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Decadal-scale periodicities in the stratosphere associated with the solar cycle and the QBO

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[1] An interactive two-dimensional model is used to analyze the response of the stratosphere to the 11-year solar cycle in the presence of a quasi-biennial oscillation (QBO). The purpose of the paper is to demonstrate how the solar cycle response of stratospheric ozone and temperature diagnosed from model simulations depends on the QBO. The analyses show that (1) the simulated response to the solar flux when no QBO is imposed is very similar in different periods, despite differences in the magnitude and variability of the solar forcing; (2) the apparent solar response of temperature and ozone is modified by the presence of an imposed QBO; and (3) the impact of the QBO on the derived solar response is greatly reduced when the observed QBO forcing is replaced by an idealized sinusoidal forcing. The impact of the QBO on the solar cycle analysis is larger when only two solar cycles are analyzed but is not negligible even for analysis of four solar cycles. Differences in the QBO contribution account for most of the differences in analyses of separate 22-year periods. The statistical significance is not always a reliable indicator that the QBO effect has been separated.

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1. Introduction

[2] Among the factors that contribute to the interannual variability of the stratosphere are two that are roughly periodic with timescales greater than a year. The first is the quasi-biennial oscillation (QBO) in tropical lower stratospheric zonal wind [*Baldwin et al.*, 2001], which affects the wind, temperature and meridional circulation in low latitudes but also has a significant impact on interannual variability in middle and high latitudes during winter [*Holton and Tan*, 1980, 1982]. The QBO also causes a variation in ozone in low and high latitudes [*Randel and Wu*, 1996, 2007]. The QBO is forced by waves in the tropics; the exact makeup of the wave forcing is not known but likely includes large-scale tropical waves such as Kelvin waves and also gravity and inertia-gravity waves [*Hitchman and Leovy*, 1986].

[3] The other periodic forcing is the variable ultraviolet (UV) flux associated with the 11-year solar cycle. Variations in the UV part of the spectrum affect the photolysis of molecular oxygen, ozone, and other compounds and therefore drive changes in the chemistry. Additionally, the UV flux changes affect the diabatic heating both directly and, through ozone changes, indirectly. Signals of the solar variability have long been sought in two of the best-observed stratospheric fields: ozone and temperature. A temperature response has been found in stratospheric data by *Remsberg and Deaver* [2005], *Hood* [2004], *Crooks and Gray* [2005], *Scaife et al.* [2000], and recent analysis by W. Randel (personal communication, 2007). Despite significant overlap in the time periods covered by these analyses, there are differences in the magnitude and vertical structure of the temperature response. However, they all have in common a maximum response in the upper stratosphere around 40–45 km (higher temperature with higher solar activity); the estimated magnitude of the peak response is in the range 1–2.5 K from solar minimum to maximum. A secondary maximum in temperature response in the lower equatorial stratosphere is present in some analyses but not in SSU/MSU4 data from 1979 to 2005 (W. Randel, personal communication, 2007) and a large uncertainty exists about the relative minimum in the middle stratosphere.

[4] Experiments with two-dimensional models, general circulation models (GCMs), or Chemistry Climate Models (CCMS) performed so far [e.g., *Brasseur*, 1993; *Matthes et al.*, 2003, 2004; *Tourpali et al.*, 2003; *Egorova et al.*, 2004; *Austin et al.*, 2006; *Schmidt et al.*, 2006; *Marsh et al.*, 2007] all show a coherent positive annual mean temperature signal throughout the stratosphere that maximizes at the equatorial to midlatitude stratopause and therefore differs from the analyses of SSU/MSU data [e.g., *Hood*, 2004]. Recent simulations with CCMs seem to better represent the observed vertical structure in the tropical stratosphere (J. Austin et al., Coupled chemistry climate model simulations of the solar cycle in ozone and temperature, submitted to *Journal of Geophysical Research*, 2007). The reason for the better agreement is not yet understood; it could be a real signal or a contamination by other signals like the QBO or the stratospheric impact of

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variable tropical sea surface temperatures (SSTs) in both the observations and the model simulations. The present study will focus on the role of interference by the QBO, as described below.

[5] Simulations face an ongoing challenge to reproduce the observed solar effects since the domain over which the observations show a solar response has extended to the lower stratosphere and troposphere [e.g., *Labitzke and van Loon*, 1988; *Kodera*, 2002; *Haigh*, 2003; *Gleisner and Thejll*, 2003; *van Loon et al.*, 2004; *Coughlin and Tung*, 2004a, 2004b; *Haigh et al.*, 2005]. Observational analyses and modeling efforts are therefore directed not only at simulation of the solar cycle response but also at determining the mechanisms for transferring the solar signal to other parts of the atmosphere not directly affected by the ultraviolet variations [*Kodera and Kuroda*, 2002; *Gray et al.*, 2001a, 2001b; *Gray*, 2003; *Matthes et al.*, 2004; *Palmer and Gray*, 2005]. There is increasing evidence that the QBO plays a role in transferring tropical perturbations, including the solar signal, to high latitudes.

[6] Observations by, e.g., *Soukharev and Hood* [2006] and *Randel and Wu* [2007] indicate a change in upper stratospheric ozone with the solar cycle of several percent: much larger than the percentage change of temperature. The increased production of reactive oxygen by higher UV flux in the Herzberg continuum during solar maximum outweighs the negative ozone tendency due to warmer temperature and higher ozone photolysis rate. Like the temperature response, the simulation of the response of stratospheric ozone is also becoming more consistent between different two- and three-dimensional models. For example, K. Matthes et al. (Report on the first SOLARIS workshop 4–6 October 2006, Boulder, Colorado, USA, Scholarly Publishing and Academic Resources Coalition Newsletter, 2007) point out a minimum in the solar cycle response of ozone in the tropical middle stratosphere that is produced in four independent models.

[7] Factors that are currently evolving in models and that might contribute to the vertical structure of the ozone or temperature response are a time-dependent solar cycle, a time-dependent QBO (either self-consistent or synthetic), variable SSTs and/or the El Niño cycle [e.g., *Marsh and Garcia*, 2007], and improvements in the model climatologies. Inclusion of aspects of the solar cycle in addition to the radiative flux, for example energetic particle precipitation [*Langematz et al.*, 2005; *Rozanov et al.*, 2005], is also a new development.

[8] Simulations of the response to solar variations have considered static conditions of fixed solar flux from either the maximum or minimum [e.g., *Haigh*, 1996, 1999; *Shindell et al.*, 1999, 2001; *Matthes et al.*, 2003; *Tourpali et al.*, 2003; *Egorova et al.*, 2004; *Schmidt et al.*, 2006; *Marsh et al.*, 2007] and fixed QBO phase from either westerly or easterly [*Balachandran and Rind*, 1995; *Rind et al.*, 2002; *Matthes et al.*, 2004, 2006] or fixed solar flux conditions together with a time-varying self-consistent QBO [*Palmer and Gray*, 2005]. The solar cycle response diagnosed from such time slice simulations can differ from time-dependent calculations for a number of reasons. (1) The actual solar flux is highly variable on short (days) to long (decadal) timescales so it is not possible to define "typical" solar maximum and minimum conditions. (2) The response of the atmosphere may shift with season so the relationship between the solar flux variations and the annual cycle may influence the response. (3) The analysis method used on time slice experiments is not the same as used for observational analysis so direct comparison is difficult. Numerical experiments are overcoming these shortcomings thanks to increased computer capacities; recent simulations include time variations of the solar signal [*Austin et al.*, 2006; *Eyring et al.*, 2006] or of both the solar signal and QBO (see K. Matthes et al., Scholarly Publishing and Academic Resources Coalition Newsletter, 2007).

[9] Beginning in 1987, *Labitzke* [1987, 2005], *Labitzke and van Loon* [1988, 2000], and *van Loon and Labitzke* [1998] published a series of papers showing a significant correlation of stratospheric temperature and geopotential height with the 11-year solar cycle when the data were separated into two time series defined by the phase of the QBO. The correlation is strong in Northern Hemisphere winter and has opposite sign in the two series: warm polar temperatures at 30 hPa correspond to high solar activity if the QBO phase is westerly while cool polar temperatures correspond to high solar activity in years when the QBO phase is easterly. Twenty years of observations have been added to the time series since the pattern was initially found and the signal has stayed strong [*Labitzke et al.*, 2006].

