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 #1 cp-2020-55-SC1

Xiong and Yang presented interesting modeling results on the role of varying surface pressure in changing Earth's temperature, which have implications on the "faint young Sun paradox". The authors' calculations using 1-D radiative-transfer model and 3-D general circulation model (GCM) suggest that increasing surface pressure warms Earth's surface due to a stronger pressure broadening effects associated with greenhouse gases. For example, their GCM simulations show a climate sensitivity of 10 K per doubling or halving surface pressure. Role of ocean heat transport is also discussed. The manuscript is in general well-written and easy to follow. The research topic is interesting and adds to the discussion on mechanisms for the evolution of Earth's climate.

Reply: Thanks for these encouraging comments.

However, this manuscript in its current form is very descriptive and lacks in-depth analysis to clarify contributions from different feedback processes and to better support the authors' interpretation of results. For occasions, a more detailed description of model and experimental setup is needed. These issues should be resolved before the manuscript can be published in Climate of the Past. Please see my detailed comments below.

Reply: Following the comments and suggestions of the referee and the other two referees, we have improved the analyses of different feedbacks and have added more descriptions of the experimental design, as shown in the following responses.

Major comments:

1. The radiation calculation. The authors fail to provide necessary information for readers to assess the performance of their radiation schemes in the 1-D model and the GCM. How complex is the 1-D radiative transfer model? Have the authors validated the solution against comprehensive line-by-line

calculations? Related information is also required for assessing the highly parameterized and tuned radiation schemes in GCM, especially when the authors are using them well away from the climate conditions for which they were tuned. Another related question, is the radiation scheme the same between the 1-D model and the GCM?

Reply: We use the same radiation scheme in our 1-D calculations and 3-D GCM simulations, which is the radiation scheme of CAM3 (Briegleb 1992; Collins et al. 2002, 2004). For shortwave radiation, the solar spectrum is divided into 19 discrete spectral and pseudo-spectral intervals, 7 for O_3, 1 for visible, 7 for H_2O, 3 for CO_2, and 1 for the near-infrared. The continuum of H_2O lines is treated with the Clough, Kneizys, and Davies (CKD) model version 2.4.1 (Clough et al. 1989). The absorption coefficients of the model are based on HITRAN2000 database (Rothman et al. 2003), which is relatively old and would cause inaccuracy in the radiative transfer calculations as shown below. But, this inaccuracy is much smaller than the uncertainty in cloud parameterizations (Cess et al. 1990, 1996; Yang et al. 2016, 2019) and the setup in snow/ice albedos (Pierrehumbert et al. 2011). For longwave radiation, the radiative transfer calculations are based on the absorptivity/emissivity formulation of Ramanathan and Downey (1986). The effect of pressure broadening on the mean line width of the bands is included. Six absorbers, H_2O, CO_2, O_3, CH_4, N_2O, and CFCs, are included in the model. Overlaps between CO_2 and H_2O, CH_4 and N_2O, N_2O and H_2O, and N_2O and CO_2 have also been considered in the calculations. The two minor bands of CO_2 at 961 cm^{-1} and 1064 cm^{-1}, important for high levels of CO_2 such as during the Archean eon, have also been included in the model (Collins et al. 2004).

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 less than 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 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. In future work, we will employ the model of CAM4_Wolf or called ExoCAM.

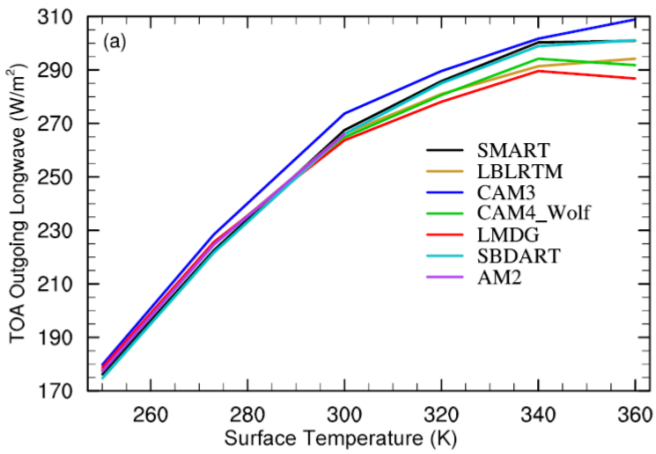

Figure A1. Outgoing longwave radiation at the top of the atmosphere for different radiative transfer models. CAM3, CAM4_Wolf, LMDG, and AM2 are the radiation transfer modules used in atmospheric general circulation models; SBDART is an independent radiation transfer model; and SMART and LBLRTM are line-by-line 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).

