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 line 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.

Reply to RC2

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 #2:

Major Comments:

1. To examine the effect of sea-ice and clouds on the model response to stratospheric ozone recovery two simulations are performed, the control and one with no sea-ice and clouds that are invisible to radiation (NCNSI). While it may not substantially change the results of the analysis it seems that one would like to make incremental changes to isolate the effects of clouds and of sea-ice. For example, a set of with invisible clouds and a set with no sea-ice or perhaps with sea-ice invisible to radiation.

Response: We thank the reviewer for this good suggestion.

Following the reviewer's suggestion, to isolate the effects of clouds and of sea-ice, two sets of experiments are conducted. In the first set, we set all the cloud fractions to zero in radiative heating rate and flux calculations and thus suppress the radiative effects of clouds. In the other set of integrations, we set the freezing temperature to -180 degree centigrade so that there is effectively no sea ice in the simulation. These two sets of experiments are denoted as "No Cloud (NC)" and "No Sea-Ice (NSI)" respectively in the following.

As in the other experiments documented in the paper, in order to examine the impact of SOR on surface temperature, two 100-year integrations, prescribed with identical concentrations of well-mixed greenhouse gases (CO_2, CH_4, N_2O, etc.) but different stratospheric ozone concentrations, are conducted in both the NC and the NSI experiments. We assess the SOR impacts by contrasting the means of appropriate variables in the last 85 years of two 100-year simulations (the difference between two equilibrium states).

As shown by Figure R4, the surface temperature response to SOR is 0.18 K in the NC experiment (Figure R4 a), which is similar to that in the NCNSI experiment. The SOR warms not only the stratosphere but also the troposphere (Figure R4 b). We also find non-significant sea ice depletion in both hemispheres, which is opposite to that in the Standard experiment (Figure R4 c). So if there were no clouds, the sea ice only makes a small effect on the stratospheric ozone forcing.

The NSI experiment confirmed the above finding. If there were no sea ice but still clouds, a near-zero global surface warming (about 0.03 K) is resulted (Figure R5 a). The warming in the troposphere in the NSI experiment is also reduced compared to the NC and NCNSI experiments (Figure R5 b). We can also see the reduction of high clouds in the UTLS, which is consistent with that in the Standard experiment (Figure R5 c).

Hence, in summary, as we have concluded, the clouds have more important impacts on the modification of stratospheric ozone forcing than the sea ice. We have added the new experiment results in the relevant texts (lines 10-14 in page 9).

2. As noted in the Introduction work by McLandress et al, 2012 suggests that stratospheric ozone recovery my lead to surface cooling. Would it be possible to generalize and support the results found with CAM3 and comments made in the text by analyzing historical CMIP5 simulations that only vary ozone? For example, the list of models in Table 2 of Sigmond and Fyfe, 2013.

Response: We thank the reviewer for this suggestion. Following the 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 differeces. Given that the forcing presccribed in the experiment is not exclusively stratospheric ozone change, these results do not lead to conclusive assessment. We have acknowledged in the revised manuscript that it takes further research to elucidate whether and how SOR leads to global warming or cooling in reality.

Figures:

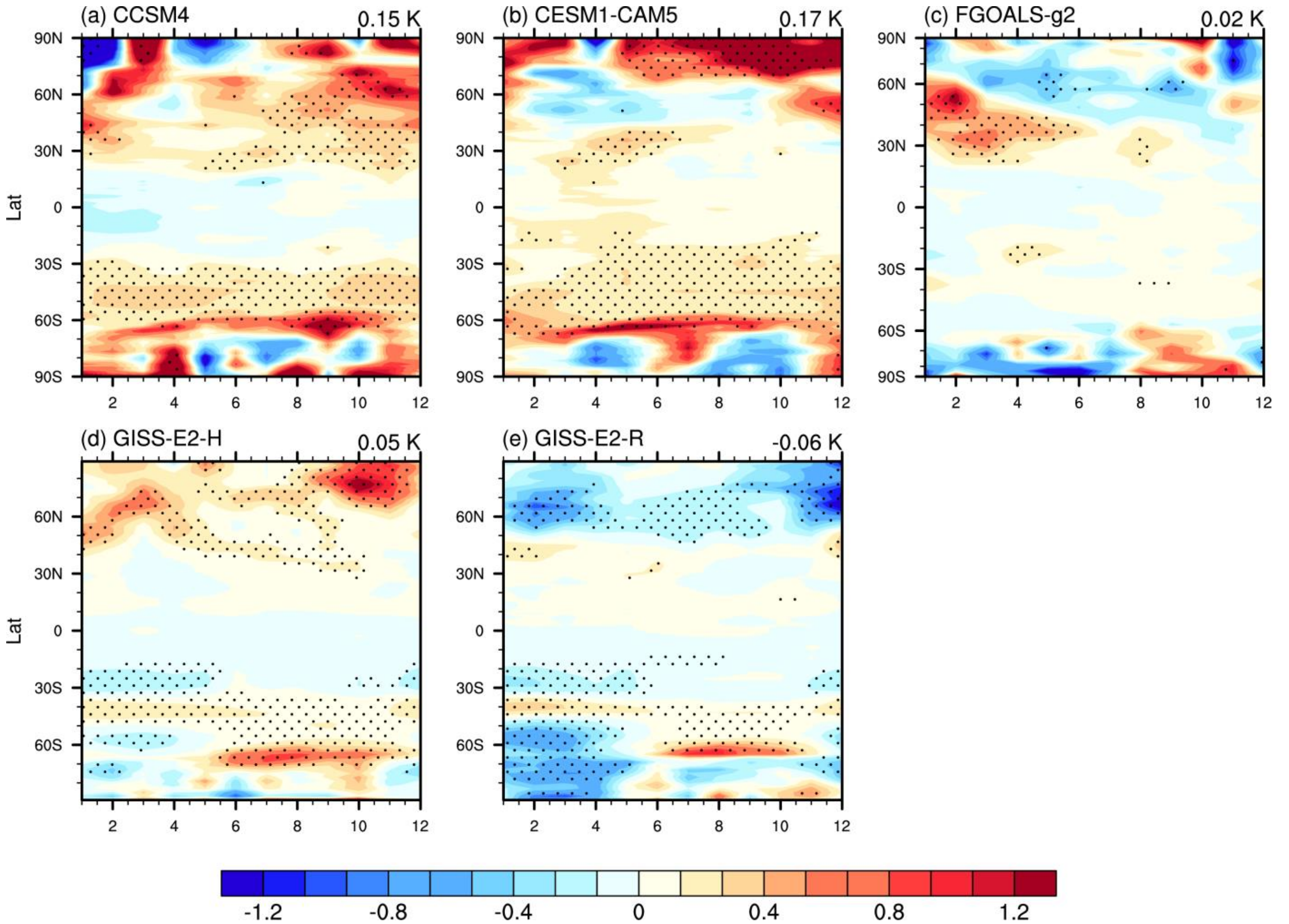

Figure R1. Zonal-mean surface temperature trends from 1960 to 2000 for historicMisc ozone only runs from (a) CCSM4, (b) CESM1-CAM5, (c) FGOALS-g2, (d) GISS-E2-H, and (e) GISS-E2-R, unit: K/40 yrs.

