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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Rossby Wave Breaking in the Stratosphere: Part I—Climatology and Long-Term Variability

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Abstract—The processes of planetary wave breaking (Rossby Wave Breaking – RWB) significantly contribute to variability in stratospheric circulation. Employing a previously developed method for identifying RWB, adapted for stratospheric circulation, this study analyzes the climatology and long-term variability of RWB processes in the middle stratosphere. The method is based on the analysis of potential vorticity (PV) contour geometry at the 850-K level using ERA5 data within the PV range 0–400 PVU (Potential Vorticity Units) determined based on PV field climatology. It was demonstrated that RWB processes exhibit intraseasonal peculiarities. Most frequently, waves break in the northern regions of East Asia and the Pacific Ocean from October to December and in April to March. In January and February, no areas with prevailing RWB processes were identified. We obtained a statistically significant increase in the number of RWB for the first half of winter (October–December) and for the end of the winter period (March and April). For midwinter (January and February), insignificant negative trends were obtained. The results of this work can be used to analyze the long-term variations in stratospheric circulation and, in particular, the occurrence of stratospheric anomalies preceding sudden stratospheric warmings.

Keywords: planetary wave breaking, stratosphere, stratospheric polar vortex, sudden stratospheric warming, potential vorticity, contours of potential vorticity

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INTRODUCTION

The circulation of air masses in the winter stratosphere is determined by the stratospheric polar vortex (SPV) and strong westerly transport of these masses [1], favoring the vertical propagation of planetary quasi-stationary Rossby waves [2]. After their breaking, these waves may lead to strong changes in the structure of the polar stratosphere [1, 3, 4]. Breaking of planetary waves (PWs) is closely related to the strongest distortions of the SPV position and changes in the SPV area, and to rapid stratospheric warmings, known as sudden stratospheric warmings (SSWs) [5, 6].

One of the methods, widely used for analysis of the stratospheric dynamics in terms of the wave processes is the method based on Fourier analysis of geopotential height along the 60° N latitude and on the calculation of the PW amplitudes and phases with the zonal wavenumbers 1 (vortex displacement), 2, and 3 (vortex split) [7]. It is well known that minor SSWs usually occur before major SSWs (e.g., [6]); minor SSWs are associated with intensification of PW1, with PW2 being minimal [8–10]. In the process of interaction of PW and polar vortex, the latter weakens; and as PW amplitude further increases, major SSWs occur. As noted in work [11], the presence of the conditioning phase, associated with the occurrence of minor SSWs before major SSWs, is a necessary, but not sufficient, condition for occurrence of a major SSW. The Fourier method is quite simple and, as such, widely used to study the stratospheric dynamics; however, it strongly smoothes out and simplifies the real processes occurring in the stratosphere, and disregards the seasonal features of SPV evolution. In work [6], we showed that the parameters of stratospheric warmings exhibit strong interannual variations, not manifested in the PW1 and PW2 dynamics [12].

An efficient tool for diagnosing the stratospheric dynamics is the analysis of the potential vorticity (PV) fields. In 1983, the authors of work [3] showed that PV variations well reflect the wave and eddy interactions during Rossby wave breaking (RWB) leading to a mixing of air masses with different vorticities in the stratosphere. The criteria, which make it possible to compare the breaking of atmospheric and oceanic waves, are irreversible deformation and mixing of material contours (PV contours, in the case of the atmosphere). The Rossby wave breaking is a ubiquitous phenomenon and, possibly, one of the most important dynamic processes influencing the stratosphere as a whole [3]. The authors of work [3] compared a region surrounding the SPV with a surf zone in the ocean (Appendix 1, Fig. A1; https://disk.yandex.ru/d/Mdxc9qy9g9Ovsw) [13]. The surf zone is a region with small PV gradient; it is formed by quasi-horizontal mixing, associated with wave breaking. The wave breaking in the surf zone, steady in time, may create preconditioning favoring SSW occurrence.

