Bull. Nov. Comp. Center, Num. Model. in Atmosph., etc., 17 (2019), 1–8

On the polar vortex streamer dynamics*

Irina V. Borovko, Vladimir N. Krupchatnikov

Abstract. Potential vorticity (PV) streamers and cutoffs are indicators to the Rossby wave breaking (RWB) near the extratropical tropopause. In the Rossby waves breaking, the formation of elongated high-PV stratospheric air tongues extending to the equator and tropospheric low PV air tongues extending to the pole are obtained. There are two types of wave breaking, which are referred to as equatorward and poleward types of the RWB. Frequently, the PV tongues are stretched into narrow filaments, the so-called PV streamers that split to PV cutoff vortices. Here stratospheric PV streamer and cutoff are stratospheric features on isentropic surfaces. In this paper, the configuration of a potential vortex field for model data is investigated. The main areas of the RWB for the winter and summer periods are shown.

Keywords: potential vorticity streamers and cutoffs, Rossby wave breaking, climate modeling.

1. Introduction

One of the problems in understanding the effects of a climate change is the dynamic response of the atmosphere to a climate change that is not well studied. The most dramatic example of nonlinear dynamics in the stratosphere is the phenomenon of planetary wave breaking, which is defined as large-scale and rapid irreversible overturning of the potential vorticity (PV) contours on isentropic surfaces. The authors of [1], studying the isentropic maps of the Ertel potential vorticity in the extra-tropical winter stratosphere, identified the breaking planetary waves and introduced the concept of a "surf zone" surrounding the polar vortex and the boundary region of steep potential vorticity gradients. Both modeling and observational studies have indicated to a poleward shift of the subtropical jet stream resulting from the enhanced greenhouse effect [2–4].

This affects the Rossby wave breaking (RWB), which is strongly related to the characteristics of the jet streams, NAO/AO phase, blocking, PV streamers and climate drift bias. These waves propagate upward from the troposphere and upon breaking, weaken the stratospheric vortex, mixing the vortex polar air and midlatitudes air at the edge of the vortex. The breaking planetary waves will tend to erode the winter polar vortex by mixing its pieces into the surrounding "surf zone". The observations made show that

*Supported by RFBR under Grant 19-17-00154.

the corresponding propagation of the extra-vortex air into the vortex is much weaker [5, 6]. Therefore, the vortex will reduce in the area but will not lose its intensity. By contrast, the diabatic effects, tending to restore the vortex to its “radiative equilibrium” structure.

The Rossby waves breaking in the stratosphere has a significant impact on the dynamic fields in the troposphere. For example, in winter in extra-tropical latitudes, the manifestation of the wave breaking is in sudden stratospheric warmings, which have a significant impact on the weather in the troposphere. Most events of extremely cold weather in winter are associated with sudden stratospheric warmings.

There are cyclonic and anticyclonic breakings. The difference between the two types of the RWB: anticyclonic and cyclonic becomes particularly clear in baroclinic life cycle simulations [7]. The wave breaking of the anticyclonic and cyclonic types have different effects on the atmosphere circulation. The basic spatial and temporal structure of the large-scale modes of intraseasonal variability in the extratropical atmosphere is known to be represented by fairly well-defined patterns, and among the most prominent are the North Atlantic Oscillation (NAO) and a zonally symmetric pattern known as the annular mode (AO in NH). After the wave breaking of the anticyclonic type in the Atlantic, a positive phase of the North Atlantic oscillation is established, as a rule, and after the breaking of the cyclonic type follows a negative one [8, 9].

To diagnose these processes, the Ertel potential vorticity is used, which is defined as

$$Q = -g(\xi_p + f)\frac{\partial \theta}{\partial p},$$

where θ is the potential temperature, p is the pressure, f is the Coriolis parameter, and ξ_p is the vertical component of the relative vorticity. The Ertel potential vorticity is commonly measured in PVU (1 PVU = 10^{-6} $\mathrm{m^2 kg^{-1} s^{-1} K}$). The potential vorticity is constant in the layer between two isentropic surfaces. So, the charts of the potential vorticity on isentropic surfaces can be used as diagnostics.

