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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Breaking of Rossby Waves in the Stratosphere: Part II—Factors Leading to Sudden Stratospheric Warmings

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Abstract—Studying the occurrence of sudden stratospheric warmings (SSWs) and their complex interrelation with tropospheric and stratospheric processes is of fundamental value for improving of our understanding of the dynamics of atmospheric circulation. This is especially important under phenomena but of global climate changes, which not only increase the frequency of anomalous atmospheric phenomena, but also intensify them. Based on a developed and adapted method for identifying Rossby wave breaking (RWB), which accounts for the specifics of stratospheric circulation, an analysis of the conditions for the occurrence of major SSWs in the Northern Hemisphere was conducted. The method relies on examining the geometry of potential vorticity contours in the stratosphere at the 850 K level using ERA5 reanalysis data. It is shown that anomalous RWB processes in November and December play a key role in preconditioning the onset of SSWs. Most of the analyzed SSW events are associated with an increase in the number of RWB events in the Asia-Pacific (AP) region in November and December, and occasionally in January. In cases where SSW initiation is linked to RWB over the Atlantic and Europe, it is also preceded by RWB anomalies in the AP region. For the identified types of wave breaking in the stratosphere, atmospheric blocking is characteristic in the troposphere, accompanied by negative near-surface temperature anomalies over Eurasia and/or North America. The increased frequency of early- and midwinter major SSW events aligns with the previously identified trend of enhanced negative temperature responses to atmospheric blocking in the Northern Hemisphere. The results of the work can be used to improve the prediction of SSWs and the associated extreme weather events, as well as for climate modeling to account for the RWB effects on stratospheric processes.

Keywords: lidar, stratosphere, planetary wave breaking, Rossby wave breaking, sudden stratospheric warming, circulation anomaly, temperature

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INTRODUCTION

The Northern Hemisphere winter stratosphere is characterized by complex air mass mixing processes caused by the penetration of planetary waves from the troposphere and their interaction with zonal flow [1–3]. These processes play a key role in the occurrence of sudden stratospheric warmings (SSWs) (see [4, 5]), accompanied by rapid temperature increases in the polar stratosphere and deceleration and reversal of zonal mean wind. Sudden stratospheric warmings can strongly influence the climate and weather conditions on a global scale.

The SSW occurrence is associated with weakening or breakup of stratospheric polar vortex (SPV), caused by adiabatic effects and advective transport of warm air masses to the polar area [2, 4]. This can lead to strong changes in the tropospheric circulation: extreme cold can encompass North America, Europe, and Asia, while anomalous warmings are observed in the Arctic [4]. The SSW events are closely related with long-term changes in the climate system, including the Arctic amplification, decrease in the area of sea ice, and global warming [6]. Studying the processes of SSW occurrence is the key to improving the reproduction of the stratospheric circulation and dynamic stratosphere-stratosphere interaction in numerical models. This, in turn, favors an increase in accuracy of seasonal forecasts and extreme weather phenomenon predictions. One or two SSW events are usually recorded during winter season. However, winters are also known with no SSWs at all. In these periods, with stratospheric polar vortex steadily kept cold and isolated until March, the conditions were created for a strong destruction of ozone layer, such as in the springs of 2011 and 2020 [7–9].

Despite the fact that the relation between the SSWs and the penetration of planetary waves from the troposphere to the stratosphere is now well established, the mechanisms of the SSW occurrence are still under active study. These waves occur under the influence of such factors as the terrain relief, the temperature difference between the continents and the ocean, as well as the baroclinic instability, and it is precisely these which drive the dynamics of the interaction between the troposphere and the stratosphere. Based on analysis of observations and model calculations, two main mechanisms of the SSW formation are conventionally singled out at the present time [4, 11, 12].

The first, bottom-up, mechanism [4] suggests that the SSWs are initiated by an enhanced penetration of planetary waves from the troposphere to the stratosphere. Atmospheric blockings [13, 14], El Niño-Southern Oscillation (ENSO) phases, Madden Julian Oscillation [15], and specific features of the formation of snow cover [4] serve as the key factors favoring this process.

The second, top-down, mechanism [4] assumes that the SSWs can be caused by internal processes in the stratosphere, even in the absence of pronounced anomalies in the troposphere. In this case, the stratosphere "preconditions" the SPV for the state at which even minimal disturbances can initiate the resonance wave amplification. A key role in this process is played by the interaction of wave activity fluxes with zonal circulation, as well as nonlinear interactions between waves in the stratosphere [16]. In addition, the phase of the quasi-biennial oscillation of zonal wind in the equatorial stratosphere creates conditions, favorable or unfavorable for penetration of the wave activity flux into the polar stratosphere, determining the "transmissivity" of the stratospheric flux [17].

Authors of work [2] (see the reviewing paper [10] for more detail) indicate that the SPV preconditioning is preceded by a spontaneous wave amplitude amplification. The preconditioning includes a few episodes of increasing activity of planetary waves, manifested as wave breaking in the potential vorticity (PV) field. A gradual shrinking of the SPV area occurs through advection of high-vorticity air into the tropics and expansion of the surf zone. This creates conditions for wave focusing, under which even a weak amplification of wave fluxes from the troposphere can initiate SSW through resonant wave amplification in the stratosphere. Besides the planetary waves, an important role in the preconditioning process is also played by gravity (small-scale) atmospheric waves that modify zonal winds in the upper stratosphere and mesosphere, favoring SPV weakening [18]. Thus, interaction between planetary and gravity waves creates a complex mechanism of the SSW preconditioning.

One of the most efficient and informative methods for studying the stratospheric dynamics, in both pre-SSW and SSW periods, is the use of PV distribution [2, 4]. In our previous work [10], we gathered data on Rossby wave breaking (RWB), which provide the possibility for a deeper analysis of the pre-SSW processes. This paper is devoted to RWB analysis for major SSW events we singled out within our research [5].

The main purpose of this paper is to identify the characteristic anomalies in the number of RWBs (henceforth RWB anomalies), their geographic distribution, and time evolution. These data will make it possible to refine the key mechanisms of the pre-SSW SPV conditioning.

