A computational study of the effect of geomagnetic activity on the planetary circulation of the Earth's atmosphere

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ABSTRACT

The effect of geomagnetic activity on the global circulation in the Earth's atmosphere is studied with the help of the non-hydrostatic mathematical model, developed earlier in the Polar Geophysical Institute. The mathematical model allows us to calculate three-dimensional global distributions of the zonal, meridional, and vertical components of the wind velocity and neutral gas density in the layer surrounding the Earth globally and stretching from the ground up to the altitude of 126 km. Simulations were performed for the summer period in the northern hemisphere (16 July) and for three distinct values of geomagnetic activity (Kp=1, 4 and 7). The simulation results indicated that the effect of geomagnetic activity on the global neutral wind system may be essential not only above 80 km but also below this altitude (in the mesosphere, stratosphere and troposphere). A physical mechanism, responsible for the influence of geomagnetic activity on the global neutral wind system in the mesosphere, stratosphere and troposphere, has been established with the help of the model calculations.

Keywords

Numerical simulation; Air flow; Global circulation; Lower and middle atmosphere.

1. INTRODUCTION

To investigate the dynamical processes, taking place in the Earth's atmosphere, not only the experimental and theoretical but also computational studies may be applied. During the last four decades, several general circulation models of the Earth's lower and middle atmosphere have been developed (e.g., see [1-12]). It can be noticed that the bulk of these models are hydrostatic, that is, the momentum equation for the vertical velocity is omitted in these models, with the vertical velocity being obtained with the help of a simple hydrostatic equation. Nevertheless, these models may be successfully utilized for simulation of the slow climate changes.

In the Polar Geophysical Institute, a few mathematical models of the atmospheric dynamics have been developed within the past two decades. In particular, the regional non-hydrostatic three-dimensional mathematical model of the wind system of the lower atmosphere has been developed [13,14]. This mathematical model has been applied in order to investigate numerically the mechanisms responsible for the formation of large-scale vortices in the Earth's lower atmosphere, namely, the formation mechanism of polar lows [15,16] and the processes of the formation of tropical cyclones [17-19].

Furthermore, in the Polar Geophysical Institute, the non-hydrostatic mathematical model of the global circulation in the Earth's atmosphere has been developed [20,21]. This model produces three-dimensional global distributions of the zonal, meridional, and vertical components of the wind velocity and neutral gas density in the troposphere, stratosphere, mesosphere, and lower thermosphere. The characteristic feature of this model is that whatever restrictions on the vertical transport of the atmospheric gas are absent. Thus, the model is non-hydrostatic.

In the study of Mingalev et al. [22], this mathematical model has been utilized in order to investigate numerically how geomagnetic activity affects the formation of the large-scale planetary circulation in the Earth's atmosphere. In the quoted study, simulations have been performed for the winter period in the northern hemisphere (16 January) and for two distinct values of geomagnetic activity (Kp=1 and Kp=4).

It is known that solar radiation, reaching the Earth's surface, is distinct in different months due to the tilt of rotational axis of the Earth. Therefore, it may be expected that the effect of geomagnetic activity on the global circulation in the Earth's atmosphere is different in the periods, corresponding to various seasons, as a consequence of different positions of the Earth along its trajectory around the Sun.

The purpose of the present work is to investigate numerically, using the non-hydrostatic model of the global wind system [20,21], how geomagnetic activity affects the formation of the large-scale global circulation of the Earth's stratosphere, mesosphere, and lower thermosphere for the summer period in the northern hemisphere (16 July) and for three distinct values of geomagnetic activity (Kp=1, 4 and 7). Thus, the present work is the continuation of the investigation begun in the study of Mingalev et al. [22], with new simulation results being submitted in the present paper.

2. MATHEMATICAL MODEL

Detailed description of the utilized mathematical model may be found in the studies of Mingalev I. and Mingalev V. [20] and Mingalev et al. [21]. The utilized mathematical model is non-hydrostatic, that is, not only the horizontal components but also the vertical component of the wind velocity is obtained by means of a numerical solution of a generalized Navier-

Stokes equation for compressible gas. Due to this peculiarity, the utilized mathematical model has the potential to describe the global neutral wind system under disturbed conditions when the vertical component of the neutral wind velocity at the levels of the lower thermosphere can be as large as several tens of meters per second [23-27]. Unfortunately, the existing hydrostatic general circulation models of the atmosphere produce the vertical component of the wind velocity having the values of several centimeters per second at levels of the lower thermosphere. These hydrostatic models cannot describe the global neutral wind system under disturbed conditions when the vertical component of the neutral wind velocity at the levels of the lower thermosphere can be rather large.

