Rossby wave breaking and blocking events associated with some atmospheric circulation regimes in the Northern Hemisphere based on a climate system model (PlaSim-ICMMG-1.0)

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Abstract. Potential vorticity (PV) streamers and cutoffs are indicators of Rossby wave breaking (RWB) near the extratropical tropopause. The Rossby wave breaking forms an elongated high-PV stratospheric air tongue that extends to the equator and a tropospheric low PV air tongue that extends to the pole. There are two types of RWB: equatorward and poleward. Frequently, PV tongues stretch into narrow filaments, so-called PV streamers that split into PV cutoff vortices. Here the terms stratospheric PV streamer and cutoff refer to stratospheric features of isentropic surfaces (PV > 2 PVU; where 1 PVU = 10⁻⁶ K·kg⁻¹ m²·s⁻¹). In this paper, we study a configuration of the potential vortex field using model data. The main areas of RWB in winter and summer are shown. Atmospheric blocking events represent some of the most high-impact weather patterns in the mid-latitudes, but they have often been the cause of unsuccessful future climate projections. In this paper, we have examined the seasonal frequency of global blocking events in relation to a change in the mean EOF index based on some modeling results obtained by using a climate system model, PlaSim-ICMMG-1.0.

1. Introduction

One of the problems in understanding the effects of climate change is the dynamic response of the atmosphere to climate change that is not well understood. The most dramatic example of nonlinear dynamics in the stratosphere is the phenomenon of planetary wave breaking. That is defined as the large-scale and rapid, irreversible overturning of potential vorticity (PV) contours on isentropic surfaces or streamers. The authors of [1] studied maps of isentropic Ertel potential vorticity in the extratropical winter stratosphere, identified breaking planetary waves and introduced the concept of a "surf zone" surrounding the polar vortex and boundary region of steep potential vorticity gradients. Both modeling and observational studies have indicated a poleward shift of the subtropical jet stream resulting from an enhanced greenhouse effect [2–4]. This shift affects Rossby wave breaking (RWB), which is related to the characteristics of jet streams, the phase of the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO), blocking events, sudden stratospheric warming, PV streamers, and climate drift bias. These waves propagate upward from the troposphere and, upon breaking, weaken the stratospheric vortex, mix the vortex polar air, and the midlatitude air at the edge of the vortex. The breaking planetary waves will tend to erode the winter polar vortex by mixing pieces of it into the...
surrounding "surf zone". The observations show that the corresponding propagation of extra vortex air into the vortex is much weaker [5, 6]. Therefore, the vortex will reduce in the area, but will not lose intensity. Opposing this will be diabatic effects, tending to restore the vortex to its "radiative equilibrium" structure. RWB in the stratosphere has a significant impact on the dynamic fields in the troposphere. For example, in winter in extratropical latitudes a manifestation of the wave breaking is sudden stratospheric warmings, which significantly impact the weather in the troposphere.

Most events of freezing weather in winter are associated with sudden stratospheric warmings. There are cyclonic and anticyclonic breakings. The difference between these two types of RWB becomes particularly evident in baroclinic life cycle simulations [7]. Wave breakings of the anticyclonic and cyclonic types have different effects on the circulation of the atmosphere. The fundamental 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 NAO and a more zonally symmetric pattern known as an annular mode of the AO in the Northern Hemisphere (NH). After wave breaking of the anticyclonic type in the Atlantic, a positive NAO phase is established, as a rule. Breaking of the cyclonic type establishes a negative one [8, 9]. We also wish to estimate the relationship between the frequency of blocking events and the NAO/AO index to understand the relationship between these events.

The Ertel potential vorticity is used to diagnose these processes, which is defined as

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

(1)

where \(q\) is the potential temperature, \(p\) is the pressure, \(f\) is the Coriolis parameter, and \(\xi_p\) is the vertical component of relative vorticity. The Ertel potential vorticity is used to diagnose these processes, which is defined as follows. The Ertel potential vorticity is usually measured in PVU (1PVU = \(10^6\) K kg\(^{-1}\) m\(^2\) s\(^{-1}\)). The potential vorticity is constant in the layer between two isentropic surfaces. Thus, we can use charts of the potential vorticity on isentropic surfaces for diagnosis. The large-scale and irreversible overturning of PV isolines on isentropic surfaces manifests Rossby wave breaking [10]. Rossby wave breaking occurs when differential advection in eddy motion leads to the meridional overturning of PV contours, such as derivative PV(\(\gamma\) < 0 [11]. An indicator of the instability of vertically propagating Rossby waves is the presence of a filamentary vortex structure, the so-called streamers, in the potential vortex field, and closed isolines, which can be cross-sections of the polar vortex by isentropic surfaces. There is no universally used PV threshold for the dynamical tropopause, but the most common choice is the 2 PVU surface (standard potential vorticity unit) [12]. (Isentropic surfaces making the transition from the troposphere to stratosphere usually feature a sharp gradient of PV between the two air masses).