The SSW preconditioning associated with RWB occurs due to two main processes: a gradual decrease in SPV area and widening of a surf zone [3]. For instance, the RWB-driven processes may strongly distort the SPV, by displacing it gradually off the pole, so that the vortex area before SSW should gradually shrink. The small SPV area favors the so-called focusing effect, when every subsequent wave disturbs an increasingly smaller vortex area. The enlarged area of the surf zone may act as a reflector, so that waves can not only be focused, but also intensified at high latitudes. Thus, immediately before SSW the waves may even show a low amplitude; however, they can be intensified and focused owing to the configurations of vortex and surf zone. Not only enhanced wave propagation from the troposphere to the stratosphere, but also SPVs in a "preconditioned state" enabling wave focusing at high latitudes, are required in order for the mean zonal wind to be reversed from westerlies to easterlies [14].

The authors of work [14] were first to present in 1987 the climatology of wave breaking in the stratosphere from 1964 to 1982, based on the theories in [3]. These authors again confirmed the conclusions from [3] that the SSWs are characterized by the preceding bursts (larger amplitudes) of PW activities and marked decreases in vortex area, implying that a "preconditioning" preceded all main SSW events. These events often culminate in polar vortex displacement or breakup, with the low potential vorticity air being over the pole. The authors of [14] revealed two regions with maximal wave breaking: over North America and Europe.

Importantly, although not guaranteeing the occurrence of a major SSW, the preconditioning always preceded major SSWs [14]. Based on [14], preconditioning and subsequent sudden warmings looked like a single continuous event, when considered from the viewpoint of wave breaking. Development of major sudden warmings starts with involvement of low-PW air masses into wave breaking; then, regions with higher-PW air masses are involved as the vortex area shrinks. The entire process usually takes no less than six weeks. Sudden warmings show strong interannual variations, if considered on PV maps at the 850-K level.

Morphologically, the processes of SSW conditioning, including RWB and SPV deformation and evolution, are associated with the formation of anticyclonic vortices. After being formed over the Aleutian Islands and Europe, anticyclones tend to advect high-vorticity air equatorward, and then westward (Fig. A2; https://disk.yandex.ru/d/Mdxc9qy9g9Ovsw). In the tropical region, the polar air is broken mainly due to diabatic effects. The Aleutian anticyclone is associated more often with RWB processes and the conditioning stage, as well as with the SSW itself. The European anticyclone sometimes participates in either single or both stages. Major warmings are always associated with vortex displacement off the pole, well described by PW1. The vortex splits sometimes and can be represented by PW2 in the geopotential height field.

As many as 40 years have already past since publication of two fundamental works [3, 14], and the PV calculation from observational data is no longer as difficult as before. Therefore, the PV analysis is widely used to study the process dynamics in both the stratosphere [15–18] and troposphere (see [19, 20] and reviews therein). The PV analysis made it possible to improve appreciably our understanding of the stratospheric dynamics, as was predicted in [3]. An assumption that the polar vortex shows maximal gradients at the vortex edges, and the neglect of the frictional and diabatic effects, leads us to a simple model of SPV evolution, which may be determined by the evolution of the SPV contours separating different PV values [4].

Studying the specific features of RWB in the stratosphere helps to improve appreciably our understanding of regularities of SSW occurrence. As later works (e.g., [17]) indicated, the processes of the planetary wave breaking show quite involved three-dimensional structure and height-specific features in the upper (1600 K ~ 40–50 km) and lower (400 K ~15–20 km) stratosphere. This is clearly seen from the joint analyses of zonal mean wind velocities and temperatures at the 10 and 1 hPa levels [6]. The plots presented in [21] clearly demonstrate the cases of the "upper" and "lower" SSW events.

The purpose of this work is to study the long-term RWB variations over the period 1979–2022 at the 850-K level over the Northern Hemisphere. According to the SSW definition in [6], PV dynamics at this level are closely associated with SSW occurrence.

MATERIALS AND METHODS

RWB Identification

Our approach is based on the method suggested in work [19]. In turn, this method is based on analysis of