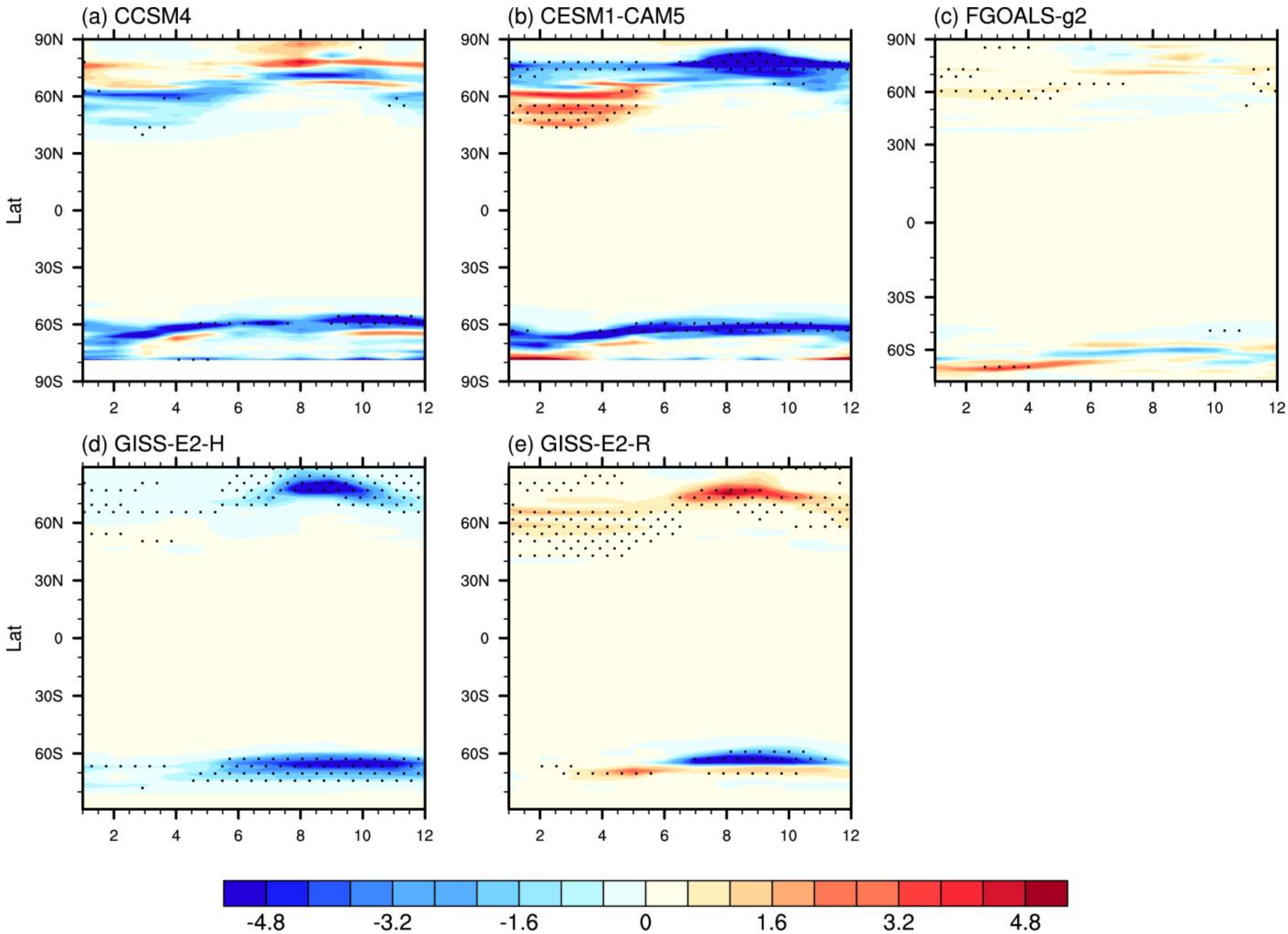

Figure R2. Zonal-mean trends of sea ice fraction from 1960 to 2000 for historicMisc ozone only runs from (a) CCSM4, (b) CESM1-CAM5, (c) FGOALS-g2, (d) GISS-E2-H, and (e) GISS-E2-R, unit: %.

