Journal of Atmospheric and Solar-Terrestrial Physics 136 (2015) 231–234

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Influence of the QBO and solar activity on interannual variability of the spring-time transition of stratosphere circulation

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ARTICLE INFO

Article history:
Received 3 February 2015
Received in revised form
11 August 2015
Accepted 19 August 2015
Available online 21 August 2015

Keywords:
Dynamics of the middle atmosphere
Spring-time transition
Solar activity
Quasi-biennial oscillations

ABSTRACT

In this paper the influence of solar activity on variability of the springtime transition dates of stratospheric circulation is investigated. To detect the influence, the springtime transition and solar activity datasets were grouped according to the phases of the Quasi-Biennial Oscillation (QBO). It was obtained that there is a dependence of spring transition dates on solar activity. In case of dividing data on early and later spring transition, the stronger influence of solar signal is revealed at late spring transition. It was also shown that under high solar activity conditions, the relation between spring transition dates and solar activity is stronger than at low one.

1. Introduction

The seasonal formation and decay of an intense cyclonic vortex over the winter pole is one of the most prominent features of the stratospheric circulation (Hamilton, 1999; Labiztke and Van Loon, 1999; Camp and Tung, 2007; Waugh and Polvani, 2010). Stratospheric polar vortex formation is observed in fall when solar heating of polar region is cut off, circulation reaches maximum strength in midwinter and then decays in later winter to spring as solar radiation returns to polar region. The springtime transition of the zonal mean flow or springtime polar vortex breakup is a change in direction of the zonal flow from eastward to the westward forced by seasonal changes of the solar heating. The reversal of zonal mean flow is observed at approximately 10 hPa pressure level typically in the first half of April. However, dynamical processes like nonlinear interaction of planetary waves with the mean flow may also influence the date of the springtime polar vortex breakup (Wei et al., 2007; Savenkova et al., 2011). As a result, there is a significant interannual variability of the springtime transition date. Such transition determines the beginning of spring season and has impacts on the hydrological cycle, vegetative growing season and ecosystem productivity. The time of stratospheric circulation transition also influences the tropospheric ozone, cloudiness and air temperature (Cayan et al., 2001; D'Odorico et al., 2002; Shepherd et al., 2002; Wei et al., 2007).

Numerous papers devoted to the investigation of springtime transition date variability present the analysis of different dynamical factors influence on spring transition date, for example, effect of planetary waves activity (Waugh et al., 1999; Karpetchko et al., 2005; Langematz and Kunze, 2006; Wei et al., 2007; Waugh and Polvani, 2010; Savenkova et al., 2011). Therefore, the aim of presented study is to consider the impact of solar activity on variability of spring transition date taking into account QBO effect.

2. Data and method of analysis

To estimate the relationship between the dates of springtime transition and characteristics of solar activity, the method of the correlation analysis (Malinin, 2008) was applied to a set of breakup data from 1971 to 2011. There are several methods to determine the breakup time of stratospheric circulation (Nash et al., 1996; Waugh et al., 1999; Wei et al., 2007; Savenkova et al., 2011). A method of date determination presented in the paper of Savenkova et al. (2011) is applied: the zonally averaged geostrophic wind at 10 hPa level taken as a proxy for the zonal mean velocity to find the climatic date of spring transition as the day of the year when the geostrophic zonal wind changes (decreases) most rapidly. Then according to this climatic spring transition day they calculate the transition day for particular year (Savenkova et al., 2011). Two sets of data were used to determine breakup dates: 10 years of UK Met Office data and 30 years of NCEP/NCAR data.

Since the number of breakup dates using NCEP/NCAR data (Kalnay et al., 1996) is more (30 years 1971–2011) we use this data set in our investigation. The data of stratospheric breakup event

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http://dx.doi.org/10.1016/j.jastp.2015.08.007
1364-6826/

are represented by numbers from 1 to 151, where 1st day corresponds to January 1 and, 151 day corresponds to May 31. As a proxy of a solar activity the yearly mean data of F10.7 radio flux were used. Solar radiation in radio wave band is not particularly distorted by the variable atmospheric characteristics and measured from Earth surface since 1950. Data of the F10.7 index were obtained from National Geophysical Information center archive, the USA [ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/]. The flux values are expressed in solar flux unit: 1 s.f.u. is equal to 10^{-22} W m^{-2} Hz^{-1}.

Information about QBO data is available on the website of Free Berlin university [http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html]. In this research the monthly mean components of a zonal flow u (0.1 m/s) of QBO were used. Positive values of a zonal wind correspond to the westerly phase of QBO, negative ones – to the easterly phase of QBO.

