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Faint young Sun problem more severe due to ice-albedo feedback and higher rotation rate of the early Earth

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[1] During the Archean (3.8–2.5 billion years ago), the Sun was up to 25% less luminous than today, yet there is strong evidence that the Earth's ocean surface was not completely frozen. The most obvious solutions to this 'faint young Sun problem' demand high concentrations of greenhouse gases such as carbon dioxide. Here we present the first comprehensive 3-dimensional simulations of the Archean climate that include processes as the sea-ice albedo feedback and the higher rotation rate of the Earth. These effects lead to CO_2 partial pressures required to prevent the Earth from freezing that are significantly higher than previously thought. For the early Archean, we find a critical CO_2 partial pressure of 0.4 bar in contrast to 0.06 bar estimated in previous studies with 1-dimensional radiative-convective models. Our results suggest that currently favored greenhouse solutions could be in conflict with constraints emerging for the middle and late Archean. **Citation:** Kienert, H., G. Feulner, and V. Petoukhov (2012), Faint young Sun problem more severe due to ice-albedo feedback and higher rotation rate of the early Earth, *Geophys. Res. Lett.*, *39*, L23710, doi:10.1029/2012GL054381.

1. Introduction

[2] The faint young Sun problem [*Feulner*, 2012] has been a challenge since the surprising relation of a much less luminous Sun [*Bahcall et al.*, 2001] and evidence for liquid surface water [*Lowe*, 1980; *Walker*, 1982] was first explicitly pointed out in 1972 [*Sagan and Mullen*, 1972]. Previous studies of Archean warming due to greenhouse gases are based on 1-dimensional radiative-convective models, which neglect meridional heat transport and feedbacks like the ice-albedo effect [*Kasting*, 2010]. In these model simulations, a CO_2 partial pressure of 0.06 bar (about 200 times pre-industrial levels) is found to be sufficient to allow for liquid surface water in the early Archean, and a partial pressure of 0.3 bar to yield surface air temperature (SAT) similar to today [*Kasting et al.*, 1984; *Kiehl and Dickinson*, 1987; *von Paris et al.*, 2008]. The few studies that have investigated aspects of the Archean climate with early and highly simplified 3-dimensional models (e.g., without a full ocean model) did not attempt to identify the critical CO_2 amount [*Jenkins*, 1993, 1996].

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2. Model Experiments

[3] An established climate model [*Montoya et al.*, 2005] has been modified to make it applicable to the Archean. The model couples a 3-dimensional ocean general circulation model [*Pacanowski and Griffies*, 1999], a statistical-dynamical atmosphere describing the large-scale circulation patterns [*Petoukhov et al.*, 2000, 2003] and a thermodynamic-dynamic sea-ice model [*Fichefet and Morales Maqueda*, 1997]. It captures all relevant processes while being fast enough to allow for a large number of equilibrium simulations. The parameterisation of the atmospheric meridional cell strength in dependence of the surface temperature field is adjusted for the small continental fraction during the early Archean by comparison with a more complex model [*Marshall et al.*, 2007]. A higher rotation rate of the early Earth is explicitly used in all three modules; in addition, mean atmospheric meridional cell boundaries [*Williams*, 1988; *Navarra and Boccaletti*, 2002] and the lapse rate parameterisation [*Zilitinkevich*, 1970] are appropriately modified. For the early Archean, our model applies a rotation rate higher than today by a factor of $\Omega = 1.6$ [*Zahnle and Walker*, 1987] and mean meridional cell boundaries of 22.5° and 52.5° [*Williams*, 1988; *Navarra and Boccaletti*, 2002] instead of 30° and 60°. Radiative transfer has been tuned to approximate the results of the MTCKD parameterisation [*Clough et al.*, 2005; *Halevy et al.*, 2009] by comparing the outgoing longwave radiation under identical boundary conditions for a range of CO_2 partial pressures and relative humidities [*Halevy et al.*, 2009]. Rayleigh scattering explicitly depends on total pressure [*Pierrehumbert*, 2010]. Wind stress is set fully free in contrast to the anomalies used in the standard version of the model. The cloud scheme differentiates between stratus and cumulus clouds, with the cloud fractions depending on humidity and vertical velocity [*Petoukhov et al.*, 2000]. The following clear-sky albedo values are used: 0.17 for bare land [*Tsvetsinskaya et al.*, 2002], 0.53 and 0.72 for thick sea ice under melting and freezing conditions, and 0.80 for sea ice covered by thick snow [*Shine and Henderson-Sellers*, 1985].

