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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Tropospheric temperature response to stratospheric ozone recovery in the 21st century" *by* Y. Hu et al.

Y. Hu et al.

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Reply to reviewer #1's reviews on "Tropospheric temperature response to stratospheric ozone recovery in the 21st century" by Y. Hu et al.

General comments: The subject of this paper is quite interesting; the possible impact of ozone recovery in the stratosphere to the temperature trend in the troposphere. It is argued that stratospheric ozone recovery likely strengthens tropospheric warming which is primarily driven by GHG increase. While it is plausible as discussed by Grise et al. (2009JCLI; see also references therein), the current study presents somewhat unexpected result that ozone-induced warming in the troposphere is not limited to the

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SH high-latitudes, where ozone recovery is maximum, but also would occur in the tropics and the NH extratropics. It is further shown that NH warming is likely stronger than SH warming (e.g. Fig. 3). This result is hard to believe. If this is true, it will change our understanding on the global warming. Here are some of my major concerns.

We thank the reviewer for the important comments, which are very helpful to improve our manuscript. The two references pointed out the reviewer will be cited for comparison and discussion. For the Southern Hemisphere, our results are consistent with previous works, especially consistent with these works for AR4 and CCMVal-1 model comparisons (e.g. Son et al.). These suggest that trends and trend differences in the Northern Hemisphere can hardly be attributed to model bias. A key point of this paper is to show these model intercomparison results as they are. The results here certainly need further studies to confirm. We will explicitly point out this in the discussion section in our revised version.

Grise et al. (2009) showed weaker cooling trends in the Arctic than in the Antarctic over 1979-1999. The difference between the two polar regions is expected since ozone depletion in the Arctic stratosphere is weaker than in the Antarctic stratosphere. Such a difference in cooling trends was actually well captured by AR4 models. Figure 1 attached below shows global and annual zonal-mean temperature trend differences between AR4 models with and without ozone depletion over 1965-1999. Regions marked with dots indicate the places where temperature trend differences have statistical significance levels higher than the 95% confidence level (t-test values are greater than 2.0). For the Antarctic polar region, temperature trend differences in the upper troposphere are statistically significant, indicating the cooling effect of ozone depletion. In contrast, trend differences in the Arctic troposphere are relatively weak and insignificant. These are qualitatively consistent with that in Grise et al. (2009) and the results in Polvani et al. (2010). In this sense, temperature trends in AR4 models for ozone recovery in the 21st century may also reliable.

For ozone recovery, our results still show stronger warming in the Antarctic lower strato-

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sphere than in the Arctic, which is also reasonably expected. The question is why the tropical and northern extratropical troposphere temperatures have stronger responses to ozone recovery. At this stage, it is difficult to give a firm answer. A plausible explanation is that some feedback mechanisms are involved as both increasing greenhouse gases and ozone recovery all warm the troposphere. For the tropical troposphere, it is well known that water-vapor feedback is an important mechanism to enhance upper tropospheric warming. For the Arctic surface, ice-albedo feedback could be responsible for the relatively strong enhanced surface warming. It is not known to us what mechanism is involved into the enhanced warming in the northern extratropical upper troposphere. We will point out this issue in the revised version.

Figure 1. Global and annual zonal-mean temperature trend differences between AR4 model with and without ozone depletion over 1965-1999.

1) Is the trend difference significant? Most figures show temperature difference between models with and without ozone-recovery forcing. However, none of them show whether the difference is statistically significant. Based on error bars in Figs. 1-3, I suspect the difference is not significant at all. In other words, the difference between the AR4 models with prescribing ozone recovery and those without it might result from model bias instead of any physical process. In fact, Fig. 2 of Polvani et al. (2010JCLI, in press) shows that AGCM integration with prescribing ozone depletion does not make any significant difference in the temperature especially in the tropics and northern extratropics. I strongly encourage authors to perform significant test at the first place. Without it, any relationship of causality cannot be established.