Another peculiarity of the utilized mathematical model consists in that the internal energy equation for the neutral gas is not solved in the model calculations. Instead, the global temperature field is assumed to be a given distribution, i.e. the input parameter of the model, and obtained from the NRLMSISE-00 empirical model [28]. This peculiarity can have the following justification. It is known that the atmospheric temperature distributions, calculated by using the existing global circulation models containing the internal energy equation, as a rule, differ from observed distributions of the atmospheric temperature. These differences are conditioned by uncertainty and complexity in various chemical-radiational heating and cooling rates. Therefore, there is no reason to expect an exact correspondence between the calculated and measured temperatures of the neutral gas. On the other hand, over the last years empirical models of the global atmospheric temperature field have been successfully developed which have a satisfactory accuracy. In the present study, we take the global temperature distribution from the NRLMSISE-00 empirical model [28] and consider it to be an input parameter of the utilized mathematical model.

The mathematical model, utilized in the present study, is based on the numerical solution of the system of equations containing the dynamical equation and continuity equation for the neutral gas. For solving the system of equations, the finite-difference method is applied. A spherical coordinate system rotatable together with the Earth is utilized in model calculations. The effect of the turbulence on the mean flow is taken into account by using an empirical subgrid-scale parameterization and the turbulence theory of Obukhov [29]. The steps of the finite-difference approximations in the latitude and longitude directions are identical and equal to 1 degree. The height step is non-uniform and does not exceed the value of 1 km.

The simulation domain is the layer surrounding the Earth globally and stretching from the ground up to the altitude of 126 km at the equator. Upper boundary conditions provide the conservation law of mass in the simulation domain. The Earth's surface is supposed to coincide approximately with an oblate spheroid whose radius at the equator is more than that at the pole.

The utilized mathematical model produces three-dimensional global distributions of the zonal, meridional, and vertical components of the neutral wind velocity and neutral gas density at the levels of the lower and middle atmosphere. More complete details of the utilized mathematical model may be found in the studies of Mingalev I. and Mingalev V. [20] and Mingalev et al. [21]. Complete details of the utilized finite-difference method and numerical schemes, applied in the mathematical model, have been presented in the paper of Mingalev et al. [30].

3. RESULTS AND DISCUSSION

The mathematical model, briefly described above, is based on the application of the dynamical equation and continuity equation for the neutral gas. It is obvious that motion of neutral molecules and atoms is not exposed to the geomagnetic field because of absence of their electric charges. Therefore, it should seem that the effect of geomagnetic activity on the global circulation in the Earth’s atmosphere ought to be absent.

However, in the upper atmosphere, electrically charged particles (electrons and ions) are present. These particles are present in the Earth’s ionosphere and magnetosphere. At ionospheric altitudes, the terrestrial atmosphere can be considered as a mixture of partially ionized gases, namely, as partially ionized plasma. No doubt, charged particles of this plasma may be affected by the geomagnetic field.

At altitudes of the E region of the ionosphere (in the 80-130 km range, approximately), intense horizontal electrical currents (so called electrojets) may take place, especially at high latitudes (auroral electrojets) [31,32]. These electrojets are the parts of a magnetosphere-ionosphere current system which includes a ring current, also [32]. It is evident that the electrojets must provide a heating of the ionospheric plasma at E-region altitudes. This heating affects not only charged particles but also ambient neutral gas due to collisions between charged and neutral particles of ionospheric plasma. It should be emphasized that the internal energy equation of the neutral gas has to include an additional term, describing the heating connected with electrical currents, taking place at ionospheric altitudes. It may be recalled that the internal energy equation for the neutral gas is not utilized in the applied mathematical model, instead, the global temperature field is assumed to be a given distribution, obtained from the empirical model.

It can be noticed that the geomagnetic activity level, Kp, depends on intensity of the magnetosphere-ionosphere current system. The more the intensity of the magnetosphere-ionosphere current system is, the higher values of the geomagnetic activity can be achieved. Variations of the magnetosphere-ionosphere current system are conditioned by inhomogeneities in the solar wind plasma, interacting with the Earth’s magnetosphere [33-35].

As was noted earlier, the heating of the neutral gas, connected with electrojets, is possible at E-region altitudes, that is, above approximately 80 km. It is understood that the temperature field of the neutral gas can be distinct under different geomagnetic activities at these altitudes. Consequently, the planetary circulation of the atmosphere can be distinct under different geomagnetic activities above approximately 80 km, too. It may be expected that, below approximately 80 km, geomagnetic activity cannot affect the planetary circulation in the Earth's stratosphere and mesosphere. In the remainder of the paper, we shall try to disprove such point of view.

In the present study, to investigate numerically, using the non-hydrostatic model of the global wind system [20,21], how geomagnetic activity affects the formation of the large-scale global circulation of the Earth's atmosphere, the simulations were performed for the summer period in the northern hemisphere (16 July) and for three distinct values of geomagnetic activity (Kp=1, 4 and 7). Modeled conditions correspond to moderate 10.7-cm solar flux ($F_{10.7}$ =101). The steady-state distributions of the atmospheric parameters were obtained, using the method of establishment, that is, the variations of the atmospheric parameters with time were calculated until they become stationary on condition that inputs to the model and boundary conditions correspond to the fixed moment, namely, 10.30 UT. The temperature distributions, corresponding to this moment, were taken from the NRLMSISE-00 empirical model [28].

