"Physics of Auroral Phenomena", Proc. XXXVI Annual Seminar, Apatity, pp. 193 - 196, 2013

Polar Geophysical Institute

SIMULATION STUDY OF THE MECHANISM OF THE FORMATION OF POLAR MESOSCALE CYCLONES AT HIGH LATITUDES OF THE NORTHERN HEMISPHERE

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Abstract. A regional non-hydrostatic mathematical model of the wind system of the lower atmosphere, developed recently in the Polar Geophysical Institute, is utilized to investigate the mechanism of the formation of polar mesoscale cyclones at high latitudes of the northern hemisphere. 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 dimensions of this region in longitudinal and latitudinal directions are 36° and 25°, respectively. Simulations are performed for the cases when this region is intersected by an arctic front, with the horizontal velocity field being asymmetric relatively the centerline of the arctic front inside and beyond it. Simulation results indicate that the origin of a convexity in the configuration of the arctic front can lead to the formation of a polar mesoscale cyclone during the period for about one day.

Introduction

A polar mesoscale cyclone (PMC) is an intense mesoscale atmospheric low pressure weather system (depression), involving strong winds, that originates over polar oceans in both the Northern and Southern hemispheres. Polar mesoscale cyclones have been referred to by other terms, such as polar low (PL), arctic hurricane, and cold air depression. Polar mesoscale cyclones are characterized by small sizes and short lifetimes in comparison with tropical cyclones. Nevertheless, polar mesoscale cyclones can cause wave surges, threat to ships, coastal flooding, and numerous fatalities for coastal communities. Therefore, prediction of polar mesoscale cyclone formation is a very important problem. Mathematical models have the potential to make significant contributions to our knowledge of the processes responsible for the formation of polar mesoscale cyclones.

Not long ago, in the Polar Geophysical Institute (PGI), a regional mathematical model of the wind system of the lower atmosphere has been developed [*Belotserkovskii et al.,* 2006]. This 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 utilized in order to investigate numerically the mechanisms responsible for the formation of large-scale vortices over the ocean surface at tropical latitudes [*Belotserkovskii et al.*, 2009; *Mingalev et al.*, 2011b, 2012b, 2013]. In pointed out studies, it was shown that the origin of convexities in the form of the intertropical convergence zone (ITCZ), having distinct configurations, can lead to the formation of different large-scale vortices, in particular, a cyclonic vortex, pair of cyclonic-anticyclonic vortices, and pair of cyclonic vortices, during the period not longer than three days.

Also, the latter regional mathematical model has been applied to verify the hypothesis of the influence of the shape of the arctic front on the initial formation of polar mesoscale cyclones. This hypothesis has been advanced and confirmed in the studies by *Mingalev et al.* [2011a, 2012a]. In these studies, simulations were performed for two cases when, at the initial moment, the simulation domain is intersected by the arctic front with different configurations, with the fields of the module of the horizontal velocity being approximately symmetric relatively to the centerline of the arctic front not only inside it but also beyond the arctic front.

The purpose of the present work is to continue the investigation of the initial stage of the formation of polar mesoscale cyclones at latitudes of the European Arctic, applying the regional mathematical model of the wind system of the lower atmosphere, developed in the PGI. Time-dependent modeling is performed for two cases in which the initial forms of the arctic front are different and contain convexities with distinct shapes, with the fields of the module of the horizontal velocity being asymmetric relatively to the centerline of the arctic front not only inside it but also beyond the arctic front.

Mathematical model

The regional non-hydrostatic mathematical model of the wind system of the lower atmosphere, developed not long ago at the Polar Geophysical Institute, is applied in the present work. In the applied 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. The characteristic feature of the model is that the vertical component of the air velocity is calculated without using 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. 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 [*Mingalev I. and Mingalev V.*, 2005; *Mingalev et al.*, 2007].