[4] Regarding atmospheric composition, we apply variable abundances of CO_2 in addition to 0.8 bar nitrogen partial pressure. Different topographies with 1% emerged surface and random continental crust distribution have been considered to test the influence of the unknown topography on the results. The area-per-depth distribution for the topographies is based on modelling results [*Flament et al.*, 2008; *Flament*, 2009], assuming present-day ocean volume, a continental crust area amounting to 20% of today's value and a mantle temperature 200 K above today as well as applying the model for mantle cooling by *Labrosse and Jaupart* [2007] with 142 Ma maximum age of the ocean floor. Three topographies exhibit randomly scattered islands and an emerged surface area of 1%. For additional sensitivity tests, the islands have

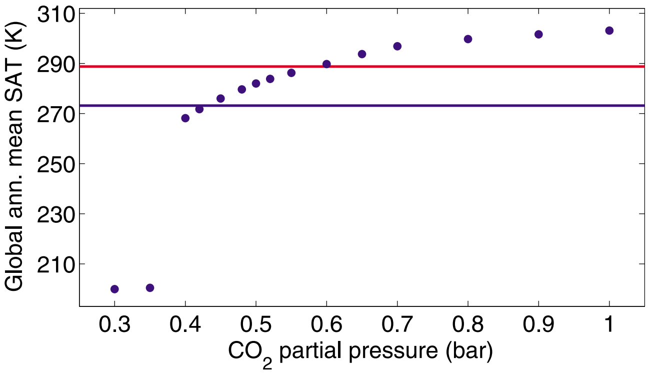

Figure 1. Early Archean surface air temperature for different CO_2 partial pressures (filled circles). The blue and red lines indicate 273 K and present-day temperature (288 K) respectively.

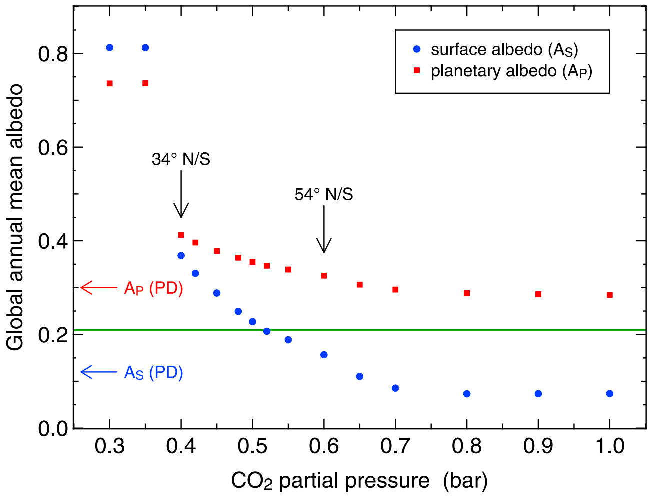

Figure 2. Surface (A_s, blue circles) and planetary (A_p, red squares) albedo for various CO_2 partial pressures. The arrows on the left indicate the present-day values. The green line marks the constant surface albedo value typically used in 1-dimensional models [*Kasting et al.*, 1984; *von Paris et al.*, 2008]. Its difference to the observed present-day surface albedo is due to an implicit representation of the albedo increase from clouds. Latitudes of the sea-ice boundary are given for the critical state as well as for the state with a mean temperature of 288 K (black arrows).

been distributed either as a polar or an equatorial archipelago. Further tests are based on 5% emerged surface area. In the following, we present results for one particular random topography; the results for the other topographies are very similar. All simulations have been integrated from an ice-free state until they approach equilibrium after 5000 years.

