



HAL
open science

Is the Faint Young Sun Problem for Earth Solved?

Benjamin Charnay, Eric T Wolf, Bernard Marty, Francois Forget

► **To cite this version:**

Benjamin Charnay, Eric T Wolf, Bernard Marty, Francois Forget. Is the Faint Young Sun Problem for Earth Solved?. *Space Science Reviews*, 2020, 216 (5), pp.90. 10.1007/s11214-020-00711-9. hal-03103930

HAL Id: hal-03103930

<https://hal.science/hal-03103930>

Submitted on 8 Jan 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Is the faint young Sun problem for Earth solved?

Benjamin Charnay · Eric T. Wolf · Bernard Marty · François Forget

Received: date / Accepted: date

Abstract Stellar evolution models predict that the solar luminosity was lower in the past, typically 20-25 % lower during the Archean (3.8-2.5 Ga). Despite the fainter Sun, there is strong evidence for the presence of liquid water on Earth’s surface at that time. This “faint young Sun problem” is a fundamental question in paleoclimatology, with important implications for the habitability of the early Earth, early Mars and exoplanets. Many solutions have been proposed based on the effects of greenhouse gases, atmospheric pressure, clouds, land distribution and Earth’s rotation rate. Here we review the faint young Sun problem for Earth, highlighting the latest geological and geochemical constraints on the early Earth’s atmosphere, and recent results from 3D global climate models and carbon cycle models. Based on these works, we argue that the faint young Sun problem for Earth has essentially been solved. Unfrozen Archean oceans were likely maintained by higher concentrations of CO₂, consistent with the latest geological

proxies, potentially helped by additional warming processes. This reinforces the expected key role of the carbon cycle for maintaining the habitability of terrestrial planets. Additional constraints on the Archean atmosphere and 3D fully coupled atmosphere-ocean models are required to validate this conclusion.

Keywords Early Earth · Paleoclimates · Habitability

1 Introduction

Let’s imagine time-travelers exploring the early Earth 3-4 billions years ago. Leaving their time capsule, they would need oxygen masks to survive in the anoxic Archean atmosphere, containing deathly high levels of carbon dioxide and possibly also methane, carbon monoxide, ammonia and hydrocyanic acid. Moreover, with no appropriate protection, they would quickly suffer from sunburn, due to the higher UV flux of the early Sun and the absence of an ozone layer. Passed these complications, they would then discover a world very different from our present-day Earth. The sky would look hazier, potentially with an orange colour. The days would be shorter and a larger moon would shine in the night-sky. The Sun would appear significantly fainter than today. However, perhaps surprisingly, most of the surface would be covered by temperate or warm liquid water oceans. These oceans would be more acidic and full of unicellular organisms forming a productive biosphere. Our time-travelers may wonder how can the climatic conditions be clement under such a fainter Sun. They would experience the faint young Sun problem, one of the most fundamental questions in paleoclimatology.

The faint young Sun problem for Earth has been reviewed in detail by *Feulner* [2012]. At that time, most of the atmospheric modelling work was based on 1D

B. Charnay
LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France.
E-mail: benjamin.charnay@obspm.fr

E. T. Wolf
University of Colorado, Boulder, Laboratory for Atmospheric and Space Physics, Department of Atmospheric and Oceanic Sciences, Boulder, CO 80302, USA.

B. Marty
Centre de Recherches Pétrographiques et Géochimiques, UMR 7358 CNRS – Université de Lorraine, 15 rue Notre Dame des Pauvres, BP 20, 54501 Vandoeuvre-lès-Nancy, France.

F. Forget
Laboratoire de Météorologie Dynamique/IPSL, CNRS, Sorbonne Université, Ecole Normale Supérieure, PSL Research University, Ecole Polytechnique, 75005 Paris, France.

radiative convective models (RCMs). While 1D RCMs remain attractive research tools due to their flexibility and computational efficiency, 1D models miss important climate feedbacks. For instance, RCMs used in early Earth and habitability studies typically omit explicit representations of clouds and surface ice and snow. Instead, the surface albedo is assigned a constant high value, to implicitly represent cloud reflectivity. By treating the radiative effect of clouds in this manner, such models fail to include the longwave radiative effect of clouds and can overestimate the greenhouse effect of background gases [Pierrehumbert, 1995; Goldblatt and Zahnle, 2011a]. They also miss cloud feedbacks related to changes in the cloud distribution.