1. MATERIALS AND METHODS

1.1. Selection of SSW Events

For analysis, we chose early and mediate major SSW events for the period of 1979–2021, the onset dates of which were before February 12. The classification by the onset dates was suggested by the authors of work [19]. The events with onsets after this date were excluded from consideration because they often represent the so-called final SSWs, associated not only with dynamic processes, but also with radiative mechanisms of intensifying solar heating [20, 21]. The events for analysis were chosen according to criteria suggested in work [5] (Table 1). This approach made it possible to concentrate on processes predominantly associated with the penetration of tropospheric waves into the stratosphere.

We included in our analysis the SSW with the onset date of December 6, 1987, (February 6, 1989) as the earliest (latest) event. Out of the 19 events selected, only four occurred prior to 1998 (0.2 events per year) and 15 events occurred after 1998 (0.6 events per year). These data confirm the tendencies presented in [5] and indicate that yearly (until January 5 [19]) and mediate (until February 12 [19]) SSW events became more frequent in recent decades. Also, the table includes the December 2000 event that is classified as minor but shows a number of unique characteristics [23]. First, this is a minor SSW, the earliest in the period under study. Second, it is associated with the major warming in January 2001, which is the only minor warming characterized by SPV split recorded based on the PV data [5]. The minor warming in December 2002 is also included in our analysis because it is closely related to the major event in January 2003.

We would like to stress that minor SSWs are often closely related to major SSWs [37]. However, two episodes of these "coupled" SSWs do not occur until early February. Exceptions were the 2000–2001 and 2002–2003 events that we just selected for analysis. These additions make it possible to take into account the important characteristics of transitional events,

Table 1. SSW events (arranged according to the onset dates)

No.	Winter period, years	Onset date	Regions with RWB anomalies				SSW group (see subsection 2.2)	Deformation scenario	Source
			month						
			X	XI	XII	I			
1	1987/1988	Dec 6, 1987	AE	AP			1	CSS	[22]
2	2000/2001	Dec 7, 2000	AE	AE, AP			1	D	[23]
3	1998/1999	Dec 13, 1998					1	CSS	[24]
4	2003/2004	Dec 17, 2003	AE, AP	AE			3	CSS	[25]
5	2001/2002	Dec 22, 2001			AE, AP		1	D	[26]
6	2018/2019	Dec 24, 2018	AE	AE, AP	AE, AP		1	8SS	[27]
7	2002/2003	Dec 27, 2002	AE	AP	AE		1	D	–
8	1984/1985	Dec 29, 1984	AE, AP		AP		2	8FS	[28]
9	2020/2021	Jan 1, 2021			AP		1	D	[29]
10	2005/2006	Jan 3, 2006	AE, AP	AP	AP		2	D	[30]
11	2012/2013	Jan 4, 2013	AE		AP		1	8FS	[31]
12	2002/2003	Jan 14, 2003	AE	AP	AE	AE	2	8SS	–
13	1986/1987	Jan 16, 1987	AE	AE	AE	AE	3	D	–
14	2008/2009	Jan 18, 2009	AE	AP	AP	AE	2	8FS	[32]
15	2009/2010	Jan 20, 2010	AE, AP	AP	AE	AE, AP	2	8SS	[33]
16	2016/2017	Jan 27, 2017	AE	AP	AE	AE, AP	2	D	[34]
17	2000/2001	Jan 30, 2001	AE	AE, AP		AP	1	8SS	–
18	2017/2018	Feb 5, 2018	AE	AE	AP	AP	2	8FS	[35]
19	1988/1989	Feb 6, 1989		AP	AE	AE	3	8SS	[36]

Early and mediate events that occurred until 1998 are highlighted in bold. Locations where RWB anomalies were recorded: AE is the Atlantic-European region (90° W–60° E); AP is the Asian-Pacific region (60° E–90° W); AE, AP are the both regions. The SSW grouping (see subsection 2.2) is according to the sequence of the RWB manifestation. The SPV deformation scenarios: CSS is a slow C-shaped split, 8FS is a rapid 8-shaped split, 8SS is a slow 8-shaped split, and D is a displacement (based on the PV maps).

which can play a key role in the process of preconditioning and occurrence of major SSWs.

1.2. Analysis of RWB Processes

The RWBs were analyzed using an algorithm adapted to the circulation conditions in the stratosphere [10]. The algorithm output the diagrams of planetary wave breakings, available for different time intervals (https://bit.ly/4f3W3DW for calculating the RWB anomalies in each month, https://bit.ly/4gaiOrl for RWB visualizing during winter before SSW). The diagrams display the days and atmospheric levels at which RWB occurred (colored symbols), as well as coordinates of the breaking centers, visualized using different colors for diverse areas.

Clustering of breaking centers for each calendar month from October to April was used to analyze the RWB anomalies (https://bit.ly/4f3W3DW). Clusters located in the sector 90° W–60° E were referred to the Atlantic-European (AE) region; and clusters in the sector 60° E–90° W, to the Asia-Pacific (AP) region. The number of atmospheric levels involved in breaking for a month was the main characteristic for the RWB estimation [10]. The breaking diagrams were used to obtain deviations of the numbers of breakings from multiyear (1979–2020) average values in separate months (https://bit.ly/3ZmMvOD). In our previous work [10], it was shown that the RWB occurrence frequency is maximal in November and December; therefore, these are the key months for occurrence of an anomalous regime in the stratosphere associated with early and mediate SSWs. Processes not only in November and December, but also in January play a significant role for events in the second half of January and early February. The variations in the number of RWBs are strong in October, with an increasing trend observed in AP region (https://bit.ly/3DbuXxm).

Thus, for each SSW event we estimated the anomalous numbers of RWBs over October–January for different SSW onset dates. These data permitted a more detailed study of how RWB anomalies influence the SSW preconditioning and evolution (see subsection 2.1).

Based on the RWB diagrams, we singled out **three groups** of SSWs (see subsection 2.2), depending on the sequence of the RWB manifestations over AP and AE areas (groups 1–3 in Table 1). In addition, we singled out **four types** of breakings for different breaking localizations and impact degree on SPV (see subsection 2.3).