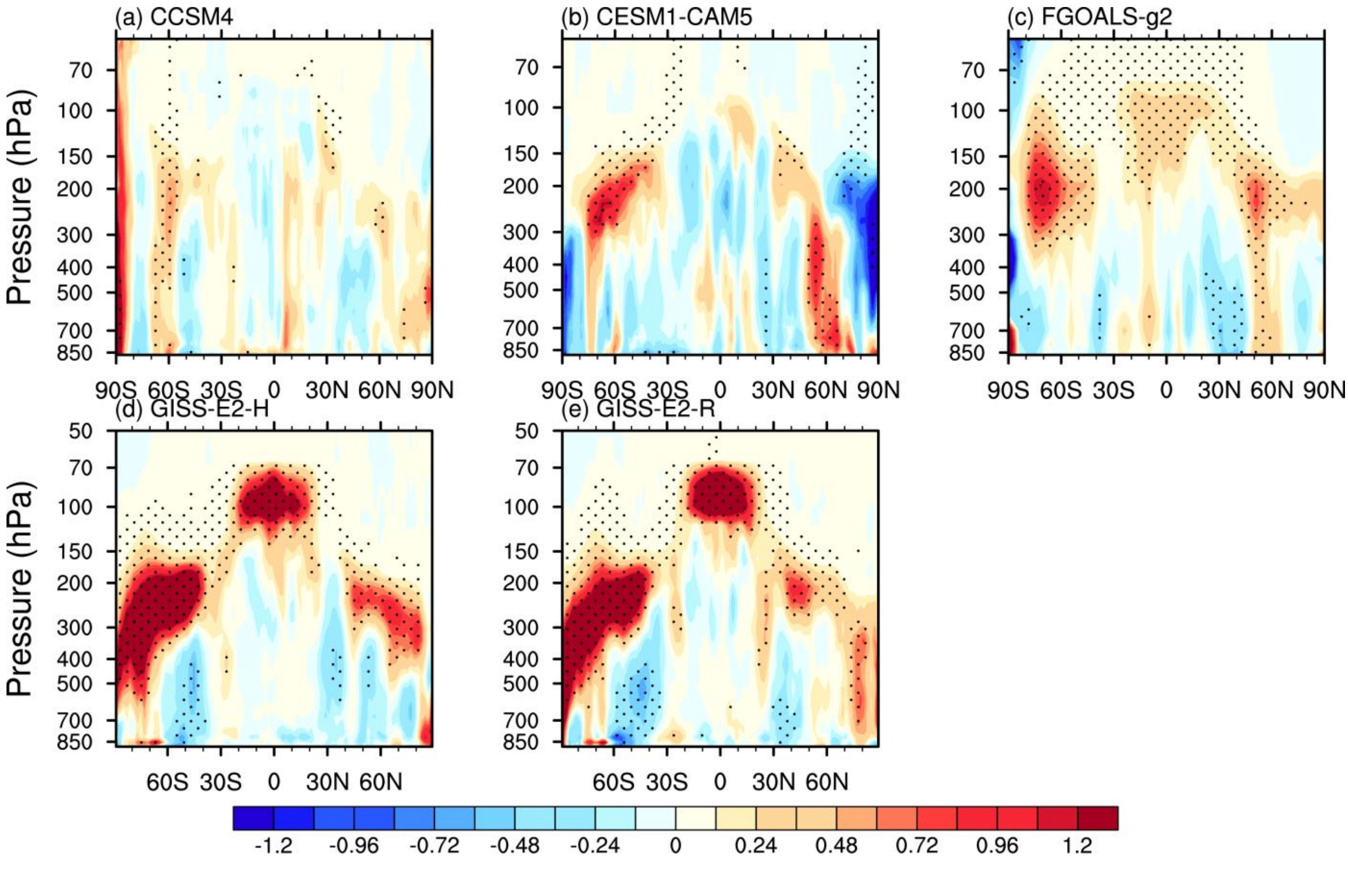

Figure R3. Zonal- and annual-mean cloud fraction trends from 1960 to 2000 for historicMisc ozone only runs from (a) CCSM4, (b) CESM1-CAM5, (c) FGOALS-g2, (d) GISS-E2-H, and (e) GISS-E2-R, unit: %.

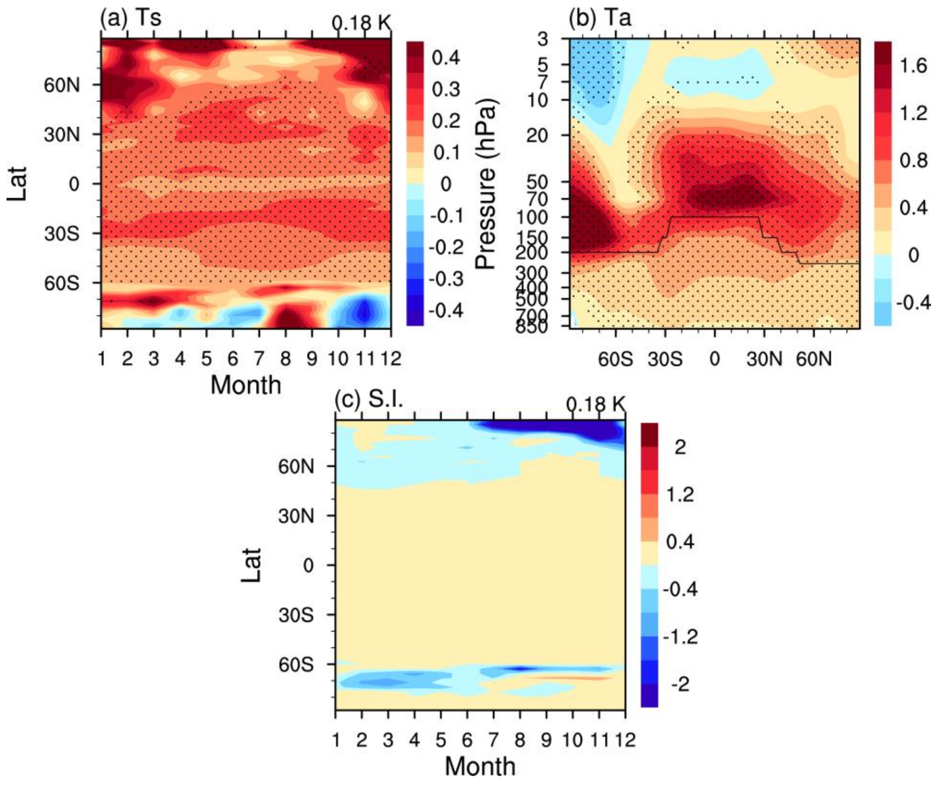

Figure R4. Responses to SOR of (a) zonal mean surface temperature, (b) annual- and zonal-mean air temperature, (c) zonal mean sea-ice fraction in the NC experiment.

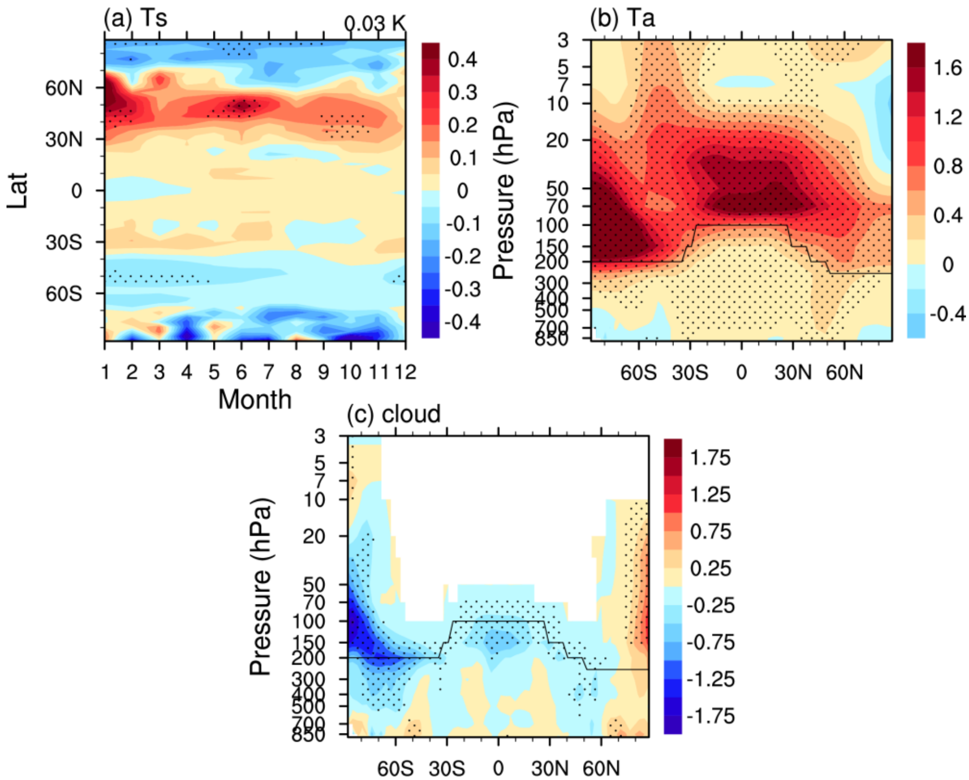

Figure R5. Responses to SOR of (a) zonal mean surface temperature, (b) annual- and zonal-mean air temperature, (c) annual- and zonal-mean cloud fraction in the NSI experiment.

Response to SC1

We thank Mr. Nowack for his comments. Our responses are itemized below.

