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Discussions

Examining the stratospheric response to the solar cycle in a coupled WACCM simulation with an internally generated QBO

A. C. Kren[1,2], D. R. Marsh[3], A. K. Smith[3], and P. Pilewskie[1,2]

[1] Department of Atmospheric and Oceanic Sciences, University of Colorado at Boulder, Boulder, Colorado, USA
[2]Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, Boulder, Colorado, USA
[3]National Center for Atmospheric Research, Boulder, Colorado, USA

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Correspondence to: A. C. Kren (andrew.kren@colorado.edu)

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Abstract

The response of the stratosphere to the combined interaction of the Quasi-Biennial Oscillation (QBO) and the solar cycle, and the influence of the solar cycle on the QBO, are investigated using the Whole Atmosphere Community Climate Model. A transient simulation was run from 1850–2005 with fully interactive ocean, chemistry, greenhouse gases, volcanic eruptions, and an internally generated QBO. The model QBO produces a realistic representation of equatorial stratospheric winds. The simulation results are analyzed to examine the modulation of the Holton–Tan effect by the solar cycle. Over ~40 yr periods a correlation is sometimes found between the northern polar geopotential heights and the 255 nm solar irradiance when the data are separated as a function of QBO phase. At other times, the correlation switches sign; it is not robust over the entire simulation. Complementing this are analyses of several additional model runs: an additional interactive QBO simulation and an ensemble of simulations using a prescribed QBO. The results raise the possibility of a chance occurrence in the observed polar solar-QBO response. In addition, we do not find a significant modulation of either the QBO period or amplitude by the solar cycle.

1 Introduction

Beginning in the 1980's, Labitzke (1987) stratified the 4 month mean winter temperatures at 30 hPa over the North Pole by the phase of the QBO and the January sunspot numbers, a measure of solar cycle variability. Results showed a statistically significant stratospheric difference in the polar stratosphere, such that during QBO west, defined as equatorial westerly winds at 50 hPa, a positive correlation with the solar cycle existed, with warmer polar temperatures and a weaker polar vortex during solar maximum. During the QBO east phase, winter temperatures showed a negative, but insignificant, correlation with the solar cycle. This pointed to a possible influence of the solar cycle on the Holton–Tan relationship (Holton and Tan, 1980), in which the phase of the QBO affects the waveguide of planetary wave propagation. The waveguide shifts into the Northern Hemisphere during QBO east, conducive for greater wave deposition over the northern pole and favoring a polar vortex that is anomalously warm and weak (Holton and Tan, 1980; Thompson et al., 2002). This reversal in the atmospheric response to the QBO over the solar cycle was also confirmed by Labitzke and van Loon (1988) over the stratosphere and parts of the troposphere using both temperatures and geopotential heights. The observed relationship was updated and confirmed in a number of publications during the following decades (e.g., Kodera, 1991; Labitzke and van Loon, 2000; Gray et al., 2004, 2006; Labitzke, 2005; Camp and Tung, 2007; Lu et al., 2009). The solar-QBO relationship in the Northern Hemisphere polar vortex has been shown to exist through 68 yr (1942–2009) of stratospheric data (Labitzke and Kunze, 2009). Though a relationship is found in the stratosphere at other latitudes and seasons, the strongest correlations are present over the northern polar region in late winter (February) when the mean stratospheric flow is westerly and vertically propagating waves intermittently disrupt the polar winter vortex (Charney and Drazin, 1961).

There is currently no well-accepted physical mechanism that can explain the apparent stratospheric response due to the 11 yr solar cycle and the QBO; if the circulation difference is truly present, it provides an additional pathway outside of direct surface heating (see for example, Gray et al., 2010) by which solar irradiance variability may influence climate. A number of studies have investigated the relationship using model simulations that incorporated a prescribed, parameterized, or internally generated QBO (e.g., Rind and Balachandran, 1995; Gray et al., 2004; Matthes et al., 2004; McCormack et al., 2007; Schmidt et al., 2010). These studies have confirmed a circulation response in the polar vortex that depends on both QBO phase and the 11 yr solar cycle (Labitzke and Kunze, 2009). In addition, Salby and Callaghan (2000) showed that observations from four solar cycles exhibited a shortened period in the QBO west phase during solar maximum years, suggesting a potential solar modulation of the QBO (Salby and Callaghan, 2004, 2006; Pascoe et al., 2005). This was later confirmed by McCormack et al. (2007) in a model study using a parameterized QBO.

ACPD
13, 25157–25184, 2013

These stratospheric differences are thought to be caused by a combination of varying ultraviolet radiation, which exhibits variability of 100 % near 100 nm and 6 % at 200 nm (Gray et al., 2010), and the QBO effect on the extratropical planetary waves to produce the solar-QBO response (e.g., Rind and Balachandran, 1995).

In this study, we show results from a historical simulation from the fully coupled Whole Atmosphere Community Climate Model (WACCM-4) (Marsh et al., 2013) with interactive ocean, chemistry, varying greenhouse gases, sea ice, volcanic forcing, solar spectral irradiance, and an internally generated QBO. The simulation was run from pre-industrial conditions into the present (1850–2005) and provides 156 yr simulated (approximately 13–14 solar cycles) to analyze the response to both solar and QBO forcing over the whole stratosphere. Section 2 describes the WACCM simulation and methodology. Section 3 discusses the solar response in WACCM and the internally generated QBO. Section 4 examines the high latitude response to both solar and QBO forcing and the potential chance occurrence of the solar-QBO response. Section 5 presents the major conclusions from this study.

