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A new pathway for communicating the 11-year solar cycle signal to the QBO

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[1] The response of the equatorial quasi-biennial oscillation (QBO) to zonal-mean ozone perturbations consistent with the 11-year solar cycle is examined using a $2\frac{1}{2}$ dimensional model of the tropical stratosphere. Unique to this model are wave-ozone feedbacks, which provide a new, nonlinear pathway for communicating solar variability effects to the QBO. Model simulations show that for zonal-mean ozone perturbations representative of solar maximum (minimum), the diabatic heating due to the wave-ozone feedbacks is primarily responsible for driving a slightly stronger (weaker) QBO circulation and producing a slightly shorter (longer) QBO period. These results, which are explained via an analytical analysis of the divergence of Eliassen-palm flux, are in general agreement with observations of quasi-decadal variability of the QBO.

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1. Introduction

[2] The equatorial quasi-biennial oscillation (QBO) in zonal wind is among the most extraordinary and far-reaching circulations of the middle atmosphere [e.g., *Baldwin et al.*, 2001]. Perhaps the most intriguing aspect of the QBO is its possible role as an amplifier and global communicator of the 11-year solar cycle signal. As *Labitzke and van Loon* [1988] discovered, a quasi-decadal variation, consistent with the solar cycle, is observed in polar stratospheric temperatures when the data are stratified according to the phase of the equatorial QBO. Subsequent observational studies have reinforced the connection between the QBO and the 11-year solar cycle [*Salby and Callaghan*, 2000; *Soukhrarev and Hood*, 2001; *Gray et al.*, 2004; *Labitzke*, 2004].

[3] Attempts to isolate mechanisms linking the QBO and solar cycle have been primarily limited to two-dimensional (2-D) models. For example, *Lee and Smith* [2003] calculated the stratospheric ozone response to the 11-year solar cycle using two different ozone data sets and compared the results with a fully interactive 2-D chemical-radiative-dynamical model. They showed that the combination of the solar cycle, QBO, and volcanic eruptions produces a solar ozone signal that has a similar pattern to observations, though different magnitude. *McCormack* [2003] also used a fully interactive 2-D model to show that the solar cycle could modulate the QBO, provided there was a realistic simulation of the semi-annual oscillation in the model's upper stratosphere. Although recent studies show improved correspondence between model simulations and observations [e.g., *Matthes et al.*, 2004], missing from these studies is wave-ozone feedbacks, a process that has been shown to be important to the QBO system [e.g., *Echols and Nathan*, 1996; *Cordero et al.*, 1998; *Cordero and Nathan*, 2000].

[4] The wave-ozone feedback process pivots on wave-like perturbations in the wind and temperature fields producing wave-like perturbations in the ozone field. The phasing and structure of these three wave fields, which are coupled to each other as well as to the background distributions of wind, temperature and ozone, directly affect wave transience and wave dissipation, processes vital to the driving of the zonal-mean circulation. Thus any perturbation to the wave-ozone feedbacks, solar cycle induced or otherwise, will be imparted to the zonal-mean field. Indeed, as our numerical and analytical results show, solar cycle induced changes in the zonal-mean ozone field can affect the wave-ozone feedbacks and thus the QBO.

2. The Model

[5] We employ *Cordero and Nathan*'s [2000] $2\frac{1}{2}$ dimensional model of the tropical stratosphere, wherein the circulation is governed by zonal-mean and linear wave descriptions of the primitive and ozone continuity equations. Thus the model accounts for wave-mean flow interactions but not wave-wave interactions. The model circulation is driven by a prescribed Kelvin wave (phase speed = 30 m/s) and a prescribed Rossby-gravity wave (phase speed = -30 m/s) at the lower boundary. The model domain extends from ~100 hPa to ~10 hPa in the vertical, from the equator to 45°N in the meridional direction, and is periodic in the zonal direction. The vertical and horizontal resolutions are, respectively, 0.5 km and ~2.5° latitude. The model does not account for either annual variation in equatorial upwelling or extratropical Rossby wave forcing. Nevertheless, the model self-consistently accounts for zonal-mean ozone feedbacks as well as wave-ozone feedbacks and produces QBOs in wind, temperature, and ozone that are in good agreement with observations.