Analyzing these temperature distributions, obtained for three distinct values of geomagnetic activity (Kp=1,4 and 7), we can see that they are very similar below approximately 80 km, whereas, above this altitude, they may be rather different. Thus, it can be seen from the NRLMSISE-00 empirical model that, for the summer period in the northern hemisphere, the influence of a level of geomagnetic activity on the global distribution of the atmospheric temperature ought to be absent at altitudes of the troposphere, stratosphere, and mesosphere, while this influence ought to be appreciable at altitudes of the lower thermosphere. This fact can be confirmed by Fig. 1.

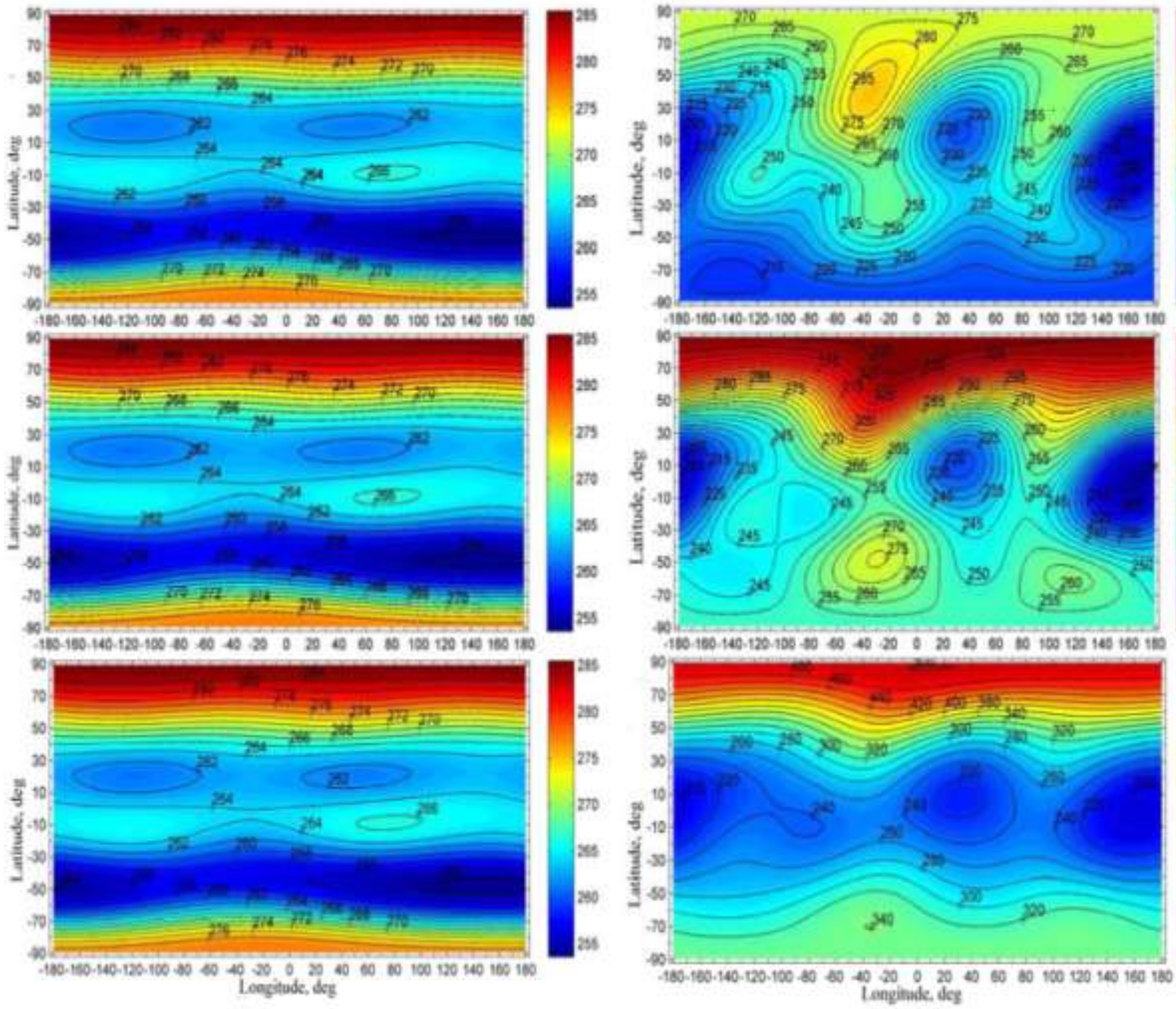

Figure 1: Global distributions of the atmospheric temperature (K), obtained from the NRLMSISE-00 empirical model for 16 July, UT=10.30 and calculated at 50 km altitude (left column) and at 110 km altitude (right column). The results were obtained for three distinct values of geomagnetic activity: Kp=1 (top panel), Kp=4 (middle panel) and Kp=7 (bottom panel).

As was noted earlier, the global temperature field is assumed to be a given distribution, i.e. the input parameter of the utilized mathematical model. The global distributions of the vector of the simulated horizontal component of the wind velocity, calculated with the help of the mathematical model and obtained for three distinct global temperature fields, corresponding to three values of geomagnetic activity (Kp=1, 4, and 7), are shown in Figs. 2 and 3.