We agree that statistical significance tests have to be presented. Therefore, we have re-plotted all figures, in which temperature trends with t-test values greater than 2.0 (significance levels higher than the 95% confidence level) are marked with dots. As shown below, temperature trends and trend differences in most tropospheric/stratospheric regions are statistically significant, especially in the northern troposphere that is of the main interest. For example, re-plotted Figures 4, 5, 9, and

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10 in the manuscript are shown below as Figures 2-5. Re-plotted Figures 6-7 in the manuscript are not shown here, which also show dominant significant trends. We also tested statistical significance for trend differences Figures 1-3 in the manuscript. It is found that trend differences at all levels have t-test values greater than 2.0.

Figure 2 (corresponding to Figure 4 in the manuscript). Global and annual zonal-mean temperature trends. (a) AR4 models without ozone recovery, (b) AR4-models with ozone recovery, and (c) CCMVal-1 models.

Figure 3 (corresponding to Figure 5 in the manuscript). Global and annual zonal-mean temperature trend differences between AR4 models with and without ozone recovery (a) and between CCMVal-1 and AR4 models without ozone recovery (b).

Figure 4 (corresponding to Figure 9). SAT trends for AR4 model. (a) Without ozone recovery, and (b) with ozone recovery.

Figure 5 (corresponding to Figure 10). SAT trend differences between AR4 models with and without ozone recovery.

2) Model sensitivity test might be helpful. Extending the above comment, the comparison among different model sets is not quite clean. This is particularly true if the signal is relatively weak. To get a better insight, author may want to perform sensitivity test using a single CCM. In the experiment, one can prescribe time-varying or fixed ODS. By comparing these two experiments, one can have a clearer picture. It will also help for authors to identify the relevant mechanism(es).

Thanks for the good suggestion. We are going to carry out simulations using WACCM. One problem is that such simulations takes very long time because coupled ocean-atmosphere GCM simulations are required, while AGCM simulations with prescribed SST would largely damp out ozone forcing. We will present the simulations results in future work.

3) More analyses are needed. Although authors attributed tropospheric temperature

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change to the radiation (e.g., O3, CO2 and H2O) and dynamics (e.g., Brewer-Dobson circulation), no evidence is presented. Using CCMVal-1 models, one can at least plot time series of chemical species as a function of pressure and latitudes. It can be used to support authors' argument. As a possible dynamical forcing, Brewer-Dobson circulation is also discussed in the paper. It however cannot change temperature in the low troposphere which is commonly shown in the paper. Are there any other dynamical processes which modify tropospheric temperature over the whole globe?

We do not know how to plot time series of a chemical as a function of pressure and latitude. Instead, we make a scatter-plot of 70 hPa global and annual mean ozone trends versus 300 hPa temperature trends from 7 CCMVal-1 models (one CCMVal-1 model does not have ozone data). It shows a significant correlation of about 0.63 (see attached Figure 6).

For dynamical processes, we will cite the paper by Butchart et al. (2006) which showed strengthened Brewer-Dobson circulation in CCMVal-1 models. Temperature trends in the troposphere are determined by radiation, convection, advection, and feedback processes. It is difficult to diagnose the budgets of these contibutions from AR4 output.

Figure 6. Scatter plot of 70 hPa global and annual mean ozone versus 300 hPa global and annual mean temperature, derived from CCMVal-1 models.

Specific comments: 1. P22020 L2-8: Abstract is unnecessarily long. I suggest authors to cut first 3 sentences.

Yes, we will make the abstract shorter.

2. P22020 L3: Cite the CCMVal-2 report.

We prefer not to cite references in the abstract. In addition, the first few sentences will be cut.

3. P22022 L6: This is true only in the SH.

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In fact, both Hartmann et al. (2000) and Hu and Tung (2002) showed decreased wave activity and accelerated westerly winds in NH. They all attributed it to ozone depletion in the stratospheric Arctic.

