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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.

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This paper presents an interesting study of simulated trends of tropospheric temperatures by different GCM experiments, categorized by the way how ozone recovery has been treated in such numerical experiments. It was argued that the fingerprints of ozone recovery on tropospheric temperature profile as well as surface temperature can be detected in both hemispheres. The dependences on seasonality, on latitude, and on altitude were also discussed.

The topic investigated in this paper is a scientifically important one with practical societal application. The authors did a good job documenting their data analysis ap-

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proaches and the results. There is no assessment of the statistical significances of virtually all trends discussed in the paper. It is also lack of in-depth discussion or physics-based articulation. It is not clear to me whether the authors tried to interpret the trend analysis as a simple radiative-convective response of troposphere to the stratospheric ozone recovery, or as more sophisticate chain events of troposphere-stratosphere dynamical interactions in response to the stratospheric ozone changes, or both. Moreover, the CCMVal-1 simulations used surface temperature obtained from the AR4-NO-O3 experiments. Given the tight coupling of tropospheric temperature profiles to the surface, this leads to a question how much the trends in CCMVal-1 results are actually from such prescribing of surface temperature instead of responses to ozone recovery. This question is not addressed in current manuscript.

We thank the viewer for in-depth reviews, which are important to improve our paper. We completely agree with the reviewer's comments/suggestions and will make changes in our revised version. Replies to specific comments are as follows.

I feel that substantial and extensive revisions are needed in order to make this study publishable. Below please find my major concerns.

1. Assessment of statistical significance of trends. As pointed out by other two reviewers, essentially no statistical significance has been discussed for all figures presented in this manuscript. Two questions to be addressed are (1) whether each trend derived here is statistically significant, i.e., significantly different from zero; (2) whether each trend from ozone-recovery simulation (AR4-O3 and CCMVal-1) is statistically different from its counterpart from the AR4-NO-O3 simulation. Both can be investigated by the Student's t-test with properly taking the auto-correlation timescale into account (refer to Leith, J Applied Meteo, 1973 and Bretherton et al. J Clim, 1999 for details of such estimations). Once the statistical significances are determined, the interpretation and articulation should be modified accordingly.

We agree with all three reviewers that statistical significance tests need to be presented

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to show the separation of trends between models with and without ozone recovery. All figures have been re-plotted, with showing student t-tests. The three attached figures below are examples for demonstrating temperature trend differences and their statistical significance (temperature trends and trend differences in other figures are also significant, not shown here). Regions with dots are the places where trend differences have statistical significant levels higher than the 95% confidence level (t-test values are greater than 2.0). As one can see, significant trend differences are dominant in these plots.

Figure 1 (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 2 (corresponding to Figure 7 in the manuscript). 300 hPa temperature trend differences between AR4 models with and without ozone recovery (a) and between CCMVal-1 models and AR4 models without ozone recovery (b).

Figure 3 (corresponding to Figure 10). SAT trend differences between AR4 models with and without ozone recovery.

2. Spread among ensemble members. All analyses here are done to the ensemble average of a certain number of GCMs. The behavior of individual GCM is not discussed. It is important to examine the spread among different GCMs, especially whether different GCM members show trend differences with opposite signs. For example, when an ensemble trend of AR4-O3 (or CCMVal-1) is slightly larger than the counterpart of AR4-NO-O3, do differences in all individual GCMs exhibit same sign? Or some GCMs have negative differences and some have positive differences in the AR4-O3 vs. AR4-NOO3 trends, which leads to an averaged slightly positive difference? The implications and conclusions of such two scenarios, even both giving similar ensemble difference, are quite different. Therefore, it is needed to investigate the individual behavior and state the spread among GCM members.

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Following the suggestion, we have plotted global and annual mean trends at all levels for individual models in the attached Figure 4 below. It demonstrates that all AR4 models without ozone recovery all produce consistently weaker warming trends in the troposphere (dot), while all AR4 models with ozone recovery (cross) and CCMVal-1 models (right-cross) all generate consistently stronger warming trends.

Figure 4. Global and annual mean temperature trends for AR4 and CCMVal-1 models. Dots: AR4 models without ozone recovery, crosses: AR4 models with ozone recovery, and right-crosses: CCMVal-1 models.