The contour of potential vorticity with a value of 2PVU determines the dynamic tropopause. Therefore, we can interpret the formation of filamentary structures/streamers of the polar vorticity to penetrate the stratospheric air into the troposphere. Potential vorticity streamers and cutoffs are indicators of Rossby wave breaking near the extratropical tropopause.

This article aims to concentrate on the wave breaking processes and the associated blocking events. We use a standard empirical orthogonal function (EOF) analysis based on monthly anomalies of the simulated sea level pressure data (SLP) for the months of December-February (DJF). Empirical orthogonal functions (EOFs) were first used in meteorology in [13, 14]. Atmospheric blocking events are the most high-impact weather patterns in the mid-latitudes. Unfortunately, there is still no comprehensive theory of blocking, and the modern models do not accurately reproduce the occurrence of blocking events.

The process of blocking the western stream in the extratropical atmosphere is one of the essential meteorological phenomena (for example, [15–17]). Blocks often form as an anticyclonic anomaly, changing the direction of the zonal flow, so that eastern winds appear in some parts of the blocking area.
It is worth noting that integrations of historical and anthropogenic scenarios were analyzed in several articles (for example, in [18–21]) to identify possible changes in the blocking frequency in a warmer climate using climate models participating in the Coupled Model Inter-Comparison Project phase 5. Several methods have been obtained to better simulate blocking events in numerical models, although completely reliable simulations remain elusive.

2. Data and methods. Model and numerical experiments
This paper analyzes the potential vorticity fields for the data obtained by the atmosphere general circulation model of intermediate complexity PlaSim-ICMMG-1.0 [22]. In this model, the prognostic values are relative vorticity, horizontal divergence, temperature, and surface pressure. We recorded grid fields with a resolution of 64 levels in latitude and 128 in longitude and 15 levels from the surface up to 25 hPa. Thus, the minimum horizontal scale described by the model is about 300 km. The Earth system model PlaSim-ICMMG-1.0 was developed as a modular structure that allows creating a range of models of the earth system of average complexity by choosing different options for different climate and carbon cycle components. The model is capable of performing integrating with different time scales. The structure was designed to work modularly to facilitate the interconnection of more complex components with increased processing power. As a test, we calculated the parameters of the climate system for 100 years. The initial state of the atmosphere was obtained in previous experiments with the full version of the autonomous PlaSim model [23]. The model was running for 52 years to obtain the stationary state.

3. Results. Simulation of the dynamics of polar vortex streamers and blocking events
3.1. Polar vortex streamer
The method to identify filamentary structures was proposed in [24]. For each pair of contour points, we checked whether (1) the direct spherical distance between two points is less than a certain threshold distance d and (2) the length of the section of the contour enclosed by two points is longer than the threshold distance l. Figure 1 presents an illustration of the method. The part of the contour between two selected points was defined as a streamer. In this paper, we use this method to identify streamers of the main contour. The values of d and l determine the scale of the eddy structure. In our work, we took these values equal to 800 and 1500, respectively. The parameters d and l selected in this way make it possible to recognize synoptic-scale structures. Larger structures do not come into view.

![Figure 1.](image)

Figure 1. A schematic of the streamer identification. The shaded domain corresponds to a stratospheric streamer (From [24]).

Figure 2 presents examples of a streamer and cutoff. In the left panel the streamer is between 240 and 270E, and in the right one, the cutoff is near 300E.
Figure 2. Examples of a streamer and cutoff: (a) a streamer (b) a cutoff. The solid line is isoline of potential vorticity.

Table 1 shows the number of vortex structures for four years of data taken in increments of one day. We divided the streamers into two types - stratospheric and tropospheric. The stratospheric streamers are long tongues of stratospheric air that spread into the troposphere. The tropospheric streamers are, consequently, tongues of troposphere air. We can see that the number of vortex structures of the synoptic-scale in winter is small for the level line $q=350$ K and increases from south to north. The instability region lies to the north of the 50th parallel. In mid-latitudes, the zonal wind speed on the tropopause in winter exceeds the Rossby critical speed, and the disturbances are locked in the lower atmosphere. In the summertime, the maximum of streamers frequency is between isolines of 330 and 350 K.

| $\theta$ K | Month | number of eddy 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 Figure 3, there are locations of the stratosphere and troposphere streamers in January on a surface with a potential temperature of 310 K. Most of the streamers developed above the continents. We can explain this location by the fact that diabatic PV anomalies and the underlying topography in the used model can influence the near tropopause streamers. Figure 4 shows the locations of the stratosphere and troposphere streamers in July on a surface with a potential temperature of 330 K. In the summer data, the minima over the oceans are not as pronounced as in winter.
Figure 3. Stratosphere (left) and troposphere (right) streamers (black circles) of contours with potential vorticity equal to 2PV at a surface with $\theta = 310$ K in January.