[10] These analyses have generated a large number of studies to explain them. The studies fall into two general categories: (1) efforts to show that the decadal to 11-year signal is a result of the QBO or other dynamical processes that coincidentally follows the 11-year solar cycle and (2) efforts to establish a physical mechanism for the unexpected correlation. Among the early papers, *Salby and Shea* [1991] performed a statistical study of the probabilities of the 11-year periodicity given the short record (at that time about 3.5 solar cycles), the single point per year sampling of wintertime mean temperatures, and the known influence of the QBO on the high latitude winter stratosphere. They found out-of-phase decadal cycles for the separate time series from the easterly and westerly phases of the QBO resulted from these factors; no solar cycle was included in their work. Although this study implies that the signal could be a statistical artifact, more recent papers support the interpretation of Labitzke and van Loon that the anomalies represent a true solar signal [*Salby and Callaghan*, 2000; *Soukharev and Hood*, 2001]. *McCormack* [2003], *McCormack et al.* [2007], *Cordero and Nathan* [2005], and *Salby and Callaghan* [2004, 2006] explored mechanisms through which the solar cycle could affect the QBO; these studies contribute to increasing evidence that the QBO itself depends on the solar cycle.

[11] In the present paper, we focus on the problems associated with separating the QBO and solar signals in the middle atmosphere using multiple linear regression analysis. In other words, we focus on the problems associated with the analysis of results rather than searching for a new or unexpected form of interaction. To this end, we extend the analysis of *Lee and Smith* [2003], which investigated the ozone response to the solar cycle in satellite data and a two-dimensional chemical-dynamical model. The model simulations included time-varying solar flux, volcanic aerosols timed to reproduce the eruptions of El Chichón and Mt. Pinatubo, and/or a parameterized QBO in the

tropics. With all three of these externally applied forcings included, the model did a reasonably good job of representing the solar cycle in stratospheric ozone diagnosed from observations. However, multiple regression analysis was not able to remove either the QBO or the volcanic effects, so the solar cycle analysis differed significantly when they were included. The extensions included in the present study are (1) investigation of the response of temperature as well as ozone, (2) more realistic forcing of the QBO and solar cycle, (3) examination of the impact of the smoothness of the solar variations and the QBO momentum forcing on the response, and (4) additional diagnostic analysis to determine more precisely the causes for the variations found in the different model cases. Here, we address only the multiple regression analysis of the response to imposed variations. The intriguing and still unexplained response of stratospheric winter high-latitude temperatures and other fields to the solar cycle when data are stratified by the phase of the QBO is not addressed.

[12] Section 2 gives a brief description of the model and analysis. Section 3 describes the results of several simulations that look in particular at the role of the QBO on the apparent solar cycle and the dependence of the signal on the period and phase of the QBO. Conclusions are given in section 4.

2. Model and Analysis

2.1. SOCRATES Numerical Model

[13] The SOCRATES model is a global two-dimensional model of the middle atmosphere. It has been used for numerous studies of the chemistry and energetics of the middle atmosphere. The model was extended to its current domain (surface to 3×10^{-5} hPa) in 1998. Papers that describe this version of the model are by *Brasseur et al.* [2000], *Chabrillat et al.* [2002], and *Khosravi et al.* [2002]. The model and detailed description are available from https://cdp.ucar.edu/index.jsp.

[14] For investigating interannual ozone variability using SOCRATES, *Lee and Smith* [2003] incorporated a time-dependent solar cycle that varied on the basis of the observed monthly average $F10.7$ cm flux. They also included a parameterization of the QBO and specified varying stratospheric aerosols that included two volcanic eruptions. Note that other forcing, including planetary and gravity wave fluxes from the troposphere and emissions of anthropogenic gases, has no interannual variability in these model simulations. The simulations described in this paper have several differences from those of *Lee and Smith* [2003]. To accommodate longer runs, the $F10.7$ flux input was extended using monthly observations of $F10.7$ from 1954 (www.sec.noaa.gov). As shown by *Lee and Smith* [2003], the values were converted to flux per wavelength using a variable scaling factor derived from observations from November 1989 (solar maximum) and September 1986 (solar minimum) provided by J. Lean. The QBO was based on the observed equatorial winds and therefore varies from one cycle to the next. We also investigated using a sinusoidal solar flux with approximately the same period and amplitude.

[15] Three different parameterizations for the QBO were used: relaxation to observations, relaxation to a sinusoidal forcing with the same average phase and amplitude as the observations, and relaxation to a sinusoidal forcing with the same average amplitude as the observed QBO but opposite phase. The observed QBO was taken from the data set compiled by M. Giorgetta (http://www.pa.op.dlr.de/CCMVal/Forcings/qbo_data_ccmval/u_profile_195301-200412.html) that has been extended in altitude to cover the range 90–3 hPa; the full altitude range is used in the simulations.

[16] The basic dynamical integration of the SOCRATES models solves for temperature and the stream function of the two-dimensional transformed Eulerian mean circulation but not directly for the zonal wind. The QBO relaxation is applied to the heating, which is then used in the thermodynamic equation, as described by *Politowicz and Hitchman* [1997]. The forcing uses the time derivative of the wind in order to give a QBO phase that agrees with observations. The latitudinal structure is symmetric about the equator and falls off exponentially away from there. No QBO forcing is applied in high latitudes. Despite the simplified dynamics of the SOCRATES model, the response to the QBO forcing shows in general good fidelity to the observations. Regression coefficients of ozone to the two QBO indices (not shown) have spatial structures that are quite similar to those of the two QBO decompositions from SAGE II ozone shown by *Randel and Wu* [1996, Figure 6]. The variation of Northern Hemisphere geopotential and wave amplitude with the lower stratospheric tropical QBO wind [*Holton and Tan*, 1980] is also reproduced in the model.

[17] The model runs do not include variations from increasing greenhouse gases, variable stratospheric aerosols due to volcanic eruptions, and other external forcing (sea surface temperature, etc.). Figure 1 shows the monthly $F10.7$ fluxes used in the model runs and the QBO forcing at 28 hPa for the observations and for the sinusoidal forcing. Note that for both the solar $F10.7$ and for the QBO, the actual oscillations vary significantly in amplitude and in period.

2.2. Time Series Analysis (Multiple Regression Analysis)

[18] The response of an atmospheric parameter to forcing is determined by performing a multiple regression analysis against specified scalar indices representing forcing terms (described below) for each model grid point. All of the forcing terms are included in the analysis even if that forcing is not present in a particular model run. For example, in model cases where the solar flux is held constant, the analysis still includes the solar cycle index as one of the set of variables in the multiple regression algorithm. In the analysis of model integrations for which there were no variations in the solar flux, the observed monthly mean flux was used as a solar index.

[19] The model data are averaged for each month and deseasonalized by removing the monthly average taken over the analysis period. The regression uses two QBO indices, a solar flux index, and a linear trend. The resulting time series is represented by

$$F(t) = \alpha F10.7 + \beta \mathrm{QBO1} + \gamma \mathrm{QBO2} + \tau \mathrm{Trend} + \varepsilon,$$

where ε is the residual. A 2σ (twice the variance) criterion is used to determine statistical significance. In the SOCRATES

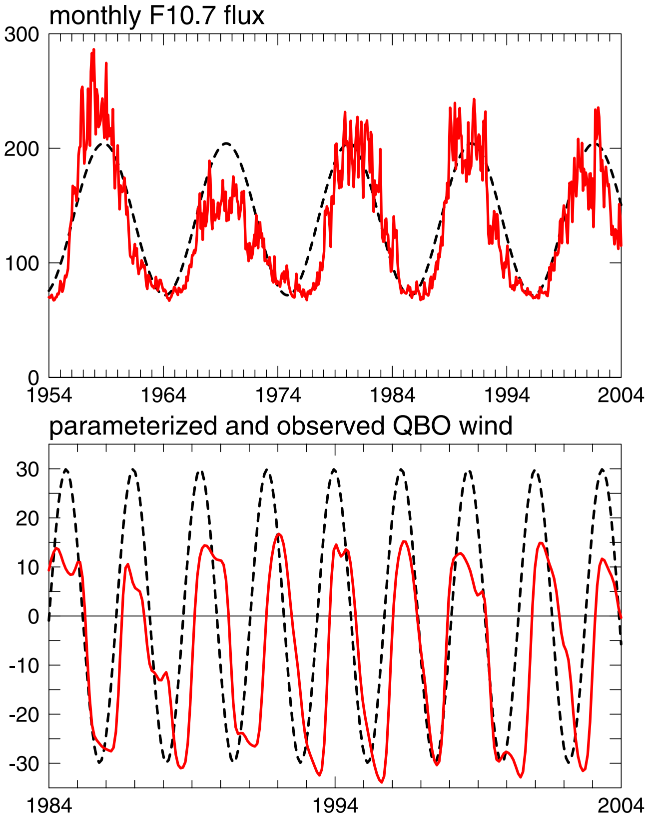

Figure 1. (top) The red solid line is the monthly mean $F10.7$ radio flux used to force the model in the "observed solar forcing" integrations; the black dashed line is a sinusoidal approximation. (bottom) The red solid line shows a 20-year subset of the monthly mean QBO wind at 28 hPa used to force the model in the "observed QBO forcing" integrations; the black dashed line is an approximation used to force the model in the "sinusoidal QBO forcing" integrations.

model, the solar flux variations at all wave numbers are scaled exactly to the monthly $F10.7$ flux using the values provided by *Lean et al.* [1997], so the index used in the regression analysis is exactly proportional to the flux at the top of the atmosphere. In the actual atmosphere the correlation of fluxes at different wave numbers is less than one and the flux varies on timescales of less than a month.