4. P22023 L14: It is worth to note that details of prescribed ozone are not documented.

Yes, the sentence will be added.

5. P22024 L25: is around 300 hPa -> is found around at 300 hPa

It will be changed.

6. P22025 L20: Is it a global mean temperature trend?

It is global mean. We will make it clear.

7. P22025 L23: It depends on the time period of analysis.

Agree. We will point out this.

8. P22026 L9- : It should be noted that Figs. 4 and 5 are already shown by Son et al. (2009, see their Fig. 8).

Figures 4 and 5 are not exactly same as in Son et al. (2009). First, Son et al. (2009) calculated trends over 2000-2099, while ours are over 2000-2050. Second, Son et al. (2009) did not show trend difference between CCMVal-1 models and AR4 models without ozone recovery. Third, Son et al. did not show averaged trends over all CCMVal-1 models. However, we will mention the figures by Son et al. (2009), although they have very different interests.

9. P22028 L17: This difference should not be attributed to the interactive ozone chemistry as indicated by Son et al. (2010JGR).

The situation in the Northern Hemisphere may be different from that in the Southern Hemisphere because CCMVal-1 models do show different spatial patterns of trend differences from that in AR4 model. It is probably better for us to say both interactive ozone chemistry and better resolved stratosphere in CCMVal-1 models lead to different tropospheric temperature responses to stratospheric ozone recovery. It is difficult to exclude contributions from interactive stratospheric chemistry.

10. P22028 L21: The temperature response in the NH is most interesting part. But, it is not analyzed at all: : :

As pointed out above, it is difficult to diagnose feedbacks and dynamical processes from AR4 model output. However, we will add more discussion here.

11. Figures: Many figures can be combined. It would help readers. I suggest authors to combine Figs. 2 and 3, Figs. 4 and 5, Figs. 6-7, and Figs. 9-10.

We agree that it is good to combine these figures. However, they have different ranges of values. In addition, it will leave blank spaces.

Interactive comment on Atmos. Chem. Phys. Discuss., 10, 22019, 2010.