2 Data and methodology

2.1 WACCM Simulation

In this study, we use WACCM as the atmospheric component of the National Center for Atmospheric Research (NCAR) Community Earth System Model (CESM), denoted CESM1 (WACCM) (Marsh et al., 2013). It extends from the surface to the lower thermosphere (140 km) with 66 vertical levels of variable vertical resolution of $\sim$ 1.1 km in the troposphere above the boundary layer, 1.1–1.4 km in the lower stratosphere, 1.75 km at the stratopause, and 3.5 km above 65 km; horizontal resolution is 1.9° latitude by 2.5° longitude. This model has been shown to agree with the observational record (Marsh et al., 2013). For brevity, we refer to CESM1 (WACCM) as WACCM for the remainder of this paper.

ACPD
13, 25157–25184, 2013

This study examines a transient simulation conducted as part of phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). It is a historical simulation from the pre-industrial period (1850) to the present (2005). The experimental setup is described in detail in Marsh et al. (2013). This simulation includes changing greenhouse gases, specified volcanic activity, interactive ocean, chemistry, and sea ice, and solar spectral irradiance variability from Lean et al. (2005) which is scaled by 0.9965 to agree with new estimates of Total Solar Irradiance (TSI) from the Total Irradiance monitor (TIM) on the NASA Earth Observing System Solar Radiation and Climate Experiment (SORCE) satellite (Rottman, 2005). This newest TSI measurement shows an irradiance of $1360.8 \pm 0.5\,\mathrm{W\,m^{-2}}$ over the recent solar minimum in 2008, lower than previous estimates of TSI (Kopp and Lean, 2011). This WACCM simulation includes for the first time a QBO internally generated by a parameterization of inertial gravity waves, as described by Xue et al. (2012), and thus differs from the experiment presented in Marsh et al. (2013).

Figure 1 shows monthly mean equatorial winds in the stratosphere from observations (top) at Singapore (1° N/104° E) and the internally generated QBO (bottom) in WACCM. For clarity, we show the last ten years of the simulation (1996 to 2006). As shown by Xue et al. (2012), the internally generated QBO has a latitudinal span of 20° (results not shown), which is in agreement with observations. We note that the timing does not match as would be expected since the QBO is internally generated; the period, however, is close to observed (as discussed in Sect. 3) at around 28 months. QBO westerlies are longer lasting (between 10 and 40 hPa) than easterlies, consistent with the observations (Baldwin et al., 2001). The peak amplitude of the QBO is strongest during the easterly phase at $\sim 30\,\mathrm{m\,s^{-1}}$, while westerlies are weaker, between ~ 15 and $20\,\mathrm{m\,s^{-1}}$, also consistent with the observed QBO. One potential shortcoming of the internally generated QBO, evident in Fig. 1, is that it does not descend to 100 hPa, as seen in observations. The simulated QBO west phase does not even reach 50 hPa. As a result, similar to several studies which include a simulated QBO with insufficient

ACPD
13, 25157–25184, 2013

descent (e.g., Giorgetta et al., 2002, 2006; Palmer and Gray, 2005; Schmidt et al., 2010), we defined the period and phase of the QBO from the model winds at 30 hPa.

2.2 Analysis methods

For examining the solar cycle response in WACCM, we grouped years into solar maximum and minimum using the annual mean 255 nm irradiance because it is at the center of the Hartley band (Marsh et al., 2007), where absorption of ultraviolet radiation by ozone is maximum (Gray et al., 2010) and therefore, is appropriate for detecting a stratospheric solar cycle temperature response from ozone heating. In addition, the 255 nm irradiance is highly correlated (0.96) to the solar 10.7 cm radio flux, a frequently used proxy for solar activity. Examining the combined solar cycle and QBO response over the high latitude stratosphere, the data was stratified according to QBO phase (east or west) and the 255 nm solar irradiance. Unless noted otherwise, we followed the Chiodo et al. (2012) definition of westerlies when the monthly mean equatorial wind at 30 hPa was greater than 5 $\mathrm{m\,s^{-1}}$ and easterlies when below $-10\,\mathrm{m\,s^{-1}}$. The analysis methods include monthly mean wind, temperature, and geopotential height data from the simulation. Because the WACCM simulation included increasing greenhouse gases into the 21st century, the geopotential height and temperature data were detrended to remove any linear increase and allow for better detection of the combined solar cycle and QBO response in the atmosphere. Figure 2 shows the 255 nm spectral irradiance (in $\mathrm{mW\,m^{-2}\,nm^{-1}}$) over $\sim$50 yr periods through the entire model simulation. There are a total of 54 solar maximum years and 48 solar minimum years.

3 Solar cycle response and QBO modulation

We first examined the solar cycle response by computing the annual average temperature difference (in K) between solar cycle maximum and minimum (as identified in Fig. 2) in the stratosphere, averaged over the equatorial region from 25° S to 25° N.

The result is shown in Fig. 3. The response in stratospheric temperature shows the double-peak structure seen in observations and past model simulations. In the tropical lower stratosphere, there is a temperature change of ~ 0.4 K between solar minimum and maximum near 50 hPa. This lower stratospheric change below 50 hPa, however, is not significant, as evidenced by the large uncertainty of 1.5 to 2 K. Another change of ~ 0.4 K is present in the upper stratosphere just below 1 hPa. These results are in agreement with results from a suite of several coupled chemistry climate models by Austin et al. (2008). While the model mean temperature change from Austin et al. (2008) is slightly higher (~ 0.5 K) in the upper stratosphere than our WACCM simulation, our model uncertainty shows that it is in relative agreement. The stratospheric temperature changes are also consistent with the pattern of changes in stratospheric ozone from Chiodo et al. (2012), who used WACCM 3.5, although the lower stratospheric temperature change is slightly higher than the ozone response (~ 70 hPa). The temperature changes are consistent with observations in the lower and upper stratosphere from ERA-40 data (Chiodo et al., 2012), but the solar cycle response in WACCM (~ 0.4 K) is on the lower end of the observed range of ~ 1 K. The combined solar cycle and QBO response in the atmosphere is examined in Sect. 4.

