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Combined effects of QBO and 11-year solar cycle on the winter hemisphere in a stratosphere-troposphere coupled system

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[1] Combined effects of the quasi-biennial oscillation (QBO) and the 11-year solar cycle (SC) on the winter hemisphere are investigated with an idealized mechanistic circulation model of a stratosphere-troposphere coupled system. A zonal momentum forcing is imposed to mimic a westerly or easterly phase of the QBO and a heating anomaly associated with the SC is introduced around the stratopause. A series of long time integrations of 39,600 days are performed to obtain statistically significant results for forty-six combinations of these experimental parameters. The obtained dependence of the temperature response in the polar stratosphere on the combination of QBO and SC are qualitatively consistent with the observed responses. The difference in the winter polar stratosphere between the solar maximum and minimum phase is highly significant at above the 95% confidence level in many cases of the QBO westerly runs. The SC effect is, however, relatively small compared to the QBO effect. **Citation:** Ito, K., Y. Naito, and S. Yoden (2009), Combined effects of QBO and 11-year solar cycle on the winter hemisphere in a stratosphere-troposphere coupled system, *Geophys. Res. Lett.*, *36*, L11804, doi:10.1029/2008GL037117.

1. Introduction

[2] The time variation of the solar irradiance over an 11-year solar cycle (SC) reaches up to 8% in the ultraviolet (UV) wavelength of 200–250nm [*Lean et al.*, 1997], though the variation of total solar irradiance is very small, about 0.1%. Some observational studies [e.g., *McCormack and Hood*, 1996; *Crooks and Gray*, 2005] and numerical studies with general circulation models (GCMs) using the ozone changes calculated with 2-D chemical models [*Matthes et al.*, 2003] have confirmed a solar signal of about 1.0–2.0 K in the equatorial stratopause region due to the large variation of solar UV radiation.

[3] In late winter, an apparent signal of SC can be identified in the northern polar stratosphere, if the data are stratified according to the phase of the quasi-biennial oscillation (QBO) of the equatorial mean zonal wind in the lower stratosphere [*Labitzke*, 1987]. The update of the correlation coefficient r between the monthly mean temperatures at the North Pole and the 10.7-cm solar flux in February for 59 years from 1948 to 2006 is positive and strong ($r > 0.6$) between 30 hPa and 150 hPa in the QBO westerly phase, while it is negative and weak ($0 > r > -0.4$) in the same pressure range in the QBO easterly phase [*Labitzke et al.*, 2006].

[4] For early winter, on the other hand, *Kodera and Kuroda* [2002] showed negative temperature anomaly in the polar stratosphere in the solar maximum (Smax) phase without the stratification of the data according to the QBO phases as shown by *Kodera and Kuroda* [2002, Figure 13]. *Kodera and Kuroda* [2002] proposed a dynamical mechanism of remote influence of SC to explain the positive anomaly in the equatorial lower stratosphere together with this negative one in the polar stratosphere: The stronger westerlies in the subtropics around the stratopause due to increased solar forcing deflect planetary waves from higher latitudes, and that results in weakening the wave-induced mean meridional circulation (MMC) which accounts for the temperature anomalies in the lower stratosphere. In this paper, the mechanism is referred to as the weakening mechanism of MMC regardless of the season, although *Kodera and Kuroda* [2002] originally proposed it for early winter.

[5] In the Smax phase, temperature anomaly around the stratopause region may play an important role in the interannual variations of the global scale circulations even in late winter under the QBO westerly or easterly phase through the weakening mechanism of MMC. The remote influences of the temperature anomaly near the stratopause have been investigated intensively with sophisticated high-end GCMs in the last decade [*Matthes et al.*, 2004; *Palmer and Gray*, 2005; *Rind et al.*, 2008]. However, large internal variability in winter polar region requires long enough numerical integrations for statistically reliable arguments, and the exact intensity and profile of the remote influence is still unclear [*Matthes et al.*, 2003].

