

On the dynamics of the spring seasonal transition in the two hemispheric high-latitude stratosphere

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ABSTRACT

The seasonal transition is one of the main features of the atmospheric general circulation and is particularly manifest in the high-latitude stratosphere. To explore the dynamics of stratospheric seasonal transition in both hemispheres, the observational features of the annual cycle and seasonal transition in high-latitude stratosphere are investigated using the 38-year ERA-interim reanalysis. Climatological analysis shows that tropospheric planetary waves propagate to the stratosphere and affect significantly the winter-to-summer stratospheric seasonal transition over both hemispheres, but with a much stronger wave activity in austral spring than its boreal counterpart. The austral spring seasonal transition occurs first at the stratopause then propagates down to the lower stratosphere due to enhanced planetary wave breaking, weakening the westerlies. In boreal spring, the seasonal transition occurs simultaneously across the depth of the stratosphere, mainly due to the solar radiation and weaker planetary wave activity. Interannual variability analysis shows that the timing of stratospheric seasonal transition is closely linked to the intensity of upward propagation of planetary wave activity, i.e. the stronger the upward propagation of planetary wave activity in high-latitudes in spring the earlier the stratospheric seasonal transition. Transition indexes are defined and the probability distributions of the indexes show that there are two types of transition in both hemispheres: synchronous/asynchronous in the Northern Hemisphere (NH), and steep/moderate transitions in the Southern Hemisphere (SH). A composite analysis shows that before the transition, stronger wave activity leads to asynchronous rather than synchronous transition in the NH, which propagates downward from the stratopause. In the SH, a moderate rather than steep transition is obtained, which occurs earlier and takes longer to propagate from the upper to lower stratosphere.

Keywords: seasonal transition, stratosphere, planetary wave propagation

1. Introduction

The stratosphere houses the Earth's ozone layer, which affects the energy balance of the lower atmosphere, and plays an important role in weather and climate variability. In fact, previous studies indicate that the circulation changes in the stratosphere affect tropospheric weather and climate, especially at high latitudes (IPCC, 2013). The dynamical stratosphere-troposphere coupling has been shown to occur on a wide range of time scales by numerous studies (Thompson and Wallace, 1998;

Baldwin et al., 2003; Limpasuvan et al., 2004; McDaniel and Black, 2005). This coupling has a significant downward effect, suggesting that the knowledge of the variability of the stratosphere can have useful predictive power for the troposphere and may lead to extending the tropospheric predictability limit.

In the high-latitude stratosphere, a strong seasonality is observed in both the Northern Hemisphere (NH) and the Southern Hemisphere (SH) represented by a cold temperature, with a well-developed westerly flow, during the winter season, and a warm temperature, with quite steady moderate easterly winds, during the summer season

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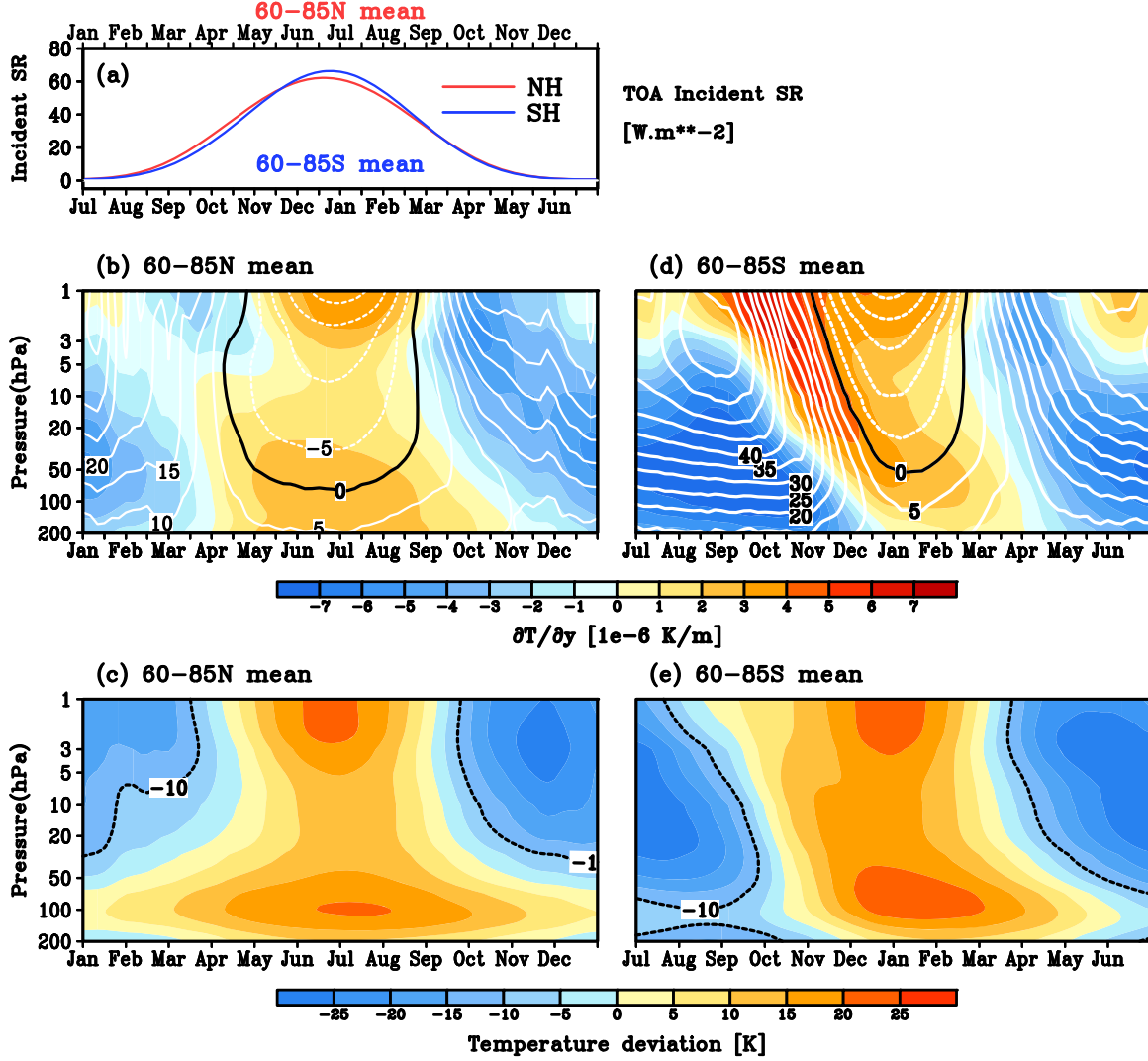


Fig. 1. Seasonal cycle of NH and SH (a) incident solar radiation at the top of the atmosphere; (b) and (d) zonal-mean zonal wind (contour) and temperature gradient (shaded); (c) and (e) zonal-mean temperature deviations from the global mean (shaded and contour). All variables are averaged over 60–85° of NH and SH, respectively.

(Fig. 1b–e). The winter to summer seasonal transition indicates a general circulation adjustment, e.g. the breakdown of the polar vortex and the reversal of the zonal-mean zonal wind. The resulting effect of these seasonal transitions propagates downward to the troposphere. Previous studies on abrupt seasonal change of the general circulation show a seasonally well-established atmospheric general circulation, especially the summer circulation, is initiated from the stratosphere. For example, the onset of the Asian summer monsoon can be traced back to the high-latitude stratosphere (Xue et al., 2002). From this perspective, an improved understanding of the dynamics of the stratospheric seasonal transition will definitely help us to predict the tropospheric general circulation adjustments, such as the onset of the Asian summer monsoon.

The basic thermodynamic background of the seasonal transition is the annual cycle of solar radiation. At the beginning of spring, the increasing solar radiation initiates a weakening of the temperature gradient between the winter and summer hemispheres, and the westerlies in the winter hemisphere weaken and gradually shift to easterlies following the thermal wind balance. Meanwhile, the planetary waves propagate upward into the stratosphere where they break and dissipate (Charney and Drazin, 1961), contributing further to the deceleration of westerlies. The planetary waves propagation can be accompanied by abruptly increased polar stratospheric temperature yielding what is known as sudden stratospheric warming (SSW) (Butler et al., 2015), often observed in NH winter, but quite occasionally in the SH

winter. It has been documented that the NH has more planetary wave activity than the SH due to greater land-sea contrast and more extensive orography (Scaife and James, 2000). The SH polar vortex is therefore far stronger than its northern counterpart, and its seasonal breakdown in austral spring/summer occurs later in the season compared to that of the NH. Different seasonalities of planetary waves in the two hemispheres could therefore affect the seasonal transition of two hemispheres' polar region in different ways (Hirota et al., 1983, for early satellite observations). This topic is not yet fully understood and not well explored.

The motivation for this study is to further explore the seasonal variation in stratospheric high-latitude regions and provide an understanding of the influence of planetary wave activity on the seasonal transition in both hemispheres. Precisely, the objective of this paper is twofold, namely, (i) the investigation of the dynamics of stratospheric seasonal transition in both regions, and (ii) the interaction between planetary wave activity and the mean flow, and the contribution of upward planetary wave propagation to the seasonal transition in the stratosphere. Section 2 describes the data and analysis approach used here. Section 3 discusses the climatological features of the seasonal transition in the stratosphere in both hemispheres. The influence of upward planetary wave propagation on stratospheric seasonal transition of both hemispheres is analysed in Section 4. Discussion is given in Section 5, and a summary and conclusion are given in Section 6.

2. Data and analysis approach

The data used in this study come from the European Centre for Medium Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA – Interim) dataset (Dee et al., 2011) from 1979 to 2016. The data consist of daily fields of zonal and meridional wind, temperature, vertical velocity and geopotential height, with a horizontal resolution of $1 \times 1^\circ$, distributed over 37 pressure levels extending from 1000 to 1 hPa. The data are used to characterize the state of the stratospheric annual cycle, and to calculate the Plumb wave activity and Eliassen-Palm (E-P) fluxes (Andrews et al., 1987). For dynamical and thermodynamical consistency, we also chose to use the incident solar radiation at the top of the atmosphere from the ERA-Interim instead of other satellite data source.