3. QBO phase influence on spring transition date

The solar activity influence on intensity of the north polar vortex in the stratosphere in winter and on the mean meridional circulation is in detail considered in Labitzke's studies (Labitzke, 1982; Labitzke et al., 2006). Labitzke and colleagues suggested that the Sun influences the intensity of the north polar vortex in stratosphere in winter, and that the QBO is needed to identify the solar signal. Her studies were devoted to the consideration of relation between geopotential heights in the area of polar vortex and solar activity. Correlation for all years from 1942 till 2006 between geopotential heights and solar F10.7 index is very small $r=0.1$. But grouping the data according to QBO phases results in statistically significant correlation for the westerly phase of QBO $r=0.69$, number of cases 36 (Labitzke et al., 2006).

Quasi-Biennial Oscillation are fluctuations in the atmosphere, which can be best observed in changes of vertical structure of the equatorial stratosphere winds, i.e. zonal winds blowing from the east to the west (the easterly phase) change the direction over time, blowing from the west to the east (the westerly phase). The period of QBO varies in space and time, with average value about 28 months at all levels (Baldwin et al., 2001). Numerous studies approve that an optimum choice of QBO levels for analysis are 40 hPa, 30 hPa and 50 hPa. But it is still difficult to explain why exactly this or that level gives the best correlation (Dunkerton et al., 1988; Camp and Tung, 2007; James and Shepherd, 2014). Therefore, we decided not to be limited to these levels, and used levels from 70 hPa up to the level of 10 hPa, all possible levels provided by the Free Berlin University database.

The initial data were checked for a trend presence. In interannual variability of spring transition dates and solar flux both positive trends which describe 9% of dispersion of initial selection and 1% respectively were detected (Malinin, 2008). The trend received within dates of spring transition is statistically significant with a probability of about 0.05 by t-test, therefore, for the further analysis the trend was removed. The trend obtained within the solar activity data on the basis of the F10.7 index was statistically insignificant.

We did not find the direct dependence between spring breakup date and solar activity. The correlation coefficient for all years $r=0.2$ and the scatter diagram is represented in Fig. 1.

Therefore, for detection of the Sun activity signal at the dates of spring breakup, it was decided to group the breakup data from 1971 till 2011 according to phases of QBO as it was suggested in Labitske's study (Labitzke et al., 2006), but considering different pressure levels.

After sorting the dataset according to the QBO phase and pressure levels, positive statistically significant correlations were found at QBO east phase, at the level of 30 hPa ($r=0.6$, $n=17$) and 15 hPa level ($r=0.5$, $n=24$) with a confidence level of about 0.05. The received results are shown in the Table 1.

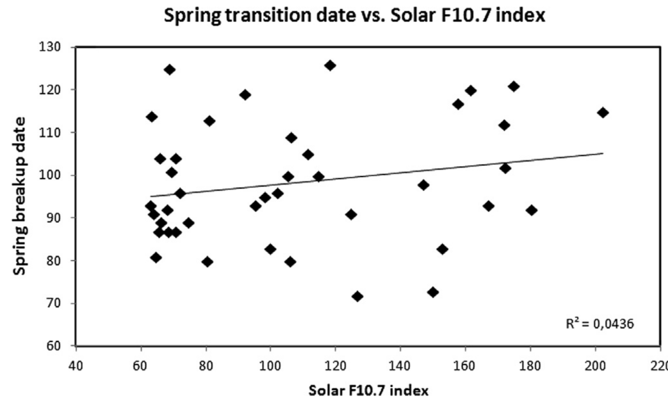

Fig.1. Scatter diagram of spring transition dates plotted against solar radio flux (index F10.7 (s.f.u.)) from 1971 till 2011, r is correlation coefficient, n is a number of cases.

Table 1
Correlation coefficients between spring transition dates and yearly mean values of solar radio flux (index F10.7 (s.f.u.)) at various QBO phases and at different geopotential levels where n is a number of cases, t^* and t_{cr} are significance assessment criteria.

QBO phases	QBO levels						
	70 hPa	50 hPa	40 hPa	30 hPa	20 hPa	15 hPa	10 hPa
QBO west phase	0.4 $n=28$	0.3 $n=30$	0.3 $n=27$	0.0 $n=24$	0.0 $n=18$	−0.1 $n=23$	0.1 $n=16$
QBO east phase	0.0 $n=15$	0.01 $n=11$	0.2 $n=14$	**0.6** $n=17$ $t^*=3.0$ $t_{cr}=2.1$	0.4 $n=23$	**0.5** $n=24$ $t^*=3.0$ $t_{cr}=2.1$	0.4 $n=25$

The scatter diagrams for two highest correlation coefficients $r=0.6$ and $r=0.5$ from the Table 1 are presented in Fig. 2. At higher solar activity the spring transition occurs later and the process is modulated by QBO.