The large-scale and irreversible overturning of the PV isolines on isentropic surfaces manifests the Rossby wave breaking [10]. The Rossby wave breaking is to occur when differential advection in the eddy motion results in the meridional overturning of the potential vorticity (PV) contours such that the derivative $\mathrm{PV}_y < 0$ [11]. An indicator to the instability of the vertically propagating Rossby waves is the presence of filamentary vortex structure (the so-called streamers) in a potential vortex field as well as of closed isolines, which can be cross-sections of the polar vortex by isentropic surfaces. There is no universal PV threshold value for the dynamic tropopause, but the most common choice is 2 PVU surface (a standard potential vorticity unit) [12]. Isentropic surfaces making the transition from the troposphere to the stratosphere a feature of a sharp gradient of the PV between the two air masses.

Generally, the contour of a potential vortex with a value of 2 PVU determines the dynamic tropopause. Therefore, the formation of filamentary structures of the polar vortex can be interpreted as the penetration of the stratospheric air into the troposphere.

The only possible experimental method of studying the atmosphere circulation is the mathematical modeling. Thus, we need an adequate atmosphere model to investigate what effect the climate changes will have on the RWB. In this paper, the configuration of the potential vortex field in the model data is investigated.

2. Numerical experiment

To study the problem in question, a general atmospheric circulation model, Planet Simulator, is used [13]. It was developed at the Meteorological University of Hamburg and designed to identify feedbacks between components of the climate system. This model is related to the class of intermediate complexity models because the processes affecting the atmosphere circulation are presented in the form of simple parameterizations. The model consists of several computational blocks: atmospheric, oceanic, biospheric, land surface and sea ice. The model data have the resolution of 64 nodes in latitude and 128 in longitude and 15 levels from the surface up to 25 hPa. Hence, the minimum horizontal scale described by the model is about 300 km. To attain the stationary mode, the model was run for a period of 52 years. In this paper, the data for four years are studied. Here we present the data for January and July.

The method to identify filamentary structures was proposed in [14]. For each pair of points of the contour, it is checked whether the direct spherical distance **d** between two points is less than a certain threshold distance d, and whether the length **l** of the section of the contour enclosed by these two points is longer than the threshold distance l. The method is illustrated in Figure 1. The part of the contour between these two points is identified as a streamer. In this paper, we use this method to identify streamers of

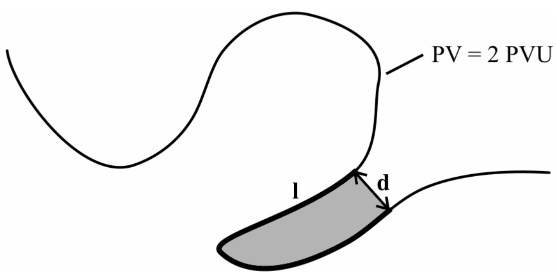

Figure 1. A schematic depiction of the streamer identification. The shaded domain corresponds to a stratospheric streamer

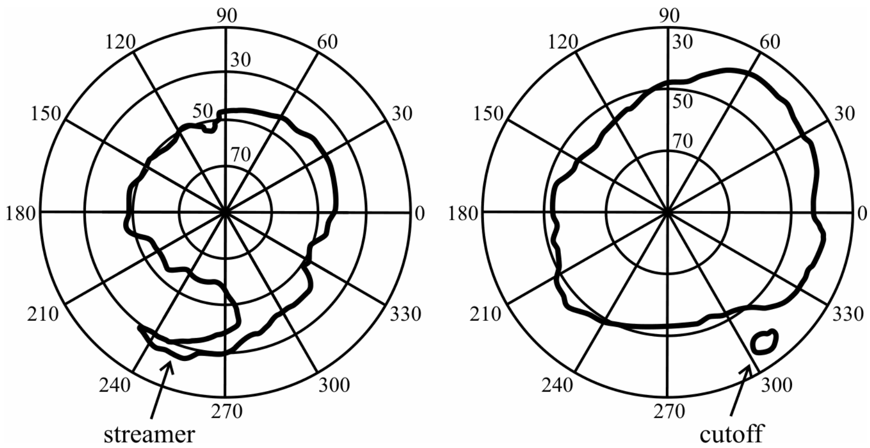

Figure 2

the main contour. The values of d and l determine the scale of the eddy structure. In our work, we take the values of 800 and 1,500, respectively. The parameters d and l selected in this way make it possible to recognize synoptic scale structures. Larger structures do not come into the view.