[20] *Lee and Smith* [2003] described two approaches for defining the QBO index. They showed that, with a QBO index based on the exact sinusoidal QBO momentum forcing, it was possible to remove most of the QBO contamination from the solar cycle analysis. There is unfortunately no observational counterpart to this exact QBO index. In this paper, we use the other QBO index considered by *Lee and Smith* [2003] in order to better compare with analyses used for observations. This other index is intended to represent the QBO indices used in observational analyses, which is typically the deseasonalized zonal wind in the lower stratosphere at one or more specific pressure levels. To approximate the index based on Singapore wind in the SOCRATES model, we use the model zonal mean zonal wind at the equator at 28 and 10 hPa.

[21] Different approaches have been used in observational analyses to determine the QBO index that best removes the oscillations; several are tested in this paper (see section 3.5). *Lee and Smith* [2003] used a single QBO index; as a result the analysis gave large residuals (QBO contamination of the solar response analysis) in the equatorial lower stratosphere that represent an inability to separate out the QBO signal at points where the time series was approximately orthogonal to the QBO index. *Randel and Wu* [1996, 2007] and *McCormack et al.* [2007] determined the two leading QBO patterns from singular value decomposition and used these to determine the two QBO indices at each point. A similar method that involved the two principle components of the residual, after all other periodicities had been removed, was used by *Crooks and Gray* [2005]. *Soukharev and Hood* [2006] account for the different phase relationships by shifting the QBO index forward or backward in time to line up with the wind variations at a particular point in latitude and pressure. In a study that focuses on the polar winter response, *Haigh and Roscoe* [2006] define a new composite QBO-solar index as the product of the original solar and QBO indices.

3. Results of Multiple Regression Analysis

[22] To facilitate comparison with other observational and modeling studies, the results from multiple regression analysis of the model data are presented as percentage change of ozone and absolute change in temperature per 100 units of $F10.7$ solar flux. The magnitudes should be multiplied by a factor of 1.3–1.5 to estimate the net changes from solar minimum to solar maximum. The factor is variable because it depends both on which years are used to determine the maximum and on what averaging period is used in the solar flux time series. Ranges in use for the latter include monthly mean, annual mean, and 81-day (approximately three solar rotations) averages.

3.1. Basic Cases With Solar Cycle and QBO

[23] Figure 2 shows the percentage change in ozone in response to the solar cycle for a 43-year analysis period for six different model runs. This period covers approximately an integral number (four) of solar cycles. Shading indicates where the signal is not significant at the two sigma level. The results shown include all combinations of three QBO scenarios (no imposed QBO; QBO forcing based on observations, and sinusoidal QBO forcing) and two solar flux scenarios (no variation in solar flux and solar flux variation from observed monthly mean $F10.7$). Note particularly two parts of the figure. Figure 2a shows that almost no variability of the atmosphere in the SOCRATES model during this period projects onto the solar cycle. Figure 2b, with no imposed QBO and with solar flux variations based on the observed $F10.7$ variation, will be considered to be the actual solar cycle in the model. Analyses of other runs will therefore be compared to this field to see how well they are able to reproduce the solar response.

[24] The diagnosed solar cycle variations in ozone for all cases in which the solar flux is variable (Figure 2 right) have a number of similarities: the largest response is in the upper stratosphere of about 1.5–1.9% per 100 $F10.7$ units; the response is global but in most cases is maximum in the

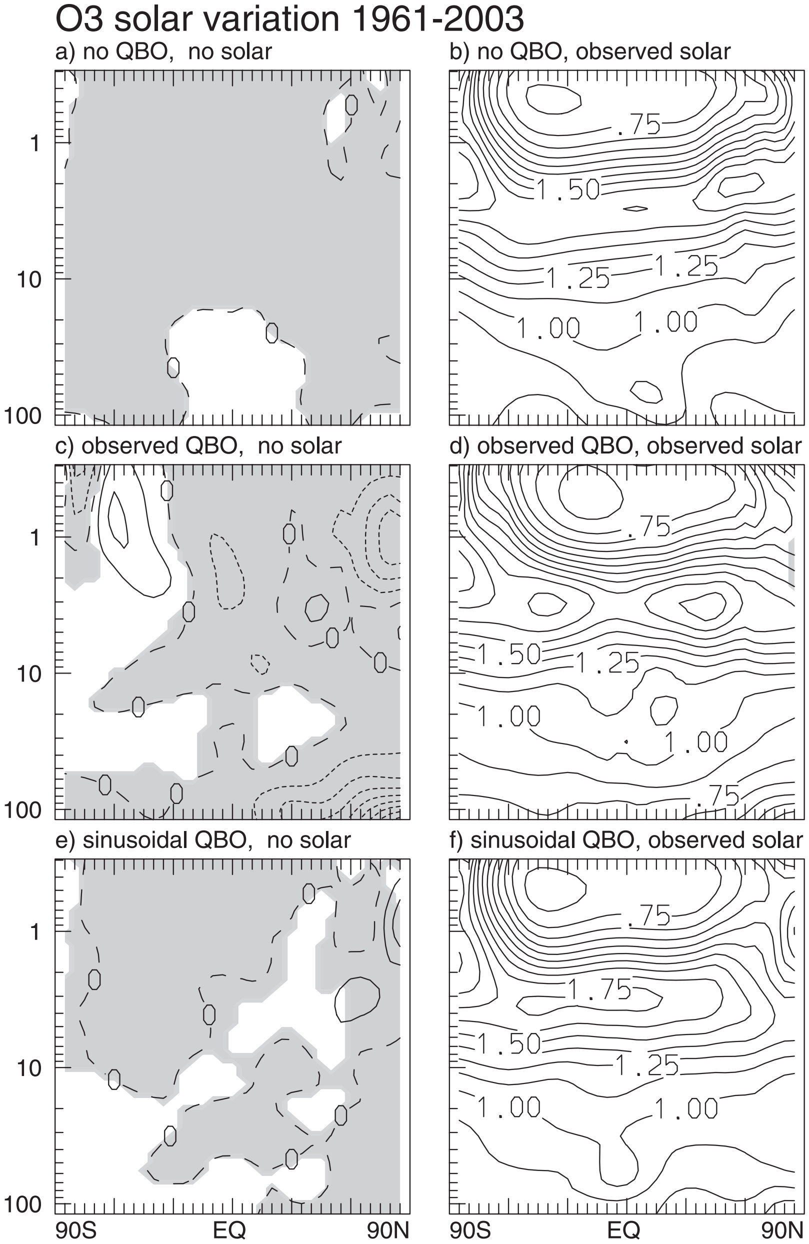

Figure 2. Latitude-pressure cross sections of the response of ozone to solar cycle variation (in percent change per 100 units of $F10.7$) from six different model integrations over 43 years. The rows from top to bottom correspond to no QBO forcing, QBO forcing from observations, and sinusoidal QBO forcing. The columns from left to right correspond to no solar flux variations and solar flux variations from observations. The solid contours indicate positive values, the long dashed line is the zero contour, and negative contours are dashed. Contour interval is 0.125%. The shading indicates the signal is not significant at the 2σ level.

Southern Hemisphere high latitudes. The apparent solar response where there is a QBO but no solar forcing (Figure 2c) may be a result of the relationship between the period of the observed QBO and the solar flux [e.g., *Salby and Callaghan*, 2006].

[25] The analyzed solar response of the model simulations with observed solar and observed QBO forcing (Figure 2d) has a somewhat different structure than the other analyses. There is a minimum in the ozone response in the tropical upper stratosphere formed by a decrease in the equatorial response and increases in the responses in the subtropics of both hemispheres. The analyzed response of the simulations in which the QBO forcing is less variable (bottom row) does not have such a minimum and, in that respect, more closely resembles the basic response in the model.

