Response to Reviewer 1

1 Overview

Suggestion: Major revisions

This manuscript examines the impact of increasing stratospheric radiative damping on the period of the QBO. The scale of the increase in stratospheric radiative damping is based on results from a radiative transfer model in Plass (1956). Radiative damping causes dissipation of vertically propagating waves, which can lead to mean flow accelerations and internal oscillations, namely the Quasi-Biennial Oscillation (QBO) of the tropical stratosphere. This paper investigates the sensitivity of the QBO to increased radiative damping rate in a classical one-dimensional model of the QBO. It is reported that increased radiative damping would decrease the height scale of wave dissipation, and would be expected to lead to modest decreases in the QBO period (by 5-15% depending on the model formulation). Comprehensive climate models do not produce robust projections of the future QBO period, disagreeing on the sign of any future change. This disagreement is primarily thought to arise from competition between increasing wave stress (which tends to reduce the period) and increasing upwelling (which tends to increase the period). The mechanism proposed in this paper is an additional process that could potentially impact the QBO period in the future, and could already be happening in reality and in comprehensive climate simulations of the QBO.

The identification and characterization of a new process that could lead to changes in the QBO period is a worthwhile endeavor, and is appropriate for publication in this journal. One-dimensional models of the QBO are appropriate tools for characterizing the existence, sign, and order of magnitude of this radiative-dynamical sensitivity. This paper is careful to show how the results are sensitive to the formulation of the model, and those sensitivities help contextualize the argument. This paper has good potential, although at present the approach requires more justification, and the presentation could benefit from easing some of the tension between competing objectives of interpretability and predictive value. First, the radiative damping projections cited in the paper are of questionable relevance to the work presented. Second, the focus in the manuscript on producing a deterministic prediction of future period change appears to be inconsistent with the uncertainty stemming from the formulation of the model. If the radiative damping can be grounded on a more reliable basis, and the emphasis in the paper can be shifted to focus on the interpretation of the hypothesized mechanism and its attendant uncertainties without asking too much of its predictive value, then the paper can be recommended for publication. As such, major revisions are recommended.

We thank you for your insightful comments and suggestions and will address them point by point as below.

2 Major revisions

To elaborate on the recommendations for major revision:

First, the manuscript relies on a projection of radiative damping from Plass (1956), who diagnosed radiative cooling rates with a fixed temperature profile in response to a doubling of CO_2. However, the connection between the Plass analysis and the radiative damping rate is not obvious. Radiative cooling rate has units of [K s^{-1}], whereas radiative damping rate has units of [s^{-1}]. The cooling rate results of Plass cannot be used to isolate a change in radiative damping rate because the Plass result also includes changes in radiative equilibrium temperature, both of which impact the radiative cooling.

In his last section (i.e., section 4), Plass (1956) mentioned "The change in the equilibrium temperature at the surface of the earth with CO_2 concentration…" in order to counter "The argument has sometimes been advanced that the CO_2 cannot cause a temperature change at the surface of the earth because the CO_2 band is always black at any reasonable concentration…"

When Plass (1956) calculated the radiative cooling rates in other sections, he didn't deal with radiative equilibrium temperature at all. Instead, he obtained them for $\frac{1}{2} \times \mathrm{CO_2}$, $1 \times \mathrm{CO_2}$, and $2 \times \mathrm{CO_2}$ with a fixed temperature profile.

Let's quote Dickinson (1973): "Thus we resorted to an entirely numerical approach for obtaining a Newtonian cooling coefficient $a_0(z)$ for small departures from the reference temperature profile $T_0(z)$. That is, if $Q(T)$ is the infrared cooling rate for a temperature profile T(z), then

$$a_0(z) = \frac{\boldsymbol{Q(T_0+\delta)-Q(T_0-\delta)}}{\boldsymbol{2\delta}}$$

where δ is a small temperature perturbation (we used $\delta = 0.1^o K$)."

Assuming $Q(T)$ for $1\times \mathrm{CO_2}$ or $2 \times \mathrm{CO_2}$ is a smooth function, we can infer that if $Q(T)$ for $2 \times \mathrm{CO_2}$ at some altitude level is approximately 50% larger than that for $1 \times \mathrm{CO_2}$ at the same altitude level, then $\mathrm{a}_0(z)$ for the former is also approximately 50% larger than that for the latter at that altitude level. Note that the shape of the profile $\mathrm{Q}(z)$ in Fig. 1 depicted by Dickinson (1973) is very similar to that of the profile $a_0(z)$ in his Fig. 3. In other words, the value of $a_0(z)$ is approximately proportional to that of $\mathrm{Q}(z)$.

In addition, we don't need to know how radiative equilibrium temperatures change in response to increasing CO_2 concentration when we study how the wave-mean flow interactions generate the QBO, because the temperature fields associated with atmospheric waves relax back to the zonal mean temperatures rather than radiative equilibrium temperatures.

Finally, Dickinson (1973) implied that below the 0.2 hPa level the value of an estimated Newtonian cooling coefficient $a(z)$ is not sensitive to how a temperature profile $T(z)$ is chosen (refer to his Eqs. (2) and (3)).

The usage of the Plass value of 50% should be either (1) justified in light of these considerations or (2) an alternative reliable estimate should be provided of the radiative damping rate response to CO2 doubling (an order of magnitude estimate is fine). If no projection of radiative damping rate with CO2 doubling exists in the literature, then one should be produced (e.g. using a radiative transfer model). Such a projection of radiative damping rate, necessary for the arguments in the paper, would constitute a valuable contribution in its own right.

The maximum value we used is **30%** rather than the Plass value of 50% (refer to lines 215-219 in the revised manuscript). Plass (1956) claimed "The probable error of the cooling rate is estimated by introducing arbitrary variations into the original transmission functions and calculating their influence on the final result. The probable error obtained in this manner is about 10 per cent below 20 km, increasing to 30 per cent at 50 km and becoming rather uncertain above 60 km. Again, the relative differences between the various curves should be considerably more accurate than their magnitude."

Even if we regard the probable error of the cooling rate is 30 percent, the relative differences between the various cooling rates calculated by Plass (1956) should be considerably smaller 30 percent. Since the relative differences in cooling rates calculated by Plass (1956) are around 50% above 35 km, our value of 30% is smaller than the lower bound of uncertainty, i.e., 50% - 50%*30% = 35%. In other words, our choice of 30% is a conservative estimate.

Second, there is tension in the manuscript between the interpretability and predictive value of the results. Using the 1D model makes a strong decision in favor of interpretability, which is well justified by the approach and the results. Noting that the QBO period in the basic state and the response to changes in radiative damping are both highly sensitive to minor changes in the model formulation, it appears that the 1D model can provide, at best, the sign and order of magnitude of the period change in response to an increase in radiative damping. Therefore, modeling decisions that sacrifice the interpretability of the final results without impacting the sign or order of magnitude of the final result should be justified or avoided. Two example decisions in the paper are as follows. For each, the sacrifice of interpretability should be (1) justified in terms of predictive value or some other objective or (2) the simpler case should be considered:

• The Holton (1972) formulation used in this paper is driven by asymmetric waves (a Kelvin wave and a Rossby wave with different dispersion relations and wavenumbers). The Plumb (1977) formulation is driven by symmetric wave stress (equal and opposite gravity waves), allowing for clear interpretation of the model dynamics in terms of a small number of dimensionless parameters. Is there a benefit to using asymmetric wave forcing in this paper that justifies it at the cost of sacrificing the interpretability of the symmetric formulation?

