the low latitudes of the northern and southern hemispheres, the motion of the air is primarily westward. At the middle latitudes of the northern and southern hemispheres, the motion of the air is primarily eastward. Maximal absolute values of the horizontal wind velocity take place over the Pacific Ocean. At the high latitudes of the northern and southern hemispheres, the motion of the air is primarily westward. In essence, the global wind system of the Earth's lower and middle atmosphere, calculated with the help of the new version of the mathematical model, corresponds qualitatively to the global circulation, obtained from observations for January conditions.

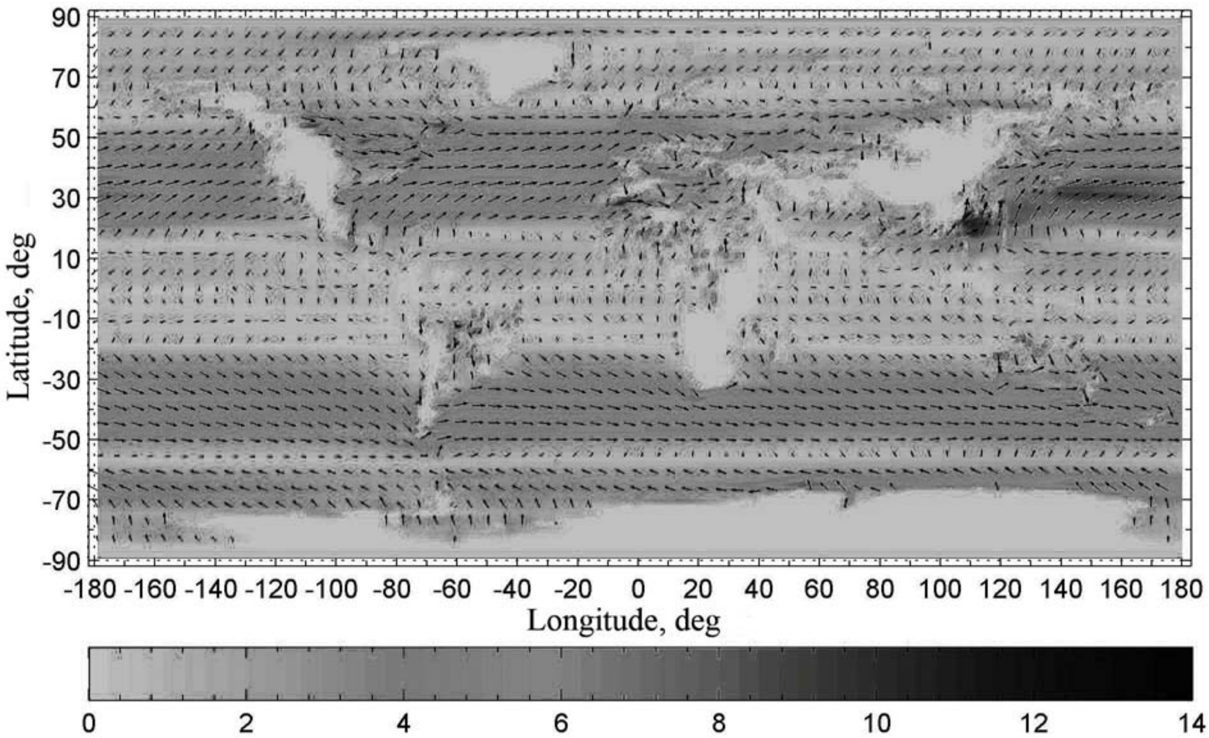

Figure 1. The distribution of the vector of the calculated horizontal component of the air velocity (m/s) as a function of the longitude and latitude at the altitude of 0,6 km, computed 17 days and 4 hours after the beginning of calculations. The degree of shadowing of the figure indicates the module of the velocity in m/s.

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, with the relief of a planet having been taken into account. In the new version of the mathematical model, a planetary surface can contain mountains and depressions. A planetary surface is approximated by using one of the existing digital maps of the surface relief of a planet. 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 characteristic feature of the new version of the mathematical model is that it is non-hydrostatic. Moreover, 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. It was demonstrated that the new version of the mathematical model can produce the global wind system of the Earth's lower and middle atmosphere which is qualitatively similar to the global circulation, obtained from observations. Furthermore, 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.

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References

Mingalev, V.S., Mingalev, I.V., Mingalev, O.V., Oparin, A.M., and Orlov, K.G. (2010) Generalization of the hybrid monotone second order finite difference scheme for gas dynamics equations to the case of unstructured 3D grid. *Computational Mathematics and Mathematical Physics*, 50(5), 877–889.

Mingalev, I.V., Rodin, A.V., and Orlov, K.G. (2012) A non-hydrostatic model of the global circulation of the Venus atmosphere. *Astronomicheskii Vestnik,* 46(4), 282-296.

Mingalev, I.V., Orlov, K.G., and Mingalev, V.S. (2014a) A computational study of the transformation of global gas flows in the Earth's atmosphere over the course of a year. *Open Journal of Fluid Dynamics*, 4, 379-402, *http://dx.doi.org/10.4236/ojfd.2014.44029.*

Mingalev, I.V., Astafieva, N.M., Orlov, K.G., Mingalev, V.S., Mingalev, O.V., and Chechetkin, V.M. (2014b) Numerical modeling of the initial formation of cyclonic vortices at tropical latitudes. *Atmospheric and Climate Sciences*, 4, 899-906, *http://dx.doi.org/10.4236/acs.2014.45079.*

Mingalev, I.V., Rodin, A.V., and Orlov, K.G. (2015) Numerical simulations of the global circulation of the atmosphere of Venus: Effects of surface relief and solar radiation heating. *Solar System Research,* 49(1), 24–42.

Mingalev, I.V., Orlov, K.G., Chechetkin, V.M., Mingalev, V.S., and Mingalev, O.V. (2015) Self-consistent numerical modeling of the global wind system and heat regime of the lower and middle atmosphere. *The present Proceedings.*

Picone, J. M., Hedin, A. E., Drob, D. P., and Aikin, A. C. (2002) NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues. *J. Geophys. Res*.**,** 107 A, (SIA 15), 1-16.