

Influence of the quasi-biennial oscillation and El Niño–Southern Oscillation on the frequency of sudden stratospheric warmings

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[1] Stratospheric sudden warmings (SSWs) are a major source of variability during Northern Hemisphere winter. The frequency of occurrence of SSWs is influenced by El Niño–Southern Oscillation (ENSO), the quasi-biennial oscillation (QBO), the 11 year solar cycle, and volcanic eruptions. This study investigates the role of ENSO and the QBO on the frequency of SSWs using the National Center for Atmospheric Research’s Whole Atmosphere Community Climate Model, version 3.5 (WACCM3.5). In addition to a control simulation, WACCM3.5 simulations with different combinations of natural variability factors such as the QBO and variable sea surface temperatures (SSTs) are performed to investigate the role of QBO and ENSO. Removing only one forcing, variable SSTs or QBO, yields a SSW frequency similar to that in the control experiment; however, removing both forcings results in a significantly decreased SSW frequency. These results imply nonlinear interactions between ENSO and QBO signals in the polar stratosphere during Northern Hemisphere winter. This study also suggests that ENSO and QBO force SSWs differently. The QBO forces SSW events that are very intense and whose impact on the stratospheric temperature can be seen between December and June, whereas ENSO forces less intense SSWs whose response is primarily confined to the months of January, February, and March. The effects of SSWs on the stratospheric background climate is also addressed here.

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1. Introduction

[2] Sudden stratospheric warmings (SSWs) dominate the interannual variability of the polar stratosphere during Northern Hemisphere winter [e.g., *Labitzke and Naujokat*, 2000]. They are prominent examples of dynamical wave mean flow interactions, and play a key role in the coupling between the stratosphere and the troposphere on seasonal timescales [*Dunkerton*, 2001; *Kuroda*, 2008a, 2008b; *Marshall and Scaife*, 2010]. These warmings are characterized by a strong increase in temperature and a rapid change of zonal wind in the middle stratosphere on time-scales of a few days. The sudden warming is classified as a

major warming when the typically westerly winds become easterly at 60°N and 10 hPa. The warming event is classified as minor when there is a strong increase in temperature, but the zonal winds at 60°N and 10 hPa remain westerly.

[3] Since their discovery in Berlin [*Scherhag*, 1952], SSWs are well observed but their frequency of occurrence and their prediction remains a difficult task. Major warmings occur approximately every other winter whereas minor warmings happen up to five times each winter. The variability in the polar stratosphere is partly caused by various forcings outside of that region, such as the quasi-biennial oscillation (QBO), the El Niño–Southern Oscillation (ENSO), the 11 year solar cycle, and volcanic eruptions, in addition to the natural internal variability of the stratosphere. Therefore, these natural forcing factors might also have an impact on the occurrence of SSWs. Unfortunately, routine observations of the stratosphere are only available for about 50 years; hence, it is difficult to statistically isolate the influence of these factors on stratospheric variability. In addition to the short data record problem, aliasing of different factors has also been observed, e.g., El Niño winters often coincide with the easterly phase of the QBO, which makes the separation of the different factors in the stratosphere even more difficult.

[4] In spite of the observational constraints, qualitative relationships have been found between several forcings and

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Table 1. Overview of Different Sensitivity Experiments Performed With WACCM3.5

Name	QBO	SSTs	Dates
Control	observed	variable	1953–2005 (53 years)
FixedSST	observed	climatological	1975–2004 (30 years)
NoQBO	persistent weak easterlies	variable	1975–2004 (30 years)
NoQBOfixedSST	persistent weak easterlies	climatological	1975–2004 (30 years)

stratospheric variability, such as the conceptually well understood influence of the QBO on stratospheric variability. The first evidence of the QBO signal in the extratropical northern stratosphere was presented by *Holton and Tan* [1980, 1982]. They showed that more (fewer) warmings, resulting in a warmer and more disturbed (colder and stronger) polar vortex, appear during the east (west) phase of the QBO. This is related to the shift of the zero wind line. A poleward displacement of the planetary waveguide with more wave flux directed to the polar regions occurs in QBO east years while more equatorward propagation is observed during the west phase of the QBO. Later studies [*Gray et al.*, 2001a, 2001b; *Gray*, 2003; *Pascoe et al.*, 2006] have emphasized the additional importance of winds in the upper stratosphere for the development the QBO signature in Northern Hemisphere (NH) winter.

