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Interactions of stationary planetary waves during winter 2008-2009 and 2018-2019 sudden stratospheric warmings

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ABSTRACT

In the stratosphere, there is a correlation between changes in the amplitudes of stationary planetary waves. This correlation is most clearly manifested during sudden stratospheric warmings (SSWs). An analysis of wave-wave and wave-mean flow interactions during winter 2008-2009 and 2018-2019 sudden stratospheric warmings was made using the equation of perturbed potential enstrophy. It is shown that wave-wave interactions make the least contribution to the wave activity variation during the 2008-2009 SSW, the contribution of all interactions is comparable during the 2018-2019 SSW.

Keywords: enstrophy, potential vorticity, planetary waves, wave activity

1 INTRODUCTION

Planetary-scale waves, in particular, stationary planetary waves (SPW) are one of the main objects of stratosphere dynamic researches. Interacting with the mean flow, the SPW lead to the deceleration (sometimes even reversal) of the stratospheric jet stream during winter on one side and the conditions of their propagation depend on the mean flow on the other. As a result, so-called stratospheric vacillations occur, i.e., irregular amplitude variations of the SPW and the intensity of the mean flow [1]. Such effects are mainly due to nonlinear wave-wave and wave-mean flow interactions in the stratosphere. Nonlinear interactions are most clearly exerted during sudden stratospheric warming (SSW) – strong thermodynamic phenomena in the winter polar stratosphere that affects the middle atmosphere and also causes significant changes in the troposphere, mesosphere, and lower thermosphere. The emergence of SSW is associated with the propagation of planetary waves from the troposphere to the stratosphere and their further interaction with the zonal circulation [2, 3].

This study is based on the analysis method of the variability of the perturbed potential enstrophy (potential Ertel's vorticity squared) caused by nonlinear wave-mean flow and wave-wave interactions [4, 5]. The object of this paper is to assess the contribution of various terms to the potential enstrophy balance equations for stationary planetary waves with a zonal wave number m = 1 (SPW1) and m = 2 (SPW2) during the SSW of two types – with the splitting of the stratospheric polar vortex in winter 2008-2009 and with its displacement in winter 2018-2019 using UK Met Office reanalysis data. Figure 1 shows composites of geopotential height at the level of 10 hPa, averaged over two weeks of the SSW development.

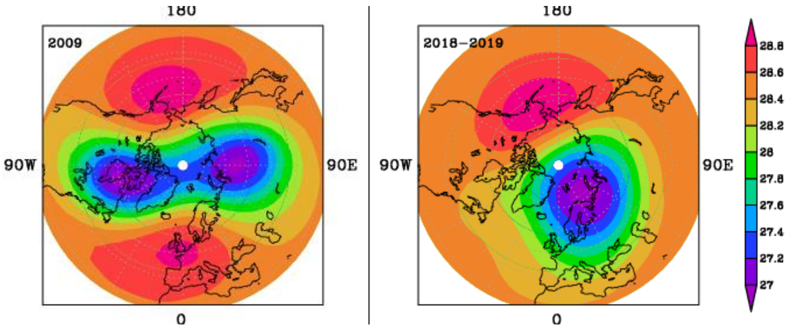

Figure 1. Composites of geopotential height, at the level of 10 hPa, averaged over two weeks of SSW development: splitting – left panel, displacement of the stratospheric polar vortex – right panel.

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2 METHOD OF NONLINEAR INTERACTIONS ANALYSIS

As noted above, the method to analyze nonlinear interactions of planetary waves includes the investigation of conservation of the potential enstrophy. To obtain the balance equation of perturbed potential enstrophy, the conservation equations of Ertel's potential vorticity (EPV) are used and multiplied by perturbed EPV. The eddy enstrophy balance equations in log-pressure coordinate system for SPW1 and SPW2 – equation 1 and 2, respectively:

$$\begin{gathered}\frac{1}{2}\frac{\partial \overline{P_1'}^2}{\partial t} = -\overline{P_1'\left(\overrightarrow{V_1'}\cdot\vec{\nabla}P_2'\right)} - \overline{P_1'\left(\overrightarrow{V_2'}\cdot\vec{\nabla}P_1'\right)} - \overline{P_1'\left(\overrightarrow{V_2'}\cdot\vec{\nabla}P_3'\right)} - \\ -\overline{P_1'\left(\overrightarrow{V_3'}\cdot\vec{\nabla}P_2'\right)} - \overline{P_1'\left(\overrightarrow{V_1'}\cdot\vec{\nabla}\bar{P}\right)} - \overline{P_1'\left(\bar{\vec{V}}\cdot\vec{\nabla}P_1'\right)} + \overline{P_1'S_1'},\end{gathered} \tag{1}$$

$$\begin{gathered}\frac{1}{2}\frac{\partial \overline{P_2'}^2}{\partial t} = -\overline{P_2'\left(\overrightarrow{V_1'}\cdot\vec{\nabla}P_1'\right)} - \overline{P_2'\left(\overrightarrow{V_1'}\cdot\vec{\nabla}P_3'\right)} - \overline{P_2'\left(\overrightarrow{V_3'}\cdot\vec{\nabla}P_1'\right)} - \\ -\overline{P_2'\left(\overrightarrow{V_2'}\cdot\vec{\nabla}\bar{P}\right)} - \overline{P_2'\left(\bar{\vec{V}}\cdot\vec{\nabla}P_2'\right)} + \overline{P_2'S_2'},\end{gathered} \tag{2}$$

where the subscripts denote the zonal wave number, P' and $\bar{P}$ are the perturbed and zonally averaged components of the Ertel's potential vorticity; $\overrightarrow{V'}$ and $\bar{\vec{V}}$are the perturbed and zonally averaged components of wind vector; S' represents the perturbation of diabatic sources and sinks and terms describing the subscale contributions to the momentum equation. The term on the left side of equations denotes the wave transience and can be defined as a measure of wave activity variability [6, 7]. The first four terms of the Equation 1 and the first three terms of the Equation 2 in the right part describe the nonlinear wave-wave interaction; then the interaction of waves with the mean flow and the last one is dissipation.

