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Variability of the springtime transition date and planetary waves in the stratosphere

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ABSTRACT

The interannual variability of the springtime transition date of the stratospheric circulation is analyzed on the basis of the data assimilated in the UK Met Office and NCEP/NCAR models. As a proxy for the zonal mean flow we use the geostrophic wind calculated at 65.7 N from geopotential heights of the 10 hPa pressure level. The results show that the springtime transition date depends on the planetary-wave activity in the stratosphere and there is a tendency to the later date with a rate of about 4 days per decade. The significant correlation between the interannual variability of the spring transition date and amplitudes of stationary planetary wave with zonal wave number 1 is found. A noticeable dependence of the breakup date on the NAM index and the QBO phase is observed.

1. Introduction

The general circulation of the stratosphere in winter is controlled by both radiative and dynamical processes induced by the solar heating and nonlinear interactions of the mean flow with planetary waves (PWs). The springtime transition of the zonal mean flow is forced radiatively by seasonal changes of the solar zenith angle, and observed at approximately 10 hPa in the first half of April. Dynamical processes significantly influence the date of the springtime polar vortex breakup. As a result, there is a significant interannual variability of the springtime transition date (Waugh et al., 1999; Wei et al., 2007; Pogoreltsev and Savenkova, 2010). Many authors (e.g., Haklander et al., 2007; Newman et al., 2001; Christiansen, 2001; Polvani and Waugh, 2004; Hinssen and Ambaum, 2010) demonstrated that the variability of the eddy heat flux, which is a proxy of the wave activity entering the stratosphere, is of primary importance for interannual variability of the polar vortex breakup date. The interannual variability of the poleward heat flux is dominated by stationary planetary waves (SPWs). One can add that an especially significant contribution is provided by the SPW with zonal wave number 1 (SPW1), and one can expect a correlation between amplitudes of SPW1 and dates of the spring transition. The quasi-biennial oscillation (QBO) modulates the wave activity flux into the stratosphere. As a result the strength of the polar vortex depends on the phase of the QBO. Thus, the spring date is also expected to be dependent on the QBO phase.

The long-term variability of the polar vortex breakup date is of a special interest in the context of the climate change. The results of the corresponding analysis were presented by Waugh et al. (1999), Waugh and Polvani (2010), Karpetchko et al. (2005), Langematz and Kunze (2006), and Wei et al. (2007). These studies found no statistically significant trends in the Arctic in the vortex location and strength (Karpetchko et al., 2005; Langematz and Kunze, 2006). However, for the beginning of spring may have definite tendencies. For example, a tendency toward late date of the spring transition was found by Wei et al. (2007) and Offermann et al. (2004). In this paper we present additional evidence for a dynamical link of the interannual variability of spring transition dates with variability of the planetary wave activity. In particular, we statistically show that the variability of SPW1 amplitudes can drive the spring date variability, and this process is modulated by the QBO and Northern Annular Mode (NAM) index, that has not been presented in literature yet. The time series of the spring transition dates is constructed on the basis of a new proposed algorithm. This algorithm uses mean zonal wind values for the definition of the date and does not use any threshold values.

2. Data and method

To analyze the interannual variability of the spring breakup date and its relation with the PW activity, the data assimilated in

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the UK Met Office model were used (Swinbank and O'Neill, 1994). The upper boundary of the UK Met Office model is set relatively high (0.1 hPa and even 0.03 hPa since 2010), which means that most likely dynamical processes in the stratosphere are adequately reproduced by the model. The geopotential heights of the 10 hPa pressure level at 67.5 N latitude during January–June were used to calculate the geostrophic zonal mean wind. Unfortunately, the UK Met Office data are available only since the end of 1991. To analyze the longer time series of the spring transition date and PW activity, the geopotential heights of the 10 and 30 hPa levels from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) were used (Kalnay et al., 1996). Late-winter and spring months were considered since 1971. Although the main objective of this study is to determine climatic changes in the spring transition date, we did not analyze the NCEP/NCAR data for 1948–1970 because of a relatively low reliability of the NCEP/NCAR reanalysis in the stratosphere for the years before satellite observations were introduced. At first, we analyzed only the "satellite era" data (since 1979), but then added the reanalysis for 1971–1978 to increase the statistical significance of the obtained results. For 1971–1978, the NCEP/NCAR model is capable of reproducing the QBO at low latitudes (Kistler et al., 2001). Therefore, we included the 1971–1978 time interval in our consideration. Data on the QBO of the zonal flow obtained from ground-based and satellite observations are available from 1953 to the present. In this study we used the monthly mean zonal wind averaged over levels of 40 and 50 hPa. For 1971–1975 the measurements were done at the station Maledives (GAN/Maledives, 00.41S/73.09E). Since 1976, the observational data in Singapore have been used (Singapore, 01.22N/103.55E). Positive values of the zonal flow at 40–50 hPa correspond to the westerly phase of the QBO (w-QBO), and negative ones are for the easterly QBO phase (e-QBO). The QBO data were taken from the website of the Free Berlin University http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html. Index of the NAM was taken from the site of Mark Baldwin http://www.nwra.com/resumes/baldwin/nam_index_1958-2006.txt.