From Fig. 1 it is clear that breakup dates of stratospheric circulation from winter to summer have strong interannual variations. Stratospheric spring transition is divided on early breakup which happens in March, middle-in April and late one in May. For more detailed analysis the influence of the Sun on early and later stratospheric breakup was considered. From available data of breakup date since 1971 till 2011 we distinguished an average day which is April 8 (98-th day).

Then, the grouped according to QBO phases and levels, dates of spring transition and corresponding to them the F10.7 solar flux indexes were divided on 2 groups of early and later breakup dates. Early transition days are taken as days less or equal to 98 and later transition are taken as dates after the 98th day. The received results on correlation coefficients between spring transition dates and yearly mean values of solar radio flux are presented in Table 2.

From Table 2 high, statistically significant correlation coefficients with a probability of about 0.05 by t-test are observed at QBO east phase, late breakup dates at 10–15 hPa levels, $r=0.6$ in both cases. The received results are confirmed by results of other investigations (Savenkova et al., 2011). In the study Savenkova et al., (2011) it was shown that early spring transition occurs because of high activity of planetary waves. In the case of the late spring transition dates the planetary wave activity is very weak and transition occurs due to seasonal changes of the middle

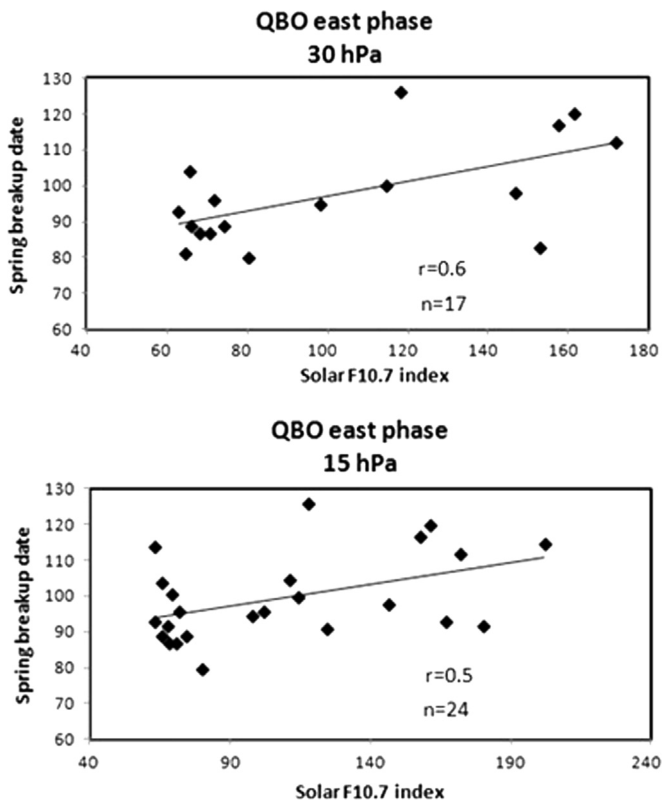

Fig.2. Scatter diagrams of spring transition dates plotted against solar radio flux (index F10.7 (s.f.u.)) for high correlation coefficients r=0.6 and r=0.5 at QBO east phase, 30 hPa and 15 hPa respectively.

Table 2
Correlation coefficients between spring transition dates and yearly mean values of solar radio flux (index F10.7 (s.f.u.)) grouped according to the early/later transition date and various QBO phases and geopotential levels, n is a number of cases, t^* and t_{cr} are significance assessment criteria.

Transition date/ QBO phases	QBO levels						
	70 hPa	50 hPa	40 hPa	30 hPa	20 hPa	15 hPa	10 hPa
Early dates, QBO-w	0.1 n=15	−0.1 n=13	0.1 n=12	−0.1 n=12	−0.5 n=9	−0.5 n=9	−0.2 n=9
Late dates, QBO-w	0.4 n=12	0.4 n=16	0.3 n=15	0.2 n=12	0.0 n=9	−0.1 n=8	−0.2 n=7
Early dates, QBO-e	−0.5 n=9	0.0 n=9	−0.2 n=11	0.1 n=11	0.1 n=14	0.3 n=14	0.1 n=14
Late dates, QBO-e	0.4 n=6	0.4 n=3	0.4 n=3	0.5 n=6	0.5 n=9	**0.6** n=10 t^*=2.5 t_{cr}=2.3	**0.6** n=14 t^*=2.6 t_{cr}=2.2

atmosphere heating over the polar region associated with the absorption of ultraviolet radiation. We find the relation between late transition and solar flux too, though now it is difficult to say why exactly these levels give high correlations.