[26] Figure 3 shows the variations of temperature for the solar cycle in the same six cases. Note that the significance is lower than for ozone, particularly in high northern latitudes but also, in the case with QBO forcing from

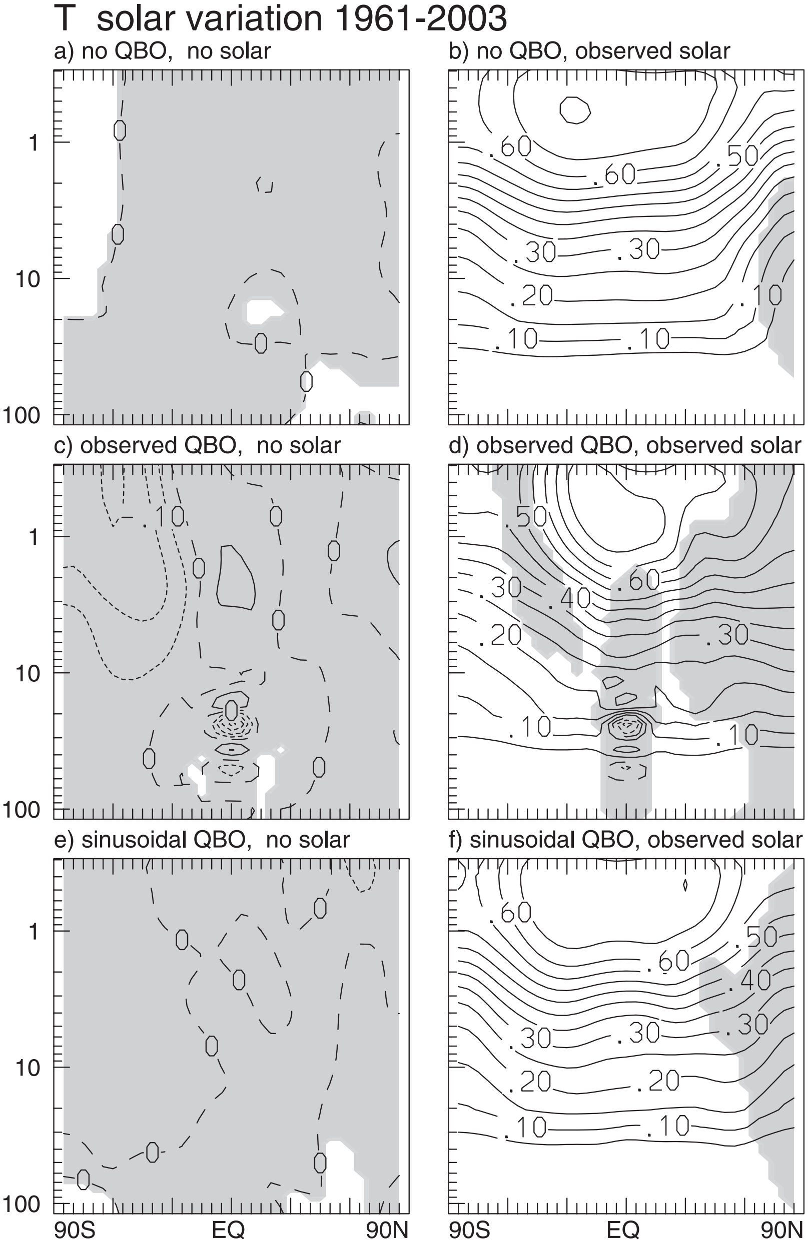

Figure 3. As in Figure 2 but for the response of temperature to solar cycle variation (in K per 100 *F*10.7 units) from six different model integrations. Contour interval is 0.05 K.

observations, through the depth of the tropical stratosphere. The solar cycle response maximum of 0.6–0.7 K per 100 *F*10.7 units occurs in the vicinity of the stratopause. Like the ozone response, the temperature signal has a broad maximum across all latitudes. The response peaks at low latitudes but is still large at both poles. As in the case for ozone, the impact of the QBO on the apparent solar response is most evident when the QBO forcing is based on observations (Figure 3d).

[27] If the QBO and solar cycle impacts on the analyzed solar cycle response are independent, then the sum of the two effects should be equal to the analyzed solar response when both effects are included. For the SOCRATES model, the two fields are similar (Figure 4) although not identical. Even with the simplified dynamics of the SOCRATES model, the presence of a QBO has some effect on the way the stratosphere responds to variable solar forcing. We consider two possible reasons for this net effect. (1) Even though the net momentum forcing is zero when averaged over a QBO cycle, the imposition of a QBO might alter the model climatology and, as a consequence, alter the way that the atmosphere responds to solar flux variations. (2) The QBO in the model, as determined by the tropical zonal wind, might depend on the solar flux. We have examined the SOCRATES data to check for these two possibilities. The annual average temperature, winds, etc. are quite similar with or without a QBO. However, the multiyear averages of the monthly dynamical fields do have some differences. Specifically, adding a QBO to the model causes some small but not negligible changes in the poleward flow

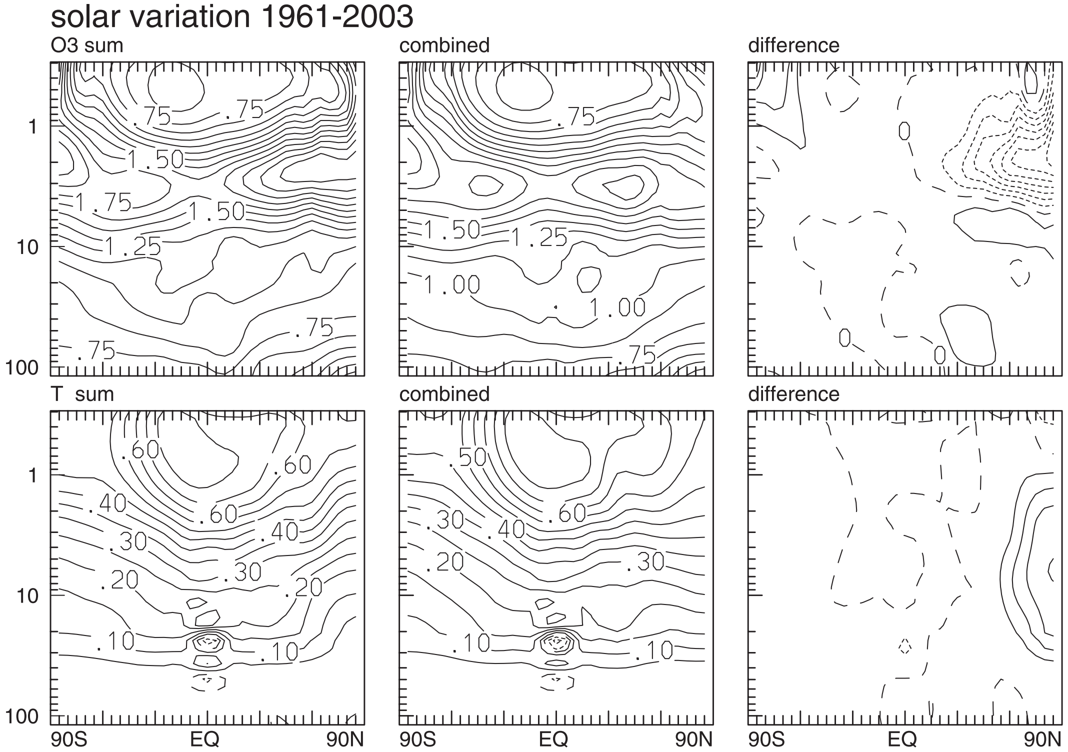

Figure 4. The analyzed response of (top) ozone and (bottom) temperature to solar cycle variations. (left) The sum of the analyzed solar signals from two cases: one with QBO forcing but no solar flux variations and the other with no QBO forcing but with solar flux variations based on observed *F*10.7 flux. (middle) The analyzed solar signals from a case that includes both solar flux variations and QBO forcing. (right) The difference between the left and center figures. Contours for the left and center figures are as in Figures 2 and 3 for ozone and temperature, respectively (significances are not shown). Contour intervals for the right figures are 0.1% for ozone and 0.04 K for temperature.

in the NH stratosphere, primarily during NH winter. There are resulting changes, also small, in the composition of transported species such as ozone and water.

[28] Since the QBO forcing is prescribed, it should not be affected by the solar cycle. However, the actual lower stratospheric wind in the model depends not only on the prescribed forcing, meant to represent the zonal mean of the momentum driving by dissipating waves, but also on other radiative and dynamical processes. It could, in principle, include a response to the solar cycle variations. However, comparison of the tropical winds in the model runs with and without solar variability indicates that the SOCRATES QBO does not develop a solar cycle. Therefore, the differences seen in Figure 4 are interpreted as being due to the changes in the atmospheric circulation, transport, and composition when a QBO is included in the model. The presence of the QBO changes the basic climate of the model, which then affects the way the atmosphere responds to solar flux variations.

[29] The variability of the observed QBO winds may have some contribution from the solar cycle [e.g., *McCormack et al.*, 2007] but there are also other sources of variability, including a tendency for phase transitions to occur during certain months and a tendency for the westerly shear zones to descend more rapidly than easterly shear zones [e.g., *Pascoe et al.*, 2005]. There may also be variations in the wave forcing from the troposphere. If one assumes that the principal sources of QBO variability are not associated with the solar flux variations, then the changes in the apparent solar response due to the QBO can be interpreted as contamination, i.e., that the analysis is not able to isolate the solar response from other processes. This is the way the term contamination is used in this paper. Note that if the QBO is affected in a major way by the solar cycle, a separation of the two processes will never be achieved.