3. Critical CO_2 Partial Pressure

[5] We find that a CO_2 partial pressure of 0.4 bar (about 1400 times pre-industrial levels) is needed to prevent the Earth from falling into a snowball state for a solar luminosity amounting to 75% of today's value (1024 Wm^{-2}). This critical state for the early Archean is characterized by a sea-ice boundary (defined by 10% annual mean sea-ice cover) of 34° and a global mean surface air temperature of 268 K. Note that this critical SAT is lower than the temperatures assumed in earlier modelling studies to define the limit for global glaciation, e.g., 273 K in *von Paris et al.* [2008]. Figure 1 shows the dependency of global mean SAT on CO_2 abundance with extremely low temperatures corresponding to snowball states. An average SAT similar to present-day is reached at 0.6 bar with an annual mean sea-ice boundary at a latitude of 54°, about 5° lower than today.

[6] The critical CO_2 amount derived here is significantly larger than the partial pressures derived in previous studies. This is predominantly due to the sea-ice albedo feedback. As shown in Figure 2, surface and planetary albedo are much larger for the critical state than the present-day values that are usually kept fixed in 1-dimensional model simulations. The variation in albedo turns also out to be larger than ±0.02 which is used as an estimate in a sensitivity experiment of the latest study based on a 1-dimensional model [*von Paris et al.*, 2008], and it explains the relatively small difference of CO_2 abundances between the states with 288 K and the critical state.

[7] The strong effect of the sea-ice albedo feedback for the critical CO_2 partial pressure turns out to be enhanced by the impact of the higher rotation rate of the early Earth. This dynamic change leads to a significant steepening of the meridional temperature profile and a slight overall cooling (Figure 3), which can already be observed for CO_2 abundances that correspond to states with an ice-free ocean. In combination with the ice albedo feedback, the effect turns out to be strong enough that the state with a CO_2 partial pressure of 0.40 bar (the critical state for $\Omega = 1.6$) would have a sea-ice boundary of 62° under present-day rotation rate. Accordingly, the critical CO_2 partial pressure for $\Omega = 1.0$ would amount to 0.35 bar only.

[8] The larger equator-to-pole temperature difference due to the higher rotation rate is consistent with earlier studies using different types of models [*Hunt*, 1979; *Kuhn et al.*, 1989; *Jenkins*, 1993] and can be attributed in our simulations of the

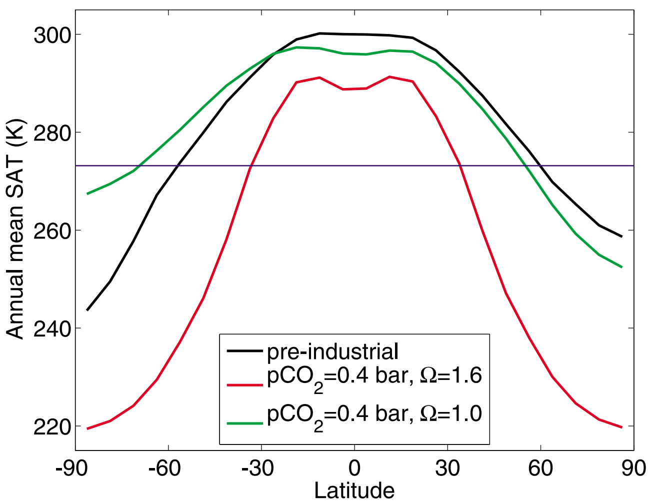

Figure 3. Annual and zonal mean SAT for three different states: pre-industrial (black), the critical state of the early Archean (pCO_2 = 0.4 bar, Ω = 1.6, red) and a state with the same CO_2 partial pressure but with present-day rotation rate (Ω = 1.0, green). The blue line indicates a temperature of 273 K.