There are several methods to estimate the breakup of polar vortex and/or springtime transition date. One may define it as the time when the area within a given polar vorticity contour falls below a certain value (Manney et al., 1994; Waugh and Randel, 1999), or when the zonal wind velocity falls below zero or another critical value (Waugh et al., 1999; Wei et al., 2007). Such definitions are somewhat vague because of irregular oscillations of the wind around the chosen critical value for a long time in some years. Hence, it is difficult to rigorously determine the day when the springtime transition takes place. More generally a choice of the particular polar vorticity contour and other critical values is subjective as was noted by Waugh et al. (1999), and, therefore, the breakup criteria are subjective as well. The time series of the zonal mean wind at 10 hPa pressure level and 67.5 N latitude during late-winter and spring of 2008 is shown in Fig. 1. It is seen that the zonal mean velocity oscillates around zero for a long time, thus making the determination of the exact moment of the spring breakup very complicated. In this paper we introduce a new and more formalized method for determination of the onset of the springtime transition.

We use the zonally averaged geostrophic wind $\overline{U}_g$ calculated from the UK Met Office geopotential height data at 10 hPa level as a proxy for the zonal mean velocity

$$\overline{U}_g = -\frac{1}{2\Omega a \sin\varphi}\frac{\partial\overline{\Phi}}{\partial\varphi},$$

where Ω and a are the Earth's rotation rate and radius, correspondingly, φ is the latitude, $\Phi = gh$ is the geopotential, g is the acceleration due to gravity, and h is the geopotential height, and overbars denote zonally averaged values. The climatological behaviour of the zonal mean flow at 10 hPa and 67.5N between January and June was obtained by averaging $\overline{U}_g$ over 1992–2009 years. Fig. 1 presents the observed zonal mean wind (solid line) and the calculated geostrophic one (dashed line) for 2008 to demonstrate a very good agreement between seasonal variations of both.

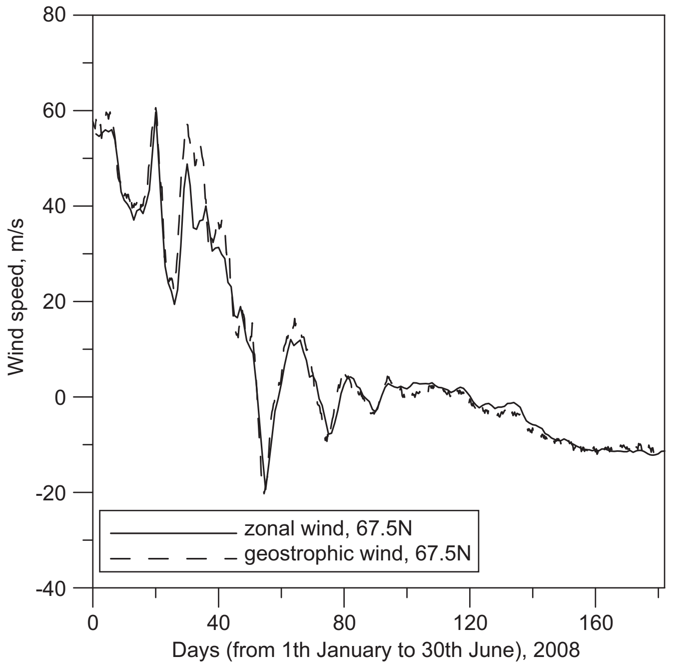

Fig. 1. Behaviour of the observed and geostrophic zonal wind at 10 hPa pressure level during January–June, 2008.

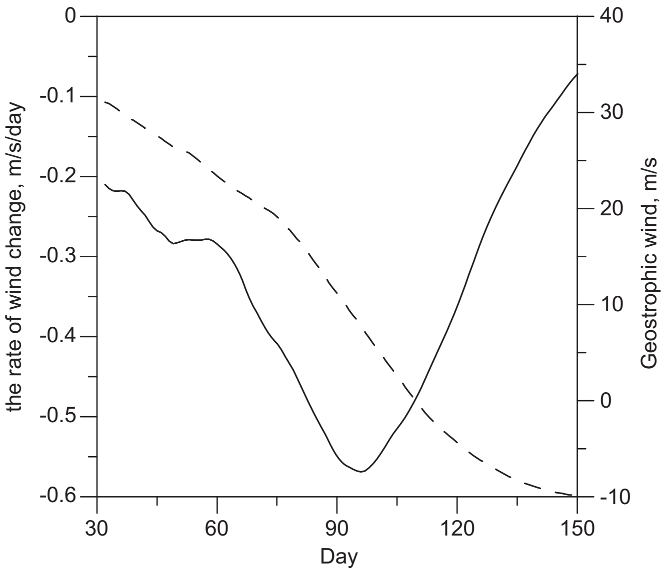

Fig. 2. The climatological behaviour of the geostrophic wind (averaged over 1992–2009 years) and its rate of change (solid and dashed lines, respectively).

We define the climatic date of springtime transition (averaged over 1992–2009 years) as the day of the year when the geostrophic zonal wind changes (decreases) most rapidly. To suppress strong variations of the temporal gradient, the geostrophic zonal wind was smoothed with a 31-day "window". The results for the climatological wind (averaged over 1992–2009 years) and its rate of change are shown in Fig. 2 with solid and dashed lines, respectively. It is clearly seen that the climatic spring transition date is the day where the gradient is negative and reaches its maximum by absolute value that is around the 6th of April. Then, we computed the residual error between the observed changes in the geostrophic zonal wind for each year and its multi-year average. By shifting the observed time series with respect to the averaged one, we determined the delay or advance of the springtime transition date for the particular year as the one for which the residual error is minimal. Because the time interval between early and late breakup of the polar vortex is about 2 months (Wei et al., 2007), we performed the shift within ± 30 days with respect to the 6th of April. The climatic (averaged over 1971–2009 years) springtime transition date based on the NCEP/NCAR reanalysis data is shifted by 7 days towards earlier date in comparison with the date calculated from the UK Met Office data, that is, to the 30th of March.