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

The values of $d$ and $l$ determine the scale of the eddy structure. The form of the contour enclosed between the boundary points determines the relation of $l/d$. The number of streamers found strongly depends on the parameters of $d$ and $l$. In this paper, we took the value of 2 as the minimal one, which can indicate instability. The dependence of the number of streamers on $d$ at fixed $l/d$ is studied in this paper.

3.2. Blocking events
The interaction of the mean flow and vortices, which leads to the anomalous state of the mid-latitude jet, is associated with propagating and breaking waves in the upper troposphere and stratosphere. We have addressed these issues in this article. Extreme weather events in extratropical latitudes are usually associated with blocking anticyclones. In [25], the main blocking areas for NCEP/NCAR reanalysis data were obtained. We used blocking diagnostics based on the gradients of geopotential height. This diagnostics was proposed in [15] and developed further in [26]. For each point with coordinates, indices are determined.

\[
\begin{align*}
GHGS(\lambda_0, \varphi_0) &= \frac{Z_{500}(\lambda_0, \varphi_0) - Z_{500}(\lambda_0, \varphi_S)}{\varphi_0 - \varphi_S} \\
GHGN(\lambda_0, \varphi_0) &= \frac{Z_{500}(\lambda_0, \varphi_N) - Z_{500}(\lambda_0, \varphi_0)}{\varphi_N - \varphi_0}
\end{align*}
\]  

(2)

where $Z_{500}$ is the height of the geopotential surface, 500 mbar, $\varphi_S = \varphi_0 - 15^\circ$, $\varphi_N = \varphi_0 + 15^\circ$, and $\varphi_0$ is the central latitude of blocking. We consider a situation as instant blocking when $GHGS(\lambda_0, \varphi_0) > 0$, $GHGN(\lambda_0, \varphi_0) < -10$ m (degree of latitude)$^{-1}$. 
Figure 5 shows the main areas of atmospheric blocking according to the NCEP/NCAR reanalysis data. Atmospheric blocking has been linked to planetary wave collapses, an idea based on the geographic overlap between the location of such waves and regions where there is a higher frequency of blockings [27].

To compare the frequency of blockings in winter according to the NCEP/NCAR reanalysis data and according to the simulation data using the PlaSim-ICMMG-1.0 model, a data set of simulation fields was prepared, recorded with a step of one day. The central blocking latitude, $\phi_0$, has seasonal variability and varies with longitude, as well as interannual variability, for example, due to the NAO. The average annual central blocking latitude fluctuates by about 15 degrees across the hemisphere. To determine $\phi_0$ at each longitude, we can draw a line through the maxima of the kinetic energy of unsteady vortices in the Northern Hemisphere. Figure 6 shows the number of blocking situations determined by the relations (2) for each point. We considered two seasons: winter (December to February) and summer (June to August). Less pronounced maxima are in the Greenland region, the Chukotka and Alaska region, and Western Europe. The difference from the reanalysis data (see Fig. 5) is that the Pacific maximum is less pronounced. The summer data show two regions with the highest blocking frequency, the Atlantic Ocean and Eastern Europe.

In this paper, based on modeling data, we investigate what states of the global atmospheric circulation are favorable for the winter season’s blocking conditions to last several days. To weed out
small time scale events, which make a small contribution to the large-scale circulation of the atmosphere, we consider winter season data averaged over ten days taken from the PlaSim-ICMMG-1.0 sixty years simulation. We use the EOF method applied to an area from 40 to 80 degrees of latitude to describe the winter atmospheric circulation variation. The aim is to find the relationship between the main mode index and the blocking frequency. Due to inaccuracy in the topography data, we apply spatial averaging filters.

Typically, weaker blocking criteria are used for averaged data than for instant blocking. In this case, we consider the situation as blocking when $GHGS(\lambda_0, \varphi_0) > 0$, $GHGN(\lambda_0, \varphi_0) < -3$ m (degree of latitude)\(^1\).

Figure 7 shows the number of blocking events. Despite the weaker conditions, the blocking criteria were met only in a few small areas: in Western Europe, in Eastern Europe north of the Black Sea, in northeastern Yakutia, and Northern America. The largest maximum is observed in Western Europe, while in the instant data case, the European maximum is not greater than the Pacific one. Thus, in the Atlantic region an instant blocking situation is more likely to lead to a prolonged blocking.