Examples of streamers and cutoffs are presented in Figure 2. In the left picture, a streamer is between 240 and 270 degrees of the east longitude and, in the right one, a cutoff is near to 300 degrees of the east longitude.

The table shows the number of vortex structures. Streamers were divided into two types—stratospheric and tropospheric. The stratospheric streamers are long tongues of the stratospheric air that spread into the troposphere. The tropospheric streamers are tongues of the troposphere air, respectively. The tropospheric streamers are usually related to the cyclonic RWV and the stratospheric streamers are related to anticyclonic ones. It is seen from the table that the number of vortex structures at the synoptic scale in winter is small for the level line $\theta = 350$ K and increases from South to North. The instability region lies to North of the 50th latitude. In mid-latitudes, the zonal wind speed in the high tropopause in winter exceeds the Rossby critical speed, and the disturbances are locked in the lower atmosphere.

θ, K	Month	The number of vortex structures			
		Stratospheric streamers	Tropospheric streamers	Stratospheric cutoffs	Tropospheric cutoffs
350	January	6	6	7	3
330	January	8	15	12	30
310	January	26	24	56	61
330	July	33	61	149	189
350	July	60	27	156	67

In the summer time, a maximum of the streamers frequency is between the isolines of 330 and 350 K. This zone is located about 40 North latitude and 10 kilometers high. It is characterized by large tropopause height gradients. A large number of streamers indicates that there is an active mixing in this region.

In Figure 3, there are locations of the stratosphere and troposphere streamers in January on the surface with the potential temperature of 310 K. The black circles in the figure indicate to the points whose coordinates are obtained by averaging the coordinates of all streamer nodes. Most of streamers locate above the continents. This can be explained by the fact that in the model used near to the tropopause, streamers can be influenced by diabatic PV anomalies and by the underlying topography. In Figure 4, locations of the stratospheric and tropospheric streamers in July on the surface with the

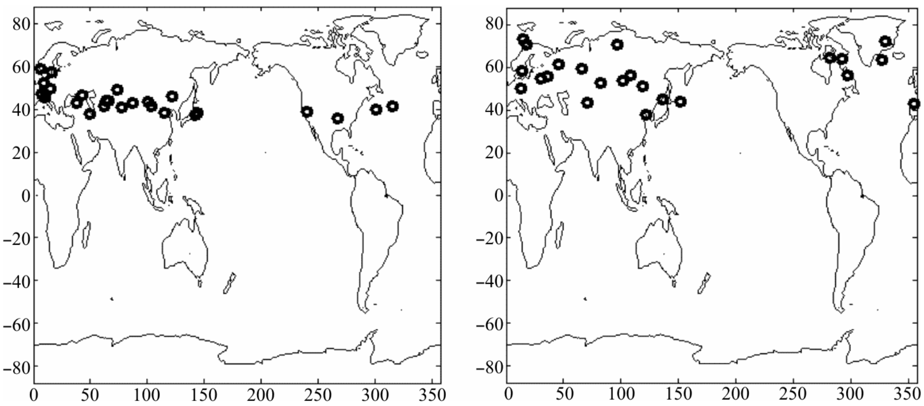

Figure 3. Stratospheric (left) and tropospheric (right) streamers of the contours with the potential vorticity equal to 2 PV at the surface with $\theta = 310$ K in January