Equations 1 and 2 was transformed for complete description of the potential enstrophy balance execution. Terms 3 and 4 were added to the right side of the equations for SPW1 and SPW2, respectively:

$$\pm\bar{P}\,\overline{\left(\overrightarrow{V_1'}\cdot\nabla P_1'\right)}, \tag{3}$$

$$\pm\bar{P}\,\overline{\left(\overrightarrow{V_2'}\cdot\vec{\nabla}P_2'\right)}. \tag{4}$$

The penultimate term of Equations 1 and 2 was combine with expressions 3 and 4 with a minus sign. Then, taking into account the continuity equation, i.e.:

$$P'\bar{P}\,\mathrm{div}\left(\rho_0\overrightarrow{V'}\right)/\rho_0 = 0, \tag{5}$$

where, ρ_0 is the density, which is a function of height only. Thus, the balance equations of the perturbed potential enstrophy for SPW1 and SPW2:

$$\begin{gathered}\frac{1}{2}\frac{\partial \overline{P_1'}^2}{\partial t} = -\overline{P_1'\left(\overrightarrow{V_1'}\cdot\vec{\nabla}P_2'\right)} - \overline{P_1'\left(\overrightarrow{V_2'}\cdot\vec{\nabla}P_1'\right)} - \overline{P_1'\left(\overrightarrow{V_2'}\cdot\vec{\nabla}P_3'\right)} - \overline{P_1'\left(\overrightarrow{V_3'}\cdot\vec{\nabla}P_2'\right)} - \frac{1}{\rho_0}\mathrm{div}\left(\rho_0\bar{P}\overline{P_1'\overrightarrow{V_1'}}\right) - \\ \overline{P_1'\left(\bar{\vec{V}}\cdot\vec{\nabla}P_1'\right)} + \bar{P}\,\overline{\left(\overrightarrow{V_1'}\cdot\vec{\nabla}P_1'\right)} + \overline{P_1'S_1'},\end{gathered} \tag{6}$$

$$\begin{gathered}\frac{1}{2}\frac{\partial \overline{P_2'}^2}{\partial t} = -\overline{P_2'\left(\overrightarrow{V_1'}\cdot\vec{\nabla}P_1'\right)} - \overline{P_2'\left(\overrightarrow{V_1'}\cdot\vec{\nabla}P_3'\right)} - \overline{P_2'\left(\overrightarrow{V_3'}\cdot\vec{\nabla}P_1'\right)} - \frac{1}{\rho_0}\mathrm{div}\left(\rho_0\bar{P}\overline{P_2'\overrightarrow{V_2'}}\right) - \overline{P_2'\left(\bar{\vec{V}}\cdot\vec{\nabla}P_2'\right)} + \\ \bar{P}\,\overline{\left(\overrightarrow{V_2'}\cdot\vec{\nabla}P_2'\right)} + \overline{P_2'S_2'}.\end{gathered} \tag{7}$$

In the transformed equations, the meanings of the left parts terms, the first four terms of the Equation 6 and the first three terms of the Equation 7 in the right parts remained unchanged. Next are the divergence, the advective term, the wave-mean flow interaction and dissipation. Similarly, a balance equation for the potential enstrophy mean zonal value can be developed:

$$\frac{1}{2}\frac{\partial \bar{P}^2}{\partial t} = \frac{\bar{P}}{\rho_0}\operatorname{div}\left(\rho_0 \bar{P}\vec{\bar{V}}\right) - \bar{P}\,\overline{\left(\vec{V_1'}\cdot\vec{\nabla}P_1'\right)} - \bar{P}\,\overline{\left(\vec{V_2'}\cdot\vec{\nabla}P_2'\right)} + \bar{P}\bar{S}. \qquad (8)$$

3 DISTRIBUTION OF PLANETARY WAVES AMPLITUDES, ZONAL WIND COMPONENT AND TEMPERARURE DURING SSW

To investigate the equations of perturbed and mean zonal potential enstrophy, i.e., the contribution of different terms, UK Met Office reanalysis data was used [8]. Calculations were carried out for situations, when a major sudden stratospheric warming was observed as during this phenomenon wave activity usually increases.

Figure 2 shows the distribution of the mean zonal wind and changes in temperature during winter 2008-2009, when the SSW, with the splitting of the stratospheric polar vortex was observed. The amplitudes of planetary waves with zonal wave numbers m = 1-3 are presented in Figure 3. The sudden stratospheric warming on January 20 (Figure 2, lower panel) was preceded by an abnormally SPW2 amplitude increase and SPW1 increase (Figure 3, middle and upper panels).

Winter 2018-2019 data, when the SSW with the displacement of the stratospheric polar vortex was observed, are presented in Figures 4 and 5. An increase of SPW1 amplitude was observed on December 24 (Figure 5, upper panel), which was accompanied by a reversal of the mean zonal wind in the stratosphere (Figure 4, upper panel) and the sudden stratospheric warming (Figure 4, lower panel). An increase of SPW2 and SPW3 amplitudes was observed both before and after the SSW – Figure 5, middle and lower panels.