[6] In this study, we perform a series of numerical experiments with a mechanistic global circulation model to extract the combined dynamical effect of the temperature anomaly near the stratopause with a QBO westerly or easterly wind forcing in late winter. Simplification of physical processes enables us to perform a parameter sweep experiment with much longer time integrations compared with the high-end GCMs. *Gray et al.* [2004] employed a seasonal run to focus on the timing of onset of the first stratospheric sudden warming (SSW) event, while we employ the assumption of perpetual winter to investigate the dynamical situation of the period when SSW events occur not for the first time. The QBO phase is fixed in westerly or easterly. These series of experiments help to untangle the puzzling problem about the mechanism of observed SC influences on the polar stratosphere depending on the phase of QBO.

2. Numerical Model, Experimental Setup and Analysis Method

[7] The mechanistic circulation model used in this study is the same as that used by *Naito and Yoden* [2006]; a three-

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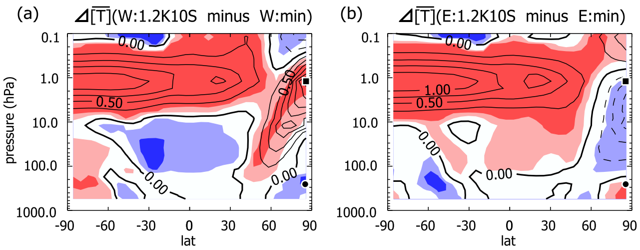

Figure 1. Latitude-height sections of the difference of $\overline{[T]}$ (K) between (a) “W:1.2K10S” and “W:min” and (b) “E:1.2K10S” and “E:min”. Counter interval is 0.25 K. Zero line is drawn by a thick solid line. Light (heavy) color indicates the 80% (95%) confidence level. Red (blue) color shade of the significance indicates positive (negative) difference. Two symbols (rectangle and circle) at the North Pole indicate the data points for frequency distributions shown in Figure 2.

dimensional global primitive-equation model of a dry atmosphere, based on AGCM5. It has the horizontal resolution of T21 spherical harmonics truncation and the vertical representation of 42 σ levels ($\sigma \equiv p/p_{\mathrm{surface}}$; p is pressure) from the surface to the mesopause. A sinusoidal surface topography of zonal wavenumber 1 is given in the northern hemisphere (NH). To produce a westerly or easterly phase of the QBO, an idealized zonal momentum forcing is imposed in the zonal momentum equation as the run WWWW or EEEE of *Naito and Yoden* [2006]; the QBO-wind forcing is mainly in the lower stratosphere with the maximum intensity of 40 m/s. The latitudinal profile is Gaussian about the equator, with an e-folding scale of about 17° in latitude. Hereafter, we refer these experiments as W runs or E runs, respectively.

[8] The radiative process is approximated by a Newtonian heating/cooling scheme in the form of $\partial T/\partial t = \cdots -\alpha_T\{T - (T^* + \Delta T^*)\}$, where $T(\lambda, \phi, \sigma, t)$ is the temperature at longitude λ, latitude ϕ, σ, and time t. The coefficient $\alpha_T(\sigma)$ is the relaxation time and $T^*(\phi, \sigma)$ is a prescribed basic temperature profile. These values are the same as by *Naito and Yoden* [2006] to represent a perpetual boreal winter which can be regarded as a state of the solar minimum (Smin) phase. For the Smax phase, we introduce an idealized anomaly of the basic temperature field around the stratopause in the form:

$$\Delta T^*(\phi,\sigma) = A \times \exp\left[-\left(\frac{\log\sigma + 6.7}{1.2}\right)^2\right] \times \begin{cases} 1, & \phi < \phi_c, \\ \exp\left[-\left(\frac{\phi - \phi_c}{30^\circ}\right)^2\right], & \phi > \phi_c, \end{cases} \quad (1)$$