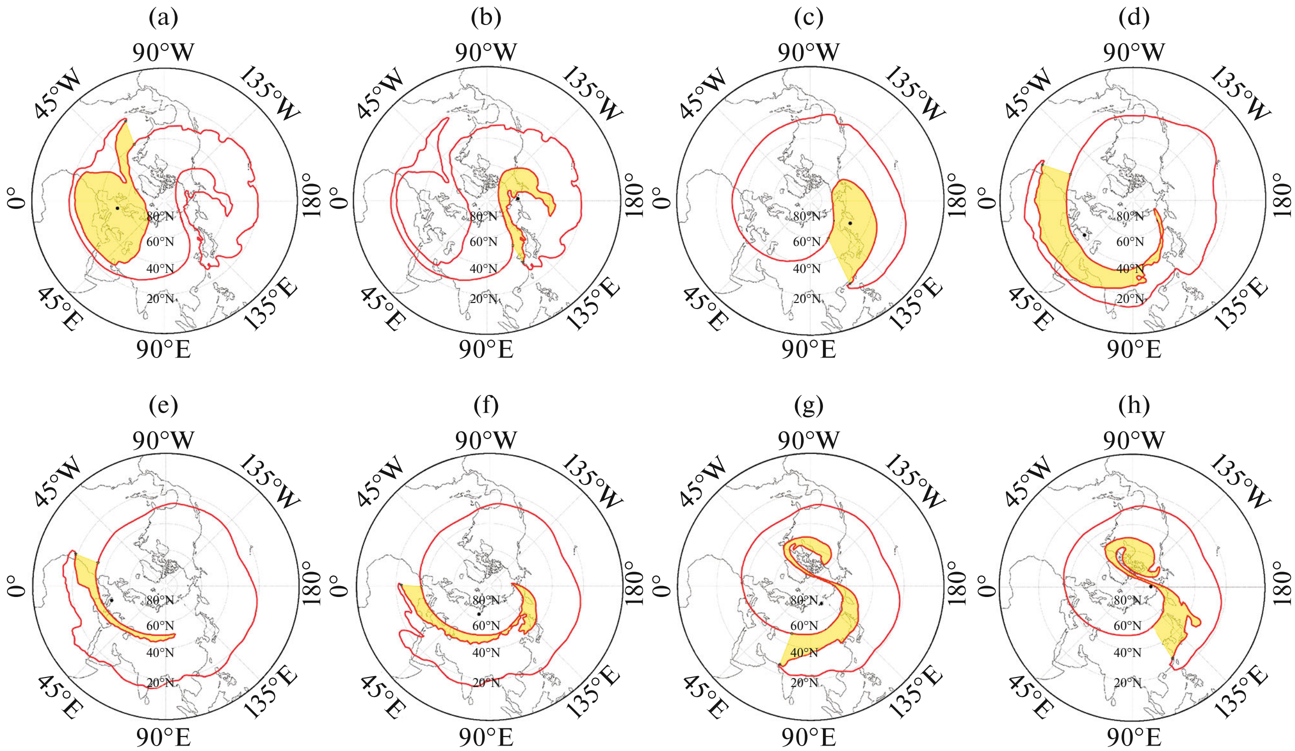

Fig. 1. Examples of primary RWB for different PVU values. Gray shading shows a region of breaking wave; black circle indicates the center of the braking area (calculated as the geometrical center of polygon of the area, i.e., mean positions of all polygon points) [19]: (a) January 20, 2009 (220 PVU); (b) January 20, 2009 (220 PVU); (c) January 18, 2001 (220 PVU); (d) December 1, 1987 (140 PVU); (e) December 6, 2016 (120 PVU); (f) December 6, 2016 (140 PVU); (g) December 6, 2016 (180 PVU); and (h) December 6, 2016 (200 PVU).

the geometry of PV contours (PV isolines for different atmospheric levels), showing if there are the wave-breaking features for a PV contour [19, Fig. 1]; also, we determine the centers of wave-breaking areas followed by clustering the centers found:

$$PV = -g\frac{\partial\theta}{\partial p}(\zeta_\theta + f), \qquad (1)$$

where g is the acceleration due to gravity; θ is the potential temperature; p is the pressure; ζ_θ is the relative vorticity, perpendicular to the potential temperature surfaces; and f is the Coriolis parameter. Here, PV is in the potential vorticity units (PVU).

The clustering parameters are chosen using an approach, which was utilized in [19] and is close to winter conditions of circulation in the troposphere. Clustering is used to identify the regions most significant from the viewpoint of the wave breaking occurrence frequency. The regions in which the wave breaking centers were recorded rarely were not considered. The ECMWF ERA5 reanalysis data [22] for a level of 850 K (32 hPa) were used to consider the PV contours from 0 to 400 PVU with the contour interval of 20 PVU. The contours were chosen using PV climatology data at the 850-K level (https://disk.yandex.ru/d/Mdxc9qy9g9Ovsw/mean_contour). Figure 1 presents examples of the identified RWB regions and their centers.