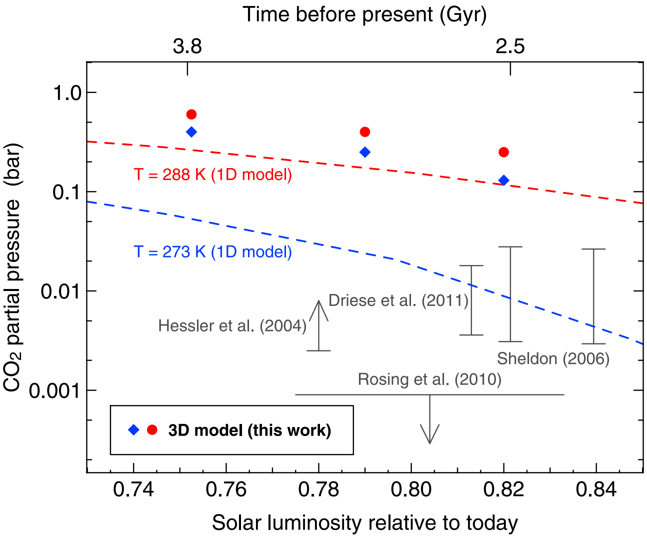

Figure 4. The results of this study (blue diamonds for the critical states and red circles for the states with 288 K) are compared to the partial pressures required for mean surface air temperatures of 273 K and 288 K based on 1-dimensional model results (blue and red dashed lines) [*von Paris et al.*, 2008]. Estimated limits for CO_2 partial pressure from geochemical studies are shown in dark grey [*Hessler et al.*, 2004; *Sheldon*, 2006; *Rosing et al.*, 2010; *Driese et al.*, 2011].

early Archean to a reduction of meridional heat transport, changes in cloud cover (and thus albedo) as well as a spatially non-uniform decrease of the lapse rate. As the ocean plays a significant role for the changes in total meridional heat transport, our results underline the importance of using full ocean models in studies of the Archean climate.

[9] The critical CO_2 partial pressure for the early Archean is clearly above those derived from 1-dimensional models even if we tune our radiative transfer code towards approximately representing the GBKM parameterisation [*Halevy et al.*, 2009] which is similar to the one used in earlier studies [*Kasting et al.*, 1984; *von Paris et al.*, 2008], but has been argued to overestimate warming in CO_2-rich atmospheres [*Wordsworth et al.*, 2010]. In that case, our critical CO_2 partial pressure is still higher by a factor of 5 compared to 1-dimensional results (0.28 bar versus 0.06 bar [*von Paris et al.*, 2008]).

4. Implications for the Middle and Late Archean

[10] For the middle and late Archean, likely limits of greenhouse gas concentrations are emerging from geochemical studies. 3.1 and 2.5 billion years ago, solar luminosity was 21 and 18% lower, and the rotation rate of the Earth 1.5 and 1.4 times higher than today. Applying these boundary conditions, but using our early Archean reference topography, the model results for the minimum CO_2 partial pressures required to avoid global glaciation amount to 0.25 and 0.13 bar. These values are clearly above the geochemical estimates [*Sheldon*, 2006; *Rosing et al.*, 2010; *Driese et al.*, 2011] and will be even higher if the increased albedo due to larger continental fractions is taken into account. Note that the validity of the lowest estimate [*Rosing et al.*, 2010] has been subject to debate [*Dauphas and Kasting*, 2011; *Reinhard and Planavsky*, 2011]. However, in contrast to 1-dimensional modelling results, a pure CO_2 solution to the faint young Sun problem for the middle and late Archean is excluded even for the high end of the geochemical constraints (Figure 4).

[11] Note that other greenhouse gases (in particular methane) contributed to late-Archean warming. However, the 3-dimensional effects discussed in this study which raise the critical CO_2 partial pressure with respect to 1-dimensional models are independent of the specific mixture of greenhouse gases that cause the long-wave radiative forcing. Therefore, our results imply that larger critical concentrations than previously estimated are also required for the late Archean. Depending on the precise upper limit of CO_2 abundance, the carbon dioxide-methane greenhouse solutions currently favored for the late Archean [*Haqq-Misra et al.*, 2008] could thus be in conflict with geochemical constraints. However, other factors could have contributed to Archean warming. For example, *Goldblatt et al.* [2009] suggested that a higher nitrogen partial pressure on the early Earth could have amplified the greenhouse effect of other gases, and *Rosing et al.* [2010] hypothesized that a lack of biologically induced cloud condensation nuclei might have decreased the planetary albedo.

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