Figure 4 shows a wavelet power spectrum (top) of the QBO along with the annually averaged 255 nm solar irradiance from Lean et al. (2005) for examining the solar cycle influence on the QBO. Wavelet analysis is very useful for detecting the dominant modes of variability in a dataset and to determine how those modes will vary over time (Torrence and Compo, 1998). The wavelet analysis shows that the whole QBO period varies significantly over the simulation period. The greatest power, however, is present between 20 and 40 months, with maximum power centered near 28 months. These results show that the internally generated QBO period is in excellent agreement with observations (Baldwin et al., 2001).

It is evident from Fig. 4 that while the whole QBO period varies by over 20 months, the variability is not caused directly by the solar cycle. For example, there are times when the period of the QBO varies in lock step with the solar irradiance. At other times,

ACPD
13, 25157–25184, 2013

though, the apparent correlation reverses. In addition, although not shown, no power is present at timescales of 10–11 yr (120–132 months), meaning that there is no long term solar cycle variation present in the QBO period. We also determined the length of both QBO phases (east and west) over the length of the simulation and of the peak winds (detrended zonal mean zonal winds) in each respective cycle. Table 1 lists the mean and standard deviation of the peak QBO amplitudes and the length of QBO phases grouped by years of solar maximum and minimum. The average peak QBO winds are $\sim 27\,\mathrm{m\,s^{-1}}$ for the easterly phase and $\sim 17\,\mathrm{m\,s^{-1}}$ for the westerly phase. The peak winds exhibit no significant difference between minima and maxima in the solar cycle. In addition, similar to the whole QBO period, the duration for both east and west phases does not show a significant modulation difference between solar maximum and minimum. These results are in agreement with the findings of Schmidt et al. (2010) who used an internally generated QBO in the HAMMONIA model and with Fischer and Tung (2008) who analyzed an equatorial zonal wind dataset (1953–2007) and found that while the whole QBO period was anticorrelated with the solar cycle during the first three solar cycles, it became positively correlated in the latter three cycles. There is one caveat: since the internally generated QBO is forced primarily by a parameterization of inertial gravity waves (Xue et al., 2012), the source of the waves is largely deterministic. However, once the waves propagate through the stratosphere, any potential modulation of these waves (e.g., such as from changes in stratospheric ozone and heating) and thereby the QBO, are well represented in WACCM. Given this caveat, our study does not find a significant modulation of the QBO by the solar cycle.

4 High latitude response to solar and QBO forcing

In this section, we present the stratospheric response to the solar cycle and QBO and compare to past observational and modeling studies. We first investigated the high latitude response in late winter. We chose February, when the mean flow in the stratosphere is westerly, planetary waves are large and variable, and the QBO can influence the polar vortex through wave-mean flow interaction processes. Additionally, the largest change in the polar vortex to the combined solar-QBO interaction was found in February (Labitzke and Kunze, 2009). For comparison to the results of Labitzke and Kunze (2009), we first plotted the monthly mean geopotential heights at 30 hPa at 90° N in February as a function of the solar cycle and separated by QBO phase. Figure 5 shows the geopotential heights for both QBO east and west versus the 255 nm solar irradiance, along linear regression fits. While the WACCM simulation produces differences in the high latitudes as a function of the QBO (not shown) that are similar in magnitude and timing to the observed Holton–Tan variations (e.g., Pascoe et al., 2005; Naoe and Shibata, 2010), there is no statistically significant difference in the polar vortex strength when the solar cycle is introduced, as evidenced by the weak correlations. In addition, the correlations during QBO east (0.24) and west (–0.10) are the opposite of what is expected by Labitzke and Kunze (2009).

Table 2 shows the correlations for 35–40 yr periods starting in 1850 between the 30 hPa geopotential heights at 90° N in February and the 255 nm solar irradiance for QBO east and west. At times, the high latitude response agrees with past observational and modeling studies (e.g., Rind and Balachandran, 1995; Matthes et al., 2004; Labitzke and Kunze, 2009), but it is not consistent over the entire simulation period. During QBO east, the correlation starts out negative, in agreement with Labitzke and Kunze (2009), but becomes positively correlated in the latter half of the simulation. The same also occurs during QBO west: the correlation changes from positive to negative.

To complement these results we examine an ensemble of four WACCM3.5 Chemistry-Climate Model Validation (CCMVal-2) (SPARC CCMVal, 2010) runs. The report describing CCMVal-2 activity states that the WACCM3.5 climatological global mean temperature and trends in the stratosphere were in good agreement with the observational record. WACCM3.5 accurately shows the annual mean and annual cycle of ozone (Chiodo et al., 2012). These transient simulations were forced with the same time-varying solar forcing as in the WACCM4 run described in this present study; they also included volcanic eruptions (Tilmes et al., 2009), greenhouse gases and evolv-