1. "In reference to the comment in your short summary concerning previous studies on cloud adjustments to ozone forcing (also discussed in section 1 of your discussion paper), please see the opposing clear-sky and cloud radiative long-wave effects of upper tropospheric and lower stratospheric ozone changes and high clouds in
   • Nowack, P. J., Abraham, N. L., Maycock, A. C., Braesicke, P., Gregory, J. M., Joshi, M. M., Osprey, A., and Pyle, J. A.: A large ozone-circulation feedback and its implications for global warming assessments, Nature Climate Change, 5, 41–45, doi:10.1038/nclimate2451, 2015.
   Note in particular Figure 4 and the discussion on Supplementary Figure S6. Can you say more about the nature of the positive tropical ozone long-wave forcing you find?"

Response: The ozone change in our paper is an idealized stratospheric ozone recovery (SOR) scenario (see Figure 1), in comparison to the ozone depletion in the upper troposphere and lower stratosphere in Nowack2015 (Figure 3a). The warming in the tropopause induced by SOR results in the decrease of high clouds in UTLS, which is consistent with the increase of cloud seen in Nowack2015 (Figure 4). We have pointed this out in Section 5 in the revised paper.

One aspect of our idealized ozone prescription is that the ozone change is positive throughout the stratosphere, including the tropical UTLS region. This renders very positive forcing across all the latitudes. We have also pointed this out in the revised paper.

2. Finally, you mention in section 2 the representation of coupling between wind stress and sea ice dynamics in the model. Do you know whether the choice of a slab ocean model as compared to a deep ocean model could affect dynamical atmosphere-ocean interactions?

Response: A number of previous works (DeConto et al., 2007;Cvijanovic and Caldeira, 2015) investigated the role of sea ice with the slab-ocean model. Particularly, Danabasoglu and Gent (2009) compared the slab ocean and the fully coupled configurations of CCSM3 (similar configuration to ours) and showed that the slab ocean setup provides a good estimate of the climate sensitivity of the fully coupled model. Moreover, we compared our CAM3-slab ocean simulations results to the coupled atmosphere-ocean simulations by CESM1 (CAM5), the climatology and variability of the sea ice extent have similar magnitude in the slab-ocean model. All these suggest the sea-ice responses simulated in our experiments are likely valid, although, as we have acknowledged in the revised Conclusion Section, it warrants further research to test the robustness of the sea ice, as well as cloud, responses across different models and in reality.

3. Out of interest, what part of the sea ice responses do you think is driven by the regional cloud forcings (in that sense the sea ice feedback and the regional cloud feedback are, as you say, partly related)?

Response: The sea ice and clouds are coupled components in the high latitude climate system, which implies their feedbacks are potentially related. It is beyond the scope of this paper to elucidate how they are coupled. However, in an accompanying study of us (Hu et al., 2016), we find both cloud and sea ice responses to SOR tend to cool the local surface climate. We have mentioned this in the revised paper.

In our results, cloud-induced decrease of downward IR is only a small part of the total downward IR decrease, less than one-third.

Reference:

Cvijanovic, I., and Caldeira, K.: Atmospheric impacts of sea ice decline in CO2 induced global warming, Climate Dynamics, 44, 1173-1186, 10.1007/s00382-015-2489-1, 2015.

Danabasoglu, G., and Gent, P. R.: Equilibrium Climate Sensitivity: Is It Accurate to Use a Slab Ocean Model?, J Climate, 22, 2494-2499, 2009.

DeConto, R., Pollard, D., and Harwood, D.: Sea ice feedback and Cenozoic evolution of Antarctic climate and ice sheets, Paleoceanography, 22, n/a-n/a, 10.1029/2006PA001350, 2007.

Hu, Y., Xia, Y., Liu, J., and Huang, Y.: Stratospheric ozone-induced indirect radiative effects on Antarctic sea ice, To be submitted to Nature - Climate Change, 2016.

Response to SC2

We thank A. F. Tuck for his comments. Our response are itemized here.

3. The authors might like to consider the conclusions reached in the attached .pdf, which examined factors like cloud cover, surface nature and temperature, and the important influence of actual local observations of ozone and water vapour. The use of matching observed outgoing long wave radiation to underlying cloud was a useful innovation.

Response: We thank Dr. Tuck for his comments. We recognize the importance of PSC and its interactions with ozone, as well as other atmospheric and surface variables, which jointly defines polar climate and potentially affects climate of greater region through modifying heating rate and atmospheric temperature structure, as discussed by Hicke and Tuck (2001). Such interactions are accounted for in our simulations to the extent that PSCs are simulated in the CAM3.

Reference:

Hicke, J., and Tuck, A.: Polar stratospheric cloud impacts on Antarctic stratospheric heating rates, Q J Roy Meteor Soc, 127, 1645-1658, 10.1002/qj.49712757510, 2001.

Strong modification of stratospheric ozone forcing by cloud and sea ice adjustments

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Abstract. We investigate the climatic impact of stratospheric ozone recovery (SOR) with a focus on the surface temperature change in atmosphere-slab-ocean coupled climate simulations. We find that although SOR would cause significant surface warming (global mean: 0.2 K) in a climate free of clouds and sea-ice, it may result in surface cooling (-0.06 K) in the real climate. The results here are especially interesting in that the stratosphere-adjusted radiative forcing is positive in both cases. Radiation diagnosis shows that the surface cooling is mainly due to a strong radiative effect resulting from significant reduction of global high clouds and, to a lesser extent, from an increase in high-latitude sea ice. Our simulation experiments suggest clouds and sea ice are sensitive to stratospheric ozone perturbation, which constitutes a significant radiative adjustment that influences the sign and magnitude of the global surface temperature change.

1 Introduction

Observational records show that stratospheric ozone has declined prior to the late 1990s and then started stabilizing and even slowly increasing, especially in the Polar Regions (WMO, 2007, 2011). It is expected that the ozone layer would return to the pre-1980 level in the 2050s (Bekki, 2011). It is known that ozone is a greenhouse gas, and that stratospheric ozone has a warming effect on tropospheric-surface climate, which has been demonstrated by early simulation works with radiative-convective models (Ramanathan and Dickinson, 1979;Lacis et al., 1990). Consistent with such understanding, ozone depletion generally leads to a negative radiative forcing (after accounting for stratospheric temperature adjustment) that cools the climate (Forster and Shine, 1997;Hansen et al., 2005;Conley et al., 2013;Myhre et al., 2013;Macintosh et al., 2016). On such basis,

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one would expect that stratospheric ozone recovery (SOR) exerts a positive forcing that should lead to troposphere and surface warming. The single-column simulation by Hu et al. (2011) agrees with such expectation, although their efforts to distinguish the responses to SOR in full general circulation models (GCMs) is impeded by climate sensitivity differences between the two groups of models (McLandress et al., 2012). Very interestingly, McLandress et al. (2012) show a weak troposphere-surface cooling in response to SOR in a coupled chemistry-climate model (CCM). As presented below, such a weak cooling is also seen in our simulation with an atmospheric GCM coupled to a slab-ocean model. These results raise important questions: how does surface cooling result from the positive radiative forcing of SOR in GCM simulations? Why do GCMs and radiative-convection models yield opposite results? In this paper, we are motivated to answer these questions and reconcile the contradiction of the warming prediction based on single-column model simulations.