The SPV deformations in the SSW periods were analyzed using daily PV maps (https://doi.org/-10.5281/zenodo.7450999; https://bit.ly/4fYrC3u). This approach made it possible to refine the existing classification regarding the deformation scenarios, including vortex split and displacement [5]. The classification is important for a better understanding of the SPV dynamics and its relationship with different SSW scenarios. These results are analyzed in subsection 2.2. In this work the method of composite averages (superimposed epoch method) [38] was used to analyze the circulation anomalies in the troposphere and stratosphere, corresponding to periods with different RWB types (subsection 2.3). We analyze the air temperature at the 1000- and 10-hPa levels, geopotential at the 500-hPa level, as well as anomalies in the wave activity flux (vertical component) using the Plumb equation [39] for 500 hPa in the troposphere and 10 hPa in the stratosphere. All parameters were obtained using daily ERA5 reanalysis data [40] from 1979 to 2021 with the spatial resolution of 1.5°.

2. RESULTS AND DISCUSSION

2.1. Analysis of Main RWB Regularities for SSW Events

The figures (https://bit.ly/3ZmMvOD) and Table 1 show that the RWB anomalies in October are more frequent in the AE region during the 17 winter seasons with early and mediate SSW events. The numbers of RWBs below normal in October were recorded only in 1998, 2000, and 2020. The increased numbers of breakings in the AP region were observed only in four winter seasons, with high numbers also observed in the AE region in these same years. This conclusion turned out to be unexpected considering that the total number of RWBs is observed to increase predominantly in the AP region (https://bit.ly/3DbuXxm). It is logical to hypothesize that the earliest SSWs should be associated with wave breakings in the AP region. However, the pattern turned out to be opposite: anomalies in October in the AE region play a more significant role. Winter 2021/22 may serve as an example, when there was one of the most stable SPVs [41], and a positive RWB anomaly in October was recorded in the AP region.

The situation changes in favor of the AP region in November: an increase in the number of RWBs in AP region during nine winter periods, versus six periods in AE region. During 2020–2021, increases in the number of RWBs in the Northern Hemisphere were recorded neither in October nor November. Positive anomalies were observed in both regions during winters 2000/01, 2005/06, and 2018/19. Two of the earliest SSWs (on December 7, 1987, and in December 2000) are associated with the RWB anomalies in the AE region in October and in the AP region in November. The anomalies were recorded during December 1987 in the AP region and during November 2000 in both regions.

After analysis of December in 15 winter periods (except the earliest warmings), we found that increased numbers of RWBs were characteristic for seven periods in the AP region and for eight periods in the AE region. An increase in the number of RWBs throughout the Northern Hemisphere was noted in just two cases (2001 and 2018). In January, four events were associated with anomalies in the AP region, and the same number of events in the AE region. Data in the Table 1 indicate that some combinations of RWB anomalies in the Northern Hemisphere were recorded almost always before SSW. The pre-SSW period is frequently characterized by anomalies in the AE region, although the total number of RWBs is markedly smaller in the AE than in the AP region.

We note that RWB occurrence frequency in October is about a factor of three smaller in AE than in AP region; and it can turn out to be insignificant when compared with the processes in AP region in November–December ([10], Figs. 1 and 2). The RWBs in October can probably be considered as predictors of the early and mediate SSWs, together with the most intense processes during November–January. Therefore, we devoted the main attention to November–January in the analysis of the predominant processes over the two regions before SSW. It was found that in the first half of the winter (such as in 1984, 1987, 1998, 2000, 2001, 2005, 2008, 2012, 2016, 2018, and 2020) and sometimes in January (2001 and 2018), there are more wave breakings in the AP than in the AE region. Figure 1 presents the RWB clustering centers; the sizes of the circles reflect the contributions of these centers to the total number of RWBs.

The contributions of wave breakings in the AE region strongly increased in November–December 2002, January 2003, November–December 2003, November 1986, January 2009 and 2017, and February 2018 (Fig. 2). The number of RWBs for AE region was maximal in November 1986. It is noteworthy that during 2002 and 2003 there occurred equal numbers of breakings in both regions; however, more RWBs occurred in the western part of the Northern Hemisphere. Anomalous number of breakings is always recorded in the AE region when their total contribution increases (see Table 1). Thus, it can be concluded that the SSW is determined by a combination of RWB anomalies over AE and AP regions.