3. Possible redundancy between CCMVal-1 and AR4-O3. The fact has been well established that, for climate zones such as tropics, its mean temperature profile in the troposphere largely follow the moist adiabatic profile, which is a consequence of radiative-convective equilibrium. As a result, the mean tropospheric temperature profile can be well constrained by the surface temperature and the lapse rate. The change of lapse rate in troposphere is primarily determined by lapse-rate and water vapor feedbacks (most time it is collectively noted as clear-sky water vapor feedback due to the tight coupling of lapse-rate and water vapor feedbacks).

As the authors stated, CCMVal-1 used the surface temperature produced by AR-4 O3 experiments as the lower boundary condition. The change of tropospheric lapse rates in both CCMval-1 and AR-4 O3 are primarily responsive to the surface temperature and tropospheric water vapor feedbacks in such GCMs. Therefore, this leads to a question to what extent the temperature trends of CCMVal-1 and AR-4 O3 are redundant, especially for zone-averaged profiles? Figures 2-3 indeed show nearly identical trends in CCMVal-1 and AR-4 O3.

My understanding is that CCMVal-1 models were included here for their sophisticated treatments of ozone chemistry and better resolved stratospheric dynamics. However, such prescribing of surface temperature seemly is the primary contributor to the tropospheric temperature trends. Thus, the value of including CCMVal-1 would be greatly

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reduced. Therefore, this issue needs to be explicitly discussed and addressed.

We completely agree with the reviewer's comments on this issue that tropospheric temperature trends are largely determined by prescribed SST, throughout water-vapor lapse-rate feedback processes. We did not explicitly and extensively address this issue in the text. In the revised version, we will add discussion on this point.

For global and annual mean, it appears that the overlap of vertical profiles trends from AR4-O3 and CCMVal-1 models is largely due to prescribed SST. On the other hand, trends in CCMVal-1 models do show different temporal and spatial patterns from that in AR4-O3 models (see Figures 6-7 in the manuscript). This could be an interesting point for adding CCMVal-1 models.

4. Physical interpretation of the results The change of ozone in stratosphere can induced changes in downward infrared radiation and affect temperature in troposphere, which could be understood in the framework of radiative-convective equilibrium. It also can modify meridional temperature gradient in the mid- and lower-stratospheres, which then can induces dynamic responses to such change and a chain of stratosphere-troposphere interactions to propagate to the troposphere. Both are mentioned in the paper. It confused me that sometimes the trends are attributed to the first mechanism and sometimes to the second one, with few quantitative or physical-based convincing arguments.

It seems to me at least a quick back-envelope investigation can be done to check whether the magnitudes of trends (global-mean or zonal mean) seen in this paper are consistent with those estimated from 1-D radiative-convective equilibrium model (as done by Ramanathan and Dickinson or by Forster and Shine). The ozone profiles from CCMVal-1 should be enough to provide such two snapshots (current and post-recovery eras), together with temperature, water vapor, and cloud profiles, a back-envelope estimation could be done. Such estimation would be very helpful in interpreting the results.

Yes, a weakness of our paper is that we did not distinguish the two mechanisms very

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well. In the revised version, we will introduce the results in radiative-convective models by Ramanathan and Dickinson or by Forster and Shine in the Introduction section, and interpret the GCM results with the second mechanism. One difficulty is that it is hard to diagnose the feedback and dynamical processes. Thus, we probably can only give qualitative discussion, rather than quantitative discussion.

Following the suggestion, we use a radiative-convective model to calculate temperature changes between 2001 and 2050, with vertical ozone profiles from CCMVal-1. Ozone profiles at 2001 and 2050 are linearly regressed values, rather than the real values in the two years. Vertical relative humidity distribution is fixed, i.e., the Manabe-Wetherald type, with surface relative humidity of 80%. It shows that surface temperature change is about 0.11 K over 2001-2050 (see attached Figure 5).

Figure 5. Temperature changes between 2001 and 2050, calculated from a radiative-convective model. Figure 5b is zoomed on the box in Figure 5a.