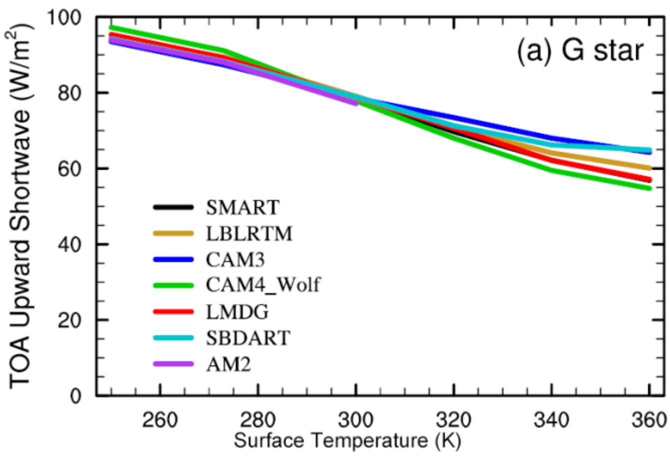

Figure A2. Upward shortwave flux at the top of the atmosphere (TOA) from different radiation transfer models. The experimental designs are same as those in Figure A1. The incoming stellar radiation at TOA is 340 W m^{-2}, and the solar spectra is used in these calculations. This figure is from Yang et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

2. On multiple occasions, the authors attribute the temperature changes in their simulations to climate feedbacks, such as ice albedo, water vapor, and cloud feedback, but fail to substantiate their claims in a quantitative manner. I understand that a complete feedback quantification for multiple GCM simulations demands large amounts of resources, but there are cheaper solutions, e.g., the

approximated partial radiative perturbation (APRP) method (Taylor et al., 2007). Although not providing a complete quantification, APRP can quantify the shortwave feedbacks really well, which, in my opinion, will offer important insights on temperature responses in the authors' simulations.

Reply: Thank you very much for the suggestion of using the "Approximate Partial Radiative Perturbation" (APRP) method. We did the analyses and the results are shown in Table A1 below. From this table, there are several significant findings. (1) In the three coldest states (0.5 OHT, 0.5 bar surface pressure, 0.04 bar CO_2; 1.0 OHT, 0.5 bar, 0.04 bar CO_2; and 0.5 OHT, 0.5 bar, 0.06 bar CO_2), the largest change in the shortwave radiation, above -100 W m^{-2} (comparing to the cases of 1.0 bar), is related to surface albedo. This is because these three cases enter a globally ice-covered snowball state. In other cases, the surface albedo feedback is positive, acting to warm the surface when the air pressure or CO_2 concentration is increased. (2) In the snowball states, the cloud albedo effect is positive, warming the surface, because of the largely decreased cloud water path and the high surface albedo. In the first three groups of experiments, the cloud albedo feedback is negative when the surface pressure is increased to be higher than 1.0 bar, acting to cool the surface. This is likely due to the fact that the cloud water path in the atmosphere increases with temperature. (3) The change of no-cloud (clear-sky) shortwave radiation flux is due to the combined effect of the changes of water vapor amount and of Rayleigh scattering of the dry air. In general, when the background air pressure is larger, the Rayleigh scattering is stronger, promoting a cooling effect on the surface. Exceptions are the three snowball experiments within which the no-cloud shortwave radiation change is negative with a large magnitude, comparing to the case of 1.0 bar. This is due to the fact that in the snowball state specific humidity of the atmosphere is low, so that shortwave absorption by water vapor decreases greatly.

Table A1: The radiative response simulated by APRP method (Taylor et al. 2007). $dQ\alpha$, dQcld, dQcs is the surface albedo, cloud, and no-ncloud (clear-sky) atmospheric shortwave radiative responses, respectively.