where A is the maximum value of the basic temperature anomaly and is set to 1.2 K or 2.4 K to study the nonlinearity of the response. The radiative forcing anomaly has a local maximum in the vertical near the stratopause at $\sigma = \exp(-6.7)$(approximately 1.2 hPa). The parameter ϕ_c is the latitude of the northern limit of constant ΔT^* and the forcing anomaly becomes smaller toward the North Pole from the latitude ϕ_c. This form mimics an idealized solar heating anomaly as by *Kodera and Kuroda* [2002, Figure 15]. The parameter ϕ_c is swept from 25°S to 25°N by five degree interval to investigate the sensitivity to the meridional extent of the anomaly.

[9] In sum, there are three control parameters: the QBO phase, A, and ϕ_c. We perform two runs of W or E in the Smin phase and refer it as W:min or E:min. For the Smax phase, we perform twenty-two W runs and twenty-two E runs by changing A (1.2 or 2.4 K) and ϕ_c(25°S–25°N). These runs are referred to, for example, as W:1.2K25S for a W run with A = 1.2 K and ϕ_c = 25°S.

[10] Eleven 3600-day time integrations are done with a time step Δt = 15 min after 1200-day spin up integration from each initial state of an isothermal atmosphere (240 K) at rest with a small initial disturbance. We analyze 39,600 days of data in the pressure coordinate.

[11] We use a large sample method as a statistical test to judge the difference of sample means between Smax and Smin runs after replacing the sample sizes by effective sampling sizes in order to take account of the persistence of the sequential daily data (see *Naito and Yoden* [2005] for details). In this report, we call the differences “significant” if the confidence level ranges between 80% and 95% and “highly significant” if it is over 95%.

3. Results

3.1. A Typical Example: A = 1.2 K and ϕ_c = 10°S

[12] Figure 1 shows the anomaly fields of the time-mean zonal-mean temperature in the Smax run from the Smin run ($\Delta\overline{[T]}$, where square bracket denotes the zonal-mean and an over line does the time-mean) in the QBO westerly or easterly phase for A = 1.2 K and ϕ_c = 10°S. As a direct response to the anomalous SC forcing ΔT^* prescribed by the equation (1), the model southern hemisphere (SH) and low latitudes in NH around the stratopause level is warmer in the Smax runs in both phases of the QBO. Aside from this temperature anomaly, there are several regions where significant temperature change occurs. In the W runs, the maximum of $\Delta\overline{[T]}$ (W:1.2K10S − W:min) in the stratosphere is 2.0 K centered at 86°N and 1.2 hPa. High- and mid-latitude stratosphere and mid-latitude upper troposphere in NH are coherently warmer in the Smax run. Highly significant difference is seen as low as at 100 hPa. In the E runs, on the other hand, the minimum of $\Delta\overline{[T]}$ (E:1.2K10S − E:min) is −0.86 K at 86°N and 12 hPa, though the difference is not “highly significant” but “significant”. These results for the particular parameter setting are consistent with “Labitzke’s relationship”, that is, the anomalous SC forcing ΔT^* leads to the higher temperature in the winter polar stratosphere in case of the QBO westerly phase, and leads to the slightly lower temperature in case of the QBO easterly phase.

[13] The occurrence frequency of SSW event can account for the above result. SSW events occur more frequently in W:1.2K10S (315 times) than in W:min (287 times), while the occurrence of SSW events in E:1.2K10S (565 times) is nearly the same as in E:min (568 times). Here, we used the same criterions to define SSW event as *Naito and Yoden* [2006].

