# Reply to RC1

We thank the reviewer for his/her thoughtful and constructive comments that help improve the quality of our manuscript. We have incorporated the reviewer's suggestions in the revised manuscript. Our point-to-point response to the reviewer's comments are shown below.

Anonymous Referee #1:

**Major Revisions:**

1. This paper serves as a converse of the ozone depletion paper of Grise et al. (2013), who concluded that, although stratospheric ozone depletion has a negative radiative forcing, the cloud changes due to stratospheric ozone depletion induce a net warming effect on the climate system. Given that both studies use the same CAM3 model and examine stratospheric ozone changes, it is surprising that the authors did not appreciate the strong connection between the two studies.

**Response:** We thank the reviewer for pointing out the consistency between the results of our study and Grise et al. (2013), and have modified the paper to recognize the connections between the two studies. These include: line 12 in page 6, line 23 in page 8, and lines 3-4 in page 9.

2. So, it is a bit perplexing that the authors of this study have chosen CAM3 for their analysis, as their cloud adjustment in this study is likely quite biased as a result. It's probably beyond the scope of this paper to ask the authors to run additional simulations using different models, but perhaps the few historicalMisc runs from CMIP5 models that isolate stratospheric ozone depletion could provide some clues about inter-model spread (http://cmip-pcmdi.llnl.gov/cmip5/docs/historical_Misc_forcing.pdf). I would be highly surprised if the results from the CAM3 model are representative of all climate models (or the real world, for that matter). All that being said, this study is important because it shows that this effect occurs in at least some climate models, and the authors perform a much more rigorous diagnosis of the radiative effects of ozone recovery than in previous studies. I would just ask the authors to be very cautious about making any general conclusions about their results (as they do on the top of page 10), until a more comprehensive suite of models can verify them.

**Response:** We thank the reviewer for cautioning us the potential deficiencies of the CAM3. The choice of CAM3 was because it had already been used in our previous research when this study began and also it takes less computing time to integrate compared to the later versions. We recognize the discrepancies especially concerning clouds in CAM3 compared to other models as pointed out by the reviewer.

Following this and the other reviewer's suggestion, we have analyzed the CMIP5 experiments. Five CMIP5 models, CCSM4, CESM1-CAM5, FGOALS-g2, GISS-E2-H, and GISS-E2-R, have ozone-only historical experiments, which, however, does not isolate the effects of stratospheric ozone depletion (http://cmip-pcmdi.llnl.gov/cmip5/docs/historical_Misc_forcing.pdf). We calculated, using RRTMG, the instantaneous forcing of ozone change from 1960 to 2000 to be negative: -0.20 W $m^{-2}$, although most models (except GISS-E2-R) show weak global warming (Figure R1). The global- and annual-mean sea ice and cloud changes are shown in Figures R2 and R3 respectively, both of which show statistically significant (stippled) responses, such as high level cloud increase and Antarctic sea ice reduction, to ozone forcing, although the pattern, magnitude and even sign of the changes are of noticeable inter-model differences, which supports the reviewer's point about inter-model spread. However, given that the forcing prescribed in the experiment is not exclusively stratospheric ozone change, these results may also reflect the complications of the impact of tropospheric ozone change.

In response to this important comment of the reviewer, we have acknowledged in the revised Conclusion Section that results presented here is based on only one model and it takes further research to verify its robustness. We also like to mention here that since the submission of this paper, we have started additional experiments, using different model configurations such as CESM1-CAM5 and different prescriptions of stratospheric ozone change. The preliminary results suggest that the high-cloud and sea ice responses as reported in this paper is at least qualitatively similar (robust) in these experiments. We intend to present these results in a following-up paper.

**Specific (Minor) Revisions:**

1. Page 3, Lines 13-17: How does your methodology compare to the COOKIE experiments (http://www.euclipse.eu/downloads/Cookie.pdf ) used by previous studies? It sounds similar, but not exactly the same.

**Response:** Our methodology is similar to the Clouds On Off Klima Intercomparison Experiment (COOKIE). We don't consider the cloud radiative effects, but consider cloud and precipitation in hydrological cycle including latent heat release, which is same as the COOKIE setup. We have noted the similarity to COOKIE in our experiment design in the revised paper.

2. Page 3, Line 22: How realistic is the ERA-Interim ozone data compared to more commonly used satellite-derived ozone data sets? For reference, the ozone data used to force the CMIP5 models is provided at http://www.pa.op.dlr.de/CCMVal/AC&CSPARC_O3Database_CMIP5.html.