Plumb (1977) provided a simpler and elegant theoretical framework to illuminate the essence of the QBO. What is more, Plumb (1977) paved the way for the experimental tour de force (Plumb and McEwan 1978) guided by “a small number of dimensionless parameters”. Plumb and McEwan (1978) demonstrated how a standing internal wave with sufficiently large amplitudes forced at the lower boundary of an annulus of salt-stratified water generated an oscillatory mean flow with relatively long periods compared to the period of the internal wave. This incarnation of the QBO analog cleared up any lingering doubts about the theory of wave-mean flow interactions.

However, the Plumb (1977) formulation is best suited to study non-rotating systems such as those in laboratories rather than the planetary-scale rotating Earth system. Although some authors used it to illustrate the stratospheric QBO by introducing a Kelvin wave and an “anti-Kelvin wave”, there is no “anti-Kelvin wave” in the terrestrial atmosphere. The Holton (1972) formulation was based on the observations that planetary-scale waves in the Equatorial lower stratosphere are dominated by Kelvin waves of zonal wavenumber 1-2 and mixed Rossby-gravity waves of wavenumber 4 (Andrews et al. 1987).

• Another source of the tension is in the choice to include changes in the buoyancy frequency N in the projections of the model response to radiative damping changes. Including the small (2.5%) changes in N seems to be so marginal that its effects are primarily to sacrifice interpretability without a clear benefit. It can still be useful to include a sensitivity study to changes in N, but this sensitivity study should be distinguished from the main line of argumentation in the paper. Note that in the 1D model, the buoyancy frequency N and radiative damping μ are always multiplied together, such that their combined effects are tantamount to considering a ($1.5 * 1.025 \rightarrow$) ≈54% change in radiative damping (or buoyancy frequency) alone, not significantly different than the 50% change in radiative damping.

Following your suggestion by excluding the small changes in N, we have redone a lot of experiments. Subsequently, figures 3, 5, and 6 have been re-plotted and the manuscript has been revised accordingly.

3 Minor comments

It would be appreciated if the following minor comments regarding the content and structure of the paper were addressed:

• The decomposition of $\bar{u} = \bar{u}_{sa} + \bar{u}_{QBO}$ in equation (5) gives the impression that the evolution of $\bar{u}_{QBO}$ depends only on $\bar{u}_{QBO}$, and that the influence of $\bar{u}_{sa}$ has been factored out. Yet $\bar{u}_{sa}$ still impacts the evolution of $\bar{u}_{QBO}$ through the wave forcing $\bar{F}_i$. Because $\bar{F}_i$ is nonlinear in the zonal wind profile, the SAO will impact the wave forcing, which changes the mean wind and then alters the diffusion profile. So, the dynamics are not simply resulting from the sum of a linear QBO dynamic and a linear SAO dynamic. Given the limitations of this decomposition, what benefit is provided by its inclusion?

Yes, we agree with your reasoning and expected that the simulated QBO periods should be sensitive to G, the imposed semiannual forcing. However, the simulated QBO periods are not sensitive to the imposed semiannual forcing provided that G does not exceed the values employed by HL (refer to lines 314-316 of the version with track changes).

We used "the decomposition of $\bar{u} = \bar{u}_{sa} + \bar{u}_{QBO}$ in equation (5)" to highlight this bizarre behavior and further illustrated that the deficiency is closely related to the insufficient height of the model top.

• Lines 301-312 list all numerical values from Figure 6. Is it necessary to list all numerical values when the figure provides their approximate value? If so, then perhaps a table can be supplied instead of the figure or in the supplementary information. I suspect that the relevant information from Figure 6 can be conveyed in a more concise way.

We have eliminated this unpleasant verbosity.

• In the Introduction, the following question is raised: "Does the competing effect between [upwelling and enhanced wave stress] leave some room for increasing stratospheric radiative damping to exert an influence on the QBO period?" (Line 137) In the Conclusions, comprehensive QBO models are noted to have significant variance in their projections of period. A quantitative comparison would be useful here; allowing that the 1D model provides at best an order of magnitude estimate, is there reason to believe that period changes in GCMs are small enough that radiative damping could potentially impact their sign? Their magnitude? Or on the contrary, are the period changes in GCMs large enough in magnitude that radiative damping would not be expected to have a significant bearing on the sign or magnitude of the change?

We are not in position to answer those important questions. This report aims to provoke the readers to think and/or conduct more researches to answer them.

• Lines 343 - 345: Recently, doubt has been cast on the role of upwelling on QBO amplitude (Match and Fueglistaler, 2019, 2020). A more nuanced assessment would be appreciated than "The amplitude decrease is associated with a strengthened residual mean circulation, also consistent with the literature, although the vertical structure of the circulation response is nontrivial."

Done.

4 Edits

(166) “mixing Rossby-gravity wave” should be “mixed Rossby-gravity wave”

Done.

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Response to Reviewer 2

This is the first review of the manuscript "The Impact of Increasing Stratospheric Radiative Damping on the QBO Period" by Tiehan Zhou, Kevin DallaSanta, Larissa Nazarenko, Gavin A. Schmidt, Paper # acp-2020-925. The approach of the paper is to conduct sensitivity experiments using 1-D mechanistic model to find an impact of radiative dumping in the stratosphere to QBO period. Experimental parameters in this paper are Newtonian cooling (alpha; unit:s-1)/Brunt-Vaisala frequency (N; unit: s-1), and the upper boundary conditions (G). Diagnostics are monthly zonal wind, and the frequency power spectra using the fast Fourier transform. The results are interesting and relevant to Atmospheric Chemistry and Physics because this paper is trying to ascertain the trend of the QBO period in a warming climate, focusing on the radiative damping that would influence that period. But I suggest a major substantial revision since I have serious concerns about generalization and validation of authors' results. (mainly described in the line-by-line comments).

We thank you for your helpful comments and suggestions and will address them point by point as below.

Major comments

1. Statistical significance L047 "the doubling of CO2 shortens the QBO period by 4.7%" What kind of meaning does a value of 4.7 hold for the science? Results of sensitivity experiments using 1D model mostly depend on an assumption of the experimental design, here in Newtonian cooling profiles of Fig. 1. Can you show realistic vertical profiles of Newtonian cooling with standard deviations? And then, you can estimate errors about the shortening of the QBO period, from an assumption of errors of Newtonian cooling.

The reviewer 1 suggested that we should focus on the interpretation of the hypothesized mechanism and its attendant uncertainties without asking too much of its predictive value. Thus, the numbers such as 4.7% are used for qualitative interpretation rather than quantitative prediction. For example, in Section 4, We found that when the Brunt-Väisälä frequency was decreased by 2.5%, the simulated QBO period was slightly lengthened from 30 months to 30.2 months; we also found that when the scale height in the stratosphere was decreased by 2.3%, the simulated QBO period was shortened from 30 months to 29.3 months. Those findings only suggest that the increase of the stratospheric radiative damping contributes more to the shortening of the QBO period than the shrinkage of scale height in the stratosphere while the contribution of the change in the Brunt-Väisälä frequency is almost negligible. By the way, we also added into the manuscript some discussions on the uncertainties in the relative change of cooling coefficient.

2. Scale height Scale height would be changed in a warming climate. How does the change of scale height due to the temperature change in a warming climate affect the QBO period?

An extra sensitivity test has been conducted. Accordingly, a paragraph has been added in the manuscript (refer to lines 409-417 of the revised version with track changes).

3. Ozone The ozone also affects QBO period. It is useful for readers to assess an effect of the ozone on the QBO period using 1D model in a warming climate. Shibata, K., and M. Deushi (2005), Radiative effect of ozone on the quasi-biennial oscillation in the equatorial stratosphere, Geophys. Res. Lett., 32, L24802, doi:10.1029/2005GL023433.

Yes, ozone does affect the QBO period, and we are studying this issue. This paper addresses the impact of the doubling of CO_2 concentration on the QBO period from the viewpoint of increasing stratospheric radiative damping. According to the latest Scientific Assessment of Ozone Depletion completed in 2018, ozone will heal completely before the CO_2 concentration is doubled. Thus, we chose not to deal with ozone in this study.

