Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 12 (2010), 1–7

The influence of the stratosphere polar vortex dynamics upon a low troposphere thermal stratification

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Abstract. In this paper, the response of the extratropical troposphere to a decrease in the polar stratosphere temperature, which is followed by strengthening the polar vortex, is studied with the use of the spectral general circulation model with symmetric boundary conditions on the surface and a heat source given analytically.

1. Introduction

In the dynamic meteorology, a 30 km atmosphere layer is divided into the two layers: troposphere and low stratosphere by several different methods. Usually, the division is made in terms of a vertical temperature gradient, characterizing the degree of the atmosphere layer stratification: the troposphere is a weakly stratified layer (with respect to a vertical displacement of the air pattern) and the stratosphere is strongly stratified. Heating the Earth's surface, the solar radiation forms a state of radiative balance of a layer, which is dynamically unstable (for example, in tropics), or baroclinically unstable (as in the medium latitudes). The heat/moment transfer, conditioned by the large-scale motions of the atmosphere occurs in the finite-width layer, which can be considered as troposphere. In this layer, the time scales of the transfer are relatively short: from several hours for the convective transport to several days for the baroclinic eddy transport.

Another feature of the troposphere is that particles of the tropospheric air reach the ground layer of the atmosphere and can retain there during the time period of 7–10 days. This peculiarity of the tropospheric air is an important characteristic of the troposphere having an essential meaning for climate. The troposphere can be considered as a layer in which circulation redistributes the main part of the entropy, obtained by the atmosphere by heating near the surface. So, the troposphere can be considered as a thermal layer of the atmosphere, and the tropopause — as a higher boundary of this layer. The tropopause height and the thermal stratification are determined by the dynamic balance between radiative processes and dynamic (baroclinic) fluxes of heat and entropy. It should be mentioned that the question of how dynamic and radiative processes interact for supporting a static stability and the mean meridional potential temperature gradient still remains open.

In this paper, an attempt is made to obtain the relations between these quantities having a fundamental meaning for the atmosphere dynamics. Above the layer of the large-scale turbulent heat transport, the atmosphere has a more stable state. Approximately, it can be considered that the radiative balance state of the stratosphere is dynamically stable and deviations from this state are possible due to the external forcing formed by planetary waves, propagating from the troposphere. The atmospheric waves transfer the angular moment $m = \Omega a \cos\varphi + u$ and energy (but not heat) from the troposphere to the lower stratosphere. Here $a \cos\varphi$ is angular moment per mass unit related the Earth's axis, Ω is the Earth's angular velocity, a is the Earth's radius, u is a zonal component of a wind, and φ is latitude. Their contribution in the energy balance is inessential as compared to radiative processes in the layer lower than 80 km, but their influence on the angular moment balance is essential.

Changes in the zonal moment conditioned by transport of the angular moment by waves are called wave resistance. In the stratosphere, the negative wave resistance induced by the planetary Rossby–Blinova waves causes the meridional circulation of mass, the negative resistance being balanced by the Coriolis deviation of the flux from the north direction. The mass conservation law requires that there be an updraft in the tropical zone and a downdraft in the medium latitudes. The updraft causes cooling or heating, which is balanced by radiative heating or cooling. Sometimes such a circulation is called forced or diabatic circulation. It should be noted that the wave resistance and, consequently the forced meridional circulation generally take place in the wintertime because it is the western zonal flow that can be a waveguide for the planetary Rossby–Blinova waves propagating from the troposphere. Theory of the vertically propagating linear Rossby–Blinova waves was proposed with G. Charney and P. Drazin in [1]. While now, it serves a basis for understanding of some aspects of interaction of the stratosphere and the troposphere. In spite of the presence of forced circulation, the stratification in the stratosphere is determined, in general, by the radiative balance and it is strongly stable because of the vertical distribution of the heating profile due to ozone. Because of this, the vertical fluxes of transport are suppressed, and time scales become sufficiently exceed those in the troposphere.

The main interest of the investigator is focused on mechanisms of the stratosphere and the troposphere interaction in the layer consisting of higher troposphere and lower stratosphere. Dynamically, this layer is defined as the one, in which isentropic surfaces are not completely in the stratosphere and do not intersect the Earth's surface.

In the winter period, large-scale meanders of a tropospheric stream propagate higher and are destroyed at the stratosphere stream level, resulting in a decrease of the stratosphere stream velocity with a downdraft of momentum. The influence of the planetary waves manifest, generally, on the zonally-symmetric component of the flow.