[5] On the other hand, *van Loon and Labitzke* [1987] found that warm ENSO (El Niño) events seemed to be associated with a weaker polar vortex, a warmer polar stratosphere, and more sudden warmings but did not assess any significance because of the short record available. More recently, *Mitchell et al.* [2011] showed that the observed vortex is significantly more disturbed in El Niño years as compared to La Niña years. General circulation model studies [*Sassi et al.*, 2004; *Manzini et al.*, 2006; *Garcia-Herrera et al.*, 2006] were able to isolate the ENSO signal and showed that the anomalous warming observed during a warm ENSO event in the NH polar region is due to increased propagation of ultralong Rossby waves toward high latitudes. As the waves dissipate in the stratosphere, the background zonal flow decelerates, and the mean meridional circulation strengthens, which might favor the occurrence of SSWs. In fact, *Sassi et al.* [2004] and *Camp and Tung* [2007] did find increased SSWs frequencies during El Niño events in WACCM1 simulations and National Center for Atmospheric Research/National Centers for Environmental Prediction (NCEP/NCAR) reanalysis, respectively.

[6] Therefore, the occurrence of SSWs might be favored by the east phase of the QBO and warm ENSO events. However, recent studies have shown that these responses might change when they operate simultaneously and also in combination with the 11 year solar cycle. The direct solar cycle signal in the upper tropical stratosphere [*Kodera and Yamazaki*, 1990; *Hood et al.*, 1993] modifies the internal mode of the polar night jet through dynamical interactions and therefore might influence the occurrence of SSWs [*Kodera and Kuroda*, 2002; *Gray et al.*, 2010]. *Labitzke* [1987] and *Labitzke and van Loon* [1988] first noted a combined solar-QBO effect at high latitudes: more SSWs occur during QBO east, solar minimum and QBO west, solar maximum conditions. *Gray et al.* [2001a, 2004, 2006] suggest that this is related to the interaction of wind anomalies from both QBO and solar signals in the upper tropical stratosphere which influence the development and

timing of SSWs. The QBO modulation of the solar signal has been also confirmed in GCM and CCM studies [*Matthes et al.*, 2004, 2010]. In terms of ENSO-QBO interactions, *Wei et al.* [2007] and *Calvo et al.* [2009] showed that the extratropical QBO signal weakens and shortens during warm ENSO events. In turn, the warm ENSO signal also weakens when it coincides with the easterly phase of the QBO [*Calvo et al.*, 2009; *Garfinkel and Hartmann*, 2007] and is not even observed during solar maximum conditions [*Kryjov and Park*, 2007].

[7] All these nonlinear interactions complicate the current understanding of the influence of these forcing factors on the SSWs frequency. In our work, we use NCAR's state-of-the-art chemistry-climate model, WACCM3.5, to investigate the role of various SSW forcings, separately and together, and examine the SSW response as well as changes in mean stratospheric climate.

2. Model and Experimental Description

[8] WACCM3.5 is based on the Community Atmosphere Model, version 3.5 (CAM3.5) with the vertical model domain extended to ~140 km. WACCM3.5 uses the finite volume dynamical core of *Lin* [2004] with 66 vertical levels. The horizontal resolution for WACCM3.5 runs presented here is $1.9^\circ \times 2.5^\circ$ (latitude \times longitude). WACCM3.5 is based on WACCM3 described by *Garcia et al.* [2007]. The physical parameterization changes from WACCM3 to WACCM3.5 are described by *Richter et al.* [2010]. They primarily include changes to the convective parameterization and substantial changes to the gravity wave drag parameterization. *Richter et al.* [2010] also describe in detail WACCM3.5's dynamical climatology.

[9] Here we present four WACCM3.5 simulations shown in Table 1. Our control simulation is the REF-B1 simulation (control) carried out as part of the CCMVAL2 experiment series [*Stratospheric Processes and their Role in Climate CCM Validation Activity (SPARC CCMVal)*, 2010]. In this simulation observed sea surface temperatures (SSTs), anthropogenic and natural surface gas abundances, solar and geomagnetic activity, and volcanic aerosols are prescribed following observations from 1953 to 2005. As WACCM3.5 does not internally generate a QBO, we relax the tropical winds to observations as described by *Matthes et al.* [2010] and *Richter et al.* [2010].

