

Interactive comment on “Uncertainty of the CO₂ threshold for melting a hard Snowball Earth” by Y. Hu and J. Yang

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Reply to Prof. Kasting's reviews on “Uncertainty of the CO₂ threshold for melting a hard Snowball Earth”

We thank Prof. Kasting's instructive reviews on our manuscript, which are critically important for improving the paper, especially on the issue of pressure-induced and collision induced CO₂ absorption. Replies to reviews are as follows.

1. First, and most importantly, the model assumes a constant, 1-bar surface pressure (as far as I could tell I did not see this pointed out explicitly). This same invalid assumption was made by Pierrehumbert (2004, 2005), and it is the main reason why his model failed to deglaciate from a hard Snowball. When you outgas a few tenths of

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a bar of CO₂ into a 1-bar atmosphere, the surface pressure does not remain at 1 bar. It increases! This makes a substantial difference to the amount of greenhouse warming that is predicted. I pointed this out in my review of Abbot and Pierrehumbert (JGR, 2010), referenced in this manuscript, and my comment is acknowledged in their paper as a personal communication. What they say, actually, is that the change in surface pressure doesn't make much difference below 0.1 bar of added CO₂. But what this implies, and what the figure I sent to them shows, is that it does make a big difference above 0.1 bars. The present calculation goes to 0.2 bars, and the underestimate of the greenhouse effect is significant. If I had access to the figure that I sent to Dorian Abbot, I would attach it here. Unfortunately, I'm off on sabbatical, and I don't have access to my home computer. Perhaps the authors could obtain this from Dorian.

We agree that the contribution of CO₂ partial pressure to the total surface pressure is important, and that the increase in total surface pressure would lead to pressure-broadening of CO₂ absorption. In addition, collision-induced absorption of CO₂ is also important as CO₂ level is sufficiently high.

Following the suggestion by Prof. Kasting, we have modified the model we used (CAM3), by considering the contribution of CO₂ partial pressure to total surface pressure. The radiation module of CAM3 includes pressure-broadening of CO₂ absorption. We re-run the model for various CO₂ levels, with consideration of pressure broadening, and results are shown in Figure 1a (below). Comparison of the results here with that in Figure 1b in the previous manuscript demonstrates that surface temperatures have no significant differences as CO₂ volume mixing ratio is less than 0.1. However, as CO₂ volume mixing ratio is greater than 0.1, global- and annual-mean, equatorial annual-mean, and January maximum surface temperatures are about 8, 6.7, and 3.2 K higher than our previous results, respectively. These suggest that CO₂ contribution to total pressure and pressure broadening of CO₂ absorption are indeed important for studying the CO₂ threshold for melting the hard Snowball Earth, and that deglaciation of the Snowball Earth could happen at the CO₂ level of 0.37 bar (CO₂ volume mixing

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ratio equals to 0.2).

Since CAM3 does not include the effect of collision-induced CO₂ absorption, we use the radiative-convective model developed by Prof. Kasting and his colleagues and examine the effects of both pressure-broadening and collision-induced absorption (CIA) on surface temperatures. Results are shown in Figure 2. It is found that the effect of CIA can cause another 6 K and 10 K increases in surface temperatures for CO₂ mixing ratio of 0.1 and 0.2, respectively. The dashed-square line suggests that about 0.18 bar of CO₂ (volume mixing ratio equals to about 0.12) is sufficient to melt the Snowball Earth. We have got the plot by Prof. Kasting from Dr. Dorian Abbot. Our simulation results of surface temperatures actually have higher values than Prof. Kasting's.

These results and relevant discussion will be added to the revised version.

Related issues: i) What surface pressure assumption did LeHir et al. (2007) use? This should be checked. ii) (p. 132) "Indeed, further increasing CO₂ results in T_{Bot} asymptotic to 271.35 K." This result is misleading, as it is entirely the result of the constant 1-bar surface pressure assumption. Note that the variation in surface pressure was done correctly by Caldeira and Kasting (1992). They based their EBM on 1-D calculations published by Kasting and Ackerman (Science, 1986). In that calculation (which was not for a Snowball Earth), we ran pCO₂ up to 100 bar for both present and early Earth. The greenhouse effect of CO₂ does not become asymptotic at high CO₂ levels. Rather, it accelerates as the atmosphere becomes thicker. Venus is a good example of this phenomenon.

For issue i), we did not think that Le Hir et al. (2007) considered the contribution of CO₂ partial pressure to the total pressure. They never mentioned such an issue in their paper. The reason why they got higher surface temperatures than ours and Pierrehumbert's is because their model has very strong cloud forcing. The positive cloud forcing at 330 ppmv of CO₂ is up to 50 Wm⁻². CAM3 never reached such a large cloud forcing.

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For issue ii), it is our fault that we did not make the statement clear. The asymptotic behavior is because of the prescription of sea-ice, which requires that surface temperature must be below -1.8°C. For low levels of CO₂, surface temperatures increase with increasing CO₂. For very high levels of CO₂, however, the prescribed sea-ice acts as a cooling source that maintains surface temperature below -1.8 °C. The asymptotic behavior does not mean that further increasing CO₂ does not lead to increase in surface temperature. The same method was also used by Le Hir et al. (2007). We will address this statement clearer in the revised version.