The focus here is on low-frequency intraseasonal variability. To remove the effect of high-frequency variation we use a 5-day low-pass filter, and keep the pentad (5 days) means. To describe the intraseasonal variability of the transition in high-latitude stratosphere, we analyse the main features of temporal and spatial distribution of

the circulation variables (see Section 3.1), following the seasonal change from winter to summer, where the zonal-mean zonal winds turn from westerly to easterly. Here we consider the December, January and February (DJF) to represent boreal winter and austral summer, and June, July and August (JJA) to represent boreal summer and austral winter. The period March to May is the boreal spring, and September to November is the austral spring. Seasonal transitions are discussed based on the evolution from winter to summer in each hemisphere. For reference, the pentad associated with zonal wind reversal is defined as the transition time.

In this study, a wave activity flux (WAF) that indicates a propagating packet of planetary waves in three-dimensional space is calculated following Plumb (1985). The WAF is conventionally used to analyse propagating planetary waves in three-dimensional space from the troposphere to the stratosphere. The WAF vector (F_s) defined on the sphere is calculated in log-pressure coordinates (Plumb, 1985) and takes the form:

$$F_s = p \cos \phi \begin{pmatrix} \frac{1}{2a^2 \cos^2 \phi} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] \\ \frac{1}{2a^2 \cos \phi} \left[\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right] \\ \frac{2\Omega^2 \sin^2 \phi}{N^2 a \cos^2 \phi} \left[\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial z} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial z} \right] \end{pmatrix} \quad (1)$$

where p is pressure, and ϕ , λ and z are latitude, longitude and height, respectively. A prime denotes perturbations to the zonal-mean field. The stream function, Earth's rotation rate, radius of the Earth, and buoyancy frequency are represented, respectively, by ψ , Ω , a , and N . Daily pressure level data from ERA-Interim are used for the calculation of WAF F_s , and a low-pass 5-day means are applied to obtain low frequency components.

To examine the probability distribution of annual transition indexes of both hemispheres (defined in Section 4) over all 38 years, we use Gaussian mixture model technique (Hannachi, 2007; Turner and Hannachi, 2010). Here the system probability density function (PDF) $f(x)$ may be decomposed as a weighted sum of a number c of Gaussian distributions as:

$$f(x) = \sum_{k=1}^c \alpha_k g_k(x, \sigma_k, \mu_k) \quad (2)$$

with

$$g_k(x) = \frac{1}{\sigma_k \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{x - \mu_k}{\sigma_k} \right)^2}, \quad (3)$$

and $\alpha_1, \dots, \alpha_c$ are the c mixing proportions of the mixture model and they satisfy

$$0 < \alpha_k < 1, \text{ for all } \alpha_k, k = 1, \dots, c, \text{ and } \sum_{k=1}^c \alpha_k = 1. \quad (4)$$

In the above equations, μ_k and σ_k are, respectively, the mean and standard deviation of the k 'th Gaussian $g_k(x)$, $k = 1, \dots, c$. The model parameters $\alpha_k, \mu_k, \sigma_k$, for $k = 1, \dots, c$, are estimated using the expectation – maximization algorithm, see, e.g. Hannachi (2007) for more details.

3. Climatology of NH and SH stratospheric seasonal transition

A simple argument based solely on the seasonal symmetry of the solar cycle would lead to a symmetric climatological seasonal transition cycle between the NH and SH. However, this is not the case as shown in Fig. 1. Figure 1a shows that the maximum of solar radiation over the SH is slightly larger than over the NH due to the elliptic orbital revolution. In spring, the northern hemispheric heating starts earlier than that of the SH, which is also shown from the temperature gradient (Fig. 1b and d). Meanwhile, the westerlies in the winter weaken, and change to easterlies according to the thermal wind balance. We take the zero contour line of the zonal-mean zonal wind as the indicator of wind change from westerlies to easterlies (Fig. 1b and d). A clear difference between the two hemispheres stands out. In the NH high-latitudes, the stratospheric seasonal transition occurs almost simultaneously across the stratospheric depth. However, in the SH the transition occurs in the stratosphere first, then propagates to the lower stratosphere, as indicated from the strong negative temperature gradient turning to strong positive gradient. In particular, the zero contour line of zonal wind shows a clear tilt from 1 to 50 hPa. This tilt can be observed in the SH temperature deviation (from the global mean) reversal in austral spring, but not for NH in boreal spring (Fig. 1c and e). Note also another difference between Fig. 1c and e in the lower and middle stratosphere, namely, the boreal winter is not as ‘cold’ as the austral winter (compare the dashed contour lines), leading to a shorter winter westerly period in the NH than in the SH, especially due to the earlier transition from westerlies to easterlies in the NH. There seems to be a heating over the northern stratospheric high-latitudes from January to March. It is suggested that this could be due to Rossby waves generated in the troposphere and travelling upward to the stratosphere. The long waves are dissipated there, decelerating the westerlies and warming the polar region. When the strong heating occurs, the stratospheric temperature rises quickly and leads to a SSW event.

To grasp the overall features of the dominant planetary wave activities in both hemispheres, we show in Fig. 2 the

longitude-time profile of geopotential height deviation at 60° from the zonal-mean at different levels. In the NH, the predominant planetary wave number 2 can be recognized in the mid-troposphere (Fig. 2c), and the lower stratosphere (Fig. 2b). In the mid- and upper stratosphere (e.g. Fig. 2a), the planetary wave number 1 is predominant. The planetary waves are active during winter, and start to become weaker in March, as shown in the temporal distribution of the vertical component of Plumb wave activity flux (WAFz) at 100 hPa (Fig. 2g). There is a strong upward propagation of planetary waves from 60°E to 150°W during winter, suggesting a source for the slight warming observed in the stratosphere in the boreal winter (Fig. 1c), along with somewhat weaker downward propagation from 140°W to 60°W (see also Harada and Hirooka, 2017). For the SH, the planetary waves are dominated by wave number 1 in the troposphere and the stratosphere (Fig. 2d–f). The planetary wave in mid-troposphere is also active during winter, and then becomes weaker in spring. In the SH stratosphere at 100 hPa and 10 hPa, the planetary wave is less active in winter but then becomes more active in austral spring starting in September (Fig. 2d and e). The maximum vertical WAF at 100 hPa is in October around 60°E to 180° (Fig. 2h), which is even larger than that over NH in April, which means that active planetary waves significantly affect later seasonal transition in the SH.

To examine in more detail the planetary wave activity in the stratosphere, we compare in Fig. 3 the vertical profiles of geopotential height deviations (from the zonal-mean) and the WAF over high-latitudes in both hemispheres. January and April represent the boreal winter and spring, as July and October represent the austral winter and spring, respectively. The wave activity in boreal winter (Fig. 3a) is quite strong, especially in the region west of the Aleutian High. The upward vertical component of the fluxes showing upward propagation of wave activity, converges at the Aleutian High. This localized wave packet convergence contributes to the development and maintenance of the quasi-barotropic structure of the Aleutian High, and directly causes a deceleration of the westerlies in the neighbouring region and a downward propagation downstream the Aleutian High (Harada and Hirooka, 2017). This pattern remains consistent in boreal spring (Fig. 3b), but is much weaker, pointing to a weakening of the Aleutian High in spring. For the SH, from winter (Fig. 3c) to spring (Fig. 3d), the upward propagation and convergence of wave packets increase significantly around the region west of the Antarctic high. In particular, in austral spring, the Antarctic high and Antarctic low are stronger and shift westward compared with that in austral winter. Another remarkable feature is that in boreal winter and austral spring (Fig. 3a and d),

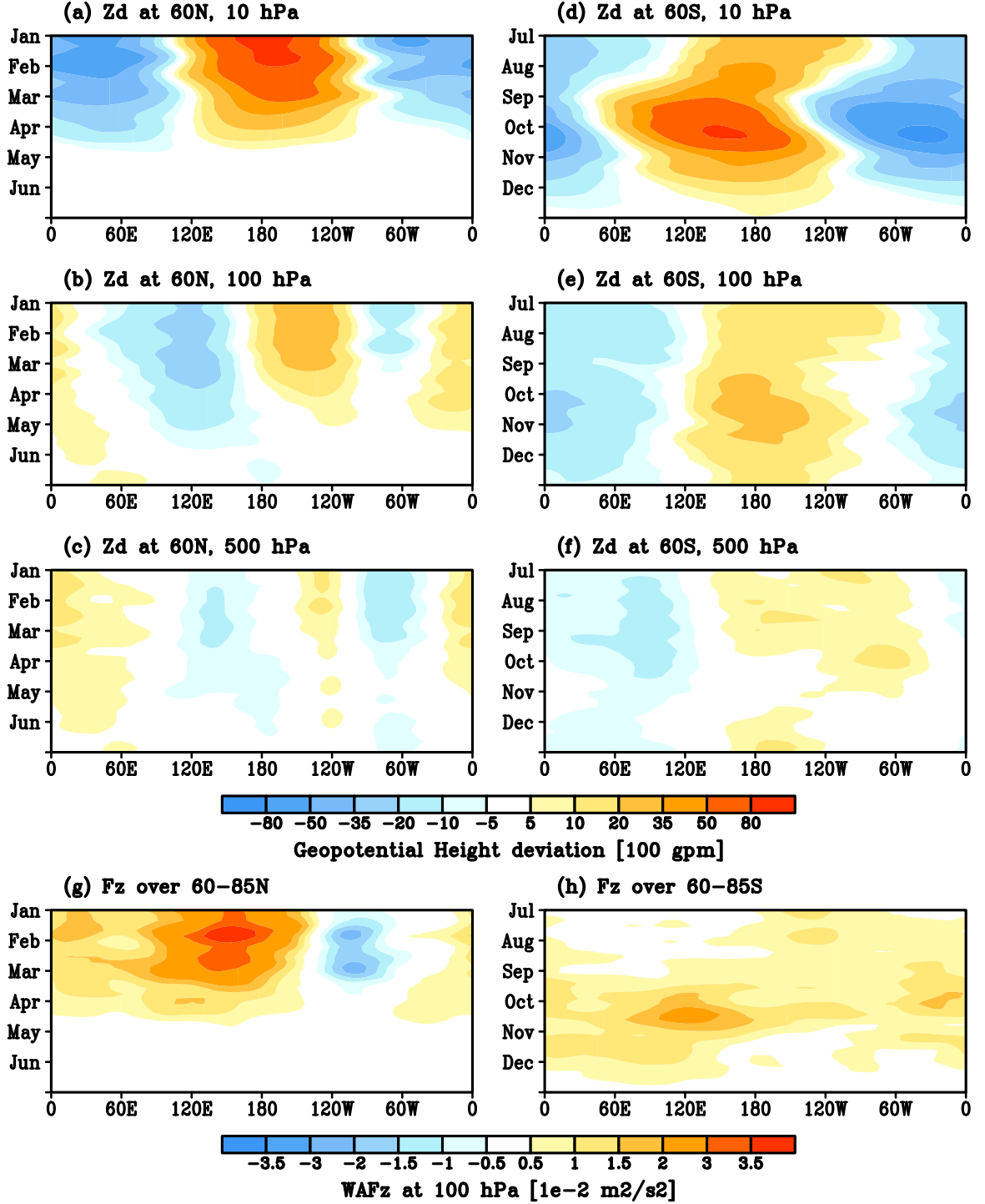


Fig. 2. Longitude-time cross sections of geopotential height deviation from the zonal-mean for three different vertical levels at (a–c) 60°N and (d–f) 60°S, along with WAFz at 100 hPa averaged over (g) 60°N–85°N and (h) 60°S–85°S.