3. Variability of the springtime transition date

Figs. 3 and 4 show the variability of the spring-time transition date, calculated according to the UK Met Office and NCEP/NCAR data. One can see that the springtime transition date varies in the range of about 2 months from mid-March to mid-May. Fig. 4 shows that there exists a noticeable trend toward later dates for the NCEP/NCAR data. It should be noted that the trend is substantially weaker during the last two decades (Fig. 3), and we observe some kind of saturation in the springtime breakup date. The trend obtained can explain also the difference in the climatic springtime transition dates calculated with the UK Met Office (1992–2009) and NCEP/NCAR (1971–2009) data. The ratio of the absolute value of the linear trend to standard deviations for spring transition dates calculated using the NCEP/NCAR data is around 2. The time interval considered includes 41 years and the trend obtained is statistically significant with a probability of about 0.05 by the t-test (Bendat and Piersol, 1986). A large interannual variability of the spring-time transition dates can be connected with the timing and characteristics of the so-called final stratospheric warming (Waugh and Rong, 2002; Waugh and Polvani, 2010). The detail analysis of the stratospheric warming events is beyond the scope of the present paper. However, the preliminary results obtained from the UK Met Office data analysis show that early spring breakup dates are usually connected with the final warmings in the second half of March (for instance, 1992, 2005). In the case of the late spring transition dates the PW activity is very weak in March and there is no any additional heating of the polar region in the stratosphere (2001, 2006, 2010).

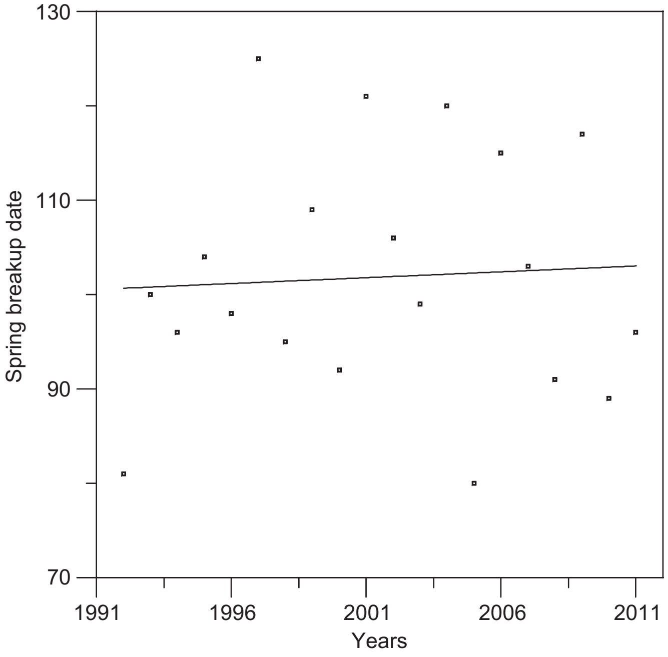

Fig. 3. Springtime transition dates, calculated using the UK Met Office data.

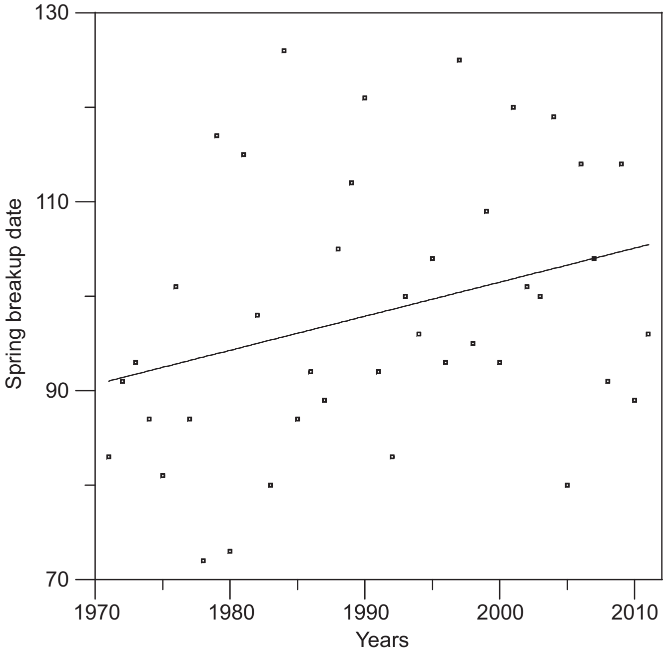

Fig. 4. Springtime transition dates, calculated using the NCEP/NCAR data.

4. Influence of planetary waves on the transition date

The changes of amplitude of the zonal harmonic with the wave number $m=1$ and the zonal mean wind at the 10 hPa level obtained on the basis of the UK Met Office data analysis are presented in Figs. 5–8 for 2008–2011, respectively. These figures show that there is an enhancement of the PW activity just before the breakup date. This provides the evidence that dynamical processes influence the stratospheric circulation during springtime transition time interval. It is seen that the zonal mean flow is rather weak during early breakups, which can be explained by the presence of strong traveling and stationary PW. When spring transition is late, the zonal mean flow is positive in March, while the amplitudes of PW are smaller.