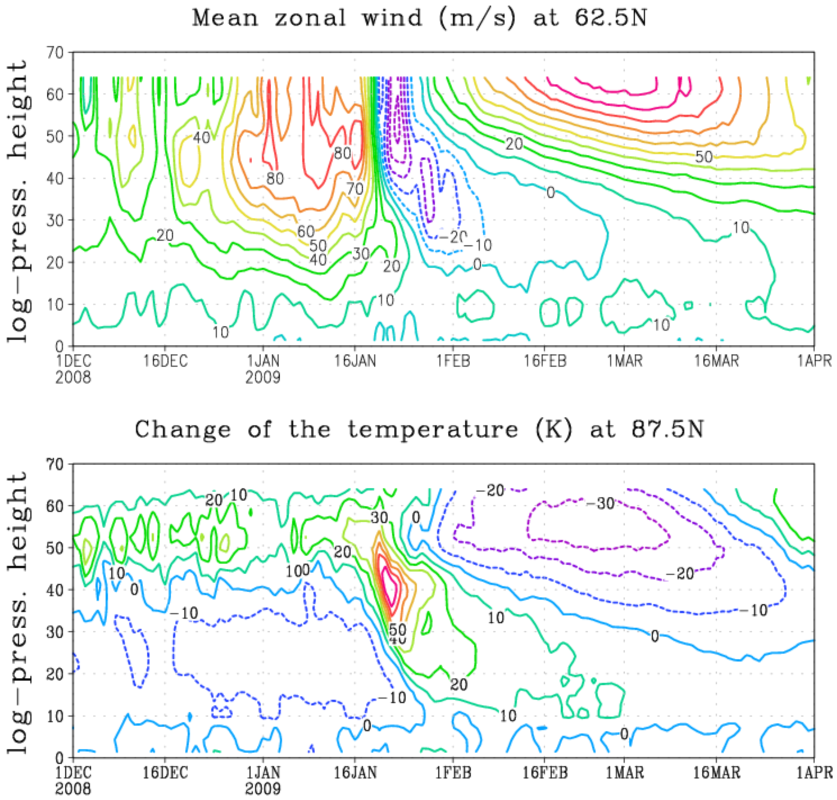

Figure 2. The time-altitude cross-sections of the mean zonal wind at latitude 62.5°N (upper panel); the change of the zonal mean temperature at 87.5°N (lower panel). Winter 2008-2009.

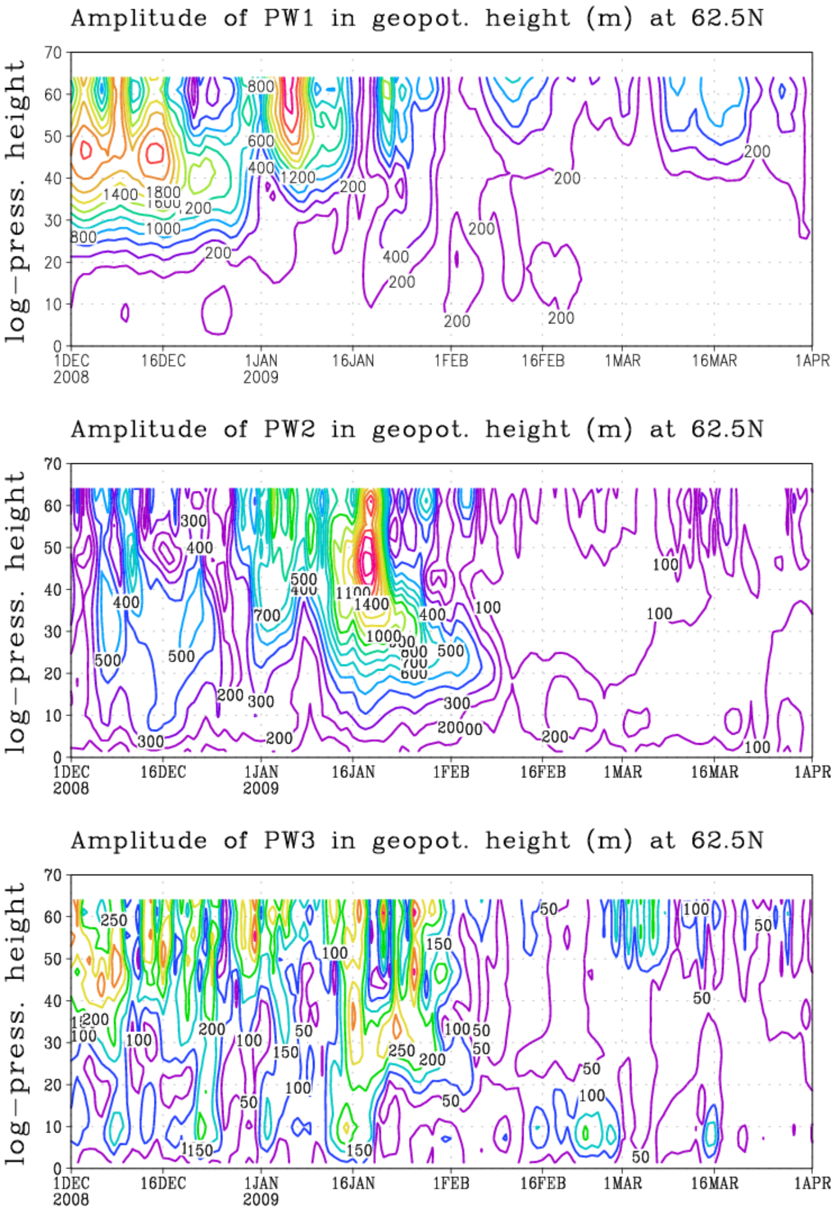

Figure 3. The time-altitude cross-sections of the amplitude of zonal harmonic with m = 1 (upper panel), m = 2 (middle panel) and m = 3 (lower panel) in the geopotential height at latitude 62.5°N. Winter 2008-2009.

