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Response of the dynamic and thermodynamic structure of the stratosphere to the solar cycle in the boreal winter

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ABSTRACT

The response of the dynamic and thermodynamic structure of the stratosphere to the solar cycle in the boreal winter is investigated based on measurements of the solar cycle by the Spectral Irradiance Monitor onboard the SORCE satellite, monthly ERA-Interim Reanalysis data from the European Center for Medium-Range Weather Forecasts, the radiative transfer scheme of the Beijing Climate Center (BCC-RAD) and a multiple linear regression model. The results show that during periods of strong solar activity, the solar shortwave heating anomaly from the climatology in the tropical upper stratosphere triggers a local warm anomaly and strong westerly winds in mid-latitudes, which strengthens the upward propagation of planetary wave 1 but prevents that of wave 2. The enhanced westerly jet makes a slight adjustment to the propagation path of wave 1, but prevents wave 2 from propagating upward, decreases the dissipation of wave 2 in the extratropical upper stratosphere and hence weakens the Brewer–Dobson circulation. The adiabatic heating term in relation to the Brewer-Dobson circulation shows anomalous warming in the tropical lower stratosphere and anomalous cooling in the mid-latitude upper stratosphere.

1. Introduction

The Sun is the most important source of energy in the Earth's climate system and variations in the intensity of solar radiation influence both the weather and climate (Chen et al., 2015; Rind, 2002, 2008; Shang et al., 2013; Wang et al., 2015; Zhao et al., 2012). Gray et al. (2010) showed that there are two main mechanisms, bottom-up mechanism and top-down mechanism, by which solar activity affects the Earth's climate. The top-down mechanism is connected to solar ultraviolet radiation. Solar ultraviolet radiation is mainly absorbed by ozone in the tropical stratosphere, which changes the meridional temperature gradient and wind field in the atmosphere. This further affects the propagation of stratospheric planetary waves in the winter hemisphere (Balachandran and Rind, 1995). Therefore, the solar radiation change can affect the interaction between the stratospheric circulation and the planetary waves (Haigh, 1996, 1999; Kodera and Kuroda, 2002; Shindell et al., 1999, 2006).

There are propagating anomalies of circulation associated with 11 years solar cycle in the stratosphere–troposphere system. Baldwin and Dunkerton (2005) analyzed the downward propagating anomalies of temperature and wind. Some studies indicated the possible mechanism of the downward propagating anomalies (e.g., Ambaum and Hoskins, 2002; Shaw and Perlwitz, 2013; Hitchcock et al., 2013; Hitchcock and Simpson, 2014). The solar cycle can also affect planetary wave activity in the coupled stratosphere–troposphere system (Perlwitz and Graf, 2001; Perlwitz and Harnik, 2003; Powell and Xu, 2011). The variation of stratospheric ozone is also associated with 11 years solar cycle (Austin et al., 2008; Yamashita et al., 2010; Gray et al., 2009) and can affect the stratospheric wave propagation (Hu et al., 2015). However, in the research of the response temperature to solar cycle, models have defects and large uncertainties (Mitchell et al., 2015a,b; Maycock et al., 2017). Multiple linear regression is an effective to separate influences of solar cycle and other signals on temperature (Lee and Smith, 2003; Yamashita et al., 2010; Matthes et al., 2013; Mitchell et al., 2015a,b).

However, much of the previously reported work on the effects of the solar cycle have only considered either quantitative dynamic or radiative processes or made a qualitative analysis of both processes. Hence there is a lack of quantitative analysis of the combined radiative and dynamic

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effects of the solar cycle, especially the respective effect on planetary waves 1 and 2.

The latest satellite data from the Spectral Irradiance Monitor (SIM) shows that the variation in the solar ultraviolet irradiance near 200 nm is c. 7%, which is much greater than the variation in the total solar irradiance (Haigh et al., 2010; Harder et al., 2009; Hirooka and Kuroda, 2004). On the other hand, the signals of the solar cycle in the atmosphere could possibly be created by many processes and the magnitudes of the signals are different among the seasons and the locations. Therefore it is necessary to accurately analyze shortwave heating anomalies over the solar cycle and their impact on the dynamic and thermodynamic structure of the stratosphere.

2. Data and methods

This study focused on the two winter months of December and January when the ultraviolet heating gradient in the Northern Hemisphere is more sensitive than at other times because the solar zenith angle is at a minimum.

2.1. Data

The dynamic analysis used the monthly ERA-Interim global reanalysis data from the European Center for Medium-Range Weather Forecasts. The satellite observations were assimilated over almost the entire ERA-Interim period after a 4D-Var analysis and the adequate bias corrections for ozone data. Therefore the ozone in the reanalysis dataset is considered to be reliable for the stratosphere (Dee et al., 2011).

The daily spectrum of solar irradiance (2004–2012) observed by the SIM instrument onboard the SORCE satellite was obtained from http://lasp.colorado.edu/home/sorce/data/ (Haigh et al., 2010; Harder et al., 2000). As the dataset is during 2004–2012 which cannot cover a whole solar cycle, we chose 2008 as the weak solar year and 2004 as the median solar year. We then extrapolated the state in a strong solar year. Table 1 gives the irradiance in different spectral bands in the strong and weak solar phases. There was a 7% change in the ultraviolet irradiance in the range 204–233 nm, which is in accordance with the study of Hirooka and Kuroda (2004). And this value is much larger than the variation of c. 0.1% in the total solar irradiance (Harder et al., 2009; Gray et al., 2010; Frohlich, 2006; Willson and Mordvinov, 2003).

