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Numerical Modeling of the Initial Formation of Cyclonic Vortices at Tropical Latitudes

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Abstract

To investigate the initial formation of large-scale vortices at tropical latitudes a regional non-hydrostatic mathematical model of the wind system of the lower atmosphere, developed earlier in the Polar Geophysical Institute, is utilized. 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 are produced by the utilized model. Simulations are performed for the case when the limited three-dimensional simulation domain is intersected by an intertropical convergence zone in the west-east direction. Simulation results indicated that the origin of two convexities in the north direction in the configuration of the intertropical convergence zone can lead to the formation of three distinct tropical cyclones during the period of about four days.

Keywords

Numerical Simulation, Air Flow, Lower Atmosphere, Tropical Cyclones

1. Introduction

Tremendous damage and numerous fatalities may be produced by severe tropical cyclonic storms and hurricanes. Therefore, prediction of tropical cyclone origin is very important problem. The physical theory of tropical cyclone origin is still far from completion despite of considerable efforts. Nevertheless, some aspects of tropical cyclogenesis are commonly understood, in particular, in the late stages of formation as well as in a fully devel-

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oped stage (see [1]-[4] and references therein). Unfortunately, modern scientific facility does not allow somebody to measure detailed three-dimensional fields of thermodynamical and gas dynamical parameters of the lower atmosphere with sufficient accuracy to understand the physical mechanisms responsible for the initial formation of tropical cyclones. To investigate these physical mechanisms, not only the experimental and theoretical but also computational studies may be applied. However, most of numerical studies of tropical cyclone genesis explore how a tropical cyclone forms from pre-existing large-scale disturbances of the troposphere, or from vortices, those are precursors to tropical cyclones (for example, see [5]-[12]). Thus, many of the details of the initial stage of the formation of tropical cyclones are still unresolved.

In the present study, to investigate the initial stage of the origin of large-scale vortices at tropical latitudes a mathematical model of the wind system of the lower atmosphere, developed earlier in the Polar Geophysical Institute (PGI), is utilized. This mathematical model is the regional version of the non-hydrostatic mathematical model of the global wind system in the Earth's atmosphere, developed earlier in the PGI [13] [14] and applied in order to investigate numerically how the horizontal non-uniformity of the atmospheric gas temperature affects the formation of the middle atmosphere global circulation for different geophysical conditions [15]-[18].

The regional non-hydrostatic mathematical model of the wind system of the lower atmosphere, utilized in the present study, was earlier applied in order to investigate numerically the mechanisms responsible for the formation of large-scale vortices in the Earth's lower atmosphere. In particular, this model was applied to investigate the formation mechanisms of a large-scale vortex over an ocean surface [19] [20]. This regional model was applied to investigate the formation mechanism of polar lows [21] [22], too. Also, this regional model was applied to verify the hypothesis of the influence of the shape of the intertropical convergence zone (ITCZ) on the process of the formation of tropical cyclones [23] [24]. In these investigations, it was shown that the origin of convexities in the form of the intertropical convergence zone, having the specific configurations, can lead to the formation of different large-scale vortices, in particular, a single cyclonic vortex, pair of cyclonic-anticyclonic vortices, and pair of cyclonic vortices, during the period not longer than three days.

The purpose of the present study is to continue these investigations and to study numerically, applying the regional mathematical model of the wind system of the lower atmosphere, the initial stage of the origin of large-scale vortexes in the vicinity of the intertropical convergence zone. Simulations are performed for the case when the limited three-dimensional simulation domain is intersected by an intertropical convergence zone in the west-east direction. It is supposed that, at the initial moment, the intertropical convergence zone contains two convexities in the north direction. Time-dependent modeling is performed during the period of about four days.

2. Mathematical Model

The regional mathematical model of the wind system of the lower atmosphere, developed not long ago at the PGI, is utilized in the present study. The characteristic feature of the 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 air 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.

In the utilized 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 model is based on the numerical solution of the system of transport equations containing 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 momentum equations for all components of the air velocity, the effect of the turbulence on the mean flow is taken into account by using an empirical subgrid-scale parameterization similarly to the global circulation model of the Earth's atmosphere developed earlier in the PGI [13] [14].