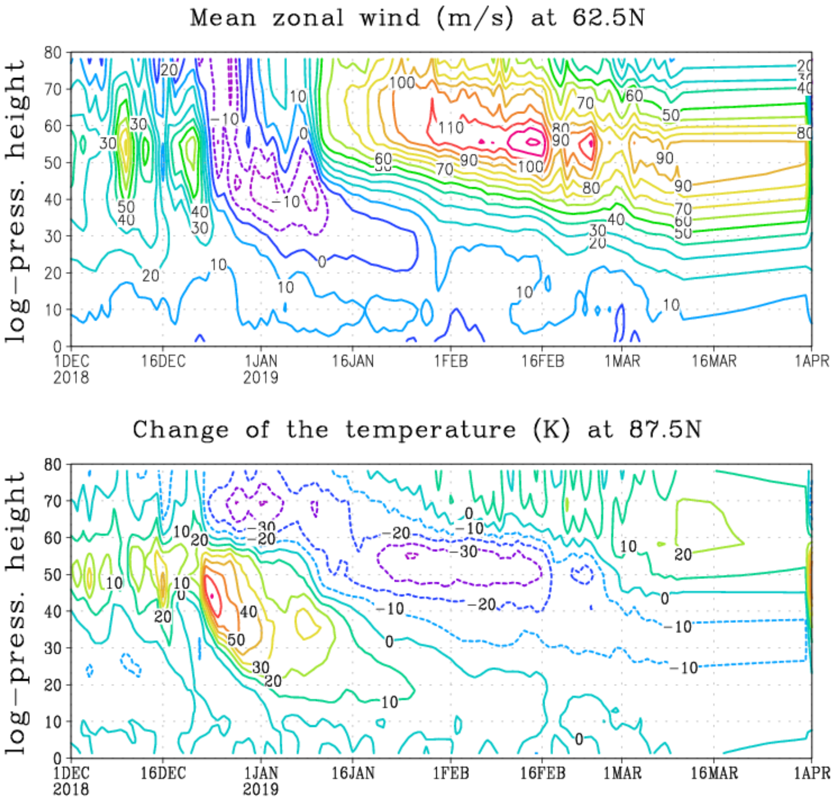

Figure 4. The time-altitude cross-sections of the mean zonal wind at latitude 62.5°N (upper panel); the change of the zonal mean temperature at 87.5°N (lower panel). Winter 2018-2019.

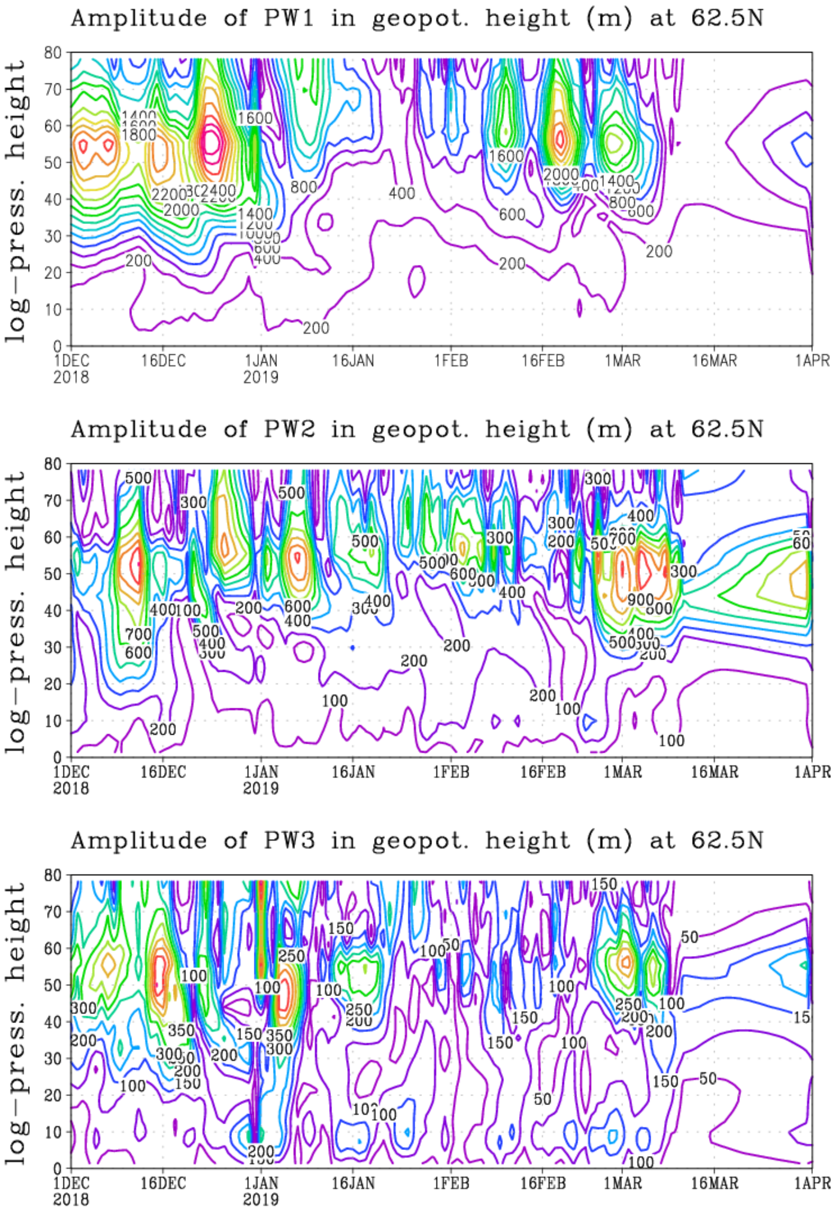

Figure 5. The time-altitude cross-sections of the amplitude of zonal harmonic with m = 1 (upper panel), m = 2 (middle panel) and m = 3 (lower panel) in the geopotential height at latitude 62.5°N. Winter 2018-2019.