L10-16. Why the authors do not show that QBOs simulated in this paper are derived only from planetary waves and that gravity waves are not included? Without manifestation about exploring the response to enhancing radiative damping of only planetary waves in the experiments, their conclusion would lead to misleading.

Richter et al. (2020) pointed out that the largest uncertainty in the response of the QBO in a warming climate comes from the representation of parameterized gravity waves in climate models. Section 5 suggested that high-resolution models such as those used by Kawatani et al. (2011, 2019) be used to further our understanding.

L15-16. Most climate models project a strengthening of tropical vertical residual velocity, as you mentioned in the introduction. This could contribute to projecting a lengthening of the QBO period, which is opposite direction to the authors' conclusion.

As discussed in Sections 1 and 5 of the manuscript, our focus is placed on how the physical processes other than wave momentum flux entering the stratosphere and tropical vertical residual velocity could exert an influence on the trend of the QBO period in a warming climate. This report doesn't intend to answer the question: Will the QBO period ultimately become longer or shorter in the warming climate?

L232. "QBO was not essential for QBO theory" You can estimate QBO power with/without SAO. To what extent does the SAO impact the QBO power spectrum?

QBO and SAO power spectra were not estimated separately. They are plotted separately for the sake of visual effects. As per Plumb (1977), the SAO exerts little, if any, influence on the QBO power spectrum in this kind of model configurations.

Minor comments L301-323. Redundant descriptions. You can omit most of them.

The redundancy has been eliminated.

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The Impact of Increasing Stratospheric Radiative Damping on the QBO Period

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Abstract. Stratospheric radiative damping increases as atmospheric carbon dioxide concentration rises. We use the one-dimensional mechanistic models of the QBO to conduct sensitivity experiments and find that when atmospheric carbon dioxide concentration increases, the simulated QBO period shortens due to the enhancing of radiative damping in the stratosphere. This result suggests that increasing stratospheric radiative damping due to rising CO_2 may play a role in determining the QBO period in a warming climate along with wave momentum flux entering the stratosphere and tropical vertical residual velocity, both of which also respond to increasing CO_2.

1. Introduction

The quasi-biennial oscillation (QBO) dominates the variability of the equatorial middle and lower stratosphere and is characterized by a downward propagating zonal wind regime that regularly changes from westerlies to easterlies. The QBO period ranges from 22 to 34 months with its average being slightly longer than 28 months. The QBO not only manifests itself in the equatorial zonal winds, but also leaves an imprint on the temperature in both the tropics and extratropics (Baldwin et al., 2001 and references therein).

The QBO has far-reaching implications for global weather and climate systems. First of all, the QBO exerts a marked influence on the distribution and transport of various chemical constituents such as ozone (O_3) (e.g., Hasebe, 1994), water vapor (H_2O) (e.g., Kawatani et al., 2014), methane (CH_4), nitrous oxide (N_2O), hydrogen fluoride (HF), hydrochloric acid (HC1), odd nitrogen species (NO_y) (e.g., Zawodny and McCormick, 1991), and volcanic aerosol (Trepte and Hitchman, 1992). Secondly, it is well appreciated that the QBO influences the extratropical circulation in the winter stratosphere, which is commonly known as the Holton–Tan effect (Holton and Tan, 1980; Labitzke, 1982). It has been noted that the effect of the QBO on the extratropical winter stratosphere impacts the severity of stratospheric ozone depletion (e.g., Lait et al., 1989). Furthermore, taking account of the QBO improves the simulation and predictability of the extratropical troposphere (e.g., Marshall and Scaife, 2009). Finally, through its modulation of temperature and vertical wind shear in the vicinity of the tropical tropopause, the QBO influences tropical moist convection (Collimore et al., 2003; Liess and Geller, 2012), the El Niño-Southern Oscillation (ENSO) (Gray et al., 1992; Huang et al., 2012; Hansen et al. 2016), the Hadley circulation (Hitchman and Huesmann, 2009), the tropospheric subtropical jet (Garfinkel and Hartmann, 2011a, 2011b), the boreal summer monsoon (Giorgetta et al., 1999), and the Madden-Julian Oscillation (Yoo and Son, 2016**)**. Intriguingly, the QBO is also reported to influence the activities of tropical cyclones (Gray et al., 1984; Ho et al., 2009), albeit this issue is still unsettled (Camargo and Sobel, 2010) and needs further study.

Efforts to understand and simulate the QBO have been ongoing ever since its discovery by Ebdon (1960) and Reed et al. (1961). Lindzen and Holton (1968) and Holton and Lindzen (1972) developed the classical theory of the QBO. Namely, as waves propagate upward, they are attenuated by thermal damping, encounter critical levels, and accelerate and decelerate the mean flow, providing momentum sources for both the westerly and easterly phases of the QBO.

Holton and Lindzen's (1972) model (hereafter referred to as HL model) was further simplified by Plumb (1977), the elegance of which made it a standard paradigm for the QBO. In Plumb's (1977)

Boussinesq formulation, the QBO period is inversely dependent upon both the momentum flux and thermal dissipation rate. Hamilton (1981) further highlighted the role of the radiative damping rate on both the realistic vertical structure and the realistic period of the QBO.

By adopting higher vertical resolutions and incorporating various gravity wave parameterization schemes, many state-of-the-art climate models have shown the capability to self-consistently simulate the QBO (Scaife et al., 2000; Giorgetta et al., 2002, 2006; Rind et al., 2014, 2020; Geller et al., 2016a; Richter et al., 2020a, 2020b). Given the important implications of the QBO for the global climate system, it is natural to ask how the QBO will change in a warming climate.

Giorgetta and Doege (2005) showed a shortening of the QBO period in their doubled CO_2 experiments. They reasoned that both the weakening of the tropical upwelling and the prescribed increase of gravity wave sources lead to the reduction of the QBO period in a warming climate. However, most climate models project a strengthening rather than weakening of tropical upwelling in a warmer climate (Butchart et al., 2006; Butchart 2014; Li et al., 2008). Employing a model without any parametrized non-orographic gravity waves, Kawatani et al. (2011) demonstrated that the intensifying tropical upwelling in a warming climate dominates the counteracting effect of enhanced wave fluxes and consequently projected a lengthening of the QBO period. Using fixed sources of parametrized gravity waves, Watanabe and Kawatani (2012) also projected an elongation of the QBO period in a warming climate and ascribed it to the stronger tropical upwelling. Analyzing four Coupled Model Intercomparison Project phase 5 (CMIP5) models that could simulate a reasonable QBO, Kawatani and Hamilton (2013) found that the projected trends of the QBO period were inconsistent in sign. They further investigated the 60-year operational balloon-borne radiosonde observations provided by the Free Berlin University and detected no significant trend in the QBO period. Richter et al. (2020b) investigated the response of the QBO to doubled and quadrupled CO2 climates among eleven models that participated

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in Phase 1 of the Stratospheric-tropospheric Processes And their Role in Climate QBO-initiative (QBOi; Butchart et al., 2018), and found no consensus on how the QBO period would respond to a changing climate. Recently, Butchart et al. (2020) evaluated ten Coupled Model Intercomparison Project phase 6 (CMIP6) models with realistic QBO in two Shared Socioeconomic Pathways (SSPs, Gidden et al., 2019) scenario simulations and surprisingly found that the QBO period shortens in seven of those ten models in both in both SSP3-7.0 and SSP5-8.5 scenarios although only two and three models show a significant shortening trend in the respective scenarios.

