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Investigation of stationary planetary waves interactions at different stages of SSW using reanalysis data

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ABSTRACT

The evolution of various nonlinear processes associated with the propagation of stationary planetary waves (SPW) during sudden stratospheric warmings (SSW) is studied from the troposphere up to the lower mesosphere levels. Based on data of the UK Met Office (UKMO), the spatiotemporal structure of the processes of planetary waves interaction with each other and with the mean flow, as well as wave activity, potential enstrophy flux divergence and advection, was analyzed. Such an analysis was performed for the 2008-2009 winter, when an SSW, accompanied by the splitting of the stratospheric polar vortex, was observed and for the 2018-2019 winter, when an SSW with the displacement of the stratospheric polar vortex was observed. The results show that these SSWs are succeeded by significant differences in the nonlinear processes under consideration. It is also demonstrated that during the SSW with the stratospheric polar vortex displacement the contribution of various processes to the balance of the disturbed potential enstrophy for SPWs with different zonal wavenumbers is comparable. In addition, during the SSW with the stratospheric polar vortex splitting, the exchange of waves with the mean flow makes the greatest contribution to the perturbed potential enstrophy balance.

Keywords: stationary planetary wave, sudden stratospheric warming, stratospheric polar vortex, perturbed potential enstrophy

1 INTRODUCTION

Planetary-scale waves, in particular, stationary planetary waves (SPW) which are determined by a constant phase surface fixed relative to the Earth, propagate with group velocities, providing energy and momentum transfer from the troposphere. The impact of waves travelling from the underlaying dense troposphere and characterized by strong nonlinearity causes anomalies of stratospheric circulation [1]. For example, interacting with the mean flow, waves affect the structure of the stratospheric polar vortex [2, 3]. The most pronounced effects of nonlinear interaction of waves with the mean flow, as well as between waves, leading to the generation of secondary SPWs, are manifested during sudden stratospheric warming – 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 [4, 5]. In many studies, it was assumed that the predictor of SSW is the amplification of stationary planetary waves with zonal wave numbers 1 and 2 (SPW1 and SPW2) [6]. At the same time, sometimes too little emphasis is put on the internal dynamics of the process and, as shown in [7, 8], in order to study the prerequisites and development of the SSW, nonlinear interactions of waves with each other and with the mean flow must be analyzed interchangeably with tropospheric-stratospheric interactions and such phenomena as El Niño-Southern Oscillation (ENSO), The Madden-Julian oscillation (MJO) and the quasi-biennial oscillation of the zonal wind in the equatorial stratosphere (QBO).

SSW, in turn, lead to interannual and intraseasonal variability of the stratospheric polar vortex. During the sudden stratospheric warmings, the polar vortex breaking down within a few days, which is accompanied by warming at high latitudes and the reversal of the sign of the meridional temperature gradient, therefore, the westerly winds become very weak and even easterly [9, 10]. Sudden stratospheric warming is classified depending on the degree of maturity and duration into major and minor. The first type is characterized by a change in the mean zonal wind at 60° N and at 10 hPa altitude from westerly to easterly in winter (from November to March) and an additional condition is a positive gradient of the mean zonal temperature at 10 hPa in the latitudinal band from 60 to 90° N. During this warming the stratospheric

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polar vortex splitting or displacement from polar latitudes is observed [11]. The final stratospheric warming, which occurs in the spring, is rank specifically [12], but they are not the subject of this research.

One of the ways to study the internal dynamic causes the SSW development associated with the nonlinear interactions of the SPW with each other and with the mean flow is to study the variability of the perturbed potential enstrophy – the potential vorticity squared. When the properties of a planetary wave are changing, a transfer of enstrophy to another wave is necessary to meet conservation requirements. With this approach, the contribution of various processes to the balance of potential enstrophy is investigated [13, 14].

2 DATA AND METHODS

The traditional approach to estimate wave activity and the wave-mean flow interaction is the Eliassen-Palm approximation, which was formulated in [15]. Subsequently, Andrews and McIntyre generalized the law of wave action conservation for unsteady waves in the presence of dissipation and sources [16]. In this case, the generalized Eliassen-Palm theorem:

$$\frac{\partial \hat{A}}{\partial t} + \vec{\nabla} \cdot \overrightarrow{F_{EP}} = D, \tag{1}$$

where $\frac{\partial \hat{A}}{\partial t}$ is the term describing the wave nonstationarity, D is the term responsible for sources and/or sinks. These terms are the longitude-averaged quadratic functions of the wave characteristics. The value $\hat{A}$ was proposed to be called the density of wave activity, and $\overrightarrow{F_{EP}}$ – the Eliassen-Palm wave activity flux [17]. Each term of Equation 1 represents various dynamic and thermodynamic processes that contribute to acceleration or deceleration of the mean zonal flow, that is, determine the effect of waves on the mean flow, as well as on the meridional circulation. Such an approach of wave activity studying was obtained for non-stationary and non-conservative waves and does not include the terms responsible for nonlinear interactions between waves. In this work, an approach allowing to analyze the interactions of SPWs with the mean flow (the waves effect on the zonal circulation), and among themselves, based on the potential enstrophy balance equation is applied [13]. The derivation and transformation of the balance equations of the perturbed potential enstrophy for SPW1 and SPW2 is presented in [18] – Equation 2 and 3, respectively:

$$\frac{1}{2}\frac{\partial \overline{P_1'}^2}{\partial t} = -\overline{P_1'\left(\overrightarrow{V_1'} \cdot \vec{\nabla} P_2'\right)} - \overline{P_1'\left(\overrightarrow{V_2'} \cdot \vec{\nabla} P_1'\right)} - \overline{P_1'\left(\overrightarrow{V_2'} \cdot \vec{\nabla} P_3'\right)} - \overline{P_1'\left(\overrightarrow{V_3'} \cdot \vec{\nabla} P_2'\right)} - \frac{1}{\rho_0}\operatorname{div}\left(\rho_0 \bar{P}\,\overline{P_1'\overrightarrow{V_1'}}\right) -$$

$$\overline{P_1'\left(\bar{\vec{V}} \cdot \vec{\nabla} P_1'\right)} + \bar{P}\,\overline{\left(\overrightarrow{V_1'} \cdot \vec{\nabla} P_1'\right)} + \overline{P_1' S_1'}, \tag{2}$$

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

$$\bar{P}\,\overline{\left(\overrightarrow{V_2'} \cdot \vec{\nabla} P_2'\right)} + \overline{P_2' S_2'}. \tag{3}$$

In these equations, S' represents the perturbation of diabatic sources and sinks and terms describing the subscale contributions to the momentum equation, $\overrightarrow{V'}$ and $\bar{\vec{V}}$are the perturbed and zonally averaged components of wind vector, P' and $\bar{P}$ are the perturbed and zonally averaged components of the Ertel's potential vorticity, ρ_0 is the density, which is a function of height only, the subscripts denote the zonal wave number. The term on the left side of equations denotes the wave transience and can be defined as a measure of wave activity variability [14, 19]. The first four terms of the Equation 2 and the first three terms of the Equation 3 in the right part describe the nonlinear wave-wave interaction; then the divergence and the advection of potential enstrophy flux, the wave-mean flow interaction and dissipation.

In order to investigate the interactions between SPW at different stages of the SSW, wave activity variations, as well as the spatiotemporal structure of nonlinear processes, data from the UK Met Office reanalysis were used [20]. Calculations were carried out for situations when the SSW with the stratospheric polar vortex splitting was observed in the 2008-2009 winter – Figure 1a, and the SSW with the stratospheric polar vortex displacement during the 2018-2019 winter – Figure 1b.