[30] Since the differences in Figure 4 are small away from northern high latitudes, we can conclude that differences between the solar response in models with and without the QBO are due to the linear superposition of two effects: the solar response and the QBO contamination. In other words, the imposed QBO leads to a periodicity that is interpreted by the analysis as a component of the solar cycle. This occurs with almost the same magnitude and structure whether or not the model includes variable solar flux.

3.2. Dependence on the Analysis Period

[31] Despite the impact of the QBO on the diagnosed solar cycle, the analysis still indicates that the basic aspects of the response are similar in the model cases presented so far. However, bear in mind that these analyses are performed for 43-year analysis periods. In reality, we do not have good global measurements of either temperature or ozone in the stratosphere for such a long period. Ozone analyses have used SBUV (the Solar Backscatter Ultraviolet

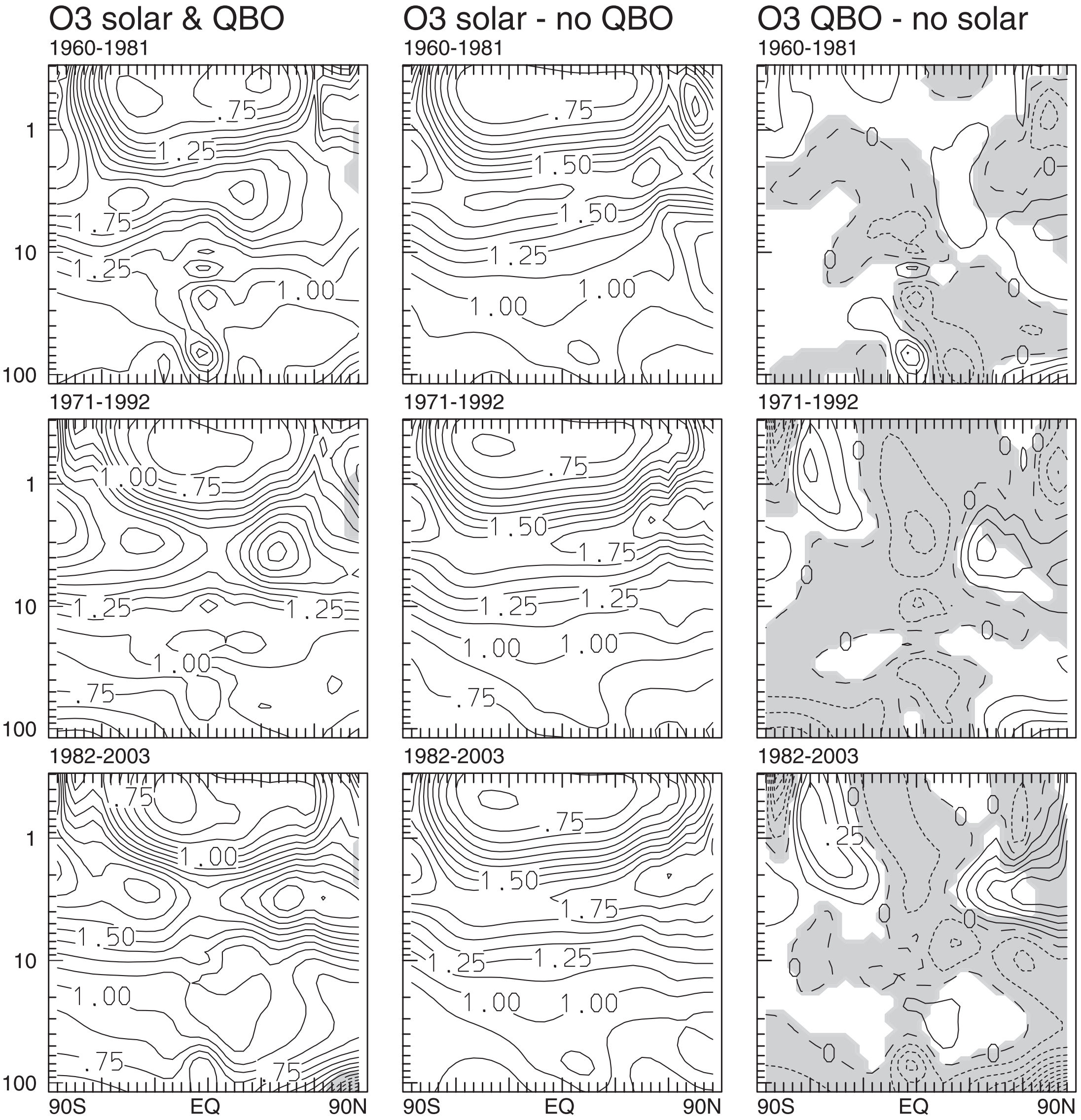

Figure 5. The response of ozone to solar cycle variation (in percent change per 100 *F*10.7 units) from the model integration forced (left) with observed QBO winds and observed solar flux variations, (middle) with observed solar flux variations and no QBO, and (right) with observed QBO variations and no solar cycle. The results are from three overlapping 22-year periods. Contours and shading are as in Figure 2.

instrument, 1978–2003) or SAGE I and/or II (the Stratospheric Aerosol and Gas instrument 1979–1981 and 1984–2005) [*Hood*, 2004; *Soukharev and Hood*, 2006; *Lee and Smith*, 2003; *Randel and Wu*, 2007]. Temperature analyses have used HALOE [*Remsberg and Deaver*, 2005], SSU data [*Scaife et al.*, 2000] or historical analysis of radiosonde data [*Labitzke*, 1987; *Labitzke and van Loon*, 1988] but most commonly have relied on the NCEP or ERA objective analysis data [*van Loon and Labitzke*, 2000; *Crooks and Gray*, 2005; *Haigh*, 2003]. The latter two data sets have a longer record using a series of similar instruments but are strongly influenced by changes in satellite instruments and have only a limited sensitivity to temperature in the upper stratosphere.

[32] Figure 5 shows how the ozone analyses over approximately two solar cycles (22 years) change depending on the specific analysis period. Figure 5 left is made from the model integration that includes solar cycle and QBO, both forced from observations. The examples are 1960–1981, 1971–1992, and 1982–2003. The later two periods show an ozone response with a minimum in the equatorial upper stratosphere, flanked by maxima. In this respect, the results from these periods are similar to the 43-year analysis of the same integration (Figure 2d). Note also that the analyzed solar response in the equatorial lower stratosphere is not consistent over the three periods.

[33] To break down the contributions to these patterns, we repeat the analysis of 22-year periods using results from the model run that includes a solar cycle but no imposed QBO and results from the model run including a QBO forced from observations but no solar flux variations. As discussed above, the analyzed solar responses over a 43-year period from the two cases approximately add to give the solar response when