Three-dimensional atmospheric general circulation models (GCMs) coupled to simple ocean/sea-ice models represent a significant improvement in the simulation of the climate system compared to 1D RCMs. GCMs allow for a self-consistent and coupled treatment of numerous dynamical and physical processes occurring in planetary atmospheres. Of particular importance for Earth’s climate system, is the treatment of water in its various thermodynamic phases. In particular, water is responsible for the sea-ice albedo, water vapor greenhouse and cloud feedbacks, which can all strongly impact the climate sensitivity. Shortly after the review from Feulner [2012], several papers using 3D atmospheric GCMs coupled to simple ocean/sea-ice models were published, providing a fresh new perspective and some answers about former proposed solutions to the faint young Sun problem [Charnay et al., 2013; Wolf and Toon, 2013, 2014; Le Hir et al., 2014; Kunze et al., 2014; Teitler et al., 2014; Charnay et al., 2017; Wolf et al., 2018]. According to these modelling studies, the faint young Sun problem appears less severe than initially thought, notably because of cloud feedbacks leading to optically thinner low clouds on the early Earth.

In parallel, new geological and geochemical constraints were obtained during the last decade, changing the general view about the evolution of Earth’s atmospheric nitrogen, as well as constraints on atmospheric CO₂ and surface temperatures during the Archean. In particular, some of these recent studies suggest relatively high pCO₂ values, which mitigate the faint young Sun problem.

This paper constitutes a general review of the faint young Sun problem for Earth, highlighting atmospheric modelling results and some laboratory measurements obtained during the last decade. In section 2, we describe the environment of the early Earth, in particular the evidence for a weaker Sun, for the presence of surface liquid water, and for the fraction of emerged

land. We also detail constraints on the ocean temperature and atmospheric composition/pressure. Section 3 lists different proposed solutions to the faint young Sun problem, including the effects of greenhouse gases, atmospheric pressure, clouds and the fraction of emerged land. For each solution, we highlight recent results from climate modelling and paleosol studies. Section 4 reviews the lessons from 3D global climate models and the differences compared to 1D atmospheric models. Section 5 discusses the role of the carbon-cycle and life to regulate the early Earth’s climate. Finally, we conclude in section 6 with a summary and possible directions for future research.

2 The environment of the early Earth

2.1 Evidence for a weaker Sun

It has been well established in models of solar evolution that solar luminosity has slowly increased over the lifetime of the Sun. 3.8 billions years ago the early solar flux is calculated to have been 25% lower than today and it has slowly intensified since (see e.g. Newman and Rood [1977]; Gough [1981]). This is because the fusion of hydrogen into helium increases the mean molecular weight of the core. To maintain the balance between the pressure gradient force and gravity, the core contracts and warms. The increased densities and temperatures enhance the rate of fusion and hence, the star’s luminosity increases with time. This model is very robust. Furthermore, it is based on a model of the Sun which agrees very well with solar neutrinos measurements and helioseismology observations.

Can this model be questioned? Is it possible to imagine a young Sun brighter than expected that could resolve the faint young Sun problem and possibly explain the very warm temperature that have been reported by some studies? More than for the Earth, such a possibility has been discussed to resolve the enigma of early Mars covered by rivers and lakes 3.5 - 4 billions years ago [Whitmire et al., 1995; Forget et al., 2013; Haberle et al., 2017].

The only way to explain a brighter early Sun while remaining consistent with the robust theory mentioned above is to assume that it was more massive initially and that it subsequently lost the excess mass in a solar wind much more intense than today [Whitmire et al., 1995]. Solar luminosity is proportional to the fourth power of solar mass M_{\odot} , and since a planet’s orbital distance r is inversely proportional to M_{\odot} , and the solar flux varies as r^{-2} , the flux at a planet scales as $F \sim M_{\odot}^6$ [Whitmire et al., 1995]. Therefore a few percent of the

mass would be sufficient. An initial mass of $\sim 6\%$ higher than today makes the Sun as bright as today 4.5 Ga.

For years, this assumption has been regarded with skepticism by the community, because of the lack of evidence and the success of the "Standard Solar Model" of the Sun. However, a decade ago some inconsistencies between the standard solar model predictions and measurements of the solar CNO abundances were revealed *Asplund et al.* [2009]; *Caffau et al.* [2008, 2010]. Interestingly a younger more massive Sun was then suggested to explain these inconsistencies [*Guzik and Musack*, 2010; *Turck-Chièze et al.*, 2011]. Overall assuming an early massive Sun has consequences on the modelled solar evolution and leaves traces on the numerous observational constraints that are available for the Sun itself (seismic properties, neutrino fluxes, composition). Yet the most recent studies on the subject conclude that these datasets cannot rule out the early massive Sun hypothesis (See *Wood et al.* [2018]; *Buldgen et al.* [2019], and references therein).