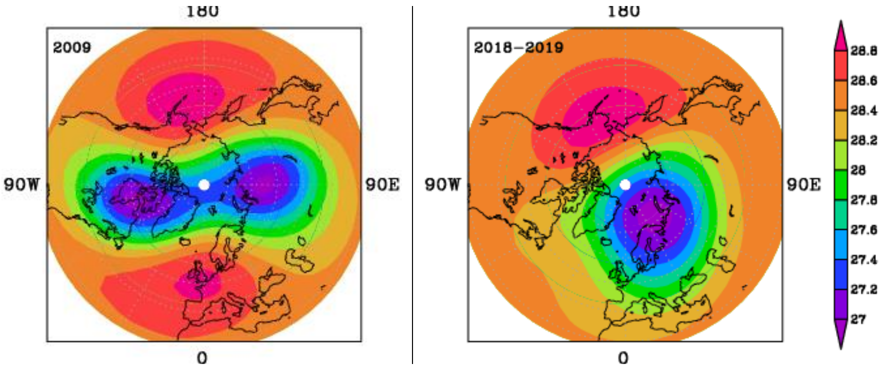
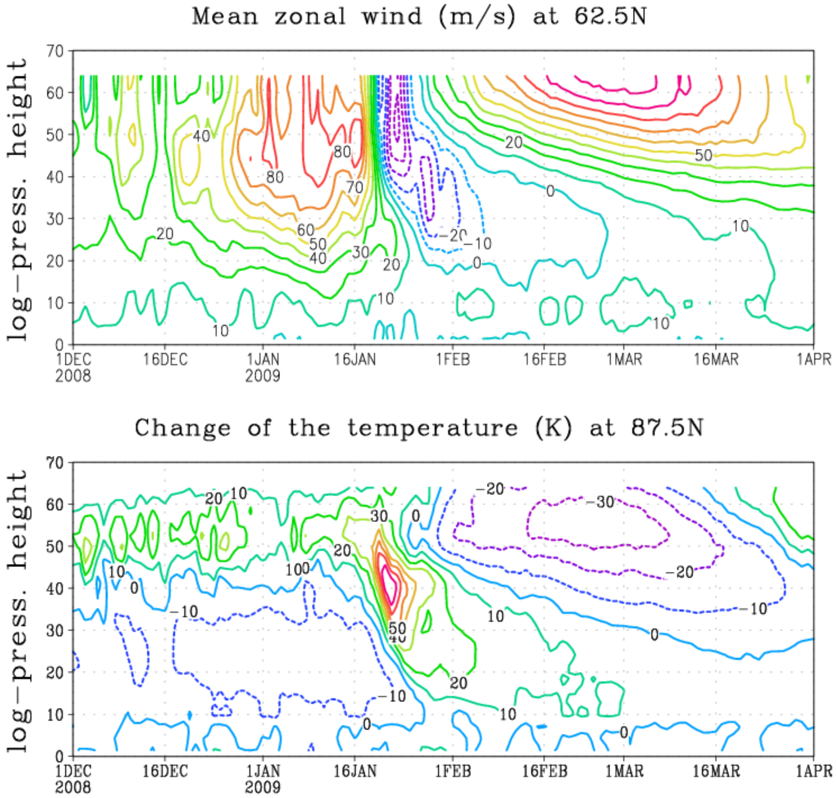


Figure 1. Composites of geopotential height, at the level of 10 hPa, averaged over two weeks of SSW development: splitting – left panel, displacement of the stratospheric polar vortex – right panel.

Figure 2 shows the distribution of the mean zonal wind and changes in temperature during winter 2008-2009, when the SSW was observed on January 20. Winter 2018-2019 data, when the SSW was observed on December 24, are presented in Figure 3.


Mean zonal wind (m/s) at 62.5N

Change of the temperature (K) at 87.5N

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.

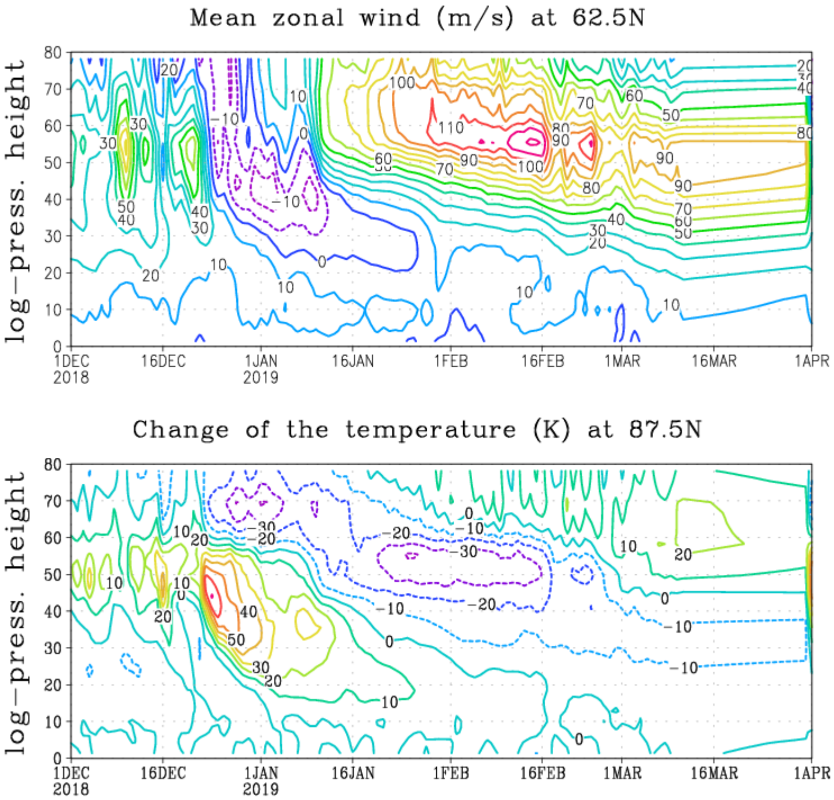


Figure 3. The time-altitude cross-sections of the mean zonal wind at latitude 62.5°N (upper panel); the change of the zonal mean temperature at 87.5°N (lower panel). Winter 2018-2019.

3 RESULTS

Based on the UKMO reanalysis data, latitude-height cross sections of terms in the perturbed potential enstrophy balance were constructed – Figures 4-15: time changes in wave activity – panels a), wave interactions with the mean flow – b), wave-wave interactions panels c) and d), divergence of the potential enstrophy flux – e) and advection – panels f). The results were averaged over 5 days, i.e. the days before; during, maximum temperatures in the stratosphere are observed and after the SSW. The values are given in $10^{12}(\mathrm{kg}\cdot\mathrm{m}^{-3})^2\cdot PVU^2$/day units, where $1PVU = 10^{-6}\ \mathrm{K}\cdot\mathrm{m}^2\cdot\mathrm{kg}^{-1}\cdot\mathrm{s}^{-1}$ in Figure 4 and all subsequent figures of this section.

3.1 SSW with the stratospheric polar vortex splitting

For the SSW with the stratospheric polar vortex splitting during the 2008-2009 winter, the dates for averaging are: January 14-18, 2009 – Figures 4 and 7, January 19-23, 2009 – Figures 5 and 8, January 24-28, 2009 – Figures 6 and 9. The latitude-height cross sections of the terms in the disturbed potential enstrophy balance for SPW1 in Figures 4-6 show that sudden stratospheric warming with splitting is accompanied by a change in the SPW1 wave activity in the middle latitudes, followed by a shift to high ones. The maximum values are observed at the level of 30 and 45 km. During the considered time intervals, an increase in the wave activity of SPW1 is accompanied by a decrease in SPW2 and vice versa – Figures 4a-9a. Wave-mean flow and wave-wave interactions damp rapidly with SSW development and are observed at middle latitudes in the upper stratosphere and lower mesosphere. Advection and divergence of potential enstrophy flux are significant only before the onset of the SSW in high latitudes at altitudes of 45-60 km.

The results for SPW2 are in Figures 7-9. Panels a) show areas of wave activity increase and decrease in the middle and high latitudes at 40-55 km with maximum before the onset of warming and during its development. The SPW2 wave activity is twice the SPW1 wave activity. The SPW2-mean flow interaction is observed in the same area and is damp rapidly. The interaction of the wave with the mean flow is almost not observed during the last days of the considered time intervals. Wave-wave interactions are greatest before the onset of warming and are observed in the middle and high latitudes, the contribution of these terms is insignificant. Advective processes and divergence of the potential enstrophy flux determine the change of the SPW2 wave activity before and during the SSW at high latitudes – Figures 7e-8e and 7f-8f. The contribution of these terms is an order of magnitude more than the contribution of similar terms for SPW1. During the SSW development last days, changes in the SPW2 wave activity, the wave-mean flow nonlinear interaction, the potential enstrophy flux divergence and advection are observed mainly in the middle latitudes and at lower stratospheric levels. Nonlinear interactions between waves are practically not observed – Figure 9c and 9d.