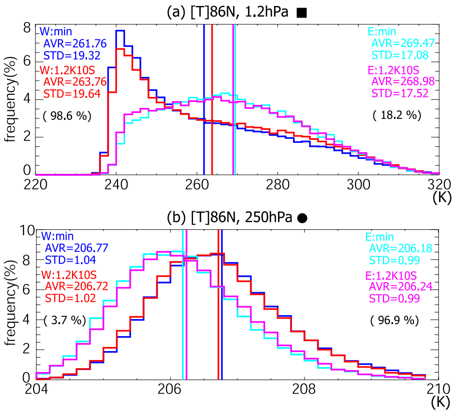

Figure 2. Frequency distributions of $[T]$ at ϕ = 86°N for (a) p = 1.2 hPa and (b) p = 250 hPa for 39,600 days in "W:min" (blue), "W:1.2K10S" (red), "E:min" (cyan), and "E:1.2K10S" (magenta). Width of the bins is 2.0 K and 0.2 K, respectively. Vertical lines denote $\overline{[T]}$. The values of average and standard deviation are written for each dataset. The percentage indicates the chance that the Smax run is warmer than the Smin run.

[14] A vertical dipole pattern of the temperature anomalies is found between the mesosphere and the stratosphere in the polar region with warmer stratosphere in the W runs and colder stratosphere in the E runs. A horizontal dipole pattern is also seen between the polar region and the equatorial region in the lower stratosphere. These patterns are consistent with the facts that the wave-induced MMC is strengthened by the anomalous SC forcing ΔT^* in case of the QBO westerly phase (not shown).

[15] It is also worth noting that a vertical banding structure in the troposphere is seen as a result of the anomalous SC forcing ΔT^* in the stratopause level. In the W runs, negative anomaly in the winter polar region and positive anomaly in the summer polar region are highly significant. In the E runs, on the other hand, positive anomaly in the winter polar region and negative anomaly in mid-latitudes of summer hemisphere are highly significant. A similar banding structure has been reported by *Haigh* [2003] not only in an atmospheric GCM study of the response to the thermal perturbations in the lower stratosphere but also in a multiple regression analysis using the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis dataset, although the magnitude of the banding structure in our present result is small compared to those results.

[16] Figure 2a shows the frequency distribution of $[T]$ at 86°N and 1.2 hPa for 39,600 days in W:1.2K10S, W:min, E:1.2K10S and E:min. The time-mean temperature $\overline{[T]}$ in the E runs is higher than that in the W runs over 5 K. The temperature distribution in the W runs is highly skewed with a large fraction of low-temperature days near the radiative equilibrium temperature, while relatively large number of high-temperature days in the E runs reflects the frequent occurrence of SSW events. The percentage in parentheses in Figure 2 is the chance that the 39,600-day mean temperature in the Smax run is higher than that in the Smin run with the same QBO forcing. The large number of sample size gives the statistical significance of the time-mean temperature difference between W:1.2K10S and W:min at a confidence level of 98.6%, though the difference is much smaller than the differences between the W runs and the E runs. The frequency of low-temperature days decreases and that of high-temperature days increases in W:1.2K10S(red line) compared to the distribution in W:min(blue line).

[17] Figure 2b shows the same plot as in Figure 2 (a) but at 250 hPa. The difference of the time-mean temperature between Smax and Smin run is highly significant in both QBO phases, though the difference is as small as 0.05 K in the W runs and 0.06 K in the E runs. The difference in the frequency distribution between Smax and Smin run is distinguishable, although the QBO forcing has much larger impact on the variation than the anomalous SC forcing.

3.2. Parameter Sweep Experiments

[18] In order to show the sensitivity of the response in the winter polar region to the intensity (A) or the latitudinal extent (ϕ_c) of the anomalous SC forcing ΔT^*, the temperature differences between Smax and Smin runs at 86°N for the forty-four combinations of the external parameters are summarized in Figure 3. It shows the differences of the 39,600-day mean of the zonal-mean temperature $\Delta\overline{[T]}$ from 770 hPa to 0.06 hPa, for 11 values of ϕ_c: (a) W:1.2Kϕ_c − W:min, (b) E:1.2Kϕ_c − E:min, (c) W:2.4Kϕ_c − W:min, and (d) E:2.4Kϕ_c − E:min.