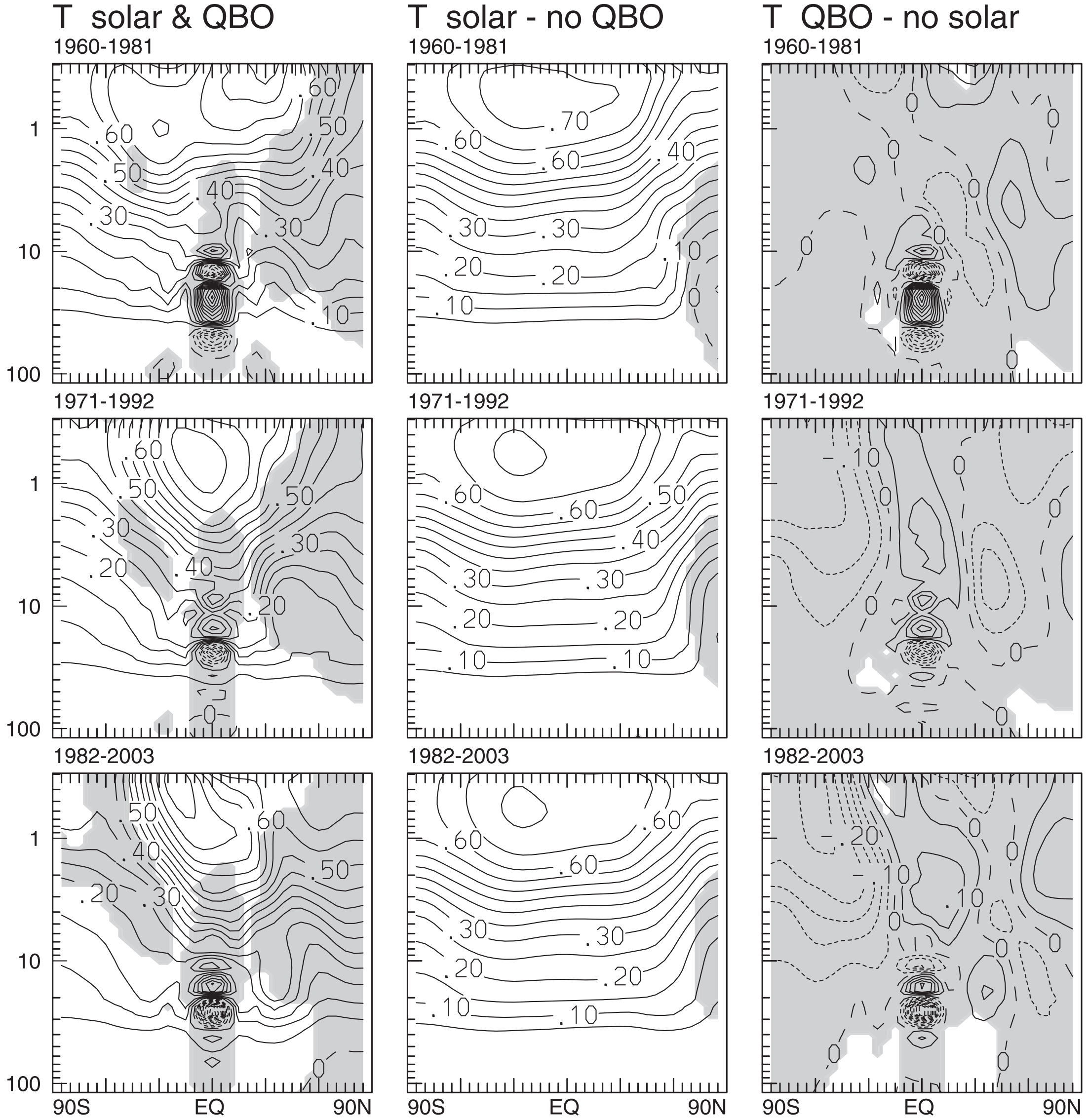

Figure 6. The response of temperature to solar cycle variation (in K per 100 *F*10.7 units) from the model integration forced (left) with observed QBO winds and observed solar flux variations, (middle) with observed solar flux variations and no QBO, and (right) with observed QBO variations and no solar cycle. The results are from three overlapping 22-year periods. Contours and shading are as in Figure 3.

both sources of variable forcing are included. The same is true for the shorter 22-year periods.

[34] Figure 5 shows that the ozone response to solar forcing is quite similar in the three periods when there is no QBO forcing in the model. Where the apparent response due to QBO contamination is not significant, it has minimal impact on the analyzed response of the model forced with both contributions. However, where the apparent response due to contamination is calculated to be significant, for example high NH latitudes in the middle stratosphere in the first two periods, it contributes to the solar response calculated in the analysis.

[35] One thing to note in Figure 5 is that the analysis of the SOCRATES simulations for all periods indicates an ozone response that is positive throughout the tropical stratosphere, even when the QBO is included. This is a change from *Lee and Smith* [2003], which found a negative ozone solar response in the tropical stratosphere. Although some of the difference is due to the use of two QBO indices in the current analysis process (see section 3.5), a more important difference is that no volcanic aerosols are included in the model in the current study. The variable aerosol content in the stratosphere was responsible for the negative ozone response in low latitudes found by *Lee and Smith* [2003]. Several observational analyses of ozone data with significant overlap in time to the most recent case shown in Figure 5 find a negative response in the lower or middle stratosphere. In analysis of SBUV data by *Hood* [2004], tropical negative response values were calculated to be significant whereas in analysis of SAGE I and II data (1979–2005) by *Randel and Wu* [2007], the tropical negative values were calculated to be not significant.

[36] The temperature response over the same three periods (Figure 6) shows lower significance than the ozone

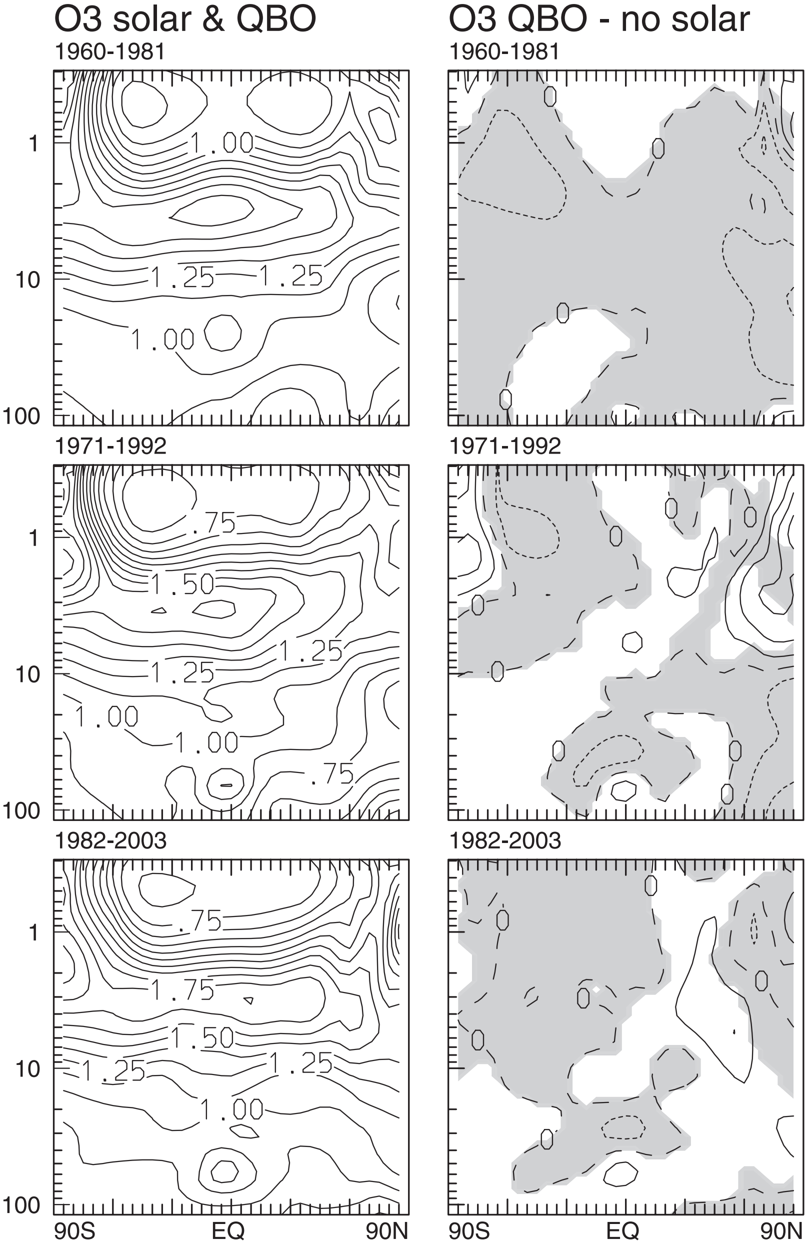

Figure 7. The response of ozone to solar cycle variation (in percent change per 100 *F*10.7 units) from the model integration forced (left) with sinusoidal QBO winds and observed solar flux variations and (right) with sinusoidal QBO winds and no solar cycle. The results are from three overlapping 22-year periods. Contours and shading are as in Figure 2.

response and also has noticeable differences between periods. Over the later two periods the maximum response is confined to low latitudes while over the first period the response is stronger at midlatitudes of both hemispheres and has a local minimum near the equator. The temperature solar response for the two diagnostic runs, solar forcing only and QBO forcing only, are also shown. The solar forcing case (Figure 6 middle) gives very similar results for the three periods. The apparent response in the QBO forcing case has only limited regions where it is statistically significant in any of the three periods but nevertheless causes obvious contamination of the calculated solar response. A response that is calculated to be significant (nonshaded) in the model case forced with both QBO and solar cycle indicates that the additional variance due to inclusion of the QBO is not so strong as to cause failure of the statistical test. The solar response in the presence of a QBO is not significant in the regions of highest QBO variance: at the equator in the middle and lower stratosphere and in the Northern Hemisphere high latitudes.