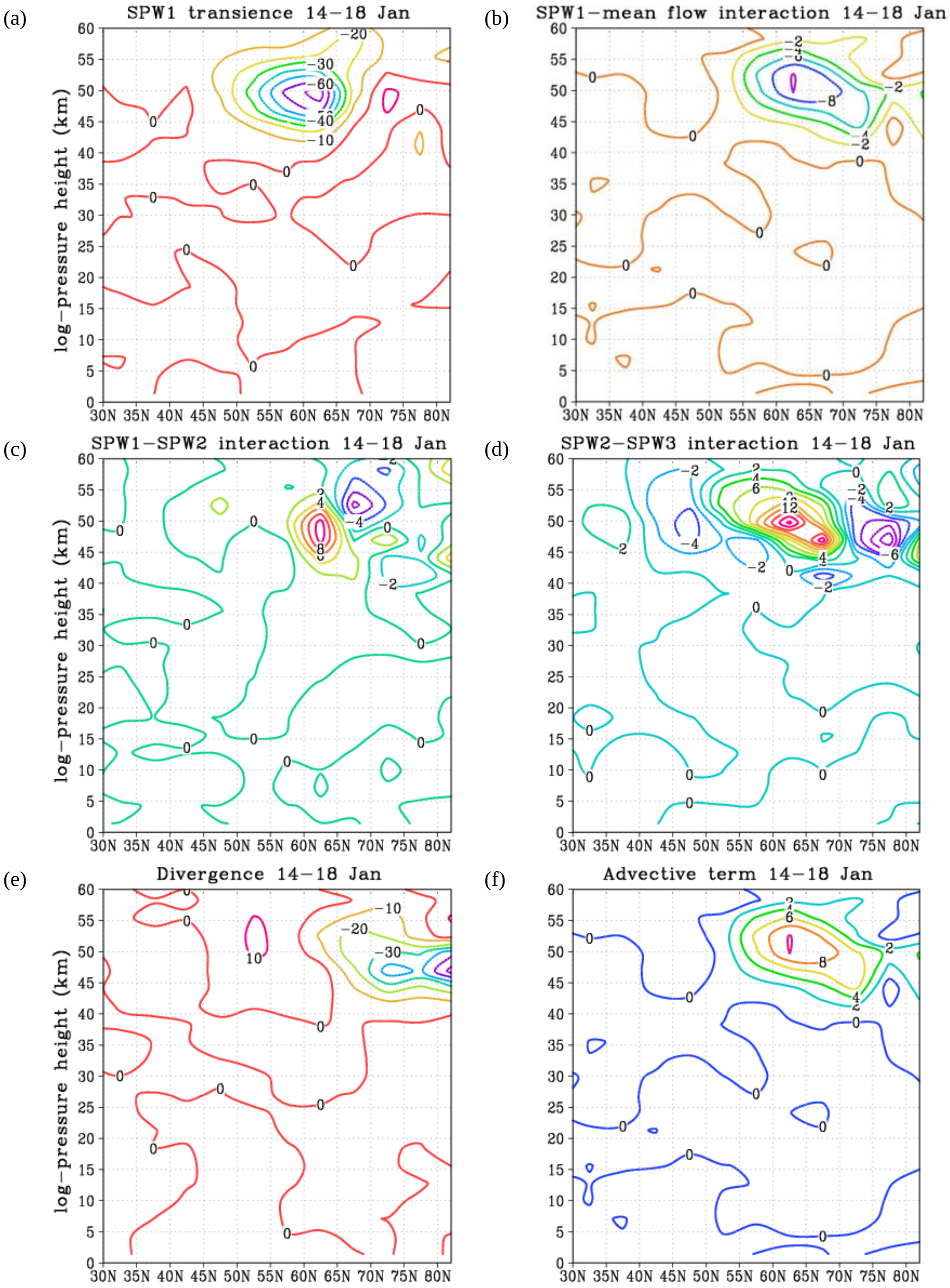


Figure 4. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW1, averaged for January 14-18, 2009.

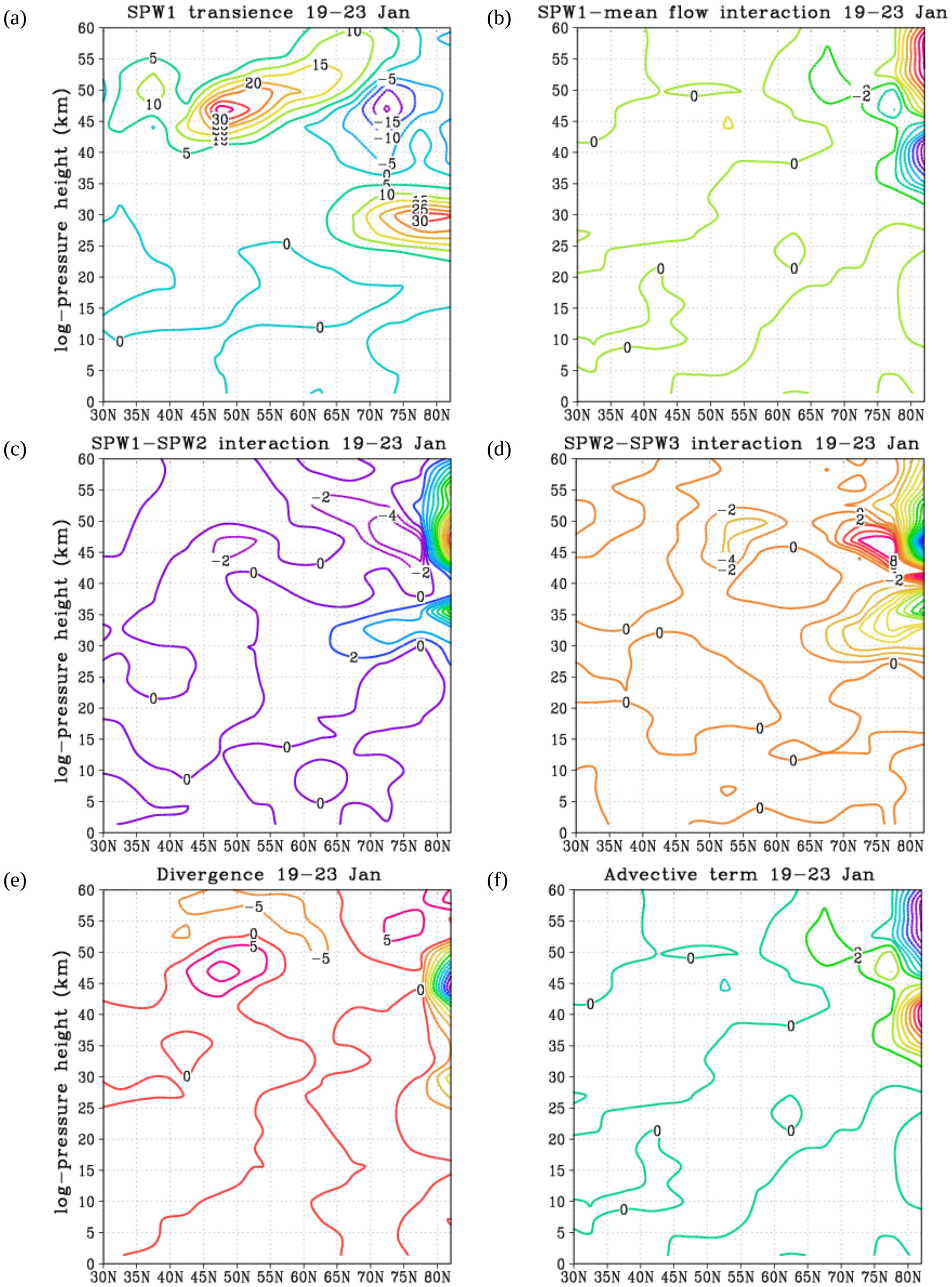


Figure 5. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW1, averaged for January 19-23, 2009.

