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A warm or a cold early Earth? New insights from a 3-D climate-carbon model

Benjamin Charnay [a,b,*], Guillaume Le Hir [c], Frédéric Fluteau [c], François Forget [d], David C. Catling [b,e]

[a] LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, Univ. Paris Diderot, Sorbonne Paris Cité, 5 Place Jules Janssen, 92195 Meudon, France
[b] Virtual Planetary Laboratory, University of Washington, Seattle, WA 98125, USA
[c] Équipe de paléomagnétisme, Institut de Physique du Globe de Paris, UMR 7154, Sorbonne Paris Cité, 1 rue Jussieu, 75238 Paris cedex 5, France
[d] Laboratoire de Météorologie Dynamique, IPSL/CNRS/UPMC, Paris 75005, France
[e] Department of Earth and Space Science, University of Washington, Seattle, WA 98125, USA

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ABSTRACT

Oxygen isotopes in marine cherts have been used to infer hot oceans during the Archean with temperatures between 60 °C (333 K) and 80 °C (353 K). Such climates are challenging for the early Earth warmed by the faint young Sun. The interpretation of the data has therefore been controversial. 1D climate modeling inferred that such hot climates would require very high levels of CO_2 (2–6 bars). Previous carbon cycle modeling concluded that such stable hot climates were impossible and that the carbon cycle should lead to cold climates during the Hadean and the Archean. Here, we revisit the climate and carbon cycle of the early Earth at 3.8 Ga using a 3D climate-carbon model. We find that CO_2 partial pressures of around 1 bar could have produced hot climates given a low land fraction and cloud feedback effects. However, such high CO_2 partial pressures should not have been stable because of the weathering of terrestrial and oceanic basalts, producing an efficient stabilizing feedback. Moreover, the weathering of impact ejecta during the Late Heavy Bombardment (LHB) would have strongly reduced the CO_2 partial pressure leading to cold climates and potentially snowball Earth events after large impacts. Our results therefore favor cold or temperate climates with global mean temperatures between around 8 °C (281 K) and 30 °C (303 K) and with 0.1–0.36 bar of CO_2 for the late Hadean and early Archean. Finally, our model suggests that the carbon cycle was efficient for preserving clement conditions on the early Earth without necessarily requiring any other greenhouse gas or warming process.

1. Introduction

Life likely emerged on Earth before 3.5 Ga, during the Hadean or the early Archean (Buick et al., 1981; Nisbet and Sleep, 2001; Bell et al., 2015). Studying the atmosphere and the climates of the Earth during its first billion year is critical for understanding the environment in which life emerged and developed. Oxygen isotopic ratio of Archean marine cherts have been interpreted to suggest hot oceans with temperatures between 60 °C (333 K) and 80 °C (353 K) (Knauth and Lowe, 2003; Robert and Chaussidon, 2006), compatible with the thermophiles inferred from evolutionary models of the ancient life (Gaucher et al., 2008) and possibly with the indications for a low ocean water viscosity (Fralick and Carter, 2011). However, such an interpretation has been strongly debated (Kasting and Howard, 2006; van den Boorn et al., 2007; Marin-Carbonne et al., 2014; Tartese et al., 2016) and other analyses suggest temperate oceans with temperatures lower than 40 °C (Hren et al., 2009; Blake et al., 2010). Moreover, at 3.5 Ga, the presence of glacial rocks at 20–40° latitude implies global mean surface temperatures below 20 °C (de Wit and Furnes, 2016), at least episodically.

In addition, previous modeling of the carbon cycle on the early Earth by Sleep and Zahnle (2001) and Zahnle and Sleep (2002) suggested that the Archean was cold unless another strong greenhouse gas was present. They also suggested that the Hadean was likely very cold because of the weathering of impact ejecta, particularly during the Late Heavy Bombardment (LHB). Therefore, the temperature of the early oceans remains an open question.

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* Corresponding author.
E-mail address: benjamin.charnay@obspm.fr (B. Charnay).

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Here, we use a 3D climate-carbon model with pCO_2 ranging from 0.01 to 1 bar in order to determine physically plausible climates of the late Hadean and early Archean Earth. In section 2, we describe the climate simulations. In section 3 and 4, we analyze the carbon cycle and the effect of the LHB with respect to carbon cycle responses. We finish with a conclusion in section 5.

2. Climate modeling

2.1. Description of the model

We simulated the atmosphere of the early Earth using the Generic LMDZ GCM (Global Climate Model). This model solves the primitive hydrostatic equations of meteorology using a finite difference dynamical core on an Arakawa C grid. It uses robust and general parameterizations in order to simulate planets very different from the present-day Earth. The Generic LMDZ GCM has already been used for studying the temperate and cold climates of the Archean Earth (Charnay et al., 2013), the climates of early Mars with high CO_2 pressures (Forget et al., 2013), and the runaway greenhouse effect on terrestrial planets with high amounts of water vapor (Leconte et al., 2013). It is thus adapted for simulating the early Earth with high amounts of CO_2 and potentially hot and moist climates.

The radiative scheme is based on the correlated-k method. At a given pressure and temperature, correlated-k coefficients in the GCM are interpolated from a matrix of coefficients stored in a 7×9 temperature and log-pressure grid: $T = 100$, 150, 200, 250, 300, 350, 400 K, $p = 10^{-1}$, 10^0, $10^1, \ldots, 10^7$ Pa. We used 36 spectral bands in the thermal infrared and 38 at solar wavelengths. Sixteen points were used for the g-space integration, where g is the cumulative distribution function of the absorption data for each band.