[37] Comparison of the model cases in Figures 5 and 6 shows that it is the QBO that is primarily responsible for differences in the solar response during the three relatively short (22 year) periods. Current research mentioned in the Introduction is looking into how and to what extent the solar cycle could affect aspects of the QBO. As noted in the

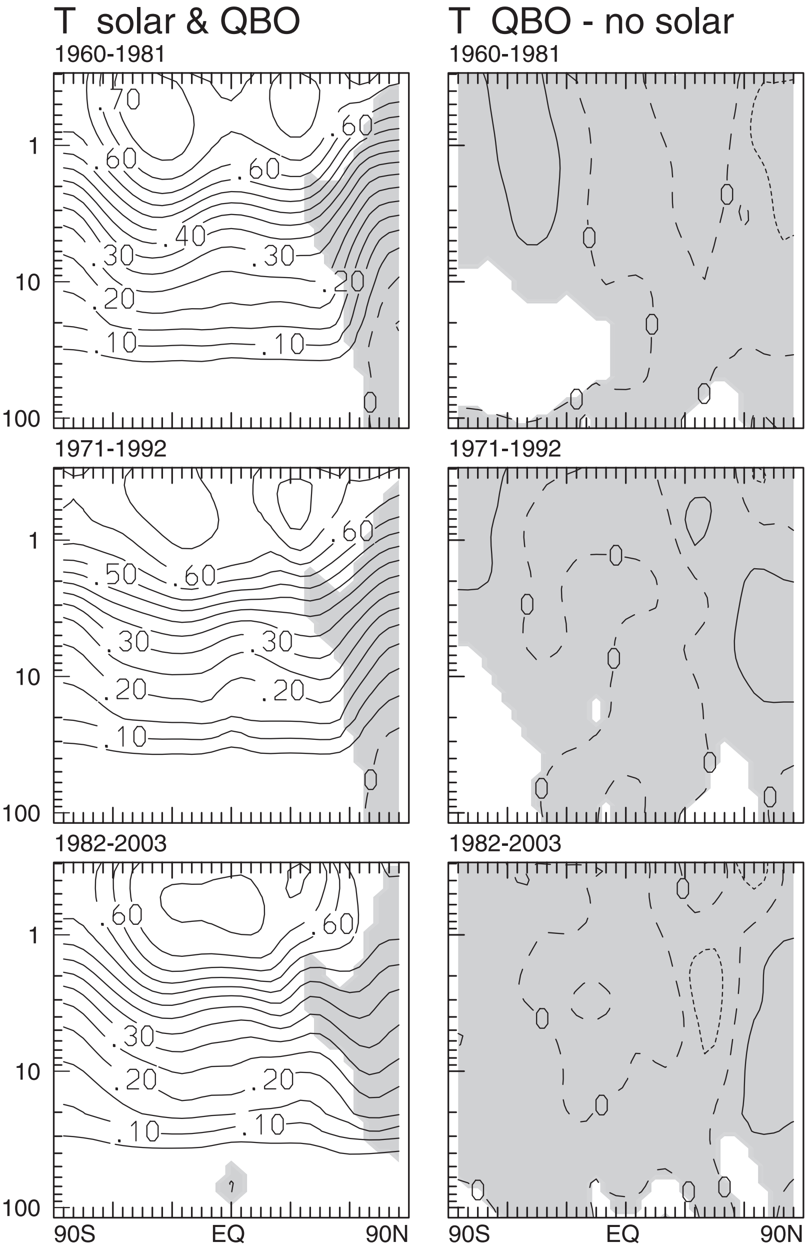

Figure 8. The response of temperature to solar cycle variation (in K per 100 $F10.7$ units) from the model integration forced (left) with sinusoidal QBO winds and observed solar flux variations and (right) with sinusoidal QBO winds and no solar cycle. The results are from three overlapping 22-year periods. Contours and shading are as in Figure 3.

discussion of Figure 4, the background atmosphere in the high-latitude stratosphere changes when a QBO is included, so the differences between the cases with and without a QBO owe something to this change. However, the solar and QBO effects on the apparent solar response are approximately independent over much of the stratosphere; this supports the interpretation of the difference in apparent solar response with a QBO included as contamination.

3.3. Solar Response to a Sinusoidal QBO

[38] In Figures 2 and 3, the apparent solar cycle due to the QBO is smaller when the forcing is exactly sinusoidal. For example, the magnitudes of the responses in Figures 2e and 3e are smaller than are the cases forced with the observed QBO winds (Figures 2c and 3c). Likewise, the structure of the solar response in Figures 2f and 3f are more similar to the case with no QBO (Figures 2b and 3b). Figure 7 shows analysis of the solar response of ozone over 22-year periods when the sinusoidal QBO forcing is used with and without the solar cycle (left and right, respectively). Although the solar response in this case (Figure 7 left) is now closer to the response in the absence of a QBO (Figure 5 middle), it nevertheless shows some evidence of contamination. A similar situation occurs for analysis of the temperature response (Figure 8).

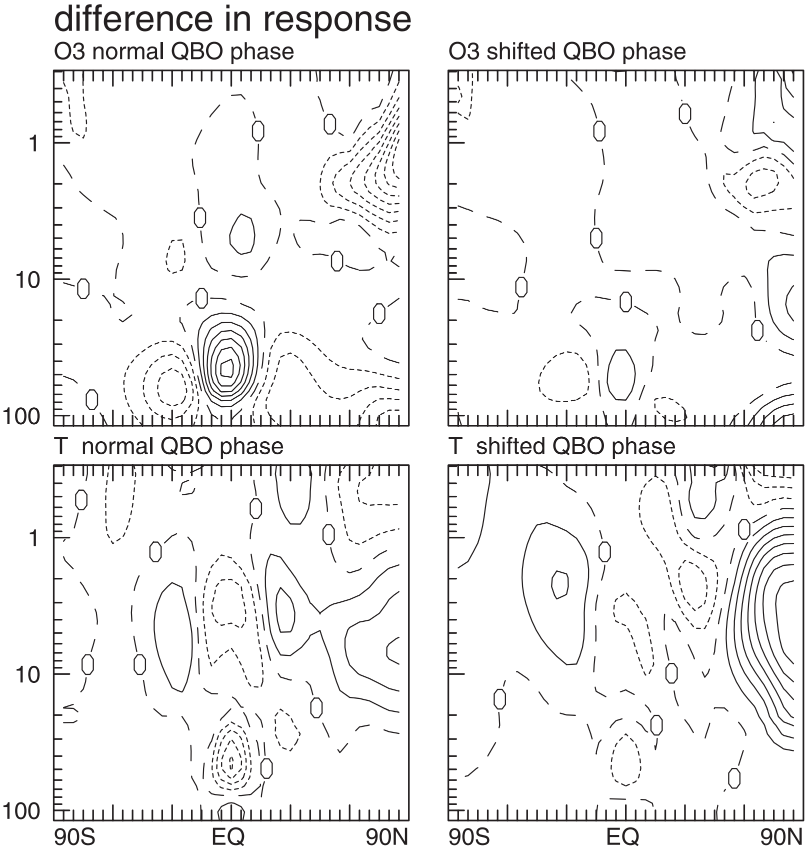

Figure 9. The difference between the response of (top) ozone (units are percent) and (bottom) temperature (units are K) to solar cycle variation when the QBO is included from that with no QBO. (left) A sinusoidal QBO forcing in phase with the observed variation and (right) a sinusoidal forcing out of phase. Contour intervals are 0.1% for ozone and 0.02 K for temperature.

[39] With the sinusoidal QBO forcing, there is no correlation between it and the solar cycle. However, as stated earlier, the actual wind in the tropical lower stratosphere depends not only on the imposed forcing, but also on other processes. In particular, beating between the QBO and the annual cycle can lead to oscillations with a longer period [*Salby and Shea*, 1991].

[40] For symmetry, we also investigated a set of model runs in which the QBO was based on observations and the solar flux variations were sinusoidal. In this case (not shown), all of the results are almost indistinguishable from the results with monthly varying solar flux.

3.4. Dependence on Relative Phases of the QBO and Solar Cycle

[41] The following experiments are used to determine if the impact of the QBO on the analyzed solar cycle depend on a special relationship between the QBO and the solar cycle over the period of analysis. In these integrations, the QBO forcing was shifted by one half cycle throughout the integration. In the results presented above, the sinusoidal QBO forcing term at the beginning of the model run was zero and increasing at 35 hPa. In the shifted QBO phase runs, the QBO forcing term was zero and decreasing at the same location. Figure 9 left shows the difference in the analyzed response of ozone and temperature to the solar forcing from two model integrations: one with sinusoidal QBO forcing approximately in phase with the observed QBO (see Figure 1) and the other with no QBO forcing, i.e., the differences are between Figure 2f and 2b and between Figures 3f and 3b. Figure 9 right shows the corresponding differences between the solar response in the model case with sinusoidal QBO forcing with the opposite phase and that with no QBO forcing. Temperature differences are small but those for ozone are sometimes appreciable.