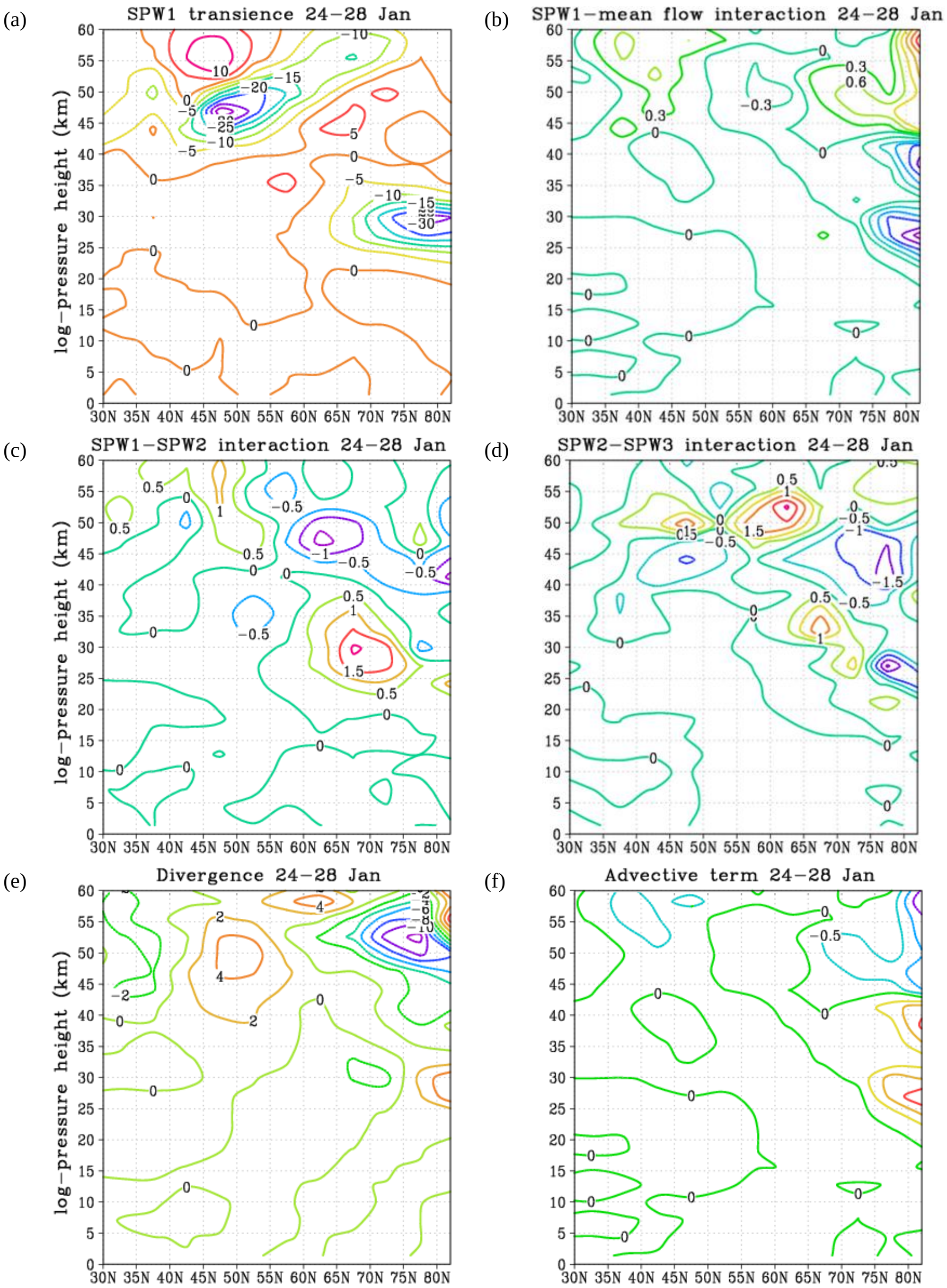


Figure 6. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW1, averaged for January 24-28, 2009.

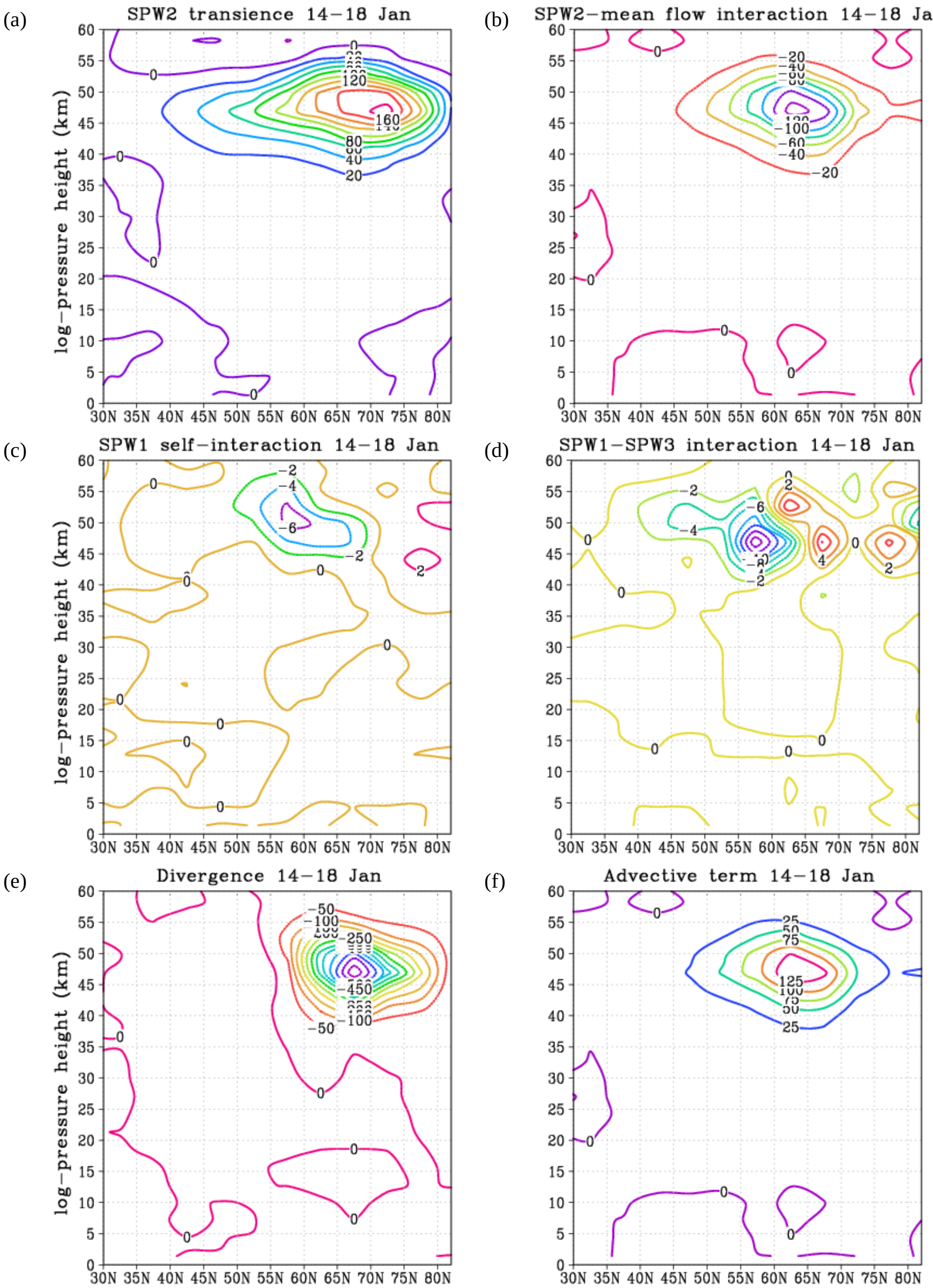


Figure 7. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW2, averaged for January 14-18, 2009.