One prominent deficiency of the one-dimensional radiative-convective models is that they neglect effects of clouds as well as snow and ice albedo. Thus, results from these simplified models may not realistically represent the responses to SOR. Hence, our hypothesis is that the radiative adjustment of clouds and sea ice may override the forcing of SOR and change the direction of surface temperature change in more sophisticated GCMs. To test this hypothesis, we perform two sets of SOR forcing experiments using a three-dimensional climate model, one with standard settings and the other with cloud and sea-ice artificially removed in the simulation. Comparison of the two sets of simulations shall elucidate the effects of cloud and sea ice. In the following sections, we will describe the configuration and results of these experiments, dissect the simulations from a radiative budget perspective, and summarize our main findings in order.

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2 Model and experiment design

Here, we conduct and analyze a series of SOR experiments using the NCAR Community Atmosphere Model, version 3 (CAM3) coupled with a Slab Ocean Model (SOM) (Collins et al., 2006;Neale et al., 2010). All of the runs presented below are made with T42 horizontal resolution (~2.8°x2.8°) and coupled to a 50-meter-deep SOM. The SOM configuration uses a simple ocean component (Kiehl et al., 2006;Danabasoglu and Gent, 2009), combined with a thermodynamic sea ice component that is based on the Community Sea Ice Model (CSIM5, (Briegleb, 2004)) and allows for a fully-interactive treatment of surface exchange processes in CAM3. Danabasoglu and Gent (2009) compare the slab ocean and the fully coupled configurations of CCSM3 and find that the slab ocean setup provides a good estimate of the climate sensitivity of the fully coupled model. Although the slab-ocean component lacks explicit representation of ocean currents, GCM surface winds drive the sea ice dynamics, with advection simulated as a cavitating fluid (Flato and Hibler, 1990, 1992). Compared with the coupled atmosphere-ocean simulations by CESM1 (CAM5), the annual cycle of climatological sea ice extent has similar magnitude (varying from 3 to 15×10^6 km^2) in SOM. The variabilities of the annual-mean sea ice extent are also similar (about 2-3×10^6 km^2) in SOM and coupled atmosphere-ocean simulations.

In order to isolate the effect of clouds and sea ice, two sets of experiments are conducted here. In the first set, we use standard settings of the model, without any modification of cloud and sea ice. In the other set of integrations, we set the freezing temperature to -180 degree centigrade so that there is effectively no sea ice in the simulation. We also set all the cloud fractions to zero in radiative heating rate and flux calculations and thus suppress the radiative effects of clouds, which is similar to the configuration of the Clouds On Off Klima Intercomparison Experiment (COOKIE). To restore radiative energy balance, following Koll and Abbot (2013) we reduce the solar constant by 120 W m^{-2}, because CAM3 has a global mean cloud forcing of ~30 W m^{-2}. These two sets of experiments are denoted as “Standard” and “No Cloud No Sea-Ice (NCNSI)” respectively in the following. The global and climatological mean surface temperature is 291.4 K in the NCNSI experiment, which is comparable to the climatology in the Standard experiment (about 2 K warmer). Note that the cloud modification used here does not affect the generation of clouds in GCM integration or related latent heating of the atmosphere. The hydrological cycle, as reflected by the climatology of precipitation, in the NCNSI experiment is similar to that in the Standard experiment. Thus, the NCNSI simulation provides a reasonable hypothetical world for comparing the radiative responses to SOR.

In order to examine the impact of SOR on surface temperature, two 100-year integrations, prescribed with identical concentrations of well-mixed greenhouse gases (CO_2, CH_4, N_2O, etc.) but different stratospheric ozone concentrations, are conducted in both the Standard and the NCNSI experiments. The monthly mean ozone volume mixing ratios averaged over 1999-2003 (scenario 2000) and 1979-1983 (scenario 1979), taken from the ERA-Interim reanalysis (Dee et al., 2011), are

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prescribed in these two integrations to represent "present" (2000) and "recovery" (1979) scenarios respectively. In order to eliminate the influence of tropospheric ozone, the ozone below 200 hPa in the recovery scenario is fixed at scenario 2000 level. To see the impact of SOR, the idealized ozone change in the recovery scenario above 200 hPa is set to the absolute value of the difference between 1979 and 2000 (Figure 1 a). In comparison, the ozone in the recovery scenario increases by about 28 Dobson Unit (DU) in the tropics and subtropical regions, about 63 DU in Arctic and about 73 DU in Antarctic (Figure 1 b). Both scenario experiments are initialized from an equilibrated present-day CAM3 simulation with Sea surface temperature (SST) prescribed to be the climatological mean values of the period 1980-2000. The atmospheric states in all these experiments approach steady states after 10 years of integration. We assess the SOR impacts by contrasting the means of appropriate variables in the last 90 years of two 100-year simulations (the difference between two equilibrium states).

3 Surface temperature change

As shown by Figure 2, SOR causes noticeable changes in not only stratospheric but also tropospheric and surface climate. The stratosphere in both the Standard and NCNSI experiments is significantly warmed, as expected from the radiative heating effect of stratospheric ozone. On the other hand, SOR leads to tropospheric and surface warming in the NCNSI experiment, while noticeable cooling is seen in the Standard experiment (compare Figure 2 a and b). The global and annual mean surface temperature change is +0.2 K and -0.06 K in the two experiments, respectively. The surface warming in the NCNSI experiment occurs in all seasons and at most latitudes. In comparison, surface cooling in the Standard experiment is the strongest in the two polar regions (reaching -0.8 K in Arctic in boreal autumn), and is also strong (about -0.2 K) over the high-latitude Southern Oceans (40^{o}S-70^{o}S).

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The results here support our hypothesis that the different responses to SOR (cooling vs. warming) are caused by clouds and sea ice. It is interesting that the same SOR perturbation drives surface climate changes in opposite directions due to effects of clouds and sea ice. This is especially interesting because the stratosphere-adjusted forcing of SOR (as detailed in the following section) is similar (positive) in the NCNSI and Standard experiments.

4 Radiation diagnosis

4.1 Instantaneous forcing

We calculate the instantaneous radiative forcing (IRF) of SOR using a radiative transfer model, RRTMG (Mlawer et al., 1997). The radiative forcing is calculated as the change in top-of-atmosphere (TOA) radiation fluxes in response to the stratospheric ozone change (from 2000 to 1979 values) at every grid box using monthly-mean temperature, water vapor, and cloud profiles from a 2000 equilibrium integration. Following Cronin (2014), we use the insolation-weighted method to calculate the monthly-mean solar zenith angle. The global and annual mean forcing values are provided in Table 1. Due to ozone absorption of shortwave solar radiation (mainly in the 200-315 nm UV region) and longwave terrestrial thermal emission (mainly around 9.6 μm), the SOR as prescribed in our experiments induces a *positive* (downward at TOA, i.e., warming) forcing in both the NCNSI and Standard experiments. The global mean values are 0.49 W m^{-2} and 0.60 W m^{-2}, respectively. Note that in our idealized SOR scenario (Figure 1), the ozone change is positive throughout the stratosphere, including the tropical UTLS region, which renders very positive forcing across all the latitudes. In both experiments, the longwave forcing has a flat zonal mean pattern, due to compensating effects of the latitudinal variations in surface thermal radiation and ozone concentration (black lines in Figure 3 a and b). In contrast, the shortwave SOR forcing peaks at two poles as shown in Figure 3 c and d, which is caused by the higher local ozone concentration.