[10] Three more simulations were designed to elucidate the role of the QBO and ENSO on the SSW frequency. They were performed for only 30 years because of limited computational resources. FixedSST is the same simulation as the control except climatological SSTs for each year are repeated and used as boundary conditions. Climatological SSTs represent a neutral ENSO phase conditions. The time mean of SSTs in the Niño 3.4 region is the same as in the control simulation, and there is a small seasonal cycle. In

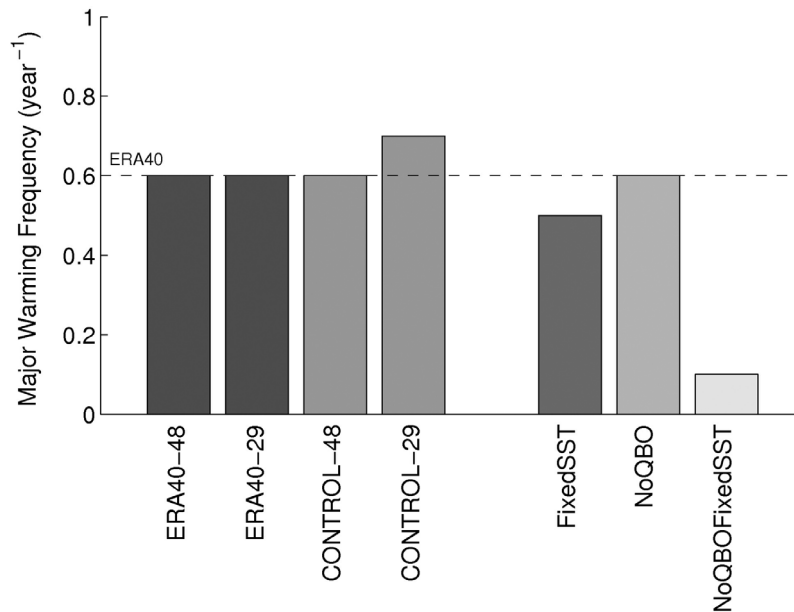


Figure 1. Frequency of occurrence of major warmings (number of events per year). For ERA40 and control, the frequency is shown on the basis of 48 winters (1958–2005) as well as 29 winters (1975–2005). Warming frequencies for FixedSST, NoQBO, and NoQBOFixedSST are calculated for 29 winters (1975–2005). Warmings are counted during the months of November through March.

FixedSST, neutral conditions persist throughout the year and there are no El Niño or La Niña events. Therefore, this simulation can be used to isolate the effect of the QBO. NoQBO is the same as the control except the tropical winds were not relaxed to observations and are free to change. However, as WACCM does not internally generate a QBO, the tropical winds remain weak easterly in the QBO region throughout the simulation. In the time mean, the tropical winds are much more easterly in NoQBO as compared to the control between 20 and 45 km. As the NoQBO simulation has very little variability in the Tropical winds, it can be used to study the impact of ENSO (as variable SSTs are included in this simulation). Finally, NoQBOFixedSST is the same as the control but with no QBO and climatological SSTs instead of the observed ones. This simulation is used to study the effect of not having QBO and ENSO simultaneously. All of the described simulations still include observed anthropogenic and natural surface gas abundances, solar and geomagnetic activity, and volcanic aerosols and were designed to elucidate the role of the QBO and ENSO on the SSW frequency.