![Figure 7. Number of blocking events (December-February).](image)

Although the local anomalies resulting from wave breaking are, to some extent, regionally related, the location of the breaking determines how these anomalies interact with the background flow and affect the circulation pattern, including the EOF [28–30].

We calculated the EOFs for the surface pressure fields obtained using the PlaSim-ICMMG-1.0 model results from December to February, considering an area lying north of 20N. In the model used, the grid converges towards the pole, so we constructed EOFs for the pressure anomalies multiplied by a grid cell area corresponding to latitude.

Figure 8 presents the primary pressure mode for this data. It explains 16.6% of the variability and represents the Arctic dipole characterized by an increased pressure over America and a decreased pressure over Eurasia. The well-known Arctic dipole may be regarded as a manifestation of the AO (for example, [31–33]). A new atmospheric pattern emerges, the Arctic dipole [33] has been accompanied by a radical shift in the Arctic atmospheric circulation patterns because of loss of the Arctic Sea ice since 2001.

We counted the number of blocking events with a negative and positive primary mode index (Figure 9). Approximately 2/3 of blockages in Western Europe occur when the primary mode index is negative. When blocking is in Eastern Europe, the negative phase of the primary EOF mode also prevails. The blocking process over North America in the model occurs only during the EOF index’s positive phase. The frequency of blockings in northeastern Asia is approximately the same, both during the EOF’s positive and negative phases. Thus, the simulation data showed that blocking events can be associated with a specific structure of low-frequency oscillations of atmospheric dynamics, namely, the EOF phases.
Figure 8. Primary EOF mode of surface pressure fields obtained using the PlaSim-ICMMG-1.0 model results from December to February.

Figure 9. Number of blocking events during (a) negative and (b) positive index of primary EOF.

4. Conclusions and future research
In this paper, we do not give a comprehensive review of the literature on polar vortex streamers, but rather present some results of modeling vortex streamers by using a climate model of intermediate complexity. Using numerical experiments, we also wanted to show how blocking variations are associated with the internal dynamics, namely the surface pressure primary EOF phases.

The study of stratospheric circulation is a topic of research provided by two-dimensional vortex dynamics. Two-dimensional patterns, such as the streamers of vortices in straining flows, are directly related to stratospheric wave breaking.

In this paper, we computed the number of streamers and cutoffs in different seasons. In subtropics, the number of streamers in summer is more than in winter, because in winter there is a strong jet stream that provides stability of Rossby waves. Besides, we studied the dependence of the number of streamers on their scale. In the above-used model the grid spacing at mid-latitudes is about 300 km, so Rossby waves caused by smaller-scale inhomogeneities are not considered. There are only a few eddy structures in the Pacific. The Ertel potential vortex streamers and cutoff can be an indicator of wave breaking, and they indicate the probability of extreme weather conditions. Therefore, the streamers identification method can be used for diagnosis of Rossby wave breaking. As the polar vortex elongates, we have to note that it becomes hydrodynamically unstable, and this instability will affect
the upper troposphere and stratosphere. That means that the Potential Vorticity streamers are connected with surface pressure systems and present during high-impact weather patterns in the mid-latitudes.

Two types of Rossby wave breaking based on the upper-level trough behavior are anticyclonic wave breaking (AWB) and cyclonic one (CWB). AWBs are characterized by positively tilted troughs being advected anticyclonically. They occur preferentially on the jet’s equatorward side. CWBs show negatively tilted troughs wrapping up cyclonically. They occur mostly on the jet’s poleward side. The Rossby wave breaking process study will help better understand weather and climate systems’ dynamics under a warming climate. A physically plausible strong latitudinal PV gradient in the lower stratosphere inhibits breaking at lower levels. It encourages a vertical propagation of wave disturbances up the vortex edge, where they amplify with height and eventually break equatorward at upper levels. However, when wave breaking occurs in the lower stratosphere, the lower stratospheric PV gradient is destroyed, inhibiting the propagation up the breaking level. It thereby screens the upper portion of the vortex from the waves.

We also need to understand the relationship of these processes in the stratosphere with the loss of sea ice in the Arctic and some extreme weather events like blocking. Extreme weather events are likely to increase in the future due to the global warming and climate change; so good knowledge about the main influences on these events is essential. These processes require a consideration that is more careful in order to understand their mechanism. Therefore, we plan appropriate experiments to simulate these processes. A logical continuation of this study would be some modeling of climate dynamics with different climate scenarios.

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