The intensity and the evolution of the early solar wind remain open questions. Unfortunately, the basic mechanisms responsible for producing winds from solar-like main sequence stars are still not understood well enough to provide quantitative information. Ideally, much could be learned by observing stellar winds around other stars at various ages. However stellar winds from solar-mass stars are very difficult to observe directly owing to their low optical depth. Some studies have been performed by looking for the Ly α signature of the charge exchange that occurs when the ionized stellar wind collides with the neutral interstellar medium [*Zank*, 1999; *Wood et al.*, 2002, 2005]. Analysing these observations for stars of various ages suggest that stellar winds may decrease exponentially with time and that most of the extra mass was lost in less than a few hundreds of million years [*Wood et al.*, 2005; *Minton and Malhotra*, 2007]. Observations of the radio emission of young solar-type stars suggest a total solar mass loss lower than 2% after 100 Myr [*Fichtinger et al.*, 2017]. Finally, observations of stellar spin down rate have been used to argue in favour of a large and sustained mass loss and a more massive young Sun [*Martens*, 2017], but they also suggest an exponential decrease of the mass loss [*Gallet and Bouvier*, 2013].

Therefore the key difficulty in solving the faint young Sun problem with a more massive sun is to keep the Sun sufficiently massive and bright for one or two billion of years, throughout the Archean. Observations of young solar analogs tend to rule out this possibility, although more data are required to be certain [*Wood et al.*, 2018]. In the future, it may be possible to constrain the Sun's ancient mass and its evolution by looking for remaining

signatures of the early solar wind and the effects of a solar mass-loss history on the orbital dynamics in the planetary system, including possible signatures in the geological and climate record [*Minton and Malhotra*, 2007; *Spalding et al.*, 2018].

2.2 Evidence for liquid water

The oceans might have formed rapidly in a gigantic deluge, a few Myr after the cataclysm that led to the Earth-Moon system, 4.5 Gyr ago [*Sleep et al.*, 2001]. Some models predict that oceans could have formed even earlier and could have partly survived the Moon forming event [*Genda and Abe*, 2005]. The first evidence for the presence of liquid water on Earth derives from the analysis of fragments of Archean zircons. Zircons are U-rich magmatic minerals that are resilient enough to have survived several mountain building cycles. Some of them contain fragments having U-Pb ages up to 4.2-4.4 Ga [*Wilde et al.*, 2001; *Mojzsis et al.*, 2001]. These old zircons present oxygen isotopic compositions that cannot be explained by a dry magmatic genesis and require contribution of material having been hydrothermally altered at low temperature. Direct geologic evidence of oceans stems from the occurrence of pillow basalts and layered banded iron formations in 3.8 Ga units, demonstrating underwater magmatism and sedimentation at, or prior to, that time. Well preserved formations with low metamorphic grades around 3.5 Ga ago in NW Australia and South Africa. Hydrothermal quartz at that ages contain fluid inclusions which contain mixtures of hydrothermal end-member(s) and Archean seawater [*Foriel et al.*, 2004]. Coupled Cl-K-Ar study suggests a salinity comparable to the modern one and, possibly temperatures in the range 20-40°C (see below) [*Marty et al.*, 2018]. Both thermal modelling and field evidence are consistent with the occurrence of liquid water on Earth within a few tens of Ma after the formation of the solar system, with direct evidence for oceans at 3.8-3.5 Ga.

2.3 Constraints on the fraction of land

The fraction of emerged land affects the surface albedo and thus the planetary energy budget. The emergence of land required the development of continents able to float over the denser mantle. Hence the continental lithosphere needed to be strong enough to support crustal thickening and high reliefs [*Rey and Coltice*, 2008]. The period of time when this happened is difficult to estimate and models are generally based on the distribution of old continental crust terrains, as well

as on the petrology and geochemistry of these geological units [Allegre and Rousseau, 1984; Belousova et al., 2010; Dhuime et al., 2012; Pujol et al., 2013]. These models propose major pulses of crustal generation in the period 4 Ga - 3 Ga that resulted in 60-80% present-day volume at 3 Ga (see Figs. 5 & 6 in Hawkesworth et al. [2019]). After 3 Ga, the net growth rate diminished because crustal destruction became effective and competed efficiently with crustal generation. This period of time may mark the onset of modern-style plate tectonics. A lower continental crust volume combined with potentially a larger ocean volume [Pope et al., 2012] logically implies less emerged land during the Archean than today. Flament et al. [2008] estimated that the fraction of emerged land was lower than 12% and probably around 2-3% (compared to 27% today).