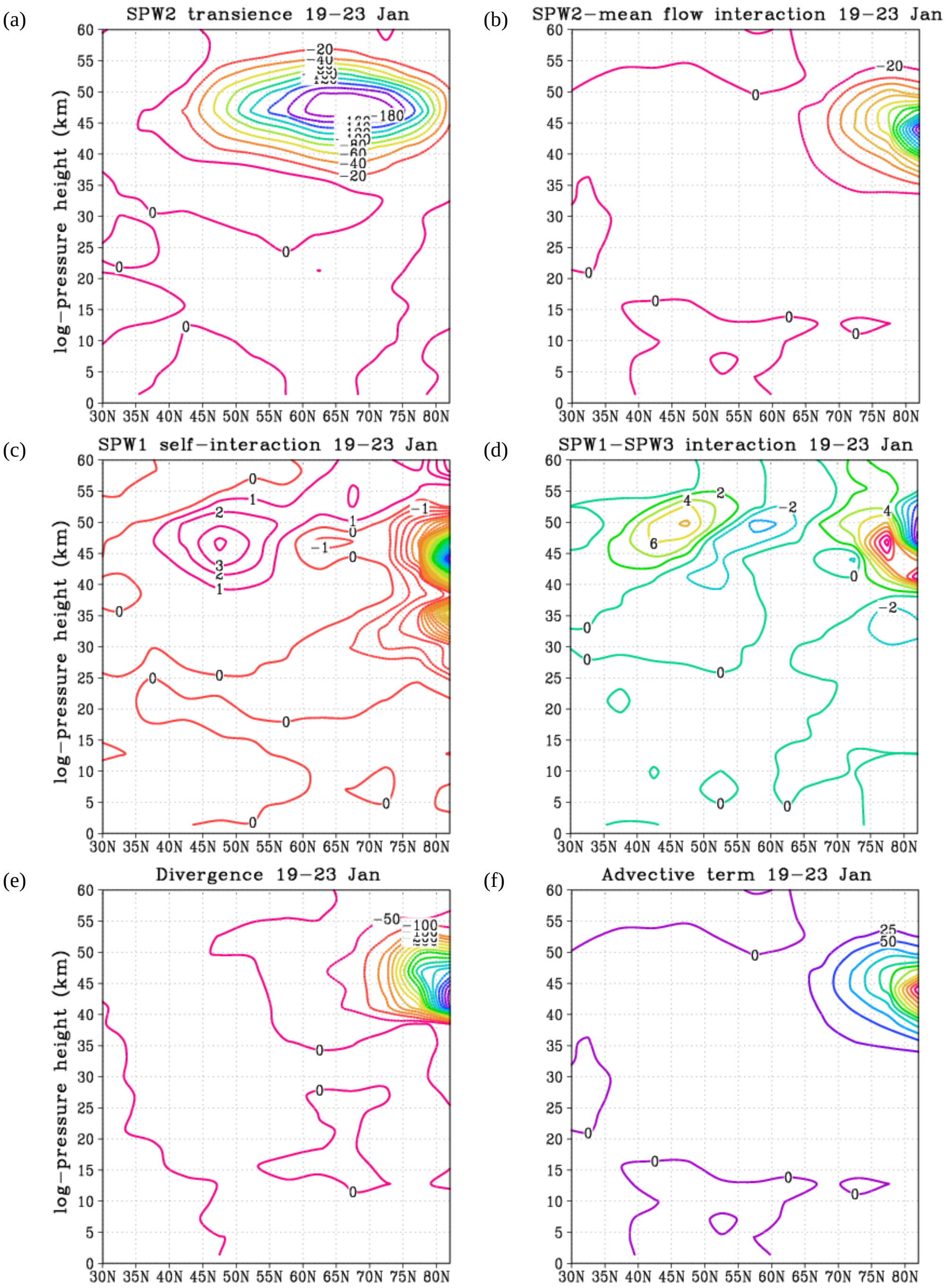


Figure 8. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW2, averaged for January 19-23, 2009.

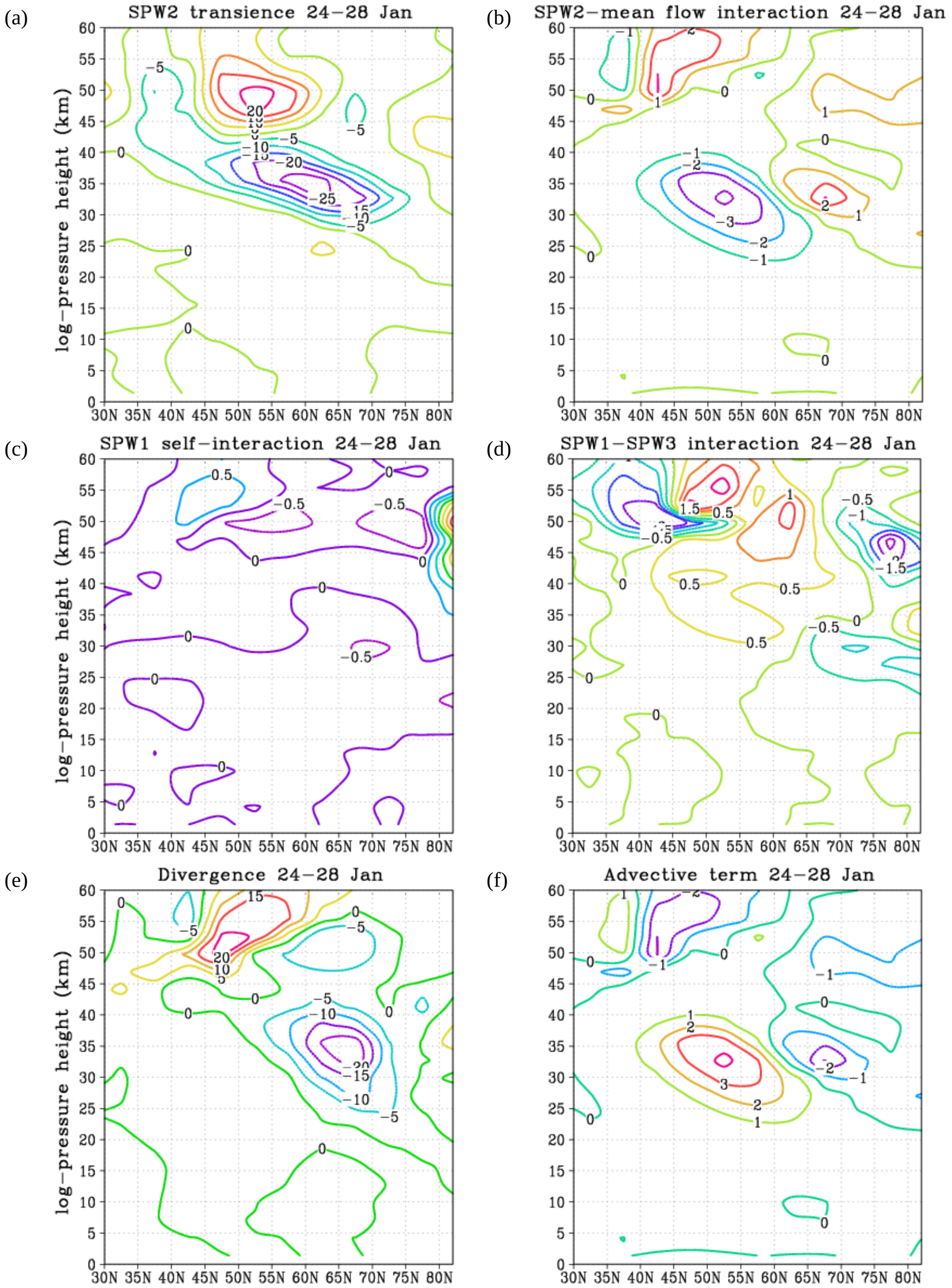


Figure 9. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW2, averaged for January 24-28, 2009.

3.2 SSW with the stratospheric polar vortex displacement

For the SSW with the stratospheric polar vortex displacement during the 2018-2019 winter, the dates for averaging are: December 17-21, 2018 – Figures 10 and 13, December 22-26, 2018 – Figures 11 and 14, December 27-31, 2018 – Figures 12 and 15. The latitude-height cross sections of the terms in the perturbed potential enstrophy balance for SPW1 are in Figures 10-12. The results show that the wave activity change and the interaction of SPW1 with the mean flow are observed both in the middle and high latitudes during the SSW development with the stratospheric polar vortex displacement at the upper boundary of the stratosphere and higher (higher than the change in similar terms during SSW, accompanied by splitting). SPW1 wave activity during the 2008-2009 SSW twice the SPW1 wave activity during the 2018-2019 SSW. During the SSW development last days, the wave activity change is the strongest and is observed in the mesosphere of high latitudes – Figure 12a. Before the onset of warming, the SPW1-mean flow nonlinear interactions are equally intense, regardless of the polar vortex position during the SSW. In addition, relative to the 2008-2009 winter, the contribution of the wave-wave interaction terms is greater and there is a significant contribution of SPW3 after SSW at high latitudes – Figure 12. Wave-wave interaction affects the potential enstrophy balance along with wave-mean flow interaction throughout all the time intervals under consideration. The contribution of potential enstrophy flux advection and divergence is greatest before and during the SSW at high latitudes with a gradual shift to the middle ones at above 35 km. The contribution of these processes to the potential enstrophy balance for SPW1 during a sudden stratospheric warming with a displacement is an order of magnitude more than during the SSW with splitting.

The results for SPW2 in Figures 13-15 show a similar change in wave activity and wave-mean flow interactions (middle and high latitudes, upper stratospheric boundary, lower mesosphere). The contribution of these terms to the equation for SPW2 is several times less during SSW with displacement than with splitting, but is comparable to the contribution of SPW1 during 2018-2019 winter. Wave-wave interactions make a significant contribution, and SPW3 contributes to the secondary waves generation before the onset of SSW. The SPW1-SPW3 interaction is observed in the middle latitudes before the SSW with a shift to high latitudes during its development – Figures 13d-15d.