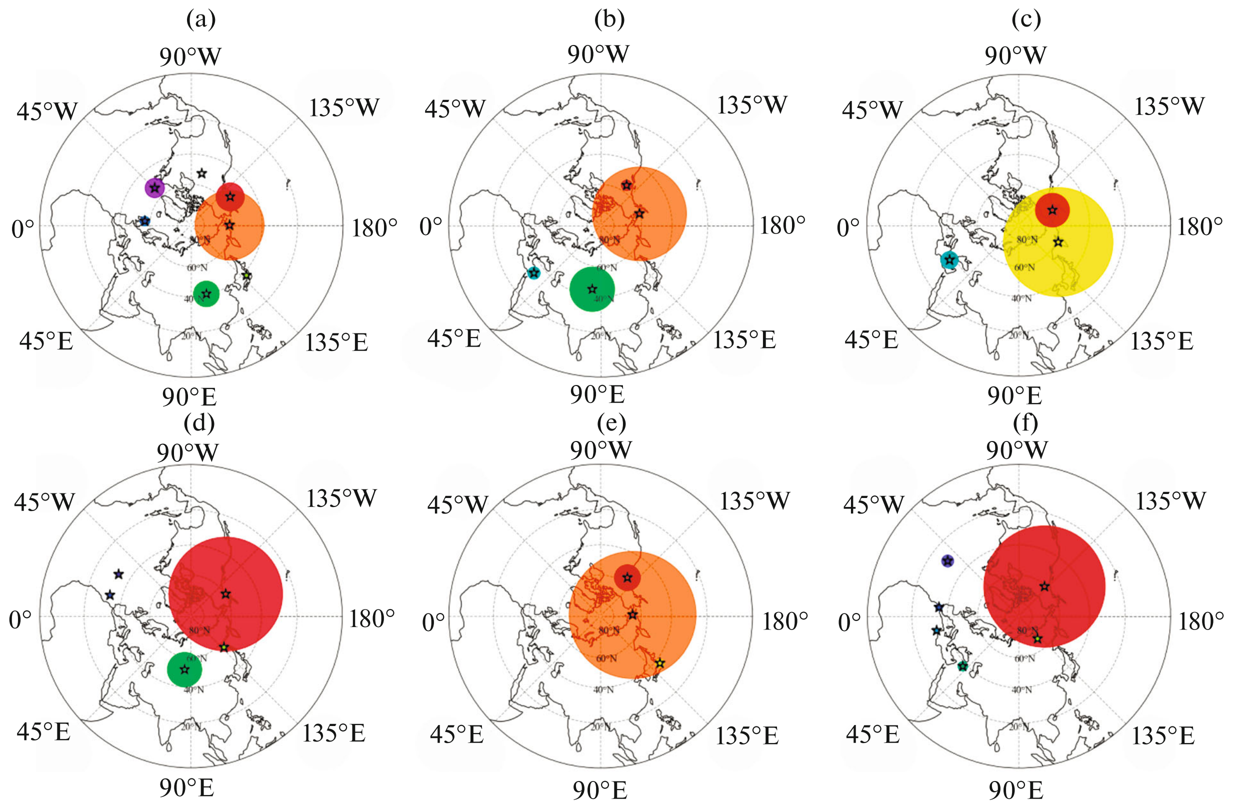

Fig. 1. The RWB relationship at the centers with the predominance of the processes in the AP region (sizes of circles are shown in accordance with the percentage contributions of RWBs; the maximum is noted in 2012 (95%), orange circle), colors of circles correspond to colors of clusters used for the breaking diagrams (https://bit.ly/4f3W3DW): (a) November–December 1984; (b) November–December 1987; (c) November–December 2001; (d) November–December 2008; (e) November–December 2012; (f) November–December 2018; star indicates the cluster center.

2.2. SSW Grouping according to Sequence of RWB Manifestations over AP and AE Areas

Analysis of the RWB diagrams and PV maps for November–January made it possible to classify the SSWs, based on the predominant RWB sequence in the AE and AP regions and on the corresponding forms of the SPV displacement/split.

Group 1. The main criterion for the classification is the presence of stable (in time) RWBs in the AP region (Figs. 3a and 1b), slowly evolving into SSWs. The RWBs, characteristic for this group, are associated with the so-called Canadian warmings [42]. The RWBs are observed in the AE regions in some cases (such as in November 2000); however, the SPV displaces owing to the advection of low-vorticity air masses over the Pacific Ocean (Figs. 3b–3d). The events during Decembers 1987, 1998, 2001, 2002, 2003, and 2012 (persisting into January 2013), 2018, 2020, November 2000, and January 2001 are the members of this group (see Table 1).

Most characteristic for group 1 (see Table 1) is the SPV displacement (three cases in scenario D), as well as a C-shaped deformation and a slow split of SPV (three cases in CSS). These processes can last for 7–10 days (Figs. 3b–3d). An exception is December 2012–January 2013, when the low-vorticity region also expanded from the direction of the Pacific Ocean (Figs. 3c and 3d); however, this process lasted for just three days, and the SPV deformed into an “8” shape (scenario 8FS) (https://bit.ly/3VoBb3a). Atypical for this group is also the December 2000 event, when during the period from December 13 to 16 there was a rapid split according to the 8FS type owing to the two-sided intensification of low-vorticity advection in both regions (https://bit.ly/4ghRqqS). However, it is important to note that the SSW in December 2000 started with the vortex displacement owing to the expansion of the anticyclonic region over the Pacific Ocean.

We also found a CSS/8FS intermediate form of the SPV deformation in the events in February 2001 and January 2019. In those cases, the one-sided direction of the vortex deformation was similar to CSS, but the vortex was closer to the 8FS in shape. That process was denoted as 8SS. On the whole, it can be concluded that SPV displacements or a slow vortex split are characteristic for group 1. These changes usually develop gradually, stressing the importance of the time