[42] If the impact of the QBO on the analyzed solar response depended only on the phase of the wind relative to the solar cycle, one would expect that the differences in Figure 9 right would be opposite to those in Figure 9 left. However, for both ozone and temperature, there is no fixed relationship between the two cases with different QBO phases. For example, the original QBO phase maps into a positive temperature response in the subtropics and midlatitudes of the Northern Hemisphere stratosphere while the opposite phase of the QBO also maps into a positive response there. Such a result could occur if it is not the QBO forcing alone, but rather the interaction of the QBO with other processes in the model, that is responsible for the residual seen in the figures. This conclusion is consistent

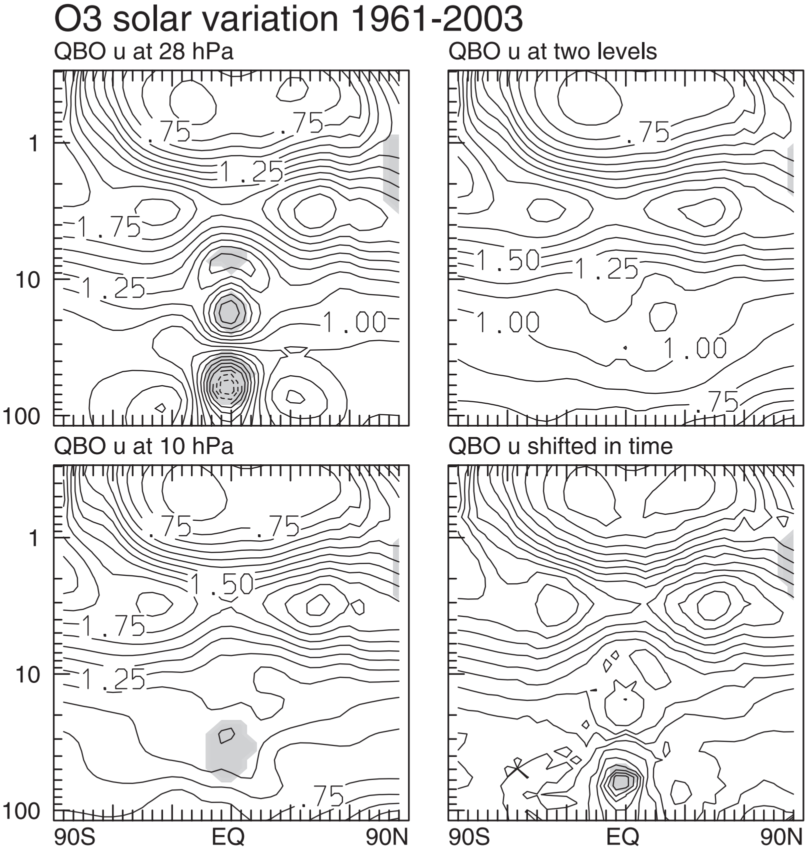

Figure 10. The response of ozone to solar cycle variation (in percent per 100 *F*10.7 units) from analysis using three different indices for the QBO in the regression analyses. See text for a description. Contours and shading are as in Figure 2.

with extensive observational evidence indicating that the QBO responds to annual and semiannual variations in the atmosphere and vice versa [*Baldwin et al.*, 2001].

3.5. Dependence on QBO Index

[43] All of the analysis presented so far has used two QBO indices chosen to be approximately in quadrature; the indices are the model monthly average zonal winds at 28 and 10 hPa. The choice of these follows the observational analysis of *Randel and Wu* [1996, 2007], in which they use time series of principal components of the ozone QBO. *Lee and Smith* [2003] is one of a number of previously published studies that used a single QBO index. With only a single index, the regression analysis cannot remove QBO signals at locations where the QBO-induced oscillation of the variable (temperature or ozone, for example) is at quadrature with the wind time series used for the index. Since the QBO is not actually sinusoidal, the quadrature is not exact. In addition, this will not account completely for irregularities in the QBO caused, for example, by the tendency of the QBO westerly shear zones to descend faster than the easterly shear zones [e.g., *Baldwin et al.*, 2001] or by seasonal variations in the QBO [*Baldwin et al.* 2001; *Pascoe et al.*, 2005].

[44] Another method for avoiding the problems with the QBO was used and tested by *Soukharev and Hood* [2006]. In their analysis, the QBO index, defined by the time series of seasonally averaged zonal wind at a specific point, is shifted in time to line up either in phase or out of phase with the time series of the variable being analyzed. For example, if the zonal mean temperature at some point in latitude and pressure has maxima that lag those of the QBO index by one season, the QBO index used in the analysis will be shifted by that amount before the regressions are done.

[45] Figure 10 shows the regression analysis of solar response of ozone for four different analyses: (1) using a single QBO index at 28 hPa, (2) using a single QBO index at 10 hPa, (3) using two QBO indices (same as Figure 2d), and (4) shifting the QBO index from 28 hPa in time in the manner proposed by *Soukharev and Hood* [2006]. All cases use the model run forced with observed QBO variability and observed monthly mean variations in solar flux. The results indicate that none of the methods completely removes the apparent solar response due to the QBO. All three of the examples using a single QBO index introduce spurious solar response signals into the analysis. The example using two indices is able to remove most of the tropical response in ozone but cannot remove it completely in the temperature analysis (Figure 3). The method of *Soukharev and Hood* performs better in high latitudes but cannot completely eliminate the tropical response. Note, however, that their method performs very well for QBO

forcing that is exactly sinusoidal (not shown); the problems stem from the irregular periodicity of the oscillation.

4. Summary and Conclusions

[46] The SOCRATES two-dimensional chemical-radiative-circulation model includes a thorough representation of middle atmosphere chemistry and radiation. As in all global two-dimensional global models, the dynamics are highly simplified. The model is not intended to be comprehensive but is a useful tool for investigating the response of the middle atmosphere to forcing by the solar cycle over multiple decades. The model includes a parameterization of the quasi-biennial oscillation in tropical zonal wind. This paper investigates various aspects of the solar cycle in stratospheric temperature and ozone in the model and how those are affected by the QBO.

[47] The analysis uses multiple linear regression analysis to separate the QBO and solar cycle responses in stratospheric temperature and ozone. For the solar cycle, the regression index is the $F10.7$ cm radio flux. In the model this is exactly proportional to the solar flux at UV wavelengths. In reality, the proportionality is not exact but is high for wavelengths important in the stratosphere photolysis and heating [*Donnelly*, 1991]. The index for the QBO in the regression is based on the model zonal mean wind in the equatorial lower stratosphere. This is similar to indices used in observational analyses. Note that although the exact QBO momentum forcing is known in the model, this is not used as an index.

[48] The results show that the analyzed solar signals in both ozone and temperature are affected by the presence of the QBO. Even for a time series that includes four solar cycles, the analysis is not able to completely remove the contamination of the solar signal by the QBO. Multiple model cases were tested using several forms of QBO and solar forcing. The results show that the impact of the QBO on the solar analysis is larger for the more irregular QBO based on observations than for the QBO with sinusoidal forcing. *McCormack et al.* [2007] also found that the solar cycle response of stratospheric ozone changed when their model included a QBO. However, in the two-dimensional model that they used, the solar cycle and the QBO actually interacted with each other; this made it difficult to distinguish contamination from a true interaction.

[49] Since all of the analyses presented use a multiple linear regression technique, there is a possibility that limitations in the technique itself could be responsible for some of the difficulty in separating QBO and solar signals. Other analysis methods that have been applied to the solar response or to the separation of it from the QBO include singular value decomposition [*Randel and Wu*, 1996], empirical mode decomposition [*Coughlin and Tung*, 2004a], compositing single-season data by phase of the QBO [*Labitzke et al.*, 2006], and compositing by the strength of the $F10.7$ flux [*Kuroda et al.*, 2007]. An evaluation of the efficacy of these analysis methods is beyond the scope of this paper. However, as a check on the first-order impact of the QBO on the solar cycle, we also calculated the temperature and ozone solar responses by creating composites of the periods with high and low $F10.7$ and differencing them. When calculated from data from the model case with no QBO, this difference field is quite similar to the solar response fields in Figures 2b and 3b; when calculated from data from the model case with QBO included, the difference field is similar to Figures 2d and 3d.

[50] In summary, the results from this two-dimensional model illustrate how difficult it is to separate the solar cycle forcing in analysis of time series when other quasi periodic but not precisely known forcings are also present. This can be a serious problem for the QBO, which has an effect on the ozone and temperature that is much larger than the expected direct solar effect in many parts of the stratosphere. The difficulty in extracting the solar signal from the observed time series comes particularly because the combined effect of the annual and QBO periods leads to a secondary periodicity of about a decade [*Salby and Shea*, 1991; *Salby and Callaghan*, 2006].

[51] In this paper, the analysis problem associated with the QBO is a contamination, not a real solar signal. However, one might choose to interpret it otherwise if indeed the variations in the QBO are influenced by the solar flux, as suggested by recent studies [e.g., *McCormack et al.*, 2007]. On the other hand, the observational link between the periodicity of the QBO and the solar flux [*Salby and Callaghan*, 2000] is less robust in a more extended record [*Hamilton*, 2002]. Even if further investigation confirms the solar influence on the QBO, it cannot be assumed that the solar cycle is the only, or even the leading, cause of QBO variability. There is ample evidence that the QBO responds to other factors such as the annual cycle [*Baldwin et al.*, 2001; *Pascoe et al.*, 2005]. A physical effect of the solar flux on the QBO may or may not be the reason for the particular QBO variability observed but, either way, that QBO variability leads to a misdiagnosis of the direct solar response itself.

[52] **Acknowledgments.** We dedicate this paper to the memory of Dr. Hyunah Lee, who planted the seeds for the investigation. The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation. K. Matthes is supported by a Marie Curie Outgoing International Fellowship within the 6th European Community Framework Programme. We thank Bill Randel and Dan Marsh for helpful comments on this paper.

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