

Interactive comment on “Radiative effects of ozone on the climate of a Snowball Earth” by J. Yang et al.

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Received and published: 31 October 2012

Reply to the review by M. Ishiwatari on “Radiative effects of ozone on the climate of a Snowball Earth” by J. Yang, Y. Hu and W. R. Peltier

We thank Dr. M. Ishiwatari for the very careful review, which will help us to further improve the manuscript. Our replies to the specific comments of the referee are as follows.

1. Comment: “As described in this paper, the changes of atmospheric/surface temperature with change of radiative forcing strongly depend on snow-albedo feedback and water-vapor feedback. The efficiency of these feedback processes largely change with implementations of parameterization scheme of physical processes in GCM. . . .

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a set of values of temperature change obtained by only one experiment contains large uncertainties. In order to understand the dependence of temperature on ozone concentration in Snowball states, much more experiments and analysis should be needed. At least, model ensemble experiment will be needed as performed in global warming problem (ex. IPCC report).”

Reply: We agree that it would be better to carry out more simulations to test the effect of the ozone layer with different ozone concentrations. However, the purpose of the paper is not to test the sensitivity or uncertainty of atmosphere/surface temperature responding to weak ozone changes and other physical parameterizations. Instead, we are interested in characterizing the temperature response to an expected large ozone reduction (by about half) and want to understand whether such an ozone reduction has negative radiative forcing on surface temperatures. Our results demonstrate that such a large ozone reduction does indeed result in negative radiative forcing on surface temperature. The simulations described in our paper are also idealized simulations (based upon the reduction of ozone concentration by 50%), without detailed consideration of ozone chemistry and its coupling to air temperature. Simulations of this kind are not of IPCC type, which involve the analyses of realistic scenarios intended to address the sensitivity of model projections (of surface warming for example). Our goal rather is to investigate, for an epoch of the deep geological past, the impact that an expected large variation in ozone concentration might be expected to have on the bifurcation point beyond which the global climate system might be expected to transition into an entirely ice-covered state. Ensemble analyses of IPCC type would be entirely premature in the context of the issue we are attempting to address.

2. Comment: “... the worth of this paper is, in my opinion, that opposing effects in one GCM are analyzed. . . ., I consider that the results of analysis for opposing effects in some feedback processes should be emphasized in Abstract and Conclusion, in addition to the description of the values of temperature change written in current manuscript. Moreover, remarks on uncertainties of model and on a necessity for model

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ensemble experiment might be added to Conclusion”.

Reply: We agree with the comment, and we will emphasize the changes of radiative fluxes and the effects of snow-albedo, water-vapor and cloud feedbacks in both the Abstract and Conclusions of the revised manuscript.

3. Comment: “I could not understand what are plotted in Figure 4. I feel that more explanations are needed for both of SW and LW, for example, detailed calculation methods for SW and LW.” “My guess is that SW plotted in Figure 4 is the difference of downward short wave radiation at tropopause for case with ozone and without ozone. If my guess is correct, I cannot understand the physical meaning of $Net = SW + LW$; SW is obtained as model difference while LW is a results of case with ozone.” “p3591 l26-27: I cannot understand the reason why surface albedo influences Net radiation. I imagine that this problem is caused by my misunderstanding for SW. I hope that some description are added.”

Reply: In Figure 4, SW is shortwave absorption by the stratosphere multiplied by tropospheric coalbedo. The tropospheric coalbedo is 1.0 minus the albedo at the tropopause. Only a part of the shortwave absorption by the stratosphere is meaningful for the troposphere and surface, the remainder will be scatted/reflected back to the space by the troposphere and surface if there were no stratosphere. For example, assume that under present-day conditions, the stratosphere absorbs 10 Wm^{-2} solar radiation, which reduces the radiation reaching the troposphere-surface system. The troposphere-surface system would reflect $\sim 30\%$ of this radiation if it were not absorbed by the stratosphere so that the actual loss of solar radiation to the troposphere and surface is only two-thirds of that absorbed in the stratosphere, i.e. 7 Wm^{-2} . This method is the same as that employed by Ramanathan and Dickinson (1979), which the referee might like to consult for further detail concerning this standard methodology.

Surface albedo contributes to the albedo at the tropopause and thereby affects SW and Net. LW is downward longwave emission from the stratosphere to the troposphere.

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Both SW and LW are taken from the same numerical experiment. This has been addressed in Table 1 of the paper, but following the suggestion of the referee we will emphasize this further in the caption of Figure 4.

4. Comment: “* p.3592 l24-25: Why the longwave radiation decreases in polar region? It may be good to add the reason to manuscript.”

Reply: This question concerns the “50%_Lower_WBD” scenario. In this scenario, the most significant decrease of ozone concentration is within the polar region. Therefore, the largest decreases of air temperature of the stratosphere are also over the polar region as shown in Fig. 3e of the paper, which acts so as to reduce the longwave radiation from the stratosphere to the troposphere.

References: [1] Ramanathan, V. and Dickinson, R. E.: The role of stratospheric ozone in the zonal and seasonal radiative energy balance of the earth-troposphere system, J. Atmos. Sci., 36, 1084-1104, 1979.

Interactive comment on Clim. Past Discuss., 8, 3583, 2012.

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