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The importance of time-varying forcing for QBO modulation of the atmospheric 11 year solar cycle signal

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[1] We present results from three multidecadal sensitivity experiments with time-varying solar cycle and quasi-biennial oscillation (QBO) forcings using National Center for Atmospheric Research's Whole Atmosphere Community Climate Model (WACCM3.1). The model experiments are unique compared to earlier studies as they use time-varying forcings for the solar cycle only and the QBO, both individually and combined. The results show that the annual mean solar response in the tropical upper stratosphere is independent of the presence of the QBO. The response in the middle to lower stratosphere differs depending on the presence of the QBO and the solar cycle but is statistically indistinguishable in the three experiments. The seasonal evolution of the solar and the combined solar-QBO signals reveals a reasonable agreement with observations only for the experiment in which both the solar cycle and the QBO forcing are present, suggesting that both forcings are important to generate the observed response. More stratospheric warmings occur during solar maximum and QBO west conditions. This appears to be the result of a QBO modulation of the background zonal mean wind climatology, which modifies the solar signal. Depending on the background wind, the small initial early winter solar signal in the subtropical upper stratosphere/lower mesosphere is enhanced during QBO east and diminished during QBO west conditions. This consequently influences the transfer of the solar-QBO signal during winter and results in the observed differences during late winter.

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1. Introduction

[2] The role of the quasi-biennial oscillation (QBO) in the solar response of the middle atmosphere and the troposphere is a challenging topic and has been the subject of a number of observational and modeling studies (for a recent review, see *Gray et al.* [2010]). In particular, the vertical structure of the solar cycle signal in temperature and ozone in the tropical stratosphere in observations and modeling studies, as well as the dynamical response at high latitudes, is of interest. The direct solar signal in the tropical upper stratosphere is acceptably represented in current chemistry-climate models (CCMs). However, larger differences in the vertical structure of the solar signal among the different CCMs as well as among different observational data sets occur below 10 hPa [*SPARC CCMVal*, 2010]. These uncertainties in the observations in the tropical lower stratosphere might be related to nonlinear interactions or aliasing with other signals such as the QBO, El Niño-Southern Oscillation (ENSO), and volcanoes. *Austin et al.* [2008] argue that a time-varying forcing might be responsible for the more realistic vertical structure of the solar signal in CCMs and do not find a significant relation to the presence of a QBO. *Schmidt et al.* [2010] use the HAMMONIA model with constant solar cycle forcing and a self-consistent QBO, and they are able to reproduce the tropical solar signal. *Matthes et al.* [2010] found that the tropical solar signal in temperature and ozone in CCM simulations using constant forcings exhibited a double peak in altitude, and at least in the Whole Atmosphere Community Climate Model (WACCM), the vertical structure is related to the presence of a QBO. *Tsutsui et al.* [2009] used the same version of WACCM as in *Matthes et al.* [2010] with time-varying forcings but without a nudged QBO. They could not reproduce the double-peak solar signal documented by *Matthes et al.* [2010]. So far, only a few CCMs can produce an internally generated QBO, and to the best of our

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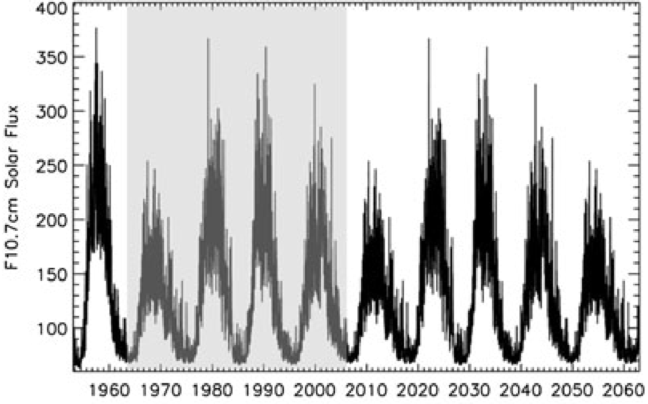
knowledge, no investigation of the solar-QBO relationship using time-varying solar forcings has been performed in a CCM with an internally generated QBO.

[3] The solar signal and its possible modulation by the QBO at high latitudes as well as the mechanisms for its transfer are other long-standing issues [*Gray et al.*, 2010]. *Labitzke* [1987] and *Labitzke and van Loon* [1988] found during solar maximum years a statistically significant warming of the polar stratosphere with more stratospheric warmings in late winter during the west phase of the QBO but a statistically significant cooling in the east phase of the QBO. *Kodera* [1991] and *Kodera et al.* [1991] already proposed a mechanism for this observed solar-QBO modulation as a working hypothesis from observational as well as highly idealized general circulation model (GCM) experiments, in which the solar effect was included by modifying the radiative heating rate and the QBO effect by incorporating a zonal momentum source in the equatorial stratosphere. They note that solar activity and the equatorial QBO produce mean zonal wind anomalies in the upper stratosphere during early winter which modulate planetary wave propagation. Through wave-mean flow interaction, this early winter signal is transported to the late winter lower stratosphere. The results of their GCM experiments show a modulation similar to the observed correlations by *Labitzke* [1987] and *Labitzke and van Loon* [1988]. *Matthes et al.* [2004] were able to reproduce parts of the observed solar-QBO relationship in GCM experiments with more realistic solar and QBO forcings but only when they prescribed a QBO profile throughout the whole depth of the equatorial stratosphere. They confirmed results by *Gray et al.* [2001] that equatorial winds in the upper stratosphere are important for determining interannual variability in the polar night jet. *Gray et al.* [2004] further worked on the solar-QBO interaction with idealized model experiments and ERA-40 reanalyses. They show the influence of solar-QBO interactions on the timing of stratospheric sudden warmings and propose a mechanism by which the zonal wind anomalies in the equatorial/subtropical upper stratosphere associated with the QBO and the solar cycle either reinforce each other or cancel each other out following the work by *Kodera et al.* [1991]. During solar minimum and QBO east as well as during solar maximum and QBO west conditions, the anomalies reinforce each other and result in more stratospheric sudden warmings, again in agreement with the observed Labitzke and van Loon relationship. Also, *Camp and Tung* [2007] confirmed parts of the findings by Labitzke and van Loon and pointed out that the polar warming during solar maximum years is particularly prominent for the quiet QBO west phase and that the solar signal during the disturbed QBO east phase is smaller and not statistically significant and can be of either sign. The 11 year solar signal in the stratosphere is characterized by an early winter tropical warming and a late winter polar warming due to wave-mean flow interaction involving planetary waves [*Kodera and Kuroda*, 2002]. The remaining question is how the solar signal interacts with the QBO signal and whether the proposed working mechanisms by *Kodera* [1991] and *Gray et al.* [2004] can be confirmed. Since CCMs differ in their dynamical and chemical representation of stratospheric mean climate and variability, the representation of a small signal such as the solar signal is challenging and has not been discussed in detail in the CCM validation activity of Stratospheric Processes and their Role in Climate [*SPARC CCMVal*, 2010]. This study contributes to the understanding of the observed solar-QBO relationship by analyzing WACCM3.1 experiments with time-varying solar cycle and time-varying prescribed QBO and hence a more realistic representation of solar and QBO signals than earlier studies. The experiments with WACCM3.1 are designed specifically to separate the influence of the solar cycle and the QBO without taking any greenhouse gas (GHG) or sea surface temperature (SST) changes into account. A recent study with WACCM3.1 under constant solar cycle and QBO forcing conditions revealed different, statistically significant signals for the two QBO phases in the tropical middle and lower stratosphere as well as at high latitudes in particular in the Southern Hemisphere (SH) and discussed the ozone budget for QBO east and west conditions in detail [*Matthes et al.*, 2010]. Here we will investigate the representation of the solar signal in the tropical and polar stratosphere under time-varying forcings and especially focus on the role of the QBO in modulating the stratospheric and tropospheric solar signal throughout the year. A comparison to analyses from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) reanalysis by *Labitzke et al.* [2006] is included as well. The paper is structured as follows: section 2 describes the model and experimental design. Section 3 describes the analysis methods used for analysis. The annual mean solar signal in temperature and ozone from a multiple linear regression (MLR) analysis are presented in section 4. Section 5 presents results from a composite analysis with respect to the solar and the QBO phases in the tropical lower stratosphere and the dynamical response during NH winter in the stratosphere. Section 6 discusses the QBO modulation of the background wind climatology and proposes a mechanism for the solar-QBO modulation. Conclusions are given in section 7.