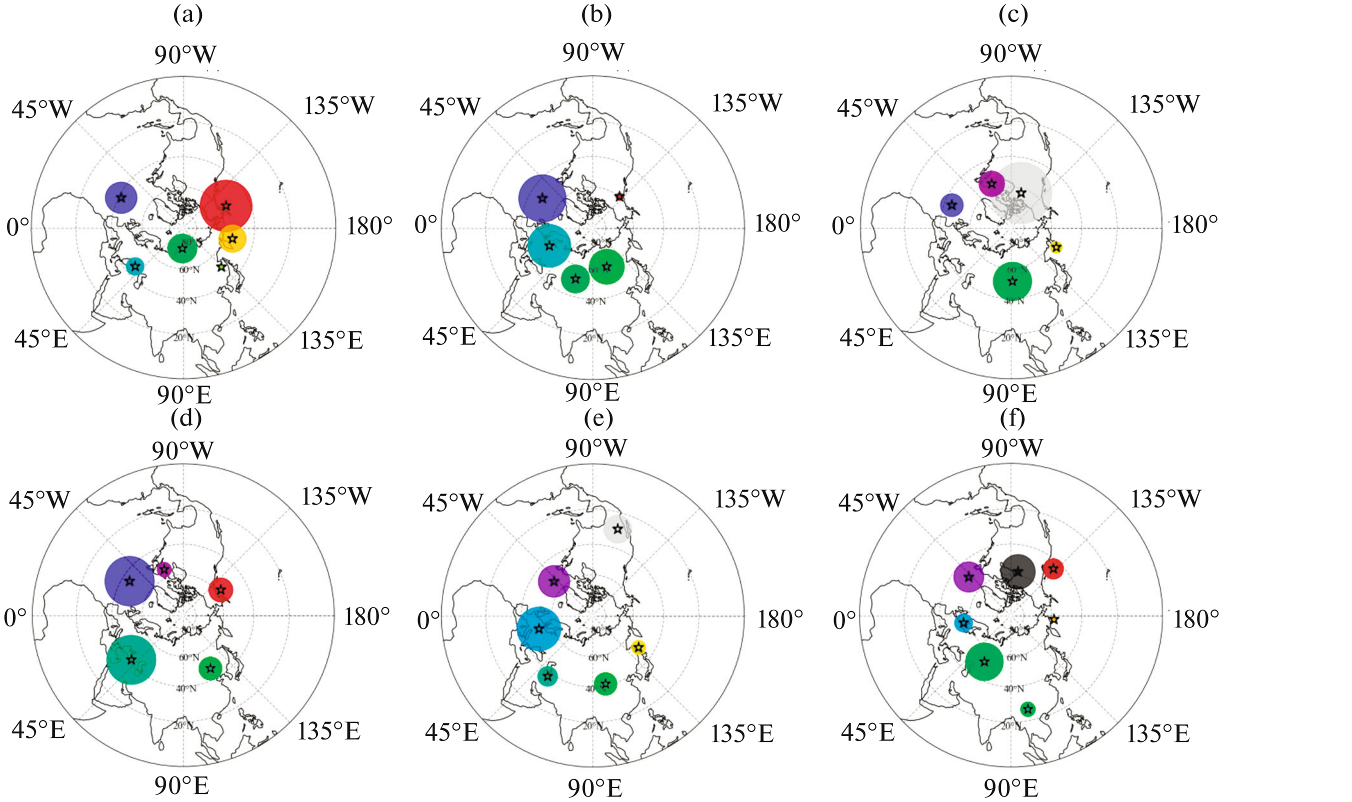

Fig. 2. RWB relationship with the predominance of the processes in the AE region: (a) November–December 2002; (b) January 2003; (c) November–December 2003; (d) November–December 1986; (e) January 2009; and (f) January 2017.

dynamics of the PV advection for SSW preconditioning and realization.

Group 2. The main criterion for singling out this group is the presence of stable RWBs over the AP region, not finalizing into SSW. Instead, SSW starts with the RWB activation in the AE region (Fig. 4a). The events in the December 1984 (Figs. 4b–4d), January 2003, 2006, 2009, 2010, and 2017, and February 2018 are classified into this group. Among the forms of the SPV deformation, most frequent is a rapid split 8FS (three cases) for two–three days (Figs. 4b–4d), as well as a slow split 8SS (two cases). Also, cases were noted with SPV displacement (scenario D) during January 2006 and 2017. The Table 1 indicates that later events very probably belong to group 2.

Thus, it can be concluded that the predominant anomalous intensification of regular RWBs over the Pacific Ocean leads to the occurrence of the earliest SSW events. Later events are formed under the influence of the RWB intensification in the AE region.

Our results confirm the presence of the preconditioning stage before SSW occurrence. The intensity of RWBs associated with this stage strongly vary from one year to another. The "preconditioning" periods, preceding the early and mediate SSW events, are not a regular process from the viewpoint of the RWB climatology. Instead, they probably reflect the consequences of anomalies in the troposphere–stratosphere exchange, creating conditions for the SSW occurrence.

We did not classify the events in January 1987, February 1989, and December 2003 (*group 3* in Table 1). January 1987 was preceded by the RWB anomalies in the AE region in November–December 1986, followed by the activation of breakings over Asia during late December–January (https://bit.ly/3Bejay1). The RWBs were predominant over Asia and Atlantic in November–December 2003 (https://bit.ly/4g9SfT4); the SSW in February 1989 was characterized by weak RWB anomalies in the AP region, preceding the SSW; the SSW onset is associated with RWB in the AE region (https://bit.ly/3OSgIQY), making it closer to group 2 events.

2.3. Analysis of Atmospheric Circulation Conditions Corresponding to RWB

For analysis of the conditions of circulation corresponding to the RWB periods, we singled out four types of pre-SSW breakings, classified using diagrams.

(1) AP type is the most frequently encountered RWB type, for which the breaking centers are grouped predominantly over Asia and the Pacific Ocean (see Fig. 3a).