4.2 Stratospheric adjustment

Ozone heats the stratosphere due to its absorption of solar radiation. Here, the stratospheric adjustment, i.e., the radiative impact due to stratospheric warming in response to SOR, is calculated using a kernel method, following Zhang and Huang (2014) and Huang et al. (2016). The stratospheric temperature kernels of Shell et al. (2008) are used here. The stratospheric temperature change is calculated as the temperature difference between the 1979 and 2000 equilibrium integrations. As higher stratospheric temperatures mean more thermal radiation radiated to the space, stratospheric adjustments evaluated here are negative in both experiments (see Figure 3 a and b). Nevertheless, the stratosphere-adjusted forcing (SAF, i.e., instantaneous forcing plus stratospheric adjustment) remains positive in both NCNSI (0.30 W m^{-2}) and Standard experiments (0.29 W m^{-2}). In addition, we also calculate the SAF with RRTMG using the fixed dynamical heating method (Ramanathan and Dickinson,

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1979), and find the SAF in the Standard experiments to be 0.21 W m^{-2}, which is in agreement with the kernel method. Note that as discussed by Huang et al. (2016), the adjusted forcing evaluated using TOA flux equals that evaluated using tropopause flux if the stratosphere adjusts to a radiative equilibrium. The fact that the stratosphere-adjusted forcing is positive indicates that the weak cooling in the Standard experiment is not predictable from SAF, but is influenced by tropospheric adjustments.

4.3 Tropospheric adjustments

Here we analyze the radiative contributions by other atmospheric and surface variables, namely temperature, water vapor, sea-ice (albedo) and clouds, mainly using the kernels of Shell et al., (2008). Note that the radiative effect of clouds is obtained using the cloud forcing adjustment method that incorporates the instantaneous forcing and stratospheric adjustment calculated above (c.f. Huang (2013) and Huang and Zhang (2014)).

In the Standard experiment, we find the radiative effects of clouds and sea-ice to be strongly negative (-0.39 and -0.10 W m^{-2}, respectively; see Table 1). The cloud effect consists of -0.26 W m^{-2} in the longwave and -0.13 W m^{-2} in the shortwave, which is in good agreement with the 0.25 W m^{-2} effect in response to stratospheric ozone depletion reported by Grise et al. (2013). This cloud radiative effect offsets the warming effect of SOR forcing (a SAF of 0.29 W m^{-2}). As a result, there is a weak global cooling in surface temperature (-0.06 K). The radiation budget is balanced by the positive radiation changes (reduction of outgoing radiation) caused by the surface cooling (0.08 W m^{-2}) and by atmospheric temperature and water vapor changes (-0.04 and 0.10 W m^{-2}, respectively).

In order to separate the fast adjustments in the troposphere from surface temperature-related feedback effects, we conduct a SOR experiment using CAM3 with fixed SST and sea ice (Fixed-SST/SI). Two simulations forced with prescribed climatological SST and SI averaged over the years 1980-2000 are performed with different ozone concentrations as described above. The stratosphere and troposphere-adjusted forcing (effective radiative forcing, ERF) is obtained by contrasting the averages over the last 15 years of the two 35-year integrations. The ERF is found to be 0.01 W m^{-2}, consisting of an instantaneous forcing of 0.60 W m^{-2}, a stratospheric adjustment of -0.31 W m^{-2}, and a tropospheric adjustment of -0.28 W m^{-2} (which is mainly contributed by clouds: -0.25 W m^{-2}) (Table 1). Evident from these results, the cloud radiative effect in the

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Standard experiment is largely a tropospheric adjustment, which together with the stratospheric adjustment offsets instantaneous forcing of ozone and results in a neutralized ERF.

In comparison, in the NCNSI experiment, without the offsetting negative radiative effects of clouds and sea ice, a significant global warming (0.2 K) results from the SOR forcing, which gives rise to a radiative effect of -0.26 W m^{-2}. The water vapor feedback in this experiment is strong and positive (0.77 W m^{-2}), although it is offset by the atmospheric temperature feedback (-0.77 W m^{-2}).

In summary, these results show that significant radiative cooling effects caused by the adjustments of clouds and sea ice in response to SOR explains the weak global cooling in the Standard experiment.

4.4 Surface radiation budget

Complementary to the TOA radiation budget decomposition, we also analyze the surface radiation flux change driven by SOR. Figure 4 shows the changes in the surface radiation budget from the 2000 equilibrium integration relative to the 1979 equilibrium integration. The changes in the net surface shortwave radiation in both experiments can be explained by ozone absorption of UV radiation. In the NCNSI experiment, the global and annual mean reduction is -0.60 W m^{-2}. The maximum reduction reaches -2.4 W m^{-2} in the Northern Hemisphere and -1.6 W m^{-2} in the Southern Hemisphere. Both occur at high latitudes in summer because of the largest stratospheric ozone increases there. In the Standard experiment, the global and annual mean reduction is -0.62 W m^{-2}. Compared to the NCNSI experiment, the duration and spatial coverage of the net shortwave radiation change is also significantly modified by clouds and sea ice (Figure 4 g and j). Here we measure the cloud radiative effect (CRE) by the difference between the all-sky and clear-sky surface radiation. The changes in longwave and shortwave CRE in response to SOR are shown separately, with global and annual mean values of -0.26 W m^{-2} and 0.04 W m^{-2}, respectively. The radiative effect of sea ice is measured as the surface radiation change caused by surface albedo change, i.e., climatological surface downward shortwave radiation times surface albedo change. The global mean shortwave radiation change due to albedo change is measured to be -0.11 W m^{-2}.

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The greenhouse effect of ozone enhances the surface downward longwave radiation. This enhancement is augmented by the atmospheric warming and moistening in the NCNSI experiment, which altogether overrides the cooling effect of ozone in the shortwave (Figure 4 c). The global and annual mean net radiation change is +1.1 W m^{-2}. This explains the surface warming in this experiment. In comparison, the enhancement in the downward longwave radiation in the Standard experiment is less strong and limited to low latitude regions. This is mainly because of a strong negative change in cloud forcing (Figure 4 h). The global and annual mean net radiation change is -0.72 W m^{-2}, which explains the global cooling in this experiment.

In summary, the surface temperature responses in both experiments (Figure 2 a and b) are consistent with the changes in the net radiation at the surface (Figure 4 c and f). The comparison between the NCNSI experiment and the Standard experiment again highlights impacts of clouds and sea ice on the radiation budget, which can override the initial radiative perturbation of ozone and lead to different surface temperature responses. We will elaborate this point in the following section.