Thus, the utilized 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, which play an important role in energetic balance. The finite-difference method and explicit scheme are applied for solving the system of governing equations.

In the utilized model, the following variables are computed at each grid node: the temperature of the mixture of air and water vapor, T; densities of air and water vapor, ρ_a and ρ_v, respectively; hydrodynamic velocity of the mixture (a 3D vector), $\boldsymbol{v}$; and the total mass of water microdrops and ice microparticles in a unit volume, ρ_w and ρ_i, respectively. The governing equations in vectorial form can be written as follows:

$$\frac{\partial \rho_a}{\partial t} + \operatorname{div}\left(\rho_a \boldsymbol{v}\right) = 0 \tag{1}$$

$$\frac{\partial\left(\rho_v + \rho_w + \rho_i\right)}{\partial t} + \operatorname{div}\left[\rho_v \boldsymbol{v} + \rho_w\left(\boldsymbol{v} + \boldsymbol{v}_w^{\text{prec}}\right) + \rho_i\left(\boldsymbol{v} + \boldsymbol{v}_i^{\text{prec}}\right)\right] = 0 \tag{2}$$

$$\frac{\partial\left(\rho_{\text{mix}} \boldsymbol{v}\right)}{\partial t} + \operatorname{div}\left(\rho_{\text{mix}} \boldsymbol{v} \otimes \boldsymbol{v}\right) = -\nabla p + \operatorname{div}\hat{\tau} + \left(\rho_{\text{mix}} + \rho_w + \rho_i\right)\boldsymbol{F} \tag{3}$$

$$\begin{aligned} &\frac{\partial W}{\partial t} + \operatorname{div}\left[W_{\text{mix}} \boldsymbol{v} + W_w\left(\boldsymbol{v} + \boldsymbol{v}_w^{\text{prec}}\right) + W_i\left(\boldsymbol{v} + \boldsymbol{v}_i^{\text{prec}}\right)\right] \\ &= \left[\rho_{\text{mix}} \boldsymbol{v} + \rho_w\left(\boldsymbol{v} + \boldsymbol{v}_w^{\text{prec}}\right) + \rho_i\left(\boldsymbol{v} + \boldsymbol{v}_i^{\text{prec}}\right), \boldsymbol{F}\right] + \operatorname{div}(\hat{\tau} \cdot \boldsymbol{v} - p\boldsymbol{v} - \boldsymbol{j}) + Q, \end{aligned} \tag{4}$$

where $\boldsymbol{v}_w^{\text{prec}}$ and $\boldsymbol{v}_i^{\text{prec}}$ are the precipitation velocities of water microdrops and ice microparticles, respectively, conditioned by the presence of an external force field and determined from the Stokes relation with Cunningham's correction; $\rho_{\text{mix}} = \rho_a + \rho_v$; p is the pressure of the mixture defined as $p = \left(\rho_a R_a + \rho_v R_v\right)T$, where R_a and R_v are the gas constants of air and water vapour, respectively; $\hat{\tau}$ is the extra stress tensor whose components are given by the rheological equation of state or the law of viscous friction which is the same as in the global circulation model of the Earth's atmosphere developed earlier [13] [14], with the effect of a small-scale turbulence, having the scales equal and less than the steps of finite-difference approximations, on the mean flow having been taken into account; $\boldsymbol{F}$ is the acceleration due to an external force field, which consists of the gravity acceleration, Coriolis acceleration, and acceleration of translation, that can be written in the form (for example, see [25])

$$\boldsymbol{F} = \boldsymbol{g} - 2\boldsymbol{\Omega} \times \boldsymbol{v} - \boldsymbol{\Omega} \times \left(\boldsymbol{\Omega} \times \boldsymbol{r}\right)$$

where $\boldsymbol{g}$ is the acceleration due to gravity, $\boldsymbol{\Omega}$ is the Earth's angular velocity, and $\boldsymbol{r}$ is a radius vector from the center of the Earth to the point where the equation is applied. The following notations are used in Equation (4)