the upward WAF is strong in the longitudes of 0–120°W but very weak in the longitudes of 120°W–0. According to Fig. 2 and the horizontal distribution of WAFz (not shown), the above feature is due to the existence of a

strong wave activity source over northern Eurasia and the Pacific Ocean, and a sink over the northern part of North America in boreal winter. The strongest WAFz in austral spring (Fig. 3d) is located west of 120°W, and the

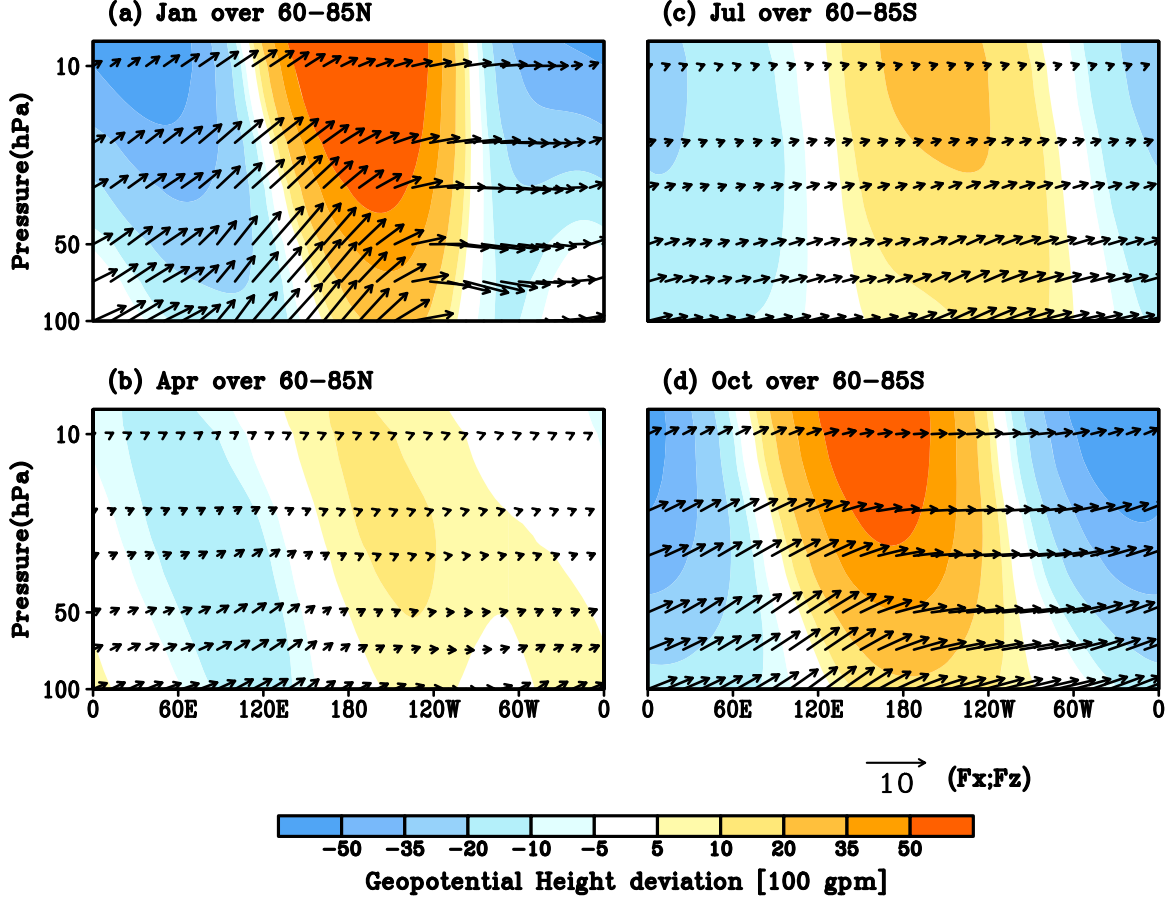


Fig. 3. Climatology of the longitude-pressure cross sections of geopotential height deviations from the zonal-mean (shaded) and WAFs (vectors) averaged over 60°N–85°N in (a) January and (b) April, and over 60°S–85°S in (c) July and (d) October.

maximum of the wave activity source is near Antarctica around 120°E with a weaker maximum source near west of the Antarctic Peninsula. This longitudinal distribution of the upward WAF is mainly due to the land–sea contrast and topography in each hemisphere.

The outcome from the comparison of Figs. 2 and 3 reveals different behaviour of the dominant planetary waves in the troposphere and stratosphere from winter to spring in both hemispheres. The planetary waves emanating from tropospheric highs, are more active in winter than in spring in the troposphere in both NH and SH. The question, however, is why is this activity (or behaviour) different in the stratosphere between the two hemispheres?

Figure 4 shows the evolution of monthly WAFz from the surface to the stratopause. We can clearly see that in the NH (Fig. 4a), the maxima of WAFz in the troposphere occur in winter. The upward propagation is strongest during the winter time (January to February), and the maximum of WAFz in the stratosphere also occurs in winter. In the SH (Fig. 4b), the temporal distribution of

WAFz in the troposphere (below 250 hPa) is similar to that of the NH, with a maximum in winter and a minimum in summer. But during austral winter (end of June to beginning of September), the upward propagation of wave activity cannot penetrate deep into the stratosphere. Theoretically this is because the strong zonal wind does not satisfy the Charney-Drazin condition of planetary wave propagation, namely,

$$0 < \bar{u} - c < U_c \quad (5)$$

where U_c is the Rossby critical velocity and c is the wave phase speed (Charney and Drazin, 1961; Holton and Hakim, 2013). For the largest scale planetary wave, U_c is about 35 ms^{-1} (Charney and Drazin, 1961). There are two peaks of planetary wave activity (and upward propagation) in the stratosphere, one in October and another but weaker one in June, consistent with the early satellite observations (e.g. Hirota et al., 1983). We also calculate the total E-P flux of wave numbers 1–3, and the result (not shown) reveals similar features to those from Plumb WAFz. It means that the whole WAFz depends mainly

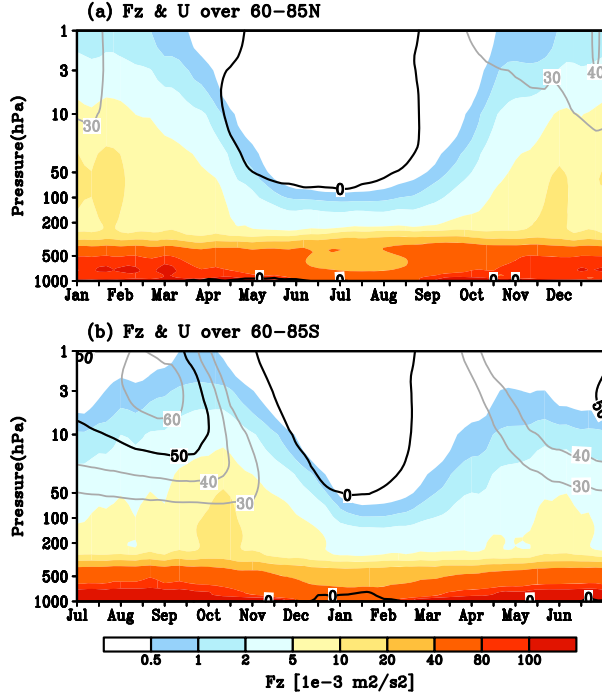


Fig. 4. Seasonal cycle of the zonal-mean WAFz (shaded) and zonal wind (contour, zonal winds equal zero and greater than 30 m/s are shown) in the atmosphere over (a) 60°N–85°N and (b) 60°S–85°S.

on the planetary waves, e.g. planetary wave numbers 1–3 are more likely able to propagate to upper layers compared to the rest of the wave spectrum.

The observed difference in the planetary wave activity in the troposphere and stratosphere between two hemispheres is confirmed further by Fig. 5. In the middle troposphere (at 500 hPa, Fig. 5a and c), the upward WAF is strong in winter and weak in spring in both hemispheres. In the middle stratosphere (at 10 hPa, Fig. 5b and d), WAFz in the NH changes from the maximum in January to near zero values in June. However, WAFz in the SH increases from winter to spring, and reaches a maximum in October. For example, the climatological value is twice that of its northern counterpart in April. In particular, from all stratospheric WAFz curves over the period 1979–2016, there are only three austral winters for which WAFz at 10 hPa reaches the mean value of WAFz in boreal winter. The interannual variability of WAFz over the NH is much stronger than over the SH, for both winter and spring seasons. Bottom boundary conditions and large-scale teleconnections, e.g. NAO, AO, and ENSO could be at the origin of this difference between both hemispheres.