**Response:** We have acknowledged in the revised paper that our ozone prescription represents an idealized (simplified) SOR scenario. One noticeable difference compared to the scenario used by CMIP5 is that the ozone change is made positive (to increase) everywhere in the stratosphere, which renders nearly uniformly positive zonal mean forcing as shown in Figure 3 in the paper and simplifies the investigation. We have also acknowledged in the revised Conclusion Section that this is another aspect that warrants further investigation.

3. Page 6, Lines 8-10 (also Page 8, Lines 20-22): As stated above, it would useful to compare your numbers to the cloud-radiative effects for ozone depletion found by Grise et al. (2013) using the same model.

**Response:** The cloud-radiative effects for ozone depletion found by Grise et al. (2013) has been added in the revised manuscript, cf. line 12 in page 6.

4. Page 8, Line 9: I don't understand the strong reduction in cloud cover in the Southern Hemisphere stratosphere in Fig. 2e. The absolute value of cloud cover and water vapor in the stratosphere should be very small here to begin with, so the changes seem too large to be physical. More explanation is warranted here. Perhaps this is also a deficiency of CAM3.

**Response:** In theory, there can be many PSCs, at least seasonal ones, in the region under question, but we agree that, as the reviewer questions, the climatology as well as the response simulated by CAM3 may be too large. The mean cloud fraction can reach 20% in boreal autumn in the Antarctic lower stratosphere in CAM3; in comparison, it is about 10% in CCSM4 and 3% in CESM-CAM5. However, as there lacks strong observational constraints, it is difficult to rule out any of these simulations. As the region under question is small, this issue is unlikely to significantly affect the global mean forcing or warming/cooling values that we are concerned with in this paper, although we agree with the reviewer this is an aspect of the CAM3 simulation that needs to be further validated in future research.

5. Page 9, Line 1: Why would Arctic sea ice increase a comparable amount as Antarctic sea ice, given that most of the ozone recovery should be in the Antarctic? Again, more explanation is warranted here.

**Response:** Firstly, in our idealized ozone change scenario, the Arctic increase is comparable to the Antarctica. Secondly, we note that as evident from the analysis of CMIP5 models, there is much larger inter-model spread in terms of sea ice response to ozone forcing. We acknowledge this is an aspect that concerns the robustness of the response and is worth further investigation.

**Technical Corrections:**

1. Page 1, Line 17: Suggest changing “slow increasing” to “slowly increasing”

**Response:** It has been changed.

2. Page 2, Line 13: sophisticated GCMs

**Response:** It has been changed.

3. Page 6, Line 11: Reinstalled? Not sure what this means. Consider a different word choice.

**Response:** It has been changed to be “balanced”.

4. Page 7, Line 19: Climatological

**Response:** It has been changed.

5. Figure 3 is barely discussed in the text. Is it essential to the paper? If so, it should be referenced and described in more detail.

**Response:** It has been referenced and described in more details in the revised manuscript, cf. line 13 and line 21 in page 5.

Reference:

Bitz, C. M., and Polvani, L. M.: Antarctic climate response to stratospheric ozone depletion in a fine resolution ocean climate model, Geophysical Research Letters, 39, 2012.

Grise, K. M., Polvani, L. M., Tselioudis, G., Wu, Y., and Zelinka, M. D.: The ozone hole indirect effect: Cloud-radiative anomalies accompanying the poleward shift of the eddy-driven jet in the Southern Hemisphere, Geophys Res Lett, 40, 3688-3692, 10.1002/grl.50675, 2013.

Haumann, F. A., Notz, D., and Schmidt, H.: Anthropogenic influence on recent circulation-driven Antarctic sea ice changes, Geophysical Research Letters, 41, 8429-8437, 2014.

Neale, R. B., Chen, C.-C., Gettelman, A., Lauritzen, P. H., Park, S., Williamson, D. L., Conley, A. J., Garcia, R., Kinnison, D., and Lamarque, J.-F.: Description of the NCAR community atmosphere model (CAM 5.0), NCAR Tech. Note NCAR/TN-486+ STR, 2010.

Polvani, L. M., and Smith, K. L.: Can natural variability explain observed Antarctic sea ice trends? New modeling evidence from CMIP5, Geophysical Research Letters, 40, 3195-3199, 2013.

Sigmond, M., and Fyfe, J. C.: Has the ozone hole contributed to increased Antarctic sea ice extent?, Geophysical Research Letters, 37, 2010.