Figs. 5–8 show also that during springtime transition there exists a strong variability of the PW1 amplitude (see, for instance, the beginning of March in 2008 and the end of March in 2011). This PW1 transience can be separated into westward and eastward traveling waves. However, this separation into the westward and eastward waves is ambiguous because the separated components partially contain the waves with equal amplitudes propagating in opposite directions (Pogoreltsev et al., 2009). These waves can be considered as a standing wave with the oscillating amplitude, which describe the irregular stratospheric variability, the so-called stratospheric vacillations (Holton and Mass, 1976). It should be noted that during springtime breakup the traveling waves with periods of about 10–15 days are active and can be observed in the mesosphere and ionosphere (Shepherd et al., 1999, 2002; Aushev et al., 2006). When the phases of these traveling waves coincide with that of SPW and standing wave, the amplitude of resulting

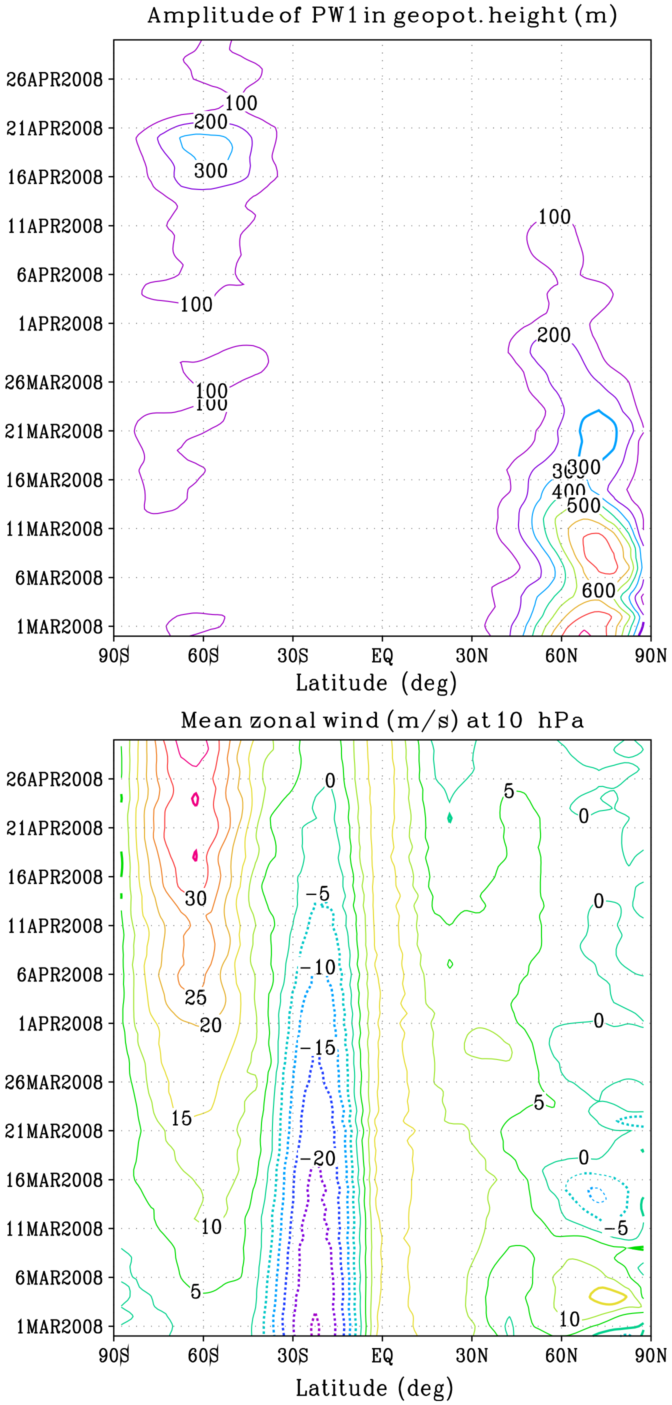

Fig. 5. Amplitude of the first zonal harmonic in the geopotential height (upper panel) and zonal mean flow (lower panel) at 10 hPa pressure level during March–May 2008. Contour intervals are 100 m and 5 m/s, respectively.