The climatological seasonality of the planetary wave activity and its vertical propagation in the two hemispheres affect the stratospheric thermal structure and the

zonal-mean circulation (Kidston et al., 2015). In boreal winter, planetary wave packets frequently emanating from the troposphere propagate upward into the stratosphere and break. This contributes to the ‘warming’ of the lower to middle stratosphere and weakening of the zonal-mean temperature gradient and zonal wind. In spring, when the wave activity and its upward propagation decrease, the absorption of solar ultraviolet radiation by ozone contributes to stratospheric warming. When the stratosphere becomes warm, seasonal transition takes place at all levels almost simultaneously.

Over the SH high-latitudes, however, westerlies are still fairly strong around the vernal equinoctial period; the strongest upward propagation of planetary wave activity begins at around this time: the critical transition period. This adds, besides the solar heating, an extra (dynamical) heating to the upper stratosphere, and the seasonal transition occurs in the upper stratosphere first. Andrews et al. (1987) provide the theoretical background for a planetary wave influence on the thermodynamic structure of the SH stratosphere and seasonal transition. The planetary waves break and their easterly angular momentum is released in the stratosphere. This process induces a deceleration of the westerlies and/or a poleward meridional circulation. Thus the mean westerly wind (the polar night jet) is weakened, leading to more planetary waves propagating upward under the moderate westerly wind condition. If this process continues the wind eventually reverses, forming a critical layer where the mean zonal wind matches the wave phase speed. This would inhibit further upward wave propagation and wave breaking would be intensified, inducing an easterly wind up to the level reached by the propagating wave. A rapid change to easterlies then takes place and the critical layer descends. The combination of this dynamical process with the reduced (or reversed) meridional temperature gradient caused by the annual cycle of solar radiation yields a reduction (or reversal) of the vertical wind shear, which leads to further reduction of the meridional temperature gradient, via the thermal wind relation. Eventually, the polar night jet is replaced by easterlies from the upper stratosphere down to the lower stratosphere and upper troposphere. As a consequence of these processes, the signal of seasonal change must occur in the upper stratosphere first then propagates downward to the lower stratosphere and eventually reaches the upper troposphere.

4. Upward wave propagation and spring seasonal transition

As described in section 3, climatological stratospheric seasonal transition is quite different between the two

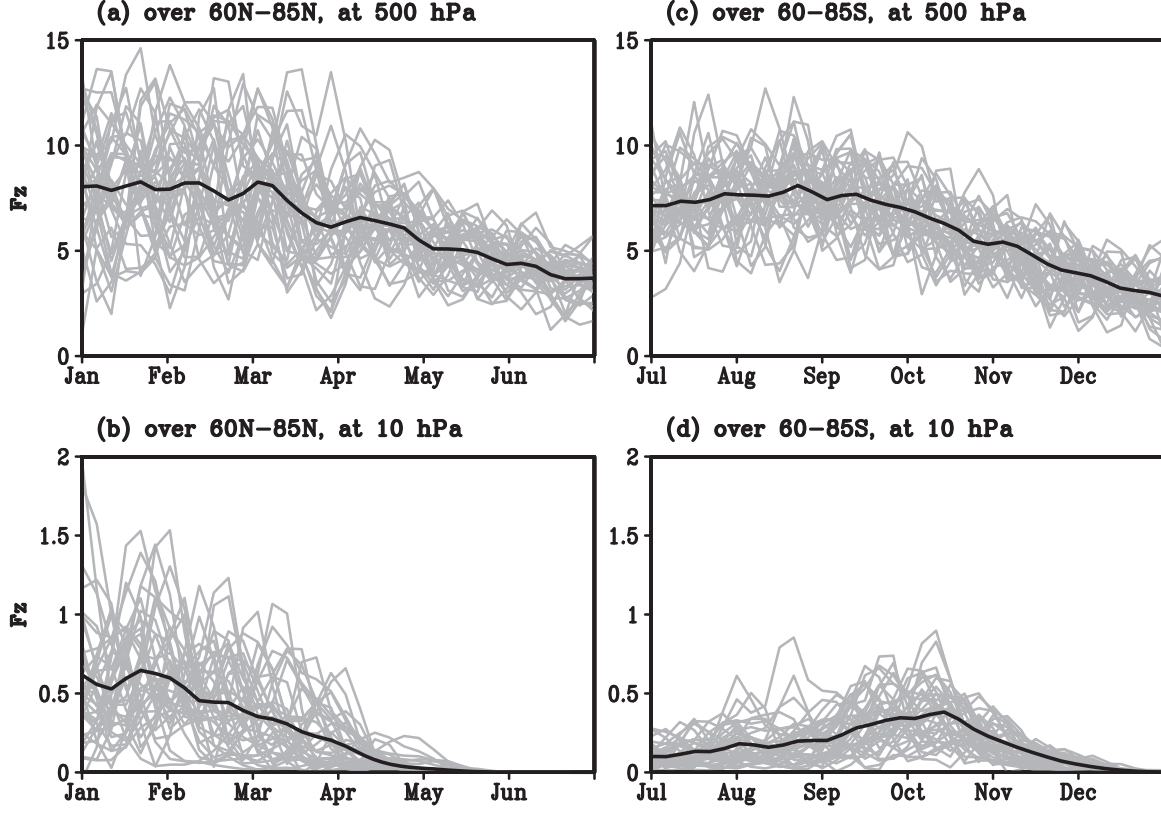


Fig. 5. Interannual variability of the evolutions of zonal-mean WAFz from winter to summer at 500 hPa (a, c) and 10 hPa (b, d), averaged over 60°N–85°N (a, b) and 60°S–85°S (c, d). Grey lines are for the years 1979–2016. The black line is for the long-term mean. Unit: $10^{-2}\text{m}^2\text{s}^{-2}$.

hemispheres due to the difference in seasonality of the planetary wave activity and its upward propagation. Strong interannual variability is observed in the upward propagation of WAFs over both hemispheres in Fig. 5. For example, in April, in some years WAFz over 60°N–85°N at 10 hPa can be three times the magnitude of the climate mean. In austral spring, WAFz over 60°S–85°S at 10 hPa can also change notably. This could affect the interannual variability of stratospheric seasonal transition. This section aims to lay down the influence of the upward propagation of planetary wave activities on the interannual variability of stratospheric seasonal transition in both hemispheres.

4.1. Effect on NH stratospheric seasonal transition

We start by examining the stratospheric seasonal transition over 60°N–85°N during spring time each year from 1979 to 2016 (Fig. 6). Taking the zonal wind change from westerly to easterly as an indicator of the seasonal change from winter to summer, we identify the reversal time at each level using the pentad mean data. To quantify the transition type in the NH, we construct an annual

transition index T_n^{NH} defined by

$$T_n^{NH} = 2P_{10}^{(n)} - (P_3^{(n)} + P_1^{(n)}) \quad (6)$$

where $P_{10}^{(n)}$, $P_3^{(n)}$ and $P_1^{(n)}$ are the transition pentads at 10, 3 and 1 hPa levels, respectively, in year n . A negative T_n^{NH} means that the seasonal transition occurs first at 10 hPa then propagates to the upper stratosphere, and vice versa for a positive T_n^{NH} . The histogram and kernel PDF of T_n^{NH} are shown in Fig. 7a. The kernel PDF estimate is strongly non-Gaussian. The PDF does not show bimodality but is very skewed and has clear shoulder, an indication that the index can accommodate two characteristic features. The relatively small sample size could prevent getting clear bimodality. A mixture model analysis, however, shows that the PDF is well approximated by a mixture of two Gaussians. These Gaussian PDFs reflect the two transition types in NH, with mixing proportions $\alpha_1 = 0.3$ and $\alpha_2 = 0.7$ centered at $\mu_1 = -4.8$ pentad (blue, transition occurs from 10 hPa) and $\mu_2 = 0.8$ pentad (red, transition occurs from 1 hPa), respectively (Fig. 7a). They are associated with two different behaviours of the transition time, which are analysed below.

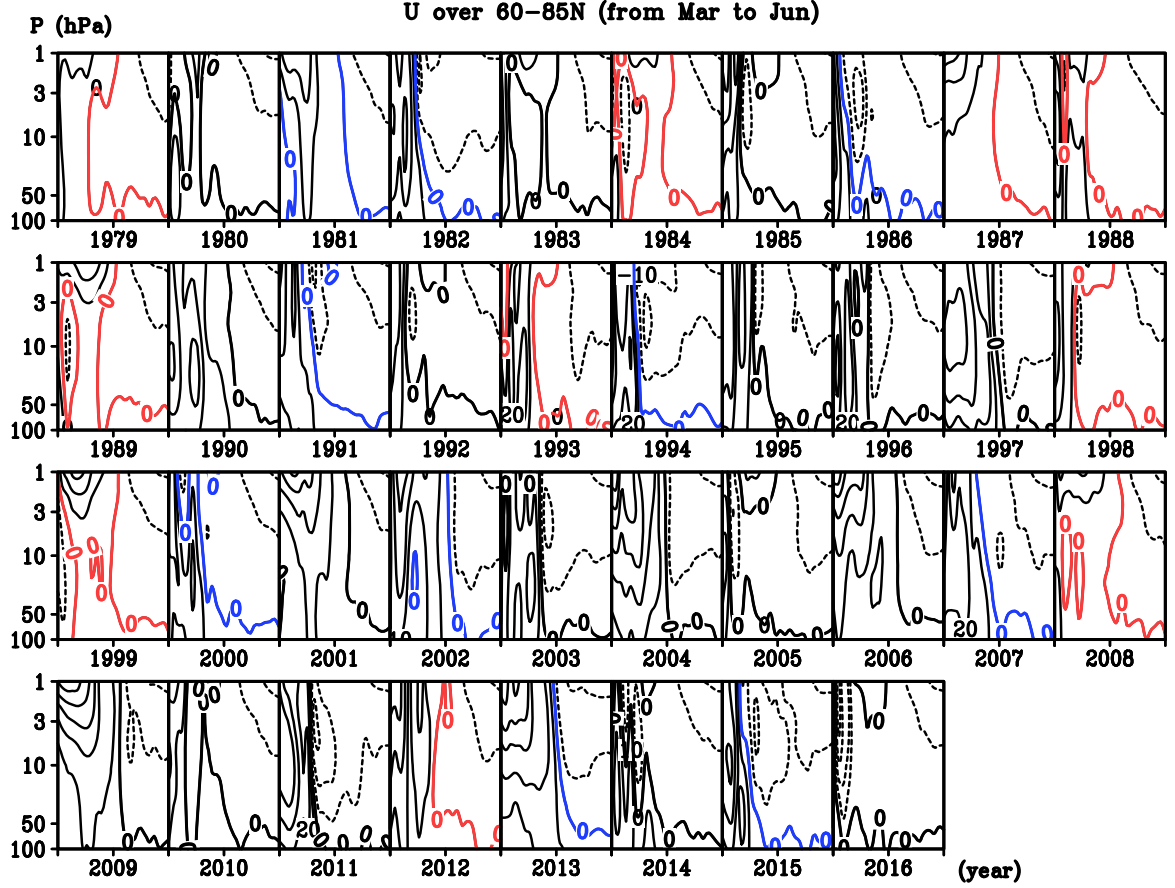


Fig. 6. Evolutions of stratospheric zonal-mean zonal wind over 60°N–85°N from March to June each year for the period 1979–2016. Contour interval is 10 m/s. The zero-contour line is shown in red or blue depending, respectively, on whether the transition is ‘extremely’ synchronous or asynchronous.