4 EVOLUTION OF NONLINEAR PROCESSES AT DIFFERENT STAGES OF SSW

Estimates of changes in terms contributions to Equations 6-8 were executed using UK Met Office reanalysis data for a 50 km altitude. Calculations were made for January 2009 (left panels) and for a period of 6 December 2018 – 5 January 2019 (right panels), when the splitting of the stratospheric polar and its displacement was observed during the SSW, respectively. Results were averaged over the middle latitude region band 52.5-62.5° N, using cosine of latitude weighting. In Figure 6 and all subsequent figures of this section, the values are given in $10^{12}(\mathrm{kg{\cdot}m^{-3}})^2{\cdot}PVU^2$/day units, where $1PVU = 10^{-6}\ \mathrm{K{\cdot}m^2{\cdot}kg^{-1}{\cdot}s^{-1}}$.

The results of calculating the terms in the Equation 8 for the mean zonal potential enstrophy are presented in Figure 6. During the SSW with splitting, a decrease of mean potential enstrophy in time (the term in the left part of Equation 8, the black line in the Figure 6) is accompanied by an increase in the interaction of SPW2 with the mean flow with a maximum about a week before warming (Figure 6a – red line). Exchange terms do not make a significant contribution over the development of the SSW with the displacement. Advection contributes to the balance about a week before the SSW in both cases (Figure 6 – blue line).

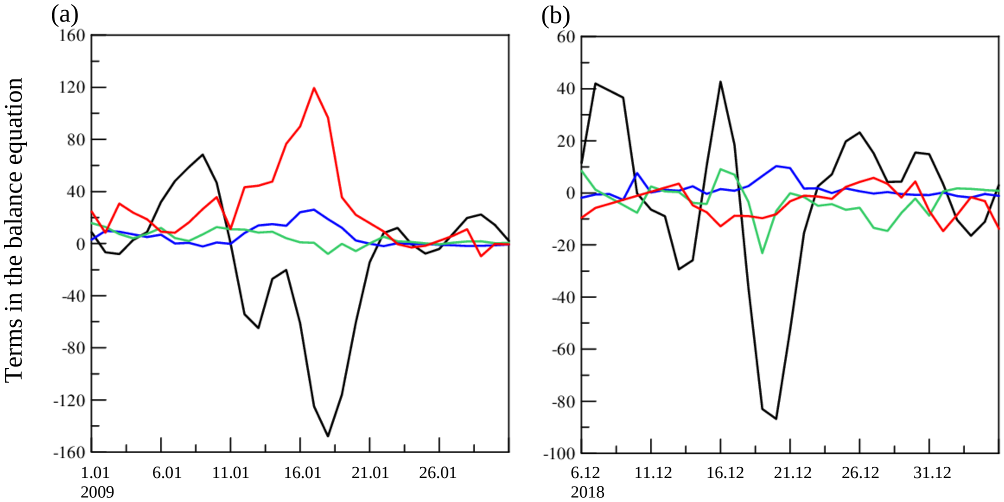

Figure 6. The terms in the mean zonal potential enstrophy balance equation, 50 km. January 2009 – a) and 6 December 2018 – 5 January 2019 – b). The time change is a black line, advective term is a blue line, exchange with the mean flow term for SPW1 is a green line, for SPW2 – a red one.

While the SSW with the splitting of the stratospheric polar vortex, SPW3 contributes to the generation of stationary planetary waves (blue lines in Figure 7a and 7c), and the terms responsible for the generation of SPW1 make the greatest contribution before the onset of SSW – Figure 7a. The terms responsible for the generation of SPW2 make the same contribution regardless of the SSW type – Figures 7c and 7d. During the SSW with the displacement of the stratospheric polar vortex, the greatest contribution is made ten days before its onset by the term responsible for the SPW1 self–interaction– the black line in Figure 7d.