It is challenging to ascertain the trend of the QBO period in a warming climate. On one hand, a speeding-up of the Brewer-Dobson circulation in a warming climate leads to a lengthening of the QBO period in most climate models. On the other hand, there is a robust increase in the vertical component of the EP flux for both eastward and westward propagating waves (Richter et al., 2020b; Butchart et al., 2020), indicating that the QBO period shortens due to the enhanced wave driving in a warming climate. The competing effects between enhanced wave driving and a faster Brewer-Dobson circulation suggests that trends in the QBO period are likely to be small and difficult to detect due to the large cycle-to-cycle variability that is reproduced by climate models (Butchart et al., 2020). In addition, uncertainty in the representation of the parameterized gravity waves make it more elusive to detect the trend of the QBO period in a warming climate (Schirber et al., 2015; Richter et al., 2020b).

Given the fact that the QBO period is influenced by the radiative damping (Plumb 1977; Hamilton 1981), a natural question to ask is whether it could play a role on the trend of the QBO in a warming climate. Plass (1956) showed that when the CO_2 concentration is increased from 330 ppmv to 660 ppmv, the cooling rate increases significantly in the middle and upper stratosphere while it is not changed below the 24 km height level. The cooling rate is increased by more than 50% around the 40 km height level (see his Figure 8).

It is well-known that enhanced wave fluxes entering the stratosphere and stronger tropical upwelling individually play a dominant role in determining the trends in the QBO period in a warming climate. Does the competing effect between them leave some room for increasing stratospheric radiative damping to exert an influence on the QBO period? In this paper, we use the HL model to isolate the effect of radiative damping on the QBO period by assuming that the momentum flux entering the stratosphere doesn't change in our experiments. Observational and modeling studies (Andrews et al., 1987; Kawatani et al., 2009, 2010, 2011; Richter et al., 2020b; Holt et al., 2020) showed that the wave forcing spectrum is similar to a discrete two-wave spectrum rather than red-noise or white-noise, all of which are illustrated in Saravanan (1990). Accordingly, the QBO is indeed sensitive to stratospheric radiative damping, and the HL model is suitable for us to conduct the sensitivity analysis.

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The remainder of this paper is organized as follows. Section 2 investigates the sensitivity of the QBO period to the radiative damping using HL's original model. Section 3 explores the sensitivity of the QBO period to the radiative damping using a modified HL model where the semiannual forcing is removed. Discussion and conclusions are presented in Sections 4 and 5 respectively.

2. Sensitivity of the QBO period to enhanced stratospheric radiative damping in the original HL model

In the HL model the governing equation of mean flow emerges after the primitive momentum equation is meridionally averaged over some suitable latitudinal belt over the equator.

$$\frac{\partial \overline{u}}{\partial t} = -\frac{1}{\rho_0}\frac{\partial}{\partial z}\left[\sum_{i=0}^{1} \overline{F_i}\right] + K_z \frac{\partial^2 \overline{u}}{\partial z^2} + G \tag{1}$$

where $\overline{u}$ is mean zonal wind, ρ_0 is mean density, $\overline{F_i}$ is the meridionally averaged vertical Eliassen-Palm flux associated with wave i, the index i refers to the individual waves, K_z is a vertical eddy diffusion coefficient, t is time, z is altitude, and G is semiannual forcing identical to that specified by HL.

The $\overline{F_i}$ is are evaluated with Lindzen's (1971) WKB formalism for equatorial waves in shear. When only infrared cooling acts to damp the waves the formulae for $\overline{F_i}$ are

$$\overline{F_0}(z) = A_0\, exp\left(-\int_{17km}^{z} \frac{\alpha N}{k(c-\overline{u})^2}\, dz\right) \qquad (2)$$

for the Kelvin wave, and

$$\overline{F_1}(z) = A_1\, exp\left[-\int_{17km}^{z} \frac{\alpha \beta N}{k^3(c-\overline{u})^3}\left(1 - \frac{k^2(\overline{u}-c)}{\beta}\right) dz\right] \qquad (3)$$

for the mixed Rossby-gravity wave. As in HL, the wavenumber k, the phase speed c, and A_0 are chosen to be $2\pi/(40{,}000\ \mathrm{km})$, $30\ \mathrm{m\ s^{-1}}$, and $0.04\ \mathrm{m^2\ s^{-2}}\rho_0(17\ \mathrm{km})$, respectively for the Kelvin wave while they are equal to $-2\pi/(10{,}000\ \mathrm{km})$, $-30\ \mathrm{m\ s^{-1}}$, and $-0.04\ \mathrm{m^2\ s^{-2}}\rho_0(17\ \mathrm{km})$, respectively for the mixed Rossby-gravity wave. In Eq. (1), $K_z = 0.3\ \mathrm{m^2\ s^{-1}}$, which is also the same as in HL. In addition, $\beta = 2\Omega/a$, where Ω is earth's rotation rate, and a is earth's radius. HL's boundary conditions stipulated that $\overline{u} = 0$ at the lowest model level (17 km) and constrained $\overline{u}$ to vary semiannually at the top level (35 km).

In our control run that is used to depict the present-day QBO all the model parameters are identical to those used by HL in their original simulation. The Brunt-Väisälä frequency

$$N = \sqrt{\frac{g}{T_0}\left(\frac{dT_0}{dz} + \frac{g}{c_p}\right)} \qquad (4)$$

In Eq. (4), g is gravity, T_0 is mean temperature, and c_p is specific heat of dry air at constant pressure. HL set N in Eq. (4) to $2.16 \times 10^{-2}\mathrm{s}^{-1}$ with a scale height $H = 6$ km. In addition, the Newtonian

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cooling profile in our control run, i.e., $\alpha(z)$ in Eqs. (2) and (3), is also identical to that in the original HL model and depicted in FIG. 1 as the black line. Namely, $\alpha(z)$ in the control run increases from $(21\ \text{day})^{-1}$ at 17 km to $(7\ \text{day})^{-1}$ at 30 km and is kept at $(7\ \text{day})^{-1}$ between 30 km and 35 km. Fels (1985) explicated why this cooling rate is suitable for simulating the QBO on the basis of the scale-dependent effect of radiative damping (Fels 1982). Hamilton (1981) demonstrated that the proper choice of $\alpha(z)$ is crucial in simulating a realistic vertical structure of the QBO.

Eq. (1) was integrated for 100 years using the forward-backward scheme (Matsuno, 1966). The vertical resolution was 250 m and identical to that in HL. The time step was 12 hr, i.e., one half of used in HL, because the 24-hr time step resulted in numerical instability in our integration.

FIG. 2a shows the time–height section of the monthly averaged mean zonal wind simulated over the first 20 years using the HL model. Both the QBO and the semiannual oscillation (SAO) are conspicuous. The fast Fourier transform (FFT) method is used to calculate the frequency power spectra. In order to more accurately derive the QBO period, the model was run for 100 years to increase the spectral resolution. Frequency–height sections of the power spectral densities (PSD) over zero to the Nyquist frequency, i.e., 0.5 cycle/month, depict two sharp lines (peaks) at $\frac{1}{30}$ and $\frac{1}{6}$ cycle/month, respectively (not shown). In order to better visualize the magnitudes of the PSD, we show two truncated frequency–height sections with FIG. 2b and FIG. 2c highlighting the QBO and the SAO respectively. FIG. 2b shows that the QBO dominates over the model domain. The peak frequency corresponds to the period of 30 months. FIG. 2c shows the SAO dominates near the model top due to the fact a semiannual forcing was imposed in the altitudes from 28 to 35 km.