5 The roles of cloud and sea ice

Figure 2 e shows the response of the cloud fraction in the Standard experiment. There is general reduction in cloud fraction, especially for those high clouds near the tropopause. The decrease in high clouds is associated with a decrease in relative humidity caused by the SOR warming of the upper-troposphere and lower-stratosphere (Jenkins, 1999;Yang et al., 2012), which is consistent with the significant increase in UTLS cirrus clouds resulted from in-situ ozone depletion in Nowack et al. (2015). This then accounts for the aforementioned negative TOA longwave cloud radiative effect (Table 1; Figure 3) and the negative change in CRE at the surface (Figure 4 h).

On the other hand, the responses of the middle- and low-level clouds are consistent with the SOR-forced equatorward shift of the eddy-driven westerly jet in the southern hemispheric mid-latitudes (see the review by Thompson et al. (2011)). This occurs especially during late spring and summer in the Southern Hemisphere. As the jet shifts, the associated storm track, precipitation, and cloud patterns follow. So cloud fraction decreases in the subtropical region (20°S-40°S), increases in the middle latitudes (40°S-60°S), and decreases in the polar region (higher than 60 degree). This then impacts the radiation budget, as documented by Grise et al. (2013). As shown by the TOA radiative effect of cloud (Figure 3 d) and surface CRE (Figure 4 g), there are strong shortwave radiation anomalies that oscillate with the latitude. We find that these radiation anomalies are largely accounted for by the redistribution of liquid cloud and have very small southern-hemispheric mean values: 0.04 W m^{-2} for surface radiation and -0.13 W m^{-2} for TOA radiation. Although SOR has a positive radiative forcing, the cloud changes due to SOR induce a net cooling effect on the climate system, which is consistent with the results in Grise et al. (2013).

Sea-ice response is important for the surface radiation budget in both polar regions. Arctic sea ice increases in boreal summer and autumn and Antarctic sea ice increases throughout the year (Figure 4 j). These increases cause considerable decreases in net shortwave radiation at surface, thus acting to cool surface temperature. Recent studies suggest that the Antarctic ozone hole has important influences on Antarctic sea ice (Sigmond and Fyfe, 2010;Bitz and Polvani, 2012;Smith et al., 2012). The large sea ice and radiation changes seen here affirm such ozone impact.

In order to isolate and compare the effects of clouds and of sea-ice, we apply the same techniques as used in the NCNSI experiment to suppress cloud and sea ice effects respectively in two additional experiments. We find that the global mean surface temperature response to SOR is 0.18 K in the No-Cloud experiment and is 0.03K in the No-Sea Ice experiment, which confirms that the suppression of the warming effect of the SOR is largely due to clouds.

6 Discussion and conclusion

The Standard and NCNSI experiments conducted here suggest that clouds and sea ice are sensitive to stratospheric ozone perturbations and their radiative effects are critical for predicting surface temperature changes. Although the stratosphere-adjusted forcing of SOR is positive in both experiments, the warming effect of ozone recovery is offset by the cooling effect caused by high-cloud reduction and sea ice increase in the Standard experiment, which results in a weak global cooling. In addition, SOR also causes equatorward shift of jet stream, precipitation and mid- and low-clouds, especially in the southern hemisphere, which results in dipole patterns of zonal mean surface shortwave radiation anomalies and corresponding temperature anomalies.

The cloud and sea ice changes in the Standard experiment emerge as significant signals in response to the SOR forcing. The reduction of high clouds can be attributed to ozone-induced radiative warming and consequent relative humidity reduction in upper troposphere and lower stratosphere, in accordance with the findings of (Jenkins, 1999;Yang et al., 2012). The sea ice changes in the Arctic and around the Antarctic are influenced by ozone-induced indirect radiative effects, which are associated with the reduction of downward infrared radiation over the sea ice edge caused by the in-situ decreases of clouds and water vapor, and also the atmospheric cooling (Hu et al., 2016). The strong sea ice response to SOR forcing suggests the ongoing SOR would mitigate Antarctic sea-ice loss from greenhouse warming in 21st century (Smith et al., 2012).

Although an isolated SOR forcing as prescribed in our experiments is hypothetical, this forcing scenario makes a very unusual case of climate change in that the radiative forcing is positive (a warming effect) but the surface temperature response is negative (cooling). The key factor that leads to the breakdown of the prediction appears to be a significant high cloud change directly resulting from the forcing. Although this result is mainly based on one GCM, a suit of experiments and diagnoses here suggest that this may be a significant rapid adjustment to stratospheric ozone forcing and may have important implications such as for climate projection and geo-engineering. It warrants further research to verify whether the cloud and sea ice responses to stratospheric ozone are robust across different GCMs and whether the responses are sensitive to details in the prescription of ozone change.

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Table 1. Radiative forcing and adjustments, evaluated at the top of the atmosphere. The columns indicate the instantaneous radiative forcing (IRF) of O_3, the stratosphere-adjusted forcing (SAF), the effective radiative forcing (ERF, i.e., stratosphere and troposphere-adjusted forcing), the stratospheric adjustment, and the radiation changes caused by cloud, sea-ice, atmospheric temperature (T_A), water vapor (WV), and surface temperature (T_S), respectively. Unit: W m^{-2}.

	IRF of O3	SAF	ERF	Stratospheric adjustment	Tropospheric/surface radiative effects				
					Cloud	Sea-ice	T_A	WV	T_S
NCNSI	0.49	0.30	N/A	-0.19	N/A	N/A	-0.77	0.77	-0.26
Standard	0.60	0.29	0.01	-0.31	-0.39	-0.10	-0.04	0.10	0.08
Fixed-SST/SI	0.60	0.29	0.01	-0.31	-0.25	N/A	-0.15	0.12	N/A

Figures

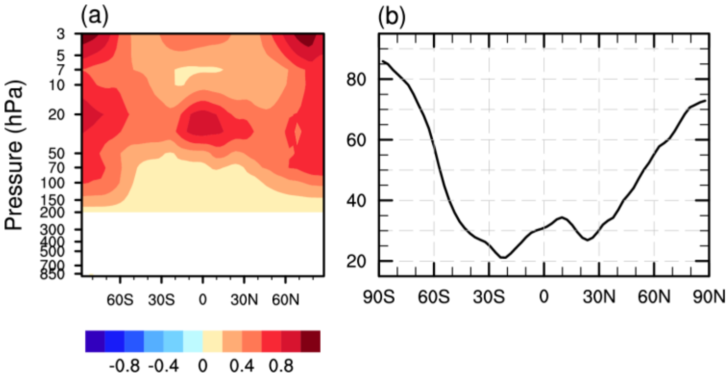

Figure 1. The distribution of SOR. (a) The vertical cross section of the annual- and zonal-mean difference of ozone, unit: ppmv. (b) The annual- and zonal-mean difference of total column ozone, unit: DU.