2. Model and Experimental Description

[4] The Whole Atmosphere Community Climate Model, Version 3 (WACCM3.1), developed at the National Center for Atmospheric Research (NCAR), is a fully interactive chemistry-climate model (CCM) extending from the Earth′s surface through the lower thermosphere ($\sim$140 km). WACCM3.1 is an expanded version of the Community Atmospheric Model, Version 3 (CAM3) and includes all of the physical parameterizations of CAM3 [*Collins et al.*, 2006]. It includes a detailed neutral chemistry model for the middle atmosphere based on the Model for Ozone and Related Chemical Tracers, Version 3 (MOZART3). The mechanism represents chemical and physical processes in the troposphere through the lower thermosphere. The species included within this mechanism are contained within the O_x, NO_x, HO_x, ClO_x, and BrO_x chemical families, along with CH_4 and its degradation products [*Kinnison et al.*, 2007]. The radiatively active gases (CO_2, H_2O, N_2O, CH_4, CFC-11, CFC-12, NO, O_3) affect heating and cooling rates and therefore dynamics. Additional processes described in *Marsh et al.* [2007] include heating due to chemical reactions, a model of ion chemistry in the mesosphere/lower thermosphere (MLT) [*Roble*, 1995], ion drag and auroral processes [*Roble and Ridley*, 1987], and EUV and Non-local

(a) Solar Forcing



(b) QBO Forcing

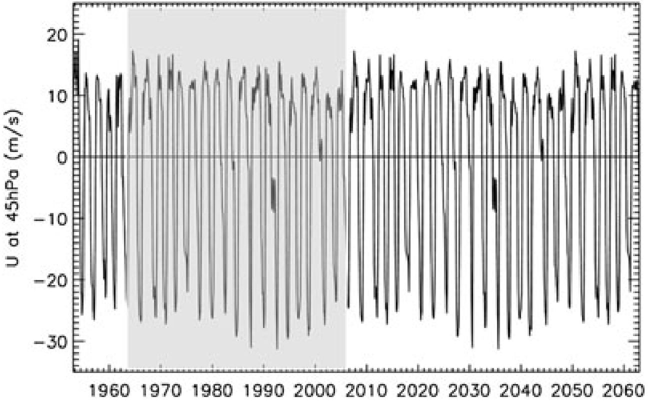


Figure 1. Forcing time series of the 110 year runs, (a) solar forcing, i.e., daily values of the f10.7, (b) equatorial wind forcing, i.e., monthly values of the 50 hPa equatorial wind. The 110 year forcing time series include observations for the period from January 1953 through December 2004 and continues by repeating twice the observed sequence from 1962 through 2004 (shaded).

Thermodynamic Equilibrium longwave radiation parameterizations [*Solomon and Qian*, 2005; *Formichev*, 1998]. The horizontal resolution used in this study is 1.9° in latitude and 2.5° in longitude, the same as in *Matthes et al.* [2010].

[5] To run the model with time-variable 11 year solar cycle and QBO forcings, 110 year time series based on observations were constructed for the 10.7 cm solar radio flux (f10.7), the K_p-index, and the equatorial wind in the stratosphere. The 110 year time series includes observations for the period from January 1953 through December 2004, which were available at the time the simulation was started, and continues by repeating twice the observed sequence from 1962 through 2004 (Figure 1). The year 1962 was chosen as a suitable point for extending the time series because both the solar cycle and the QBO were in similar phases in 1962 and 2004 and allowed a smooth continuation of the existing time series. For the solar cycle, wavelength dependent irradiance changes as described in *Marsh et al.* [2007] were scaled with daily values of f10.7. The specification of the solar cycle is the same as in *Tsutsui et al.* [2009]. Additionally, a QBO was prescribed according to *Matthes et al.* [2010] but now includes intercycle variability based on observations, with the period 1962–2004 being repeated as necessary after 2004, as described above. The model was run for 10 solar cycles with solar cycle only (SC), solar cycle and QBO (SCQBO), and for 55 years with QBO only (see Table 1). Climatological monthly varying SSTs are used as a lower boundary forcing. All other forcings are held constant under 1995 conditions, i.e., GHGs, ozone depleting substances (ODS), neutral ENSO conditions, and surface area density of sulfate aerosols to represent the stratospheric aerosol layer. The year 1995 was chosen because it provided mean present-day conditions for the background GHG and ODS concentrations and had no volcanic eruption entering the stratosphere. The model runs hence neglect ocean-atmosphere feedback as well as anthropogenic climate change effects.

3. Analysis Methods

[6] To investigate the time-varying runs, analyze the modulation of the solar signal by the QBO, and compare it to other published results, we perform MLR analysis similar to that outlined in chapter 8 of *SPARC CCMVal* [2010] as well as a composite analysis to study certain processes in more detail.

3.1. Multiple Linear Regression Analysis

[7] MLR analysis based on the method described in *Bodeker et al.* [1998, 2001] and used in chapter 8 of *SPARC CCMVal* [2010] is also applied here to monthly mean ozone and temperature fields. Since GHGs and ODS, as well as SSTs, were set constant and no volcanic eruptions are considered, the regression model contains a reduced set of detrended predictors compared to *SPARC CCMVal* [2010]. The first term is a constant offset which represents the mean annual cycle when expanded in a Fourier expansion. The second term is a linear trend term. The first QBO predictor is specified as the monthly mean 50 hPa zonal wind around the equator because at this height the correlation between equatorial winds and North polar winter temperatures is large [*van Loon and Labitzke*, 1988, Figure 2]. Since the phase of the QBO varies with height [e.g., *Gray et al.*, 2001], a second QBO predictor is included, which is orthogonal to the first and therefore accounts for the vertical phase progression of the QBO. The monthly mean f10.7 flux is employed for the 11 year solar cycle basis function. Autocorrelations of the residuals are taken into account when computing uncertainties, which are expressed as the square root of the sum of the squared diagonal elements of the covariance matrix.

3.2. Composite Analysis

[8] Experiment SCQBO allows stratification of the solar cycle response by QBO phase with a composite analysis. Solar maxima are defined to occur in years when monthly

Table 1. Solar-QBO Experiments Performed With WACCM

Experiment Name	Zonal Wind in Equatorial Lower Stratosphere	Solar Cycle Phase	Simulation Years
SCQBO	variable	variable	110
SC	-	variable	110
QBO	variable	-	50

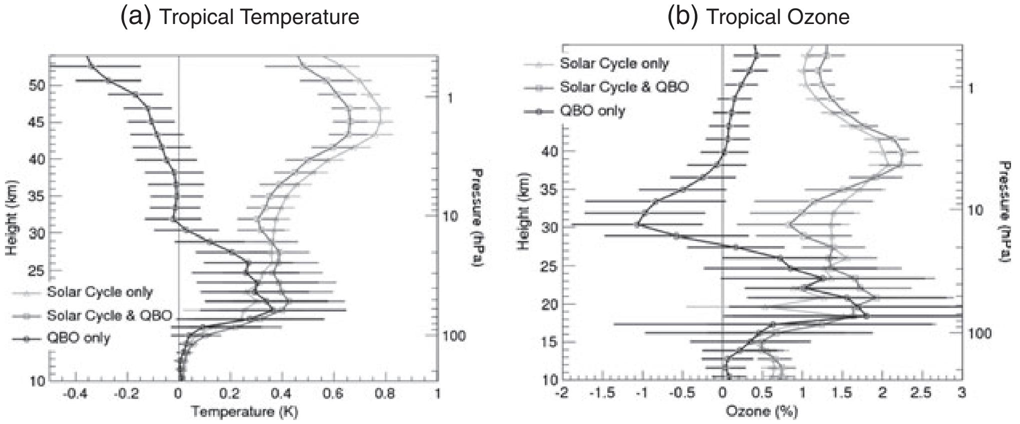


Figure 2. Annual mean tropical solar regression coefficient between 25°S and 25°N for (a) the temperature in K/130 f10.7 units and (b) ozone in %/130 f10.7 units, for the run with only solar cycle (triangles), the run with only QBO (circles), and the run with solar cycle and QBO (squares). Two-sigma uncertainties are indicated for each run. Note that the solar coefficient has been multiplied by 1.3 to represent differences between solar maximum and minimum.

mean December values of f10.7 are above 150 units and solar minima when f10.7 is below 90 units. This categorizes the solar cycle for the whole NH winter. Similarly, the zonal wind averaged between 51 hPa and 43 hPa and from 2.8°S to 2.8°N in December is used to define the QBO state for the entire NH winter. Equatorial winds larger than 7.5 m/s are in the QBO west category and winds lower than –2 m/s in the QBO east category. This definition leads to a similar number of cases for each combination of the solar cycle and the QBO (maxE = 13, minE = 14, maxW = 14, minW = 15). The robustness of this definition was tested extensively, e.g., by testing different cutoff criteria for QBO east and west or different height definitions of the QBO, by defining the QBO in each month separately or by taking a 2 month average of the state of the solar cycle and the QBO in either November/December or January/February. Since the stratosphere in early winter (December) is mainly radiatively controlled and the initial, direct solar forcing is largest, we use this time of the year to categorize the respective winter and follow the long-term solar signal through the winter. In the later part of the winter (January and February), propagation of planetary waves leads to a dynamically controlled state where wave-mean flow interactions and indirect dynamical effects of the solar cycle and the QBO occur.

