Dear Editor and Referees,

Thank you very much for handling the review on our manuscript "Examining the role of varying surface pressure in the climate of early Earth" (No. cp-2020-55). Your comments have been very helpful for improving the manuscript. In the following, we present replies (in black) to your comments (in blue). Following your comments and suggestions, we have made improvements in the revised manuscript (in red face; we will submit the revised manuscript soon if applicable).

Sincerely,

Jun Yang and Junyan Xiong,

April 30, 2021

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Response to Referee #2 cp-2020-55-RC1:

The paper is well written and presents clearly results concerning solutions to the Faint Young Sun Problem (FYSP). However, I identified a fundamental issue requiring clarification. Indeed, the authors use ClimT model, an Earth system modelling toolkit, and CAM3 (a General Circulation Model) for investigating extreme climate conditions without presenting diagnostics showing the validity of their radiative scheme. For instance, the collision-induced absorption is of great importance to the overall radiative budget in dense atmospheres, but its representation in climate models remains uncertain. If RRTGM (the radiative scheme implemented in ClimT) is a state of the art radiative transfer code (and used in many climate models), that not means that this component is adapted for this specific purpose mainly due to a lack of accurate experimental and theoretical data to explore the early Earth (and especially the surface pressure). This point is not easy to solve which explains why I recommend "rejected" rather than "major revision". If the authors want to solve this issue, the methodology is described in Wolf and Toon 2013 (study also using CAM3). Consequently sections 2.1 and 2.2 should describe the general behavior of the radiative schemes AND sets of results demonstrating the validation.

Reply: Thank you very much for the comments on radiative transfer module used in this study. Referee #1 also has the same concern. Our reply is as follows: In Yang et al. (2016), they compared the radiative transfer module of CAM3 with other radiative transfer models as well as two line-by-line radiative transfer models (SMART and LBLRTM). The results are shown in Figures A1 and A2 below. These comparisons showed that at low temperatures, the differences among the models are small, but at high temperatures (>320 K), the differences are relatively large. At 280 K, differences in longwave and shortwave radiation fluxes under clear-sky conditions between CAM3 and the two line-by-line radiative-transfer models are around 10 W m^{-2}, and at 300 K, it is less than 15 W m^{-2}. The upper limit of CO_2 amount that CAM3 can well simulate is about 0.1 bar (Pierrehumbert 2005; Abbot et al. 2013); most of our experiments shown in the manuscript are close to or less than this level.

In the study here, most of our simulations have surface temperatures equal to or lower than 310 K (except the 4.0 bar experiments within which the global-mean surface temperature is higher than 310

K, see in Table 1 of the manuscript), so the model CAM3 is roughly suitable for investigating the effects of varying surface pressure, although the radiative transfer module is not as accurate as other general circulation models (such as LMDG and CAM4_Wolf) and the two line-by-line radiation transfer models.

Of course, we agree that a better radiative transfer module should be employed in the faint young sun problem; but, this does not totally negate the value of this manuscript. The accuracy of the model in H_2O and CO_2 radiative transfer would not essentially influence the conclusion of this study. Overall, the results of this study are consistent with basic radiative transfer theories and with previous studies such as Wolf and Toon (2013, 2014), as shown in Table 2 of the original manuscript (or Table 3 of the revised manuscript). In the next step of this project, we will use the model CAM4_Wolf or called ExoCAM (developed by Dr. Eric T. Wolf, same as that used in Wolf and Toon (2013, 2014)) and we will compare the results between ExoCAM and CAM3.