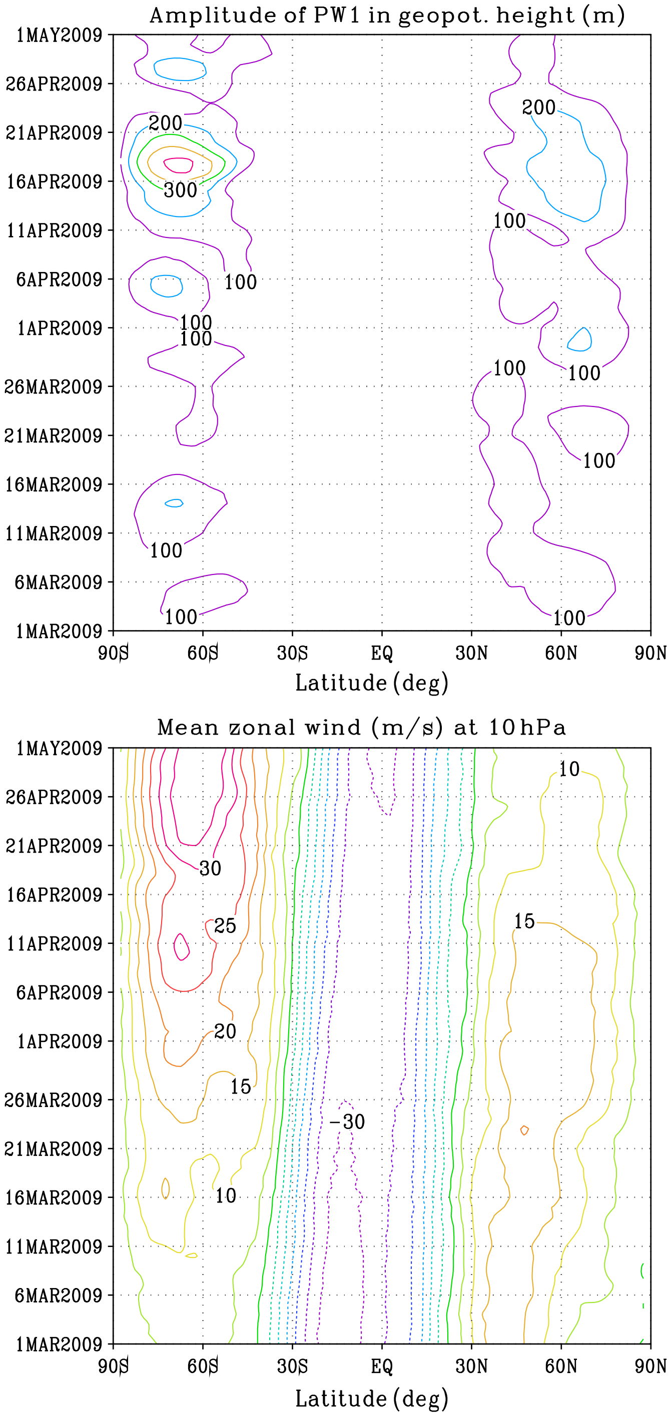

Fig. 6. Amplitude of the first zonal harmonic in the geopotential height (upper panel) and zonal mean flow (lower panel) at 10 hPa pressure level during March–May 2009. Contour intervals are 100 m and 5 m/s, respectively.

wave is amplified, which leads to a significant heating of the polar region and deceleration of the mean flow.

Fig. 9 shows the amplitude of the stationary planetary wave with the zonal wave number $m=1$ (SPW1) in geopotential height at 30 hPa level and latitude of 62.5N in March, obtained from the analysis of the data assimilated in the NCEP/NCAR model. The figure shows that there is a strong interannual variability of the amplitude, and there is a negative trend in the last decades. The *t*-test statistic is approximately 1.8 and the trend obtained is statistically significant with a probability of about 0.1. The scatter diagram for the SPW1 amplitudes at 30 hPa and the springtime transition date at 10 hPa is shown in Fig. 10. There is a significant negative correlation (correlation coefficient $r=-0.58$) of the SPW1 amplitude with spring-time transition date. It should be noted that if we remove the years when SPW1 has anomalous low or high amplitudes, then the correlation is stronger ($r=-0.7$). The observed negative correlation may (at least, partly) explain the observed trend of delaying the spring transition date. The weakening of the planetary wave activity in the stratosphere during the last decades leads to the fact that the role of dynamic processes is reduced, and springtime transition date are expected to be shifted to the date determined by the seasonal change of the solar zenith angle.

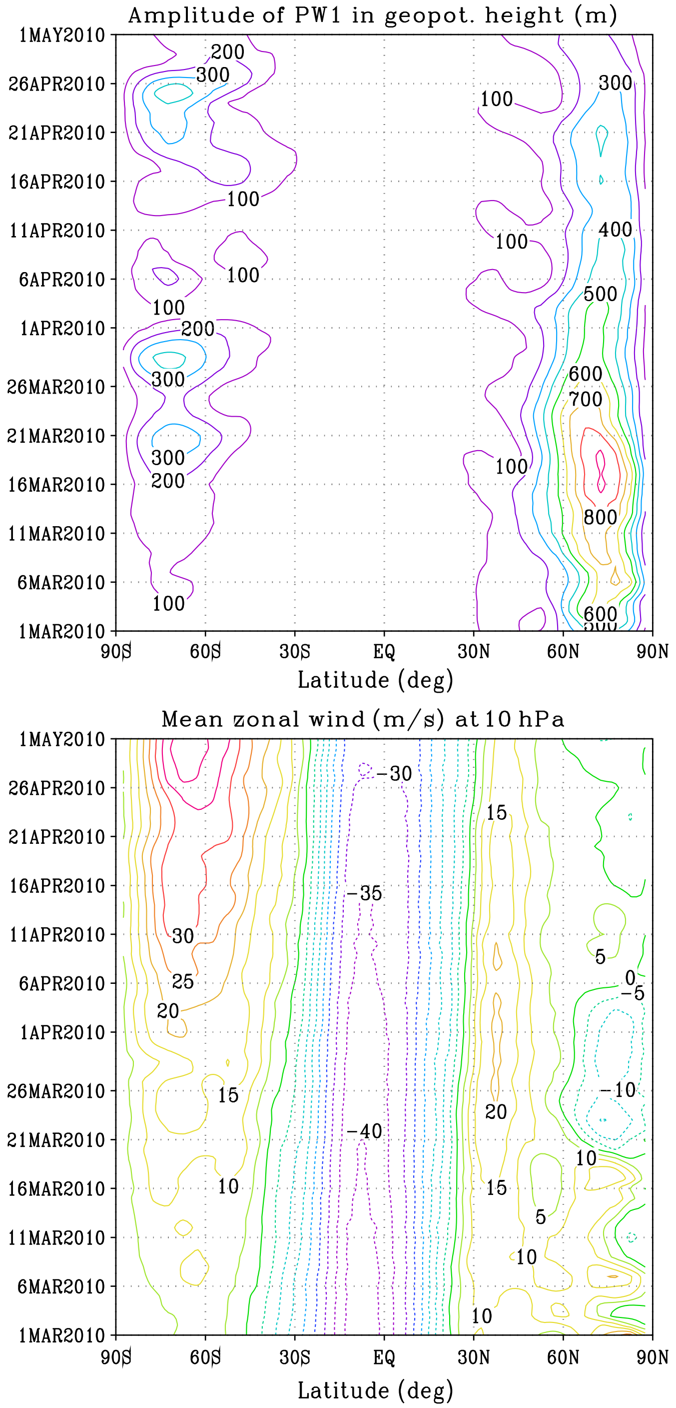

Fig. 7. Amplitude of the first zonal harmonic in the geopotential height (upper panel) and zonal mean flow (lower panel) at 10 hPa pressure level during March–May 2010. Contour intervals are 100 m and 5 m/s, respectively.