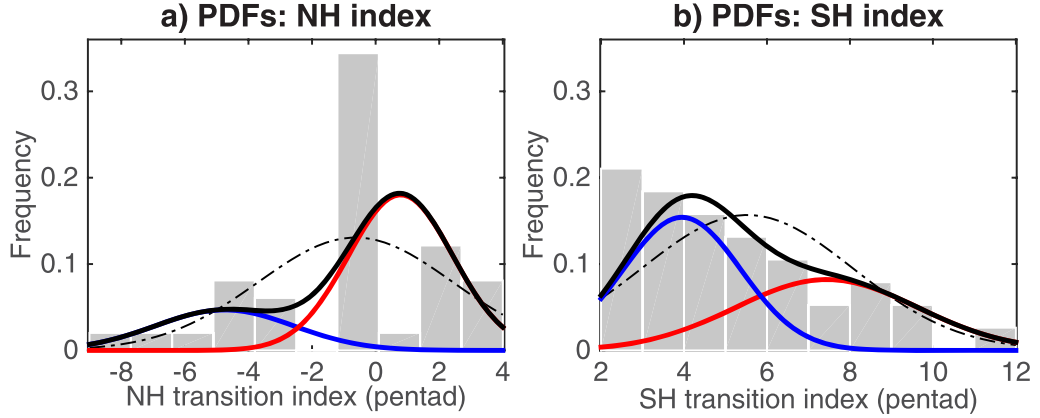


Fig. 7. Histogram (shaded) and kernel PDF estimates of the transition indexes (black solid) for the NH (a) and SH (b). The two Gaussian components of the mixture model (see text) are shown and reflect the NH synchronous (blue)/asynchronous (red) transitions in (a); and SH steep (blue)/moderate (red) transitions in (b). The Gaussian PDFs fitted to the data are also shown (dash-dot).

In most of these years, the zonal wind in the middle or lower stratosphere reverses at the same time or even earlier sometimes than that in the upper stratosphere

(marked with black and red zero contours in Fig. 6), which is similar to the climatology of the NH shown in Fig. 1b. We call this type of seasonal transition as

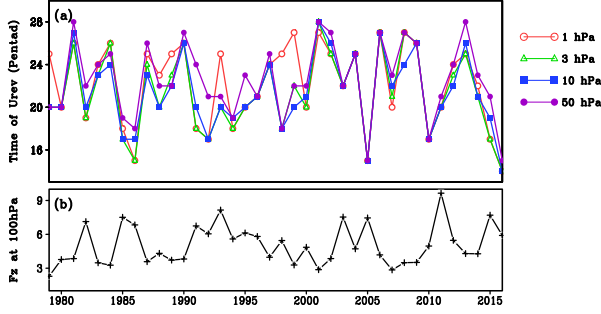


Fig. 8. Interannual variations of (a) the seasonal transition pentads at 1 hPa (red), 3 hPa (green), 10 hPa (blue) and 50 hPa (purple); and (b) spring mean of WAFz from pentads 13 to 28 at 100 hPa. Units: (a) pentads, and (b) $10^{-3} \text{ m}^2/\text{s}^2$.

‘synchronous’, or ‘non-tilted’ transition (zero contour lines are non-tilted). In the remaining years, the zonal wind reverses in the stratopause first, and are characterized by the zero contour lines being tilted from the upper to the lower stratosphere (marked with blue zero contour lines in Fig. 6), which is similar to the climatology of the SH shown in Fig. 1d. We call this type of transition as ‘tilted’ or ‘asynchronous’ transition, and we use both terms tilted/non-tilted and asynchronous/synchronous interchangeably in the sequel.

To emphasize these two types of transition we choose four levels in the stratosphere, namely, 1, 3, 10 and 50 hPa to represent, respectively, the stratopause, the upper, middle and lower stratosphere, respectively. The transition pentads at different levels are shown in Fig. 8a, the transitions occur between the 13th and 28th pentads. In most of the years, the transition occurs first at 10 hPa and almost simultaneously in the stratosphere, but in some years the transition time at 10 hPa is lagging behind that in the upper layers (at 1 and 3 hPa). Figure 8b shows the mean WAFz from pentad 13 to 28 at 100 hPa. The correlation coefficients between the time series of mean WAFz and the transition pentads vary from -0.51 (at 50 hPa) to -0.62 (at 3 hPa), and are all significant at 1% level using a student’s *T*-test. This suggests that the stronger the WAFz in spring the earlier the seasonal transition.

In order to better reveal the nature of the two transition groups, we take those years in which the absolute value of the deviation of the transition index T_n^{NH} from the average $\overline{T_n^{NH}}$, is greater than 1.5 times the standard deviation as extreme for both synchronous (non-tilted) and asynchronous (tilted) transition years. Ten years of synchronous transitions are found, namely, 1979, 1984, 1987, 1988, 1989, 1993, 1998, 1999, 2008 and 2012 (marked with red zero contour line in Fig. 6); and 10 years of asynchronous transitions, namely, 1981, 1982,

1986, 1991, 1994, 2000, 2002, 2007, 2013 and 2015 (marked with blue zero contour line in Fig. 6). Because the transition pentad varies from year to year, we take a reference pentad (‘pentad zero’) for our composite as the pentad in which the zonal wind at 10 hPa turns from westerly to easterly. Positive and negative pentads in the sequel will represent pentads relative to the reference pentad. The averages of the reference pentads are 21.3 and 21.7 for non-tilted and tilted transitions, respectively. There is just 0.4 pentad (2 days) difference between transition pentads for the above two types. This (non-significant) difference means that the solar radiation affects both types of transitions nearly equally.

Figure 9 shows a comparison between synchronous (left panels) and asynchronous (right panels) transitions. The evolution of the former (non-tilted) transitions is similar to the climatology of the NH: weaker westerlies (respectively easterlies) in the stratosphere before (respectively after) transition; the transition occurs approximately simultaneously at all the levels (except at 1 hPa). To the contrary, in the latter (tilted) case the transition occurs first in the upper stratosphere and then propagates downward along a clear tilt to the lower stratosphere (Fig. 9a and d). The temperature deviation shows that, from winter to about 1 month before the transition (pentad -6), the region of the middle to the lower layers of the stratosphere in the synchronous case is warmer than that in the asynchronous case (Fig. 9b and e). After pentad -6, the upper and middle stratosphere in the asynchronous case become warmer than that in the synchronous case. This is consistent with the evolution of the WAFz: from winter to pentad -6, WAFz at 100 hPa in the synchronous case is much stronger than that in the asynchronous case (Fig. 9c and f). In other words, in the synchronous case there is more upward propagation of planetary wave activity from the troposphere to the stratosphere until pentad -6. At 10 hPa, WAFz in the synchronous years is stronger than that in asynchronous years up until pentad -9. This contributes to warming the lower and middle stratosphere well before the transition pentad. After pentad -6, WAFz in the stratosphere for both types reaches a peak just before the transition (or reference) pentad, and it is much stronger in the asynchronous case, explaining the earlier occurrence of the transition at the stratopause. This implies that in the asynchronous case the mechanism behind the transition is dynamical. In conclusion, the above results suggest that the significant difference observed between the two types of transitions, see also Fig. 7a, is mainly controlled by the upward propagation of planetary wave activity.

