Dear Editor and Referee,

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 #3 cp-2020-55-RC2:

Focusing on the role of atmospheric pressure, Xiong and Yang present one possible solution for the faint young sun paradox. Overall, I think this contribution can move forward our understanding and I think it should eventually be published. However, I have several concerns and questions that I think should be addressed before publication (outlined below).

Reply: Thanks for comments and suggestions. Below, we reply to your comments point-to-point.

Major issues:

At page 2, line 21: First off, there is no geochemical proxy on atmospheric methane, so we simply don't know their upper or lower limit in the past. Second, Pavlov et al. (2001) on Archean kerogens didn't give an upper limit on methane concentration after their modelling exercise. Third, even if they did, many of the Archean kerogens are now believed to be contaminated by the oil drilling, therefore became an unreliable indicator for CO_2/CH_4 ratio.

Reply: We agree the referee's view on the concentration of CH_4. In the revised manuscript, we change the statement to: "Photochemical-ecosystem simulations suggested that CH_4 concentration should have been ranged from 100 to 35000 ppmv (Kharecha et al. 2005) or may be higher than 20 ppmv in > 2.4 Ga (Zahnle et al. 2006) or 5000 ppmv in ~3.5 Ga (Zahnle et al. 2019; Catling and Zahnle 2020). In our simulations, we choose an intermediate value, 1 mbar, being equal to ~1000 ppmv under a surface pressure of 1.0 bar or ~2000 ppmv under 0.5 bar."

At page 4, section 2.1: A question to the authors: the 1-D radiative transfer model also has Rayleigh scattering induced changes in planetary albedo, which then linked to the outgoing solar radiation. Did the albedo from 3-D model then coupled with the albedo parameter in the 1-D model? If not, why?

Reply: Yes, both the 1-D and 3-D models have included the effect of Rayleigh scattering and it can influence the planetary albedo. In this aspect, the two models are the same. The main differences between the two models are that the 3-D model includes the feedbacks associated with surface ice, water vapor, and clouds, and the effect of large-scale circulations (such as meridional heat transport) is also considered in the 3-D model but not in the 1-D model.

At page 15, table 2: Even if the authors can ignore the Archean high obliquity hypothesis, why is the obliquity is set to zero? Some justification is needed. Also, if ocean heat transport is a major parameter that differs from previous modeling work, what are the reasons the authors had in choosing their parameter space? Please provide more justification on the benefits of the utilized model and note how it compares to other models.

Reply: For the obliquity, referee #2 has the same comment, and our reply is as follows. 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.

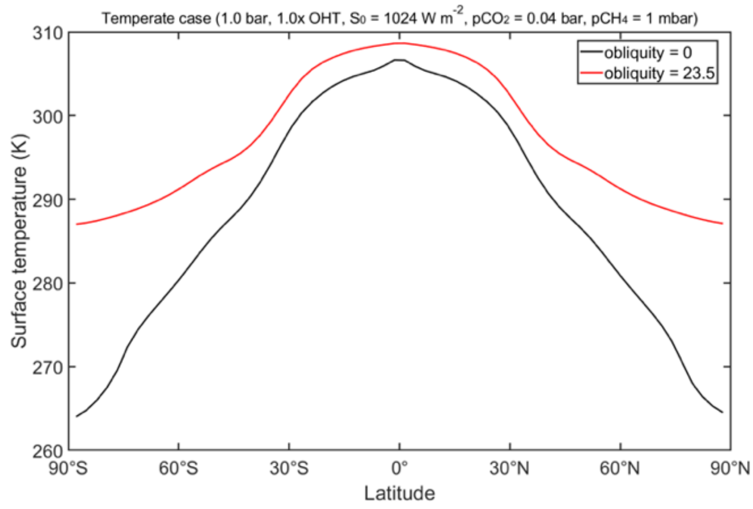

Figure A4: Annual- and zonal-mean surface air temperatures in two CAM3 simulations of different planetary obliquities: 0° for the black line and 23.5° for the red line. The background surface pressure is 1.0 bar, ocean heat transport is close to modern value, CO_2 partial pressure is 0.04 bar, and CH_4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

For the magnitude of the ocean heat transport, a lower limit of 0.5 modern value and an upper limit of 2.0 are used in this study. The lower limit is based on the study of snowball Earth initiation: during the ice edge moves closer to the tropics, the ocean heat transport is close to about 0.5 of modern value (Poulsen and Jacob 2004). The upper limit is based on the study of Olson et al. (2020), who employed the ocean heat transport under various parameters. They found that the wind stress has an upper limit of about 2 times the modern value when varying the air pressure from 0.25 to 10 bars (Figure 7 in Olson et al. 2020), so we speculated that the ocean heat transport cannot be much larger than the modern value when varying the air pressure. The real range of the ocean heat transport is required to be examined using fully coupled atmosphere-ocean models; we are doing this kind of simulations and the preliminary result is shown in Figure A3 in page 6 of the reply to Referee #1.