Sigmond, M., and Fyfe, J. C.: The Antarctic Sea Ice Response to the Ozone Hole in Climate Models, Journal of Climate, 27, 1336-1342, 2014.

Smith, K. L., Polvani, L. M., and Marsh, D. R.: Mitigation of 21st century Antarctic sea ice loss by stratospheric ozone recovery, Geophysical Research Letters, 39, 2012.

Turner, J., Bracegirdle, T. J., Phillips, T., Marshall, G. J., and Hosking, J. S.: An Initial Assessment of Antarctic Sea Ice Extent in the CMIP5 Models, Journal of Climate, 26, 1473-1484, 2013.

Figures:

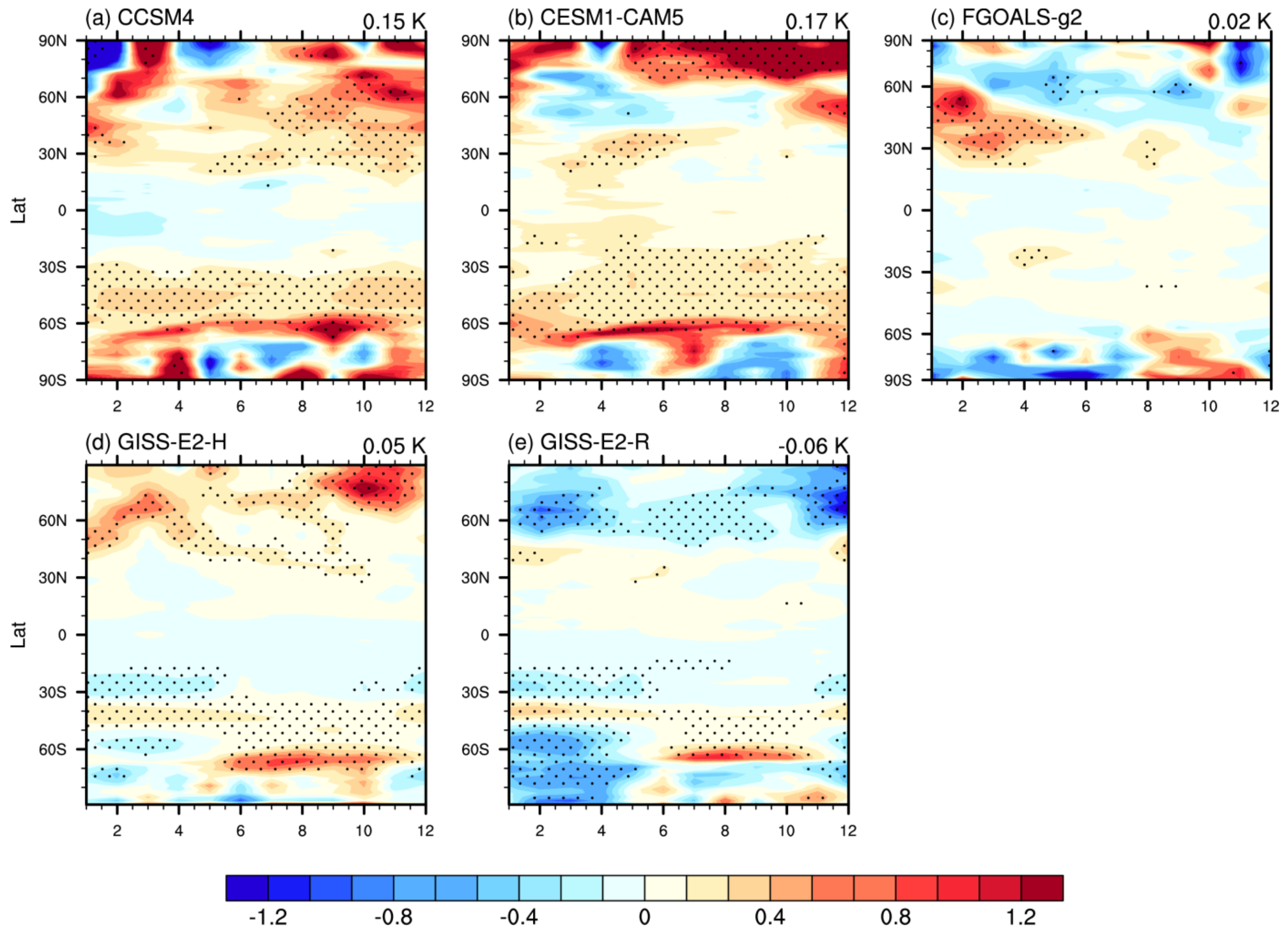


Figure R1. Zonal-mean surface temperature trends from 1960 to 2000 for historicMisc ozone only runs from (a) CCSM4, (b) CESM1-CAM5, (c) FGOALS-g2, (d) GISS-E2-H, and (e) GISS-E2-R, unit: K/40 yrs.