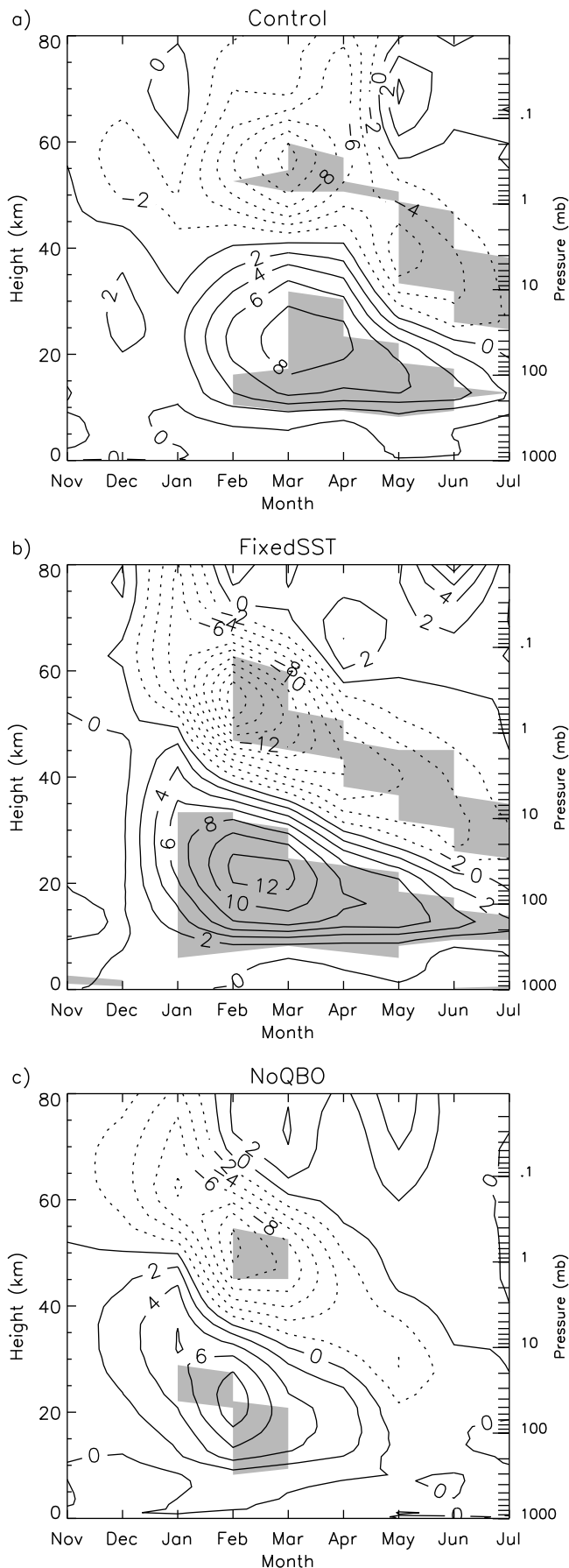
3. Results

[11] To calculate the occurrence of major SSWs we use an algorithm based on the original World Meteorological Organization (WMO) definition of SSWs [e.g., Labitzke and Naujokat, 2000]. This algorithm is the same as described by Richter *et al.* [2008]: Major midwinter warming is an event during which the temperature gradient between 60°N and 90°N at 10 hPa is positive for at least 5 days and the zonal mean wind at 60°N at 10 hPa is easterly during that time. If the temperature gradient becomes negative for less than three days and then becomes positive again, it is still considered a part of the same warming event.

3.1. SSW Climatology

[12] In the past general circulation models (GCMs) had difficulties representing SSW frequency and their timing correctly [Charlton *et al.*, 2007]. Simulations with the most recent versions of chemistry-climate models (CCMs) do a much better job reproducing the observed SSW frequency [SPARC CCMVal, 2010, chapter 4]. The simulated number of stratospheric warmings in the WACCM3.5 control simulation (grey bars in Figure 1) was compared first with the SSWs in the extended ERA-40 reanalysis (black bars in Figure 1) from 1958 to 2005 [Frame and Gray, 2010] for the common period. This comparison is shown in Figure 1. In agreement with SPARC CCMVal [2010], WACCM3.5 produces a reasonable SSW climatology with 0.6 major warmings per winter comparable to the frequency in the 48 years analyzed (1958–2005) of the extended ERA-40 data.

[13] In addition, Figure 1 also shows a comparison between the frequency of SSWs in the three model simulations performed with WACCM3.5 and different external forcings. Since these runs were performed from 1975 to 2004, the frequency of SSWs during this period is also shown for the ERA-40 data set and the WACCM3.5 control simulation. Figure 1 shows that the observed major warming frequency changes to 0.7 warmings per year between 1975 and 2004, which is still close to observations. To assess whether differences in SSW frequencies between the different time periods analyzed and between various simulations are statistically significant, we use the methodology of Charlton *et al.* [2007], described in detail in their Appendix A. Each winter is considered a separate and independent observation of frequency of SSWs. The number of years in each simulation (or data) provides a number of samples from which a mean, standard deviation, and stan-



standard error can be derived. Subsequently the information can be used to assess whether differences in SSW counts between two models runs or model and data are significant using a t test. The differences in observed SSW statistics between the time periods from 1958 to 2005 and 1975 to 2005 are not statistically significant and can be interpreted as natural decadal variability.