2.2. Methods

The radiative transfer scheme of the Beijing Climate Center (BCC-RAD) was used to calculate the daily mean ozone heating rate (Zhang et al., 2003; Lu et al., 2011). This scheme used in this study does not have the interaction process between the chemical ozone change and the radiation, so the climatic mean ozone and the variational solar radiation are considered. The solar spectrum is divided into 17 absorption bands in this scheme. There are 6 ultraviolet bands in the range of 204–455 nm, one visible band in the range of 455–833 nm, one infrared band in the range 833–1923 nm, and 9 far infrared bands integrated together whose wavelength larger than 1923 nm listed in Table 1. We used the SIM data from the SORCE satellite (Table 1) and the ozone climate values from the ERA-Interim dataset to calculate the ozone heating rate. The amount of the solar radiation flux absorbed by ozone was calculated every 30 min from sunrise to sunset and was then integrated to give the daily mean ozone heating rate.

A multiple linear regression model (similar to those of Chen et al., 2015; Dhomse et al., 2006; Lee and Smith, 2003; Zhang et al., 2014) was used to separate the influence of the solar cycle on the boreal winter stratosphere from other forcing factors (Hu et al., 2017; Rao and Ren, 2017; Yang and Yu, 2016), such as the quasi-biennial oscillation (QBO), volcanic eruptions and the El Niño Southern Oscillation (ENSO). The monthly meteorological variable (T_m) in the stratosphere was assumed to be a function of a space vector x and the time t in years and can be expressed by the multiple linear regression model as follows:

$$\begin{aligned} T_m(x,t) &= \alpha_m^0(x) + \alpha_m^{lin}(x)\cdot ts(t) \\ &+ \alpha_m^{QBO10}(x)\cdot QBO10_m(t) + \alpha_m^{QBO30}(x)\cdot QBO30_m(t) \\ &+ \alpha_m^{aero}(x)\cdot aero_m(t) + \alpha_m^{solar}(x)\cdot solar_m(t) \\ &+ \alpha_m^{ENSO}(x)\cdot ENSO_m(t) + \varepsilon_m(x,t) \end{aligned}$$

where m is the mth month of one year, α_m^0 is a constant and α_m^{lin} is the linear trend coefficient in years. The other equation coefficients, in order, are designated by α_m^* with * representing the appropriate descriptor, e.g. QBO10. α_m^* is the coefficient for QBO at 10 hPa, QBO at 30 hPa, stratospheric aerosol (most affected by volcanic eruptions), solar flux and ENSO, respectively. ε_m represents the residual. The QBO indices are the Singapore monthly mean zonal winds at 10 and 30 hPa obtained from www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/. The aerosol index is the global monthly mean stratospheric (150hpa-1hpa) aerosol optical depth at 550 nm obtained from http://data.giss.nasa.gov/modelforce/strataer/. The solar index is the F10.7 cm solar radio flux (Keckhut et al., 2005) obtained from http://lasp.colorado.edu/lisird/tss/noaa_radio_flux.html. The ENSO index is the ERSST monthly NINO3.4 index obtained from www.cpc.ncep.noaa.gov/data/indices/.

Fig. 1 shows the regressed temperature averaged over 0–20° N at 30 hPa in January associated with five indices: the solar, aerosol, QBO, ENSO and linear indices. The solar regression coefficient of 0.32 is significant at the 90% confidence level by T test. The total correlation (Fig. 1a) between the observed and estimated temperature is 0.8, which shows that the regression effect is close to the real situation. The temperature regressed on the solar index (Fig. 1b) shows an 11-year cycle at the 90% significance level. In section 3 and 4, the meteorological variables were also regressed onto the solar index term as $\alpha_m^{solar}(x)\cdot solar_m(t)$ before the composite analysis.

Based on the normalized monthly mean solar F10.7 cm index in December and January (Fig. 2), we selected four continuous and strongest (weakest) years in each cycle as the strong (weak) solar phases. Twelve January months (1979–1982, 1989–1992 and 2000–2003) were in strong solar activity phases and twelve January months (1985–1988, 1995–1998 and 2007–2010) were in weak solar activity phases. The December months used are those that directly preceded the January months.

The Eliassen–Palm flux (EPF) in equation (1) is able to diagnose the propagation of planetary waves and the transformed Eulerian mean (TEM) velocities in equation (2) can describe the Brewer–Dobson circulation (BDC) (Andrews et al., 1987; Edmon et al., 1980; Shi et al., 2015):

$$\begin{cases} F_{(\phi)} = -r_0 \cos\phi \overline{u'v'} \\ F_{(p)} = f r_0 \cos\phi \dfrac{\overline{v'\theta'}}{\overline{\theta}_p} \end{cases} \tag{1}$$

Table 1
Irradiance fluxes of solar spectrum bands for ozone absorption in strong and weak solar phases and their variation rates from the SIM instrument onboard the SORCE satellite.

Ultraviolet bands for ozone absorption (nm)	Irradiance fluxes in strong solar phase (W m^{-2})	Irradiance fluxes in weak solar phase (W m^{-2})	Variation (%)
204–233	1.1419	1.0656	7.16
233–270	3.6845	3.536	4.20
270–286	3.2598	3.1649	3.00
286–303	8.0095	7.9522	0.72
303–322	12.1555	12.0303	1.04
322–455	176.553	176.095	0.26
455–833	595.832	595.832	0.00
833–1923	469.818	469.818	0.00
1923-	86.9116	87.8715	−1.09