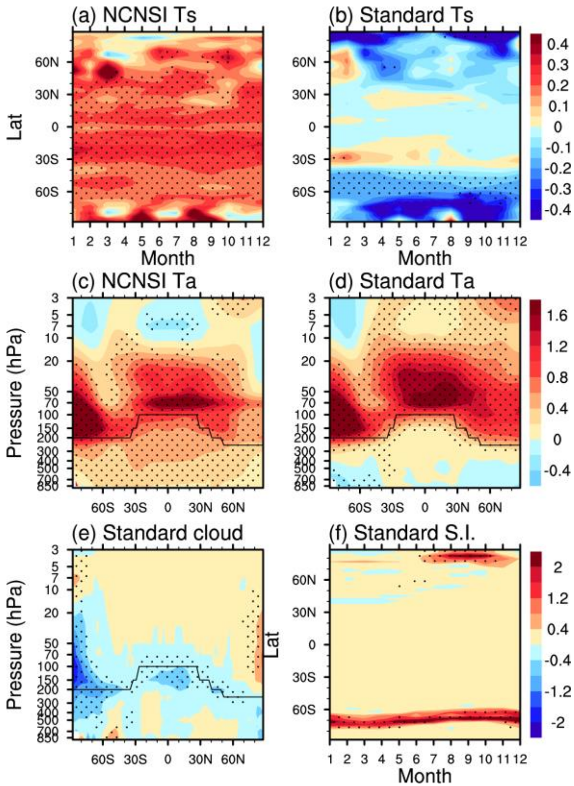

Figure 2. Responses to SOR of zonal mean surface temperature, annual- and zonal-mean air temperature, annual- and zonal-mean cloud fraction, and zonal mean sea-ice fraction. Latitude-month distribution of surface temperature in the (a) NCNSI, and (b) Standard experiment. Vertical cross section of air temperature in the (c) NCNSI, and (d) Standard experiment. (e) Vertical cross section of cloud fraction, and (f) latitude-month distribution of sea-ice fraction in the Standard experiment. In (a, b), the color interval is 0.05 K. In (c, d), the color interval is 0.2 K. In (e-f), the color interval is 0.4%. Regions with dots are the places where differences have statistical significant levels higher than the 95 % confidence level (student t-test values are greater than 2.0). Black line in (c-e) indicates the tropopause of climatology.

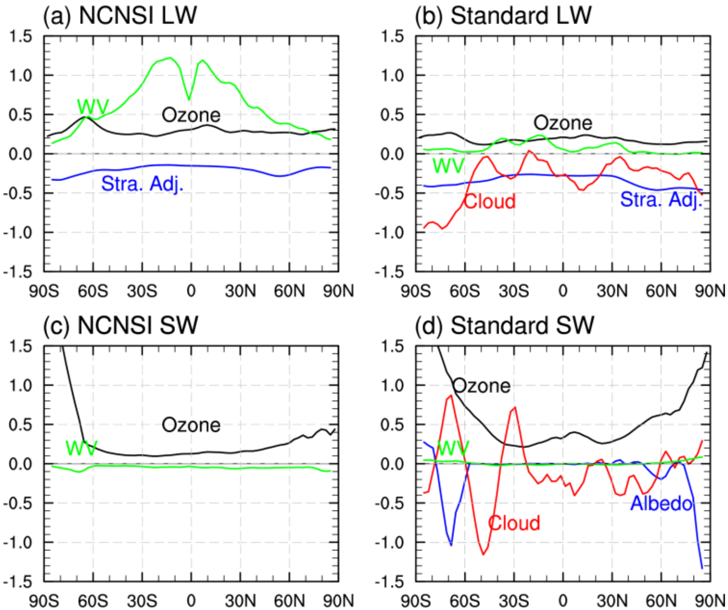

Figure 3. Annual- and zonal-mean distribution of the radiative contributions at TOA for the NCNSI experiment: (a) longwave radiation: stratospheric temperature adjustment (blue line), ozone (black line), and water vapor (green line), (c) shortwave radiation: ozone (black line), and water vapor (green line). And for the Standard experiment: (b) longwave radiation: stratospheric adjustment (blue line), ozone forcing (black line), water vapor (green line), and radiative effect of cloud (red line); (d) shortwave radiation: ozone forcing (black line), water vapor (green line), cloud (red line) and ice-albedo (blue line) effects. Negative/positive values indicate upward/downward radiative flux at TOA. The radiative forcing of ozone are calculated with RRTMG.

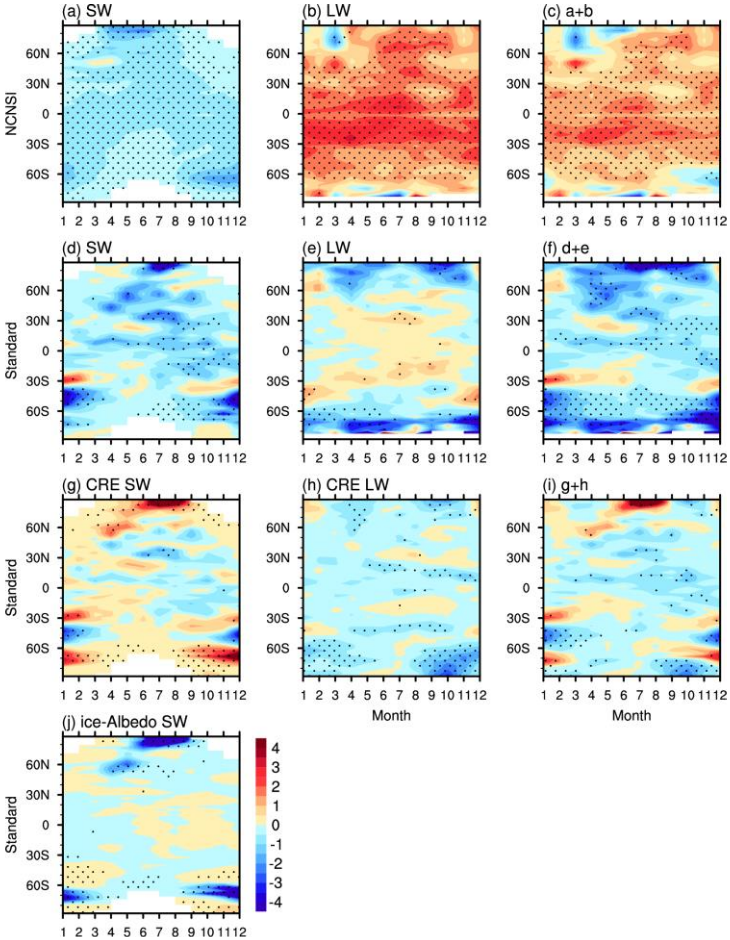

Figure 4. The latitude-month distribution of the responses to SOR of the zonal mean surface radiation budget. (a) Net shortwave, (b) downward longwave, and (c) a+b in the NCNSI experiment. (d) Net shortwave, (e) downward longwave, and (f) d+e in the Standard experiment. (g) Shortwave CRE, (h) longwave CRE, and (i) g+h in the Standard experiment. (j) The albedo-induced surface radiation in the Standard experiment. Color interval is 0.5 W m^{-2}.