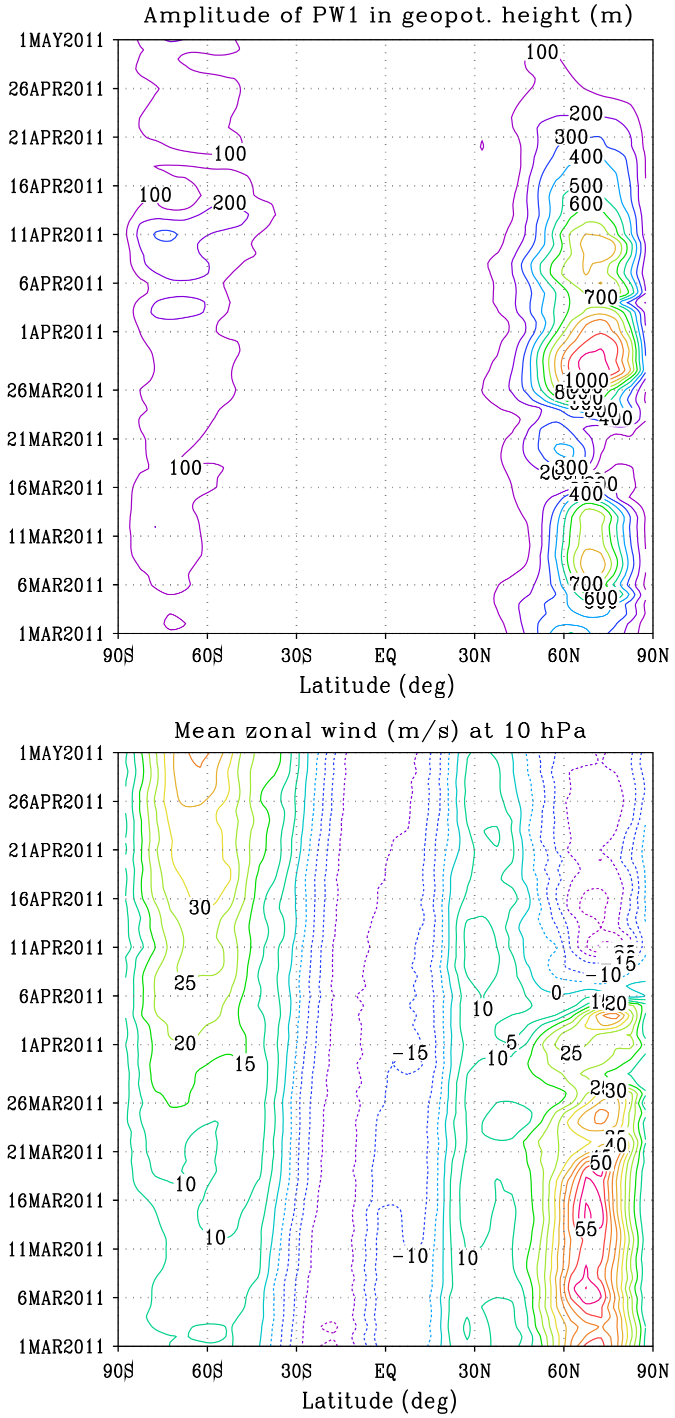

Fig. 8. Amplitude of the first zonal harmonic in the geopotential height (upper panel) and zonal mean flow (lower panel) at 10 hPa pressure level during March–May 2011. Contour intervals are 100 m and 5 m/s, respectively.

The correlation between the SPW1 amplitudes and the dates changes during the considered time interval 1971–2011. This was analyzed by calculating running correlations. The analysis was performed for de-trended time series of the spring date and the SPW1 amplitudes. For the calculation, we took a 15-year segment of the analyzed time series and made a sliding correlation analysis with a step of 1 year. The obtained correlation coefficients were prescribed to the center of each segment. The results are shown in Fig. 11. The 95% confidence level was estimated for each 15-year segment and it corresponds to the correlation coefficient of about 0.5. After 1993, there is a strong increase of correlation values. Taking into account the length of the segments, we can conclude that the correlations between the SPW1 amplitudes and the spring dates are very strong since the end of 1980th, and had moderate values before this time.