ACPD
13, 25157–25184, 2013

ing ozone depleting substances. Two differences in the CCMVal-2 runs are that sea surface temperatures are specified from observations and the QBO was included by relaxing equatorial stratospheric winds to observations (Matthes et al., 2010). Chiodo et al. (2012) found that the ensemble mean showed a realistic representation of the solar signal in the stratosphere, most notably the double peak structure in ozone and temperature over the lower and upper stratosphere, a strengthening of the polar vortex in Northern Hemisphere (NH) winter during solar maximum, and the downward propagation of zonal wind anomalies during NH boreal winter in solar max through changes in planetary wave propagation and the Brewer–Dobson circulation, consistent with the model from Kodera and Kuroda (2002). The simulations were run from 1953 through 2006 and are also listed in Table 2. The first simulation produces a correlation between the 30 hPa geopotential heights in February at the northern pole and the 255 nm solar irradiance as function of QBO phase in agreement with Labitzke and Kunze (2009); however, the correlations in the other 3 runs are contradictory. This conclusion was also found by Chiodo et al. (2012), who analyzed the zonal wind response in the same CCMVal ensemble run; they found that the apparent polar vortex response was not reproduced in all ensemble members. These results suggest that the solar-QBO interaction found by Labitzke (1987) may have occurred by chance.

To further investigate the potential chance occurrence of the polar solar-QBO response, we performed Monte Carlo sampling by adding an additional WACCM4 run using the same parameters described in Sect. 2. This second WACCM4 simulation ran from 1850 through 1943 and also included an internally generated QBO that exhibited similar features to those seen in Figs. 1 and 4. To perform the random sampling of the two simulations, we focused on the winter season (December, January, February, and March) and combined the two WACCM runs to create a total of 249 yr of winter data. For each month (DJFM), we then randomly selected 68 winters (to match with the number of years of Labitzke and Kunze, 2009) and computed the correlation between the 30 hPa geopotential heights at the North Pole and the 255 nm solar irradiance as a function of when the QBO at 30 hPa was easterly (negative) or westerly (positive). This was performed a million times for each winter month. The result is a normalized probability (Fig. 6) of the correlation (R) for east and west phases for each month. During the easterly phase, the probability curve is centered near zero from early to mid-winter (DJF), implying an equal chance of getting either a positive or negative correlation; the exception is in March where the curve shifts to a mean R that is insignificant, −0.07. For the QBO west phase, a positive skewness in the probability curve is found in December and January with a mean R of 0.13 and 0.11; during late winter, the response switches sign and becomes slightly negative. This would imply agreement with Labitzke and Kunze (2009) in early winter, followed by a reversal in late winter that exhibits the same correlation as during QBO east. The correlations in early winter are much smaller than is expected from Labitzke and Kunze (2009). The implication of the reversal in the solar-QBO response seen in QBO west is unclear. The reversal could be attributable to internal variability of the polar vortex in WACCM during late winter, irrespective of a solar and QBO combined interaction. The statistics shown in Fig. 6 can be used to determine the mean probability (over DJFM) of getting the result found by Labitzke and Kunze (2009) from these simulations. The probability of finding a correlation of −0.3 in QBO east is 5.8 % and that of finding a correlation of 0.49 in QBO west is 0.42 %.

Removing pressure level and time of year constraints, we investigated the correlation in the geopotential heights at 90° N with the 255 nm irradiance for QBO phases over the northern pole for each month of the year to see if a response was present at other times of the year. Figure 7 shows the correlation as a function of pressure level and month between 1000 and 0.01 hPa for QBO east and west in the 1850–2005 WACCM simulation. While there are statistically significant positive and negative correlations during both phases, particularly during QBO west, because these correlations are the same sign it points to an interaction regardless of QBO phase. Furthermore, these significant correlations occur primarily in late summer and autumn; there is no significant response in late winter over the depth of the stratosphere. We also examined the circulation response by computing the difference in the geopotential heights,

ACPD
13, 25157–25184, 2013

temperature, and zonal mean zonal wind between solar maximum and minimum for QBO east and west phases over the whole stratosphere (results not shown). On the annual average, we saw statistically significant differences in the heights and temperature over the thermosphere independent of QBO phase that are likely due to extreme ultraviolet variations impacting the density. When stratifying to both the QBO and solar cycle, we found the greatest signal in the monthly average polar vortex differences in late winter (February and March), similar to the results of Schmidt et al. (2010). The results, however, were the opposite of what would be expected from Labitzke and Kunze (2009). That is, during QBO east, results showed a more disturbed polar vortex during solar maximum, with warmer polar temperatures and reduced zonal mean zonal winds; during QBO west, the pattern reversed, with a strengthening of the polar winter vortex during solar maximum. This pattern of circulation change between solar maximum and minimum and QBO phase contradicts past modeling studies using a prescribed or internally generated QBO (e.g., Balachandran and Rind, 1995; Rind and Balachandran, 1995; Matthes et al., 2004, 2010, 2013; Palmer and Gray, 2005 2010; Schmidt et al., 2010), further raising questions on the robustness of the solar-QBO interaction at the northern pole in winter.

5 Discussion

Results were presented from a WACCM simulation including fully interactive ocean, sea ice, and chemistry components, varying solar spectral irradiance, volcanic forcing, and an internally generated QBO. In an expansion beyond the capabilities of past modeling studies investigating the solar-QBO interaction at high latitudes, this model included a time varying solar cycle, interactive ocean, and a simulation duration of 156 yr, longer than what was examined in prior studies. This facilitated a comprehensive analysis on the solar cycle response. Over the tropical stratosphere, a realistic solar cycle change in temperature was evident, with an increase of ~ 0.4 K in the upper stratosphere and ~ 0.4 K in the lower stratosphere during solar maximum condi-

ACPD
13, 25157–25184, 2013

tions. This pattern roughly matches the corresponding ozone changes seen in Chiodo et al. (2012); however, the lower stratospheric change is not significant. While the temperature changes are at the lower end compared with ERA-40 data (Chiodo et al., 2012), the pattern is consistent with observations and past modeling studies. The internally generated QBO was shown to produce a realistic representation of equatorial stratospheric winds. Even though the sources for the inertial gravity waves that force the QBO are largely deterministic, the WACCM model includes all the physics and chemistry necessary to show a potential QBO modulation by chemical, radiative or dynamical processes in the stratosphere. We found no evidence suggesting a significant modulation of the QBO by the solar cycle, in agreement with Schmidt et al. (2010).