$$\begin{aligned} &W_i = \rho_i\left[\frac{1}{2}\left(\boldsymbol{v} + \boldsymbol{v}_i^{\text{prec}}\right)^2 + C_i T\right], \quad W_w = \rho_w\left[\frac{1}{2}\left(\boldsymbol{v} + \boldsymbol{v}_w^{\text{prec}}\right)^2 + C_w\left(T - T_0\right) + q_{\text{mel}} + C_i T_0\right], \\ &W = W_{\text{mix}} + W_w + W_i, \end{aligned}$$

where C_i and C_w are the specific heat capacities of ice and water, respectively, which are assumed constant; T_0 is the freezing temperature of water; q_{mel} is the specific heat of ice melting at $T = T_0$; q_{ev}^0 is the specific heat of water evaporation at $T = T_0$; also, the vector of heat flux, $\boldsymbol{j}$, is given by the well-known formula, $\boldsymbol{j} = -\hat{\lambda}\nabla T$, where $\hat{\lambda}$ is the symmetric tensor of thermal conductivity coefficients; and Q is the rate of change of energy in a unit volume due to absorption/emission of infrared radiation. Concrete expressions of the model parameters, those appear in Equations (1)-(4), may be found in the studies of Belotserkovskii *et al.* [19] [20].

It can be noted that the model assumes that the water microdrops can exist only in the presence of saturated water vapor on condition that $T \geq T_0$, while the ice microparticles can exist only in the presence of saturated water vapor on condition that $T \leq T_0$. At $T = T_0$, the temperature of the matter cannot increase until all ice microparticles melt, and it cannot decrease until all water microdrops freeze.

It is assumed that the three-dimensional simulation domain of the model is a part of a spherical layer stretching from land and ocean surface up to the altitude of 15 km over a limited region of the Earth's surface. In the present study, the dimensions of this region in longitudinal and latitudinal directions are 75˚ and 25˚, respectively. The calculated parameters are determined on a uniform grid. The latitude and longitude steps are equal to

0.08˚, and height step is equal to 200 m. As pointed out previously, the finite-difference method is applied for solving the system of equations. Complete details of the utilized finite-difference method and numerical schemes have been presented in the paper of Mingalev *et al.* [26]. More complete details of the applied regional mathematical model may be found in the studies of Belotserkovskii *et al.* [19] [20] and Mingalev *et al.* [23].

3. Presentation and Discussion of Results

The present study is the continuation of the investigations of the initial stage of the origin of large-scale vortices in the vicinity of an intertropical convergence zone, fulfilled earlier [23] [24]. It is known that an intertropical convergence zone may be considered as a fluid stream, having enhanced zonal velocities, in the ambient atmospheric gas, with a zonal flow of air being westward. A meridional wind velocity directs towards the centerline of an intertropical convergence zone at levels less than approximately 3 km and directs from the centerline of an intertropical convergence zone at levels higher than approximately 3 km. A vertical wind velocity in an intertropical convergence zone is upward. Also, it is known that the form of an intertropical convergence zone may be different and, sometimes, can contain convexities with distinct shapes. The north-south position of the intertropical convergence zone responds to changes in interhemispheric temperature contrast. An asymmetry in air-sea interactions can play an important role in forming the configuration of the intertropical convergence zone [27]-[29].

In the earlier study of Mingalev *et al.* [23], the idea has been advanced that the transformation of the form of the intertropical convergence zone can influence the process of the formation of tropical cyclones. This idea has been confirmed with the help of mathematical modeling [23] [24]. In particular, it was shown that the origin of a convexity in the configuration of the intertropical convergence zone can lead to the formation of a single cyclonic vortex during the period of about one day, with the cyclonic center being close to the southern edge of the initial intertropical convergence zone [23]. Moreover, the results of mathematical modeling have indicated that the origin of a convexity of the intertropical convergence zone, having the specific forms, can lead to the formation of not only a single cyclonic vortex but also a cyclonic-anticyclonic pair [23] and pair of cyclonic vortices [24], during the period not longer than three days. It can be noted that the results of observation of the Earth's atmosphere indicated a simultaneous origin of twin tropical cyclones sometimes [30].