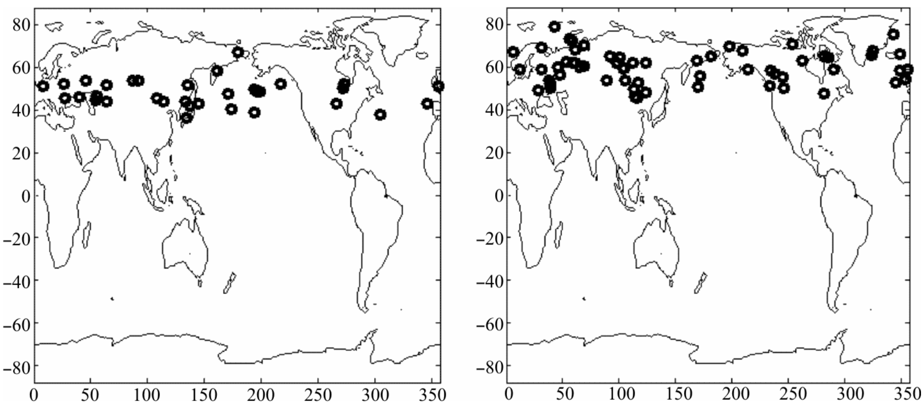

Figure 4. Stratospheric (left) and tropospheric (right) streamers of the contours with the potential vorticity equal to 2 PV at the surface with $\theta = 330$ K in July

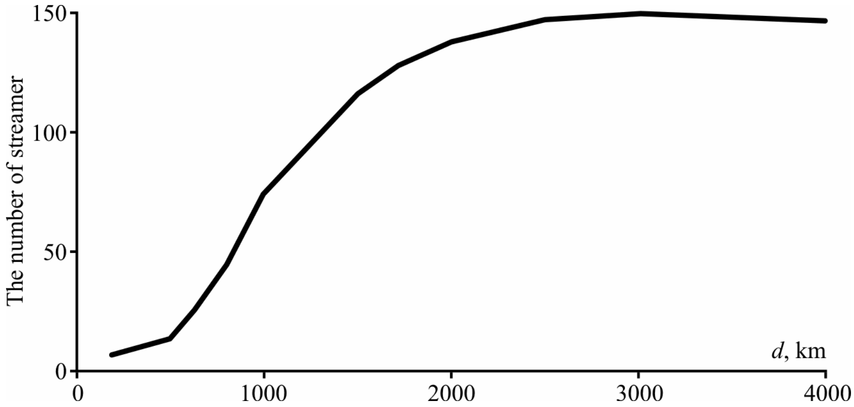

Figure 5. The dependence of the number of streamers on the scale d

potential temperature of 330 K are shown. In the summer data, the minima above the oceans are not as pronounced as in the winter data.

The values of d and l determine a scale of the eddy structure. The relation l/d is determined by the form of a contour enclosed between the boundary points. The number of streamers strongly depends on the parameters d and l. In this paper, the value of 2 is taken as the minimal which can be an indicator of instability. The dependence of the number of streamers on the scale d at a fixed value of l/d can show the characteristic scales of unstable vortex structures. It this paper, this function is obtained for the streamers at the surface $\theta = 310$ K in January at $l/d = 2$. The graph of this function is presented in Figure 5.

When d is greater than 2500 the number of streamers is nearly constant. There are few eddy structures of scale less than 600 km because this scale is not adequately described by the model used. The number of streamers increases when d is greater than 600 km and less than 2500 km.

In this paper, we do not propose a comprehensive review of the published works on the polar vortex streamers, but rather we present some results of modeling the vortex streamers using the climate model of intermediate complexity. The study of the stratospheric circulation is based on the two-dimensional vortex dynamics. Two-dimensional patterns such as the streamers of vortices in straining flows have a direct application to the stratospheric wave breaking.

In this paper, the number of streamers and cutoffs in different seasons is computed. In the subtropics, the number of streamers in the summer period is more than in winter, because in the winter period a strong jet stream provides the stability of the Rossby waves. Also, the dependence of the number of streamers on the scale is studied. It was found that most of streamers of vortex structure exceed 2,000 km.

In the model in question, the grid spacing at mid-latitudes is about 300 km, so Rossby waves caused by smaller-scale inhomogenities are not taken into account. There are few eddy structures in the Pacific.

The streamers and cutoffs of the Ertel potential vortex can be a feature of wave breaking and indicate to the probability of extreme weather conditions. The streamers identification method can be used for the diagnosis of the Rossby wave breaking. We have to note the fact that, as the polar vortex elongates, it becomes hydrodynamically unstable, and this instability will affect the upper troposphere and stratosphere. This means that potential vorticity streamers are interconnected with the surface pressure systems and are likely to be frequently present in the course of the high-impact weather in mid-latitudes. In the future, extreme weather events are likely to increase due to the global warming and climate change, so, profound knowledge about the main effects on these events is crucially important.