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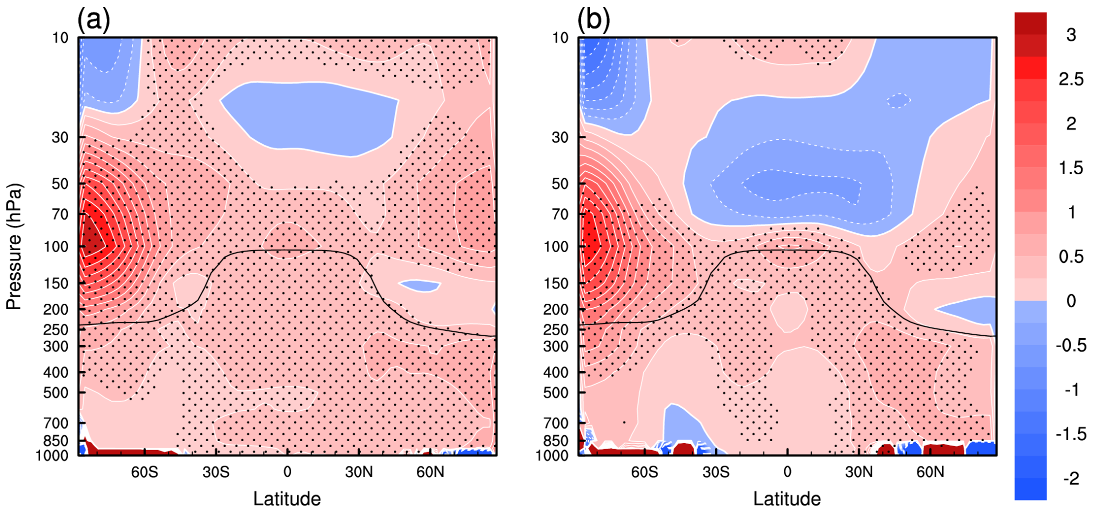

Fig. 1.

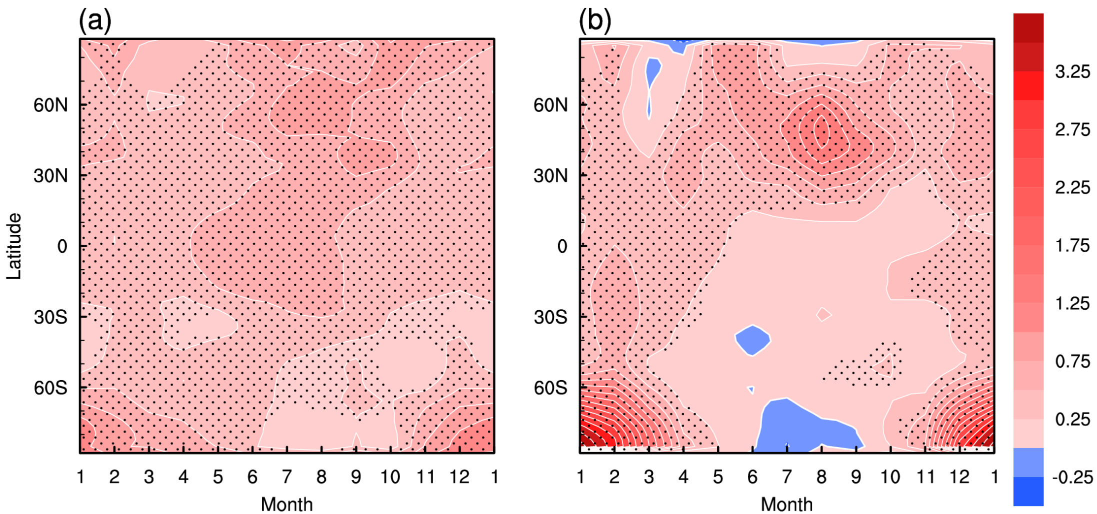

Fig. 2.

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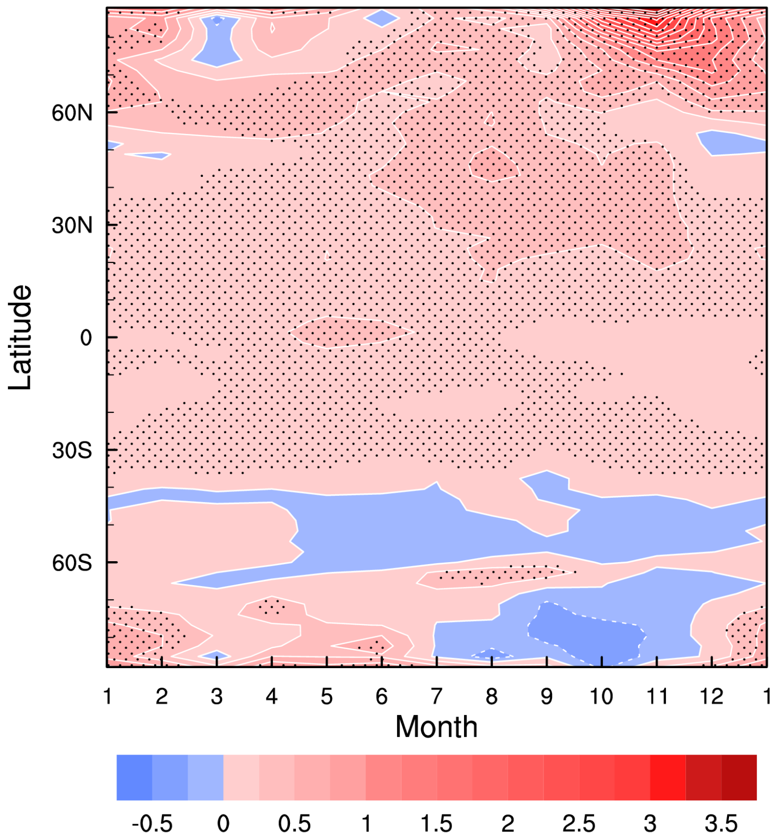
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Fig. 3.