It is worth mentioning that the QBO period shown here is longer than 26.5 months reported in the HL paper (see their FIG. 1). Using the HL model parameters, the QBO period simulated by Plumb (1977) was close to three years (refer to his FIG. 8a), which is longer than our simulated QBO period, i.e., 30.0

months. Although we could not explain why our simulated QBO period is longer than that simulated by HL, we found that when the upper boundary condition is changed from $\overline{u} = 14\sin(\omega_a t)$ and $\omega_a = \frac{2\pi}{180}$ day^{-1} used in the HL's original model (refer to their Eqs. (2)) to $\frac{\partial \overline{u}}{\partial z} = 0$ used in Plumb (1977), the simulated QBO period becomes 34.3 month (figure not shown). In other words, when we adopted the stress-free upper boundary condition as in Plumb (1977), our simulated QBO period is comparable to that simulated by him, which lends credence to our reconstruction of the HL model.

As mentioned in Section 1, when the atmospheric carbon dioxide concentration is doubled the cooling rate increases significantly in the middle and upper stratosphere while it does not change below the 24 km height level. The cooling rate is increased by more than 50% around the 40 km height level (Plass, 1956). As implied in Dickinson (1973), the estimated cooling coefficient below the 0.2 hPa level is approximately proportional to the estimated cooling rate and is not sensitive to the chosen temperature profile. In other words, the relative increase in the cooling coefficient is roughly equal to the relative increase in the cooling rate as the CO_2 concentration is doubled. Accordingly, the Newtonian cooling profile in our experimental run, i.e., $\alpha(z)$ in Eqs. (2) and (3), is specified in FIG. 1 as the red line. Namely, $\alpha(z)$ in the experimental run increases from (21 day) $^{-1}$ at 17 km to $\frac{9}{91}$ day^{-1} at 24 km, which is identical to that in the control run from 17 km to 24 km. We increased $\alpha(z)$ in the experimental run between 30 km and 35 km by 30% relative to that in the control run. In other words, $\alpha(z)$ is kept at $\frac{1.3}{7}$ day^{-1} between 30 km and 35 km in the experimental run. This percentage increase of 30% in $\alpha(z)$ for the doubled CO_2 above 30 km shown in FIG. 1 is somewhat less than that implied in the Figure 8 of Plass (1956), because we would like our estimated relative increase in $\alpha(z)$ to err on the conservative side given the inherent uncertainties mentioned by him. Between 24 km and 30 km, $\alpha(z)$ in the experimental run is formulated linearly with height from $\frac{9}{91}$ day^{-1} at 24 km to at $\frac{1.3}{7}$ day^{-1} at 30 km.

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FIG. 3a shows the time–height section of the monthly averaged mean zonal wind simulated over the first 20 years for the doubled CO_2 run, where the increased $\alpha(z)$ depicted as the red line in FIG. 1 was employed while all other parameters are identical to those in the control run. Obviously, the QBO dominates below 28 km while the semiannual oscillation (SAO) dominates above 31 km. Like FIG. 2b and FIG. 2c, we only show two truncated frequency–height sections with FIG. 3b highlighting the QBO and FIG. 3c highlighting the SAO. FIG. 3b also shows that the QBO prevails over the model domain. The peak frequency corresponds to the period of 27.9 months. FIG. 3c shows the SAO dominates near the model top due to the same imposed semiannual forcing as that in the control run.

In summary, using the original HL model we found that the increased radiative damping due to the doubling of CO2 shortens the QBO period by 7% (i.e., from 30 months to 27.9 months).

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3. Sensitivity of the QBO period to enhanced stratospheric radiative damping in the HL model without the semiannual forcing

HL pointed out that the imposed semiannual oscillation was not essential for their QBO theory. Applying $\frac{\partial \bar{u}}{\partial z} = 0$ as the upper boundary condition, Plumb (1977) showed a simulated QBO without resorting to the semiannual momentum source (refer to his FIG. 8b). In the following control run, all parameters are identical to those used in the previous control run in Section 2 except that G in Eq. (1) is set to zero with $\frac{\partial \bar{u}}{\partial z}$ also being set to zero at $z = 35$ km. Hereafter we refer to it as the Plumb model[1]. FIG. 4a shows the time–height section of the monthly averaged mean zonal wind simulated over the first 20 years using the Plumb model. As expected, the QBO emerges without any trace of SAO since $G = 0$ in Eq. (1). FIG. 4b shows that the QBO dominates over the whole model domain. The peak frequency

[1] Strictly speaking, it is the HL model modified by Plumb (1977). In this paper, we don't use his eponymous model, i.e., the simplest possible model of the QBO, where Boussinesq fluids with uniform mean density were employed, because the HL model and its variant are considerably more realistic.

corresponds to the period of 37.5 months, which is comparable to that simulated by Plumb (1977) shown in his FIG. 8b. Apparently, the QBO period from the Plumb model, i.e., 37.5 months shown in FIG. 4b, is longer than that from the HL model, i.e., 30.0 months shown in FIG. 2b. This is partly because the additional forcing G in Eq. (1) was removed in the Plumb model.

In the following experimental run, all parameters are identical to those used in the previous experimental run in Section 2 except that G in Eq. (1) is set to zero with $\frac{\partial \bar{u}}{\partial z}$ also being set to zero at $z = 35$ km. In other words, the following experimental run using the Plumb model employed the same parameters as the afore-mentioned control run using the Plumb model except that the increased $\alpha(z)$ shown as the red line in FIG. 1 was used in the following experimental run while $\alpha(z)$ shown as the black line in FIG. 1 was used in the above control run. FIG. 5a shows the time–height section of the monthly averaged mean zonal wind simulated over the first 20 years for the doubled CO_2 run. It is natural that only the QBO emerges. A comparison of FIG. 4a and FIG. 5a shows that the QBO period shortens when the infrared damping increases in response to the doubled CO2. FIG. 5b shows that the QBO dominates over the whole model domain. The peak frequency corresponds to the period of 31.6 months.

Using the Plumb model, we found that the increased radiative damping due to the doubling of CO_2 shortens the QBO period by 15.7% (i.e., decreases from 37.5 months to 31.6 months).

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4. Discussion

The semiannual forcing, G in Eq. (1), in the HL model is imposed rather than results from the wave-flow interaction. In other words, G in Eq. (1) is independent of mean flow, and is specified as $G = 0$ for $z \le 28$ km, and $G = \omega_{sa}\bar{u}_{sa}$ for $z > 28$ km where $\overline{u}_{sa} = 2(z - 28\text{km})\ \text{m s}^{-1}\ \text{km}^{-1} \sin(\omega_{sa} t)$ and $\omega_{sa} = \frac{2\pi}{180}\ \text{day}^{-1} \approx 4 \times 10^{-7}\ \text{s}^{-1}$ (refer to Eqs. (2) in HL). Therefore, we have $\frac{\partial^2 \overline{u}_{sa}}{\partial z^2} = 0$ in the HL original model. We furthermore decompose $\overline{u}$ into two components: $\overline{u}_{QBO}$ *and* $\overline{u}_{sa}$. Combining Eq. (1), the decomposition of $\overline{u}$ *as* $\overline{u} = \overline{u}_{QBO} + \overline{u}_{sa}$, the above-mentioned $\frac{\partial^2 \overline{u}_{sa}}{\partial z^2} = 0$, and $G = \omega_{sa} \overline{u}_{sa} = \frac{\partial \overline{u}_{sa}}{\partial t}$ for $z > 28$ km, yields

$$\frac{\partial \overline{u}_{QBO}}{\partial t} = -\frac{1}{\rho_0} \frac{\partial}{\partial z} \left[\sum_{i=0}^{1} \overline{F_i} \right] + K_z \frac{\partial^2 \overline{u}_{QBO}}{\partial z^2} \tag{5}$$

for $z > 28$ km.