5. Effect of the QBO and NAM on the springtime transition date

It is well known that QBO of the zonal flow at low latitudes affect the extra-tropical circulation and, thus, alter conditions for

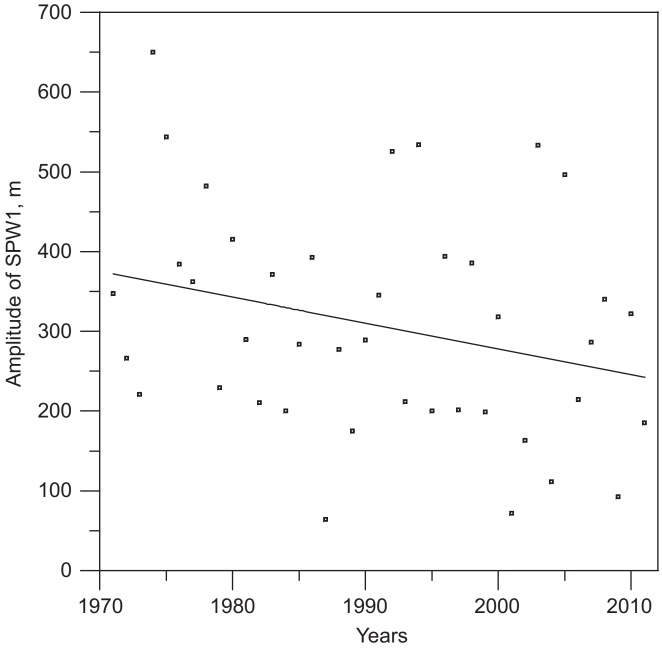

Fig. 9. Amplitude of the SPW1 in the geopotential height at 30 hPa and 62.5N in March.

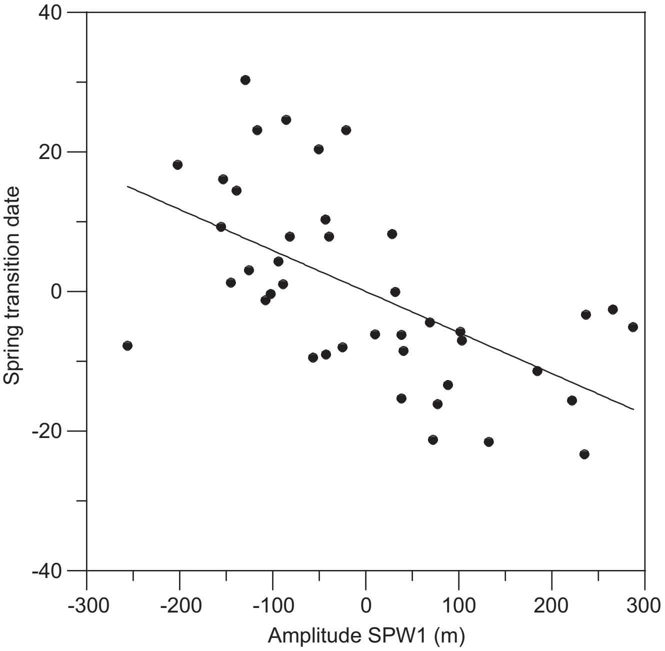

Fig. 10. Scatter diagram for the de-trended SPW1 amplitude at 30 hPa and date of the spring transition.

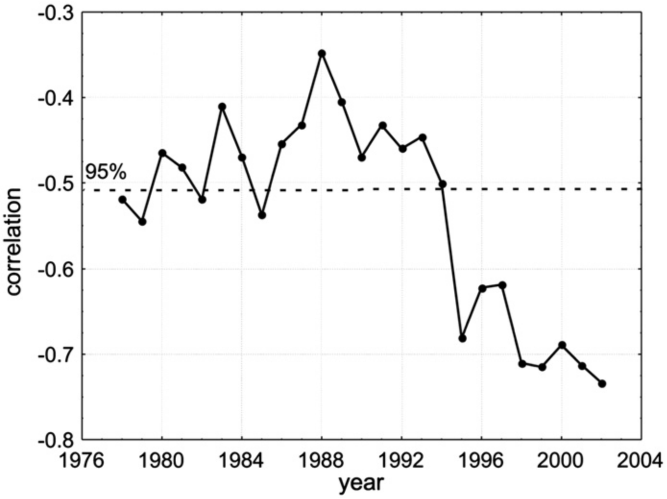

Fig. 11. 15-years running correlation between the SPW1 amplitudes and the spring breakup date.

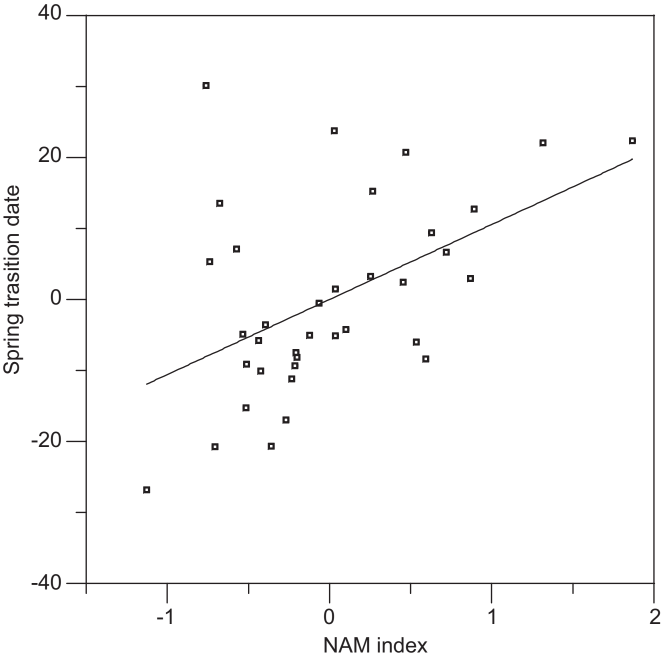

Fig. 12. Scatter diagram for the de-trended NAM index at 10 hPa averaged over March–April and springtime transition date.

planetary wave propagation (Holton and Tan, 1982; Chen and Huang, 1999; Baldwin et al., 2001). The extra-tropical QBO signal is seen mostly in the NAM (Ruzmaikin and Feynman, 2005). Therefore, we can assume that the QBO also affect the transition date of the stratospheric circulation. Correlations with time series of the springtime transition date can be found for the NAM index at different phases of QBO. Indeed, we did not find a significant correlation between the dates of the spring transition and the zonal wind at 40–50 hPa in March.

