

Interactive comment on “Net influence of an internally-generated QBO on modelled stratospheric climate and chemistry” by M. M. Hurwitz et al.

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Received and published: 12 August 2013

We thank Reviewer #1 for his/her comments. We have revised the manuscript accordingly. Our responses directly follow each comment.

M. M. Hurwitz and co-authors August 2013

> 1) The paper is really only a description of the impacts of an internally generated QBO in a CCM, with no attempt made to get at the root causes of those impacts. The authors state that the QBO "warms the Arctic lower stratosphere", "cools the Antarctic stratosphere" (p.13501), and "slows the overturning circulation" (p.13502), but provide

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no explanation why. Since the stratospheric overturning circulation is wave driven, it would seem only natural to examine the changes in resolved wave drag to try to understand the causes, but this was not done. The authors therefore need to investigate the causal effects of these changes in the residual circulation, using for example downward control calculations to help interpret the differences between the two simulations. They need to look at the seasonality and spatial pattern of the wave drag changes that are responsible for the changes.

> The author's second point in the conclusions that "the net impact of the QBO depends on both the baseline zonal winds fields and the relative changes in the tropical winds" also requires further explanation and diagnostic analysis. Why in the simulation with the QBO do the time mean zonal winds in the tropical lower stratosphere increase? What is the role of the parameterized GWs? For a paper dealing with a QBO generated by increasing the tropical GWD I found it strange that not a single figure showing the parameterized GWD was shown.

Tropical lower stratospheric zonal winds increase in the Q simulation (a mix of westerly and easterly zonal winds) relative to the N simulation (with easterly tropical zonal winds throughout). This relative shift toward westerly tropical zonal winds explains the stratospheric changes we see at low latitudes (i.e., a relative shift toward the in the QBO–westerly secondary circulation) and at polar latitudes in certain months (i.e., when there is a strong Holton–Tan relation).

Tropical zonal winds increase the most in the upper stratosphere. This relative vertical wind shear is consistent with warming of the tropical middle and upper stratosphere, and with relative downward motion (i.e., weakened tropical upwelling or negative w^*) in the tropical stratosphere (e.g., Randel et al., 1999). In the paper, we use mean age-of-air, w^* and v^* to diagnose slowing in the stratospheric overturning circulation due to the inclusion of the modelled QBO.

In the Northern Hemisphere in January and in the Southern Hemisphere winter and

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spring, inclusion of the QBO weakens planetary wave driving. By the Holton–Tan mechanism, this weakened planetary wave driving is caused by shifts in the critical zero-wind line, caused by the relative shift toward westerly tropical zonal winds in the Q simulation. In the revised manuscript, we have added figures showing the latitudinal distribution of GWD in the two simulations (Figure 1), correlations between the equatorial and extra-tropical zonal winds (Figure 9) and differences in eddy heat flux at 100 hPa (Figure 11) to support the simulated changes in high-latitude zonal wind, temperature and ozone that are shown in Figures 10 and 12.

Randel, W. J., Wu, F., Swinbank, R., Nash, J., and O'Neill, A.: Global QBO Circulation Derived from UKMO Stratospheric Analyses, *J. Atm. Sci.*, 56, 457–474, 1999.

> 2) It also seems strange that there is no discussion of the non-orographic GWD parameterization, given its central role in this study. It needs to be described in Section 2, along with the appropriate references.

The non-orographic gravity wave drag parameterization is described by Hurwitz et al. (2011b) (the first GEOSCCM formulation with a QBO signal) and Molod et al. (2011) (differences between versions of the GEOS–5 atmospheric general circulation model with and without a QBO). We refer to these papers in Section 2. In the revised manuscript, we added Figure 1, showing the latitudinal distributions of non-orographic gravity wave drag imposed in the Q and N simulations.

> 3) It is unclear to me what the authors mean by "net impact" of the QBO. At first I thought it was the time mean impact, but then realized that it is more general since they also discuss changes in variability. It needs to be made clear in the introduction what is meant by "net impact".

By "net influence" or "net impact", we mean changes in stratospheric temperature, circulation and chemistry that can be directly attributed to inclusion of the QBO in our model. We examine the net influence of the QBO on both the mean climatology and in terms of stratospheric variability. Using the GEOSCCM, we test the net influence of the

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QBO by comparing simulations where the only difference is the latitudinal distribution of non-orographic GWD in the deep tropics, leading to the presence or absence of the QBO signal (i.e., Q vs. N simulations).

We would expect the QBO to enhance variability in the deep tropics, but without this model study, the net impact of the QBO on stratospheric variability outside of the tropics is not obvious. Also, we might expect the QBO to have no net influence on the mean climate, as the impacts of the easterly and westerly phases of the QBO on e.g., subtropical secondary circulation might cancel out. This modelling study shows that the QBO in the GEOSCCM does have a net influence on both the mean climate and on extra-tropical variability.

> 4) The figures are still way too small, and as a result are very difficult to read. The authors need to provide larger figures (e.g., with fewer panels or without long labels like in Fig. 2 that take up a lot of space) in their revised version.