The study of the Rossby wave breaking process will help to better understand the dynamics of weather and climate systems in terms of the climate warming. Physically plausible that the presence of a strong latitudinal PV gradient in the lower stratosphere inhibits the breaking at lower levels, generating the vertical propagation of wave disturbances, up to the vortex edge, where they are amplified with height and eventually break equatorward at the upper levels, but, when the wave breaking takes place in the lower stratosphere, the lower stratospheric PV gradient is destroyed, inhibiting the propagation above the breaking level, thereby screening the upper portion of the vortex from the waves. In addition, it is important for us to understand the relationship of these processes in the stratosphere with the sea ice loss in the Arctic and extreme weather events. In order to understand their mechanism, these processes require consideration that is more careful. Therefore, we are planning to carry out experiments to simulate these processes.

The logical continuation of this study would be an experiment with the RCP8.5 scenario. A disadvantage of the model used is insufficient parameterization of the ocean and sea ice. Therefore, the next experiment is planned with a coupled model PlaSim ICMMG1.0.

References

[1] McIntyre M.E., Palmer T.N. Breaking planetary waves in the stratosphere // Nature. — 1983. — Vol. 305, No. 13. — P. 593–600.

[2] Davis S.M., Rosenlof K.H. A multidiagnostic intercomparison of tropical-width time series using reanalysis and satellite observations // J. Climate. — 2012. — Vol. 25, No. 4. — P. 1061–1078.

[3] Fu Q., Lin P. Poleward shift of subtropical jets inferred from satellite-observed lower-stratospheric temperatures // J. Climate. — 2011. — Vol. 24, No. 21. — P. 5597–5603.

[4] Strong C., Davis R.E. Winter jet stream trends over the northern hemisphere // Quart. J. Roy. Meteor. Soc. — 2007. — Vol. 133, No. 629. — P. 2109–2115.

[5] Manney G., Zurek R., O'Neill A., Swinbank R. On the motion of air through the stratospheric polar vortex // J. Atmos. Sci. — 1994. — Vol. 51, No. 20. — P. 2973–2994.

[6] Schoeberl M.R. Stratospheric warmings: observations and theory // Review of Geophysics and Space Physics. — 1978. — Vol. 16, No. 4. — P. 521–538.

[7] Thorncroft C.D., Hoskins B.E., McIntyre M.E. Two paradigms of baroclinic-wave life-cycle behavior // Quart. J. Roy. Meteor. Soc. — 1993. — Vol. 119. — P. 17–55.

[8] Benedict J.J., Lee S., Feldstein S.B. Synoptic view of the North Atlantic oscillation // J. Atmos. Sci. — 2004. — Vol. 64, No. 2. — P. 122–144.

[9] Franzke C., Lee S., Feldstein S.B. Is the North Atlantic oscillation a breaking wave? // J. Atmos. Sci. — 2004. — Vol. 61, No. 2. — P. 145–160.

[10] McIntyre M.E., Palmer T.N. A note on the general concept of wave breaking for Rossby and gravity waves // Pure Appl. Geophys. — 1985. — Vol. 123. — P. 964–975.

[11] Charney J.G., Stern M.E. On the stability of internal baroclinic jets in a rotating atmosphere // J. Atmos. Sci. — 1962. — Vol. 19. — P. 159–172.

[12] Holton J.R., Haynes P.H., McIntyre M.E., et al. Stratosphere-troposphere exchange // Reviews of Geophysics. — 1995. — Vol. 33, No. 4. — P. 403–439.

[13] Fraedri K., Jansen H., Kirk E., et al. The planet simulator: towards a user friendly model // Meteorol. Zeitschrift. — 2005. — Vol. 14. — P. 299–304.

[14] Wernli H., Sprenger M. Identification and ERA-15 climatology of potential vorticity streamers and cutoffs near the extratropical tropopause // J. Atmos. Sci. — 2007. — Vol. 64. — P. 1569–1586.