A specific goal of the analysis was to investigate the well-documented observed correlation of NH winter polar fields in the stratosphere with the solar cycle when the months are stratified by the phase of the QBO (Labitzke and Kunze, 2009). If the model simulated the observed pattern, we could use the model to probe the dynamical or radiative mechanisms that lead to the observed correlations. However, results of the stratospheric response to the solar cycle and QBO phase did not show a statistically significant response over the northern pole, in late winter over the depth of the stratosphere. A significant correlation between the solar cycle and geopotential heights was found in late summer and autumn but it exhibited the same sign for both QBO phases, suggesting little in the way of a QBO interaction. The examination of the high latitude response over selected ~40 yr periods showed a correlation that agreed with past observational and modeling studies over some periods, while over other periods, changed sign; it was not consistent over the entire simulation.

Data from several additional WACCM simulations were used to check the results. Analysis of an ensemble of four WACCM3.5 CCMVal simulations using a prescribed QBO also failed to reveal a consistent response of the NH polar stratosphere to the combined effects of solar cycle and QBO phase. These runs have a completely realistic QBO (specified from observations), thereby alleviating concerns that the structure of the internally generated QBO in WACCM was not capable of capturing the observed

ACPD
13, 25157–25184, 2013

relationship. To increase the amount of data available for statistical treatment, we used a second simulation of the WACCM4 case with interactive ocean and internally generated QBO. Monte Carlo sampling of all years from the two interactive simulations to examine the polar solar-QBO response at high latitudes in late winter showed a low probability of achieving the response seen by Labitzke and Kunze (2009). The analyses of the additional WACCM simulations strengthen our conclusion that the solar-QBO response may have occurred by chance.

A shortcoming of the WACCM simulation with self-generated QBO is the lack of descent of the QBO to 100 hPa, in particular during the QBO west phase which stops above 50 hPa. Perhaps this impacts the high latitude response through a possible lack of interaction of the QBO with planetary scale waves, leading to a damped response over the polar winter stratosphere. We note, however, that an ensemble of WACCM3.5 simulations using a prescribed QBO also did not show a robust high latitude response from solar and QBO forcing. Thus the shortcoming of the vertical extent of the modeled QBO is not the reason that the model was unable to reproduce the observed response.

Recent observations (i.e., Lu et al., 2009) and model simulations (Schmidt et al., 2010; Matthes et al., 2013) continue to show a circulation response over the high latitudes that depends on both QBO phase and solar cycle forcing. Schmidt et al. (2010) performed two perpetual solar maximum and minimum simulations using an internally generated QBO, each with 42 yr in length, finding a significant change in March with a more disturbed polar vortex during QBO west in solar maximum. Matthes et al. (2013) performed an improved simulation over Matthes et al. (2010) by changing from strictly perpetual solar max/solar min runs to adding a varying solar cycle with 110 yr simulated using a prescribed QBO. The result was a statistically significant circulation difference when stratified according to QBO phase and solar cycle. From the results using our WACCM4 simulation, we find agreement with these current and past modeling studies (i.e. Rind and Balachandran, 1995) in that the observed polar solar-QBO response in late winter is sometimes present, as shown in Table 2. Over a short record of ∼ 40 yr, our results are consistent with Schmidt et al. (2010), while also using an internally

ACPD
13, 25157–25184, 2013

Examining the stratospheric response to the solar cycle

A. C. Kren et al.

generated QBO. The caveat is that when the period is extended beyond the length of the observational record, the result switches sign in WACCM4 and thus the solar-QBO dependency is not robust throughout the full simulation. In addition, contrary to these other recent simulations, our results are the first to incorporate a simulation of over 150 yr with fully interactive ocean, chemistry, varying solar, and an internally generated QBO. This provides all the forcings necessary to show any potential solar-QBO interaction. We do not dismiss the possibility that there may in fact be a significant solar-QBO response in the atmosphere, as pointed out in numerous studies. However, the response in our WACCM run does not persist throughout the 156 yr period to give evidence for a statistically significant change from both solar cycle and QBO forcing.

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Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

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ACPD
13, 25157–25184, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 1. The mean and standard deviation of the QBO amplitude and duration for both east and west phases as a function of solar maximum (max) and solar minimum (min) years.

	Amplitude ($m\,s^{-1}$)		Duration (months)	
	Max	Min	Max	Min
East	27.3 ± 2.7	28.2 ± 1.8	11 ± 3.3	10.8 ± 2.3
West	17.4 ± 2.0	16.4 ± 2.2	14.7 ± 2.2	14.2 ± 2.8

ACPD
13, 25157–25184, 2013

Examining the stratospheric response to the solar cycle

A. C. Kren et al.

Table 2. Variation in the Spearman rank correlation between the 30 hPa geopotential heights in February at 90° N and the 255 nm solar irradiance for QBO east and west phases for this study (WACCM4) and four CCMVal simulations; *n* denotes the number of years in each respective phase.