2.4 Geological constraints on the temperature

A long debate is still ongoing about the temperature of the early oceans. Archean oceanic cherts (SiO₂) appear depleted in ¹⁸O relative to ¹⁶O [Knauth and Lowe, 2003; Robert and Chaussidon, 2006; Tartese et al., 2016]. A possible explanation of this trend is related to the temperature of Archean oceans. Indeed, cherts concentrate less ¹⁸O relative to seawater during their formation as oceanic temperature increases. The low $\delta^{18}\text{O}$ have thus 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; Tartese et al., 2016]. Notably, silicon isotopes coupled with oxygen isotopes also attest for oceanic temperatures warmer than today [Robert and Chaussidon, 2006]. The temperature range inferred from Archean cherts is compatible with the thermophiles inferred from evolutionary models of the ancient life [Gaucher et al., 2008], with constraints on the salinity of Archean oceans [Marty et al., 2018] and possibly with the indications for a low ocean water viscosity [Fralick and Carter, 2011]. If the interpretation of low $\delta^{18}\text{O}$ in Archean cherts is correct, such high oceanic temperatures would make the faint young Sun problem for Earth much more difficult to overcome (see section 4.2 and 5).

However, the interpretation of $\delta^{18}\text{O}$ isotope ratio as indicator of warm Archean oceans has been strongly debated. Some analyses suggest temperate oceans with temperatures lower than 40°C [Hren et al., 2009; Blake et al., 2010]. In addition, most of Archean cherts did not directly precipitate from seawater or may not be sufficiently well preserved to be used to reconstruct past oceanic temperature [Marin-Carbonne et al., 2012, 2014; Cammack et al., 2018]. Other possible explanations have been proposed as hydrothermal alteration of the seafloor

[van den Boorn et al., 2007] or as a gradual changes in the oxygen isotope composition of seawater [Kasting and Howard, 2006; Jaffrés et al., 2007]. That latter criticism has been ruled out by Tartese et al. [2016], who investigated O isotopes not in cherts but in kerogen and demonstrated that the ocean $\delta^{18}\text{O}$ composition remained almost constant. The triple oxygen isotope mass balance model from Sengupta and Pack [2018] suggests that Archean cherts precipitated in cool oceans with modern-like $\delta^{18}\text{O}$ followed by diagenetic alteration.

In addition, warm/hot Archean oceans are difficult to reconcile with the glacial evidence. The glacial Archean record includes the Huronian glaciations at 2.4 Ga and glacial rocks at 3.5, 2.9 Ga and 2.7 Ga [Kasting and Howard, 2006; Ojakangas et al., 2014; de Wit and Furnes, 2016]. The Huronian glaciations were likely Snowball Earth events, where the entire planet was encased in ice, while the others were likely only partial glaciations. They imply global mean temperatures below 20°C [de Wit and Furnes, 2016], at least episodically. The transitions from warm climates with mean surface temperature around 60°C to cold climates or Snowball-Earth events would imply major changes in the atmospheric composition and in the carbon cycle, implying unknown mechanisms. Such swings in the carbon cycle seem unlikely, although the glacial events may represent only a small fraction of the Archean period.

Finally, evolutionary models suggest thermophilic ancient life but also a mesophilic last universal common ancestor (LUCA) [Bousseau et al., 2008]. These molecular thermometers do not give information about the global mean surface temperature. Thermophily near the roots of the tree of life may reflect local warm environments (like hydrothermal vents) or survival after hot climates produced by large impacts [Bousseau et al., 2008; Abramov and Mojzsis, 2009].

We conclude that the debate about the temperature of the early oceans is not over, although the arguments for cold or temperate climates seem stronger now. We discuss later the implications of both cases in the context of the faint young Sun problem.

2.5 Geological constraints on the atmospheric composition and pressure

The atmospheric composition and pressure in the distant past are primarily estimated from models of the origin(s) of atmospheric volatiles and from models of atmospheric evolution upon interactions with outer space and exchanges with the solid Earth (see the review by Catling and Zahnle [2020] and references therein). Noble gas isotope systematics indicate that the atmosphere is an ancient reservoir that was formed a few

tens of Ma after start of solar system formation 4.56 Ga ago, by degassing of material that accreted to form our planet. The geological record of ancient sediments and their weathering profile is consistent with relatively low partial pressures of CO₂ (pCO₂ < 30 mbar) for the late Archean [Sheldon, 2006; Driese *et al.*, 2011]. A recent technique involving the modelling of the aqueous chemistry in paleosols gives higher estimations for pCO₂ during the Archean (pCO₂=24–140 mbar at 2.77 Ga, 22–700 mbar at 2.75 Ga and 45–140 mbar at 2.46 Ga) and a gradual decrease with time [Kanzaki and Murakami, 2015]. Rosing *et al.* [2010] derived a very low upper limit of ~ 0.9 mbar from the coexistence of siderite and magnetite in Archean banded iron formation. That limit based on thermodynamic arguments has yet been questioned [Reinhard and Planavsky, 2011]. Finally, Lehmer *et al.* [2020] interpreted the oxidation state of micrometeorites at 2.7 Ga as a possible evidence for a CO₂ atmospheric mixing ratio > 70%. These geological constraints on pCO₂ are generally still debated, do not cover all times of the Archean, and are often incompatible. Therefore, we do not think that they should be considered as strict limits. The geological record also suggests the onset of an oxygenated atmosphere around 2.4 Ga, called the Great Oxidation Event [Lyons *et al.*, 2014]. Removing CO₂ and O₂ from the atmospheric composition leaves N₂, water vapour, noble gases and several C species as the main atmospheric constituents.