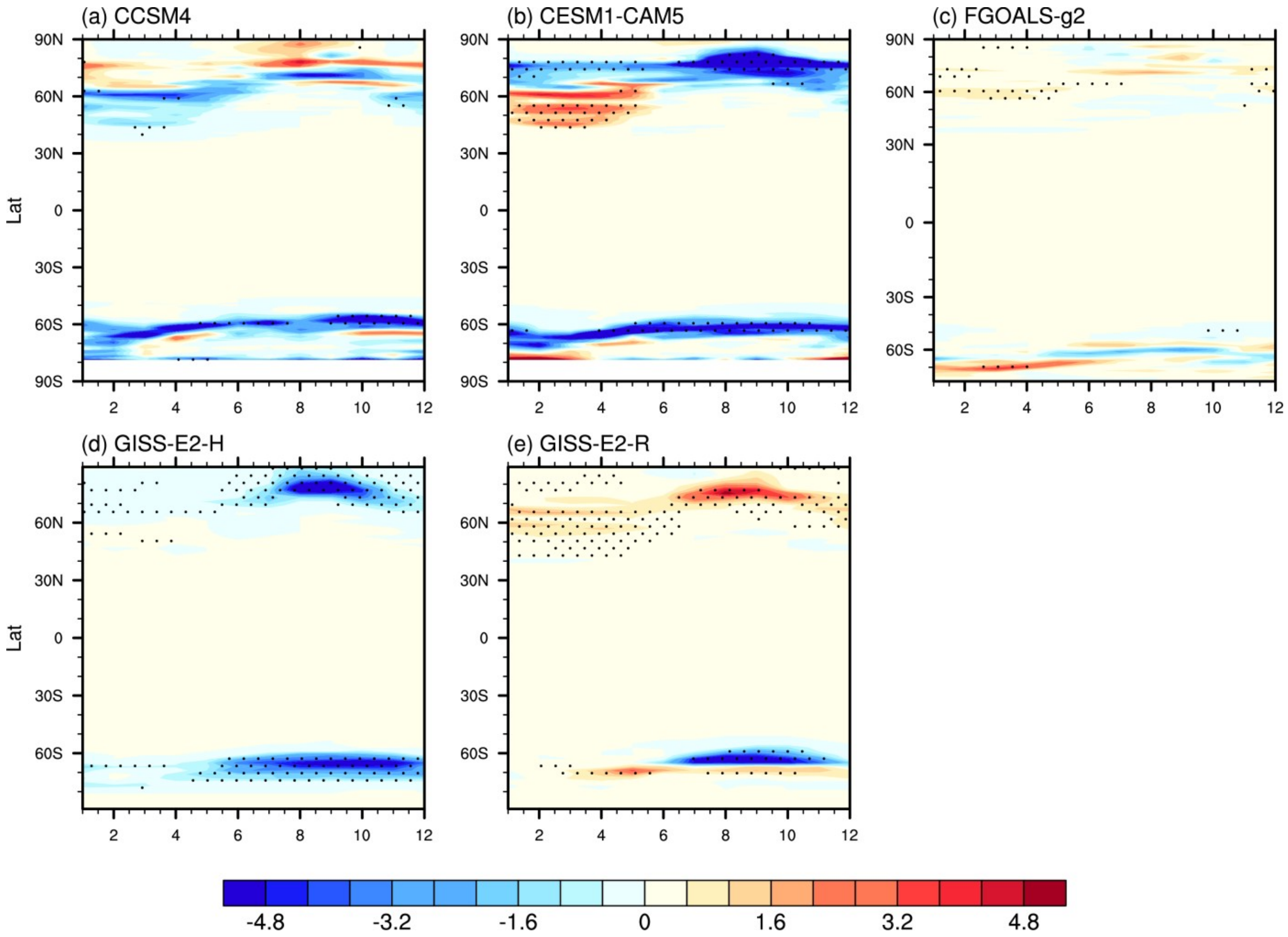


Figure R2. Zonal-mean trends of sea ice fraction from 1960 to 2000 for historicMisc ozone only runs from (a) CCSM4, (b) CESM1-CAM5, (c) FGOALS-g2, (d) GISS-E2-H, and (e) GISS-E2-R, unit: %.