> P.13501-3: It is impossible to read the labels on the color bars in Figs 2-4, so I cannot tell if a difference is positive or negative. See my major point about the figures.

We will ensure that the figures are large enough to be seen clearly prior to publication.

> abstract, l.6: "quasi-realistic tropical GWD" – The word quasi-realistic must be deleted since there are no observations of GWD to confirm this statement.

> P.13499, l.8: "quasi-realistic peak in tropical GWD" – since there are no observations of GWD, and only limited observations of GWs in the tropics, there is no justification for saying that the peak in GWD in the tropics is realistic or even quasi-realistic. Modellers often increase the parameterized non-oro GW momentum flux source because they believe there are more GWS there.

We have revised this sentence as follows: "The GEOSCCM generates a quasi-biennial oscillation (QBO) zonal wind signal in response to a tropical peak in GWD that resembles the zonal and climatological mean precipitation field."

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> abstract, l.7-8: "the modeled QBO improves the simulation of tropical zonal winds" seems a bit nonsensical since it is obvious that the tropical zonal winds in a model with a QBO will agree better with observations. It may be better to reword this sentence something like "The annual mean zonal winds in the tropics in the simulation with a QBO agree better with obs" if that is what is intended.

We have revised this sentence as follows: "As expected, the modelled QBO improves the simulation of tropical zonal winds and enhances tropical and sub-tropical stratospheric variability." "Improved simulation" implies better agreement between the simulation and observations.

> abstract, l.15-17: "Extra-tropical differences ... reflect a bias toward the westerly phase of the QBO" is unclear. A bias in what? And how do the differences in the two simulations reflect a bias?

We agree that the original wording may have confused readers. We have revised this sentence as follows: "Extra-tropical differences between the simulations with and without a QBO thus reflect the westerly shift in tropical zonal winds: a relative strengthening of the polar stratospheric jet, polar stratospheric cooling and a weak reduction in Arctic lower stratospheric ozone."

> P.13496, l.24: Reed et al 1961 did not discuss the driving mechanisms of the QBO, as implied by this reference. I therefore suggest adding references to Lindzen and Holton and Holton and Lindzen.

We have removed the reference to Reed et al. (1961), and instead refer to Lindzen and Holton (1968) and Holton and Lindzen (1972).

> P.13497, l.28-29: "QBO amplitude were negligible, typical of CCMs that lack a nudged or internal QBO signal". This is so obvious it doesn't need stating.

We have shortened this section as follows: "In the formulation of the GEOSCCM evaluated by SPARC CCMVal (2010), both tropical lower stratospheric variability and the

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QBO amplitude were negligible. In contrast, a more recent model formulation (introduced by Hurwitz et al., 2011b) can internally-generate a QBO with a realistic periodicity and amplitude, depending on the latitudinal structure of the non-orographic gravity wave drag (GWD)."

> P.13498, l.21-22: "As non-oro GWs often accompany precipitation" is a misleading statement. What about non-oro GWS in the mesosphere? It would be clearer I think to say "The generation of non-oro GWS often accompany precip"

We agree. We have revised this sentence accordingly.

> P.13499, l.7 & 9: "Q" and "N" – I don't much like these single-letter identifiers of the two simulations - they make for strange sounding sentences in my opinion, e.g., "zonal winds is well simulated in Q." How about "Run Q" and "Run N" or append "simulation" before the letters?

In the revised manuscript, we refer to the GEOSCCM simulations as e.g., "the Q simulation" where possible.

> P.13501, l.8: I presume the "observations" shown here are from the MERRA reanalysis. It would therefore be better to say "agreement with the MERRA reanalysis".

We agree. We have revised this sentence accordingly.

> P.13501, l.18-19: The sentence "the QBO warms the tropical stratosphere and Arctic lower stratosphere by ~ 1 K but cools the Antarctic stratosphere by ~ 1 K" either needs to be reworded or an explanation given as to how the high latitude temperature changes are caused by the QBO. See my first major point.

We have revised this section to reflect the fact that annual mean temperature changes in the polar lower stratosphere are not statistically significant: "Inclusion of the QBO warms the tropical stratosphere and Arctic, but cools the high-latitude upper stratosphere by ~ 1 K (Figure 3f). These temperature changes reflect a slowing of the stratospheric overturning circulation, as discussed below." We discuss the larger, statistically

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significant impacts of the QBO on polar stratospheric temperature, as well as the relationship of these impacts to changes in planetary wave activity, in Section 3.3.

> P.13504, l.17: add "winter" before "polar stratosphere" since the Holton Tan relation is to do with the NH winter polar stratosphere. As written, a positive correlation between zonal winds in the tropics and polar regions could be in summer.

In the revised manuscript, we have added Figure 9 to clarify the months in which the Holton–Tan relation is active in the Q simulation.

Interactive comment on Atmos. Chem. Phys. Discuss., 13, 13495, 2013.