3.2. Influence of ENSO and QBO on SSW Frequency

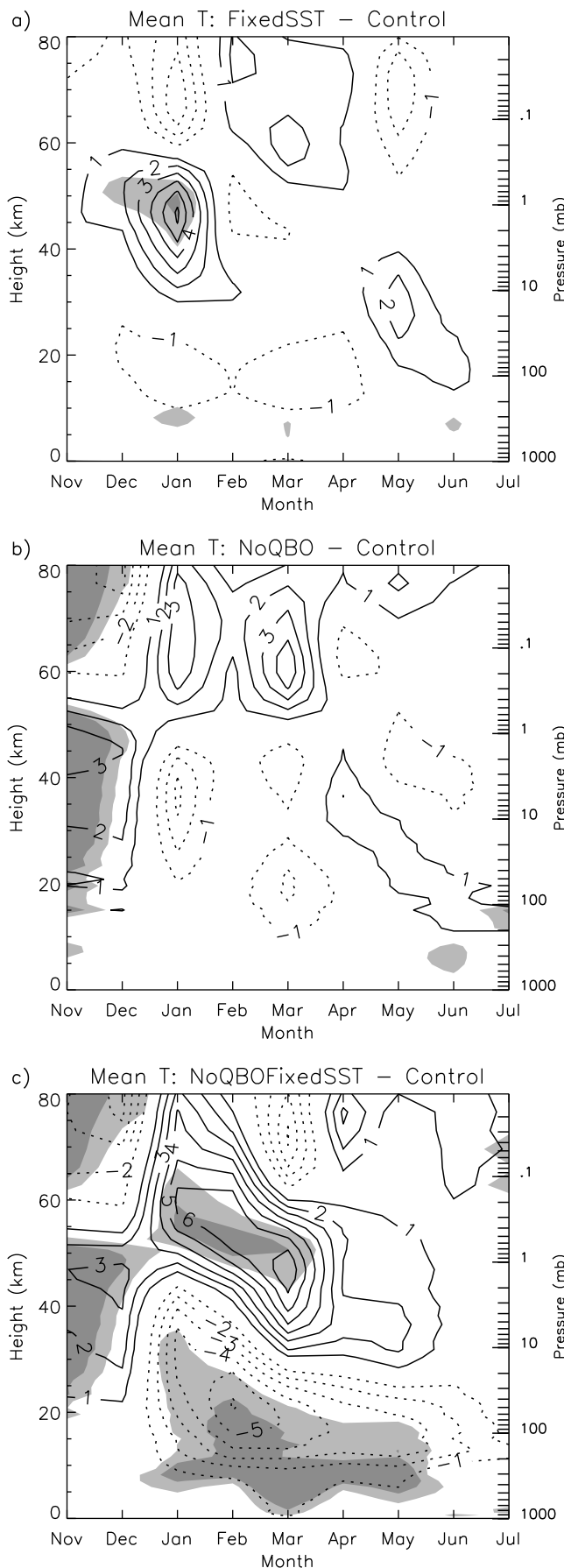
[14] Figure 1 shows the major SSW frequencies for all of the WACCM3.5 simulations. The frequency of major warmings in FixedSST (0.5) and NoQBO (0.6) is similar to that in the control (0.7) and ERA-40 (0.6). These differences are not significant as calculated with the t test at 95% or 99% confidence level. This result indicates that removing one of the forcings: ENSO or QBO does not significantly change the SSW frequency. However, when both QBO and SST variability are removed, the number of major warmings drastically decreases to 0.1 warmings per year (NoQBOFixedSST). This change is significant at the 99% t test confidence level. Therefore, in order for WACCM3.5 to reproduce the observed frequency of SSWs, at least one of the two forcings: ENSO or QBO variability, is needed.