The winter circulation differs between the stratosphere and troposphere; therefore, the algorithm [19] was adapted to height-specific features of the stratospheric circulation. As compared to the tropospheric polar vortex, the SPV is primarily difficult to handle because it can be strongly displaced off the pole or split. The "tropospheric" approach did not envisage that the analyzed PV contours can be displaced off the pole so far that the point of the pole would be outside these contours. In order for this method to be used to analyze successfully the contour geometry in these cases, we initially carried out an interpolation to the Lambert equal-area projection centered at the pole, in order to obtain a closed contour without distortions in crossing the prime meridian. Then, we examined the contours for the presence of the point of the pole (in the case when the SPV was strongly displaced off the pole), with the further analysis of the contour geometry being accordingly arranged. "Reprojecting" of contours and checking whether the point of the pole falls into them is the main difference of our approach for the stratosphere.

Still another challenge is to interpret the geometry of RWB forms. The stratospheric circulation has specific features, so that anticyclonic-type breaking makes the largest contribution to mixing. Of course, cyclonic forms are unlikely to be totally absent; but they either contribute nothing to mixing, or are an anticyclonic-type deformation for high PV values owing to the specific features of circulation in the stratosphere. Moreover, wave breaking in the stratosphere occurs on much larger scale than in the troposphere [19]. From Figs. 1e–1h for December 6, 2016, it can be seen that low-PV contours come initially into play; and then contours with increasingly larger PV values gradually become involved while moving eastward. Therefore, the breaking centers were united with a step of 30° E during clustering. For the general scheme of the algorithm of RWB analysis for the stratosphere visit https://disk.yandex.ru/d/Mdxc9qy9g9Ovsw.

Products Obtained through Analysis of Geometry and Clustering of Centers of Breaking Regions

Products available for analysis are analogous to those presented in work [19]. The freely accessible archive contains diagrams of the following types:

— RWB values for each month from October to April between 1979 and 2022, which demonstrate which days and PV values are characterized by wave breaking in specific areas. In addition to diagrams, the products show the main breaking regions for each month (https://disk.yandex.ru/d/Mdxc9qy9g9Ovsw).

— Longitude–time diagrams, showing interannual variations in the breaking numbers for each month. The calculations were carried out using the total number of contours, for which breaking was observed for a month for each longitude (https://disk.yandex.ru/d/Mdxc9qy9g9Ovsw).

Our products allowed us to analyze the climatology and long-term variations in the number of RWBs. Based on the longitude–time diagrams, we obtained the mean RWB occurrence frequency for different months. As in data from publications [19, 20], we presented not the absolute frequency of occurrence in each node, but the occurrence frequency with respect to the node of the maximum. This is required exclusively to illustrate the regions with maximal occurrence frequency. The absolute occurrence frequency is indicated by numbers for 45° sectors. Also, the diagrams were used to calculate the RWB variations for each month from 1979 to 2022. As in [19], the number of PV contours, participating in breaking for a month, was used as the main characteristic of breaking variations. As was shown in [19], the processes with involvement of a large number of contours are most significant for analysis of interactions between the RWB and polar vortex, leading to the strongest mixing of air masses in the vertical.

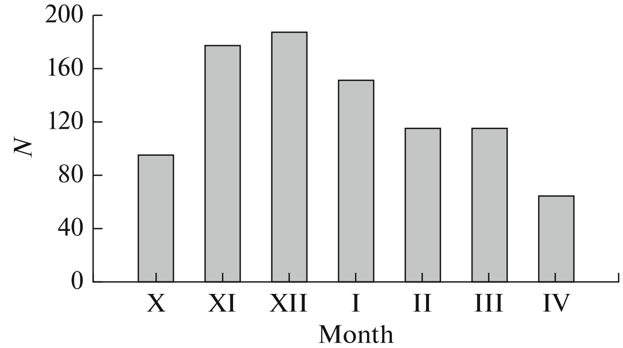

Fig. 2. Monthly mean number of RWB events for different months.

RESULTS AND DISCUSSION

In this work, we analyzed the mean indices of the RWB occurrence frequency and variations. The RWBs are the largest in number in November–December (Fig. 2).