It is well known that the horizontal irregularity of the atmospheric temperature ought to influence appreciably on the atmospheric circulation in horizontal directions. The more the horizontal gradients of the atmospheric temperature are, the higher values of the horizontal components of the wind velocity can be achieved.

This mechanism can easy elucidate the differences between the global distributions of the vector of the simulated horizontal component of the wind velocity, calculated at 110 km altitude for different values of geomagnetic activity and presented in the right column of the Fig. 3. Indeed, at 110 km altitude, the global distributions of the atmospheric temperature, calculated for three distinct values of geomagnetic activity, are rather different (the right column of the Fig. 1).

However, this mechanism cannot explain the differences between the global distributions of the vector of the simulated horizontal component of the wind velocity, calculated for three distinct values of geomagnetic activity at other altitudes (Figs. 2 and 3). Really, at altitudes of 10, 50, and 70 km, the global distributions of the vector of the simulated horizontal component of the wind velocity, calculated for three distinct values of geomagnetic activity, are rather different, whereas, the global distributions of the atmospheric temperature below approximately 80 km are practically equal, with their differences being less than 0.01 K in whole simulation domain. Thus, simulation results, obtained for July conditions, indicate that, despite of independence of the atmospheric temperature on the geomagnetic activity below approximately 80 km, the influence of the geomagnetic activity level on the global circulation of the stratosphere and mesosphere do exist.

To explain this fact, let us consider the global distributions of the simulated vertical component of the neutral wind velocity, calculated for three distinct values of geomagnetic activity. It turns out that these distributions are rather distinct not only at levels of the lower thermosphere but also at levels of the stratosphere and mesosphere (Fig. 4). Consequently, the vertical transport exists of the air from the lower thermosphere to the mesosphere and stratosphere and vice versa. This transport is influenced by geomagnetic activity level. Thus, the influence of geomagnetic activity on the global circulation in the Earth's stratosphere and mesosphere for July conditions may be explained by the vertical transport of the air which may be noticeably different under distinct geomagnetic activity levels.