4. Solar Signals

[9] In this section, we first show a comparison in the annual mean tropical response to the solar cycle in the time-varying solar cycle and/or QBO experiments from MLR analysis and discuss the agreement with other modeling studies and observations. We focus on the role of the QBO and investigate the signal in the stratosphere and its seasonal evolution with a composite analysis afterward. The results are based on monthly mean data averaged over all available model years to provide a solid basis for statistical significance.

4.1. Annual Mean Tropical Temperature and Ozone

[10] Figure 2a shows that the largest temperature response to the solar cycle occurs in the upper stratosphere, with magnitude 0.7 K at 45 km in the two experiments where a solar cycle is present (SC and SCQBO). This maximum appears regardless of the presence of a QBO. The solar signal in the QBO-only experiment starts to diverge from the other two simulations above 25 km. The QBO-only experiment (QBO) consistently shows almost zero temperature response above 30 km and a negative response above 40 km. A secondary maximum in the solar signal occurs in the lower stratosphere at around 18 km and is statistically the same in all three simulations. The occurrence of a lower stratospheric equatorial solar signal in the QBO-only experiment without solar forcing could be due to aliasing effects [e.g., *Marsh and Garcia*, 2007; *Smith and Matthes*, 2008] or to the fact that the observed equatorial winds used to relax the model winds contain a solar signal. The possibility of solar cycle modulation of the QBO phase was first suggested by *Salby and Callaghan* [2000] but remains controversial [e.g., *Hamilton*, 2002]. As discussed in section 1, there is a large uncertainty in the vertical structure of the solar signal below 32 km among different CCMs as well as among different observational data sets [*SPARC CCMVal*, 2010]. The problem may arise from the limited number of years available for a statistical analysis, which cover only four to five solar cycles. Here we try to assess the contribution of the QBO to this vertical structure in the temperature and ozone signal. The experiment with variable solar cycle and QBO (SCQBO) forcing produces a slightly larger solar cycle temperature response than the solar cycle-only case (SC) with maxima in the upper and lower stratosphere separated by a minimum in the middle stratosphere. This structure is comparable to observations [cf. chapter 8 in *SPARC CCMVal*, 2010] and is statistically undistinguishable between the SCQBO and the SC experiments.

[11] Figure 2b shows the corresponding tropical annual mean O_3 changes from solar minimum to maximum for all three experiments. During solar maximum, statistically significant ozone increases are obtained in the upper stratosphere (40 km) of about 2% in the SC and the SCQBO runs. This slightly underestimates the peak of more than 2% in, e.g., SAGE I + II data between 45 and 50 km but is in good agreement with previous modeling studies

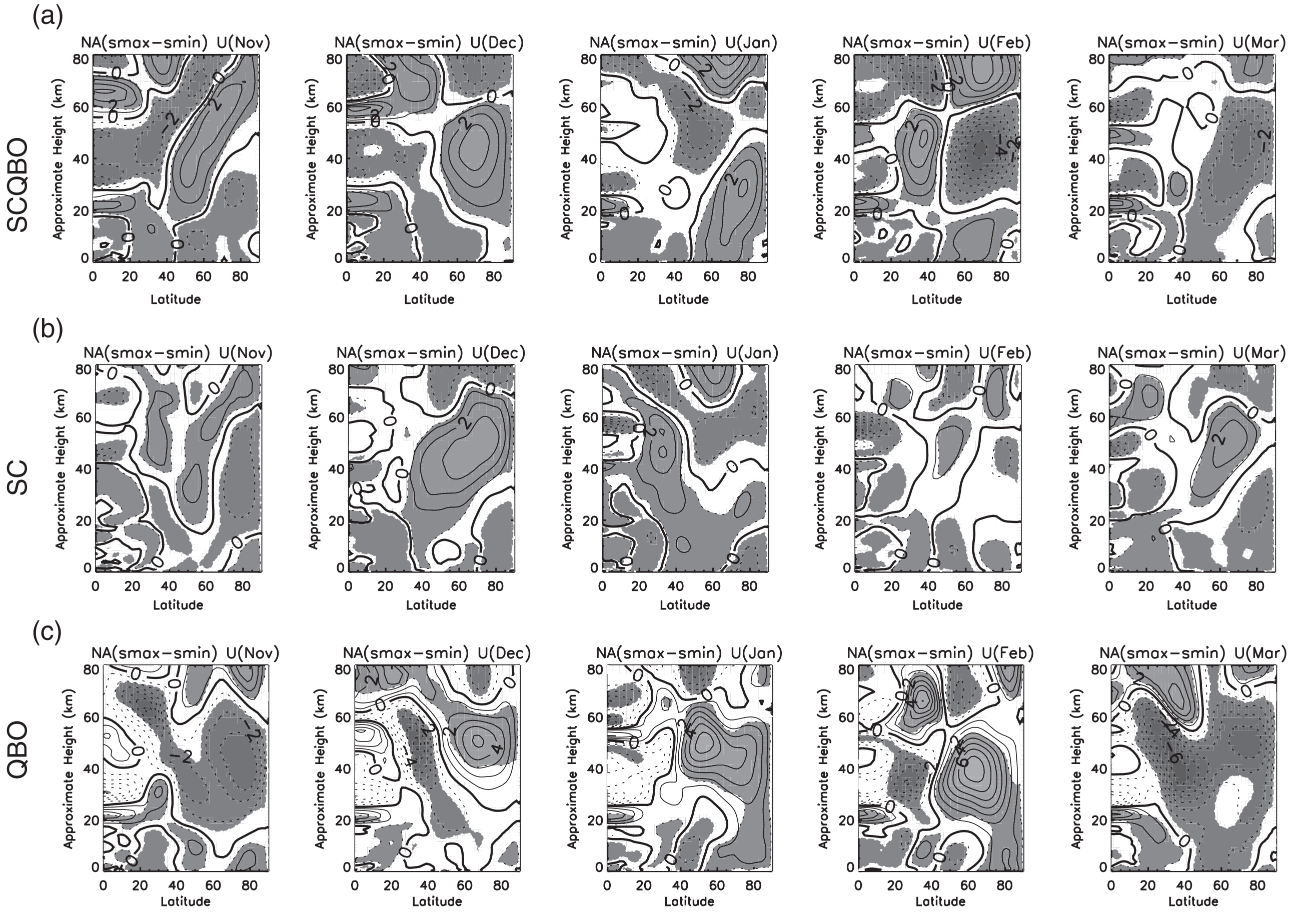


Figure 3. Differences between the solar cycle maximum and minimum without stratification to the QBO for the three experiments: (a) solar cycle and QBO (SCQBO), (b) solar cycle only (SC), and (c) QBO-only (QBO) experiments. Note that the same solar years have been selected for the experiment without solar cycle (QBO) in order to analyze possible spurious solar signals. Shading indicates 95% statistically significant anomalies.