[6] We obtain model results for three different experiments. The first experiment set uses a climatological distribution for the background ozone field and compares the

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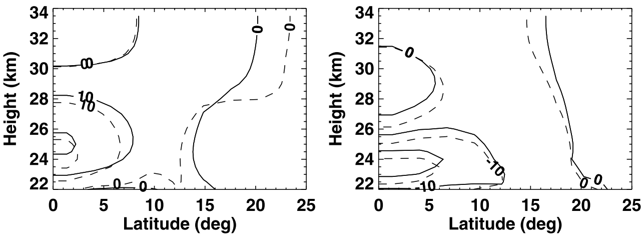

Figure 1. Model simulation of zonal wind (m/s) with wave-ozone feedbacks (dashed line) and without wave-ozone feedbacks (solid line) for a) descending westerlies and b) descending easterlies. The time of the comparison is chosen when the zero wind line at the equator reaches approximately 30 km.

QBO response with and without wave-ozone feedbacks. The second experiment examines the QBO response to a perpetual zonal-mean ozone perturbation consistent with the observed difference between solar maximum and solar minimum. The third experiment examines the QBO response to an imposed time-varying solar cycle in the zonal-mean ozone distribution. For each ozone perturbation, the model is integrated forward in time for a sufficiently long period (~10 years) to ensure that the initial transients have damped out, after which the QBO response to the ozone perturbation is examined.

3. Results

[7] The climatological simulation, which serves as a basis of comparison with the solar perturbed simulations shown later, illustrates the significant changes that the wave-ozone feedbacks impart to the QBO system. These changes are manifest in the structure and temporal variability of the zonal-winds, the descent rate of the easterlies and westerlies, the location of the subtropical zero wind line, and the amplitude of the residual circulation.

[8] Figures 1a and 1b show, respectively, snapshots of the westerly and easterly phases of the QBO with and without wave-ozone feedbacks. In both cases the zonal-mean ozone feedbacks are retained. Consider, for example, the westerly phase of the QBO, which is driven by the Kelvin wave. Near 25 km altitude, between the equator and 7° latitude, the wave-ozone feedbacks lower the altitude of the peak wind speed by ~1 km and increase its magnitude by up to 10%. The lowering of the altitude of the peak wind speed by the wave-ozone feedbacks is indicative of a faster descent rate and shorter QBO period.

[9] The wave-ozone feedbacks also shift the location of the subtropical zero wind line. There is a 1–2° equatorward shift between ~22–25 km and a 1–3° poleward shift between ~28–34 km. Such shifts underscore the potential importance of the wave-ozone feedbacks in affecting the planetary wave guide and extratropical circulation.

[10] Figure 2 shows the descending westerlies at the equator for the solar perturbed ozone simulation (top panel), climatological simulation (middle panel), and difference between the two (lower panel). In the solar perturbed ozone simulations the zonal-mean ozone was uniformly increased over the entire model atmosphere by 5%, which represents the upper limit of observed ozone variations in the tropical stratosphere over a solar cycle [*Hood*, 1997]. For this ozone perturbation the QBO period is shortened by about 2 weeks and the amplitude of the QBO at the equator is increased by up to 2%. This implies that during solar maximum, the diabatic heating due to the wave-ozone feedbacks drives a stronger QBO and produces a shorter QBO period. Correspondingly, additional simulations show that during solar minimum, the diabatic heating due to the wave-ozone feedbacks drives a weaker QBO with a longer QBO period.

[11] The difference between the solar perturbed and climatological simulations shown in Figure 2 compares well with *Soukhrarev and Hood*'s [2001] observations of zonal wind shown in Figure 3. In particular, the model simulations and observations both show the westerly and easterly phases to have shorter periods and the circulations to be stronger (weaker) during solar maximum (minimum). There are quantitative differences, however, between the model simulations and observations. For example, the model simulations underestimate the shift in period by several weeks and the variance in zonal-winds by up to ~50%. These differences, which increase without wave-ozone feedbacks, suggest that other mechanisms, which are absent from our model, may also be operating. Such mechanisms include the annual cycle in the residual circulation, the semi-annual oscillation and a broader wave spectrum to drive the QBO.

[12] Figure 4 shows the response of the equatorial zonal wind to sinusoidal variation in zonal-mean ozone. The ozone amplitude is 2.5% of the climatological value and the period is 11 years. Quasi-decadal variability in the zonal-mean wind is nearly in phase with the imposed solar cycle variation in zonal-mean ozone. The maximum west-