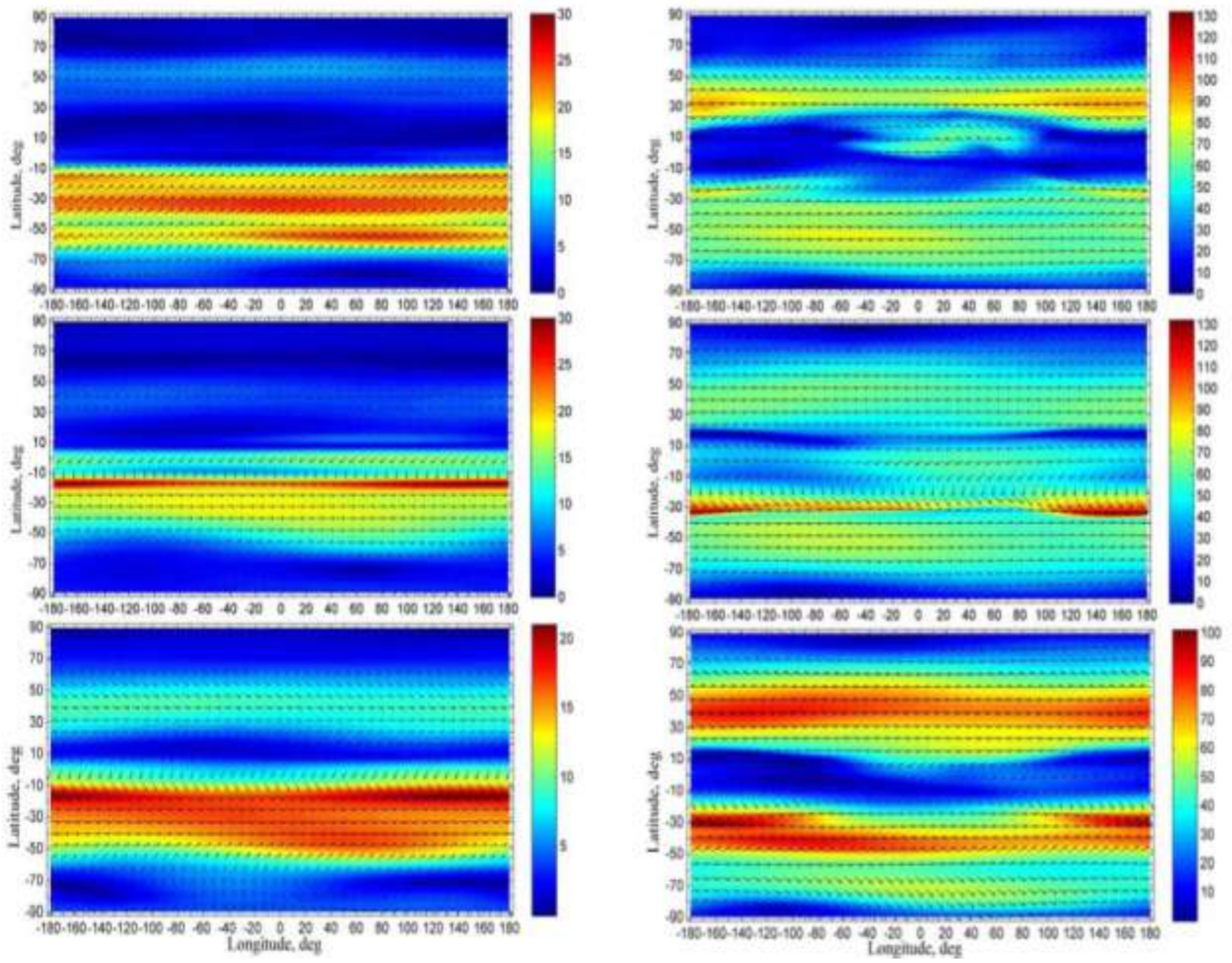

Figure 2: Global distributions of the vector of the simulated horizontal component of the wind velocity, calculated at 10 km altitude (left column) and at 50 km altitude (right column). The results were obtained for three distinct values of geomagnetic activity: Kp=1 (top panel), Kp=4 (middle panel) and Kp=7 (bottom panel). The colouration of the figures indicates the module of the velocity in m/s.

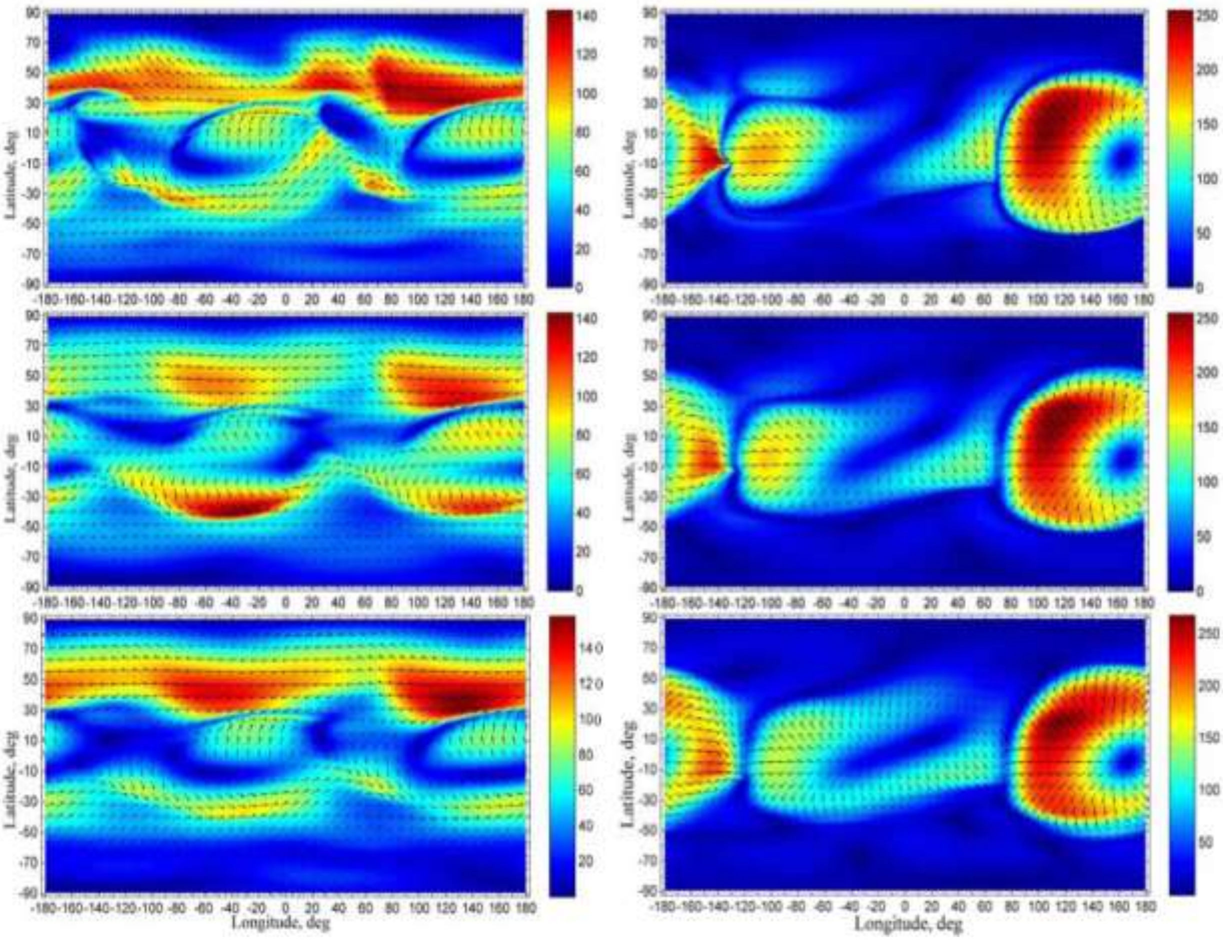

Figure 3: Global distributions of the vector of the simulated horizontal component of the wind velocity, calculated at 70 km altitude (left column) and at 110 km altitude (right column). The results were obtained for three distinct values of geomagnetic activity: Kp=1 (top panel), Kp=4 (middle panel) and Kp=7 (bottom panel). The colouration of the figures indicates the module of the velocity in m/s.