Model	Period	QBO East	QBO West	*n* (East)	*n* (West)
WACCM4	1850–1890	−0.36	0.42	12	20
WACCM4	1890–1930	0.18	0.02	14	18
WACCM4	1930–1970	0.24	−0.44	14	18
WACCM4	1970–2005	0.38	−0.31	14	16
CCMVal 1	1953–2006	−0.62	0.22	14	24
CCMVal 2	1953–2006	0.31	−0.36	14	24
CCMVal 3	1953–2006	0.18	−0.05	14	24
CCMVal 4	1953–2006	−0.23	−0.06	14	24

ACPD
13, 25157–25184, 2013

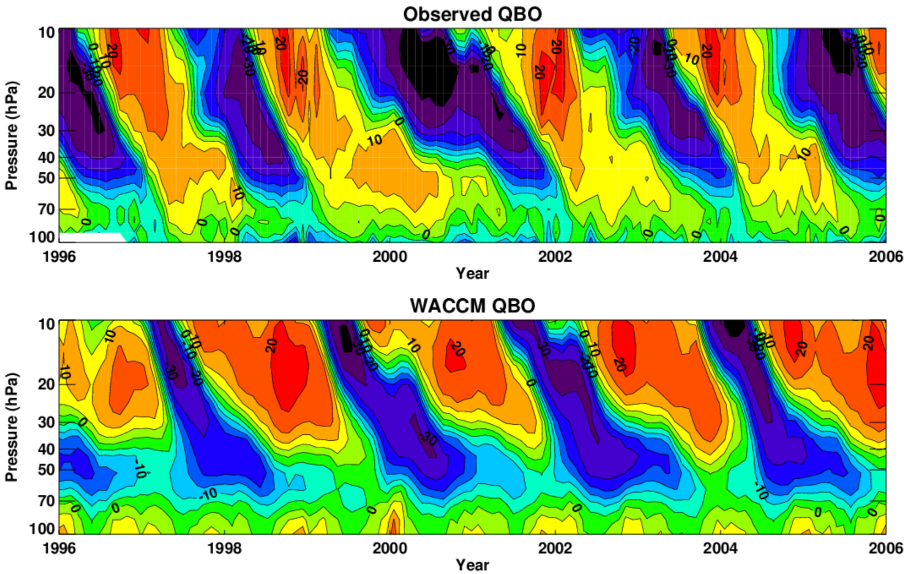


Fig. 1. Contour plot of the monthly mean equatorial winds between 10 and 100 hPa for both observations (top) at Singapore (1° N/104° E) and the internally generated QBO in WACCM (bottom). Time period is from 1996–2006. Amplitude is in m s^{-1} with contour interval of 5 m s^{-1}. Blue shading indicates QBO easterlies and red/orange denotes westerlies.

ACPD
13, 25157–25184, 2013

Examining the stratospheric response to the solar cycle

A. C. Kren et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

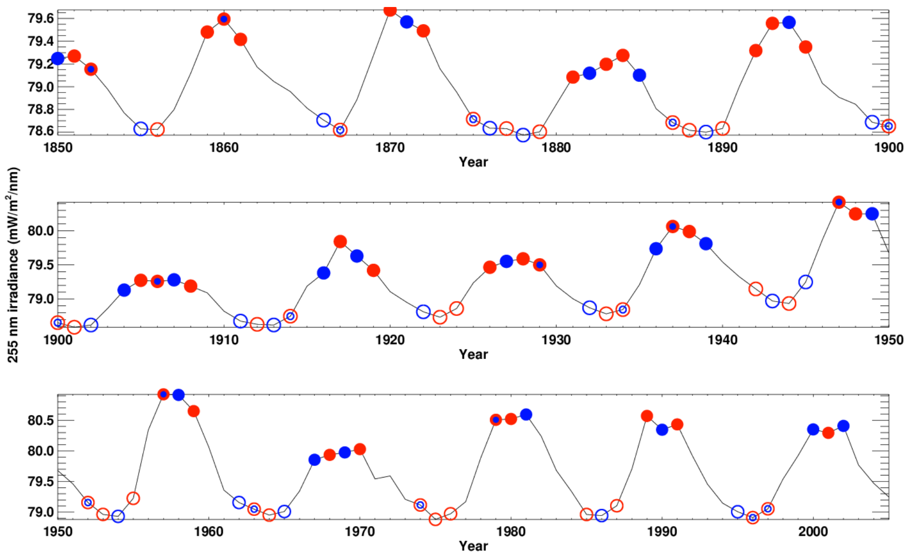


Fig. 2. The annually averaged 255 nm solar irradiance (mW m^{-2} nm^{-1}) from Lean et al. (2005) from 1850–1900 (top), 1900–1950 (middle), and 1950–2006 (bottom). Filled circles represent solar maximum years and open circles represent solar minimum years. Blue colored circles (open and filled) denote when the QBO (during solar maximum or minimum) was easterly and red circles when the QBO was westerly. Blue and red combined circles denote transition years when the QBO changed from easterly to westerly and vice versa.