In the present study, simulations are performed for the case when the three-dimensional simulation domain is intersected by an intertropical convergence zone in the west-east direction. It was supposed that, at the initial moment, the intertropical convergence zone contains two convexities in the north direction, with the deviations achieving a value of a few hundreds of kilometers. The initial form of the intertropical convergence zone may be easy seen from **Figure 1**, where it is like a light curved band. The time evolution of model parameters was numerically simulated using the mathematical model during the period of about four days. The results of time-dependent modeling are shown in **Figures 2-4**.

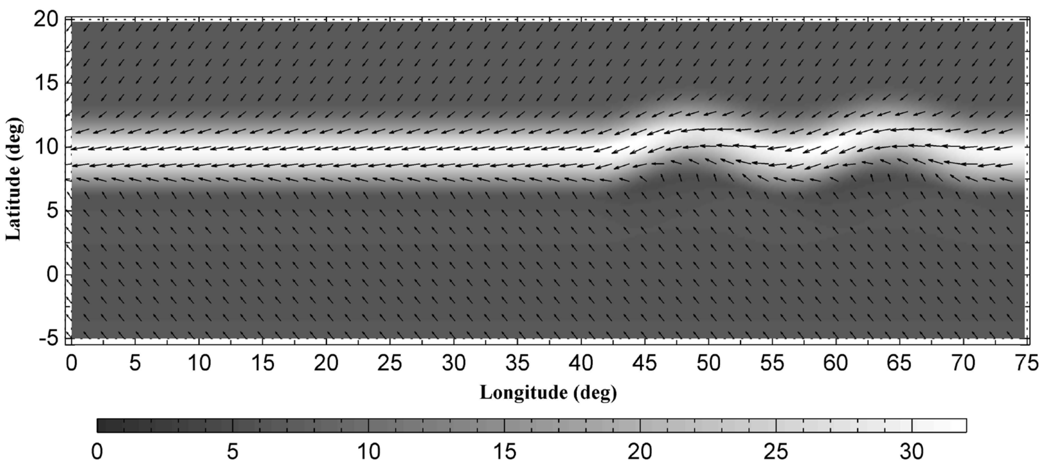

Figure 1. The distribution of horizontal component of the air velocity (m/s) at the altitude of 600 m, assigned at the initial moment. The degree of shadowing of the figure indicates the module of the velocity in m/s.

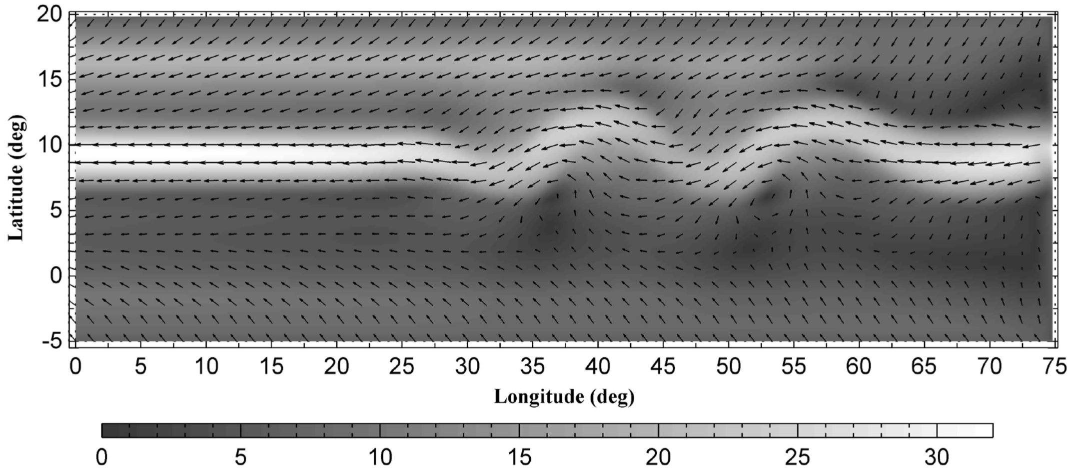

Figure 2. The distribution of horizontal component of the air velocity (m/s) at the altitude of 600 m, computed 20 hours after the beginning of calculations. The degree of shadowing of the figure indicates the module of the velocity in m/s.