2. Theoretical basis

One of the most important features of the troposphere thermal structure is stability of an isentropic surfaces slope at the extratropical latitudes [5, 6]. The potential temperature gradients (horizontal and vertical) essentially change from winter to summer, but their relation, i.e., the isentropic surface slope remains approximately constant against a year cycle background. In both hemispheres, the normalized isentropic slope is of order 1:

$$\xi = \frac{\delta_y}{\delta_z} = \left| \frac{L_y \partial_y \theta}{H_z \partial_z \theta} \right| \sim O(1), \tag{1}$$

where $\partial_y \theta$, $\partial_z \theta$ are characteristic meridional and vertical gradients of the temperature, $L_y \sim f/\beta \sim a$ is a characteristic meridional scale, a is the Earth's radius, and H_z is a tropopause height.

Relation (1) means that the difference between the potential temperature in the subtropics and in the pole and between that at the ground surface and in the tropopause is of the same order.

In the baroclinic instability theory for the two-layer quasi-geostrophic model, the parameter ξ determines stability criteria, its value $\xi = 1$ being critical for the baroclinic instability.

The thermal stratification of the atmosphere and the static stability parameter are determined by relations of balance of different kinds of energy fluxes. In the first approximation, all the processes are thought to be negligible, except for the radiative processes and a small-scale convection, however the stratification of the real stratosphere sufficiently differs from the one determined by the radiative and convective equilibrium, in general, because of baroclinic non-stationary eddies. Dynamic conditions following from (1) have a meaning for two fundamental scales of the quasi-geostsophic turbulence, the Rossby radius $L_R = \frac{NH_z}{f}$ (H_z is a tropopause height, N is buoyancy frequency) and the Rhines scale $L_\beta = \sqrt{U'/\beta}$ (U' is the turbulent velocity scale). At the Rossby radius scale, the baroclinic energy is transformed to the barotropic one. The barotropic energy is involved into the processes of the reversed cascade of energy up to the Rhines scale, where the turbulent cascade stops. At the Rhines scale, the energy is directed to forming the stream currents and the Rossby waves.

To express the Rhines scale in terms of the size of an average stream, let us assume that the turbulent velocity scale is connected with the velocity scale of the meanflow by the relation:

$$U' = \left(\frac{L_\beta}{L_R}\right)^r U,$$

where $\frac{L_\beta}{L_R}$ is a nonlinearity measure of a stream, and r is an indicator. Then it is possible to obtain an approximate estimation from (1):

$$\frac{L_\beta}{L_R} = \left|\frac{f\partial_y\bar{\theta}}{\beta(\bar{\theta}_T - \bar{\theta}_S)}\right|^{1/(2-r)}.$$

In [6], the parameter r was considered to be equal to 1.

The analysis applied in this paper to the sensitivity estimation of the isentropic surfaces slope in the medium latitudes in the full atmosphere dynamics model is, strictly speaking, applicable for the two-layer model of the quasi-geostrophic turbulence [6], therefore the conclusions will be rather of the qualitative, than of the quantitative character.

The meridional and the vertical fluxes of potential temperature are connected in the following way:

$$\overline{v'\theta'}\delta_y \sim \overline{w'\theta'}\delta_z. \tag{2}$$

In assumption of the diffusive character of turbulent streams, some relations describing the baroclinic turbulent fluxes in the horizontally-homogeneous two-layer model on β-plane are obtained in [7]:

$$\varepsilon = \frac{D}{\tau^2},$$

where D is the a diffusion coefficient, ε is the rate of the eddy energy transport through the spectrum, $\tau = \frac{NH}{fU}$ is a characteristic time, $N = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}$,

$$D \sim \beta^{-4/5}\varepsilon^{3/5}; \qquad D \sim \frac{1}{\beta^2\tau^3} \;\Rightarrow\; D \sim \delta_y^3\delta_z^{-3/2},$$

β is a barotropic vorticity gradient.

From (2), it follows the expression for a vertical flux of potential temperature follows: $w'\theta' \sim \delta_y^5\delta_z^{-5/2}$.

Under the assumption that $w'\theta' \sim \frac{\partial\bar{\theta}}{\partial z}$:

$$\delta_z \sim \delta_y^{10/7}. \tag{3}$$

3. Numerical experiment

The idea of the numerical experiments, whose results are discussed here, consists in the fact that for defining and analyzing the changes in the extratropical troposphere circulation with the controllable strengthening of a stratospheric polar vortex. By means of the system of the atmosphere dynamics equations with the zonally-symmetric forcing the sensitivity of circulation of extratropical troposphere to the thermal perturbations of the polar stratosphere is investigated.