The climatology of the mean field and wave activity for the two types of transitions are described in Fig. 10. The figure shows that the zonal wave number 1 planetary

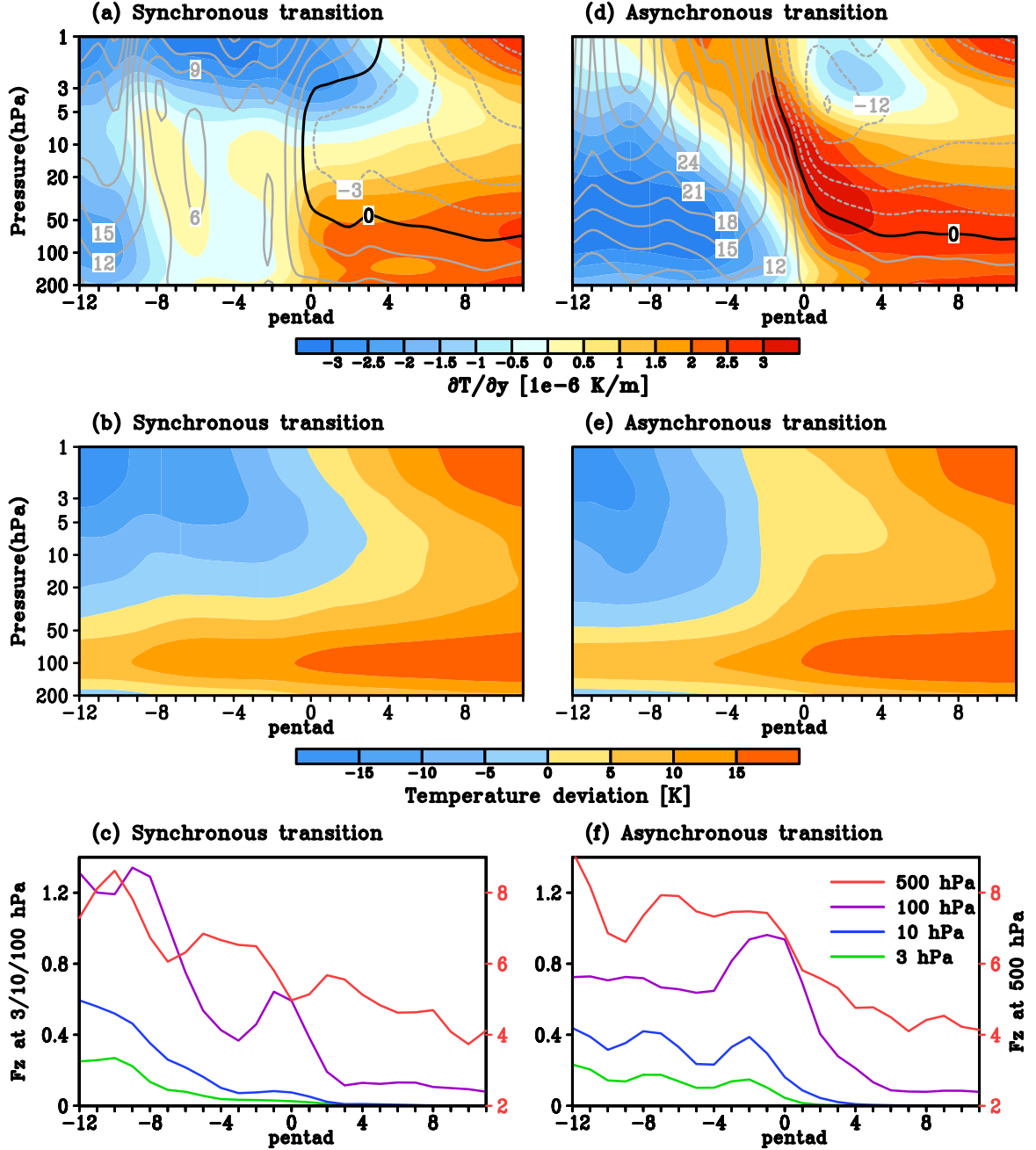


Fig. 9. Temporal evolutions during synchronous (a–c) and asynchronous (d–f) years of zonal-mean averaged over 60°N–85°N of (a and d) temperature gradient (shaded) and zonal wind (contour, in m/s), (b and e) temperature deviation from the global mean, and (c and f) upward wave activity fluxes, based on a composite analysis of 10 extreme years. Units on the horizontal axis are in pentads relative to the reference pentad.

wave is predominant in both synchronous and asynchronous cases, but it is much stronger in the latter case. In addition, the upward propagation of wave activity to the west of, and convergence around the Aleutian High, and the strength of the Aleutian High are both stronger in the asynchronous case compared to the synchronous case.

For the latter case the upward propagation reaches 3 hPa, but for the tilted case it reaches 1 hPa (around the stratopause). This implies that stronger upward propagation of the planetary wave activity leads to an asynchronous seasonal transition, i.e. a reversal of the stratospheric zonal wind from westerly to easterly that occurs first at the

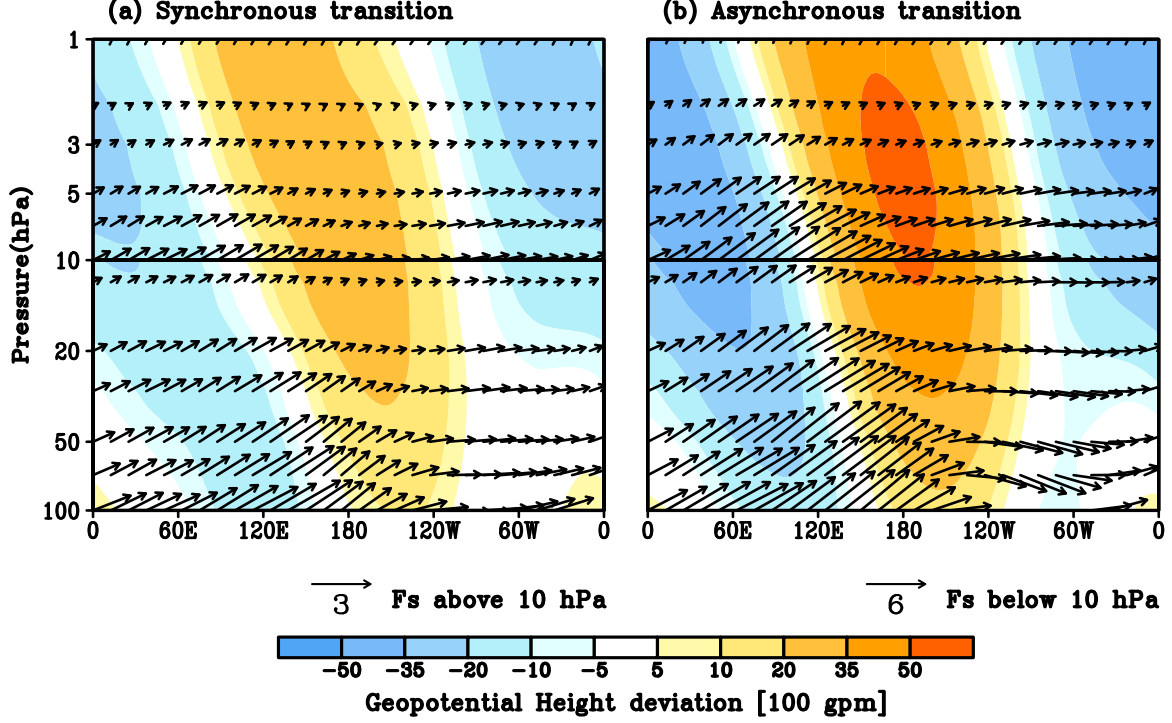


Fig. 10. The Longitude-pressure cross sections of 9-pentad prior to the transition pentad mean geopotential height deviations from the zonal mean (shaded) and WAFs (vectors) averaged over 60°N–85°N composite in (a) synchronous, and (b) asynchronous cases. Units of WAFs, m^2/s^2 .

upper stratosphere, then propagates downward to the lower levels.

4.2. Effect on SH stratospheric seasonal transition

For the SH, a tilted transition is observed in all the years (Fig. 11), indicating the earliest zonal wind reversal, which occurs always in the upper stratosphere. We note that in some years there is a strong gradient (e.g. 1980, in Fig. 11), indicating that the downward propagation occurs fast from the stratopause to 50 hPa. We refer to this type as steep transition years. The other years, associated with weak vertical gradient, are referred to as moderate transition years. To identify the transition type, and in a similar way to T_n^{NH} , we define an index T_n^{SH} , as:

$$T_n^{SH} = P_{10}^{(n)} - P_1^{(n)} \quad (7)$$

where $P_{10}^{(n)}$ and $P_1^{(n)}$ are the transition pentads in year n at 10 and 1 hPa, respectively. Large values of T_n^{SH} mean moderate transitions, and small values mean steep transitions. The histogram and PDF of SH transition index T_n^{SH} are shown in Fig. 7b. Like T_n^{NH} in section 4.1, the PDF of the index T_n^{SH} is strongly non-Gaussian, with a shoulder, slightly weaker than that of T_n^{NH} . The mixture model also yields two Gaussian components with mixing proportions $\alpha_1 = 0.6$ and $\alpha_2 = 0.4$ centered at $\mu_1 = 4.0$

pentad (steep transition) and $\mu_2 = 7.5$ pentad (moderate transition), respectively (Fig. 7b).

The correlation coefficients between the transition pentads at the 4 levels (Fig. 12a) and the WAFz mean (Fig. 12b) vary from -0.52 (at 50 hPa) to -0.61 (at 10 hPa), and all are significant at 1% level using a student's T-test. As in the NH, the stronger the WAFz in the spring, the earlier the seasonal transition in high-latitude SH stratosphere.

As for the NH, extreme (steep and moderate) transition years are defined as those years for which the absolute value of the deviation of $|T_n^{SH} - \overline{T_n^{SH}}|$ is greater than 1.5 times the standard deviation. With this definition, eight extreme steep transition years are found, namely, 1980, 1981, 1982, 1986, 1987, 1988, 1994 and 2002 (red zero contour line in Fig. 11), and eight extreme moderate transition years, namely, 1985, 1992, 1998, 2001, 2003, 2007, 2008 and 2009 (blue zero contour line in Fig. 11). The corresponding means of T_n^{SH} for extreme steep and moderate transition years are 2.4 and 9.4 pentads, respectively. Considering that all the transitions start at 1 hPa in the SH, we take the pentad in which zonal wind reverses at 1 hPa as the reference or 'zero' pentad. The 'zero' pentad mean for steep transition years is 62.4 pentad (mid-November), while it is 59.4 pentad (end of October) for moderate transitions. The difference of