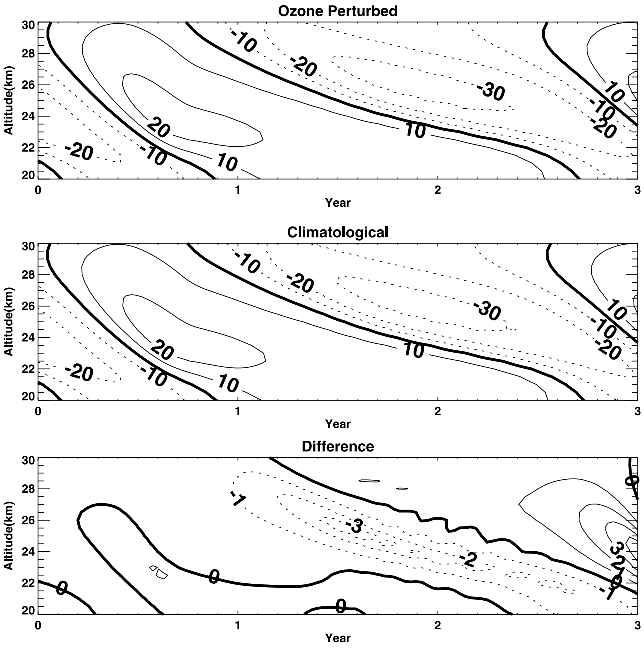

Figure 2. Vertical cross sections of the tropical westerly (thin solid lines) and easterly (thin dotted lines) zonal winds (m/s) for (top) the ozone perturbed simulation, (middle) the climatological simulation, and (bottom) the difference between the two. The bold contours correspond to the zero wind line. The "zero" point of the westerly phase starts near 30 km.

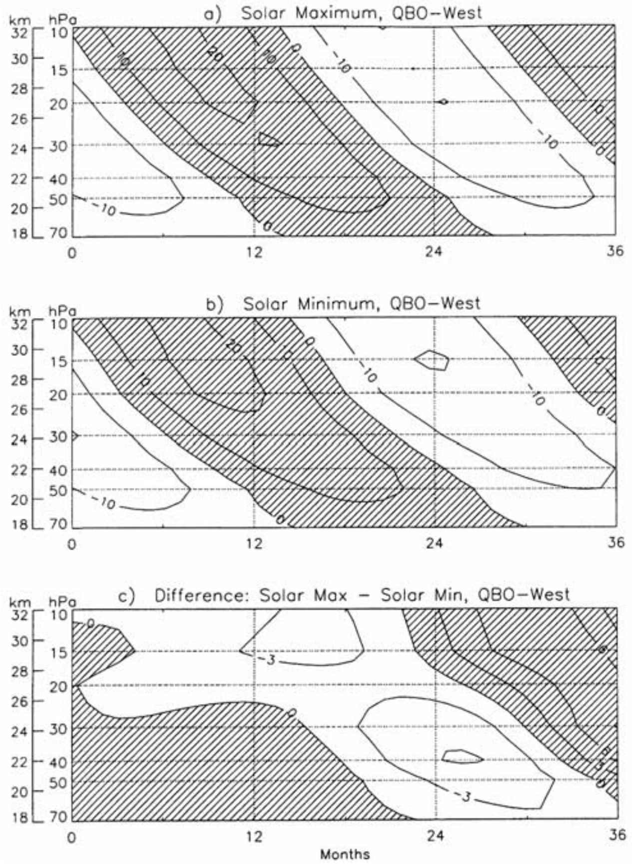

Figure 3. Observed equatorial zonal winds (m/s) for (a) solar maximum, (b) solar minimum, and (c) the difference between the two. This figure is adapted from *Soukharev and Hood* [2001], who averaged over 40 years of radiosonde data to isolate quasi-decadal variability in the tropical winds. The "zero" point of the westerly phase starts near 30 km.

erly winds, which are driven by the easterly propagating Kelvin wave, differ by 0.4 m/s (~2.5%) between solar maximum and solar minimum; the easterly winds, which are driven by the westerly propagating Rossby-gravity wave, differ by 0.2 m/s (~1%).

[13] For the westerly (easterly) phase of the QBO, the percent difference in the amplitude of the zonal wind between the ozone solar cycle simulations and the climatological simulation is ~2.5% (1%) near the equator at ~25 km altitude. Thus near the equator the westerly phase of the QBO response scales with the zonal-mean ozone perturbation amplitude. However, we find that in the subtropics (~12°N), the westerly phase of the QBO response increases to ~5%, which is indicative of a nonlinear latitudinal relationship between the QBO response and the imposed 2.5% solar perturbed ozone amplitude. In contrast to the westerly phase, the easterly phase of the QBO shows less variation with latitude in response to the solar cycle variation in ozone.

[14] The model simulations discussed above have several features in common. The wave-ozone feedbacks affect the westerly phase of the QBO more so than the easterly phase, the wave-ozone feedbacks reduce the period of the QBO, and the wave-ozone feedbacks increase the intensity of the QBO circulation. All of these solar modulated features are explained below.