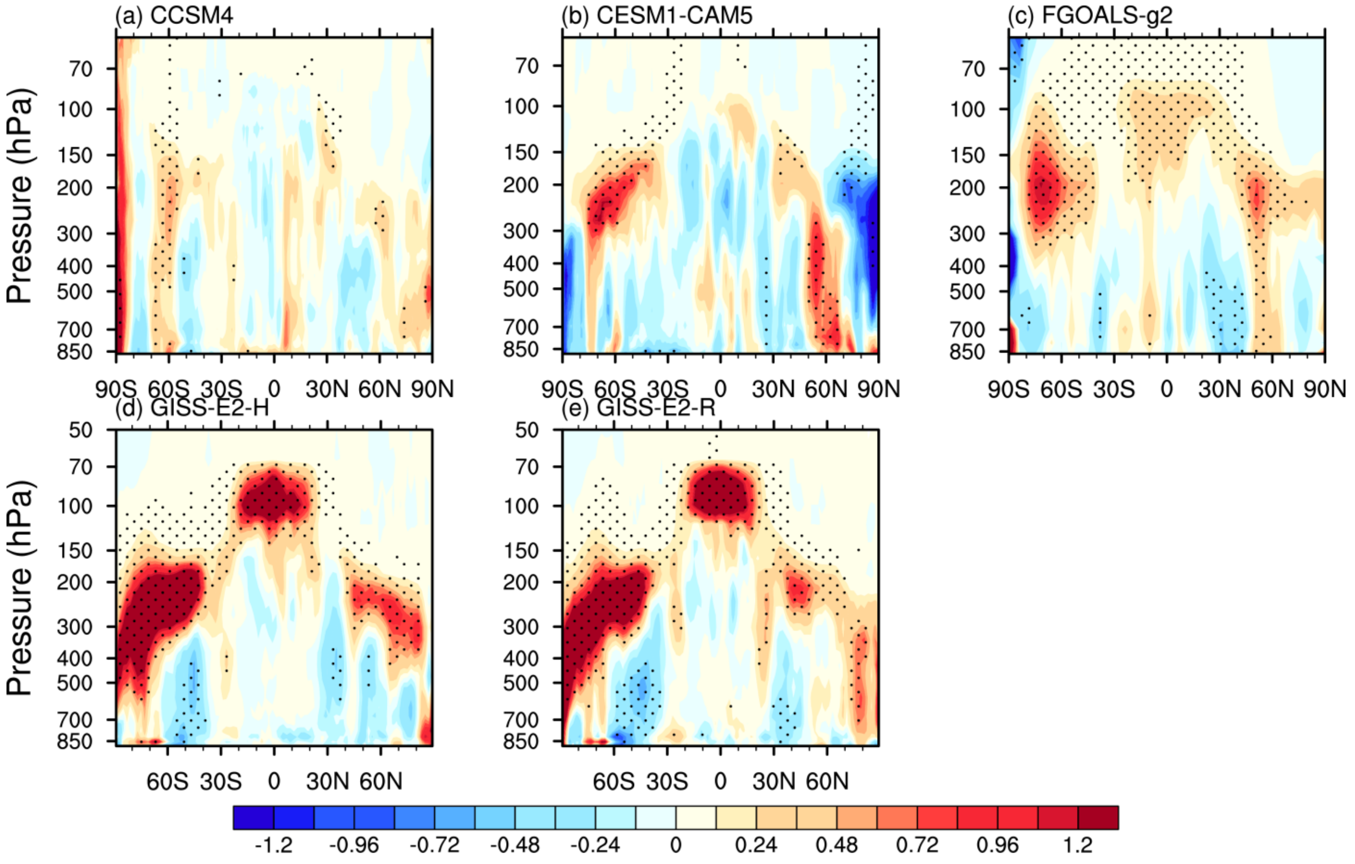


Figure R3. Zonal- and annual-mean cloud fraction trends from 1960 to 2000 for historicMisc ozone only runs from (a) CCSM4, (b) CESM1-CAM5, (c) FGOALS-g2, (d) GISS-E2-H, and (e) GISS-E2-R, unit: %.

5