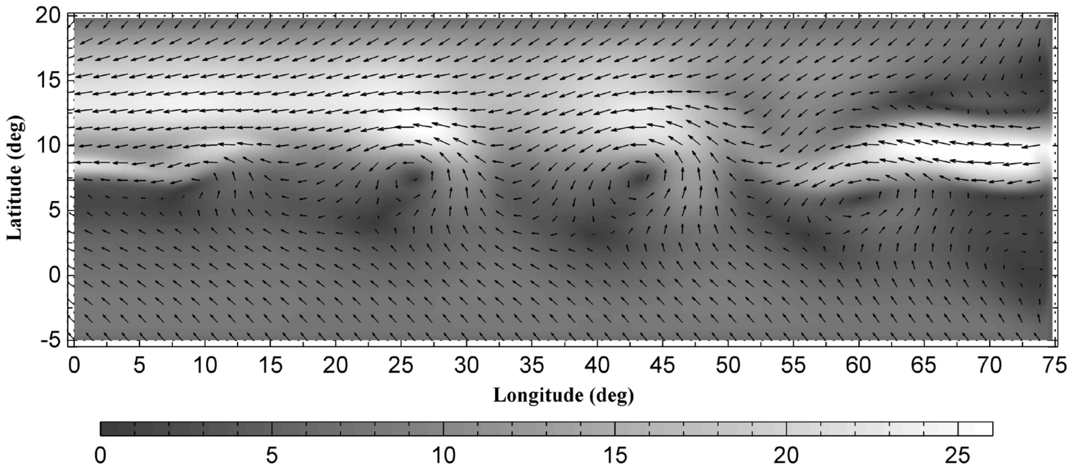

Figure 3. The distribution of horizontal component of the air velocity (m/s) at the altitude of 600 m, computed 50 hours after the beginning of calculations. The degree of shadowing of the figure indicates the module of the velocity in m/s.

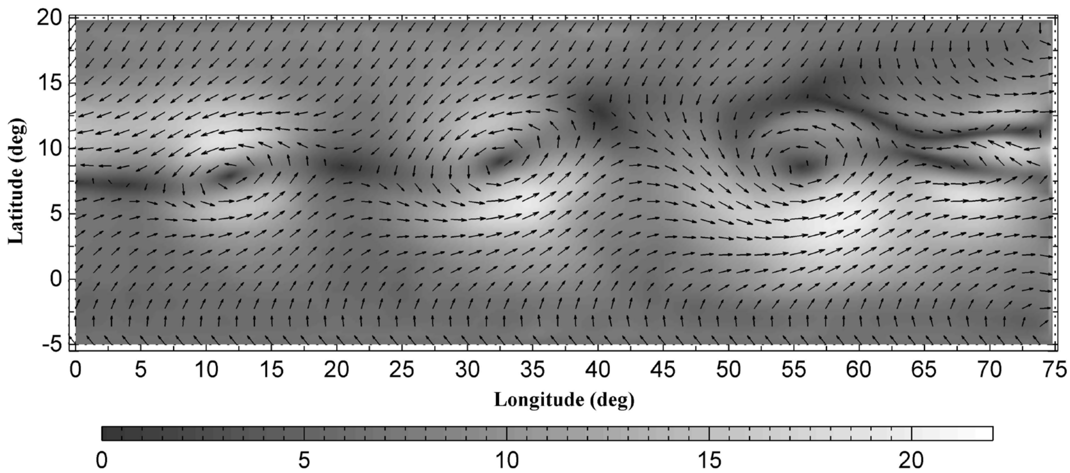

Figure 4. The distribution of horizontal component of the air velocity (m/s) at the altitude of 600 m, computed 90 hours after the beginning of calculations. The degree of shadowing of the figure indicates the module of the velocity in m/s.