It turns out that distributions of the atmospheric parameters, calculated with the help of the mathematical model, illustrate both distinctions, caused by different values of geomagnetic activity and discussed above, and common characteristic features.

Let us consider common features of the simulation results. The horizontal and vertical components of the wind velocity are changeable functions not only of the altitude but also of latitude and longitude. At levels of the troposphere, stratosphere, mesosphere, and lower thermosphere, maximal absolute values of the horizontal and vertical components of the wind velocity are larger at higher altitudes. At altitudes of the mesosphere and lower thermosphere, the horizontal domains exist where the steep gradients in the horizontal velocity field take place. At the near points, the horizontal wind velocity can have various directions which may be opposite. Also, the horizontal domains exist in which the vertical neutral wind component has opposite directions. The horizontal wind velocity can achieve values of more than 130 m/s at levels of the mesosphere. In the horizontal domains, having a configuration like a limited narrow band, the vertical wind velocity can achieve values of more than 1 m/s at levels of the mesosphere. At these levels, maximal module of the upward vertical wind component is less than the maximal absolute values of the downward vertical wind component.

As was noted earlier, in the study by Mingalev et al. [22], the non-hydrostatic mathematical model of the global circulation of the Earth's atmosphere [20,21] has been utilized in order to investigate numerically how geomagnetic activity affects the formation of the large-scale planetary circulation in the Earth's atmosphere for the winter period in the northern hemisphere (16 January) and for two distinct values of geomagnetic activity (Kp=1 and Kp=4). Let us compare the simulation results, obtained in the present study, with the results of simulation, obtained in the study of Mingalev et al. [22].

It turns out that, for the winter period in the northern hemisphere, the influence of geomagnetic activity on the global wind system above approximately 80 km is conditioned by the differences of the global temperature fields, corresponding to distinct values of geomagnetic activity. Bellow approximately 80 km, the influence of geomagnetic activity on the global wind system is conditioned by the vertical transport of the air from the lower thermosphere to the mesosphere and stratosphere and vice versa, with this vertical transport being noticeably different under distinct geomagnetic activity conditions [22]. These mechanisms of the influence of geomagnetic activity on the global wind system, identified in the study of Mingalev et al. [22] for the winter period in the northern hemisphere, are the same as the mechanisms, identified in the present study for the summer period in the northern hemisphere.