2. Second major point: The authors do not acknowledge the existence of a second type of Snowball Earth solution, namely, the "thin-ice" model. This model was first proposed by Chris McKay (GRL, 2000) and later elaborated by Pollard and Kasting (2005, 2006). This model, which is discussed also by Abbot and Pierrehumbert, deglaciates at a much lower CO₂ level than any of the hard Snowball models. The reason is that the ice is thin in the tropics, allowing sunlight to penetrate (and thereby keeping alive the algae and subsurface biota), and also lowering the surface albedo. It is disingenuous to write a paper about the difficulty in deglaciating a hard Snowball Earth without pointing out that there is a competing model that does not have this problem.

Since our main interest in the present paper is to demonstrate model-dependence of CO₂ thresholds for melting the hard Snowball Earth, we did not consider other types of Snowball Earth, such as slushball or the "thin-ice" model. Following the suggestion, we will add discussion to the revised version on other types of "Snowball Earth".

We have actually carried out simulations for thin ice in the tropics, slushball, and open ocean in the tropics. These results will be summarized in a separated paper which will mainly focus on how high surface temperature could reach during the aftermath of the Snowball Earth.

Figure caption Figure 1. (a) January zonal-mean maximum, equatorial annual-mean, and global annual-mean near-surface temperatures as a function of CO₂ mixing ratios,

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simulated by CAM3. Here, surface air pressure increases with increasing CO₂ volume mixing ratio, and pressure-broadening of CO₂ absorption is considered. (b) Surface air pressure as a function of CO₂ volume mixing ratio.

Figure 2. Surface temperature as a function of CO₂ volume mixing ratio, simulated with the radiative-convective model developed by Kasting (see <http://vpl.astro.washington.edu/sci/AntiModels/models09.html>). Dashed-dotted-circle line: surface air pressure (Ps) remains constant, i.e., 1 bar, solid black-square line: Ps increases with increasing CO₂ volume mixing ratio, with pressure-broadening of CO₂ absorption considered, and dashed-square line: Ps increase with increasing CO₂, with both pressure-broadening and collision-induced absorption of CO₂ considered. The solar constant is 94% of the present, surface albedo is 0.663, zenith angle is 60°, and the moist adiabatic process is applied.

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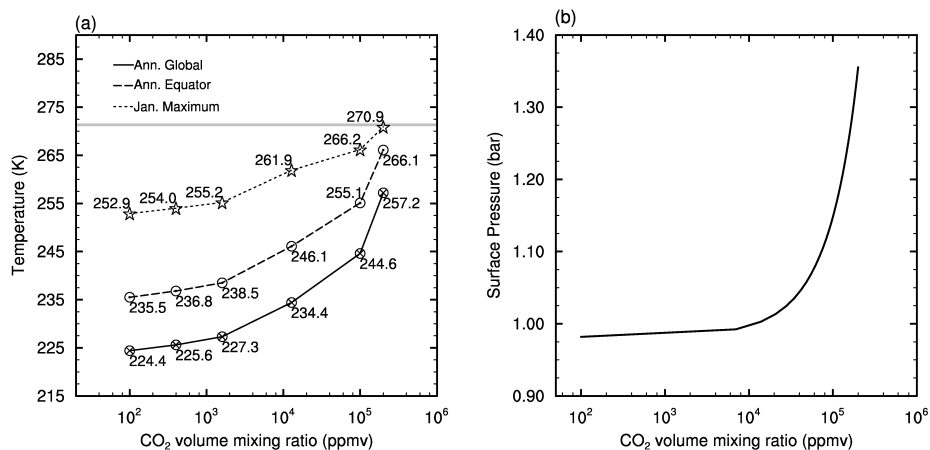


Fig. 1.

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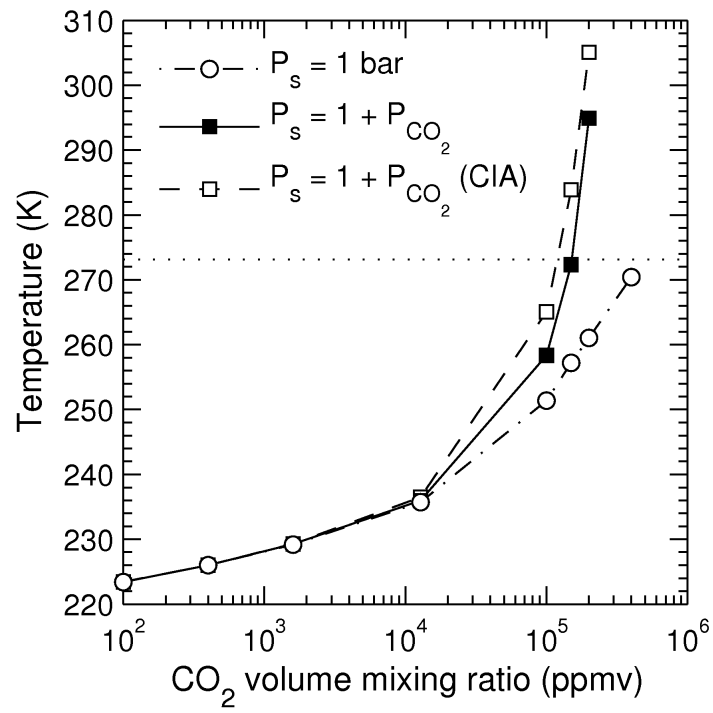


Fig. 2.