[19] As shown in Figure 3a, difference of the time-mean zonal-mean temperature $\Delta\overline{[T]}$ between W:1.2Kϕ_c and W:min in the polar region is positive with the value from 0.2 to 2.0 K near the stratopause (1.2 hPa−0.57 hPa) and the difference is highly significant or significant in most cases. On the other hand, $\Delta\overline{[T]}$ between E:1.2Kϕ_c and E:min near the stratopause are relatively small with the value from −0.9 K to 0.6 K as shown in Figure 3b. These results are qualitatively consistent with Labitzke's relationship in the sense that the difference is positive and significant in the most of W runs for the combinations of A and ϕ_c and not so significant in the E runs. The opposite sign between the mesosphere and the stratosphere at the north pole is seen in many cases of the W runs as shown in Figure 1a, which reflects the change of the wave-induced MMC in the winter middle atmosphere as shown in Figure 1. Further analysis of the W runs reveals modulation of planetary waves which are the drivers of SSWs. Stronger convergence of the Eliassen-Palm flux in the Smax phase of the W runs is seen in the midlatitude stratopause (not shown) to strengthening the wave-induced MMC, contrary to the weakening mechanism of MMC due to the increased solar forcing.

[20] The comparisons between Figures 3a and 3c or between Figures 3b and 3d show that the temperature anomalies for A = 2.4 K are weaker than those for A = 1.2 K in some cases. These results are indicative of the nonlinear nature of the responses, especially in cases of ϕ_c = 25°S −0°. Statistical significance of the difference is low for the E runs compared to the W runs in both cases of A = 1.2 K and 2.4 K. Note that in the troposphere the negative difference of the temperature is significant in most of the cases in the W runs while the positive difference is signif-