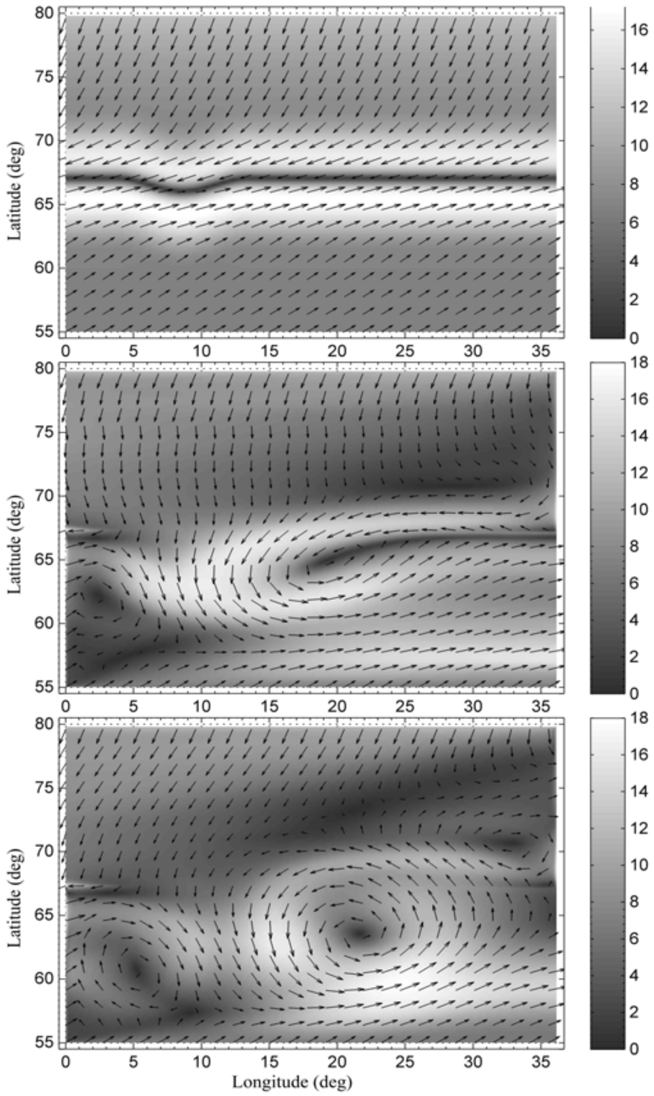

Fig.1. The distributions of horizontal component of the air velocity at the altitude of 600 m, assigned at the initial moment (top panel), computed 20 hours after the beginning of calculations (middle panel), and computed 40 hours after the beginning of calculations (bottom panel). The results are obtained for the first initial configuration of the arctic front when, at the initial moment, the modules of the zonal wind velocities at more northern latitudes relatively to the centerline of the arctic front are less than those at more southern latitudes relatively to it. The degree of shadowing of the figures indicates the module of the velocity in m/s.

Thus, the mathematical model is based on numerical solving of non-simplified gas dynamic equations and produces three-dimensional distributions of the wind components, temperature, air density, water vapor density, concentration of micro drops of water, and concentration of ice particles in the height range from 0 to 15 km over a limited region of the Earth's surface. The dimensions of this region in longitudinal and latitudinal directions are 36° and 25°, respectively. The southern boundary of the simulation region was located at 55° N. 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. The finite-difference method and explicit scheme are applied for solving the system of governing equations. The calculated parameters are determined on a uniform grid. The latitude step and longitude step are equal to 0.08°, and height step is equal to 200 m. More complete details of the applied regional mathematical model may be found in the studies of *Belotserkovskii et al.* [2006, 2009] and *Mingalev et al.* [2011a].

Simulation results

The arctic front separates the cold arctic air masses from warmer air masses. The arctic front can also be defined as the semipermanent, semi-continuous boundary of the cold arctic air mass. As a rule, the extension of the arctic front in the meridional direction does not exceed 200 km and its length in the zonal direction may be more than 2000 km. The direction along which the arctic front passes deviates from the zonal direction, as a rule, is no more than 20 degrees.

It is known from observations that, in an arctic front, a zonal flow of air is westward at more northern latitudes relatively to the centerline of an arctic front. On the contrary, a zonal flow of air is eastward at more southern latitudes relatively to the centerline of an arctic front. In an arctic front, a meridional wind velocity directs towards the centerline of an arctic front at altitudes less than approximately 2,5 km and directs from the centerline of an arctic front at levels higher than approximately 2,5 km. A vertical wind velocity in an arctic front is upward. Therefore, an arctic front may be considered as a system consisting of two air streams moving in opposite directions in the ambient atmospheric gas, with strong velocity shear taking place close to the centerline of an arctic front. In our calculations, we define the initial and boundary conditions as consistent with observational data and for the situations when the arctic front intersects the simulation domain in the west-east direction.