The mean long-term distributions of the RWB occurrence frequency are presented in Fig. 3. From the figure we can discern the increased breaking occurrence frequency over the north of East Asia, Pacific Ocean, and western coast of North America in October–December (Figs. 3a–3c). This conclusion is obvious, to some degree, because these breaking events cause the occurrence of an anticyclone in the first half of winter [23]. In turn, we note that, although the Atlantic sector with a large RWB occurrence frequency is still identified in October, in November–December the RWB events are predominant in the Eastern Hemisphere. No areas of RWB with high frequency of occurrence were detected for January and February (Figs. 3d, 3e). Areas of RWB with increased frequency of occurrence can be discerned in February in the region of the Urals. In March and April (Figs. 3f, 3g), the occurrence frequency distributions are similar to the first half of winter: the main RWB events are concentrated over East Asia and the Pacific Ocean (eastern part). Increased RWB occurrence frequency is also noted in March over the Atlantic Ocean (8%).

PW breaking is associated with generation of vertical fluxes of wave activity. The planetary-scale waves, which can propagate to the stratosphere, are mainly caused by the orography of the surface and sea/land contrasts [24, 25]; the flux is additionally amplified by baroclinic processes [26]. Our conclusions agree well with the results of analysis of the climatology of the three-dimensional Eliassen–Palm flux [27]: the flux of wave activity is found to be maximal in the northeast of Asia in the first half of winter, which, in our opinion, creates "prerequisites" for the SSW occurrence. Under the influence of larger PV gradients [28], the growth of PW activity in the first half of winter leads to the formation of an Aleutian anticyclone