Simulations were performed with a horizontal resolution of 64×48 (corresponding to resolutions of 3.75° latitude by 5.625° longitude) and with 25 vertical layers with the lowest midlayer level at 5 m and the top level at 0.5 hPa. For the cloud microphysics, we either fixed the radii of water cloud particles (e.g. 12 μm for liquid droplets and 35 μm for icy particles for present-day Earth) or we fixed the density of cloud condensation nuclei (CCN) by mass of air (e.g. 5×10^6 particles/kg for liquid droplets and 2×10^4 particles/kg for icy clouds for present-day Earth). As in Charnay et al. (2013), the oceanic transport and the sea ice formation were computed with the 2-layer oceanic model from Codron (2012).

To investigate the early Earth at 3.8 Ga, we used a solar constant of 1024 W/m^2 corresponding to 75% of the present value (1361 W/m^2). We ran simulations with no land. This hypothesis is valid for small continental surface fractions (e.g. <30% of the present-day fraction or <10% of the total Earth's surface) as we assumed at this time (Flament et al., 2008) (see also section 3.1), although the land fraction is a matter of dispute (Viehmann et al., 2014). Such small continental fraction should indeed have a negligible direct impact on the global climate. We also assumed that Earth's rotation period was 14 h. We used an atmospheric composition with 1 bar of nitrogen, a partial pressure of CO_2 (pCO_2) from 0.01 to 1 bar, and either no CH_4 or 2 mbar of CH_4 (pCH_4), spanning the range of plausible methane concentrations estimated by a model for early ecosystems (Kharecha et al., 2005). Wordsworth et al. (2017) showed that CO_2–CH_4 collision-induced absorption could have produced a strong warming on early Mars if the CH_4 mixing ratio was higher than 1%. With our CH_4 mixing ratio of 0.1–0.2%, CO_2–CH_4 CIA produce a warming lower than 0.1 K with the 1D version of the model. We thus neglected CO_2–CH_4 CIA in our 3D simulations.

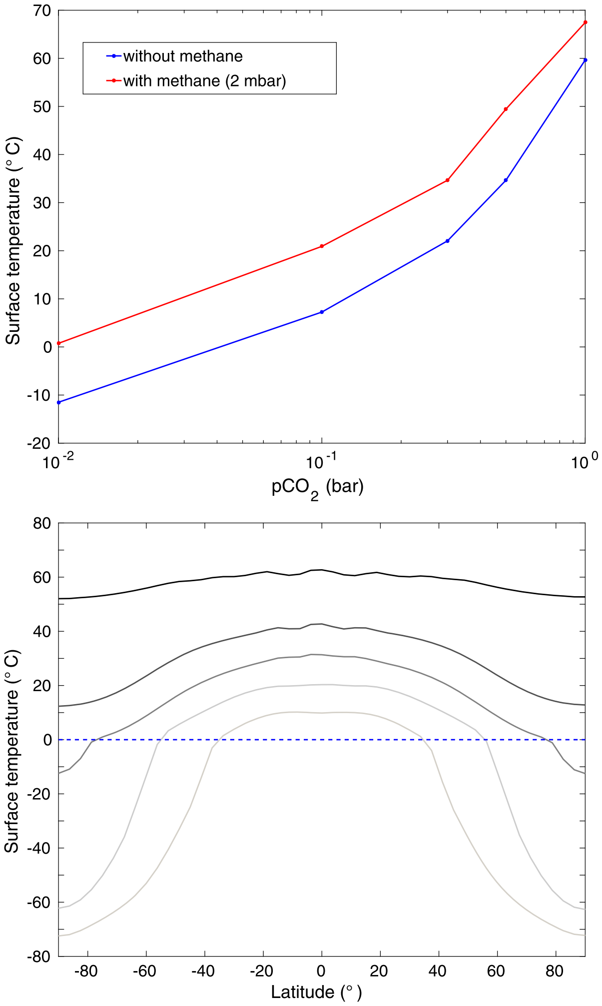

Fig. 1. Top panel: global mean surface temperature without methane (blue line) and with 2 mbars of methane (red line). Bottom panel: zonal mean surface temperature for an atmosphere with no methane and with 0.01, 0.1, 0.3, 0.5 and 1 bar of CO_2 for lines from light gray to black respectively. The blue dashed line is the freezing temperature of water. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

2.2. Results

Fig. 1 shows the global mean and zonal mean surface temperatures obtained with the GCM for present-day properties of clouds (global mean values are gathered in Table 1). Using 3.8 Ga conditions, the Earth falls into a full glaciation for the present-day pCO_2 (see Charnay et al., 2013), but it is never fully ice-covered with at least 0.01 bar of CO_2. For this case with no methane, the mean surface temperature is −11.8 °C, well below the freezing point, but there is still a cold ice-free equatorial belt between −37°N and +37°N. With 0.1 bar of CO_2, the climate is temperate (global mean surface temperature around 7.4 °C without CH_4 and 21.3 °C with CH_4). Ice-free conditions are obtained for pCO_2 higher than around 0.3 bar without methane or slightly higher than 0.1 bar with methane, corresponding to a mean surface temperature higher than around 23 °C. Our model has a climate sensitivity with pCO_2 very similar to the GCM from Wolf and Toon (2013) going up to 0.3 bar. With 0.5 bar of CO_2, the climate becomes warm (mean surface temperature around 34.7 °C without CH_4 and 49.9 °C with CH_4). With 1 bar of CO_2, the mean surface temperature is around 59.5 °C without CH_4 and around 67.5 °C with CH_4.

Ozak et al. (2016) showed that CO_2 collisional line mixing reduces the atmospheric opacity between 400 and 550 cm^{-1} producing a significant cooling (∼10 °C) for a 1 bar CO_2 atmosphere