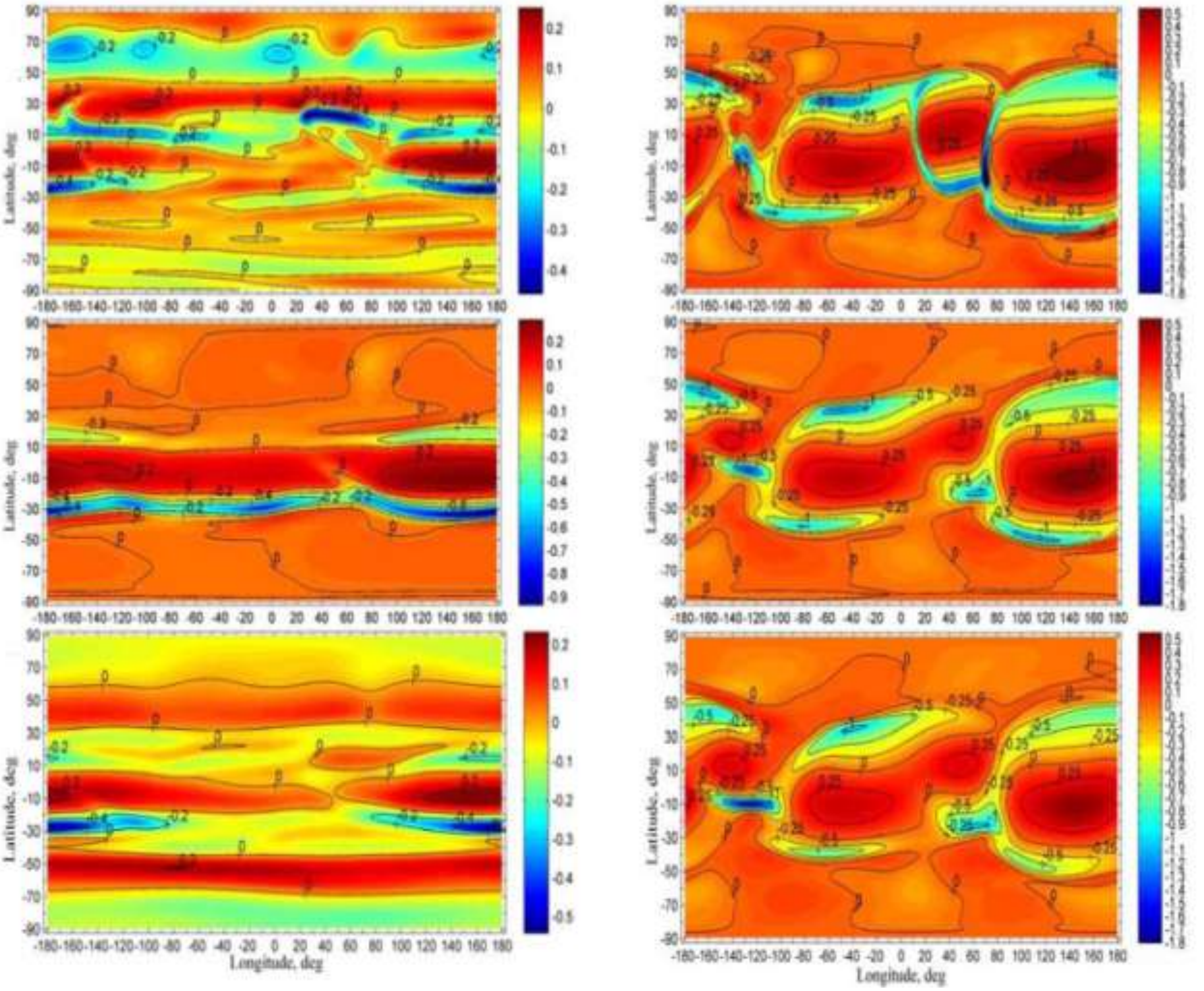

Figure 4: Global distributions of the simulated vertical component of the wind velocity, calculated at 50 km altitude (left column) and at 90 km altitude (right column). The results were obtained for three distinct values of geomagnetic activity: Kp=1 (top panel), Kp=4 (middle panel) and Kp=7 (bottom panel). The colouration of the figures indicates the module of the velocity in m/s, with positive direction of the vertical velocity being upward.

Nevertheless, there are noticeable distinctions between the simulation results, obtained in the study of Mingalev et al. [22] for the winter period in the northern hemisphere, and the results of simulation, obtained in the present study for the summer period in the northern hemisphere. From the numerically obtained results for summer period in the northern hemisphere, we can see that, at levels of the stratosphere and mesosphere, the motion of the neutral gas in the northern hemisphere is primarily westward (Fig.2), so a circumpolar anticyclone is formed. Simultaneously, the motion of the neutral gas is primarily eastward in the southern hemisphere at levels of the stratosphere and mesosphere (Fig.2), so a circumpolar cyclone is formed for winter period of the southern hemisphere.

On the contrary, from the numerically obtained results for winter period in the northern hemisphere [22], we can see that, at levels of the stratosphere and mesosphere, the motion of the neutral gas in the northern hemisphere is primarily eastward, so a circumpolar cyclone is formed. Simultaneously, the motion of the neutral gas is primarily westward in the southern hemisphere at levels of the stratosphere and mesosphere, so a circumpolar anticyclone is formed for summer period of the southern hemisphere. These facts can be confirmed by Fig. 5. It can be seen from the right column of Fig. 5 that the center of the northern cyclone may be displaced from the pole.

From numerous observations, it is well known that the global atmospheric circulation can contain sometimes so called circumpolar vortices that are the largest scale inhomogeneities in the atmospheric global wind system. Their extent can be very large, sometimes reaching the latitudes close to the equator. The circumpolar vortices are formed at heights of the stratosphere and mesosphere in the periods close to summer and winter solstices, when there is no rebuilding of the atmosphere. The circumpolar anticyclone arises in the northern hemisphere under summer conditions, while the circumpolar cyclone arises in the southern hemisphere under winter conditions. On the contrary, the circumpolar cyclone arises in the northern hemisphere under winter conditions, while the circumpolar anticyclone arises in the southern hemisphere under summer conditions.