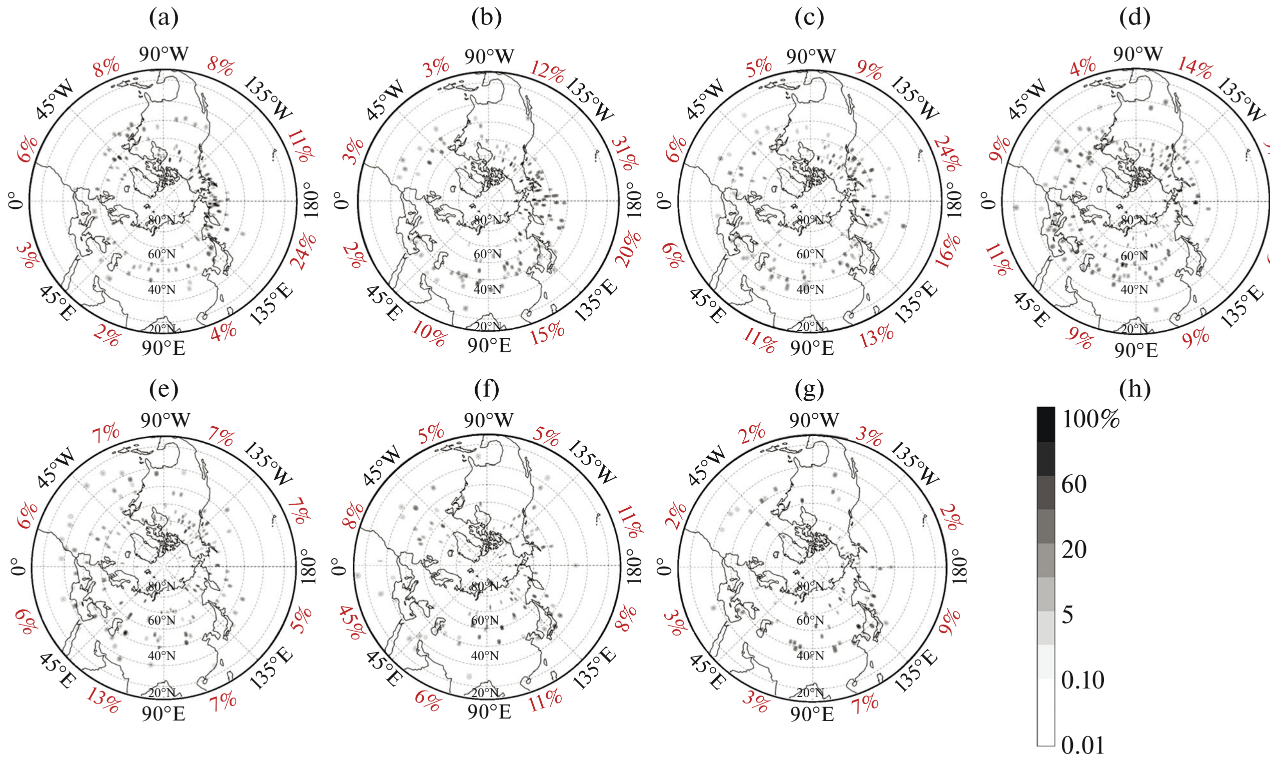

Fig. 3. Climatic mean distributions of the RWB occurrence frequency with the mean calculated over each 45° sector: (a) October; (b) November; (c) December; (d) January; (e) February; (g) March; and (h) April.

(Pacific Ocean), the structures of which were described in many works, such as in [23]. In [17], the authors indicate that increasing PW amplitudes in early winter do not spread to the upper stratosphere and favor vortex intensification in midwinter. Unlike in [14], we did not identify a distinct region with a high frequency of wave breaking over Europe. Probably, this may due to our approach, intended to identify the regions with the largest numbers of PV levels simultaneously involved in wave breaking, i.e., regions where equatorward SPV advection is maximal during breakup.

The number of RWB for the Northern Hemisphere (Fig. 4) was calculated to analyze the long-term variations. We obtained a reliable increase in the number of RWBs in early winter (October–December). Also, there is a significant positive trend in November in the region of maximal number of RWB (Fig. 4b); on the contrary, there is a negative trend in the Western Hemisphere (https://disk.yandex.ru/d/Mdxc9qy9g9Ovsw). Therefore, after the RWB occurrence frequency is averaged over the entire Northern Hemisphere, in November the positive trend is insignificant; consequently, the frequency of occurrence only for the Eastern Hemisphere is presented in Fig. 4. Insignificant negative trends were obtained for January and February, and significant positive trends are seen for March and April. This conclusion is consistent partly with results of work [29], showing increasing energy of waves in the stratosphere of the tropics, as well as in the upper stratosphere at all Northern Hemisphere latitudes. On the whole, the presence of a trend and its sign turned out to be dependent on intraseasonal features, as was the case for climatic mean distributions: the number of breaking events significantly increases in months with better-defined RWB regions over Asian-Pacific sector.

The maximal RWB occurrence frequency over the Pacific Ocean and a strong positive trend of the number of breaking events in early winter may favor the occurrence of earlier SSWs. This subsequently can influence the change in SPV "seasonality," causing a weaker vortex in midwinter and its intensification in late winter. This is indirectly indicated by the number of RWB events, decreasing in midwinter and increasing before change in stratospheric circulation in spring. These hypotheses will be verified in our further research.

One of the possible explanations could be a change in the character of atmospheric blockings, i.e., one of the key tropospheric SSW predictors [30]. In the scientific literature there is an active debate about how different anomalies in the late fall–early winter period influence the SSW occurrence [31–35]. In our work [36], we revealed a shift in response of surface air temperature to the occurrence of blockings: since the late