[15] In addition, our results reveal that the additional presence of the QBO or ENSO when the other variability factor is already present, does not change the number of SSWs significantly; despite both, warm ENSO events and the easterly phase of the QBO do act to warm the polar stratosphere and weaken the polar vortex when they operate independently and therefore potentially trigger a SSW event. These results show the nonlinear interaction between ENSO and QBO, which has already been discussed in other studies [Garfinkel and Hartmann, 2007; Calvo et al., 2009].

3.3. Intensity and Timing of Response to SSWs

[16] In this section we investigate the role of both ENSO and QBO on the intensity and timing of the temperature response to major SSW events. Figure 2 shows the polar temperature differences between winters with and without SSWs between the control, FixedSST, and NoQBO. Shaded areas represent regions with Student's t test values at the 95% significance level. Even though the SSW frequency in these simulations is similar, the intensity and temporal evolution of the polar temperature is different (Figure 2). The time altitude cross sections of polar cap temperature differences (averaged between 70°N and 90°N) between winters with SSWs and winters without SSWs in Figure 2 show that in the control run the peak in temperature response associated with the passage of SSWs occurs in March and has amplitudes of +8 K in the lower stratosphere at ~20 km and a corresponding cooling of -10 K in the lower mesosphere at ~55 km. There is a smaller secondary temperature minimum in May at ~40 km. Most of the significant warming and cooling signatures extend from March through June. It is interesting to note that the stratospheric

Figure 2. Polar (average between 70°N and 90°N) temperature differences during winters with SSWs and winters without SSWs in (a) control, (b) FixedSST, and (c) NoQBO WACCM3.5 simulations. Contour interval is 1 K. Shading represents regions with Student's t test values at the 95% level.



warming-cooling response extends through June, although the observed peak response of major midwinter warmings occurs in January/February and in our analysis SSWs are considered from November through March. This extended response could be due to the fact that WACCM's final warming occurs much later in the season than in observations [SPARC CCMVal, 2010], mainly because of the slow descent of the climatological zero-wind line. Hence, it would be interesting to validate this result with a more realistic simulation of the timing of the final warming.

[17] In the experiment with QBO but climatological SSTs (FixedSST, Figure 2b), the polar stratospheric temperature response to major warmings is stronger (+12 K) with a stronger mesospheric cooling (-15 K) and starts earlier during winter (January and February) as compared to the control. The significant warming and cooling signatures propagate smoothly downward with time starting in January and extending until June. In the experiment without QBO and variable SSTs (NoQBO, Figure 2c), the polar stratospheric warming is of similar amplitude as in the control but is initiated even earlier, i.e., in December, and its significance lasts only through March. The polar stratospheric warming in this simulation has a sharp peak in February, with warming of +7 K at 20 km, and cooling of -10 K near 50 km.

[18] The above suggests that ENSO and QBO force SSWs differently, however they can still produce similar number of warmings per year. Variable SSTs initiate warmings earlier than the QBO and whose response is confined to a shorter time period (January through April), whereas the QBO initiates stronger warmings whose temperature starts and finishes later in the year. In addition, the nonlinear ENSO and QBO interaction mentioned in section 3.2 arises here as well, since the strength and timing of polar temperature response to SSWs in the control experiment, where both variable SSTs and QBO variability are included, does not appear to be the average of the FixedSST and NoQBO simulations, where one or the other are removed. The temperature response associated with SSWs in the control starts later in the season than in FixedSST or NoQBO; the peak in the warming is reached later and the maximum value is lower.

3.4. Differences in Stratospheric Climatology

[19] In order to understand the impact of differences in SSWs and various natural forcings on the long-term mean stratospheric climate in the various WACCM3.5 simulations, the polar region climatological temperatures were compared in the three sensitivity experiments to the control experiment (Figure 3). Several GCMs do not include the QBO, so it is interesting to look at its impact on the mean stratospheric climate. In general, Figures 3a and 3b show small differences in the stratospheric polar climate in the two experiments without either variable SSTs (FixedSST) or QBO (NoQBO) compared to the control experiment

Figure 3. Long-term mean polar (average between 70°N and 90°N) temperature differences between (a) control and FixedSST, (b) control and NoQBO, and (c) control and NoQBOFixedSST. Contour interval is 1 K. Light and dark shading represent regions with Student's *t* test values at the 95% and 99% levels, respectively.