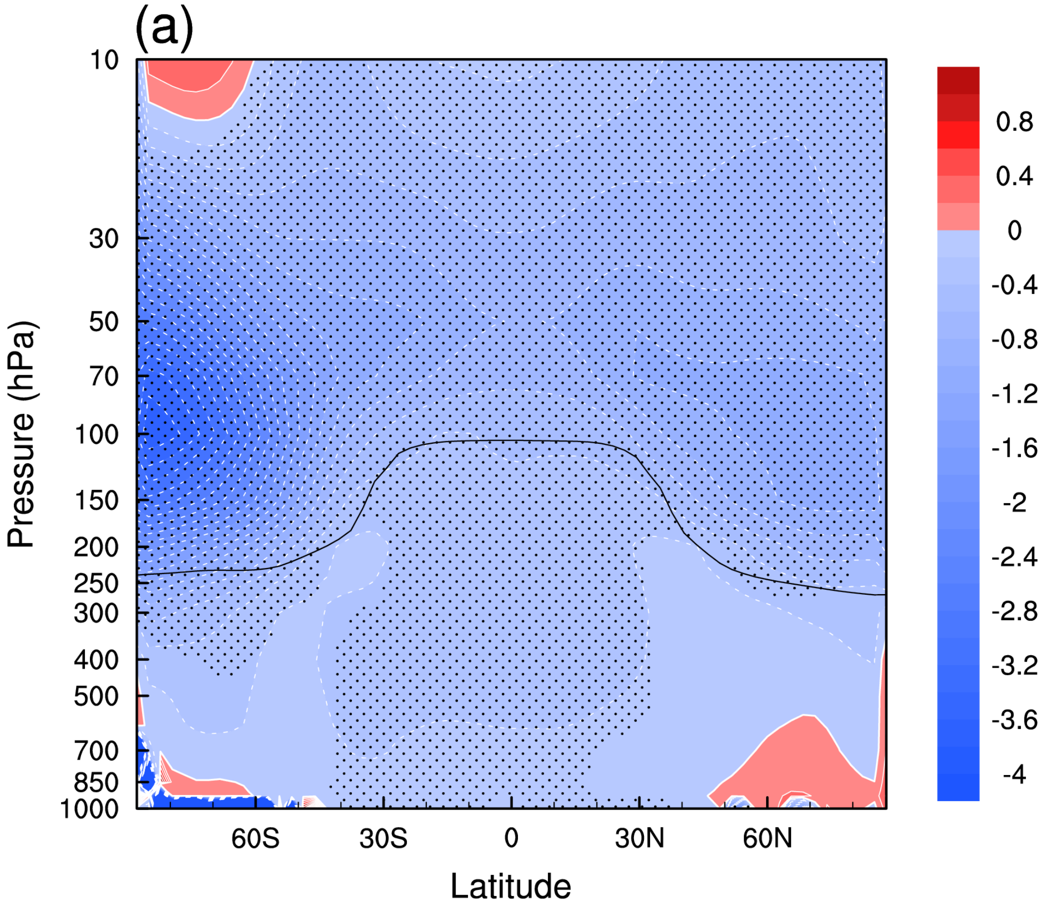

Fig. 1.

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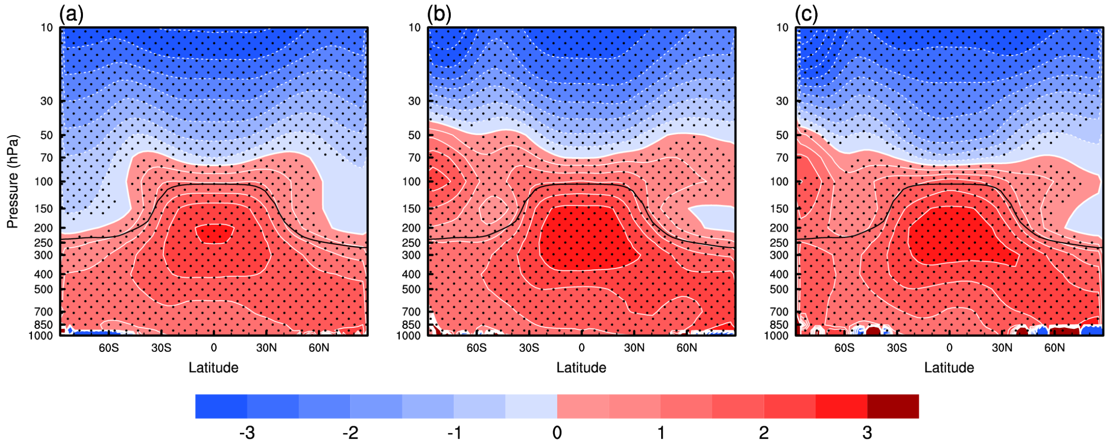

Fig. 2.

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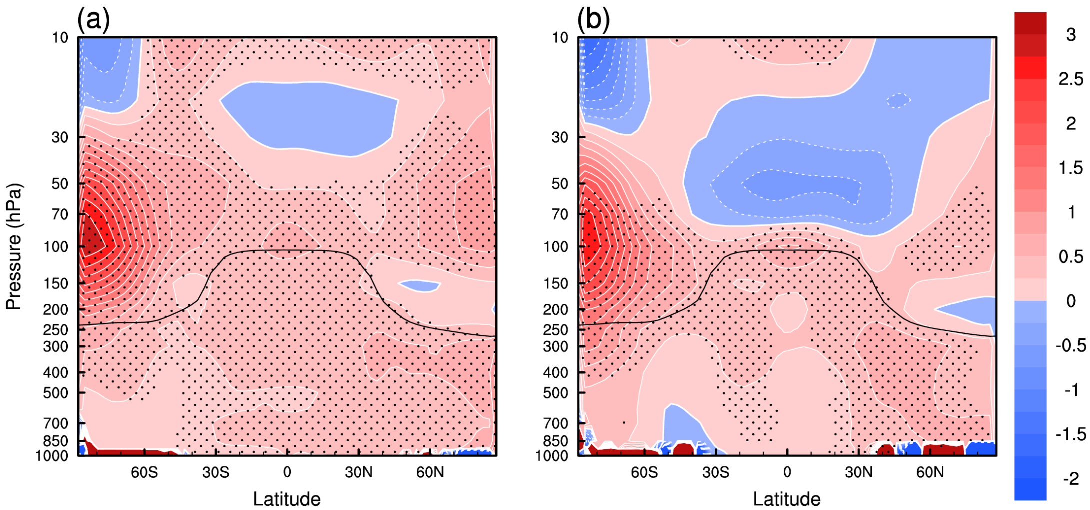