[e.g., *Brasseur*, 1983; *Haigh*, 1994; *Fleming et al.*, 1995; *Shindell et al.*, 1999; *Schmidt and Brasseur*, 2006; *Marsh et al.*, 2007; *SPARC CCMVal*, 2010]. Similar to the temperature response (Figure 2a), a statistically significant local minimum in the middle stratosphere around 30 km occurs in the run with variable solar cycle and QBO (SCQBO) compared to the QBO-only run. A larger secondary peak of 2% occurs in the tropical lower stratosphere in all three runs, which is not statistically significant. Note that, although solar cycle forcing is not present in the QBO-only run, this run does show a strong decadal signal in tropical ozone below 38 km.

[12] In WACCM, the annual mean modeled solar temperature and ozone response in the upper stratosphere agrees generally with other CCM studies [e.g., *Marsh et al.*, 2007; *Tsutsui et al.*, 2009; *Schmidt et al.*, 2010] and observations (for a review, see *Gray et al.* [2010]). The response in the tropical middle and lower stratosphere differs from other CCM studies and agrees well with ERA-40, radiosonde, and SAGE observations [*SPARC CCMVal*, 2010], as well as an ensemble of transient WACCM experiments for the recent past [*Chiodo et al.*, 2012]. The latter study uses a newer WACCM version (3.5) than this study, with improved NH winter climatology and variability, and shows a statistically significant threefold structure of the solar signal in the tropics which agrees very well with observations. Other recent CCM studies with constant SSTs comparable to our study either did not include a QBO in WACCM [*Marsh et al.*, 2007; *Tsutsui et al.*, 2009] or had a self-consistent QBO with an unrealistic phase which was in phase with the annual cycle [*Schmidt et al.*, 2010].

[13] To summarize, a qualitatively different vertical structure in the temperature and ozone solar signals occurs in all the experiments although statistically undistinguishable from each other in the lower stratosphere. The upper stratospheric response is independent of the presence of the QBO, whereas the response in the middle to lower stratosphere differs depending on the presence of the QBO and the solar cycle. *Matthes et al.* [2010] have shown, in a similar set of WACCM simulations but with constant solar and QBO forcings, that the solar response in the middle to lower stratosphere differs significantly for the two QBO phases, in agreement with the long-standing observational results of *Labitzke and van Loon* [1988]. Here we will investigate the role of the QBO for the evolution of the solar signal in the time-varying runs by comparing the experiment with the most realistic forcing, i.e., both solar cycle and QBO forcings (SCQBO), with the other two experiments using solar cycle-only (SC) or QBO-only (QBO) forcing. This may

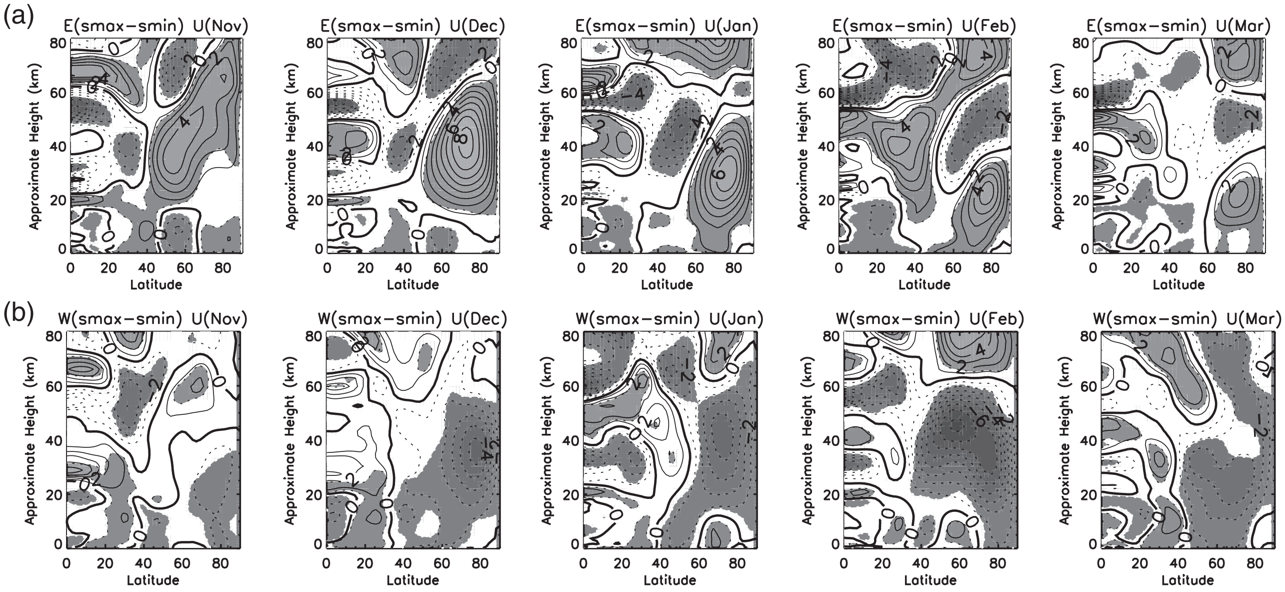


Figure 4. Composite zonal mean zonal wind differences between solar maximum and minimum from the SCQBO experiment for (a) QBO east and (b) QBO west conditions from the Earth's surface to 80 km and from the equator to the north pole; contour interval: 0.5 m/s, shading as in Figure 3.

help elucidate the solar-QBO relationship. One of the open questions besides a physical explanation for the solar-QBO relationship is whether the vertical structure in the tropical solar signal is related to the time-varying forcings and/or to the presence of a QBO [*Matthes et al.*, 2010; *Austin et al.*, 2008; *Schmidt et al.*, 2010]. The QBO-only run, which does not have a solar cycle in the radiation and chemistry, will be used in the following to test the robustness of the solar signal in comparison to the other two runs.

4.2. Seasonal Evolution of the Solar Signal: Northern Hemisphere Winter

[14] To investigate the seasonal evolution of the solar signal in all three experiments, which showed statistically significant differences in particular in the tropical annual mean temperature and ozone responses in the upper stratosphere, solar maximum minus solar minimum anomalies of the zonal mean wind without stratification by the phase of the QBO during Northern Hemisphere winter from November through March are presented in Figure 3. To check for the possibility of spurious solar signals due to the stratification procedure, the same years for solar maximum and minimum have been selected even though there was no solar cycle present in the QBO-only run and the latter is considerably shorter and hence statistically less reliable. The experiment with solar cycle and QBO (SCQBO) shows a weak but statistically significant solar modulation of the polar night jet starting with a westerly wind anomaly in the midlatitude upper stratosphere which propagates poleward and downward with time until February when an easterly anomaly in the upper stratosphere continues (Figure 3a). This behavior is in agreement with observations. The QBO-only experiment shows a comparable westerly wind anomaly as in SCQBO from December through February slowly propagating but suddenly starting and ending and switching sign in December and March (Figure 3c). The solar cycle-only experiment shows the weakest zonal wind anomalies of all three experiments and no apparent poleward-downward propagation of the zonal wind anomalies at all (Figure 3b).

5. QBO Impact on the Solar Signal

[15] Since the SCQBO experiment shows the closest relation to observed solar signals, the solar maximum minus minimum differences for this experiment are separated for the two QBO phases in Figure 4 to investigate the solar-QBO relationship. During solar maximum and QBO east years, a statistically significant westerly wind anomaly exists in November in the midlatitude upper stratosphere that grows and propagates poleward and downward with time (Figure 4a) similar to observational and other model results [e.g., *Kodera and Kuroda*, 2002; *Matthes et al.*, 2004, 2006]. This solar-induced wind signal is (as a consequence of the thermal wind relationship) directly related to statistically significant higher temperatures in the tropical and subtropical upper stratosphere due to enhanced absorption of UV radiation during solar maximum years. This is more pronounced in the east phase of the QBO but also apparent in the west phase of the QBO (Figure 4b). The subtropical upper stratosphere is very sensitive to solar changes in the radiatively dominated early part of the winter such that the small initial solar signal is amplified during the dynamically active late winter to early spring period through wave-mean flow interactions [*Kodera and Kuroda*, 2002]. Whereas the response during QBO east years is concentrated in the stratosphere in early winter (November and December), it extends all the way down to the troposphere in later winter (January and February). The modulation of the polar night jet involves refraction of planetary waves, changes their dissipation regions, and therefore modulates the Brewer-Dobson (BD) circulation. We will come back to the discussion of these changes later.