Geological measurements of the atmospheric pressure and compositions in the distant past were thought to be impossible due to the mobility of volatile elements in rocks and minerals undergoing metamorphism. Surprisingly, this assumption was not correct and new types and samples and new approaches permit measurable constraints to be determined. Marty *et al.* [2013] analyzed volatiles trapped in fluid inclusions in 3.5 Ga hydrothermal quartz from the Pilbara, NW Australia. ³⁶Ar is a primordial isotope that has been conserved in the atmosphere, as indicated by constant ³⁸Ar/³⁶Ar ratio. ⁴⁰Ar is a radiogenic isotope produced by the decay of crustal and mantle ⁴⁰K. The triple bond of N₂ makes this molecule very stable and N₂ is sometimes referred as “the sixth noble gas”. In a ⁴⁰Ar/³⁶Ar versus N₂/³⁶Ar frame, these authors found that data from vacuum crushing experiments define a straight line representing mixing between a low ⁴⁰Ar/³⁶Ar, N₂/³⁶Ar end-member representing paleo-atmospheric noble gases dissolved in seawater and an hydrothermal component rich in crustal ⁴⁰Ar and N. The extrapolated seawater N₂/³⁶Ar ratio was comparable to, or lower than, the modern value, leading Marty *et al.* [2013] to propose that the pN₂ was ≤ 1.1 bar and possibly as low as 0.5 bar. The authors also found that the N isotopic composition of

Archean air was similar to the modern composition, thus discarding the possibility of isotopically fractionating atmospheric escape of nitrogen since 3 Ga. Avicé *et al.* [2018] developed a similar study for several samples from another area (Berberton, South Africa) and proposed that the Archean pN₂ was ≤ 0.5 bar. Independently, Som *et al.* [2012] attempted to set constraints on the barometric pressure in the distant past from fossil imprints of raindrops. The rationale is that the maximum size of raindrops is a function of the P_{atm} as raindrop will fragment over a threshold size due to air drag. These authors measured 2.7 Ga imprints of raindrops and conducted in parallel analogic experiments to conclude that the Archean atmospheric pressure could not have been higher than 2.3 bar and was probably below 1.3 bar. This upper limit has been criticised by Kavanagh and Goldblatt [2015], because the analysis of fossil imprints can be biased by very rare large raindrops. Goosmann *et al.* [2018] argued that such a bias is statistically unlikely given that 18 distinct bedding surfaces were analysed by Som *et al.* [2012].

In a further study, Som *et al.* [2016] proposed an absolute barometric pressure of 0.23 ± 0.23 bar using the size distribution of gas bubbles in 2.5 Ga basaltic lava flows that solidified at sea level. The maximum size that bubbles can reach in a lava flow is a function of the external pressure on the surface of the flow, here the barometric pressure. They compared the bubble sizes for two different layers in the flow, at a given depth (which pressure can be evaluated from the weight of the lava column above) and at the flow’s surface, determined from morphological arguments. Som *et al.* [2016] suggested 0.5 bar as an upper limit for P_{atm}. Together, these studies suggest a surprisingly low barometric pressure for the Archean atmosphere, with little room for pCO₂, which given errors could not have been above 0.5 bar, and possibly in the range 0–0.2 bar. However, little is known about this long period of time for which sample ages cover about 0.8 Ga, and more detailed studies are necessary to better document the fate of atmospheric gases in the neo-Archean before the Great Oxidation Event.

3 Proposed solutions to the faint young Sun problem

With the solar constant $\sim 25\%$ weaker at 3.8 Ga [Gough, 1981], the global mean insolation absorbed by the Earth had a deficit of ~ 60 W/m² (~ 44 W/m² at 2.5 Ga) compared to the current value of 240 W/m² [Wild *et al.*, 2013]. The Earth with the present atmospheric composition and continents would have undergone a cooling

of ~ 60 K (assuming the current climate sensitivity parameter of ~ 1 K/Wm $^{-2}$ [Flato et al., 2013]), falling into a full glaciation. However, a glaciated early Earth is in contradiction with the evidence for liquid water and the temperate/warm climates discussed in the previous section. Moreover, once the Earth is fully ice-covered with a high surface albedo, increasing the solar constant to its present value would not be enough to exit from the snowball state [Sellers, 1969; Budyko, 1969; Hoffman et al., 2017]. The faint Young Sun problem becomes a paradox if we assume that the early Earth’s atmosphere and continents were the same as today. But there is no argument for such an assumption. Most of the proposed solutions to the faint young Sun problem are based on changes to the atmospheric composition, clouds or land distribution, leading to a stronger greenhouse effect or a lower planetary albedo.