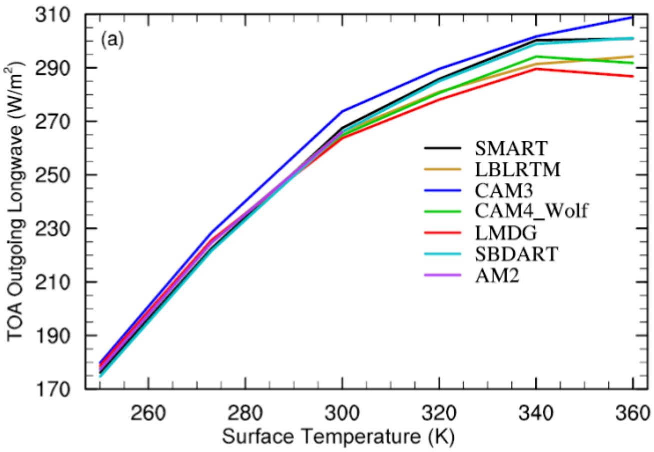

Figure A1. Outgoing longwave radiation at the top of the atmosphere for different radiative transfer models. CAM3, CAM4_Wolf, LMDG, and AM2 are the radiation transfer modules used in atmospheric general circulation models; SBDART is an independent radiation transfer model; and SMART and LBLRTM are line-by-line radiation transfer models. The surface temperature is set to be 250, 273, 300, 320, 340, and 360 K. The atmosphere is assumed to Earth-like (1 bar N_2, variable H_2O, and 376 ppmv CO_2). The temperature structures are moist adiabatic profiles overlain by a 200 K isothermal stratosphere. The atmosphere is assumed to be saturated in water vapor (relative humidity is equal to 100%). The volume mixing ratio of water vapor in the stratosphere is set equal to its value at the tropopause. This figure is from Yang et al. (2016).

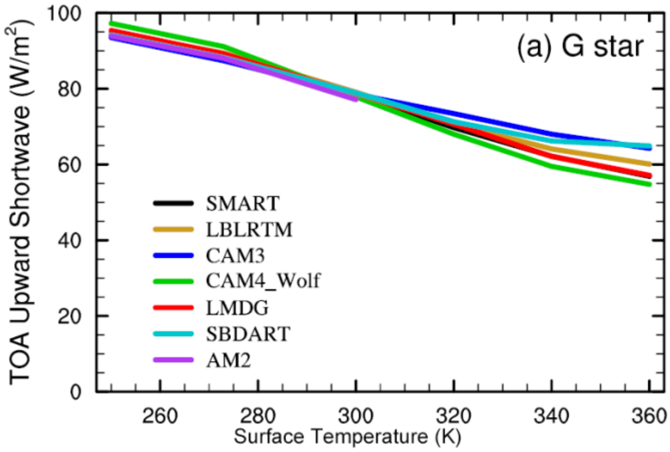

Figure A2. Upward shortwave flux at the top of the atmosphere (TOA) from different radiation transfer models. The experimental designs are same as those in Figure A1. The incoming stellar radiation at TOA is 340 W m^{-2}, and the solar spectra is used in these calculations. This figure is from Yang et al. (2016).

In addition, here is a list of suggestions to improve the manuscript

- line 4 p6. Why the obliquity is set to 0 ?

Reply: For the obliquity, we set it to be zero because we would like to omit the effect of seasonal cycle and because under this the pattern of ocean heat transport can be easily set up. We agree that this is a too simple design, and a higher obliquity (such as 23.5°) is more reasonable. A non-zero obliquity can influence the meridional gradient of solar radiation; for example, more solar radiation in high latitudes and less solar radiation in low latitudes for an obliquity of 23.5° than those for a zero obliquity. This could also influence the atmospheric circulation and clouds. Previous studies showed that the surface climate is warmer under a higher obliquity, due to the effects of ice albedo feedback, lapse rate feedback, and cloud feedback (Mantsis et al. 2011; Linsenmeier et al. 2015; Kilic et al. 2018; Nowajewski et al. 2018; Kang 2019). These suggested that the CO_2 and CH_4 concentrations for solving the faint young sun problem should be lower than those shown in this study, if a higher obliquity were used in the simulations.

Using the model CAM3, we do one test within which the planetary obliquity is increased from 0 to 23.5°. As shown in Figure A4, the global-mean surface temperature increases from 294.6 to 300.6 K, i.e., a 6.0 K warming in global mean. The trend and the magnitude of the warming are consistent with previous studies such as Linsenmeier et al. (2015). In future simulations, we will consider a non-zero obliquity, as shown in Figure A3 in page 6 of the reply to Referee #1.