Fig. 3.

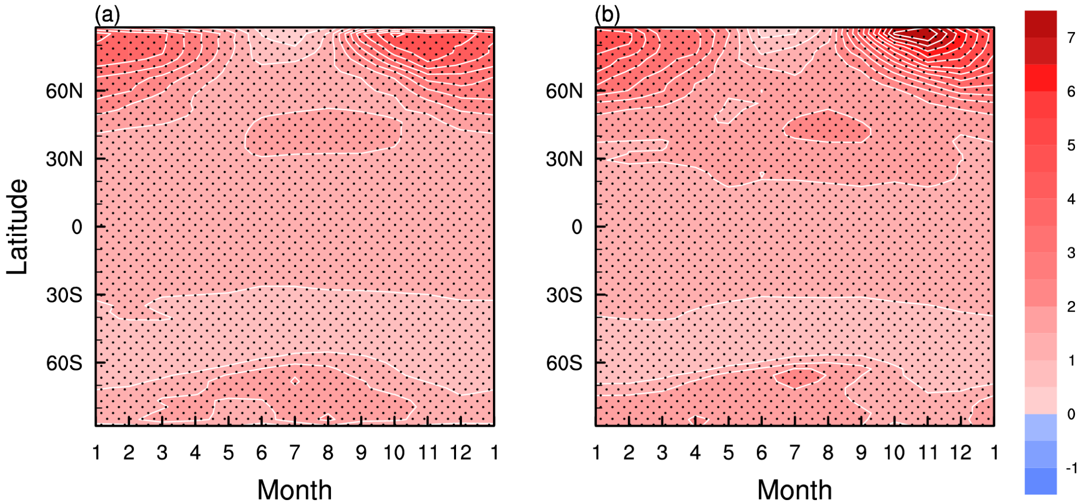

Fig. 4.

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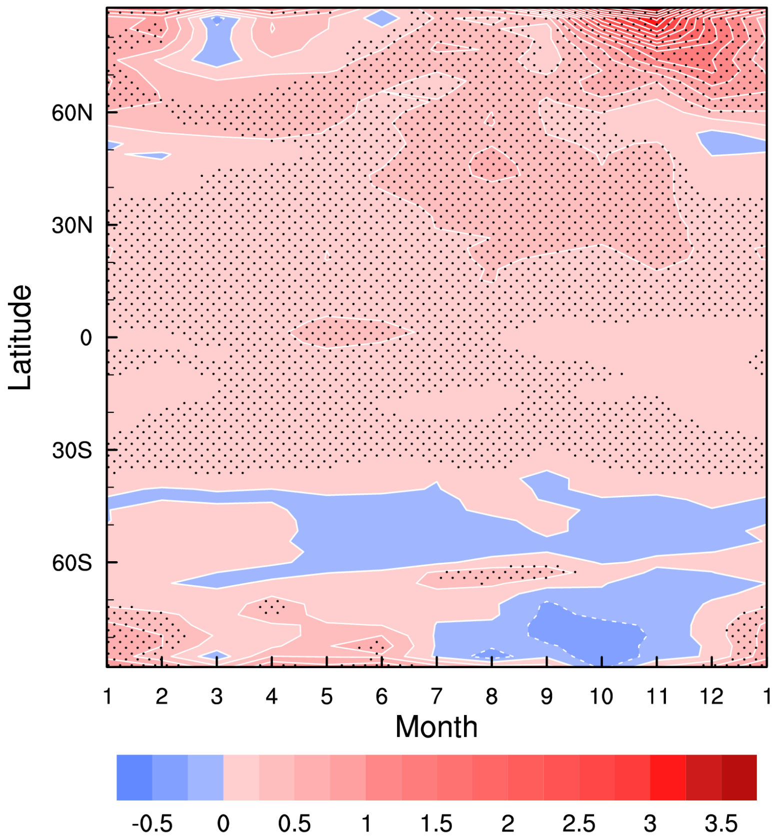
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Fig. 5.