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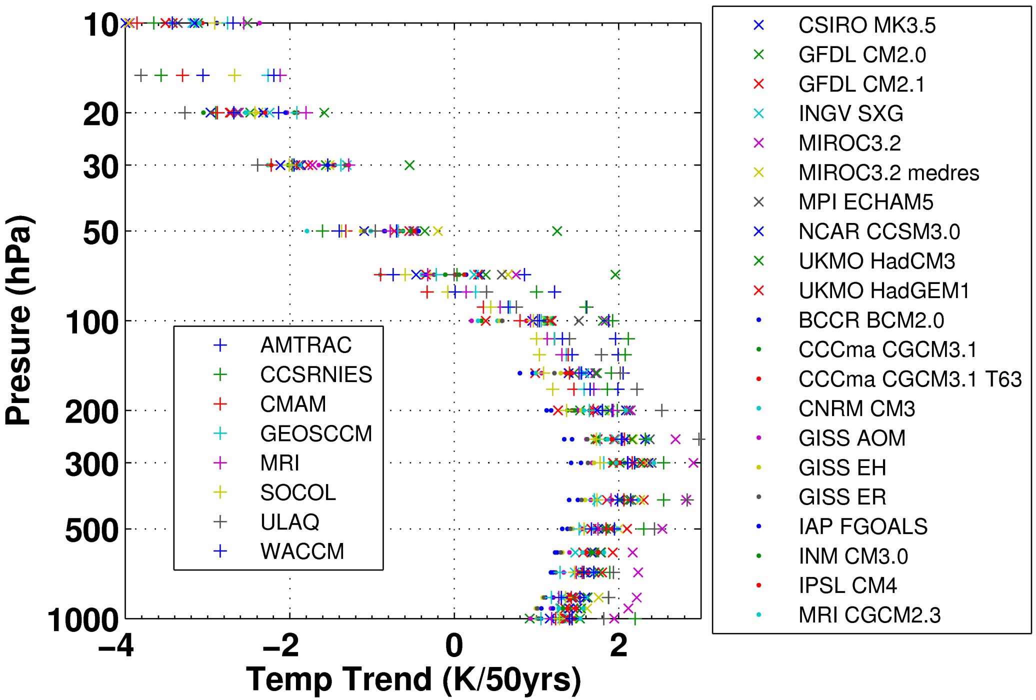

Fig. 4.

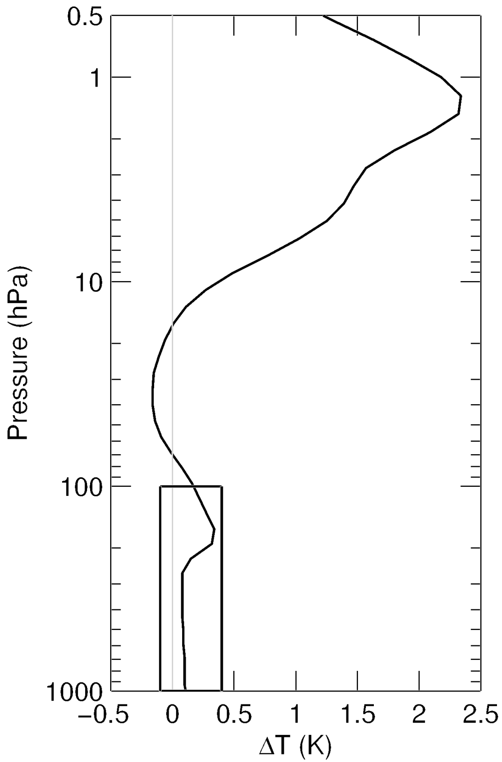

Fig. 5.

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