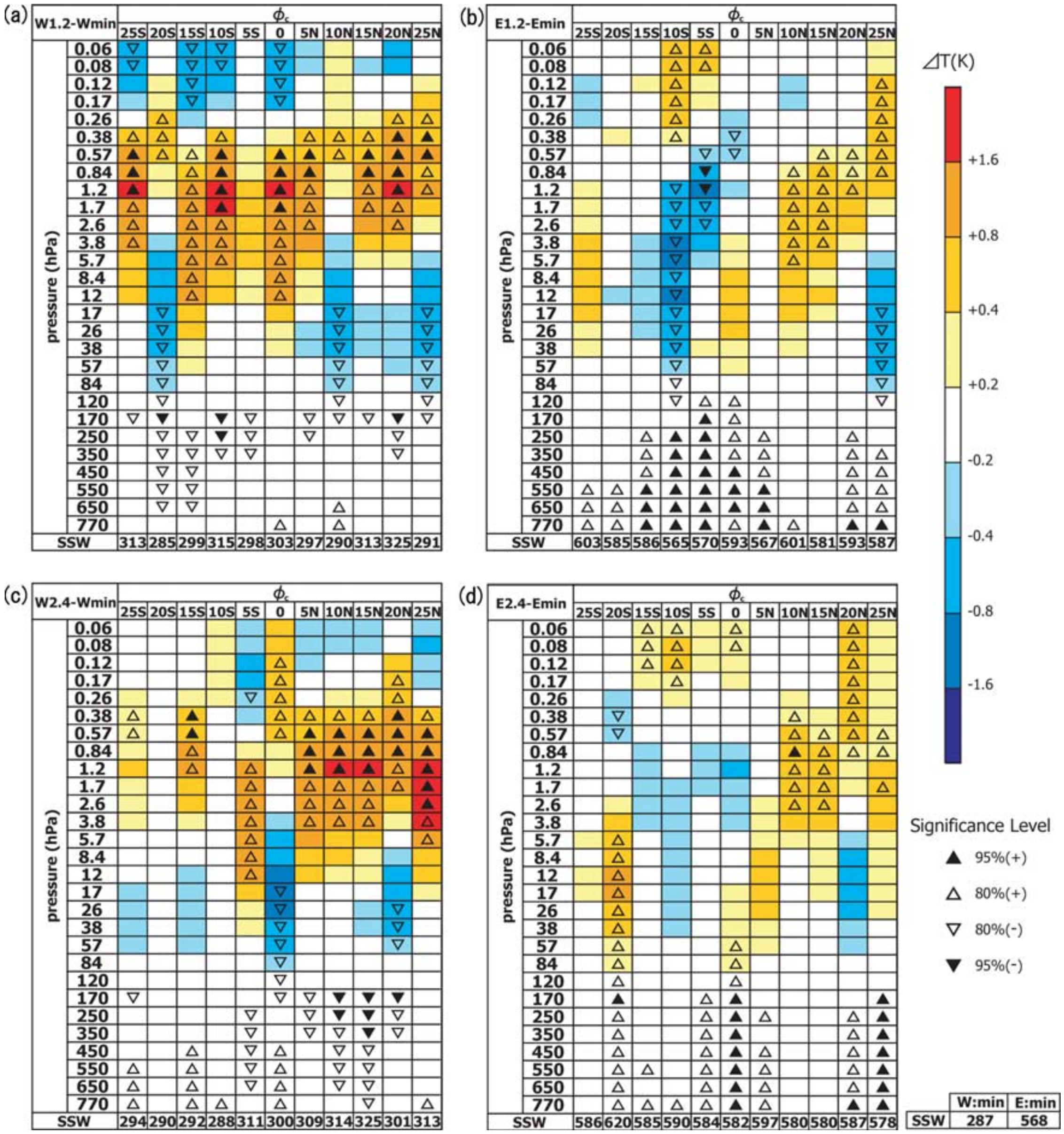

Figure 3. The differences of $\overline{[T]}$ at 86°N from 770 hPa to 0.06 hPa between Smax and Smin runs: (a) W:1.2Kϕ_c − W:min, (b) W:2.4Kϕ_c − W:min, (c) E:1.2Kϕ_c − E:min, and (d) E:2.4Kϕ_c − E:min. An open triangle indicates it is significant, while a closed one indicates that the difference is highly significant. Total number of SSW events in the Smax runs is shown on the bottom of each column. Total number in the Smin runs is shown on the rhs bottom.

icant in the cases of the E runs, although the differences are very small.

4. Concluding Remarks

[21] We performed 39,600-day numerical integrations of a simple global circulation model for forty-six combinations of the external parameters to investigate the combined effect of the quasi-biennial oscillation (QBO) and the 11-year solar cycle (SC) to the time mean state of the stratosphere-troposphere coupled system. We focused on extracting the remote influences of the SC radiative forcing anomaly around the stratopause level under the QBO westerly or easterly phase, and investigated the sensitivity to the intensity and location of the anomalous SC forcing by the parameter sweep experiments.

[22] The difference of the time-mean zonal-mean temperature in the winter polar stratosphere between the solar maximum and minimum run is positive and significant in the QBO westerly phase, while that in the QBO easterly phase is relatively small and not very significant compared to the QBO westerly phase. These results are qualitatively consistent with the relationship pointed out by *Labitzke* [1987] for late winter, while the result of the QBO westerly runs is contrary to the weakening mechanism of MMC explained in the introduction. However, the result of the QBO westerly runs does not necessarily contradict the mechanism proposed by *Kodera and Kuroda* [2002],

because their mechanism was originally proposed for early winter in which the stratospheric sudden warming seldom occurs.

[23] The obtained temperature difference in the polar winter stratosphere is significant in most of the QBO westerly runs and not much dependent on the latitudinal extent or the intensity of the anomalous SC forcing particularly as shown in Figure 3. However, the difference between solar maximum and minimum run for each combination of external parameters is much smaller than that between the QBO westerly and easterly phase, though the large number of samples enables us to detect the statistically significant difference.

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