Unlike to the 2008-2009 winter, the contribution of advective processes is significant throughout all the time intervals under consideration and is observed both in the middle and high latitudes. The values of changes in advection and divergence processes for SPW1 and SPW2 in the winter of 2018-2019 are comparable. Before the onset of the SSW with the stratospheric polar vortex splitting, the contribution of advection and divergence to the potential enstrophy balance for SPW2 is an order of magnitude more than the contribution of similar processes before the onset of the SSW with displacement – panels e) and f) in Figures 7, 8 and 13, 14.

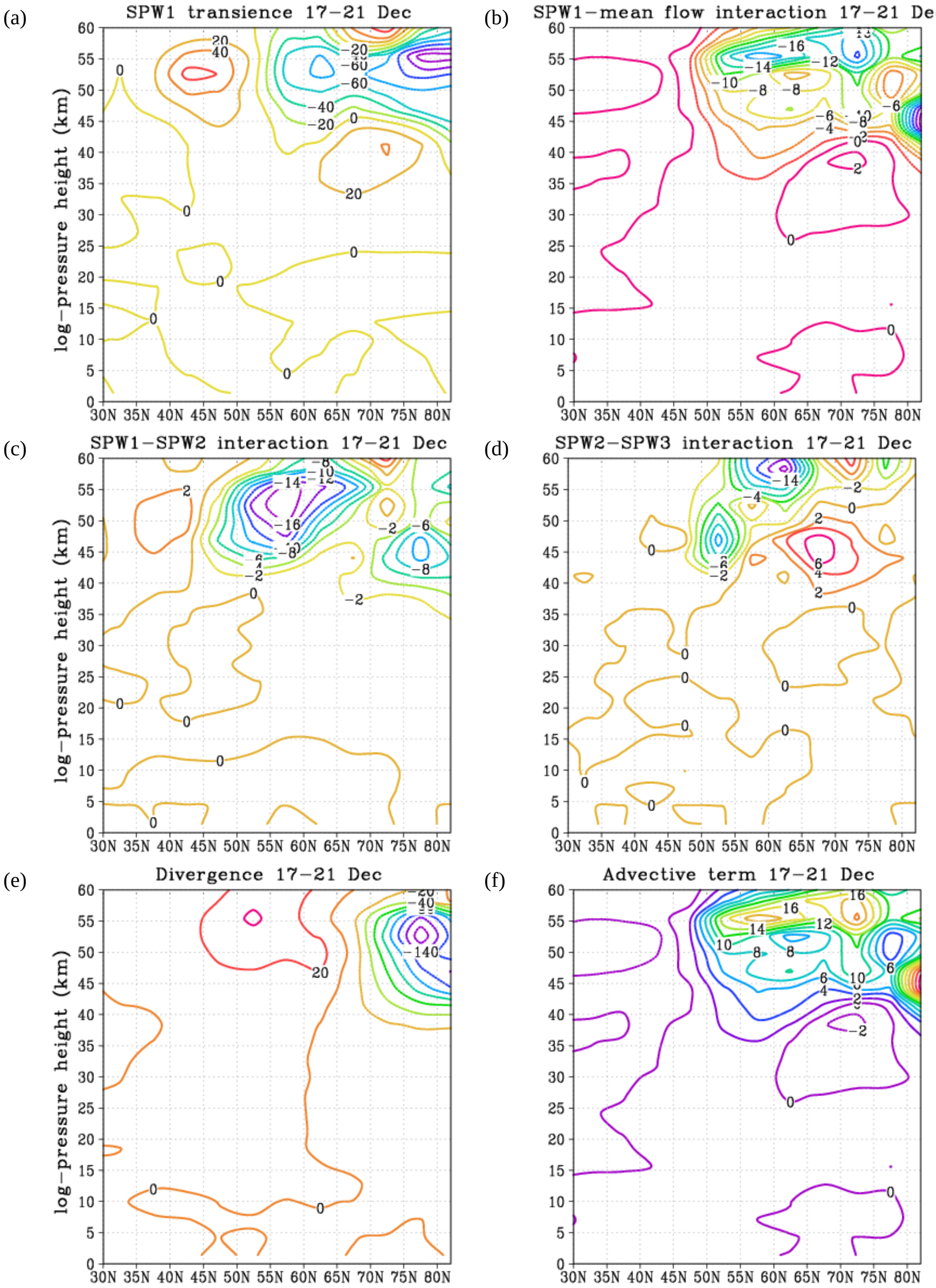


Figure 10. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW1, averaged for December 17-21, 2018.

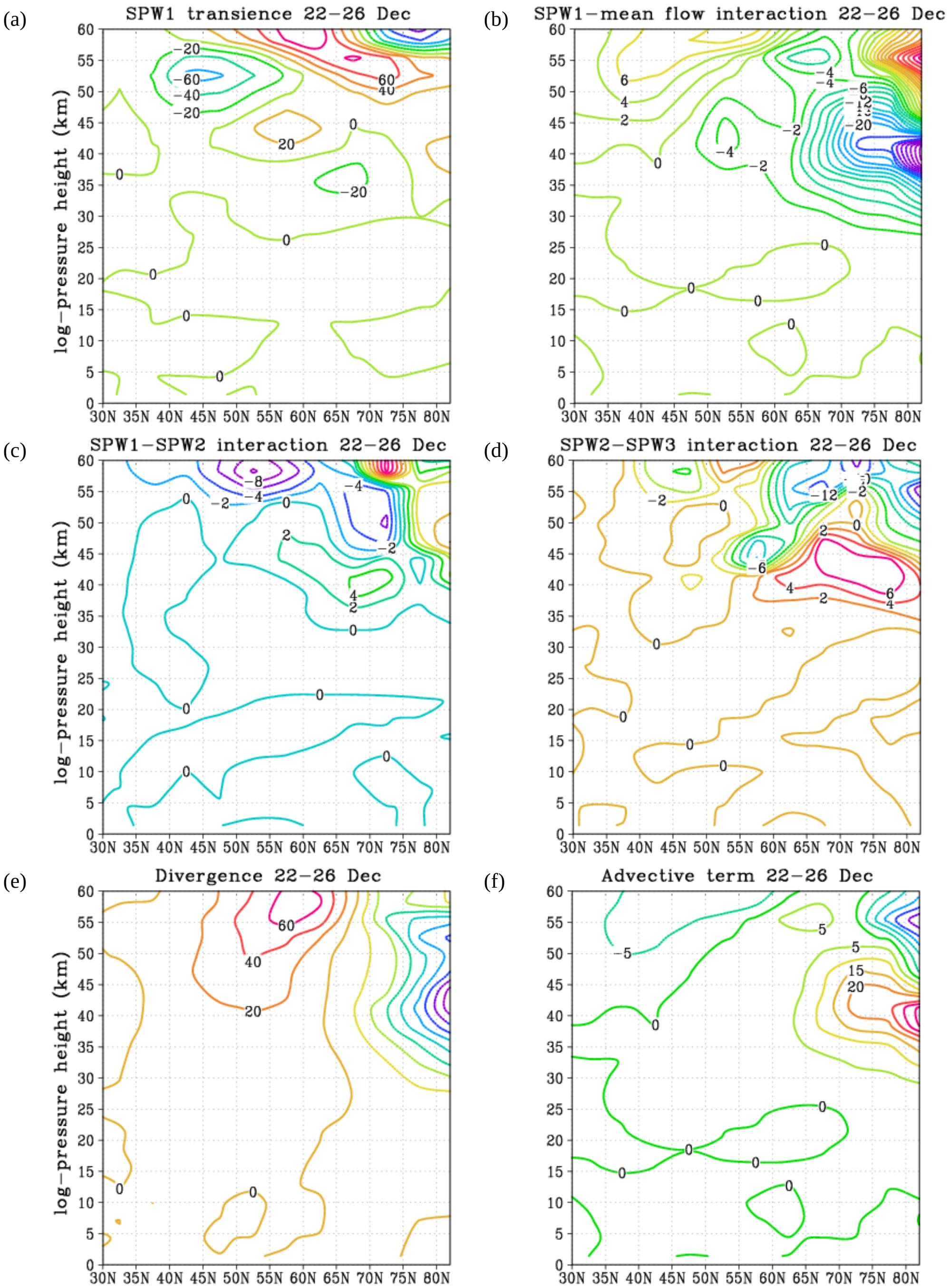


Figure 11. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW1, averaged for December 22-26, 2018.