4. Physical Interpretation

[15] Insights into how solar modulated wave-ozone feedbacks can affect the QBO are obtained by considering the latitudinally averaged divergence of Eliassen-Palm (EP) flux, $\langle \nabla \bullet \mathbf{F} \rangle$, which measures the wave driving of the zonal-mean flow, the wave driving of the residual mean meridional circulation, and the flux of wave activity [*Andrews and McIntyre*, 1976]. As shown by *Cordero et al.* [1998], the driving of the zonal mean-flow due to wave dissipation arising from wave-ozone feedbacks can be written in analytical form as,

$$\left\langle \frac{\partial \bar{u}}{\partial t} \right\rangle = -\rho^{-1} \langle \nabla \bullet \mathrm{F} \rangle \propto \sum_{j=0}^{1} m_j \exp\left[\int_{z_0}^{z} m_j dz' \right], \tag{1}$$

where

$$m_j \propto -\left[\alpha + \frac{1}{\omega_j^2 \left(B^2 + \omega_j^2 \right)} \left\{ \underbrace{ABC}_{I} - \underbrace{A \frac{\bar{\gamma}_z \omega_j^2}{N^2}}_{II} - \underbrace{\frac{j\omega_j ABa\bar{\gamma}_y}{N\left(\beta + \omega_j k_j\right)}}_{III} \right\} \right]. \tag{2}$$

Here $j = 0$ and $j = 1$ correspond to the Kelvin and Rossby-gravity waves, respectively. The symbols in equations (1) and (2) are: $\bar{u}(z)$, the zonal-mean flow; β, the northward gradient of the Coriolis parameter at the equator; $N(\mathrm{z})$, the Brunt Väisälä frequency; k_j, the zonal wave number; $\omega_j = [\sigma_j - k\bar{u}(z)]$, the Doppler-shifted, forced wave frequency; σ_j, the intrinsic frequency; and a, a positive constant. The Newtonian cooling coefficient is $\alpha(z)$ and the basic state ozone is $\bar{\gamma}(z)$. The radiative-photochemical coefficients are $A(\mathrm{z}; \bar{\gamma})$, $B(\mathrm{z}; \bar{\gamma})$, and $C(\mathrm{z}; \bar{\gamma})$. The ozone heating coefficient $A(\mathrm{z}; \bar{\gamma})$ originates from the model temperature equation, whereas the ozone production and destruction coefficients $B(\mathrm{z}; \bar{\gamma})$, and $C(\mathrm{z}; \bar{\gamma})$ originate from the model ozone continuity equation [*Nathan and Li*, 1991].

[16] The modulation of $\langle \nabla \bullet \mathbf{F} \rangle$ by wave-ozone feedbacks, measured by $m_j(z)$, depends on Newtonian cooling, $\alpha(z)$, as well as ozone photochemical heating (I), vertical ozone advection (II), and meridional ozone advection (III).

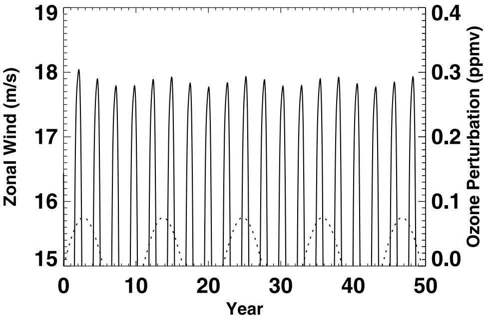

Figure 4. Time series of equatorial zonal-mean wind (m/s; solid line) at 22 km altitude resulting from an imposed solar cycle in zonal-mean ozone. The dotted line is the imposed ozone solar cycle (ppmv; dotted line) at 22 km.

In the mid to lower stratosphere, where the ratio of advective to photochemical time scales is small, ozone is approximately conserved so that term I, which involves the ozone production/destruction coefficients, can be neglected. Thus, for the Kelvin wave, vertical ozone advection (II) is the sole wave-ozone feedback process. For the Rossby-gravity wave, vertical ozone advection (II) and meridional ozone advection (III) both operate, but generally oppose each other, with II > III. Consequently, the wave-ozone feedbacks are less effective for the Rossby-gravity wave than for the Kelvin wave, as seen by comparing Figures 1a and 1b.

[17] To understand the wave-ozone feedback process better, consider II, which is the dominant feedback term in equation (2). In the lower equatorial stratosphere, the zonal-mean ozone field increases with altitude. Thus a wave-like perturbation will transport ozone rich air downward and ozone poor air upward, resulting in local heating and cooling, respectively. This produces a decrease in static stability, resulting in wave amplification. Because the vertical ozone gradient appears to be enhanced in the lower equatorial stratosphere during solar maximum, as suggested by observations [*Hood*, 1997], then the wave driving of the zonal mean flow would also be enhanced, which is consistent with our numerical results (see Figures 1–4).