As prognostic variables, the vertical component of the absolute vorticity $\zeta = \xi + f$, the horizontal divergence D, the temperature deviation from the background value t and the ground pressure p_s were taken. The thermal source is set in the Newton form with a given equilibrium temperature profile which depends on the latitude and pressure. A detailed description of the model is presented in [8]. In this model, the intensity of a stratospheric polar vortex is associated with changes in the radiative equilibrium temperature, analytically presented as:

$$T_R^1(\sigma,\varphi) = T_r(\sigma) + h(\sigma,\varphi),$$

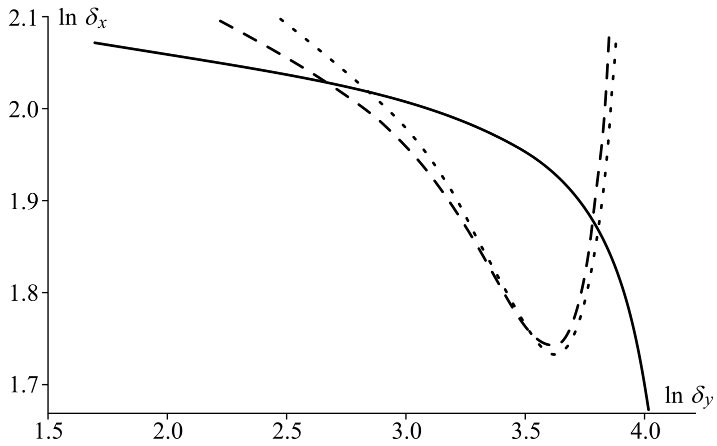
$$h(\sigma,\varphi) = \begin{cases} \sin\dfrac{\pi}{2}\Big(\dfrac{\sigma-\sigma_T}{1-\sigma_T}\Big)\cdot\Big(\Delta T_{ns}\dfrac{\mu}{2} - \Delta T_{ep}\Big(\mu^2 - \dfrac{1}{3}\Big)\Big), & \sigma \ge \sigma_T, \\ \omega(\varphi)\Gamma H \ln\dfrac{\sigma}{\sigma_T}, & \sigma < \sigma_T, \end{cases}$$

$$\omega(\varphi) = \cos\varphi, \quad T_0 \approx 210 \text{ K},$$

where σ_T is the tropopause height.

In this equation, the parameter Γ defines the temperature gradient. Large values of temperature gradient are in correspondence with large values of the radiative balance and more intensive Newton cooling in to stratosphere. Two experiments were conducted. In the first one, Γ was equal to 0 (a weak polar vortex), and in the second, Γ was equal to 4 (a strong polar vortex). In each experiment, integration was carried out for 4 years with the triangular truncation of series with 42 spherical functions horizontally and 31 levels vertically. In this paper, thermal stratification of the medium latitude troposphere is analyzed with the use of scatter charts for the quantities δ_y and δ_z. The horizontal and vertical gradients were calculated in region ($\varphi = 40$–$60°$, $\sigma = 0.3$–0.8). Averaging δ_y over the latitude is a monotonously increasing the function of σ. the operator of averaging over the latitude is denoted by square brackets [ ].

In the figure, graphs of the dependence of $[\delta_z]$ on $[\delta_y]$ are presented. They show that in our model there are two models of thermal stratification. In high layers of the troposphere, the static stability parameter decreases with σ increasing. In the upper troposphere, the temperature distribution is, generally, defined by radiative processes. In the lower troposphere, where stratification is defined by radiative and baroclinic processes, dependence (3) is confirmed by the numerical experiments. The level, where the temperature regimes change, is $\sigma \approx 550$ mb. The medium slope ratio of curves at logarithmic scale is $\alpha = 1.486$ for $\Gamma = 0$ and $\alpha = 1.619$ for $\Gamma = 4$, that is in



Dependence of $[\delta_z]$ on $[\delta_y]$ for $\Gamma = 0$ (dashed curve) and for $\Gamma = 4$ (dotted curve). A solid curve shows the dependence of $[\delta_z]$ on $[\delta_y]$ corresponding to the radiative equilibrium temperature

agreement with estimation (3). Changes of the isentropic surfaces slope in the lower troposphere, at strengthening of a stratospheric polar vortex are insignificant. It is possible to say that the isentropic surfaces slope in the lower layers of the troposphere remains constant in changes of the radiating balance temperature in the stratosphere.

4. Conclusion

In this paper, the sensitivity of the tropospheric dynamics to variations of the state of the polar stratosphere is investigated. It is shown that variations of the thermal stratification in the stratosphere cause markable changes in the troposphere circulation. It is also shown that changes of the temperature stratification at strengthening of the cooling in the stratosphere influences the dynamics of the upper troposphere, where stratification is defined by radiative processes. In the lower layers of the troposphere with a considerable contribution of the baroclinic non-stationary eddies to the dynamics, a local slope of the isentropic surfaces remains invariable and this is in agreement with the theoretical estimation (3). The zonally-symmetric component of the response of the lower troposphere to disturbances of the stratosphere polar vortex could result the action of the baroclinic waves of the synoptic scale even in the absence of the planetary waves.

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