Correlations between the spring transition date and the NAM index at 10 hPa averaged over March–April is relatively low (correlation coefficient $r=0.49$, see scatterplot in Fig. 12). However, for the easterly phase of the QBO, the correlation is very high ($r=0.85$, see Fig. 13). High correlation is not observed for the westerly phase of the QBO ($r=0.47$). Thus, we can conclude that QBO affects the spring transition date of stratospheric circulation indirectly through dynamical processes, i.e., by changing the characteristics of the NAM, which is the first one of the orthogonal components of the hemispheric scale patterns of climatic variability. It should be noted that no significant changes of a dependence of the correlation between the spring transition date and SPW1 amplitudes on the phase of the QBO were found. Only a low value increase in correlation coefficient values was observed for the westerly phase of the QBO.

It is necessary to note another interesting result. The relation between early spring transition dates and the NAM index averaged over March–April is also significant independently of the phase of the QBO ($r=0.59$, see Fig. 14). For the later spring transition date, this relationship is weaker ($r=0.35$).

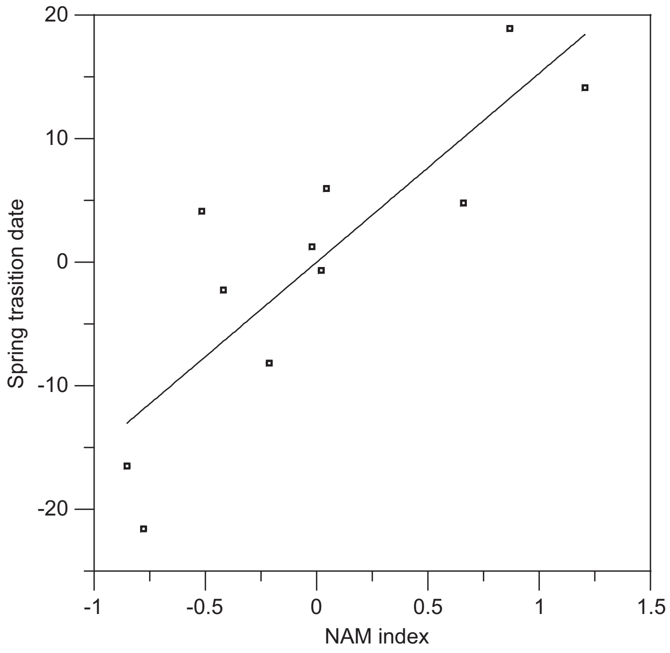

Fig. 13. Scatter diagram for the de-trended NAM index at 10 hPa averaged over March–April and springtime transition date. Easterly phase of the QBO.

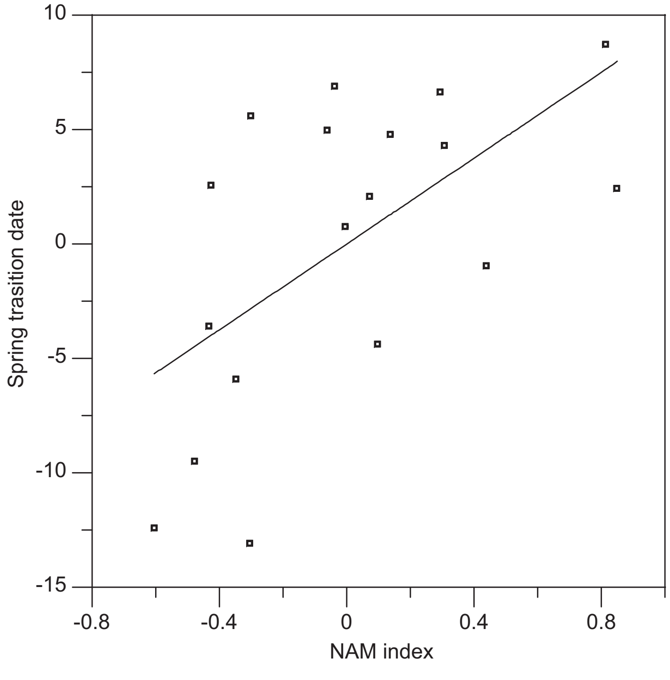

Fig. 14. The scatter diagram for the de-trended NAM index at 10 hPa averaged over March–April and early springtime transition date.

6. Summary and conclusions

We have proposed a new algorithm to characterize the beginning of spring in the stratosphere. The algorithm uses the rate of change of the mean zonal wind to determine this date. The results obtained show that the interannual variability of the springtime transition is driven mainly by wave–mean flow interactions during years with early breakup dates. In case of the late breakup date (low activity of planetary waves), the springtime transition is due to seasonal changes of the middle atmosphere heating over the polar region associated with the absorption of ultraviolet radiation. There exists a significant negative correlation between the spring transition date of the stratospheric circulation and the amplitude of SPW1. This can explain, to some extent, the delay of the spring transition date observed in recent decades as a result of the weakening of SPW1 activity in March. At easterly QBO phases, there is a statistically significant positive correlation between the spring transition date and the NAM index in the lower stratosphere. This correlation is substantially weaker in years with the westerly QBO. In case of early spring transition a positive correlation between the transition date and the NAM index averaged over March–April is found, which is independent of the QBO phase.

Acknowledgments

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