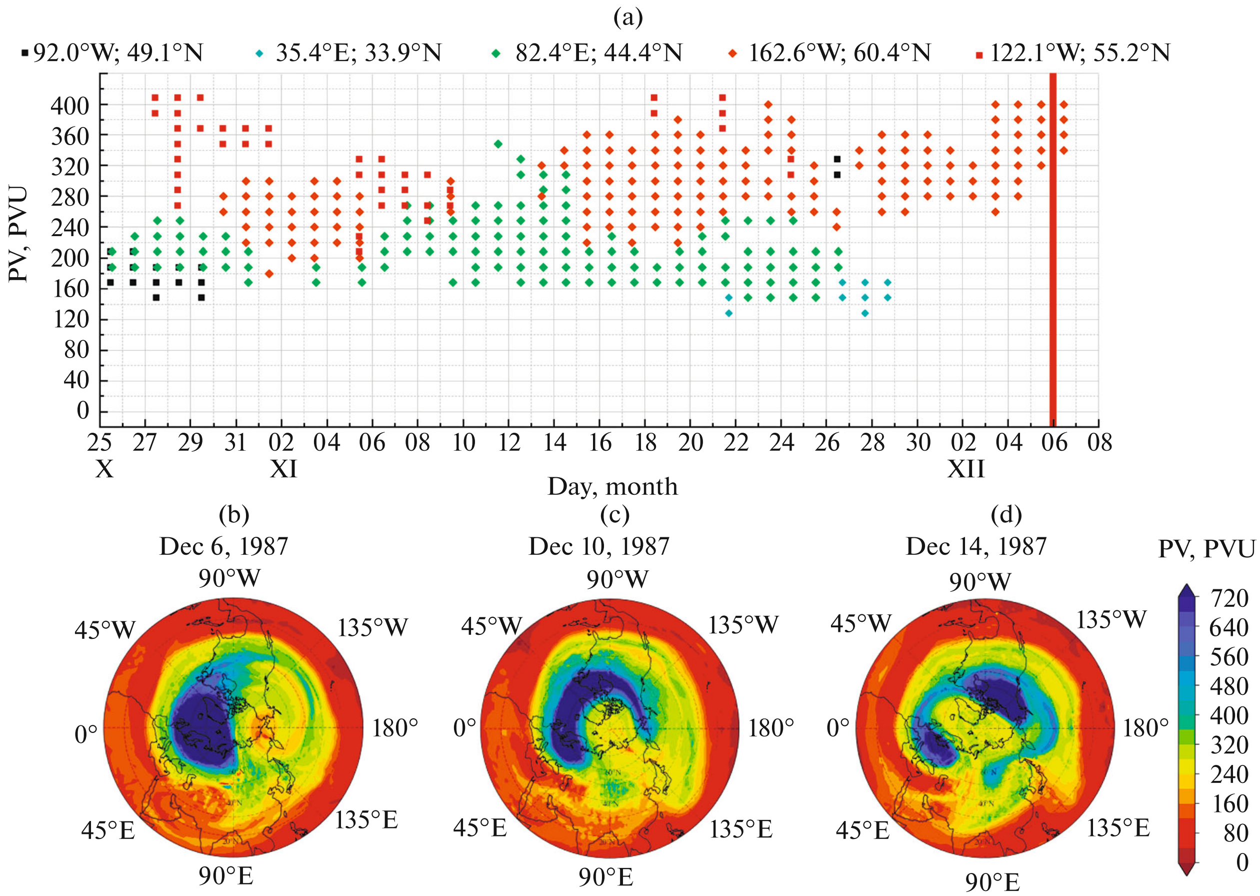

Fig. 3. (a) RWB diagram in November–December 1987 (red line indicates the SSW onset date); (b–d) PV maps (PVU abbreviates the PV units of measurements) for SSW.

(2) AE type: breaking centers are grouped predominantly over the Atlantic, such as in November 1986 (https://bit.ly/4gmz08t) and the second half of December 2016.

(3) AE + AP type: wave breakings intensify simultaneously over the Atlantic and Europe, with the breakings predominant over the Atlantic and Europe, such as in December 1984 (see Fig. 4a), the first half of January 2017, the second half of January 2003, and February 2018.

(4) AE/AP type: breakings at low-PV levels are recorded over the Atlantic and at high-PV levels over the Pacific Ocean (https://bit.ly/3BjaYfH), with the clearest examples being in December 2002, November 2000, and December 2020.

For four RWB types we chose dates (https://bit.ly/49p03xL) preceding the SSW onset dates. Type 1 processes show the largest occurrence frequency of all. This agrees well with the SSW grouping: the large part of RWBs for groups 1 and 2 is represented by type 1 processes. The processes of types 2 and 4 are characteristic for both group 1 and group 2. Type 3 RWBs are more characteristic for group 2.

Figure 5 presents the composite averages of the anomalies of the temperature at the 1000 and 10 hPa levels, of the geopotential at the 500 hPa level, as well as anomalies of the vertical component of the wave activity flux at two levels: 500 and 10 hPa. The temperature anomalies at 10 hPa demonstrate four characteristic stratospheric states. The warming is localized in the AP region for type 1 and 3 RWBs (Figs. 5d and 5n) and in the AE region, for type 2 and 4 RWBs (Figs. 5i and 5s). The SPV is displaced into the territory of North America and the Atlantic in the first three cases; while in the fourth case, one SPV part is displaced toward North America, and the other part, toward Europe, accompanied by the vortex split. The temperature anomalies (Figs. 5d and 5i) characterize the most frequent scenario of the pre-SSW SPV conditioning; while the situation in Fig. 5s favors a stronger temperature increase, but it is more rarely encountered. From Fig. 5d it can be seen that the temperature over Asia and the Pacific Ocean starts to increase as far as subtropics over North America.

The composite averages of the temperature and geopotential in the lower and middle troposphere demonstrate dipole structures with the centers of cold