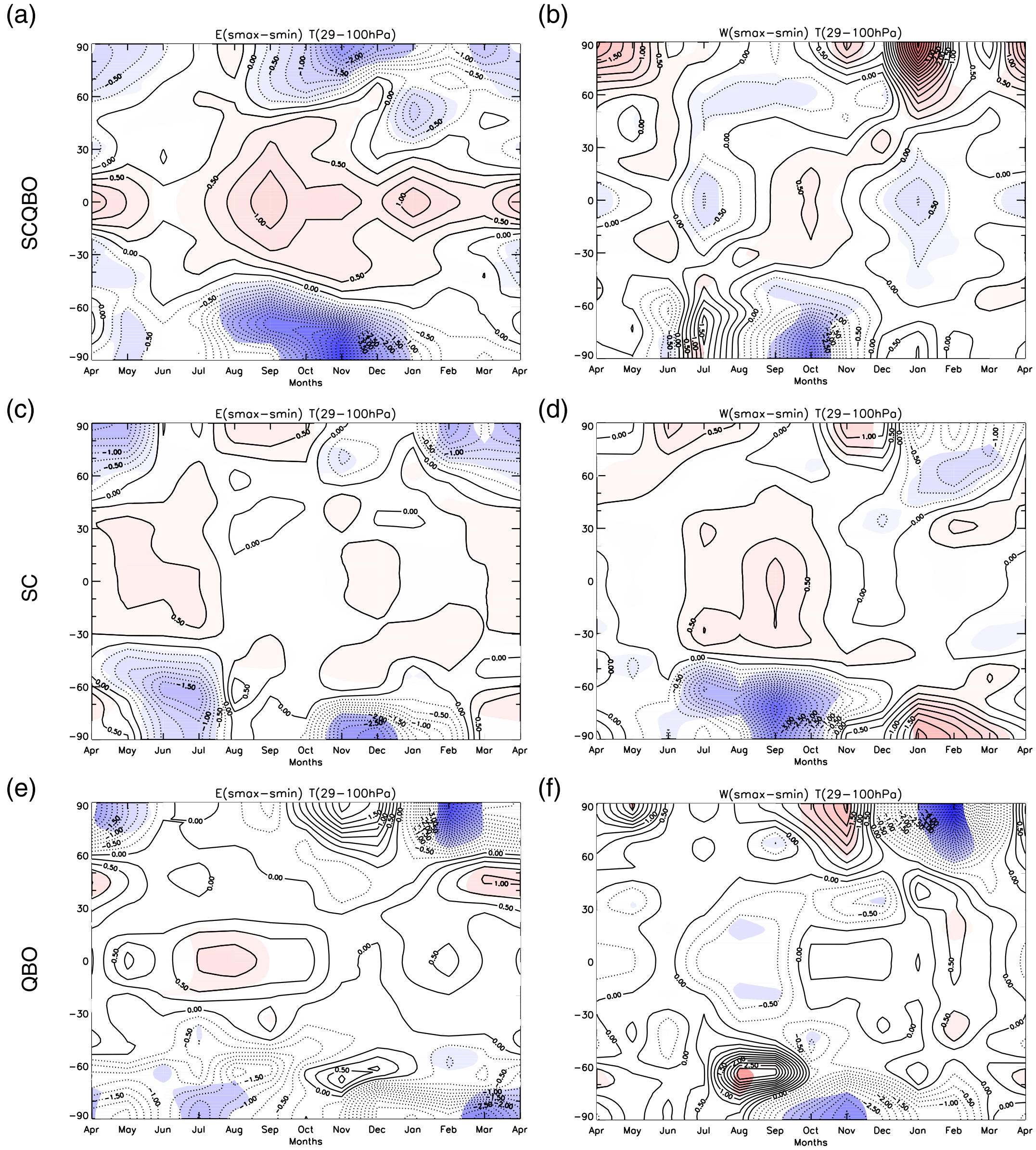


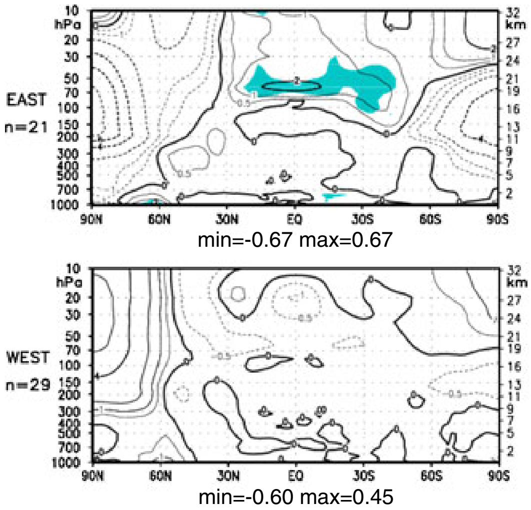
Figure 5. Seasonal march of deseasonalized lower stratospheric temperature changes between solar maximum and minimum averaged from 29 to 100 hPa from December through January in QBO east years (left) and QBO west years (right) in the (a, b) SC, (c, d) SCQBO, and (e, f) QBO experiments; contour interval: 0.25 K. Shading as in Figure 3.

[16] The QBO west years (Figure 4b) show a signal that is often of opposite sign to that in the QBO east years, with an easterly solar-induced anomaly that is already present at high latitudes in early winter (December). The zonal mean zonal wind anomalies in February are in reasonably good agreement with observations [e.g., *Labitzke*, 2003] and other mechanistic model experiments [*Ito et al.*, 2009]. However, we note that the observed solar signal during QBO west years shows a modulation of the polar night jet during NH winter similar to the QBO east case, with positive wind anomalies that move more rapidly to polar latitudes. This behavior is apparently different in the WACCM runs presented here and will be discussed later.

5.1. Lower Stratosphere: Tropics Versus Extratropics

[17] Figure 5 shows the seasonal march of the solar signals in deseasonalized zonal mean temperatures in the tropical lower stratosphere, averaged from 29 to 100 hPa, where the largest discrepancies exist between CCMs and between models and observations. Again, the anomalies are separated for QBO east (left) and QBO west years (right) and are now compared for the three different experiments. Note that the QBO phase as well as the phase of the solar cycle are defined based on their phase in December to make sure that the following months belong to the same category to investigate the seasonal march. The same years for the solar and QBO categories have been selected in all cases, although the solar

(a) WACCM (1958-2007)



(b) NCEP/NCAR (1958-2007)

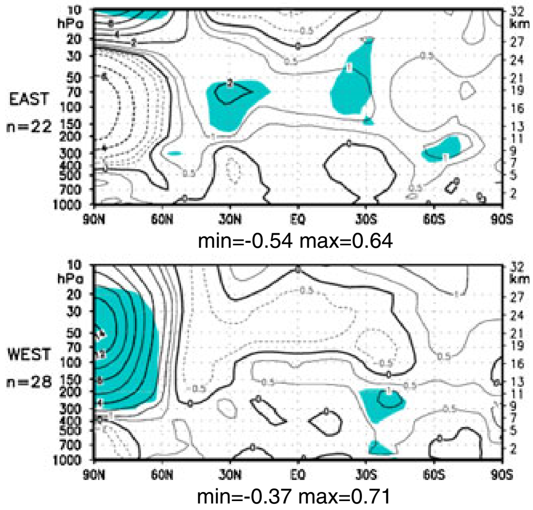


Figure 6. Vertical meridional sections between 1000 and 10 hPa (0 and 32 km) of detrended zonally averaged, monthly mean temperature differences (K) between solar maxima and minima (contour lines) in February and the correlations between temperatures and the 10.7 cm solar flux (shaded where the correlations are larger than 0.4). (upper panels) QBO east years; (lower panels) QBO west years. (a) WACCM model results from 1958 through 2007 and (b) NCEP/NCAR reanalyses for the same time interval (updated from *Labitzke* [2003]). Note that the north pole is in contrast to the other figures on the left-hand side.