3.1 CO $_2$

The first solution to the faint young Sun from Sagan and Mullen [1972] was based on a strong greenhouse effect by an ammonia-rich and highly reduced atmosphere. Such an atmosphere is now discarded in favor of a moderately-oxidized, N $_2$ - and CO $_2$ -rich atmosphere, where the latter would be the dominant greenhouse gas [Catling and Zahnle, 2020]. Solving the faint young Sun problem with a high concentration of CO $_2$ is attractive since CO $_2$ is one of the major volatiles released from magmatic degassing [Gaillard and Scaillet, 2014]. Its concentration is regulated by the carbonate-silicate cycle [Walker et al., 1981], which acts as a long-term thermostat on the climate. We discuss the ability of the carbonate-silicate cycle to moderate CO $_2$ at levels required to solve the faint young Sun problem in section 5.

Previous 1D models showed that ~ 300 mbar of CO $_2$ is required to maintain a global mean surface temperature of 15°C (288 K) during the early Archean and ~ 100 mbar of CO $_2$ at the late Archean [Owen et al., 1979; Kasting et al., 1984; Kiehl and Dickinson, 1987; von Paris et al., 2008]. Such CO $_2$ concentrations exceed the upper limits of ~ 30 mbar derived from estimates of weathering of paleosols at the end of the Archean [Sheldon, 2006; Driese et al., 2011]. From these geological constraints and 1D climate modelling results, it has been suggested that other warming processes are needed to keep the early Earth warm.

Lessons from recent studies:

3D atmospheric GCMs coupled to simple ocean/sea-ice models found that lower amounts of CO $_2$ are needed to maintain global mean surface temperatures of 15°C during the Archean (see Fig. 1 and Wolf and Toon

[2013]; Charnay et al. [2013]). According to the model from Wolf and Toon [2014], 200 mbar of CO $_2$ is required at 3.8 Ga and 40 mbar at 2.5 Ga (see Fig. 2). The case of a warm early Earth with a mean surface temperature of 60-80°C is achievable with high levels of CO $_2$ around 0.5-1 bar according to the 3D study from Charnay et al. [2017], which is significantly less than previous 1D estimations of ~ 3 bars of CO $_2$ at 3.3 Ga by Kasting and Howard [2006]. These discrepancies are mostly related to cloud feedbacks (see section 4), leading to warmer climates with 3D models. The amounts of CO $_2$ required for temperate climates from 3D models are above the geological limits from Sheldon [2006] and Driese et al. [2011]. However, we point out the fact that revised paleosol pCO $_2$ estimates exist, as discussed in the previous section. If the recent pCO $_2$ limits from Kanzaki and Murakami [2015] are correct, temperate climates would be achievable with just enhanced CO $_2$ (see Fig. 2). The pCO $_2$ required for an early Earth at 60-80°C would still remain too high, compatible with only one data point from Kanzaki and Murakami [2015] and with the constraint from Lehmer et al. [2020].

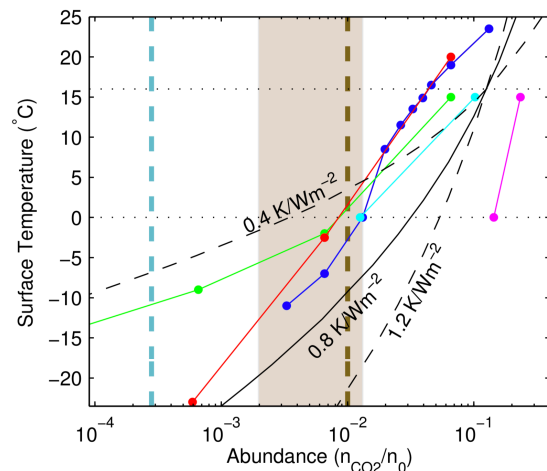


Fig. 1 Mean surface temperature as a function of CO $_2$ abundance for 0.8S $_0$. The results of the 1D models from Haqq-Misra et al. [2008] (green) and von Paris et al. [2008] (cyan) are shown, as well as the 3D models from Wolf and Toon [2013] (blue), Charnay et al. [2013] (red), as well as a 3D oceanic model with a simplified atmospheric model from Kienert et al. [2012] (magenta). The shaded region shows the CO $_2$ constraint range from Driese et al. [2011]. The vertical dashed blue and brown lines give the pre-industrial and early Earth guess (10^{-2}) abundances of CO $_2$. Figure from Byrne and Goldblatt [2014].