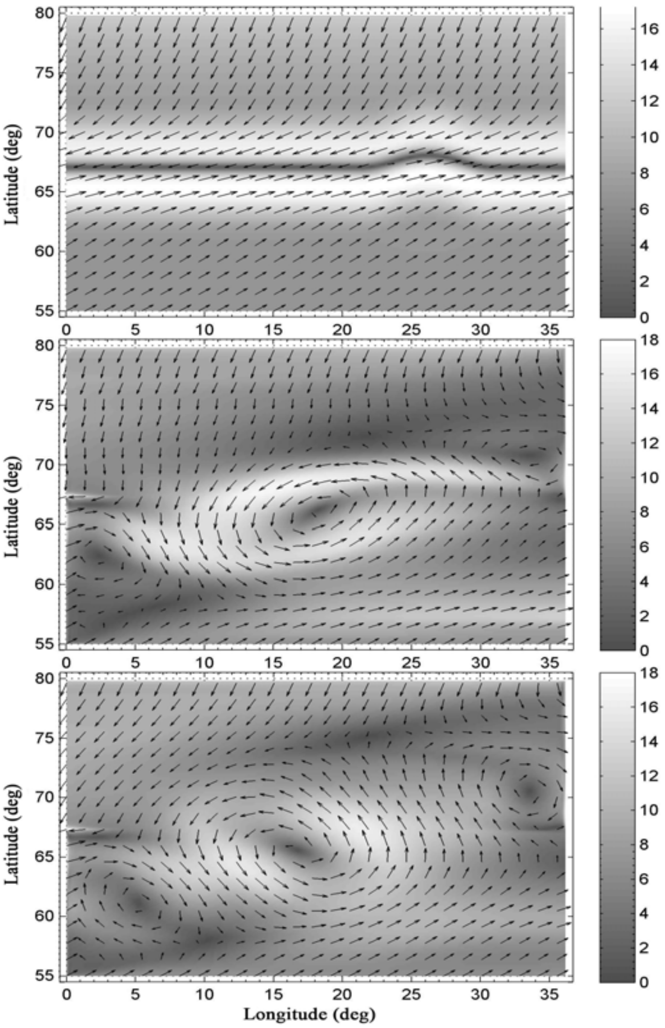

Fig. 2. The distributions of horizontal component of the air velocity at the altitude of 600 m, assigned at the initial moment (top panel), computed 20 hours after the beginning of calculations (middle panel), and computed 40 hours after the beginning of calculations (bottom panel). The results are obtained for the second initial configuration of the arctic front, with the modules of the zonal wind velocities at more northern latitudes relatively to the centerline of the arctic front being less than those at more southern latitudes relatively to it. The degree of shadowing of the figures indicates the module of the velocity in m/s.

Initially, let us consider the first case when, at the initial moment, the arctic front contains a convexity in the south direction, with the deviation achieving a value of one hundred of kilometers. It may be emphasized that, at the initial moment, the fields of the module of the horizontal velocity are asymmetric relatively to the centerline of the arctic front not only inside it but also beyond the arctic front. The initial form of the arctic front may be easy seen from the top panel of the Fig. 1, where it is like a dark curved band between two light curved bands.

The time evolution of atmospheric parameters was numerically simulated using the mathematical model during the period for about two days. The results of time-dependent modeling are partly shown in Fig. 1. It can be seen from this figure that, in the course of time, the initial distribution of horizontal component of the air velocity was considerably transformed.

The simulation results, presented in Fig. 1, show that, at the presence at the initial moment of the part of the arctic front bent to the south, when the fields of the module of the horizontal velocity are asymmetric relatively to the centerline of the arctic front, eastward from this part, approximately in 20 h, a polar mesoscale cyclone is formed which moves to the south and to the east with a velocity of approximately 11 km/h. The maximum wind velocity within the polar mesoscale cyclone is reached approximately 20 h after the simulation beginning, and then it begins to decrease slowly. The radius of this polar mesoscale cyclone is about 600-800 km.

Now, let us consider the second case when, at the initial moment, the arctic front contains a convexity in the north direction, with the fields of the module of the horizontal velocity being asymmetric relatively to the centerline of the arctic front not only inside it but also beyond the arctic front. The initial form of the arctic front may be easy seen from the top panel of the Fig. 2, where it is like a dark curved band between two light curved bands. The center of the bent part of the front is 27° eastward from the western boundary of the simulation region.

The time evolution of atmospheric parameters was numerically simulated using the mathematical model during the period for about two days. The results of time-dependent modeling are partly shown in Fig. 2.

The simulation results presented in Fig. 2 show that, at the presence at the initial moment of the part of the arctic front bent to the north, when the fields of the module of the horizontal velocity are asymmetric relatively to the centerline of the arctic front, westward from this part, approximately in 20 h, a polar mesoscale cyclone is formed which moves to the south and to the west with a velocity of approximately 5-10 km/h. The maximum wind velocity within the polar mesoscale cyclone is reached approximately 20 h after the simulation beginning, and then it begins to decrease slowly. The radius of this polar mesoscale cyclone is about 600-800 km.

Conclusions

A regional non-hydrostatic mathematical model of the wind system of the lower atmosphere, developed recently in the Polar Geophysical Institute, is utilized to investigate the mechanism of the formation of polar mesoscale cyclones at high latitudes of the northern hemisphere. 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 dimensions of this region in longitudinal and latitudinal directions are 36° and 25°, respectively. The southern boundary of the simulation region was located at 55° N. It was supposed that, at the initial moment, this region is intersected by an arctic front, which contains the convexity in the north or south directions, moreover, the fields of the module of the horizontal velocity are asymmetric relatively to the centerline of the arctic front.

The simulation results indicated that the origin of a convexity in the configuration of the arctic front, having the latitudinal dimension of about 600 km and the deviation of hundred of kilometers either in north or south direction, can lead to the formation of polar mesoscale cyclones during the period of about one day. The polar mesoscale cyclone has a horizontal extent of about 600-800 km. The horizontal wind velocity in this polar mesoscale cyclone can achieve values of 15-20 m/s during the period of 20 hours. The simulation results show that the key factor in the mechanism of the formation of polar mesoscale cyclones is the origin of a convexity in the configuration of the arctic front. As a consequence, instability of the shear air flow arises. This instability leads to considerable transformation of the wind field. As a result, polar mesoscale cyclones may be formed in the vicinity of the initial position of the arctic front in the course of time.

Acknowledgments. This work was partly supported by the RFBR grant 13-01-00063.

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