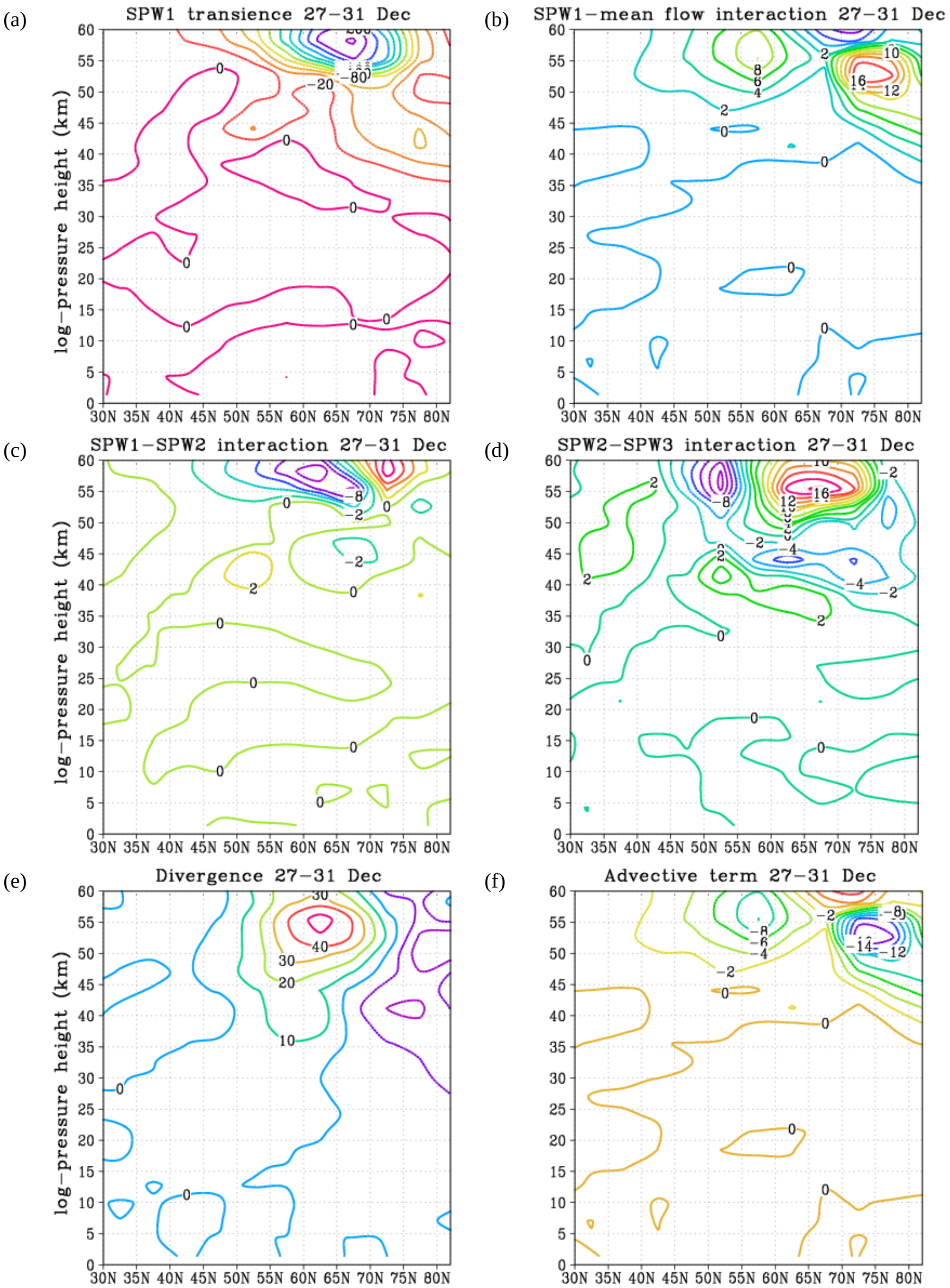


Figure 12. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW1, averaged for December 27-31, 2018.

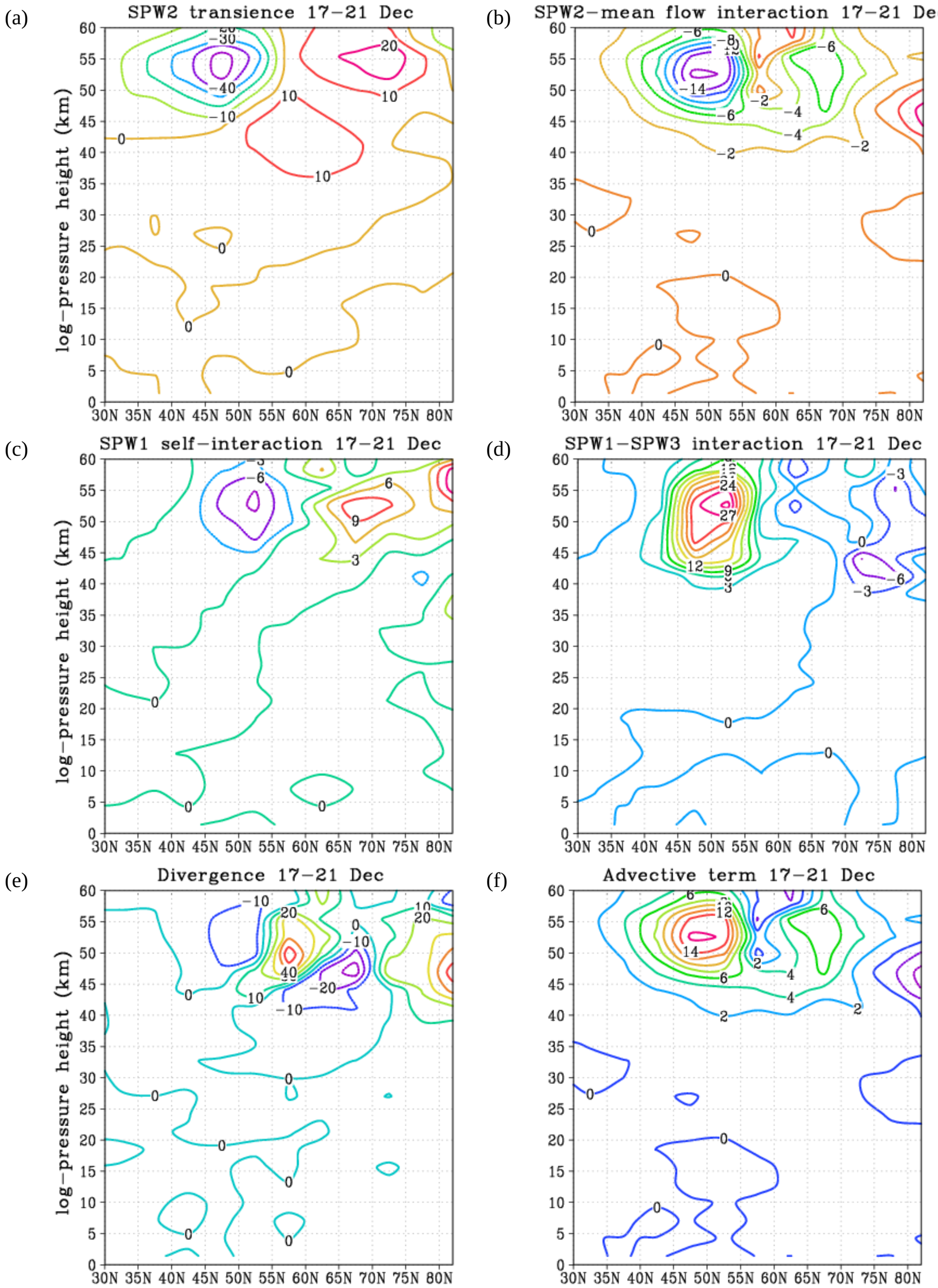


Figure 13. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW2, averaged for December 17-21, 2018.