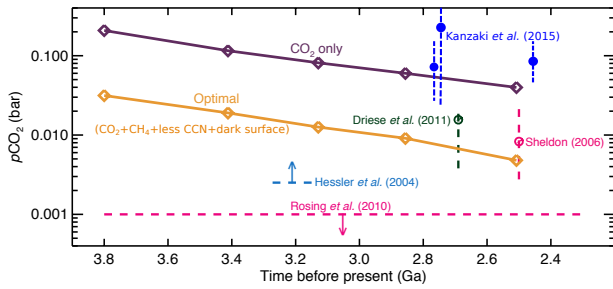


Fig. 2 The amount of CO_2 needed to maintain global mean surface temperatures of 288 K over the course of the Archean for several different scenarios. Optimal warming scenarios include 0.1 mbar of CH_4 , an 18 hour rotation rate, a dark soil surface, and reduced cloud droplet number concentrations. Figure adapted from *Wolf and Toon* [2014].

3.2 CH_4

Methane has been suggested as an important complement to CO_2 to warm the early Earth [*Kiehl and Dickinson*, 1987; *Pavlov et al.*, 2000]. Photochemical models predict that CH_4 had a lifetime typically 1000 times longer in the anoxic Archean atmosphere than in the present-day atmosphere [*Zahnle*, 1986; *Kasting and Howard*, 2006]. Abiotic sources of CH_4 like serpentinization in hydrothermal vents could have maintained concentrations up to ~ 2.5 ppm [*Tian et al.*, 2011; *Guzmán-Marmolejo et al.*, 2013]. Biogenic CH_4 flux from methanogens could have maintained much higher concentrations between 0.1 mbar and 35 mbar [*Kharecha et al.*, 2005; *Ozaki et al.*, 2018; *Krissansen-Totton et al.*, 2018b; *Schwitertman et al.*, 2019; *Sauterey et al.*, 2020]. CH_4 would have been produced by H_2 -based methanogens or by fermentors and acetotrophs decomposing the biomass produced by phototrophs (H_2 -based phototrophs and ferrophototrophs). In addition, the fractionation of atmospheric Xenon could be explained by hydrodynamic hydrogen escape during the Hadean/Archean if the H_2 mixing ratio was higher than 1% or if the CH_4 mixing ratio was higher than 0.5% (i.e. 5 mbar for a 1-bar surface pressure) [*Zahnle et al.*, 2019]. Such high concentrations of CH_4 produce a strong greenhouse by absorbing thermal radiation at $7\text{--}8\ \mu\text{m}$, the edge of an atmospheric window for a $\text{CO}_2\text{--H}_2\text{O}$ atmosphere [*Kiehl and Dickinson*, 1987; *Pavlov et al.*, 2000; *Haqq-Misra et al.*, 2008].

A limitation appears for high methane concentrations due to the formation of organic hazes. Organic hazes are expected to form when the CH_4/CO_2 ratio becomes higher than ~ 0.2 according to photochemical models and experimental data [*Zerkle et al.*, 2012; *Trainer et al.*, 2006]. There is possible isotopic evidence

of organic haze formation at 2.7 Ga [*Zerkle et al.*, 2012]. Hazes are expected to cool the surface by absorbing UV and visible solar radiation, which produces an anti-greenhouse effect [*Pavlov et al.*, 2001; *Haqq-Misra et al.*, 2008]. Although, 1D simulations that incorporate the fractal aggregate nature of haze particles suggest that this cooling effect may not be as large as previously thought [*Wolf and Toon*, 2010; *Arney et al.*, 2016]. In addition, fractal haze particles act as a UV shield, protecting both life and photolytically unstable reduced gases [*Wolf and Toon*, 2010].

Finally, it has been argued that the Great Oxidation Event caused a large decline in atmospheric methane concentration, triggering the Huronian glaciations [*Pavlov et al.*, 2000; *Kasting and Ono*, 2006; *Goldblatt et al.*, 2006]. The apparent synchronicity of the two events at ~ 2.4 Ga is an additional argument in favour of a methane-rich Archean atmosphere.