The results of simulation indicate that, in the course of time, the initial distribution of horizontal component of the air velocity was considerably transformed. In a moment of 20 hours after the beginning of calculations, a pair of tropical cyclonic vortices arose. Their centers are close to the southern edge of the initial intertropical convergence zone. In a moment of 50 hours after the beginning of calculations, these cyclonic vortices have moved in the western direction for about 10 degrees. Simultaneously, the third cyclonic vortex arose, with its center being close to the southern edge of the initial intertropical convergence zone. All arisen cyclonic vortices have moved in the western direction. In a moment of 90 hours after the beginning of calculations, the displacement of third cyclonic vortex is about 6 degrees. The horizontal wind velocity in the cyclones can achieve values of 15 - 20 m/s in the course of time. The maximum wind velocities within the vortices are reached approximately 20 h after their origins, and then they begin to decrease slowly. The radii of these three cyclones are about 800 km.

The simulation results indicate that a key factor in the modeled formation of the triplet of tropical cyclonic vortices is the origin of convexities in the configuration of the intertropical convergence zone. The origin of these convexities leads to beginning of instability of stream air flow. This instability leads to considerable transformation of the wind field. As a consequence, the triplet of tropical cyclonic vortices arises in the lower atmosphere in the course of time. In addition to that, the initial intertropical convergence zone is broken down.

4. Summary and Concluding Remarks

In earlier studies by the authors of the present work, the idea has been advanced that the transformation of the shape of the intertropical convergence zone can influence the process of the formation of tropical cyclones [23] [24]. It was shown that the origin of a convexity of the intertropical convergence zone, having the specific forms, can lead to the formation of not only a single cyclonic vortex but also a pair of large-scale vortices.

The present work is the continuation of the investigation of the initial stage of the origin of large-scale vortices at tropical latitudes. For this investigation, a regional non-hydrostatic mathematical model of the wind system of the lower atmosphere, developed earlier in the Polar Geophysical Institute, is utilized. The model is based on the numerical solution of the system of transport equations containing 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. 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. Simulations are performed for the case when this region is intersected by the intertropical convergence zone having the specific configuration. It was supposed that, at the initial moment, the intertropical convergence zone contains two convexities, having the longitudinal dimension of about 1400 km and deviations in the north direction, achieving a value of a few hundreds of kilometers.

The simulation results indicated that the twin tropical cyclones were formed during the period of about 20 hours. Their centers are close to the southern edge of the initial intertropical convergence zone. Besides, in a moment of approximately 50 hours after the beginning of calculations, third tropical cyclone arose whose center is close to the southern edge of the initial intertropical convergence zone, too. The arisen triplet of tropical cyclonic vortices has moved in the western direction. The horizontal wind velocity in the cyclones can achieve values of 15 - 20 m/s in the course of time. The radii of these three cyclones are about 800 km.

The simulation results have shown that the cause for the formation of tropical large-scale vortices in the vicinity of the intertropical convergence zone is a rise of instability of stream air flow present in this zone. The cause for the rise of this instability is the origin of the convexities in the configuration of the intertropical convergence zone. This instability leads to considerable transformation of the air flow. As a result, the intertropical convergence zone may be broken and tropical large-scale vortices can be formed in the vicinity of the initial position of the intertropical convergence zone in the course of time.

It may be expected that the simulation results of the present study, as well of studies by Mingalev *et al.* [23] [24], will be useful for tropical cyclones forecasting. The origin of the convexities in the configuration of the intertropical convergence zone, which may be observed with the help of satellite monitoring of the Earth's atmosphere, is a precursor of the formation of tropical cyclones. Incidentally, depending on the configurations of the convexities one can predict the number of tropical large-scale vortices and the regions of their appearance.

It can be noticed that, according to observations, not each cyclonic vortex, arisen in the lower atmosphere, has the potential to grow up to the long-live large-scale atmospheric vortex. It is known that, sometimes, a vortex, initially arisen in the lower atmosphere, can be attenuated in the course of time and will not achieve a status of the long-live large-scale atmospheric vortex. This peculiarity may take place for the large-scale vortices arisen in the calculations of the present study, with further transformation of the originated vortices depending on environmental conditions, in particular, on the degree of saturation of air by water vapor.

Simulations of the present study were limited by the time interval of approximately four days. Unfortunately, more prolonged time intervals are impossible for the utilized mathematical model because of limited sizes of its simulation domain and owing to tendency of the modeled vortices to move and to abandon the simulation domain in the course of time.

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