Dunkerton (1997) showed that in the presence of tropical upwelling it was gravity waves rather than large-scale Kelvin and mixed Rossby-gravity waves that contributed the bulk of QBO forcing. Consequently, Geller et al. (2016a, 2016b) pointed out that enough gravity wave momentum flux is required to model the QBO in a self-consistent manner in climate models and that the magnitude of the subgrid-scale gravity wave momentum flux plays a crucial role in determining the QBO period. Since there is no tropical upwelling in either the HL model or the Plumb model, and the semiannual forcing, G, is dependent on neither $\overline{u}$ in Eq. (1) nor $\overline{u}_{QBO}$ in Eq. (5), it is natural that planetary-scale Kelvin and mixed Rossby-gravity waves largely determine the QBO periods shown in Sections 2 and 3 due to the fact that G only exerts a weak influence on the planetary wave forcing, i.e., $-\frac{1}{\rho_0} \frac{\partial}{\partial z} \left[\sum_{i=0}^{1} \overline{F_i} \right]$ in Eqs. (1) and (5). We conducted another sensitivity test where all parameters are identical to those in the HL model except that G in both the control and experimental runs is twice as large as that used by HL. As the radiative damping profile changes from the black line to the red line above 24 km shown in FIG. 1, our simulated QBO period decreases from 28.6 months to 27.3 months (figures not shown). This smaller percentage decrease of 4.5% is not unexpected because the unrealistically larger G that is independent of $\overline{u}$ makes the model atmosphere less sensitive to the changes in the radiative damping.

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We further conducted two sensitivity tests where all parameters are identical to those in the HL model except that G in the first test is half as large as that used by HL and is equal to zero in the second test. Surprisingly, as the radiative damping profile changes from the black line to the red line above 24 km shown in FIG. 1, our simulated QBO periods decreases from 30.0 months to 28.6 months both for G being decreased by 50% and for $G = 0$ (figures not shown). This 4.7% decrease in the QBO period is somewhat smaller than the 7% reduction obtained from the sensitivity test presented in Section 2 when G is the same as that used by HL. It is surprising because the model atmosphere is expected to be more sensitive to the changes in the radiative damping as G, which is independent of $\overline{u}$, becomes smaller and smaller. Note that when our control runs adopt the black radiative damping profile shown in FIG. 1 the simulated QBO periods are not sensitive to the imposed semiannual forcing provided that G does not exceed the values employed by HL. Similarly, when our experimental runs adopt the red radiative damping profile above 24 km shown in FIG. 1 the simulated QBO periods are also not sensitive to the imposed semiannual forcing provided that G does not exceed 50% of the values adopted in HL. The question naturally arises: what is responsible for this unphysical behavior?

In Section 2, the simulated QBO periods are equal to 30 and 34.3 months when we adopted the no-slip and stress-free upper boundary condition respectively with all other parameters being identical to those used by HL. The results implicate the upper boundary conditions in the inconsistency. Plumb (1977) pointed out that the upper boundary in HL was undesirably low and implied that raising the lid to an additional 50% would be adequate for the robustness in his model. Here, we carry out a series of sensitivity tests by raising the model lid gradually from 35 km to 55 km with the one-kilometer increment. we will demonstrate how the behavior of the HL model with $G = 0$ converges with that of the Plumb model. The modified HL model, i.e., the HL model with $G = 0$ is identical to the Plumb model except that the former has the no-slip upper boundary condition while the latter has the stress-free upper

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boundary condition. Both models share the same governing equation (5). Note that we set the radiative damping rate above the 35 km level to its value at the 35 km level shown in FIG. 1.

For the radiative damping profile corresponding to the reference CO_2, FIG. 6 shows that when the model lid is placed at the 35 km level the simulated QBO period of 30.0 months with the no-slip upper boundary condition (solid black line) is apparently shorter than that of 37.5 months with the stress-free upper boundary condition (dashed black line). FIG. 6 also shows that as the model lid is raised incrementally from the 35 km level to the 46 km level, the discrepancies between the simulated QBO periods due to the different upper boundary conditions decrease monotonically. No matter whether we adopt the no-slip or stress-free upper boundary condition, the simulated QBO period is 32.4 months for the reference radiative damping profile provided that the model top is at or above the 46 km level.

Similarly, for the radiative damping profile corresponding to the doubled CO_2, FIG. 6 demonstrates that when the model lid is placed at the 35 km level the simulated QBO period of 28.6 months with the no-slip upper boundary condition (solid red line) is obviously shorter than that of 31.6 months with the stress-free upper boundary condition (dashed red line). FIG. 6 also exhibits that as the model lid is raised gradually from the 35 km level to the 40 km level, the discrepancies between the simulated QBO periods due to the different upper boundary conditions decrease monotonically. No matter whether we adopt the no-slip or stress-free upper boundary condition, the simulated QBO period for the enhanced infrared cooling due to the doubled CO_2 is 30.0 months provided that the model top is at or above the 40 km level. It is apparent that the required model top is lower when the radiative damping is augmented due to the doubling of CO_2 because the planetary waves dissipate more steeply with height in presence of the enhanced infrared cooling rates.

FIG. 6 suggests that when the model lid is sufficiently high the QBO period in response to the enhanced radiative damping due to the increasing CO_2 will decrease from 32.4 to 30.0 months. This 7.4%

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Deleted: continues decreasing to 34.3 and 33.3 months as the model lid is raised to 37 and 38 km level, respectively; is kept at 33.3 months when the model lid is placed between the 38 and 41 km levels; and it further decreases to 32.4 months when the model lid is placed at or above the 42 km level.

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decrease in the QBO period is independent of the upper boundary condition. Plass (1956) indicated that the probable error of the cooling rate was about 10% below 20 km, increasing to 30% at 50 km and that the relative differences between the cooling rates should be considerably more accurate than their magnitude. In other words, the relative differences between the various cooling rates calculated by Plass (1956) should be considerably smaller 30%. Using the HL model with its top at the 48 km level, we further conducted two experiments by adopting $G = 0$ in Eq. (1) and increasing the radiative damping corresponding to the doubled CO_2 between 30 km and 48 km by $30\% - 30\% * 30\% = 21\%$ and $30\% + 30\% * 30\% = 39\%$ respectively relative to that in the control run. The simulated QBO periods are 30.8 and 29.3 months respectively. Therefore, when the model lid is sufficiently high the QBO period in response to the enhanced radiative damping due to the doubled CO_2 will decrease by approximately $7.4\% \pm 2.5\%$.

Note that N, the Brunt-Väisälä frequency, in Eqs. (2) and (3) also changes with increasing CO_2. Richter et al. (2020b) showed that N^2 would be decreased by $\sim 5\%$ in the stratosphere when CO_2 is doubled (refer to their Figure 2c). We used the HL model to conduct a sensitivity test by adopting $G = 0$ in Eq. (1) with the radiative damping profile corresponding to the doubled CO_2 and the top of the models at the 48 km level. The rest of parameters in this sensitivity test are identical to those in all the previous runs except that the Brunt-Väisälä frequency in this experimental run was 2.5% smaller than that in the control run. The models were run for 1000 years to further increase the spectral resolution. We found that when the Brunt-Väisälä frequency was decreased by 2.5%, the simulated QBO period was slightly lengthened from 30 months to 30.2 months (figure not shown). In other words, the impact of decreasing stratospheric buoyancy frequency on the QBO period is marginal.

Analyzing eleven CCMI-1 REF-C2 climate–chemistry simulations, Eichinger and Šácha (2020) showed that the scale height in the stratosphere decreases by 2.3% per century. Accordingly, we used the HL model to conduct another sensitivity test by adopting $G = 0$ in Eq. (1) with the radiative damping profile corresponding to the doubled CO_2 and the top of the models at the 48 km level. The rest of parameters in this sensitivity test are identical to those in all the previous control runs except that the scale height in this experimental run was 2.3% smaller than that in the control run. The model was also run for 1000 years for the sake of higher spectral resolution. We found that when the scale height was decreased by 2.3%, the simulated QBO period was also shortened by about 2.3%, i.e., from 30 months to 29.3 months (figure not shown). Apparently, the shortening of the QBO period due to the warming climate is ascribed less to the shrinkage of the scale height in the stratosphere than to the enhancing of the stratospheric radiative damping. Together, the shrinking scale height and the increasing radiative damping shorten the QBO period by about 9.6%.