Group	Case	dQ_{α}(W m^{-2})	dQ_{cld}(W m^{-2})	dQ_{cs}(W m^{-2})
0.5×OHT	0.5 bar - 1.0 bar	-112.3	21.1	-18.1
	2.0 bar - 1.0 bar	9.0	-0.6	-11.3
	4.0 bar - 1.0 bar	7.2	-6.6	-23.6
1.0×OHT	0.5 bar - 1.0 bar	-121.7	15.6	-15.3
	2.0 bar - 1.0 bar	2.9	3.8	-14.3
	4.0 bar - 1.0 bar	2.7	-1.0	-27.5
2.0×OHT	0.5 bar - 1.0 bar	0.1	12.9	1.8
	2.0 bar - 1.0 bar	2.2	1.6	-13.1
	4.0 bar - 1.0 bar	2.1	-5.0	-26.3
different CO_2	0.06 bar CO_2 - 0.08 bar CO_2	-103.5	18.5	-15.4
	0.10 bar CO_2 - 0.08 bar CO_2	8.3	14.9	-0.2
	0.12 bar CO_2 - 0.08 bar CO_2	12.6	15.0	4.5

3. Role of ocean heat transport (OHT). Based on the description of experimental design, it is unclear how the mixed layer depth is prescribed, a constant everywhere, or a present-day spatial distribution? The authors have acknowledged the limitation of their approach using a slab ocean model with prescribed OHT (e.g. last paragraph on Page 13), but more discussion should be added on this. First, changing OHT while fixing the mixed layer depth is not a physically consistent approach. Ocean circulation and heat transport are usually accompanied with distinct ocean structures including mixed layer conditions. For example, ocean circulation and heat transport are greater in the present-day North Atlantic, so is the mixed layer depth. Second, the physical consistency between the prescribed OHT and the climate state should be better discussed. Is an OHT of 0.5–1.0 times the present-day value possible under a cold climate with a global mean temperature of ~210 K? Similarly, are the OHT values realistic in a warm climate of 326 K? How does a snow/ice cap impacts OHT? Is it possible that warming and freshening under a warm climate increases the ocean stratification and decreases the high-latitude OHT, making some of the authors calculations unrealistic?

Reply: Our simulations use a 50-m slab ocean and it is constant everywhere. The oceanic heat transport (OHT) is prescribed in our simulations and fixed in time. Through employed different magnitudes of OHT, we examined the effect of OHT on the surface climate. This is the first step in knowing the sensitivity of the climate system to OHT, and it is a general method used in paleoclimate studies when coupled atmosphere-ocean model experiments are computer source limited.

For the case of a global-mean temperature of 210 K, all the surface is covered by ice and snow and the planet is in a snowball state. In the snowball state, the OHT should be much less than 0.5 or 1.0 OHT, although geothermal heat-driven ocean circulation is still robust (Ashkenazy et al. 2013). However, in this study, our main concern is not the exact climate state during the snowball state but the transition phase from an ice-free state or a partly ice-covered state to a snowball state; during the transition, a 0.5-1.0 OHT is not very extraordinary, following the previous simulations of Poulsen and Jacob (2004) and Yang et al. (2012).

For the warm case of 326 K, the OHT should be lower than present, due to the reduced surface temperature gradients and weakened surface winds. So, the 1.0 or 2.0 OHT and the fixed mixed layer depth used in this study are unrealistic. But, again, our main concern is not the exact climate state after all ice/snow melts but the transition phase from a partly ice-covered state to an ice-free state. Of course, we agree that fully coupled atmosphere-ocean models are required to further investigate this problem.

Recently, we are trying to use the coupled atmosphere-ocean model CESM 1.2.2 to simulate the effect of varying surface pressure on the climate of the Archean eon. Preliminary result is shown in Figure A3. As shown in the figure, lowering the surface pressure from 1.0 bar to 0.5 bar, the planet enters a fully ice-covered snowball state; this result is similar to that found in the CAM3 experiments (see Table 1 of the manuscript). We will present the coupled simulations in a near future paper.