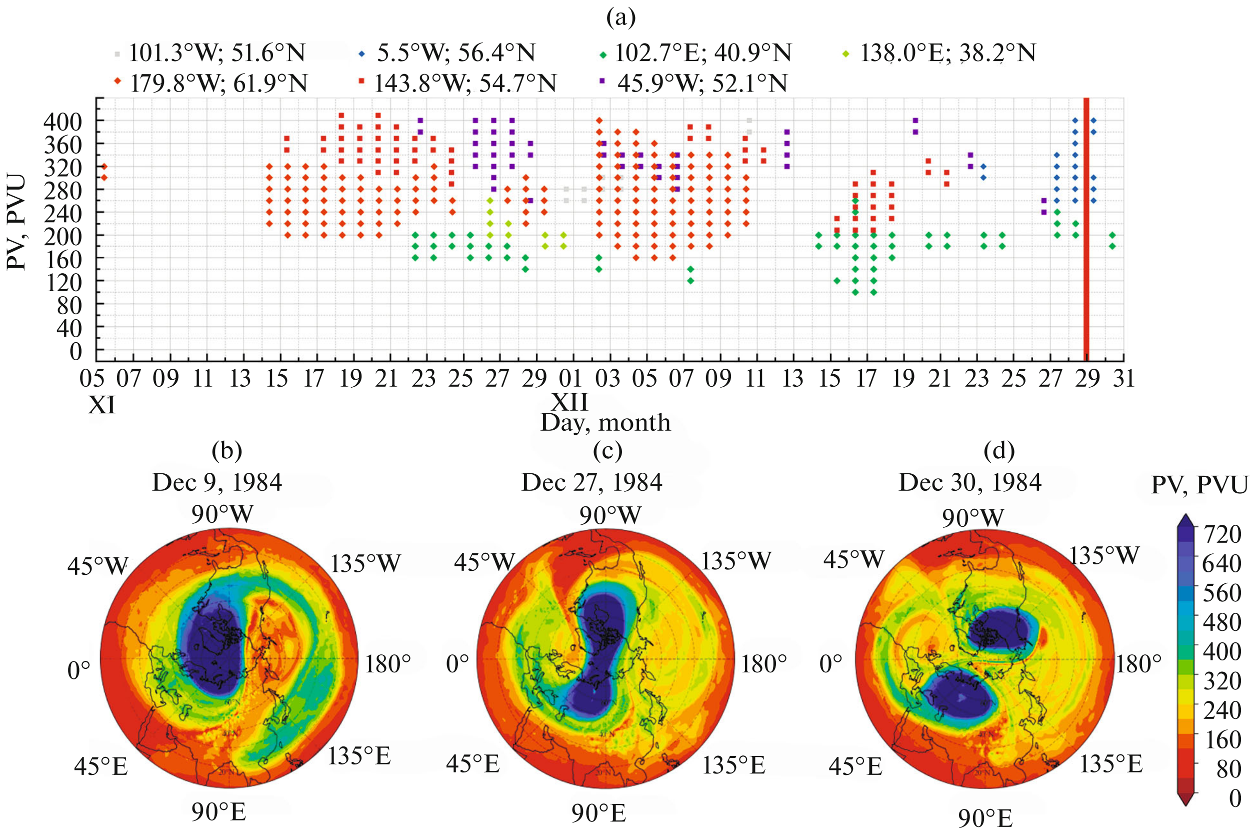

Fig. 4. Same as in Fig. 3, but for November–December 1984.

over Siberia and North America (Fig. 5). The tropospheric polar vortex is represented by areas with anomalously low geopotential, displaced into midlatitudes. Increased geopotential in the middle troposphere is predominant in the Arctic. The main areas of cold at the surface level are localized over Siberia for the first three RWB types (Figs. 5a, 5f and 5k) and over North America for type 4 RWB (Fig. 5p). This confirms that early and mediate SSWs are preceded by the amplification of the "warm Arctic–cold Eurasia" mode during late autumn and first half of winter, possibly associated with the decrease in sea ice area [6]. We note that a significant increase in the number of SSWs in the first half of winter, demonstrated in this paper, and the RWB intensification in the stratosphere, found previously [10], are possibly a consequence of the change in the troposphere–stratosphere interaction, caused by the change in the temperature in the Arctic.

Positive anomalies of the wave activity (WA) flux (intensification of upward-directed flux) at the 10-hPa level are localized in areas corresponding to the main centers of cold in Siberia and North America. An exception is type 2 RWB, for which the cooling in Siberia is associated with downward fluxes from the stratosphere to the troposphere (negative WA anomaly) (Fig. 5j). These observations agree well with analysis of separate SSW events [43], which demonstrate that their occurrence is accompanied by the vertical interaction between the troposphere and the lower stratosphere. Composite distributions refine that, starting from November, the processes of SSW preconditioning are also accompanied by intense troposphere–stratosphere exchange. At the same time, intensification of cold episodes in the troposphere can be associated with stratospheric intrusions [44].

At the 500-hPa level, the vertical WA flux is represented by an anomalous field with pronounced positive and negative anomalies. A common trait for all RWB types is the presence of anomalous WA flux from the troposphere in the region of the western Pacific coast. However, the field of the vertical component of the WA vector in the troposphere is characterized by strong variability. Our averaged analysis makes it possible to identify common regularities, but separate cases require a detailed study.

The analysis of the temperature and geopotential patterns confirmed that the increase in the number of RWBs in the stratosphere is closely related with the blocking processes in the troposphere. Intensification of positive geopotential anomalies is clearly discernible over Northern Europe for the SPV displacement events and over the northern part of the Pacific Ocean for the vortex split events (see Fig. 5), consistent with