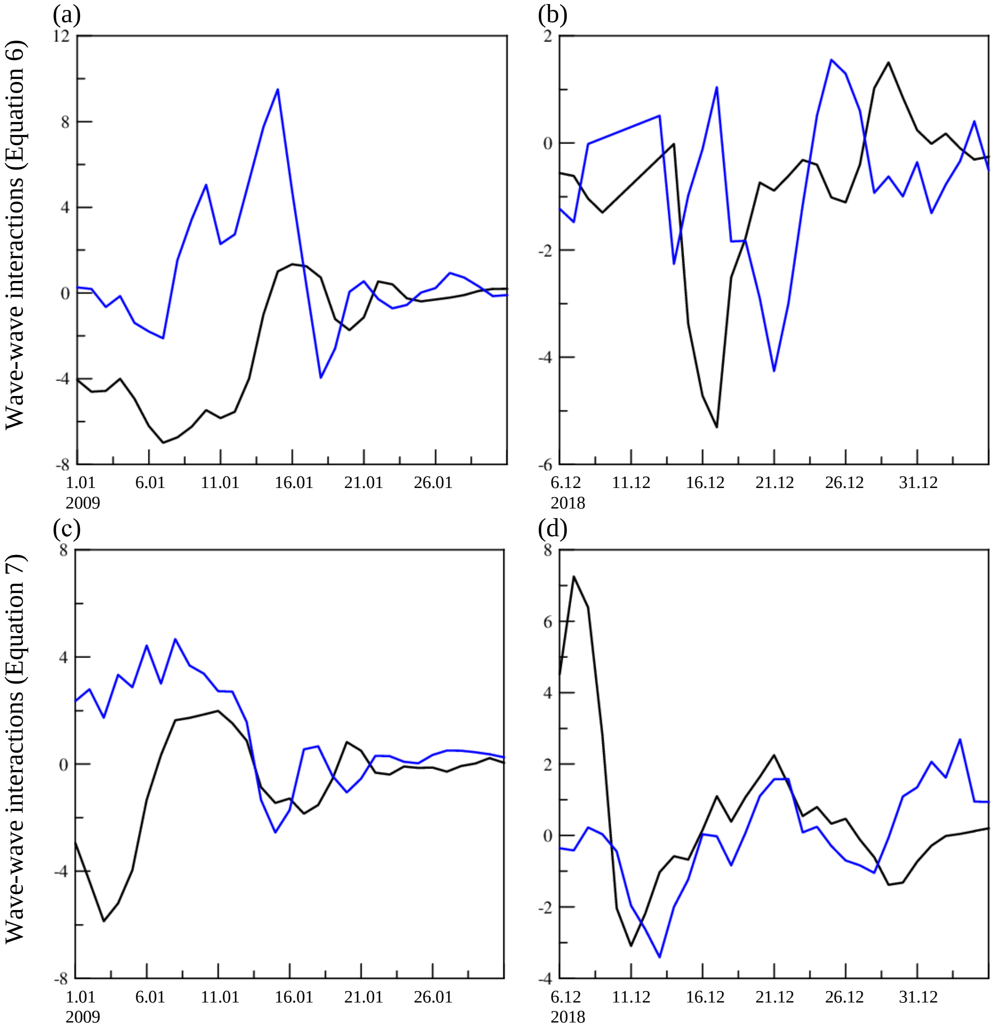

Figure 7. The terms responsible for wave-wave interactions in the balance of perturbed potential enstrophy, 50 km. January 2009 – a), c) and 6 December 2018 – 5 January 2019 – b), d). Equation for SPW1 (upper panels): SPW1-SPW2 interaction– black line, SPW2-SPW3 interaction – blue one. Equation for SPW2 (lower panels): SPW1 self–interaction – black line, SPW1-SPW3 interaction – blue.

Figure 8 shows the time-varying behavior of waves activity, and the contribution of exchange processes with the mean flow is shown in Figure 9. SSW with splitting is preceded by an increase followed by a decrease before the warming of SPW2 wave activity. SPW1 wave activity varies slightly. The SSW with the displacement is accompanied by SPW1 wave activity variations, but the order of magnitude is two times less than the change in SPW2 wave activity during winter 2008-2009. Wave activity variation isn’t observed after SSW with the splitting. After the SSW with the displacement there is a reverse trend.

Wave activity variations are caused both by wave-wave and wave-mean flow interactions. SPW2-mean flow interaction is made the greatest contribution to the perturbed potential enstrophy balance a week before the SSW with the splitting – Figure 9c. But this increase is preceded by an increase in SPW1-mean flow interaction – Figure 9a. As for analysis of wave activity variations, SSW with the displacement is accompanied by wave-mean flow interaction both before and after the warming – Figure 9b and d.

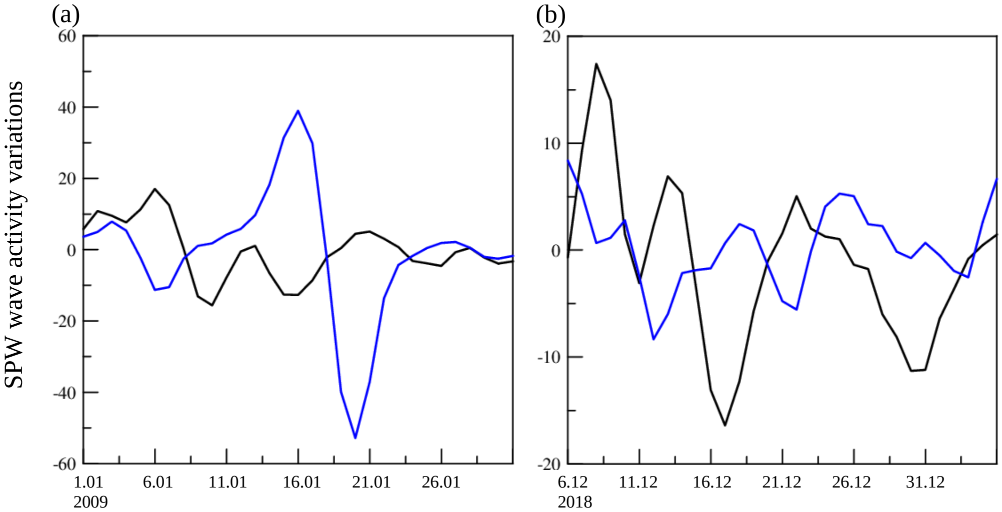

Figure 8. The terms responsible for wave activity variations in the balance of the perturbed potential enstrophy, 50 km. January 2009 – a) and 6 December 2018 – 5 January 2019 – b). SPW1 – black line and SPW2 – blue one.