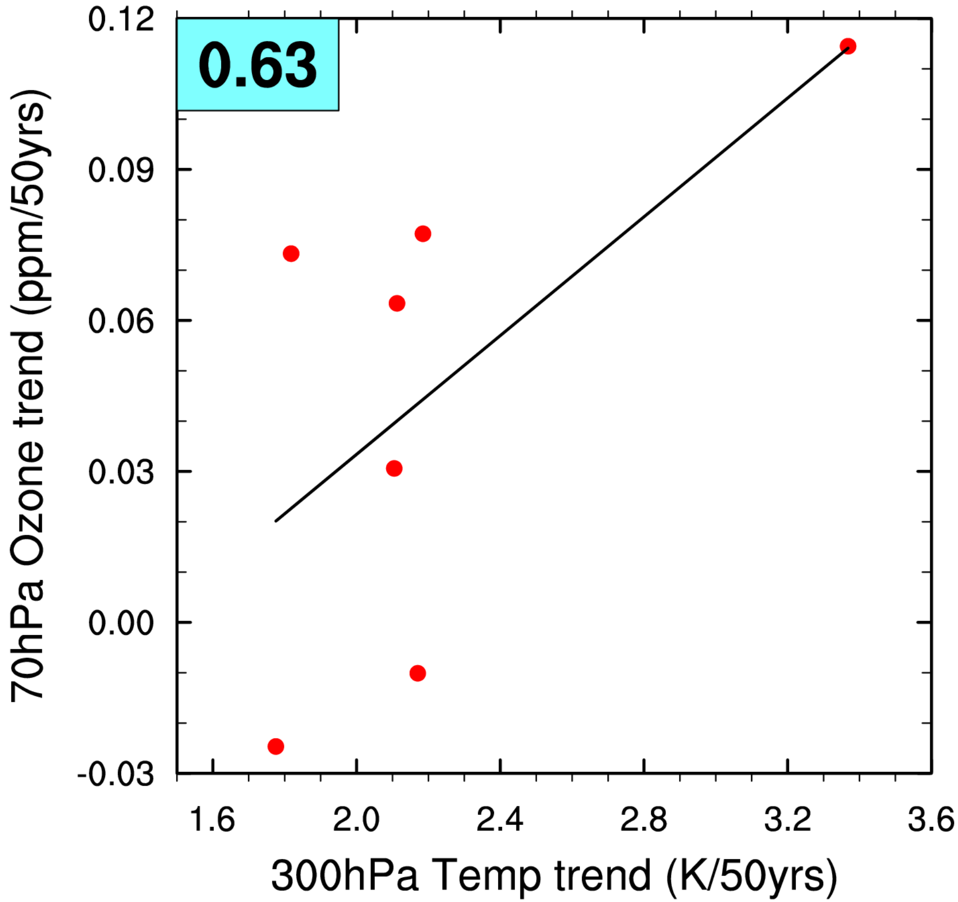

Fig. 6.

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