At page 5, line 14-15: even if pCH_4 can be set as high as 1E-3 as a modelling exercise, I wonder why the authors didn't mention the concurrent hydrogen flux (or the lack thereof), which according to Kharecha et al., 2005 Geobiology paper, is quantitatively similar to the methane concentration (on a related note, the lead author from the same research group believe the methane estimate in their Kharecha et al. 2005 paper is more reliable than their Pavlov et al. (2001) paper, on top of my major issue 1). Since this article is mainly about the effects of pressure, neglecting a major constitute in the Archean atmosphere seems a bit odd to me. Even if hydrogen eventually escape from the atmosphere, it is still a major constituent in the Archean atmosphere if outgassing is continuous. In addition, hydrogen serves as an indirect greenhouse gas that increases the lifetime of methane through scavenging radicals like OH.

Reply: Thank you very much for pointing this out. In the revised manuscript, we add one paragraph to describe the H_2 concentration during the Archean and the reason why we have not considered it in the climate simulations: "In theory, collision-induced absorption of thermal radiation by N_2-H_2 can have a greenhouse effect. This effect, however, is likely very weak during the Archean eon. The studies of Kharecha et al. (2005) and Ozaki et al. (2018) showed that H_2 mixing ratio during the Archean is less than 10^{-4}. The existence of detrital magnetite particles in Archean riverbeds indicates that the partial pressure of H_2 was likely less than 0.01 bar (Kadoya and Catling 2019). According to the radiative transfer calculations of Pierrehumbert and Gaidos (2011) and Wordsworth and Pierrehumbert (2013), the warming effect of N_2-H_2 absorption is efficient only when the H_2 mixing ratio is higher than ~0.1 and meanwhile the background air pressure is significantly greater than the present-day level."

Moreover, the model we employed (as well as in many atmospheric general circulation models those not originally developed for deep-past Earth) does not contain the radiative effect of N_2-H_2. In future, we will use ExoCAM (Wolf and Toon 2014) to examine the effect of H_2. The model ExoCAM includes the greenhouse effect of N_2-H_2.

Minor issues:

At page 1, line 22-27: One fundamental aspect about seawater temperature reconstructions the author didn't mention is that the delta-^{18}O value in seawater can change overtime. Recent analysis on iron oxides, a temperature insensitive sedimentary proxy, shows that the seawater delta-^{18}O value can increase by 15 permil since the Archean (Galili et al., 2019 Science).

Reply: Thanks for the suggestion. We add one sentence to point out this in the revised manuscript.

At page 2, line 7-13: in the texts above, the authors argued from multiple lines that the Archean seawater temperature was similar or higher than the modern value. If so, why do they argue the higher pCO_2 was maintained by a low surface temperature? The authors argument based on silicate weathering feedback seemingly contradict with their own propositions on surface temperature and pCO_2. It may be that this section just needs to be rewritten for clarity.

Reply: Thanks for the comment. We have re-written this paragraph: "The most possible solution to the faint young sun problem is large greenhouse effects from CO_2 and CH_4. 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; Kanzaki and Murakami 2015; Catling and Zahnle 2020, and references therein). For CH_4, Archean S-MIF indicated its concentration was greater than 20 ppmv (Kazaki and Murakami 2015), and fractionation of xenon isotopes suggested its concentration was higher than 5000 ppmv (Zahnle et al. 2019). Photochemical-ecosystem modeling suggested that CH_4 concentration could have been ranged from 100 to 35000 ppmv (Kharecha et al. 2005)."

At page 2, line 24-25: it might be better to reference Pavlov and Kasting (2002) Astrobiology paper for Archean pO_2. That paper was the original work that provided the most commonly cited upper limit on Archean pO_2. Also, 1% PAL of O_2 would contradict the modeling decision of not including oxygen and ozone in their bulk atmosphere composition, which also have pressure broadening effect on CO_2 and H_2O.

Reply: For the Archean eon (4.0 to 2.5 Ga) discussed in this study, pO_2 is very low as suggested by Pavlov and Kasting (2002) and summarized in the recent review paper of Calting and Zahnle (2020). In Pavlov and Kasting (2002), they wrote that "We conclude that the atmospheric O_2 concentration must have been < 10^{-5} PAL prior to 2.3 Ga." The Great Oxygen Event (GOE) began around 2.4 Ga and ended ~2.1 to 2.0 Ga. During the entire Archean eon, the atmospheric oxygen is less than 10^{-5} PAL (Calting and Zahnle 2020). Therefore, it is reasonable to exclude O_2 as well as ozone in the Archean simulations.

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