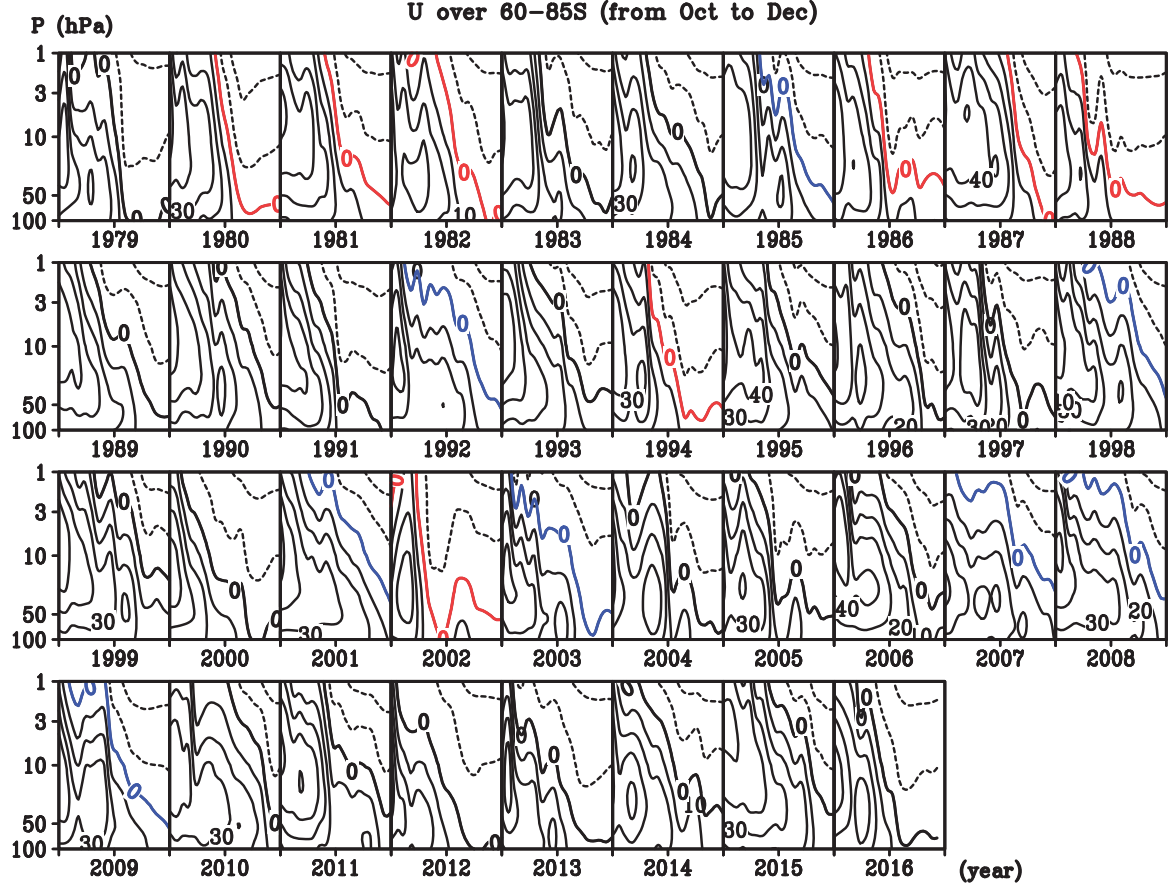


Fig. 11. Evolutions of stratospheric zonal-mean zonal wind over 60°S–85°S from October to December each year for the period 1979–2016. Contour interval is 10 m/s. The zero-contour line is shown in red or blue depending, respectively, on whether the transition is ‘extremely’ steep or moderate.

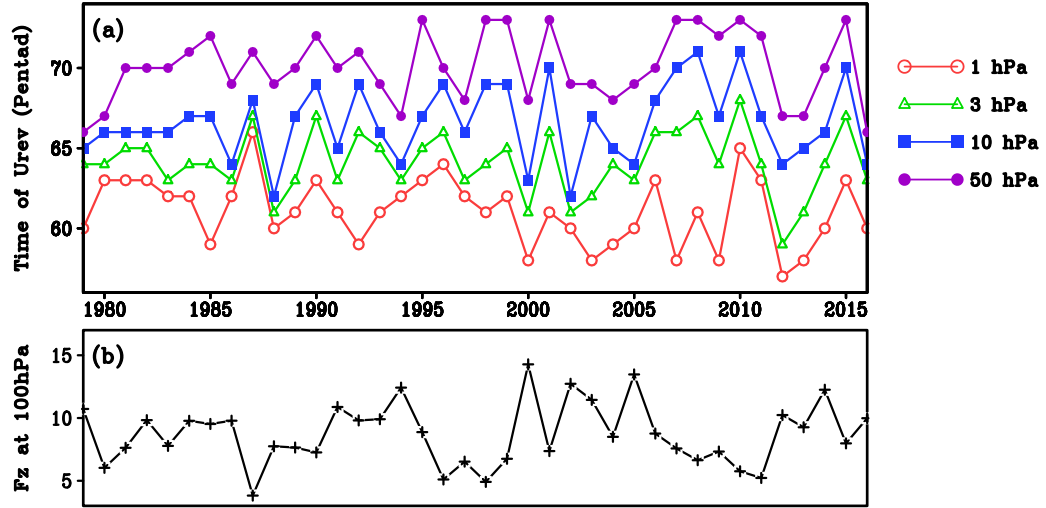


Fig. 12. Interannual variations of (a) the seasonal transition pentads at 1 hPa (red), 3 hPa (green), 10 hPa (blue) and 50 hPa (purple); and (b) spring mean of WAFz. Units: (a) pentads, and (b) $10^{-3} \text{ m}^2/\text{s}^2$.

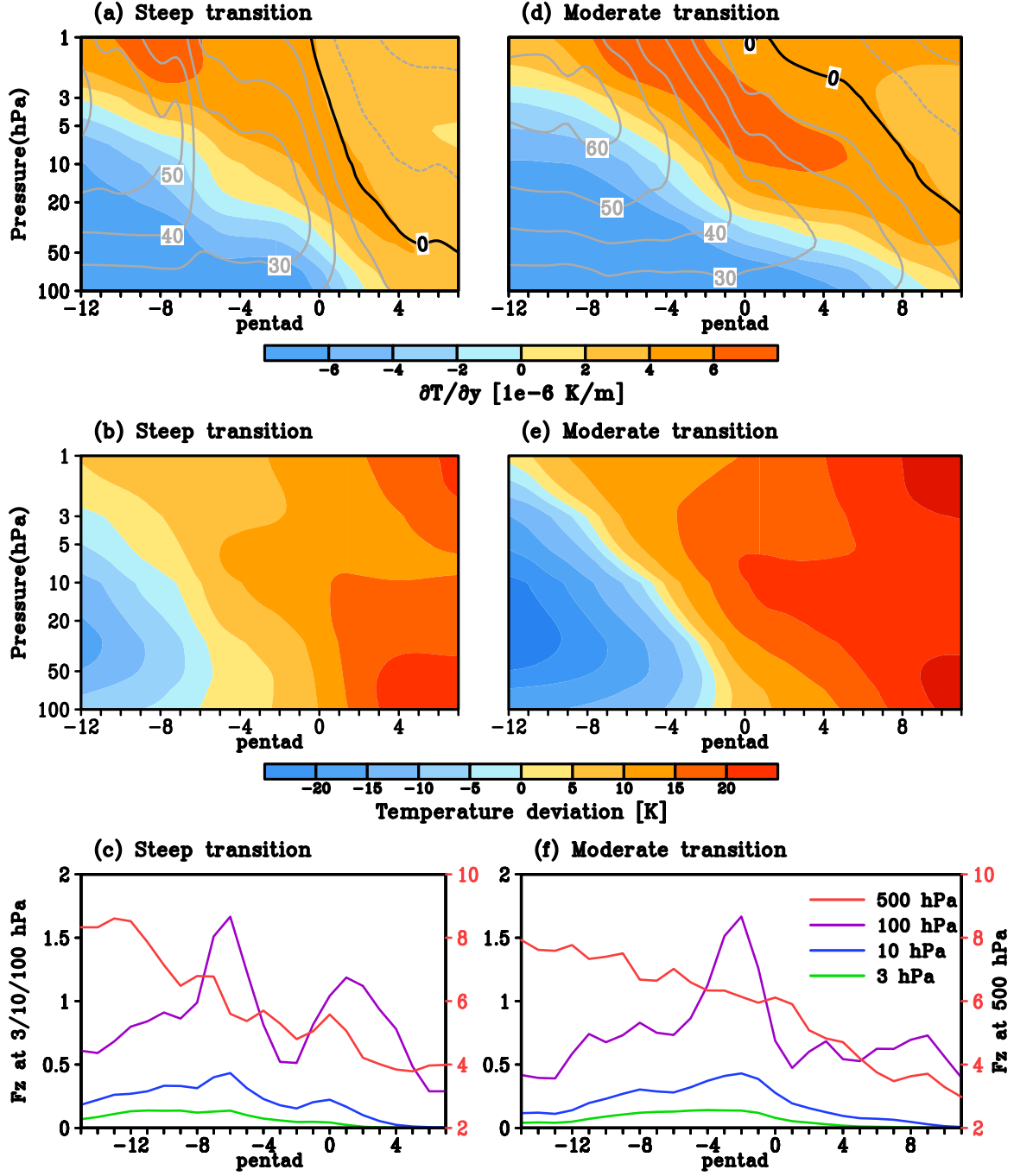


Fig. 13. Temporal evolutions during steep (a–c) and moderate (d–f) years of zonal-mean averaged over 60°S–85°S of (a and d) temperature gradient (shaded) and zonal wind (contour, in m/s), (b and e) temperature deviation from the global mean, and (c and f) upward wave activity fluxes, based on a composite analysis of 8 extreme years. Units on the horizontal axis are in pentads relative to the reference pentad.

transition starting time between the two types is about 15 days.

