Anonymous Referee #1

General Comments

This paper explores the causes behind a recent decadal warming of the tropical tropopause layer (TTL) using a series of well-designed climate model experiments with NCAR's WACCM model. The authors conclude that natural (QBO, SST) variability, rather than anthropogenic factors, are responsible for the recent warming of the TTL. They also illustrate the importance of the model's vertical resolution in simulating temperature trends in the TTL.

The manuscript is generally well written and appropriate for publication in ACP. However, after reading through the manuscript, I have some unanswered questions about the authors' methodology and their interpretation of the results, which I think should be addressed prior to publication.

Specific Comments

1. The warming trend mentioned in this paper from 2001-2011 has not continued to the present (see, e.g., recent article in EOS: DOI: 10.1002/2014EO270001). If you were to redo this analysis with slightly different end years (e.g., 2002 to 2012, 2003 to 2013), you might reach very different conclusions, so I'm not entirely comfortable with the short 11-year trend period used in this paper. The authors need to discuss the sensitivity of their results to the short period chosen for the trend analysis, and make readers aware that the warming trend has not continued (at least monotonically) from 2011 to 2014.

Response:

We thank the reviewer for this comment and confirm that the trends are sensitive to the start and end years in particular for short time series as the one from GPS-RO data investigated here. In order to address this issue, we repeated our analysis with data extending to December 2012, December 2013 and until the latest GPS-RO data available to us, i.e. March 2014 (Fig. S1). In Fig. S2, we also include now the latitude-height structure of the trends for the different time periods. By including more years beyond 2011, the trends are generally weaker (~1.0 K) compared with the trends from 2001-2011 (~1.6 K). The variability of the trend is consistent with our conclusion that the recent decadal TTL variation in temperature is mainly due to natural variability and that this positive trend might not continue so strong in the future.

Changes in manuscript:

We have added two supplementary figures to the paper as well as a paragraph to comment on this in the text.

2. When assessing the statistical significance of trends in time series, autocorrelation can sometimes inflate the significance of a trend. This is easily corrected by changing the n in equation 3 to an effective sample size (see Santer et al. 2000, as well as the Wigley 2006 paper that the authors cite). It's not clear from the text if the authors did this, but if not, they should double check to make sure that their trends are still significant after accounting for autocorrelation.

Thank you very much for this note.

We have reassessed the statistical significances of the trends and now also consider the autocorrelation effects. We added more details of our method in the text and commented the results accordingly.

3. Figures 9b-d and 10c-d are extremely difficult to read. As a reviewer, I cannot properly assess many of the statements of the authors in Sections 4.1 and 4.2 because I cannot see what they are referring to in the figures. Either the signatures the authors are discussing are not robust, or the figures need to be improved. I'm not sure what to suggest here, but I would encourage the authors to closely read their text and make sure their conclusions are readily visible in the figures.

We apologize for that this figure was difficult to read and the conclusions were difficult to follow.

We have combined Figures 9 and 10 and restructured the figure in order to be hopefully better readable now. We've also adapted the corresponding text.

4. Page 22120, Line 25: Reflecting and scattering incident solar radiation back to space does not lead to a warming of the lower stratosphere. Please rephrase.

We have rephrased this sentence to:

"Stratospheric aerosols reflect solar visible radiation, causing a net cooling at the surface, and absorb solar near-infrared and terrestrial infrared radiation, causing a warming of the lower stratosphere, which maximizes at around 20 km."

5. Figure 1c: Please explain how the QBO values are determined in the model for future years.

The QBO forcing time series in CESM-WACCM is determined from a filtered spectral decomposition of the observed climatology from 1953-2004. The resulting set of Fourier coefficients can then be expanded for any day and year into the future. We added an explanation on this to the manuscript (CESM model description).

We have added this explanation in the text.

6. Page 22126, Lines 7-9: Why are the observed SSTs and simulated SSTs (from a fully coupled model) decreasing over exactly the same period? Shouldn't the model's SST variability be internally generated and thus independent from that in the real world?

You are right, the simulated SSTs in the Natural run are internally generated from a fully coupled model. The similar decrease in both model and observations might be entirely due to internal variability of the climate system, or by chance since we have only one ensemble of simulation.

7. Sections 3.2 – Section 3.6: The uncertainty in each figure is listed in each paragraph as 0.2 K/decade. Yet, in some paragraphs, the uncertainty is stated as "small", and in other paragraphs, it's stated as "large." This is confusing. Please clarify and rephrase.

We apologize for not havening explained this clearly. "Small" or "large" means that the uncertainty is relatively small or large compared to the trend itself.

We have changed it accordingly in the text.

Technical Corrections

Page 22119, Line 4: Delete "masses"

Deleted.

Page 22119, Line 19: Delete "for"

Deleted.

Page 22120, Line 27 (and references hereafter): I think you mean Solomon et al. (2011) (which discusses aerosols), rather than Solomon et al. (2010) (which discusses stratospheric water vapor).

Thanks for the corrections.

We have checked that carefully and corrected the errors.

Page 22122, Line 10: 2100 contradicts 2099 used in Table 1.

Thanks for the corrections.

We have checked the whole paper carefully and corrected the mistakes.

Page 22124, Equation 3: Please rewrite. It has two division signs.

We have rewritten this equation.

Page 22126, Line 11: Has should be have.

Corrected.

Page 22127, Line 25: Should be “Sect. 2.3”

Corrected.

Page 22128, Line 24: Text says “insignificant”, but figure shows shading.

Corrected.

Page 22131, Line 10: Change “errors” to “arrows”

Corrected.

Page 22131, Line 19: Change “divergence” to “convergence”

Corrected.

Page 22131, Line 27: 12-16 km is in the mid-latitude lower stratosphere.

Corrected.

Section 4.1: The term upwelling (instead of upward vertical wave propagation) is mistakenly used in this section several times. Please correct.

Thanks for this comment.

We have reconstructed the figure and also corrected the description in the revised manuscript.

Page 22133, Line 9 (and elsewhere): Transit branch? Do you mean shallow, or perhaps, transition branch?

Thanks for this comment.

We have checked that carefully, and used “lower branch” here, since the region (below 100 hPa) is actually lower than the transition branch (100-70 hPa, defined by Lin and Fu, 2013).

Thank you very much for these technical comments. We have addressed all of them and highlighted the respective changes in the text.

References

Lin, P. and Fu, Q.: Changes in various branches of the Brewer–Dobson circulation from an ensemble of chemistry climate models, J. Geophys. Res., 118, 73–84, doi:10.1029/2012JD018813, 2013.