cycle-only experiment does not have a QBO and the QBO-only experiment does not have a solar cycle. In the QBO east case of the SCQBO experiment (Figure 5a), statistically significant positive temperature differences exist between 30°N and 30°S almost throughout the year. A first weak maximum is reached in February before positive anomalies dominate from May, strengthen in September, and have a strong maximum in October (+1 K). Corresponding significant negative temperature responses occur at high latitudes of both hemispheres and reach largest values in November and December, i.e., in early winter. A considerably different pattern appears for the QBO west experiment (Figure 4b), where negative solar anomalies dominate the tropics and positive anomalies the extratropics during NH winter. Statistically significant positive solar temperature signals of more than 4 K exist during late NH winter at polar latitudes, indicating a more disturbed stratosphere and hence more adiabatic warming during solar maximum QBO west winters. This behavior is in agreement with the findings of *van Loon and Labitzke* [1988], who showed that the correlations between the solar cycle and the North Pole temperature averaged between January and February are dependent on the QBO phase in the lower stratosphere. Due to the phase propagation of the QBO, this correlation changes sign with height. The corresponding solar signals in ozone show patterns that are broadly consistent with the temperature differences (not shown). The temperature differences in the SCQBO experiment are very different from the anomalies in the SC and the QBO experiments (Figures 5c–5f). In the solar cycle-only experiment (Figures 5c and 5d) and the QBO-only experiment (Figures 5e and 5f), statistically significant positive temperature anomalies dominate the tropics, whereas partly statistically significant negative temperature anomalies dominate the NH high-latitude winter hemisphere in January and February. No switch in sign similar to that seen in the SCQBO experiment occurs in these two experiments in midwinter. There is only a small, partly statistically significant difference in early winter (November, December) in the SC experiment and even earlier and similar for both QBO phases (October, November) in the QBO-only experiment. The comparison of the three experiments reveals a correspondence with observed solar-QBO responses only for the SCQBO experiment in which both forcings are present. We therefore concentrate on the analysis of this experiment in the following. The different seasonal patterns for the solar signals during the two QBO phases in the SCQBO experiment suggest a response of the global mean circulation to the solar cycle such that there is relative sinking motion and adiabatic warming at low latitudes and relative ascending motion associated with cooling at high latitudes during the east phase of the QBO and vice versa during QBO west conditions. Note that the largest changes in the lower stratosphere occurs during early winter for QBO east and late winter for QBO west years. Changes in the deseasonalized vertical component of the transformed Eulerian mean (TEM) vertical velocity, $\overline{w}^*$, averaged over the lower stratosphere (100 to 29 hPa) (see Figure S1 in the supporting information), support the picture inferred from the temperature anomalies. During solar maxima, they indicate a weaker Brewer-Dobson circulation in QBO east and stronger circulation in QBO west conditions. These circulation changes lead to adiabatic cooling or warming and hence the modeled temperature differences at low and high latitudes, which are very pronounced during NH winter/spring but weaker during SH spring. It is interesting to note that the time-varying run with both solar cycle and QBO forcing (SCQBO) presented here reproduce the observed relationship in the NH in contrast to the constant forcing runs in *Matthes et al.* [2010], which showed this response only in the SH.

5.2. Correspondence With Observed Solar-QBO Relationship

[18] To investigate the agreement with the observed solar-QBO relationship in the SCQBO experiment further, the

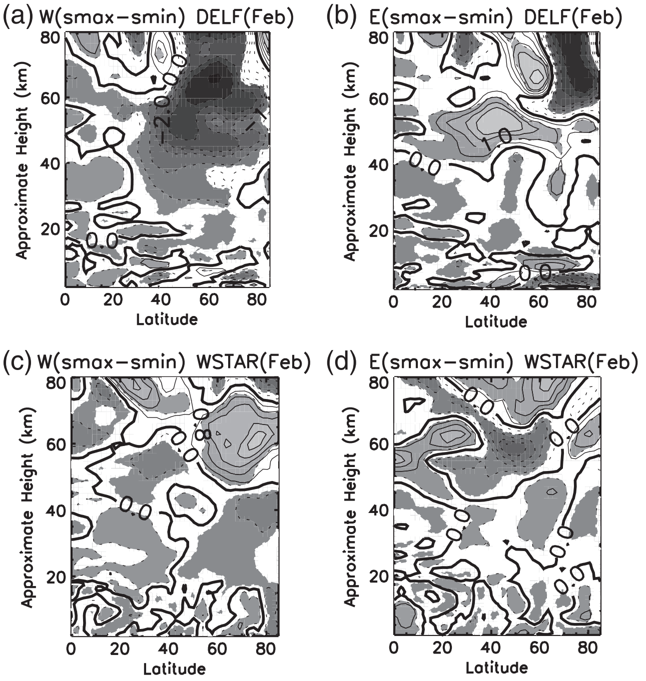


Figure 7. February composite zonal mean differences between solar maximum and minimum for the divergence of the EP-flux vector in (a) the QBO west and (b) the QBO east conditions from the Earth's surface to 80 km and from the equator to the north pole, contour interval: 0.5 m/s/d; and for the vertical component of the TEM equation $\overline{w^*}$ for (c) QBO west and (d) QBO east conditions, contour interval: 0.4 mm/s, shading as in Figure 3.

same correlation analyses are applied to WACCM and NCEP/NCAR reanalysis data of, e.g., *Labitzke* [2003] in Figure 6. Note that NH and SH are reversed in this figure. Since WACCM is forced with observed equatorial winds, we selected for comparison the period from 1958 to 2007. The latitude-height structure of the solar response for the correlation with the f10.7 and the temperature differences between solar maximum and minimum are fairly well represented by the model (Figure 6a) with maximum temperature anomalies of –8 K and hence negative correlations with the f10.7 in the NH polar lower stratosphere and +2 K and positive correlations in the tropics during QBO east years. Similarly, the effects during QBO west conditions are reproduced with a maximum of +6 K temperature anomalies at polar latitudes and –0.5 K at tropical latitudes. Note that especially the peak temperature signal in QBO west is half of the observed peak (Figure 6b) and might be due to the lower frequency of stratospheric sudden warmings (SSWs) in the WACCM version applied here. Whereas the observed SSW frequency is 0.6 warmings per year, the frequency in the run with solar cycle and QBO is 0.3. Interestingly, the run with QBO-only forcing has a similar frequency of 0.26, while the run with solar forcing only shows a considerably lower frequency of 0.18. These findings are consistent with *Richter et al.* [2011], where the inclusion of either variable SSTs or a QBO enhances the SSW frequency. The solar/QBO relationship remains true for the full 110 years of the SCQBO run, but the response in the magnitude of the correlations and the temperature differences is reduced by including more years in the analysis (not shown).

[19] Figure 7 confirms the origin of the opposite solar zonal mean temperature (Figure 6) and solar-induced zonal mean wind (Figure 4) responses for the two QBO phases in February of the SCQBO experiment. Figures 7a and 7b show the EP-flux divergence anomalies between solar maximum and minimum for QBO west and east conditions, respectively. The convergence (negative anomalies of the EP-flux divergence) during solar maximum and QBO west conditions in the midlatitude to high latitude upper

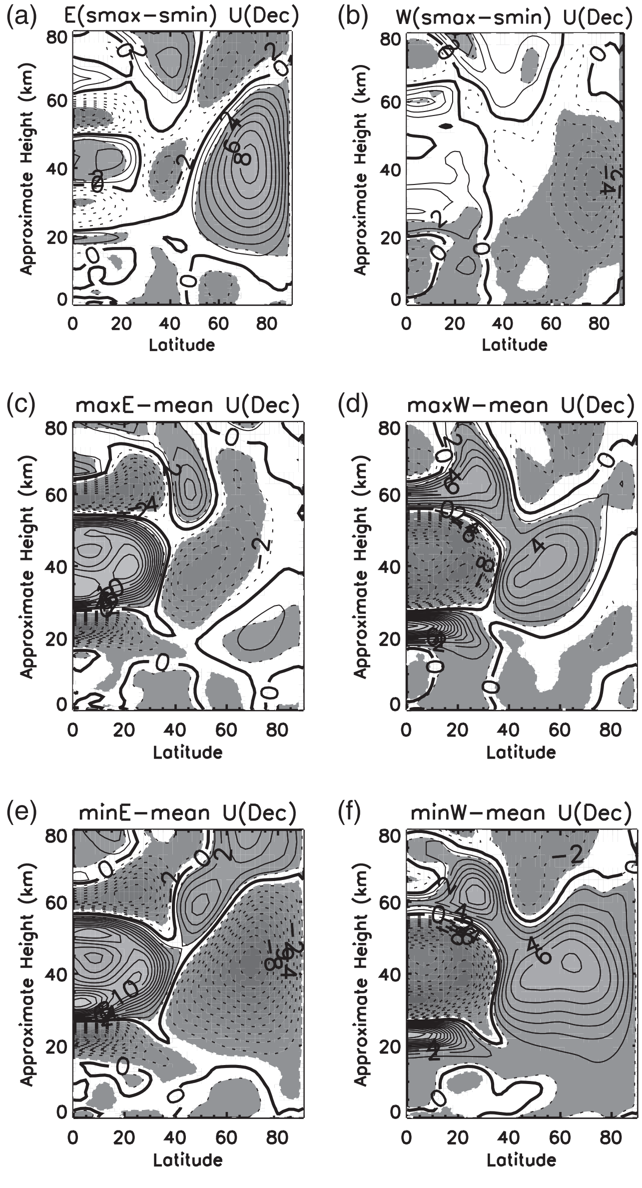


Figure 8. Zonal mean zonal wind differences in early winter (December) between (a) solar maximum and minimum for QBO east conditions, (b) solar maximum and minimum for QBO west conditions, and the difference to mean climatological conditions for (c) QBO east solar maximum, (d) QBO west solar maximum, (e) QBO east solar minimum, and (f) QBO west solar minimum; contour interval: 1 m/s. Shading as in Figure 3.