5. Conclusions

Plumb (1977) envisioned that stratospheric climate change would give rise to long-term changes in the QBO period due to changes in radiative damping and the Brunt-Väisälä frequency. Using one-dimensional (1D) models we found that the enhanced radiative damping arising from the doubling of CO2 leads to the shortening of the QBO period by about $7.4\% \pm 2.5\%$ provided that the model top is higher than the 46 km level. Furthermore, when we incorporated both the 2.3% shrinkage of the scale height and the enhanced radiative damping, the QBO period is shortened by about 9.6%. In addition, the impact of decreasing stratospheric buoyancy frequency on the QBO period is marginal. Note that those models include neither gravity waves nor tropical upwelling and assume that there are no changes in wave fluxes entering the equatorial stratosphere.

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From a comprehensive model perspective, Richter et al. (2020b) showed that the changes in period of the QBO in warming climate simulations varied quite significantly among these models. Some models projected longer mean periods and some shorter mean periods for the QBO in a future warmer climate. They argue that uncertainty in the representation of the parameterized gravity waves is the most likely cause of the spread among the QBOi models in the QBO's response to climate change.

In addition, CO2 increases in the NASA Goddard Institute for Space Studies Model E2.2-AP (Rind et al. 2020) lead to a decrease of both QBO period and QBO amplitude (DallaSanta et al., in prep.). The period decrease is associated with increases in lower stratospheric momentum fluxes (related to parameterized convection), a finding consistent with Geller et al. (2016a, 2016b) and Richter et al. (2020b). The amplitude decrease is associated with a strengthened residual mean circulation, also consistent with the literature, although the vertical structure of the circulation response is nontrivial. It is worth mentioning that horizontal momentum flux divergences could also play an important role in weakening the QBO (Match and Fueglistaler, 2019, 2020).

Our 1D models only explored how the QBO period responds to the enhancing radiative damping of planetary waves, the shrinking scale height in the stratosphere, and the decreasing stratospheric buoyancy frequency due to the increasing CO_2 concentration. In order to investigate how those factors affect gravity waves which play an even more important role in determining the QBO period than planetary waves, high-resolution models such as those used by Kawatani et al. (2011, 2019) are desirable to further our understanding. Ultimately, how the QBO period changes in response to the increasing CO_2 will be determined by the combined effects of the strengthening of tropical upwelling, the increasing of wave fluxes entering the equatorial stratosphere, the enhancing of radiative damping, and the shrinking of the scale height in the stratosphere, which warrants further research.

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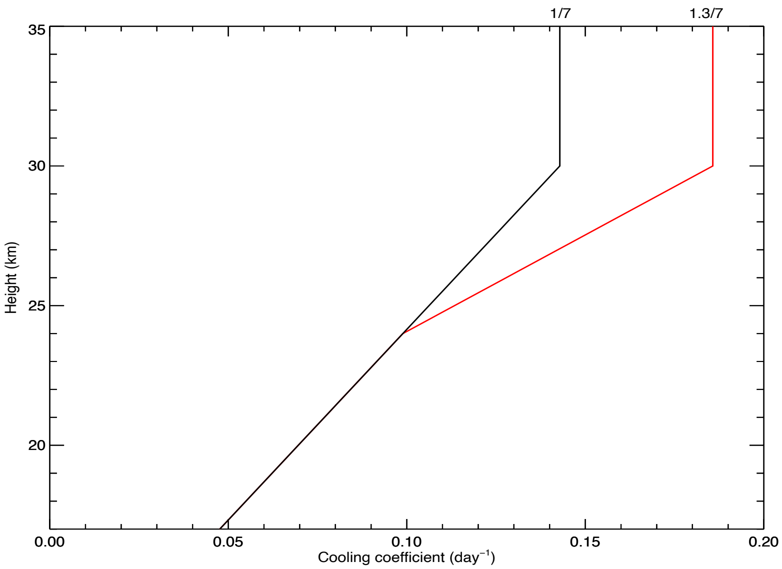

FIG. 1: Newtonian cooling profiles: The smaller values (black line) are used for the control runs while the larger values (red line) are used for the experimental runs.

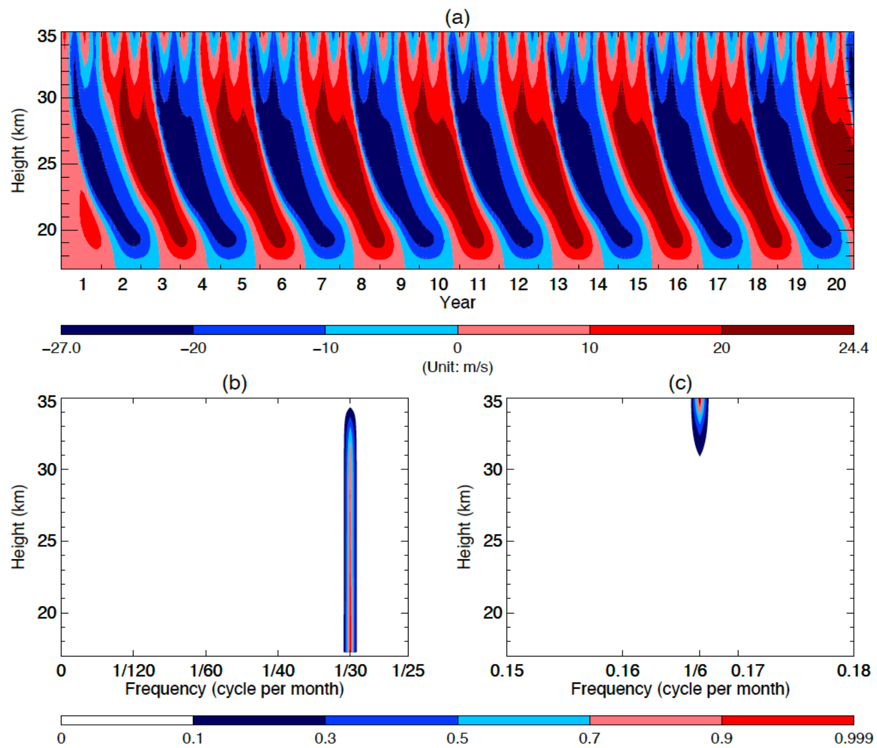

FIG. 2: (a) Time–height section of the monthly averaged mean zonal wind over the first 20 years from the HL's original model. (b) and (c) Frequency–height section of the power spectral densities (PSD) of the standardized monthly averaged mean zonal wind of the 100 years. Note that in order to better visualize the PSD in (b) and (c), we trimmed off the blank segments for the frequencies ranging from $\frac{1}{25}$ to 0.15 cycle per month and those ranging from 0.18 to 0.5 cycle per month.