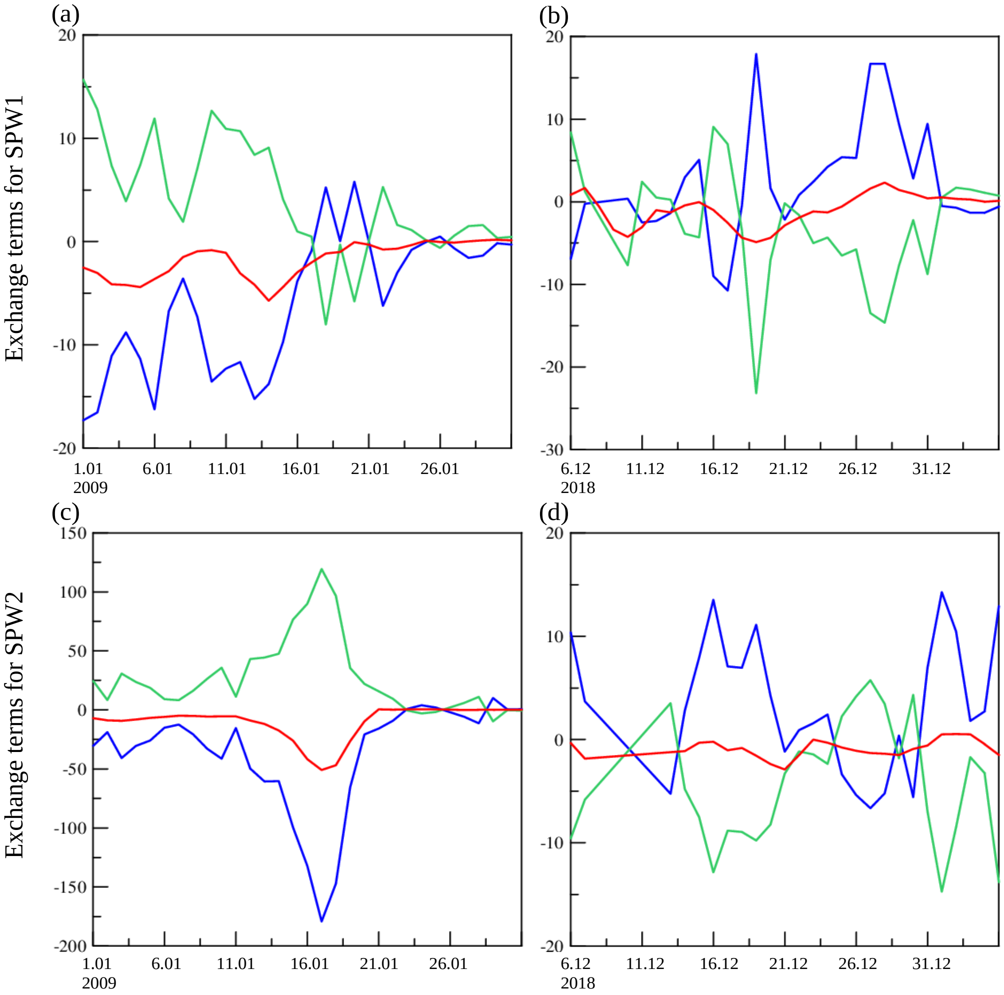

Figure 9. The terms responsible for wave exchange with the mean flow in the balance of the perturbed potential enstrophy, 50 km. January 2009 – a), c) and 6 December 2018 – 5 January 2019 – b), d). The equation for SPW1 (upper panels) and for SPW2 (lower panels): the divergence – blue line, wave-mean flow interaction term – green line, the difference of these terms – red one.

The difference between the potential enstrophy divergence and the exchange of waves with the mean flow terms is balanced by advective (black lines in Figure 10) and/or dissipative terms. Figure 10 shows that advective processes contribute a few days before the onset of SSW to the balance equation for SPW1 during winter 2018-2019 – Figure 10b, and for SPW2 during winter 2008-2009 – Figure 10c.

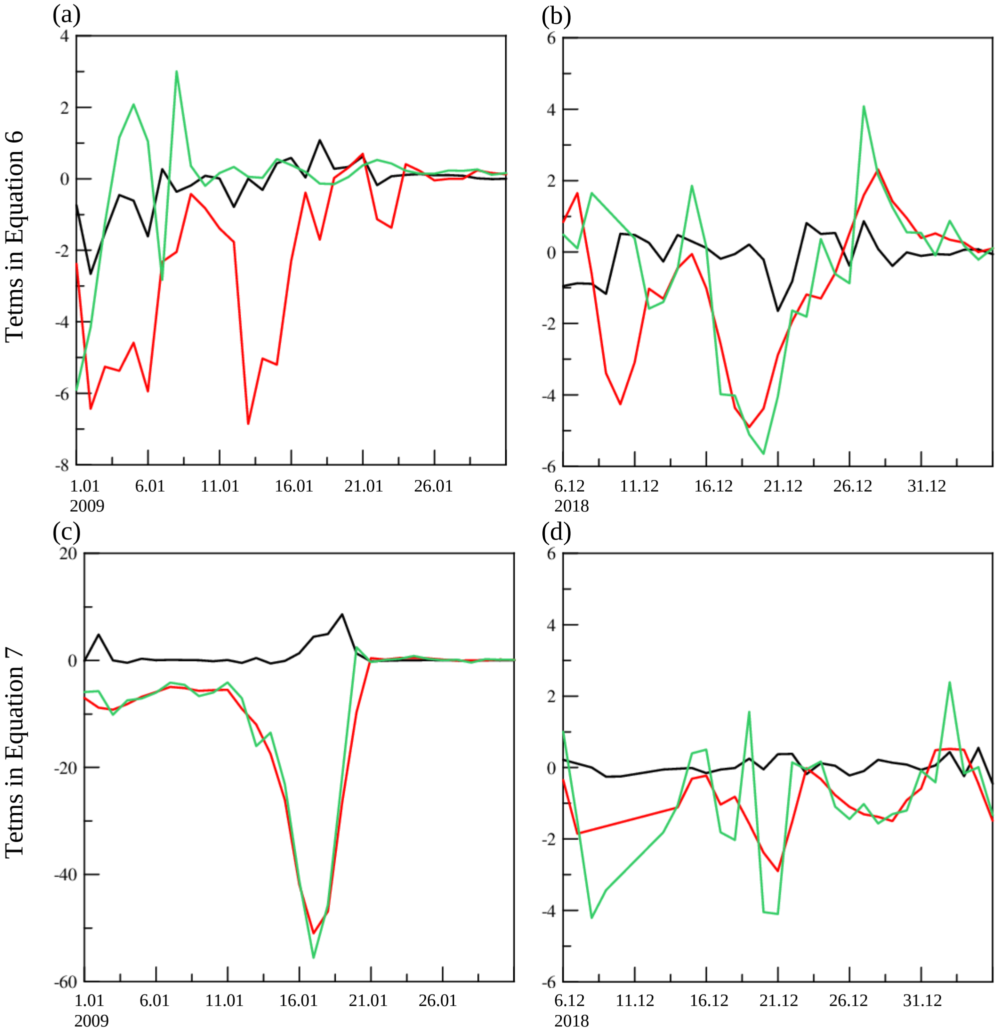

Figure 10. The terms in the balance of the perturbed potential enstrophy, 50 km. January 2009 – a), c) and 6 December 2018 – 5 January 2019 – b), d). SPW1 (upper panels), SPW2 (lower panels): advective terms – black line, the difference between the divergence and wave-mean flow interaction term – red line and the sum of divergence and wave-mean flow interaction term – green one.