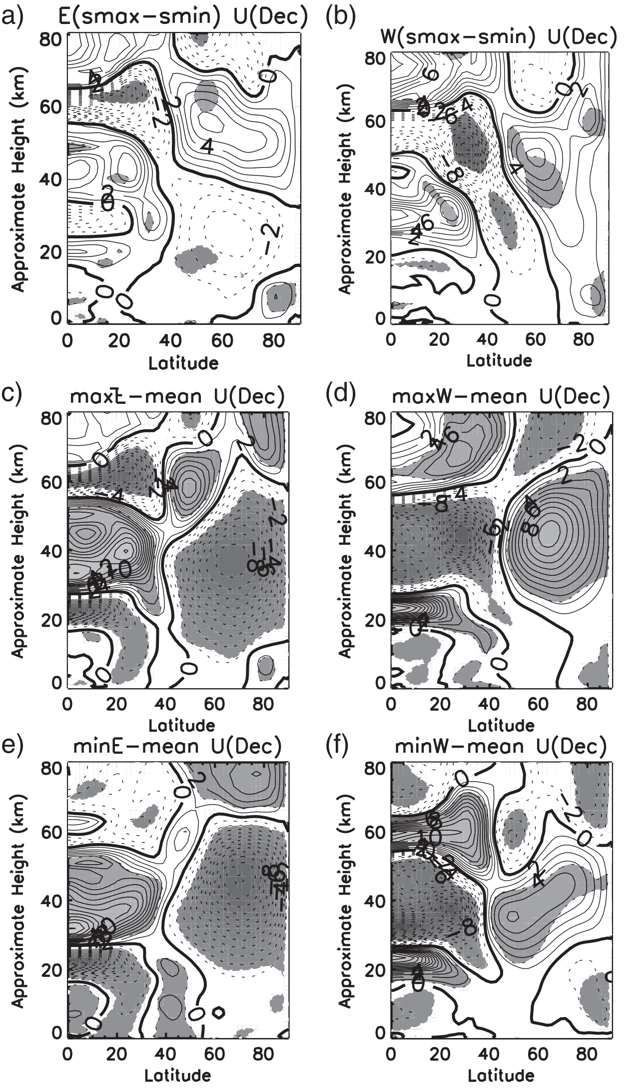


Figure 9. Stratified as Figure 8 but for the QBO-only experiment.

stratosphere/lower mesosphere correspond to a deceleration of the westerly zonal mean wind and therefore negative zonal mean wind anomalies in Figure 4b. However, during solar maximum and QBO east conditions (Figure 7b), the positive EP-flux divergence anomalies in the midlatitude upper stratosphere as well as in the midlatitude upper troposphere accelerate the westerly flow and correspond to the positive zonal mean wind anomalies in Figure 4a. The impact of these changes on wave-mean flow interactions is also evident in the vertical velocity anomalies and therefore in the BD circulation (Figures 7c and 7d). Positive vertical velocity anomalies above 50 km and poleward of 50°N correspond to relative upwelling (Figure 7c) and hence negative temperature anomalies in the high-latitude upper stratosphere and lower mesosphere for QBO west (not shown). Negative vertical velocity anomalies indicate stronger downwelling and hence relative warming as seen, for example, in the high-latitude stratosphere below 50 km for QBO west (Figure 6a). The strongest BD circulation changes occur in February during solar maximum and QBO west conditions, with a weakening in the upper stratophere and lower mesosphere and a strengthening in the lower stratosphere (Figure 7c) leading to the temperature pattern in Figure 6a.

6. Proposed Mechanism for Solar-QBO Modulation

[20] To understand the broad agreement between the SCQBO WACCM run and observations, in particular during NH winter, an investigation of the model background climatology and its QBO modulation follows. In addition, a schematic mechanism for the solar-QBO modulation is proposed.

6.1. QBO Impact on the Model Climatology

[21] Here we investigate whether and how the solar response depends on the model background climatology and whether this can explain the differences in the solar response between the two QBO phases. If the model climatology and therefore the representation of wave-mean flow interactions are not comparable to observations, the transfer of the (small) solar signal may not operate as has been pointed out by *Kodera et al.* [2003] and *Matthes et al.* [2003]. Figure 8 aims to understand the different solar response under QBO east and west conditions with respect to the background zonal mean wind climatology as well as wave propagation and dissipation during early winter, i.e., December, when the transition between the radiatively dominated to the dynamically dominated state occurs in the stratosphere. Figure 8 shows the differences between the background zonal mean wind climatology and the four combinations of solar-QBO conditions, i.e., solar maximum/QBO east, solar minimum/QBO east, solar maximum/QBO west, and solar minimum/QBO west conditions. Figures 8c to 8f confirm the existence of the so-called Holton and Tan mechanism [*Holton and Tan*, 1980, 1982] in WACCM, i.e., a more disturbed and warmer polar stratosphere during QBO east and a colder and undisturbed polar stratosphere during QBO west conditions. This relation is stronger for both QBO phases during solar minimum than during solar maximum and therefore confirms the findings by *Labitzke and van Loon* [1988], *Kodera et al.* [1991], *Gray et al.* [2004] and *Camp and Tung* [2007]. Figures 8a and 8b show the solar maximum minus minimum differences for the two phases of the QBO in December as was already presented in Figure 4. It is also worth noting the threefold structure of alternating zonal mean wind differences in the tropical stratosphere with east-west-east winds for QBO east conditions and vice versa for QBO west (see also Figure 10a). Especially notable is the extent of the zonal wind anomalies in the tropical middle to upper stratosphere into subtropical latitudes (30°N) which prevents (during QBO east conditions) or facilitates (for QBO west conditions) planetary wave propagation and leads to the described zonal mean wind changes at high latitudes (Figures 8c–8f). These results are in agreement with earlier studies on the solar-QBO relationship [*Kodera et al.*, 1991; *Gray et al.*, 2004]. Figure 9 is the same as Figure 8 but for the QBO-only experiment in order to investigate whether spurious results might be produced by our choice of sampling. Figures 9c–9f clearly show the Holton and Tan behavior; however, this is very similar for the selected solar maximum