ACPD
13, 25157–25184, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

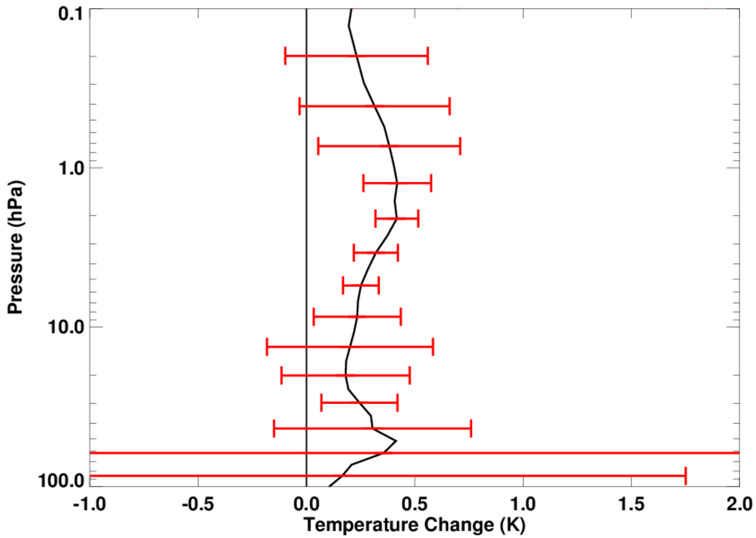
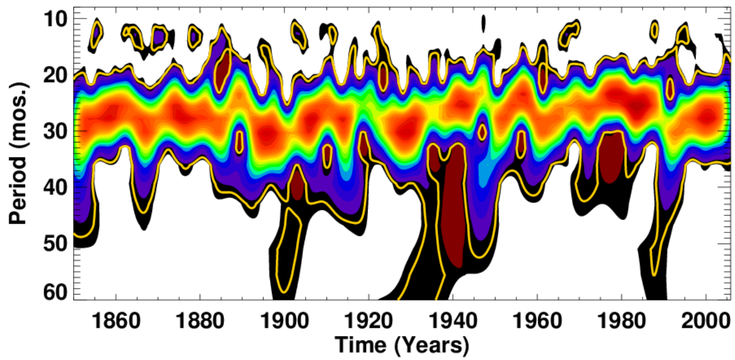


Fig. 3. Annual average temperature change (K) over the solar cycle (solar maximum minus solar minimum) between 100 and 0.1 hPa, averaged over the latitude band 25° S to 25° N. Red error bars denote the 2σ uncertainty. For emphasis, we show the zero temperature change by the vertical black solid line.

ACPD
13, 25157–25184, 2013



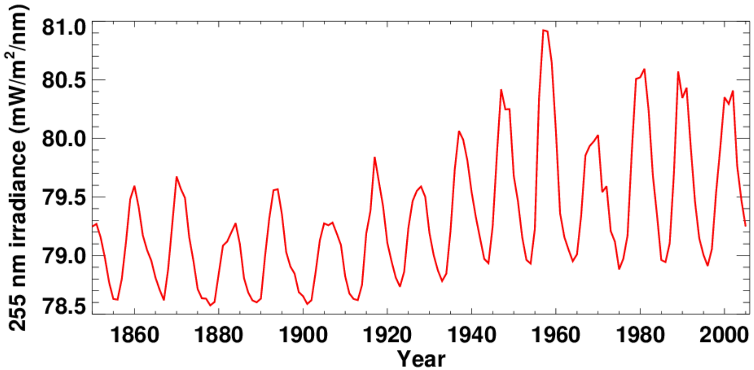


Fig. 4. (top) Wavelet power spectrum of the QBO, showing the dominant period of the QBO and its variability with time through the entire WACCM simulation. Color shading denotes the power. Bottom x-axis denotes the time (years) and left y-axis corresponds to the period (months) of the QBO. Yellow solid contours enclose regions greater than 95 % confidence. Wavelet software provided by C. Torrence and G. Compo, and is available at URL: http://paos.colorado.edu/research/wavelets/. More information on wavelet analysis is provided in Torrence and Compo (1998). (Bottom) The annually averaged 255 nm solar irradiance from Lean et al. (2005).

ACPD
13, 25157–25184, 2013

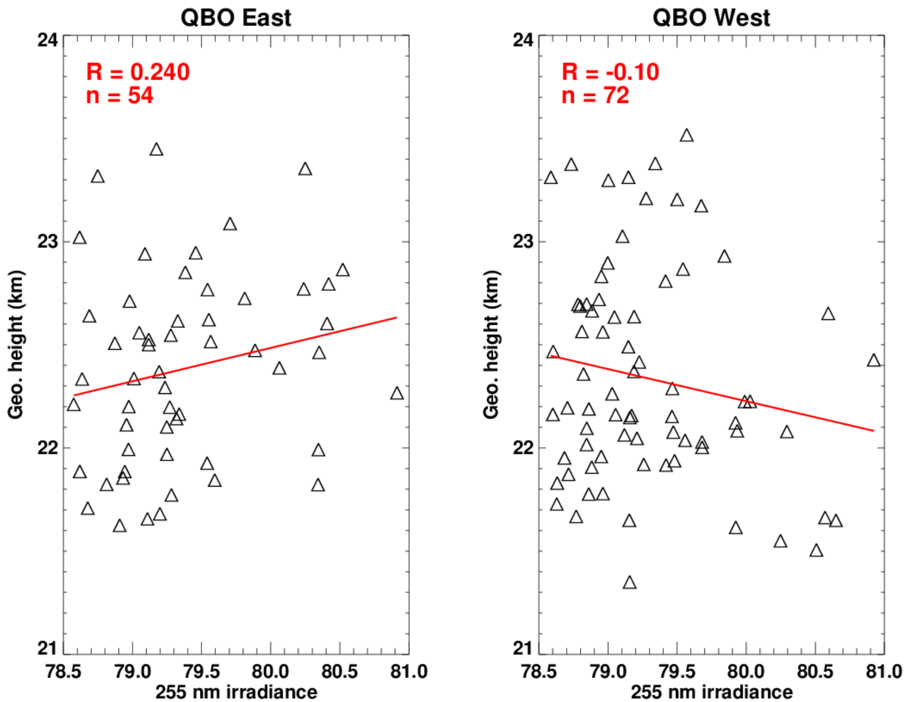


Fig. 5. Scatter diagram of the monthly mean 30 hPa geopotential heights (km) at 90° N in February plotted against the 255 nm solar irradiance during QBO easterly (left) and QBO westerly (right). Triangles represent the individual years over the model simulation (1850–2005); *n* denotes the number of years in QBO east and west, and *R* is correlation coefficient between the solar irradiance and geopotential heights.