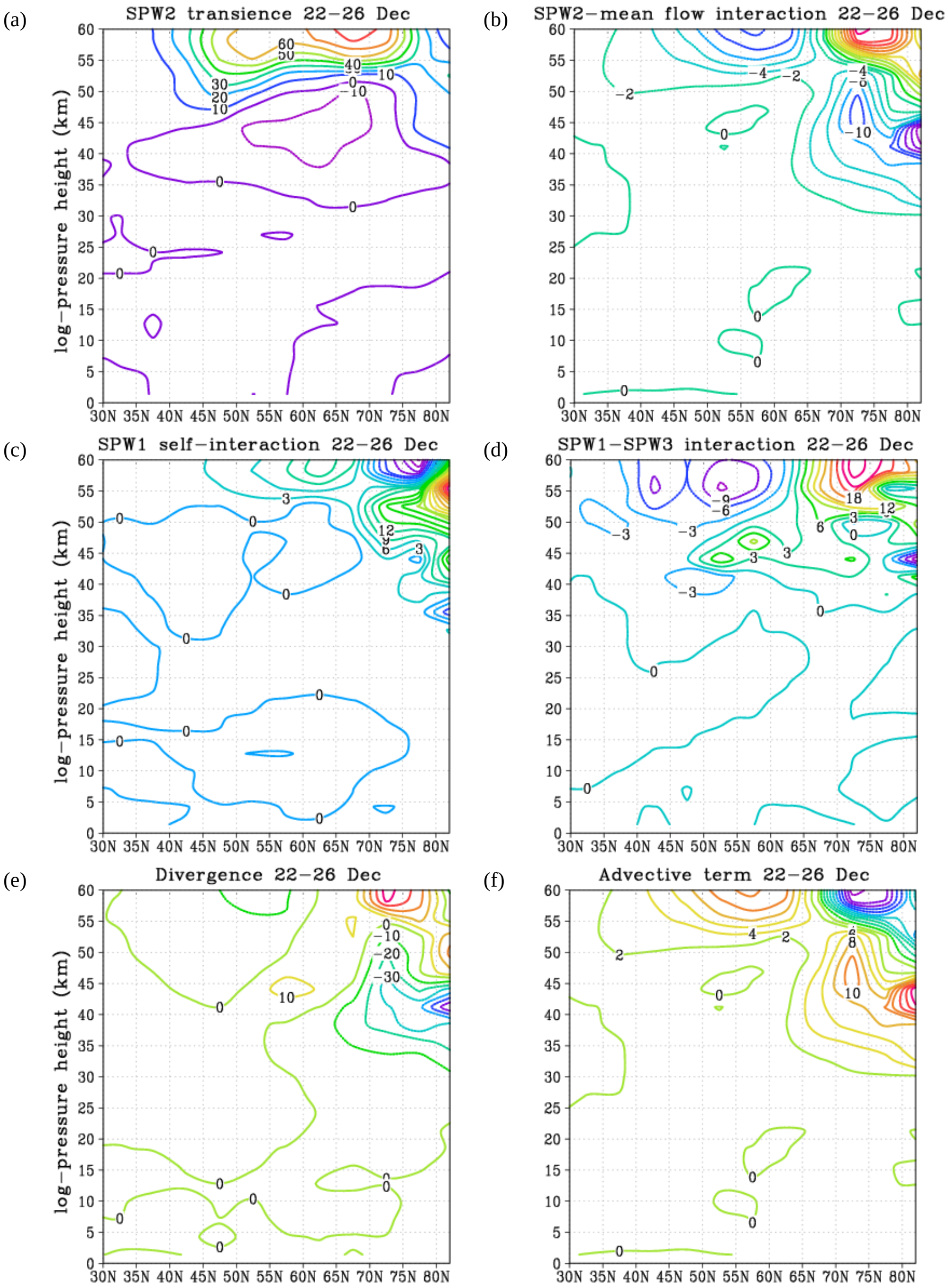


Figure 14. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW2, averaged for December 22-26, 2018.

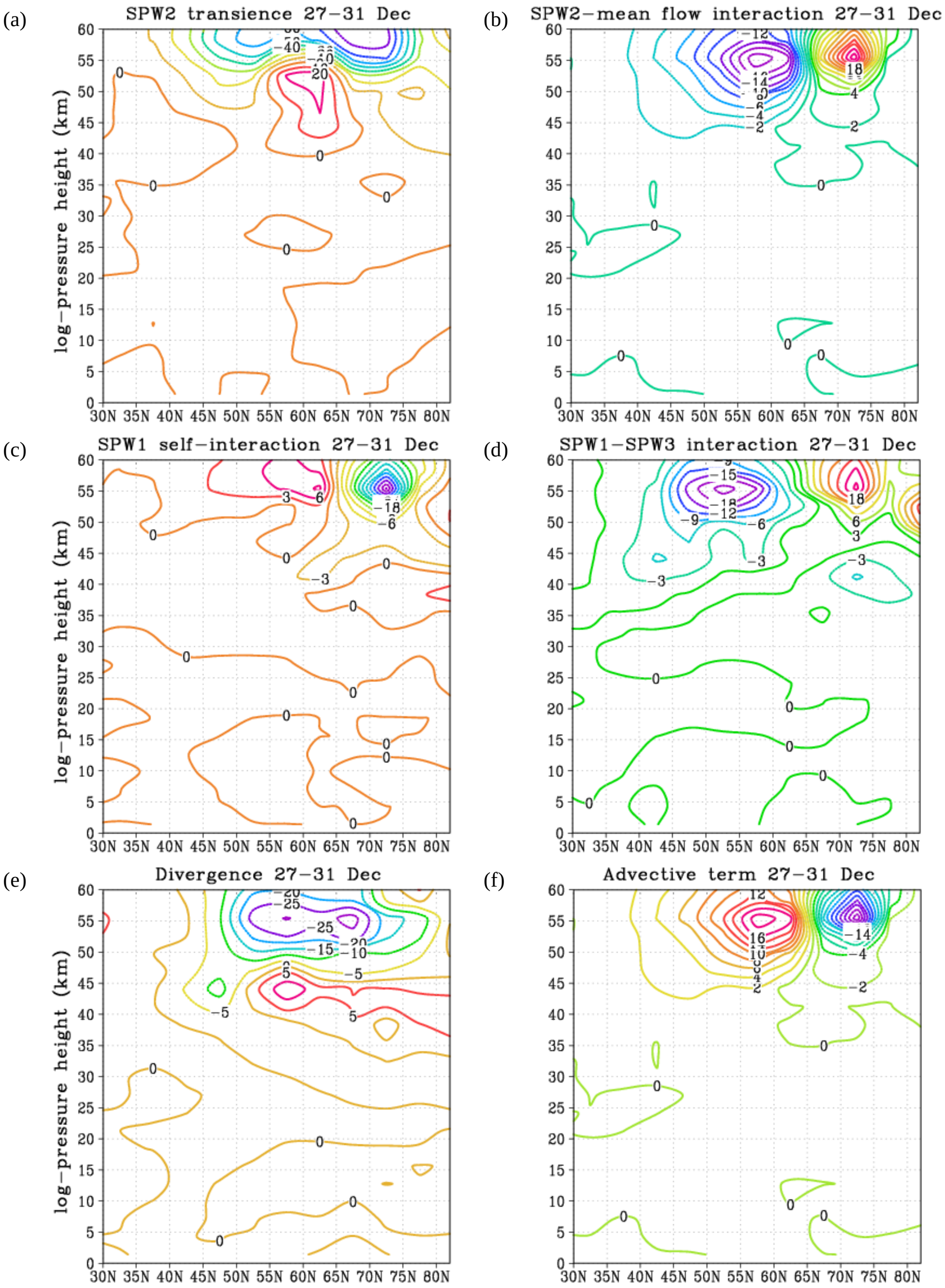


Figure 15. Latitude-height cross sections of terms in the perturbed potential enstrophy equation for SPW2, averaged for December 27-31, 2018.

4 CONCLUSIONS

Differences in the evolution of various nonlinear processes during sudden stratospheric warmings, accompanied by the splitting and displacement of the stratospheric polar vortex, were studied. For this purpose, the terms responsible for wave activity temporal variability, planetary waves interaction with each other and with the mean flow, divergence and advection in the potential enstrophy balance equations were calculated and results in spatiotemporal form were presented. The presented results demonstrate that SSW, accompanied by the stratospheric polar vortex splitting, is preceded by an increase followed by a decrease in the wave activity of SPW2. Wave activity change is observed in the middle latitudes, followed by a shift to high latitudes. Wave-wave interactions make the least contribution, and the change in wave activity is balanced by exchange terms. The potential enstrophy flux advection and divergence make the greatest contribution before and during the sudden stratospheric warming at high latitudes to the balance equation for SPW2. An assessment of latitude-height cross sections of wave activity variations and wave-mean flow, wave-wave interactions shows that during the SSW with the stratospheric polar vortex displacement the changes in these processes are observed at higher levels than during the SSW with the splitting. During the SSW with a displacement, the contribution of various processes to the balance of the disturbed potential enstrophy for SPW1 and 2 is comparable, and wave-wave interactions are observed in the middle latitudes before warming, with a shift to high ones during its development. The wave activity variations are observed in both middle and high latitudes. Further investigation of nonlinear wave-wave and wave-mean flow interactions and various nonlinear processes with the statistical processing of data for a large number of SSW yields to in-depth study of the nature of this phenomenon and dilates the possibilities of its modeling and forecasting its development.

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