(control). Temperature differences between FixedSST and the control are 1 K for most of the stratosphere, except for January, where temperature differences of ~ 5 K near ~ 50 km are found, in agreement with the earlier SSW onset in this experiment. In the run without QBO (NoQBO), the stratosphere is ~ 3 K significantly warmer and the mesosphere ~ 3 K significantly cooler in November compared to the control. The lack of a QBO in a simulation only causes the mean stratospheric climate to be different in the month of November.

[20] The largest differences from the control occur for the experiment without variable SSTs and QBO (NoQBOFixedSST; Figure 3c). In NoQBOFixedSST the lower stratosphere is up to 6K colder in NoQBOFixedSST as compared to the control throughout most of the winter and up to 7K warmer in the lower mesosphere from January through March. This is associated with a stronger polar night jet (not shown). Figure 3 demonstrates that the absence of SSWs, as happens in the NoQBOFixedSST simulation, can cause climatological temperature differences during boreal winter months up to 6 K in the polar lower stratosphere and up to 7 K in the polar lower mesosphere. It is worth mentioning that the stratospheric climate differs significantly between the NoQBO and the FixedSST simulation: in NoQBO, the November temperatures throughout the stratosphere are 1 to 3 K warmer, and in January, they are significantly colder (5 K at 40 km).

4. Summary

[21] We carried out a number of sensitivity simulations with NCAR's state-of-the art chemistry-climate model WACCM3.5 to investigate different combinations of natural forcing factors such as the QBO and ENSO and their effect on SSW frequency systematically. Solar and volcanic forcing as well as the increase in ozone depleting substances (ODSs) and GHGs were always included. We show that the presence of variable SSTs (ENSO) or the QBO are needed in WACCM3.5 to obtain a realistic frequency of SSWs. When both variable SSTs (ENSO) and QBO are removed, the SSW frequency goes down drastically from six to one warming per decade. The SSW frequency is almost unchanged when only one of these forcings is included, although longer simulations are needed to confirm statistical significances. These results further imply a nonlinear relationship between ENSO and QBO since the single forcing factor changes do not add up linearly to produce the results obtained with the simulations that include the combination of the two factors.

[22] We note that these results are based on single ensemble-members of 30 year transient simulations. Ideally, multiple-member ensembles would be performed to verify the statistical significance of these results, however these are computationally very expensive when performing separate simulations for each type of forcing, as we have done here. The remarkable drop in the frequency of SSWs when neither the QBO nor warm ENSO events are included suggests that this change is well outside of the natural (internal) variability of the polar vortex. Our experiments also provide information on where to focus future multiensemble sensitivity experiments in which the mechanisms of these nonlinear interactions may be investigated further. In hindsight, it might have been more beneficial to set the mean of the

winds in the NoQBO experiment to be the same as in the QBO to be sure that the differences seen are completely due to the added variability. That is something that will also be addressed in the future.

[23] In our study, we also investigated the role of ENSO and QBO on the timing and intensity of polar stratospheric temperature response to SSW events. In WACCM3.5 ENSO initiates polar stratospheric warming and cooling earlier in the season as compared to QBO, and the response is confined to a much shorter time period (January through April) as compared to the QBO (which produces maximum temperature response between December and June).

[24] We have not addressed the role of solar forcing here, since the variability associated with the 11 year solar cycle was present in all simulations as well as other forcings such as volcanoes, ODS and GHGs increases. However, it is worth highlighting that the simulation with only solar and volcanic forcing (NoQBOFixedSST) showed a very low frequency of SSWs compared to observations and other simulations.

[25] Examination and comparison of the mean stratospheric climate reveals a very similar background climate in the control experiment and the experiments where only one forcing, i.e., either QBO or variable SSTs, was present. The lack of SSWs in the simulation without ENSO and without QBO causes a very different stratospheric climate with a colder stratosphere and a warmer mesosphere. This indicates that the presence of SSWs plays a large role in representing the mean climate of the stratosphere correctly. To further investigate the role of the 11 year solar as well as the other external forcings, longer experiments with WACCM are under way and will be the subject of a separate study.

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