Figure 13 shows a comparison between the composites of steep (left panels) and moderate (right panels) transition types versus pentads. For moderate transitions, the

temperature gradient in the upper stratosphere is stronger than that of the steep transitions (Fig. 13a and d). The temperature deviation shows that near about 6 pentads before transition, the moderate transition case is colder in the lower stratosphere and warmer in the upper

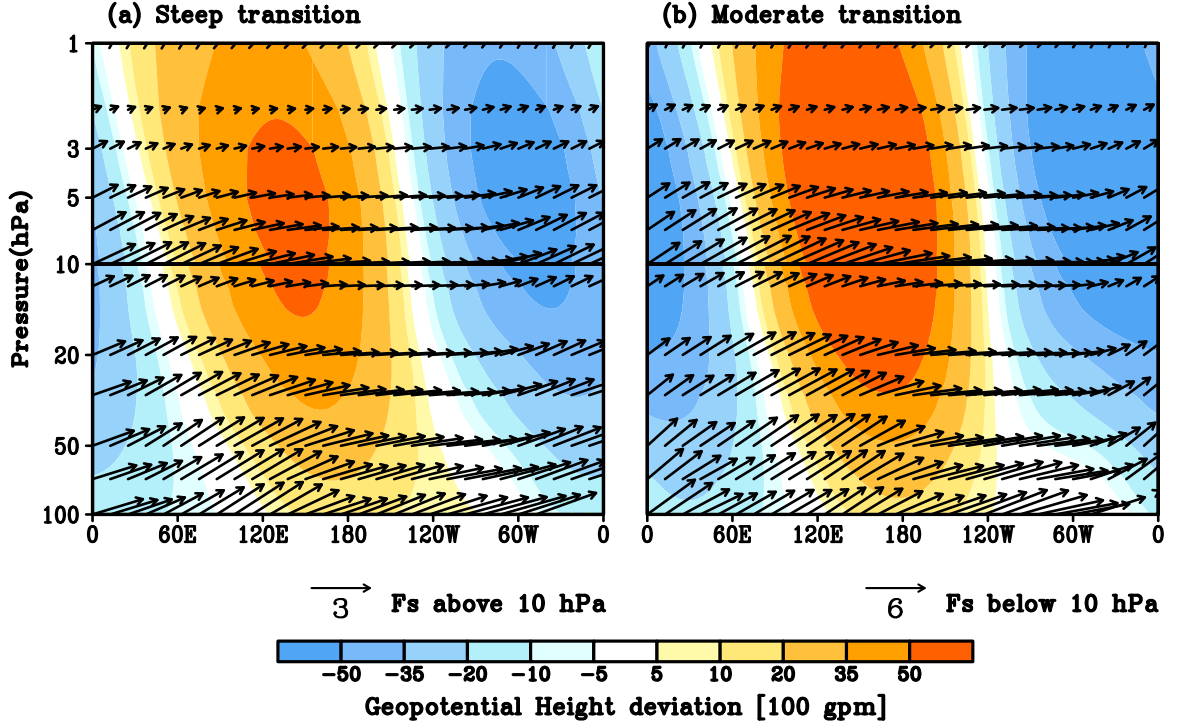


Fig. 14. The Longitude-pressure cross sections of 9-pentad prior to the transition pentad mean geopotential height deviations from the zonal mean (shaded) and WAFs (vectors) averaged over 60°N–85°S composite in (a) steep, and (b) moderate cases. Units of WAFs, m^2/s^2 .

stratosphere compared to the steep transition case (Fig. 13b and e). This implies that stronger planetary wave activity in moderate transition years propagates upward into the stratosphere and warms the upper layers first. This is supported by Fig. 13f, where WAFz peaks are observed at 100, 10 and 3 hPa, two pentads before the seasonal transition in the moderate transition case. For the steep transition case, the peaks of WAFz at the same levels are around six pentads before the transition (Fig. 13c). In the meantime, we notice that the transition time of steep years is three pentads later than that of moderate years. This suggests that the atmosphere receives more solar radiation at this transition time (Fig. 1a). During the years of steep transitions, when WAFz starts to decrease from its peak in pentad -6, more solar radiation leads to more heating of the whole stratosphere. Surely, the seasonal transition does not occur until the winter polar region receives enough solar heating. As soon as this critical warming is reached, any not-so-strong planetary WAFz can be a trigger to the final stratospheric warming (Fig. 13c, the second peak of Fz at and above 100 hPa), and can lead to a sharp change, hence the short transition. In this case and unlike the NH, the difference between the two types of the SH transitions, see also Fig. 7b, is controlled by both the upward propagation of planetary wave activity and the solar radiation.

In the SH, the planetary zonal wave number 1 is predominant in both types, with much stronger amplitude in moderate transition years (Fig. 14). Planetary wave fluxes convergence takes place around the eastern edge of the Antarctic High. This distribution contributes to the near barotropic structure of Antarctic High and Antarctic Low. The magnitude of WAFs is stronger in moderate transition years. The strong planetary wave activity contributes significantly to the upper stratospheric heating and leads to a gradual tilt of transition, explaining the long time between the seasonal transitions occurring in the upper and lower stratosphere.

5. Discussion

The predominant stratospheric variability on climatological seasonal time scale is strongly dependent on the stationary planetary waves. Wave activity can be measured with Plumb wave activity and E-P fluxes. Although Plumb WAF used here is based on unfiltered data, the filtered E-P flux for planetary wave numbers 1–3 yields similar results (not shown). A number of authors discussed the influence of different wave number components separately on the stratospheric activity (Randel, 1988; Harada and Hirooka, 2017) and the jet variability (e.g. Iqbal et al., 2017). For different individual years

there would be more details if the contributions of different wave numbers are discussed separately. But in this work we discussed the climatology and composite results for several extreme years based on the transition index, and no significant difference is obtained between previous studies and the results presented here.

Here we also discussed the influence of planetary wave activity during spring time on the seasonal transition in the stratosphere. The NH has more planetary wave activity in winter than in spring (Section 3), but the relationship between seasonal transition and wave activity in winter is more elaborate. For example, SSW is forced mostly by planetary waves, which propagate upward from the lower atmosphere and alter the stratospheric thermodynamic structure through heating the high latitudes and decelerating the mean zonal wind, and this would eventually affect the seasonal transition. But a simple linear correlation analysis does not show a significant relationship between WAFs in winter and the transition date in the stratosphere. Obviously the relationship between winter wave activity and seasonal transition is not plain linear, and further investigation is needed to figure out how winter planetary wave activity affects the seasonal transition.

Beside, we analysed the relationship between the seasonal transitions and SSWs occurring in the transition period of the NH. When SSW occurs well before the transition period, e.g. in late February, the polar vortex cannot be re-established and the westerly polar night jet remains weak enough (or even reverses to easterly) especially below 10 hPa (see e.g. the distribution of zonal-mean zonal wind in Fig. 8a), to be effectively influenced by the increasing solar radiation. In some cases the polar vortex is re-established in the upper stratosphere after mid-winter SSW (Thiéblemont et al., 2016), but the vertical propagation of planetary wave would still be prohibited by the prolonged reversed easterlies in the lower stratosphere, and the upper stratosphere is comparatively cold and dominated by stronger westerlies. In this case, the synchronous transition driven by solar radiation may easily occur. On the contrary, when SSW occurs in the transition period, which is usually called a final warming, the asynchronous transition (driven by planetary wave activity) may be realized. According to Butler et al. (2017), the following years 1979, 1980, 1984, 1989, 1999, 2007, and 2008 for major SSWs in late February (the major warming is not the final warming and it is far from the transition time), most of them are found to correspond to synchronous years. On the other hand, SSWs occurred in March in the years 1981, 1988, 2000, and 2010, major warming is closer to transition date. In this case, the occurrence number is small and the relationship is unclear.

For the interannual variability of the seasonal transition in both hemispheres, here we identified and discussed roughly two types of large-scale phenomena, i.e. synchronous/asynchronous transitions in NH and steep/moderate in SH, which are based on the upward propagation of planetary waves and small sample size of 38 years. We know that the most robust interannual signal in the tropical stratosphere is Quasi-Biennial Oscillation (QBO). Although the QBO is an equatorial phenomenon, it still does affect the stratospheric flow by modulating the effects of extra-tropical waves (Baldwin et al., 2001). QBO would also influence the seasonal transition in both hemispheres through its modulation of planetary wave propagation and breaking. The interannual variability of seasonal transition could also be influenced by other large-scale teleconnections. As shown in previous studies, the interannual variability of seasonal transition (timing and length) in the NH has been linked to variability of the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) (see Turner et al., 2007). A detailed analysis of the interannual variability of the seasonal transition is beyond the scope of this research and is left for future research.

6. Summary and conclusions

The climatological features of the seasonal transition in high-latitude stratosphere are examined. The role of planetary waves in the seasonal transition of the circulation in both hemispheres, along with the types of transitions is investigated. The seasonal transition from winter to summer in the NH occurs almost at the same time in the upper and lower stratosphere. The situation is different in the SH where the transition always starts from the stratopause and then propagates downward to the lower stratosphere, characterized by a tilted structure in zonal-mean zonal wind and temperature. The difference between the two hemispheres, regarding the structure of the transition, is associated with the difference in the seasonal cycle of the upward propagation of planetary wave activity. In the troposphere, both hemispheres have similar strength of the planetary wave activity in winter. In the stratosphere, however, the SH has less wave activity compared to the NH due to the stronger zonal-mean westerly winds in the former hemisphere, which suppress the upward wave propagation. In austral spring when zonal wind weakens, planetary waves can propagate easily into the stratosphere and break first in the upper stratosphere, weaken the zonal wind further and warm the air there. The zonal wind eventually reverses to easterly and the critical layer descends. The wave vertical propagation is limited by the forming critical line, so the transition consequently propagates from the upper to the lower stratosphere.

The interannual variability of the planetary wave activity in the NH is much larger than that in the SH. Taking the vertical component of WAF at 100 hPa as a measure of the upward propagation strength of the planetary wave into the stratosphere, simple correlation analysis shows highly significant negative correlation coefficient between wave activity in spring and the seasonal transition time in the stratosphere. This clearly indicates that stronger wave activity propagating into the stratosphere leads to earlier stratospheric seasonal transition in both hemispheres.

Two types of transition have been suggested and analysed, namely, synchronous/asynchronous in the NH and steep/moderate transitions in the SH. A composite analysis of two types of seasonal transition in the NH shows that stronger wave activity before transition leads to an asynchronous type, where the zonal wind reverses first in the upper stratosphere then subsequently in the lower stratosphere. A similar but not identical behaviour is also observed in the SH. In this latter case, where the structure is always tilted, the two types of transition are identified depending on the vertical gradient of the zonal wind reversal (the length of the transition period from the upper to the lower stratosphere). The composite analysis reveals that the average transition date of the moderate transition type is 15 days earlier than that of the steep transition type. The seasonal transition starts earlier for the moderate type due to warming in the upper stratosphere caused by stronger upward propagation of the planetary wave activity around spring time following the weakening of the westerlies. For the steep transition type, in addition to wave activity, the increasing solar radiation contributes substantially to the seasonal transition.

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