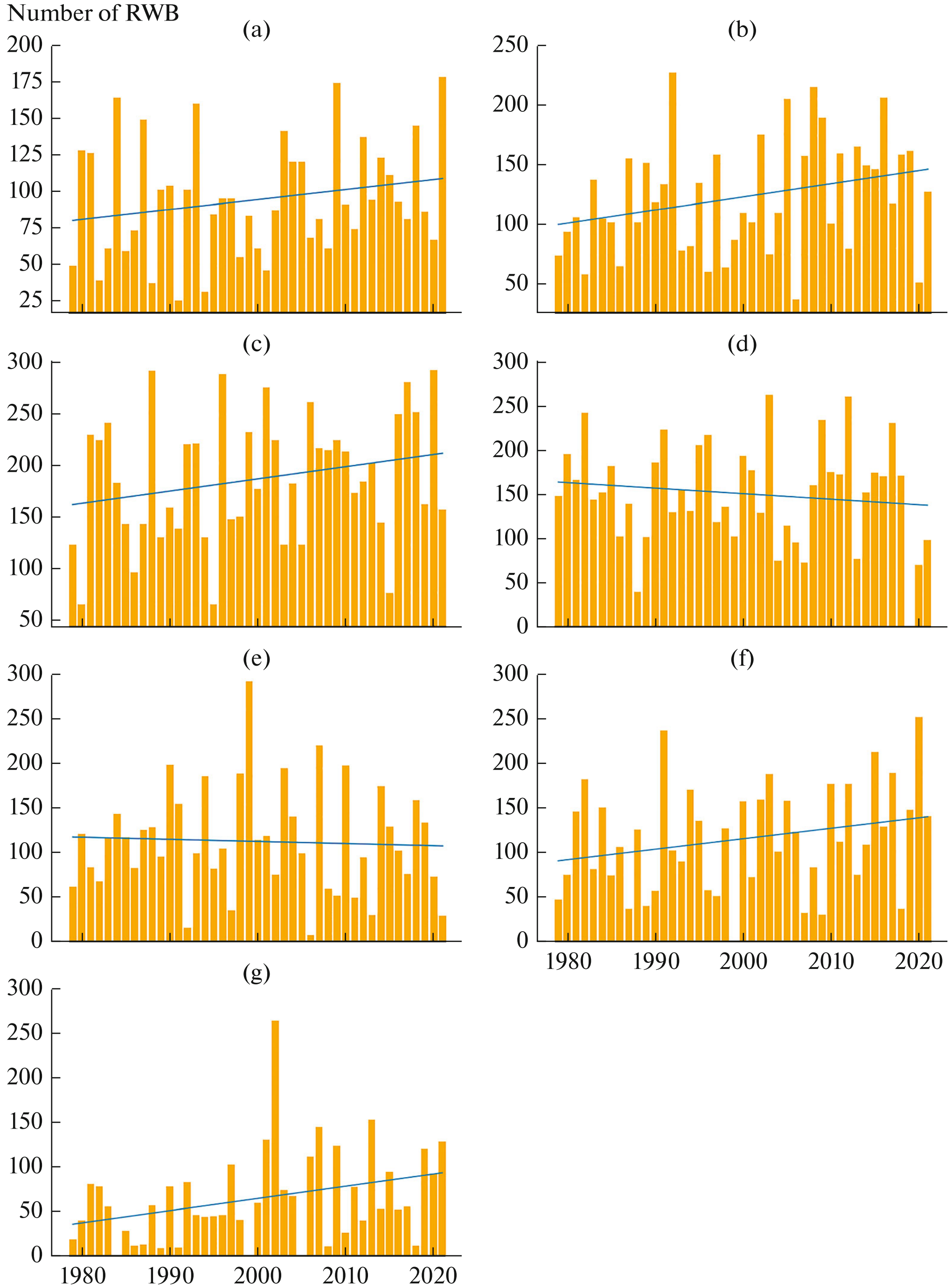

Fig. 4. Long-term variations in the number of RWB events in the Northern Hemisphere: (a) October (trend: 0.68, p-val: 0.163); (b) November (120° E–90° W; trend: 1.11; p-val: 0.059); (c) December (trend: 1.18; p-val: 0.121); (d) January (trend: −0.62; p-val: 0.392); (e) February (trend: −0.22; p-val: 0.751); (f) March (trend: 1.18; p-val: 0.111); (g) April (trend: 1.35; p-val: 0.031). P-val < 0.1 means the confidence level of 90% and higher and <0.2 means the confidence level of 80% and higher. In November, the parameter under study was determined in the Eastern Hemisphere.

1990s cold anomalies over Siberia intensify in response to occurrence of blocking and, in particular, in the early winter period. Probably, the trend obtained in Fig. 4 may reflect a strengthening of the link between the troposphere and stratosphere owing to more active PW penetration into the stratosphere. The mechanisms of occurrence of anomalies in fall and early winter are under active debate and, as demonstrated by many authors, may be due to the "Arctic amplification" phenomenon [31].

CONCLUSIONS

Our study showed that RWB events exhibit intraseasonal features. Waves break most frequently in the northern parts of East Asia and the Pacific Ocean in October–December and March–April; in January–February the RWB occurrence frequency is distributed more uniformly in the Northern Hemisphere.

We obtained a reliable increase in the number of RWB events in early winter (October–December) and in the late winter (March–April). Insignificant negative trends are obtained for the midwinter (January–February). We also noted that, for the Northern Hemisphere, the processes associated with planetary wave breaking change from year to year, which is evidence in favor of anomalous strengthening or weakening of wave activity fluxes in different years.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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