[18] The wave-ozone feedback due to term II depends on the product between the radiative-photochemical coefficient and zonal-mean ozone gradient. Thus $\langle \nabla \bullet \mathbf{F} \rangle$ is a nonlinear function of the solar cycle induced change in the zonal-mean ozone field. To see this, we write $\bar{\gamma} = \bar{\gamma}_c + \bar{\gamma}'_s$, where $\bar{\gamma}'_s/\bar{\gamma}_c \ll 1$; $\bar{\gamma}_c$ and $\bar{\gamma}'_s$ represent, respectively, the climatological and solar perturbed zonal-mean ozone fields. Insertion of $\bar{\gamma}$ into II yields the following expression for the solar perturbed portion of the divergence of EP flux:

$$\langle \nabla \bullet F \rangle'_s \propto \underbrace{A\big|_{\bar{\gamma}_c} \bar{\gamma}'_{sz} + \frac{\partial A}{\partial \bar{\gamma}}\bigg|_{\bar{\gamma}_c} \bar{\gamma}_{cz} \bar{\gamma}'_s}_{Linear\ "Solar"\ Perturbation}$$

$$+ \underbrace{\frac{1}{2}\frac{\partial^2 A}{\partial \bar{\gamma}^2}\bigg|_{\bar{\gamma}_c} \bar{\gamma}_{cz} \bar{\gamma}'^2_s + \frac{\partial A}{\partial \bar{\gamma}}\bigg|_{\bar{\gamma}_c} \bar{\gamma}'_{sz} \bar{\gamma}'_s + \cdots}_{Nonlinear\ "Solar"\ Perturbation} \qquad (3)$$

The nonlinear character of this expression underscores the importance of the wave-ozone feedback process as a means for amplifying the solar cycle signal's impact on the QBO. We have carried out several numerical tests and found that the nonlinear solar perturbation effects can augment the linear solar perturbation effects by as much as 20%. Also noteworthy is that equation (3) depends on the solar perturbed zonal-mean ozone field, $\bar{\gamma}'_s$, and its vertical gradient, $\bar{\gamma}'_{sz}$. For simplicity we have chosen a spatially uniform, solar cycle induced ozone perturbation for which $\bar{\gamma}'_s/\bar{\gamma}_c = \bar{\gamma}'_{sz}/\bar{\gamma}_{cz} =$ 2.5%. Owing to the dependence of equation (3) on both $\bar{\gamma}'_s$ and $\bar{\gamma}'_{sz}$ as well as their products, it is conceivable that a spatially non-uniform ozone perturbation may produce responses that are larger than those obtained here. Presently, reliable estimates of the spatial variation of zonal mean ozone over the solar cycle are unavailable.

5. Conclusions

[19] The most important scientific challenge regarding the linkage between the 11-year solar cycle and climate variability hinges on identifying pathways that can amplify and communicate the solar cycle signal to the global circulation. Here we have identified and explored one such pathway: wave-ozone feedbacks. These feedbacks, which involve the interactions between the wind, temperature and ozone fields, are modulated by solar cycle-like variations in the zonal-mean ozone field. These variations are imparted, via wave transience and wave dissipation, to the equatorial QBO, as evidenced by solar modulated changes in the descent rate of the zonal winds, structure and speed of the zonal winds, and intensity of the residual circulation.

[20] We find that during solar maximum (minimum), the diabatic heating due to the wave-ozone feedbacks is responsible for driving a slightly stronger (weaker) QBO circulation and producing a slightly shorter (longer) QBO period. Moreover, we find that the percent change in these solar modulated circulation features is generally consistent with observations and can exceed the percent change in the imposed solar forcing, thus underscoring the nonlinear character of the wave-ozone feedback process, a crucial point that we have demonstrated both numerically and analytically.

[21] The wave-ozone feedback process also has been shown to affect wave transience and wave dissipation in the extratropics [*Nathan and Li*, 1991]. Our current work on the extratropics shows that the wave-ozone feedbacks can affect the downward reflection of planetary waves as well as the residual circulation. Because the residual circulation provides a direct connection between the extratropical planetary waves and the QBO, its modulation by solar cycle induced changes in the wave-ozone feedback process provides another pathway for communicating the solar cycle signal between the tropics and extratropics. Indeed, the wave-ozone feedback process is likely one of several mechanisms that act in concert to amplify and communicate the solar cycle signal to the climate system.

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