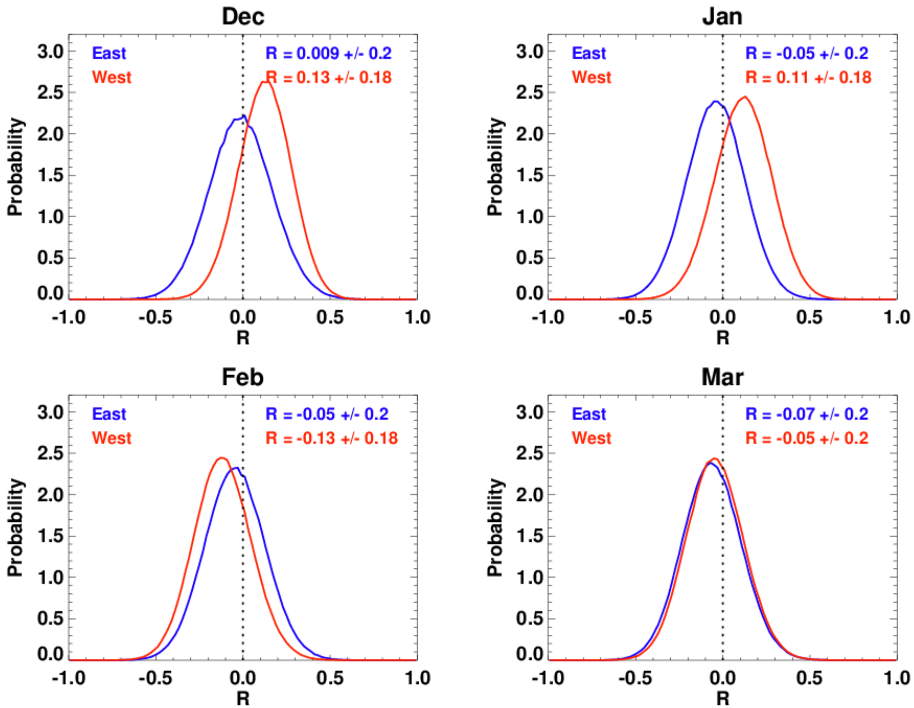


Fig. 6. Monte Carlo sampling plots showing the normalized probability of the correlation (R) between the 30 hPa geopotential heights at the North Pole and the 255 nm solar irradiance for December, January, February, and March as function of QBO east (blue) and west (red). Dotted line represents zero correlation and is shown to emphasize skewness in R. The mean and full width half max of R for each QBO phase is listed at the top right of each month.

ACPD
13, 25157–25184, 2013

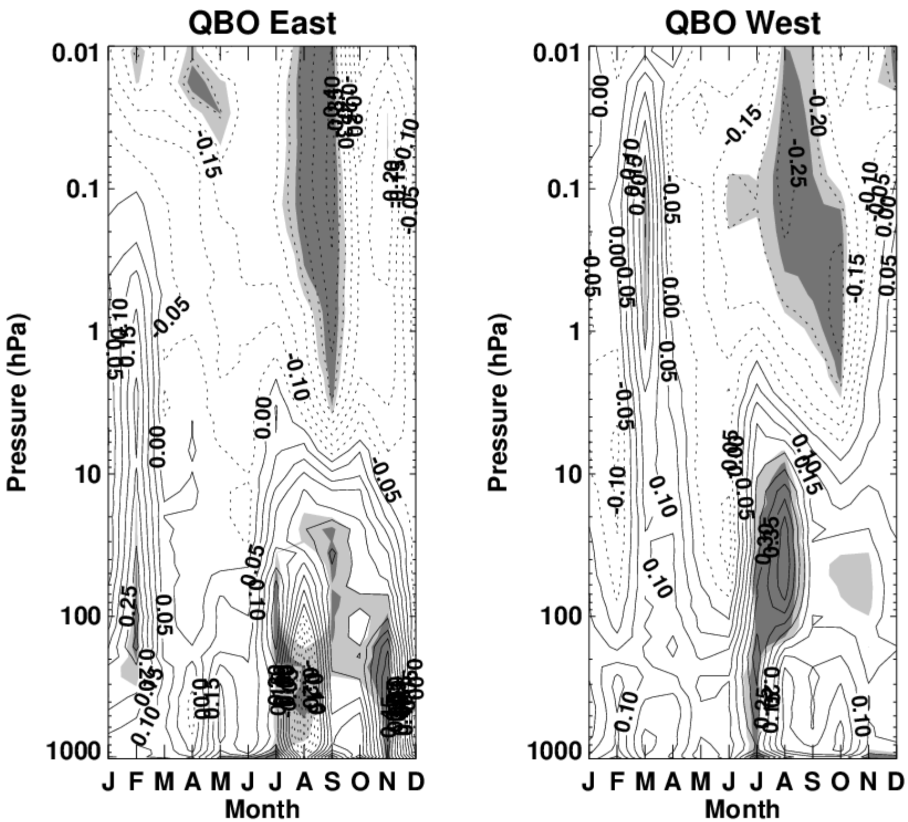


Fig. 7. Contour plot of the Spearman rank correlation between the monthly averaged geopotential heights at 90° N, as a function of pressure level and month, and the 255 nm solar irradiance for both QBO east (left) and west (right) phases. Light and dark shading indicates the significance of the correlations (90 % and 95 %) using a two-sided significance test. Contour interval 0.05. Negative values are dashed.