Figure 11 shows the contribution of the main processes to the perturbed potential enstrophy balance. Wave-wave interaction makes the smallest contribution to the balance for SPW2 – the green line in Figure 11c when analyzing the SSW with the splitting of the stratospheric polar vortex. Wave activity variation is balanced by the exchange of wave with the mean flow terms with a maximum one week before the SSW – red line in Figure 10c. Wave-wave interaction balances the SPW1 wave activity variation – Figure 11a. The contribution of all processes to the perturbed potential enstrophy balance for SPW1 and 2 is comparable during the SSW with the displacement of the stratospheric polar vortex.

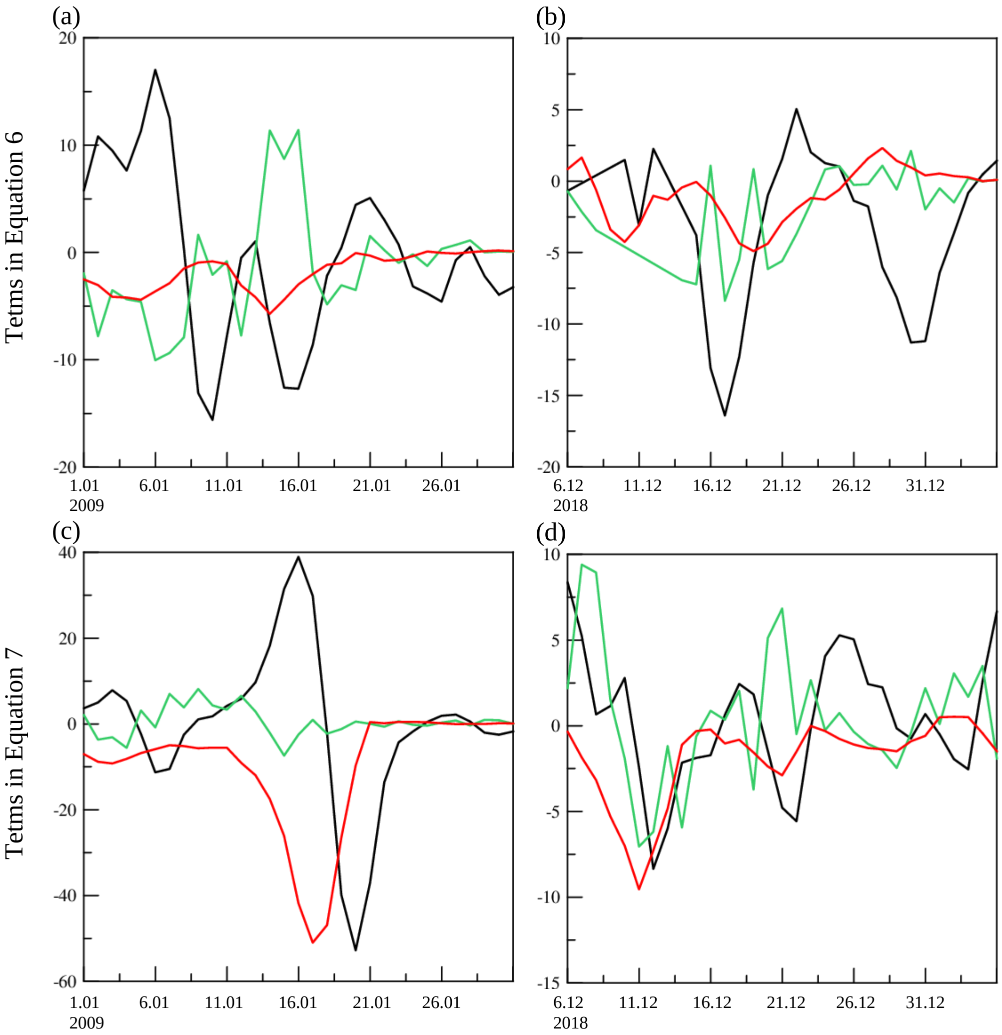

Figure 11. The terms in the balance of the perturbed potential enstrophy, 50 km. January 2009 – a), c) and 6 December 2018 – 5 January 2019 – b), d). SPW1 (upper panels), SPW2 (lower panels): wave activity variations – black line, the terms responsible for wave-wave interactions – green line, the difference between the divergence and wave-mean flow interaction term – red one.

5 CONCLUSIONS

The potential enstrophy balance equations have been used to perform the diagnostics of wave activity variations and the contribution of various processes to these variations. The presented results demonstrate the increase of nonlinear wave-wave, wave-mean flow interactions, as well as advection and divergence of the potential enstrophy flux during the development of SSW in the stratosphere. Significant differences in the nonlinear processes have been observed when analyzing wave activity variations during the SSW with splitting and displacement of the stratospheric polar vortex:

- during the development of sudden stratospheric warming with the displacement of the stratospheric polar vortex, all processes contribute to the balance, both before and after the SSW. Advection, a week before the onset of warming, makes the greatest contribution to the mean zonal potential enstrophy, both with splitting and with displacement.
- The SSW, accompanied by the splitting of the stratospheric polar vortex, is preceded by an increase followed by a decrease of SPW2 wave activity and the interaction of SPW2 with the mean flow makes the greatest contribution a week before warming. Wave-wave interactions make the least contribution, and wave activity variations are balanced by the exchange with the mean flow terms.

Further investigation of wave activity variations and nonlinear interactions between atmospheric waves and waves with the mean flow during the SSW of various types yields to in-depth study of the nature of this phenomenon and dilates the possibilities of its modeling.

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