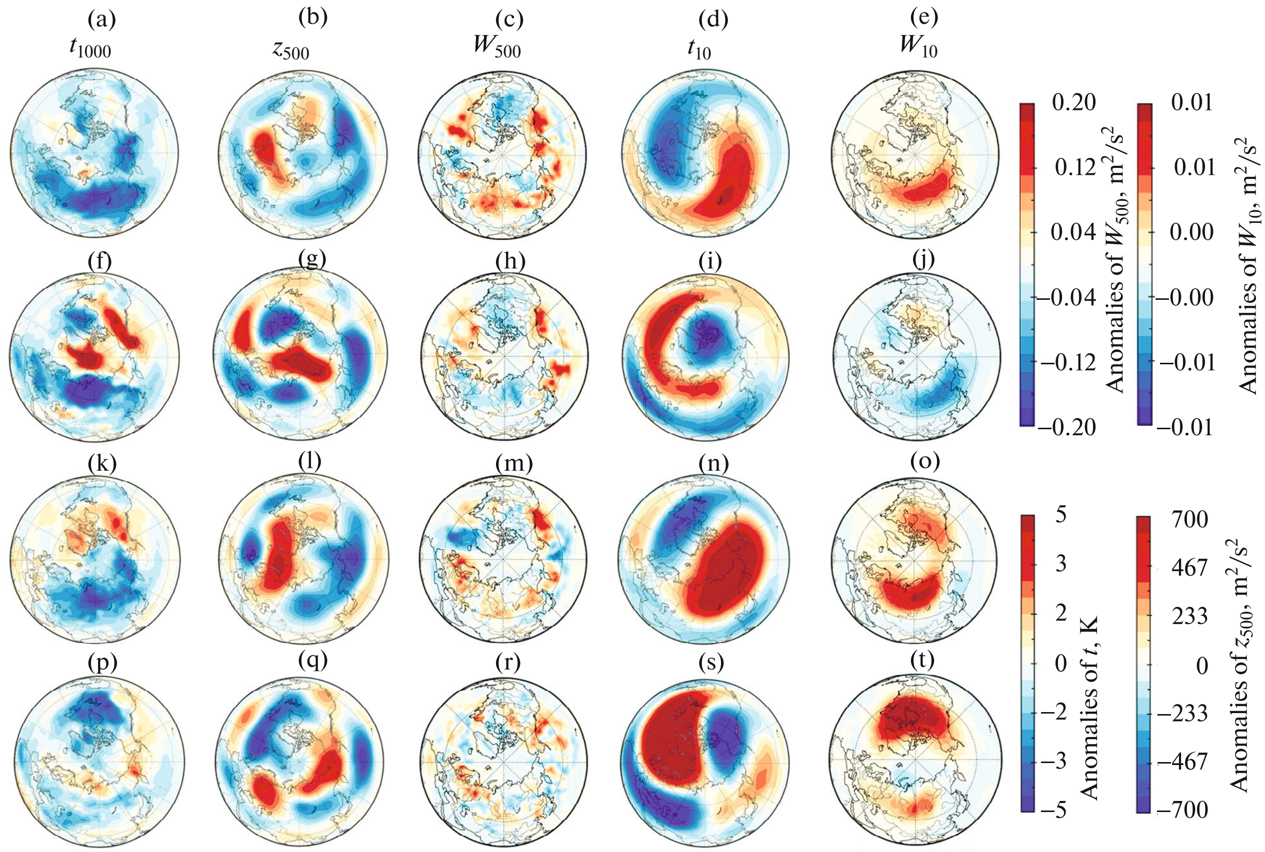

Fig. 5. Anomalies (a, f, k, p) of the surface temperature (t_{1000}), (d, i, n, s) of the temperature in the stratosphere (t_{10}), and (b, g, l, q) of the geopotential at 500 hPa (z_{500}), and of the wave activity flux at (e, j, o, t) 10 (W_{10}) and (c, h, m, r) 500 hPa (W_{500}) for (a–e) type 1, (f–j) 2, (k–o) 3, and (p–t) 4 RWBs.

previous results [13, 14]. However, the relationship between the SSWs and separate blocking events turns out to be more complex due to two key factors.

First, multiweek planetary wave intensification is required for most SSWs to occur, confirmed by the analysis of major SSWs in both the present paper, and in previous studies. Nonetheless, not each long-lasting blocking event leads to the SSW development, since blocking events occur far more frequently than SSW events [45].

Second, our results also indicate that the RWB-related processes of planetary wave intensification differ not only in duration, but also in unusually wide vertical coverage, involving many potential vorticity levels. This allows us to conclude that a determinant role in the planetary wave intensification is played not by a separate blocking event, but rather by a stable anomalous structure of wave flux in the midlatitude and high-latitude troposphere. This configuration entails a regular alternation of upward and downward wave activity fluxes, strengthening strongly the troposphere–stratosphere exchange.

The difficulty of extracting the total wave flux from separate blocking events is a well-known problem [31], and our results underline its urgency for many SSW events. Moreover, the similarity of the geopotential anomalies (see Fig. 5), the RWB intensification over the Atlantic, following the increase in the wave activity over the Pacific Ocean, as well as their mutual amplification during separate periods, indicate the sequential development of geopotential anomalies for both (AP and AE) wave types within the long-lasting stratosphere–troposphere interaction.

Of special importance for the wave activity intensification are the blocking processes, favoring displacement and isolation of separate parts of polar vortex in the troposphere over Siberia, the Pacific Ocean, and the West Atlantic. As shown in work [46], since 2000s these anomalies (see Fig. 5) had been more frequent, probably associated with northward-displaced blocking processes. This can be due to the Arctic amplification and to increased instability of circulation in the Arctic area, caused by speeded-up warming at high latitudes. Probably, these changes favor the occurrence of more frequent early and mediate SSW events, stressing the need in further study of the mechanisms of wave activity and its interaction with blocking processes.

CONCLUSIONS

Within this work, we obtained new results, deepening our knowledge of the conditions for SSW occurrence in the recent four decades.

(1) Major SSW events recorded before mid-February became more frequent after 1998. Out of 19 events selected, only four occurred until 1998 (0.2 events per year); and most SSWs were noted afterward (0.6 events per year), consistent with regularities revealed previously. A large percentage of these events are associated with RWB intensification in the stratosphere over Asian-Pacific (AP) region in November/December and sometimes in January (10 events). The other events are also preceded by periods of anomalous wave breaking over AP region; however, the onset dates of the events are related to intensification of wave breakings over the Atlantic and Europe (AE). Three events are characterized by less typical formation conditions; however, they show features similar to those described here, thus requiring an independent analysis.

(2) In addition to the commonly accepted classification of SPV deformation scenarios during SSW (vortex displacement and split), we propose a wider classification with respect to the split forms. For instance, we found two types of SPV split: slow split (December 1987, 1998, 2001, and 2018) during gradual expansion of anticyclone in the AP region, and a rapid split with a simultaneous intensification of breakings in the AE and AP regions (December 1984, January 2009, December 2000, and February 2018). Moreover, mixed forms were found, e.g., for February 2001 and 2010 and January 2003.

(3) A hypothesis is put forward to explain the nature of the SSW "preconditioning" stage. The periods of preconditioning before SSW events noted until mid-February strongly differ from multiyear average periods until mid-February by anomalously large number of RWBs, probably as a consequence of anomalous troposphere–stratosphere exchange in the early winter period (October–December).

(4) For the wave-breaking types considered here, the analysis revealed a characteristic change in the temperature and geopotential fields with features, typical for blocking situations (reversal of meridional gradient), which was accompanied by pronounced negative anomalies of the surface temperature. Therefore, the increase in the number of early and mediate major SSW events agrees with the previously found regularities of enhanced negative response of the surface temperature to the Northern Hemisphere blocking and to increase in the number of breakings in the pre-SSW "conditioning" period in the stratosphere (November–December). We stress that there should be a further search for the mechanisms, leading to the change in the main circulation patterns during the late fall–early winter period and their relationship with the change in the wave flux between the troposphere and stratosphere.

It is important to note that the data on the SSW occurrence, used in this work, are restricted to the period <50 years. For further studies, it seems to be expedient to use model calculations and ERA5 reanalysis data starting from 1940. It is also necessary to consider minor SSW events which, despite their lower amplitude, can play a significant role in the polar vortex dynamics. These aspects are beyond the scope of this paper, but their study is required for a more complete understanding of the SSW occurrence mechanisms.

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CONFLICT OF INTEREST

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

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