4. Influence of high and low solar activity on spring transition dates

It is known that solar activity changes with the period of approximately in 11 years (Haigh, 2010). The 11-year cycle of solar activity has direct effect on radiation and ozone balance in the average atmosphere. In days of a maximum solar activity, the ultraviolet radiation is raised that results in additional production of ozone and heating in the stratosphere. Such heating can influence distribution of planetary waves which operates global circulation, and also has an impact on process of stratospheric spring transition.

Table 3
Correlation coefficients between spring transition dates and yearly mean values of solar radio flux (index F10.7 (s.f.u.)) grouped according to the high/low solar activity and various QBO phases and geopotential levels, n is a number of cases, t^* and t_{cr} are significance assessment criteria.

Solar activity; QBO phases	QBO levels						
	70 hPa	50 hPa	40 hPa	30 hPa	20 hPa	15 hPa	10 hPa
Low solar activity, QBO-w	−0.2 n=14	−0.1 n=18	−0.1 n=16	0.2 n=15	−0.1 n=14	0.0 n=12	0.3 n=9
High solar activity, QBO-w	0.1 n=13	0.4 n=12	0.4 n=11	0.4 n=9	**0.8** n=4 t^*=4.7 t_{cr}=3.2	**0.8** n=5 t^*=4.9 t_{cr}=2.8	**0.7** n=7 t^*=3.6 tcr=2.4
Low solar activity, QBO-e	0.0 n=11	0.3 n=4	0.2 n=5	−0.2 n=7	−0.4 n=12	−0.4 n=11	−0.3 n=9
High solar activity, QBO-e	1 n=3	−0.9 n=4	−0.5 n=5	0.0 n=7	0.0 n=12	0.1 n=11	0.0 n=9

To investigate the influence of high or low solar activity on spring transition date, we have done the same algorithm of steps as it was described above in Section 2. High solar activity are values of index F10.7 more then 107.4 s.f.u., low ones-less or equal to 107.4 s.f.u. Value 107.4 s.f.u. is the mean of solar F10.7 index for the period of 1971–2011. The results of correlation between spring transition dates and yearly mean values of solar radio flux grouped according to the high/low solar activity and various QBO phases and geopotential levels are presented in the Table 3.

High, statistical significant correlation coefficients was found at high solar activity conditions and QBO west phase groups, at 20, 15, and 10 hPa levels, where r=0.8, r=0.8, and r=0.7 respectively with a probability of about 0.05, by t-test. We try to explain this correlation using the results of the previous studies by Anstey and Shepherd (2014) and Holton and Tan (1980). Holton and Tan (1980) were the first to propose a mechanism of how the QBO might influence the vortex and showed the relationship during solar minima: winters during the west phase of the QBO tend to be cold and undisturbed, while winters during the east phase tend to be warm and disturbed (Holton and Tan, 1980). Labitzke and Van Loon (1988) note a reversal of the Holton and Tan relationship during solar maxima (Labitzke and Van Loon, 1988; Anstey and Shepherd, 2014). They showed a situation whereby, the QBO is at west phase and solar activity is maximum, leads to the polar vortex weakening, therefore, increasing activity of planetary waves and warming (but rather at QBO east phase). In principle, increasing of planetary wave activity leads to breakup date occurs earlier. However, we obtained positive (rather than negative) correlation exactly at these conditions, which means with increasing solar activity transition occurs late. The results shown in the above-mentioned articles were executed mainly for winter months, in our research we consider spring months. Due to this discrepancy can be caused.

Also we repeated all data analysis using method of nonparametric statistics (Malinin, 2008). Results show similar output but the values of correlation coefficients are smaller, identical according to a sign, but statistically they are not significant due to small number of data.

5. Conclusion

After analysis of a relationship between the dates of springtime transition and characteristics of solar activity for a period from 1971 to 2011, it can be concluded that the influence of solar activity on break up date is revealed and it is indirect. QBO helps to identify the solar signal in the stratosphere. Early spring transition occurs because of high activity of planetary waves. In the case of the later spring transition dates the planetary wave activity is very weak and transition occurs due to seasonal changes of the middle atmosphere heating over the polar region associated with the absorption of ultraviolet radiation (late transition at Table 2, QBO east phase at 15 hPa $r=0.6$ and at 10 hPa $r=0.6$). The Sun influence on spring breakup dates is pronounced more strongly under high solar activity and QBO west phase conditions, i.e. at high solar activity conditions at QBO west phase at 20 hPa $r=0.8$ at 15 hPa $r=0.8$, and at 10 hPa $r=0.7$ (Table 3).

Acknowledgments

Research is supported by the Russian Foundation for Basic Research # 12-05-33071 and Saint-Petersburg State University support (grant 11.50.1048.2014)

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