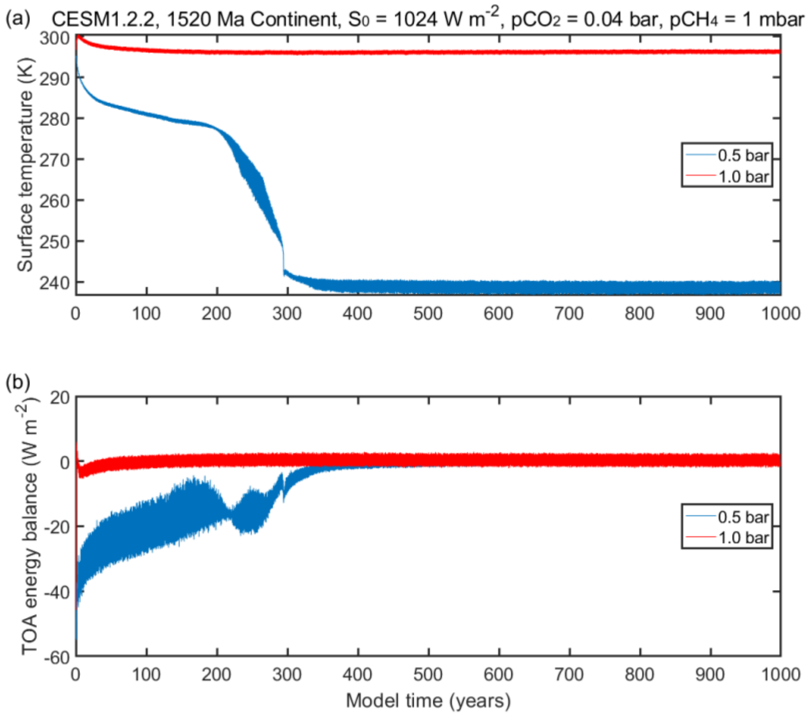

Figure A3. Time series of global-mean surface air temperature (a) and energy balance at the top of the atmosphere (TOA, (b)) in the fully coupled atmosphere-ocean experiments using the model CESM1.2.2. The surface pressure is 0.5 bar for the blue line and 1.0 bar for the red line. The stellar flux is 1024 W m^{-2} (75% of the present-day value), CO_2 partial pressure is 0.04 bar, and CH_4 partial pressure is 1 mbar. The land-sea configuration of 1520 Ma is used in these two experiments because older land-sea configuration during the Archean is unknown. The planetary obliquity is 23.5°.

Minor comments:

1. Page 1, Line 23: a low-$\delta^{18}O$ sediment infers a high ocean temperature.

Reply: Corrected.

2. Page 2, Line 1–4: Another important caveat regarding the isotopic thermometry is the assumptions on isotopic composition of seawater, i.e. a low calcium $\delta^{18}O$ may reflect a low seawater $\delta^{18}O$. This should be added to the discussion.

Reply: Added.

3. Page 3, Line 3–28: Poulsen, Tabor, & White (2015) is worth mentioning when reviewing findings in previous studies.

Reply: We added several sentences in the section of Conclusion and Discussions to address the paper of Poulsen et al. (2015): “The study of Poulsen et al. (2015) showed that varying surface pressure has significant effects on both surface temperature and precipitation. When the surface pressure is decreased (such as due to a lower concentration of O_2), Rayleigh scattering of the atmosphere decreases and more solar radiation reaches the surface; the increased surface solar radiation drives stronger convection and produces more precipitation. This is consistent with our results. But, Poulsen et al. (2015) found that the surface temperature increases with reducing surface pressure, which is opposite to the conclusion shown in our study and other previous studies such as Goldblatt et al. (2009), Wolf and Toon (2014), and Paradise et al. (2021): the surface temperature decreases with reducing surface temperature. The main contrast is from the opposite cloud feedbacks. Poulsen et al. (2015) showed that the cloud feedback associate with low-level marine stratus acts to warm the surface when the surface pressure is lowered. But, in our simulations and other previous studies, the cloud feedback acts to warm the surface when the surface pressure is increased. These contrast results also suggest that future work with limited-area or global cloud resolving models are required to examine the trend of clouds under different background air pressures." We have also cited this article in section 4.1 where we discussed the effect of varying surface pressure on precipitation.

4. Page 5, Line 3: I would not say the application of CCSM3-CAM3 was successful for the Eocene. Caballero and Huber (2013) and later studies clearly showed that Eocene climate in CCSM3 is too cold when the estimated Eocene CO_2 is used.

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

5. Model description: Please add information on model resolution and integrations length. Have the slab ocean simulations reached equilibrium?

Reply: We added three sentences to more clearly describe the model and the experimental design: "The model has 26 levels in vertical and the horizontal resolution is approximately 2.8° in longitude by 2.8° in latitude. Each experiment was run for 60 Earth years. The model always reached equilibrium within 50 years, and the averages of the final 10 years were used to analyses below."

6. Page 8, Line 22–23: the atmospheric energy transport change little when the surface air pressure is varied.

Reply: Corrected.

7. Page 8, Line 25–26: the meridional atmospheric energy transport does not change much.

Reply: Corrected.

8. Page 8, Line 29: Besides the warming of the global surface.

Reply: Corrected

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