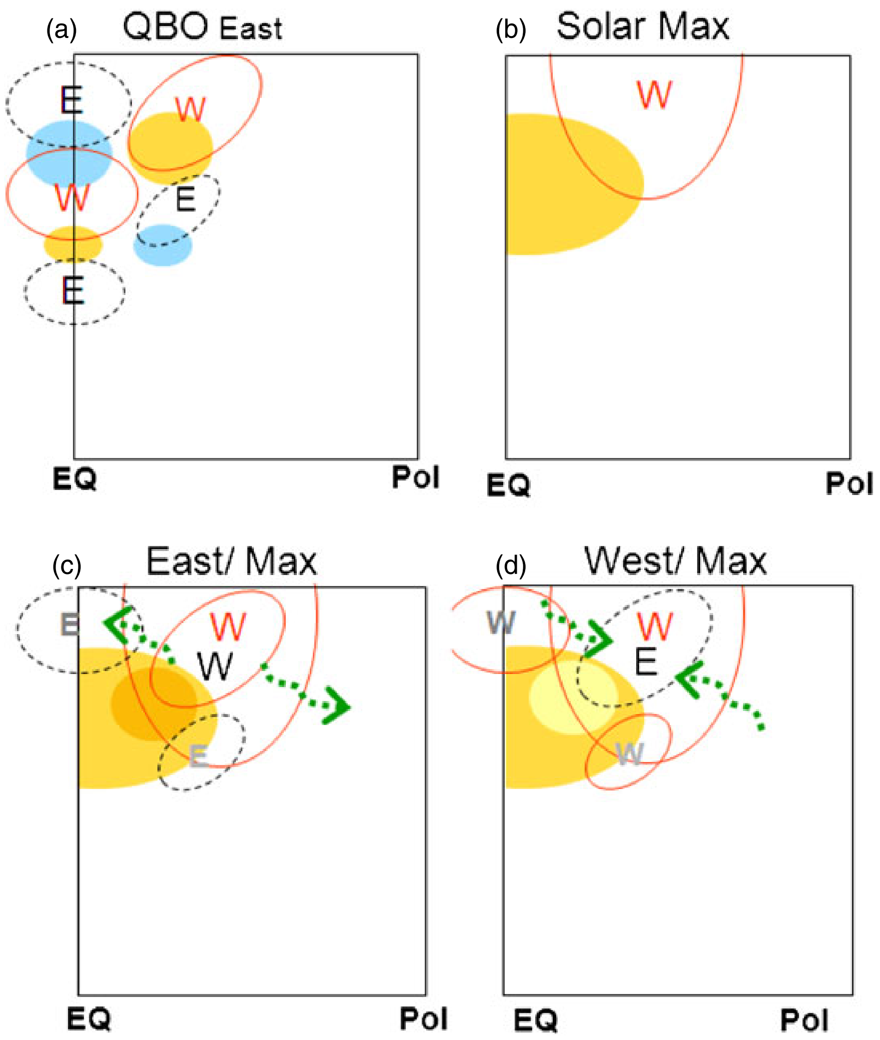


Figure 10. Schematic diagram for zonal mean wind (lines) and temperature anomalies (negative anomalies, blue; positive anomalies, orange) (a) during QBO east years and (b) during solar maximum years, and the combined solar-QBO influence for solar maximum and (c) QBO east and (d) QBO west years. Green arrows indicate planetary waves.

and minimum composites, and therefore the resulting solar differences are small and north of 60°N are statistically not significant. During solar maxima, a stronger and statistically significant westerly wind anomaly exists around 40°N and 60 km in QBO east as compared to QBO west years in the SCQBO experiment (Figures 8a and 8b); this west wind anomaly is not present in the QBO-only run (Figures 9a and 9b). We therefore suggest that the solar-QBO interaction, which is present in the SCQBO but absent in the QBO-only experiment, modifies this early winter solar cycle feature and leads to the transfer of the solar-QBO signal during the course of the winter. We summarize the findings and propose a possible mechanism for the solar-QBO modulation in Figure 10. The solar signal in the stratosphere is characterized by an early winter tropical warming and a late winter polar warming due to the interaction with planetary waves. The QBO influences the solar signal through a modulation of planetary wave propagation in the subtropical upper stratosphere and lower mesosphere in early winter through the superposition of anomalous westerly winds associated with the solar cycle and the QBO (Figures 10a and 10b). The stronger initial solar temperature signal and the corresponding westerly wind anomaly (Figure 8a) in the subtropical upper stratosphere/lower mesosphere during QBO east in December is further strengthened during this QBO phase (Figure 10c) and helps to initiate dynamical feedbacks with high latitudes and the poleward-downward propagation of the westerly wind anomaly during the course of the winter (Figure 4a). During QBO west conditions, the initial solar signal is already weaker than under QBO east conditions (Figure 4b), and hence this QBO phase acts to further weaken or damp the solar signal during NH winter in our experiments. Following the studies by *Kodera et al.* [1991] and *Gray et al.* [2004], we propose that, depending on the background wind, the small initial solar signal is enhanced during QBO east and diminished during QBO west conditions during early winter (Figures 10c and 10d). We suggest that this modulation of planetary wave activity further influences the transfer of the solar-QBO signal during NH winter and finally results in the observed solar-QBO differences in the polar stratosphere during late winter, i.e., February. As noted above, the transfer of the solar signal in observations is seen as a poleward-downward propagation of westerly wind anomalies which is faster during QBO west conditions [e.g., *Matthes et al.*, 2004]. In our model experiments this is slightly different since the QBO west phase seems to have an easterly anomaly propagating poleward-downward. For a more realistic, i.e., in agreement with observations, transfer of the solar-QBO signal, a better representation of wave-mean flow interaction and wave activity is required in the model which might exist in experiments with an improved background climatology. A self-consistent QBO might also be a prerequisite for a more realistic wave-mean flow interaction between tropics and high latitudes.

7. Conclusions

[22] The observed solar-QBO relation is investigated for the annual mean and the dynamical response during NH winter in the stratosphere with three multidecadal time-varying experiments with WACCM3.1 under different combinations of the solar cycle and the QBO as well as constant GHG, ODS, and sulfate aerosol conditions. From the comparison between observed and modeled responses, a mechanism for the solar-QBO interaction is proposed. Our major findings may be summarized as follows:

[23] 1. The solar response in the annual mean tropical temperature and ozone in the upper stratosphere is independent of the presence of a QBO. The response in the middle to lower stratosphere differs depending on the presence of the QBO and the solar cycle but is statistically indistinguishable in the three experiments.

[24] 2. The seasonal evolution of the solar signal during NH winter reveals a poleward-downward movement of westerly wind anomalies in agreement with observations for the SCQBO experiment which used the most realistic forcing, i.e., time-varying solar cycle and QBO. The solar response in the solar cycle-only and the QBO-only experiments suggests that both forcings are needed to generate a solar response similar to observations.

[25] 3. Separating the solar signal according to the phase of the QBO shows broad agreement with the observed solar-QBO signal only in the SCQBO experiment. The occurrence of more disturbed conditions and hence more stratospheric warmings in February during solar maximum and QBO west conditions is comparable to a similar result from NCEP/NCAR reanalysis although with reduced amplitude. The overall fairly good agreement with observations during NH winter in the SCQBO experiment represents an improvement compared to the constant forcing experiments by *Matthes et al.* [2010], which only showed a significant response in the SH. We note that the good agreement with observations only occurs in the time-varying runs using both QBO and solar cycle forcings even though the experiments are idealized sensitivity experiments without anthropogenically induced increases in GHGs and ODs.

[26] 4. The QBO modulates the background zonal mean wind climatology; this affects the frequency of stratospheric warmings as also noted by *Richter et al.* [2011] and modifies the solar signal. Depending on the background wind in the respective QBO phase, a mechanism for the solar-QBO interaction is proposed in which the small initial solar signal in the subtropical upper stratosphere/lower mesosphere during early winter is enhanced during QBO east and diminished during QBO west conditions. This consequently influences the transfer of the solar-QBO signal during the course of the winter and leads to the observed differences in the signal during late winter. The proposed mechanism builds on earlier work of *Kodera* [1991], *Kodera et al.* [1991], and *Gray et al.* [2004].

[27] Overall, we have shown reasonably good agreement between the model and observations mainly during NH winter and propose a mechanism for the solar-QBO modulation. However, there are several caveats. First, we were not able to carry out more than one ensemble member per case, and therefore, the response might very well differ in another realization of these runs. Second, a newer version of WACCM, version 3.5, as used for the *SPARC CCMVal* [2010] report, shows an improved stratospheric warming frequency due to the consideration of turbulent mountain stress [*Richter et al.*, 2010; *de la Torre et al.*, 2012]. This improved SSW frequency also leads to an improved poleward-downward transfer of the solar signal as well as a more realistic solar-QBO response [*Chiodo et al.*, 2012]. Third, we prescribed the QBO and therefore limit wave-mean flow interaction between the tropics and higher latitudes. To realistically represent all processes involved for the solar-QBO signal transfer, experiments with an internally generated QBO would be necessary. A last caveat is that we have only demonstrated top-down effects as the SSTs are held constant to climatological monthly varying mean values, and any atmosphere-ocean feedback or enhancement of the solar signal as discussed by *Meehl et al.* [2009] is not taken into account. Even though there are a number of caveats, the results presented here provide an important step toward a more complete understanding of the solar-QBO relationship. The proposed mechanism for the solar-QBO relation has to be tested in other more extended model experiments.

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