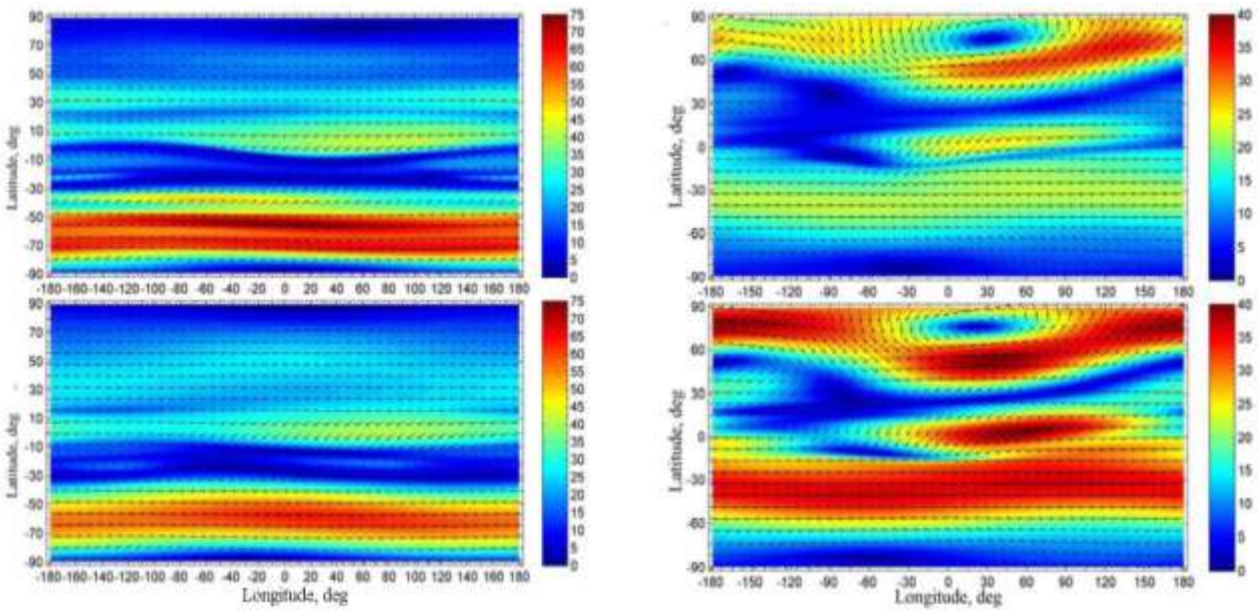

Figure 5: Global distributions of the vector of the simulated horizontal component of the wind velocity, calculated at 30 km altitude and obtained for two distinct values of geomagnetic activity: Kp=1 (top panel) and Kp=4 (bottom panel). The results were obtained for the summer period in the northern hemisphere (16 July) (left column) and for the winter period in the northern hemisphere (16 January) [22] (right column). The colouration of the figures indicates the module of the velocity in m/s.

Let us compare these experimental data with the simulation results, obtained for July and January conditions (Fig. 5). It is easy to see that the circumpolar vortices of the northern and southern hemispheres, numerically simulated at levels of the stratosphere and mesosphere in the present study for the summer period in the northern hemisphere and in the study of Mingalev et al. [22] for the winter period in the northern hemisphere, correspond qualitatively to the global circulations, obtained from observations. Incidentally, the qualitative agreement between January and June circulations in the stratosphere and mesosphere, obtained numerically and experimentally, manifests the adequacy of the utilized mathematical model.

4. CONCLUSIONS

The non-hydrostatic mathematical model of the global circulation in the Earth's atmosphere, developed earlier in the Polar Geophysical Institute, was utilized to investigate how geomagnetic activity affects the planetary circulation of the atmosphere for July conditions. The mathematical model produces three-dimensional distributions of the zonal, meridional, and vertical components of the wind velocity and neutral gas density in the troposphere, stratosphere, mesosphere, and lower thermosphere. In the utilized mathematical model, not only the horizontal components but also the vertical component of the wind velocity is obtained by means of a numerical solution of a generalized Navier-Stokes equation for compressible gas. Another peculiarity of the utilized mathematical model consists in that the internal energy equation for the neutral gas is not solved in the model calculations. Instead, the global temperature field is assumed to be a given distribution, i.e. the input parameter of the model, and obtained from the NRLMSISE-00 empirical model [28].

Simulation results, presented in this work, were obtained for the summer period in the northern hemisphere (16 July) and for conditions corresponding to moderate 10.7-cm solar flux ($F_{10.7}$ =101). Calculations were made for three distinct values of geomagnetic activity (Kp=1, 4 and 7). The steady-state distributions of the atmospheric parameters were obtained, using the method of establishment, that is, the variations of the atmospheric parameters with time were calculated until they become stationary on condition that inputs to the model and boundary conditions correspond to the fixed moment, namely, 10.30 UT.

The simulation results indicated that, in the lower thermosphere, geomagnetic activity ought to influence considerably on the formation of global wind system as a consequence of variations of the atmospheric temperature distributions due to geomagnetic activity changes. At levels of the stratosphere and mesosphere, the influence of geomagnetic activity on the global distribution of the atmospheric temperature ought to be absent, nevertheless, the effect of geomagnetic activity on the global circulation of the atmosphere exists at these levels. The influence of geomagnetic activity on the global wind system in the stratosphere and mesosphere is conditioned by the vertical transport of the air which may be noticeably different under distinct geomagnetic activity conditions. The explanation of the influence of geomagnetic activity on the global circulation in the Earth's stratosphere and mesosphere, propounded in the present study for July conditions, is similar to the elucidation, given earlier for January conditions [22]. It can be emphasized that the applied mathematical model was able to simulate this effect due to the fact that the model is non-hydrostatic.

It turned out that the simulated planetary distributions of the horizontal wind velocity, obtained for different values of geomagnetic activity, contain large-scale circumpolar vortices of the northern and southern hemispheres at levels of the stratosphere and mesosphere. These circumpolar vortices correspond well to the global circulation of the stratosphere and mesosphere, obtained from observations for July conditions. This fact manifests the adequacy of the utilized mathematical model.

It can be noted that the mathematical model, utilized in the present study, has been successfully applied for investigations of global circulations of the atmospheres not only of the Earth but also of other planetary bodies, in particular, of the Titan (the largest satellite of Saturn) [36,37] and Venus [38,39].

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