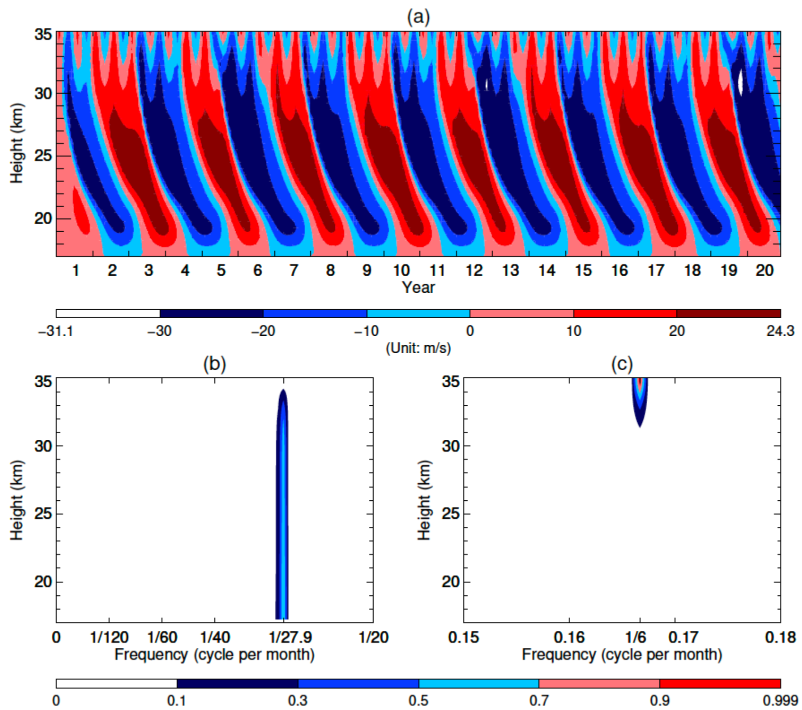

FIG. 3: (a) Same as FIG. 2a, but with the enhanced $\alpha(z)$ depicted as the red line in FIG. 1. (b) and (c) Frequency–height section of the power spectral densities (PSD) of the standardized monthly averaged mean zonal wind of the 100 years. Note that in order to better visualize the PSD in (b) and (c), we trimmed off the blank segments for the frequencies ranging from $\frac{1}{20}$ to 0.15 cycle per month and those ranging from 0.18 to 0.5 cycle per month.

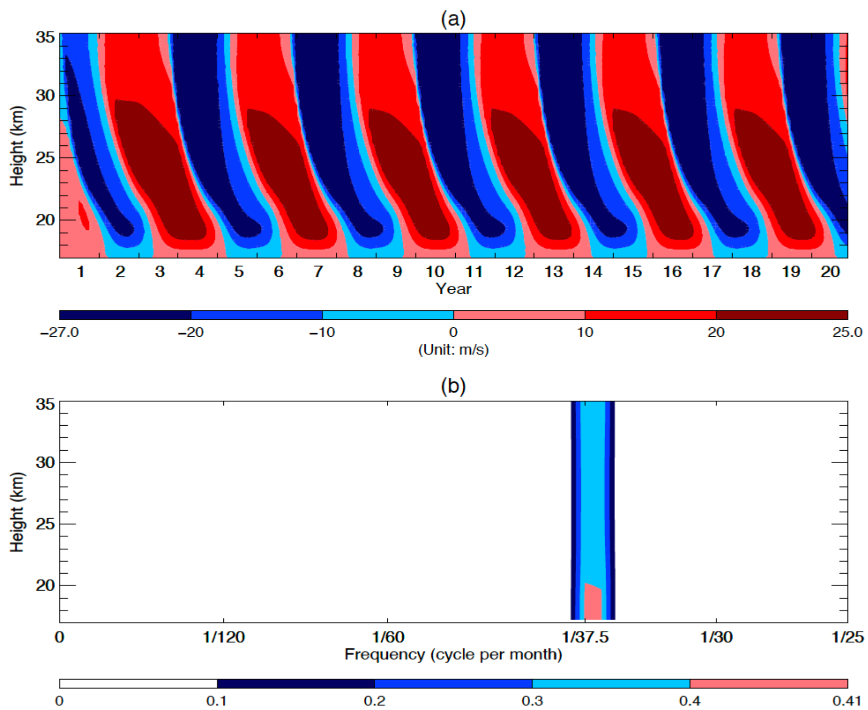

FIG. 4: (a) Time–height section of the monthly averaged mean zonal wind over the first 20 years from the HL's model without the semiannual forcing. (b) Frequency–height section of the power spectral densities (PSD) of the standardized monthly averaged mean zonal wind of the 100 years. Note that in order to visualize the PSD, we trimmed off the blank segment for the frequencies ranging from $\frac{1}{25}$ to 0.5 cycle per month.

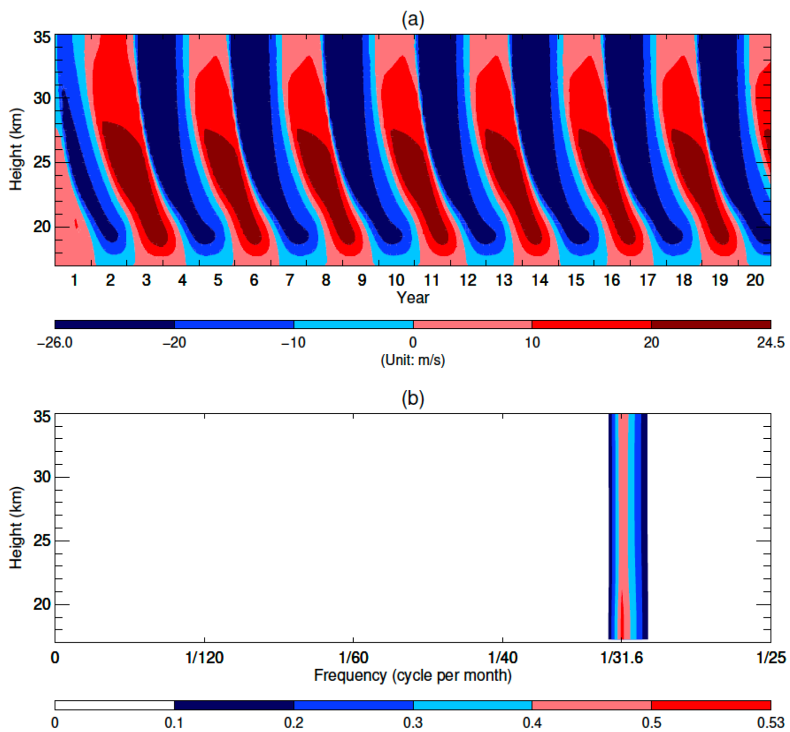

FIG. 5: (a) Same as FIG. 4a, but with the enhanced $\alpha(z)$ depicted as the red line in FIG. 1. (b) Same as FIG. 4b, but for the doubled CO_2 Run.

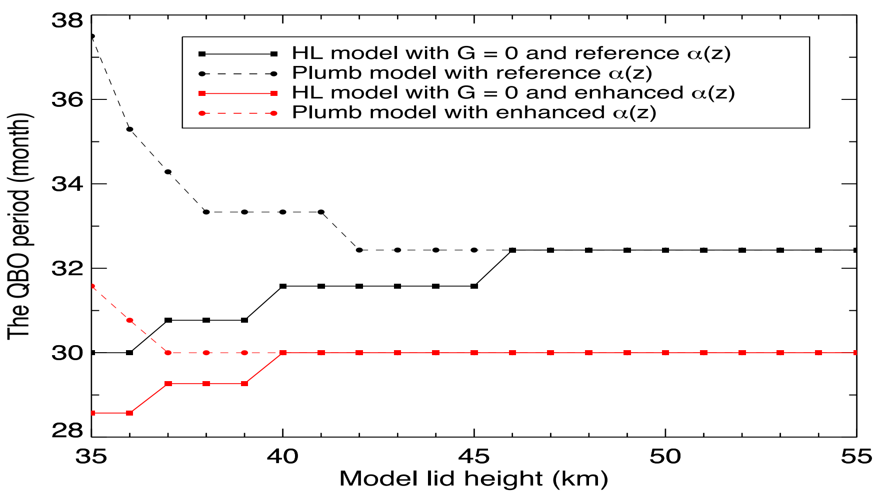

FIG. 6: The relationship between the simulated QBO period with the height of the model lid. Black and red lines depict the results from using the reference radiative damping and the enhanced radiative damping respectively while solid and dashed lines delineate the results from the HL model with $G = 0$ and the Plumb model respectively.