Reply to the review of J. Kasting on "Radiative effects of ozone on the climate of a Snowball Earth"
By J. Yang, Y. Hu and W. R. Peltier
Oct. 9, 2012

First, we thank J. Kasting for his helpful comments.

1. Kasting's Comment: "The radiative effects of ozone are, however, dwarfed by the radiative effects of CO_2 and clouds. Since we do not know the CO_2 concentration at that time, and since cloud forcing is difficult to calculate accurately, the largest uncertainties lie in those factors, not in the ozone forcing."

Reply: We agree that the radiative effects of ozone are smaller than those of CO_2 and clouds. Although relatively small, it is also significant. As we addressed that as ozone concentration is uniformly decreased by 50%, the CO_2 threshold for the initiation of a Snowball Earth decreases by 50% and meanwhile the CO_2 threshold for the deglaciation of a Snowball Earth increases by 30%. Therefore, the influences of ozone should be considered.

2. Kasting's Comment: "Even more importantly, there are alternative models or Snowball Earth, e.g. the thin-ice model of McKay (2000) and Pollard and Kasting (2005), or the Jormungand model of Abbot et al. (2011), that have much lower albedo in the tropics, and hence which deglaciate much more easily. The main goal at this point should be to decide which, if any, of these models represents the most plausible solution to the Neoproterozoic climate problem".

Reply: We had also already realized the two alternative models, the thin-ice solution and the Jormungand climate state. Actually, we have sent a paper draft (*Yang et al. 2012, in review*) to J. Geophys. Res.-Atmos in which the possibility of the Jormungand climate state has been discussed. For the thin-ice model, we think it has been well re-examined by other authors, such as *Warren and Brandt (2006)*.

3. Kasting's Comment: "One minor technical comment on the paper, which is otherwise generally well done: On p. 3587, the authors state "… a decline of stratospheric ozone would decrease stratospheric temperature and downward IR emission, causing a cooling of the troposphere and surface." References are given to two previous papers by other authors. This statement may be true although I have not checked it with my own model. But, if so, it cannot be for the reasons given. Decreasing stratospheric ozone should allow solar ultraviolet radiation to penetrate more deeply into the atmosphere. Assuming that it is absorbed, rather than backscattered, allowing UV radiation to penetrate more deeply can only warm the surface, as the region that is heated should radiate less energy to space. But if some of that near-UV radiation is backscattered, and hence reflected to space, when stratospheric ozone is reduced, then the effect may well be to cool the surface."

Reply: We agree that as the stratospheric ozone concentration decreases, it would allow more UV radiation to penetrate to surface. But, at the same time, the stratospheric temperature decreases, which reduces the IR emission from the stratosphere to the surface. The net effect depends on the competition of the two parts. In the subsection 3.2 "Radiative Fluxes and Feedbacks" of this paper draft and in other papers of various authors (*e.g., Ramanathan and Dickinson, 1979*), it has been clearly addressed that the reduction of IR emission excesses the increase of UV radiation for both the present-day Earth and a Snowball Earth; therefore, the surface temperature decreases.

References:

[1] Warren, S. G. and R. E. Brandt, 2006: Comment on "Snowball Earth: A thin-ice solution with flowing sea glaciers" by David Pollard and James F. Kasting. *J. Geophys. Res.,* **111**, C09016, doi:10.1029/2005JC003411.

[2] Yang, J., Y. Liu, W. R. Peltier, and Y. Hu, 2012: The deglaciation of near Snowball Earth states revisited, *J. Geophys. Res.-atmos., in Review*.

[3] 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.