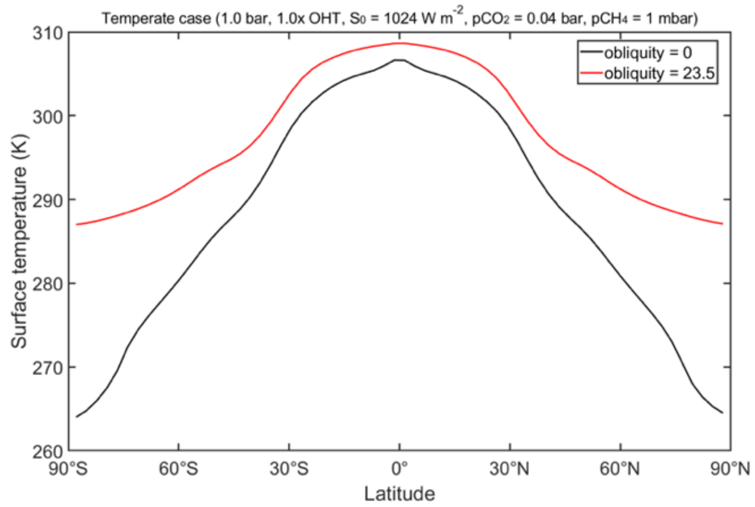

Figure A4: Annual- and zonal-mean surface air temperatures in two CAM3 simulations of different planetary obliquities: 0° for the black line and 23.5° for the red line. The background surface pressure is 1.0 bar, ocean heat transport is close to modern value, CO_2 partial pressure is 0.04 bar, and CH_4 partial pressure is 1 mbar. The global-mean surface temperature is 294.6 K for the black line and 300.6 K for the red line.

Moreover, an aqua-planet with no continent was used in this study because continental fraction during the Archean is likely much less than present and the detailed land-sea distribution was unknown (Flament et al. 2008; Hawkesworth et al. 2019).

- line 3 p5. Citations concerning the Eocene epoch are irrelevant here (to my knowledge the surface pressure is assumed held constant and the load in carbon dioxide does not overcome 1120 ppmv, so very far from values used in the present study)

Reply: Corrected. We deleted this sentence in the revised manuscript.

- p14 section 4.3. The discussion deserves more attention. As summarized by Charnay et al. 2020 (a review paper entitled “Is the FYSP for Earth Solved?”) the explanation of a temperate early Earth is not problematic anymore (as illustrated in the table 2 p15). Despite the cooling provided by the decreasing surface pressure (table 1 p5), this section does not conclude if the FYSP becomes more (or very) problematic to solve.

Reply: Thank you very much for pointing this out. We carefully read the paper of Charnay et al. (2020) and Catling and Zahnle (2020). These two papers completely renew our views on the faint young sun problem. (1) Geological constraints on CO_2 concentration during the Archean is still in debate, and possible ranges are 3-15 mbar in 2.69 Ga, 3-25 mbar in 2.5 Ga, 24-140 mbar in 2.77 Ga, 22-700 mbar in 2.75 Ga, or 45-140 mbar in 2.46 Ga (Driese et al. 2011; Sheldon 2006; Kanzaki and Murakami 2015). (2) The CO_2 concentration required to maintain a temperate climate at ~2.7 Ga is around 40 mbar under 1.0-bar surface pressure and 1 mbar CH_4 or less (Table 2 in the original manuscript). Under

0.5-bar surface pressure, the required CO_2 approximately doubles or triples, about 100-120 mbar, which is still in the range of geological constraints. (3) In the abstract of the revised manuscript, we clearly present this view: “The latter CO_2 concentration is about twice or triple the corresponding value under 1.0-bar surface pressure, but it is still within the range suggested by geological constraints.”

- p15 table 2 (Charnay et al. 2013 and Le Hir et al. 2014 both used a mixed-layer ocean (with Ekman transport for Charnay et al. so more complex than a standard mixed-layer model). please correct this point.

Reply: Corrected.

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