Lessons from recent studies:

Fig. 3 shows the global mean warming by CH_4 from a 3D GCM. It reaches up to $\sim +14$ K for $p\text{CH}_4=1$ mbar. However, the warming decreases for $p\text{CH}_4 > 1$ mbar. That is due to the absorption of near-IR solar radiation by CH_4 in the stratosphere, producing an anti-greenhouse effect [*Byrne and Goldblatt*, 2014]. That cooling appears in radiative transfer code using HITRAN 2008 or more recent versions. Most of previous 1D studies of the early Earth as *Kiehl and Dickinson* [1987]; *Pavlov et al.* [2000]; *Haqq-Misra et al.* [2008] used older databases and overestimated the greenhouse effect for high concentrations of CH_4 . That effect poses a strong limitation to solutions to the faint young Sun problem based primarily on a CH_4 greenhouse. Despite the limitations at high concentrations, CH_4 greenhouse is an excellent complement to CO_2 to solve the faint young Sun problem, filling up to 20% of the radiative forcing deficit [*Byrne and Goldblatt*, 2014]. However, it cannot be significant in prebiotic time, meaning that CO_2 greenhouse and other abiotic processes likely maintained liquid surface water before the emergence of methanogenesis.

3.3 Other greenhouse gases (NH_3 , H_2) and atmospheric pressure

As mentioned previously, *Sagan and Mullen* [1972] proposed an ammonia (NH_3) greenhouse as a solution to the faint young Sun problem. However, NH_3 is quickly photolyzed and cannot reach concentrations high enough to compensate for the faint young Sun. Yet, UV shielding by photochemical organic hazes could significantly extend the lifetime of NH_3 [*Wolf and Toon*, 2010]. 3D simulations coupling chemistry and haze microphysics

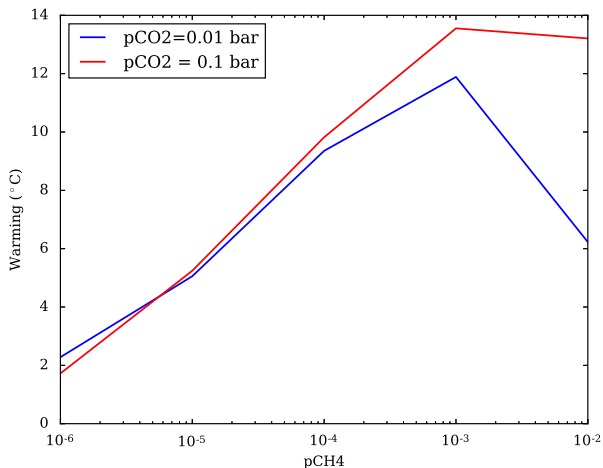


Fig. 3 Global mean warming by methane as a function of $p\text{CH}_4$ (in bar) for an atmosphere with 0.01 bar (blue) and 0.1 bar (red) of CO_2 at 3.8 Ga. Simulations done with the Generic LMD GCM using HITRAN 2008 for CH_4 opacity [Charnay et al., 2017].

will be required to verify if hazes can adequately protect NH_3 from photolysis. In any case, an NH_3 greenhouse appears as a limited solution to the faint young Sun problem, requiring a very reduced early atmosphere or high levels of biogenic CH_4 .

N_2 has no electric dipole and interacts weakly with electromagnetic field, making it a poor greenhouse gas. However, it can enhance the greenhouse effect of others gases by pressure broadening. A high pressure also increases the surface temperature by increasing the moist adiabatic lapse rate, resulting in decreased convective heat transport. Goldblatt et al. [2009] found that 2-3 times more atmospheric N_2 would have produced a warming of +3-8 K, allowing more clement conditions for the early-Earth with a CO_2 -poor atmosphere. At high pressure, N_2 and H_2 can absorb thermal radiation through collision-induced absorption (CIA). CIA of N_2 - N_2 , H_2 - N_2 and N_2 - CH_4 are responsible for most of the greenhouse effect on Titan [McKay et al., 1991], while H_2 - H_2 and H_2 -He play a significant role in the thermal structure of giant planets. Wordsworth and Pierrehumbert [2013] suggested that the early Earth could have been warmed by N_2 - H_2 CIA. This warming process strongly depends on the amount of N_2 and H_2 . It becomes efficient ($>+10$ K) for a N_2 mass column of 2-3 times higher than today and H_2 mixing ratio of ~ 0.1 . A model by Tian et al. [2005], suggested that the H_2 mixing ratio could have been as high as 0.3 in the anoxic early Earth's atmosphere, due to a weaker Jean atmospheric escape.

Lessons from recent studies:

A recent modelling work by Kuramoto et al. [2013] shows that atmospheric escape almost reached the diffusion limited regime during this time period. This implies a H_2 mixing ratio lower than 0.01 for realistic H_2 volcanic fluxes. The existence of detrital magnetite grains in Archean sandstones also suggests a low H_2 mixing ratio with $p\text{H}_2 < 10$ mbar [Kadoya and Catling, 2019]. Moreover, the previous two warming processes, pressure broadening by increased N_2 and N_2 - H_2 CIA, both require a N_2 mass column 2-3 times higher in the past. Such a high surface pressure is not consistent with geological and isotopic constraints discussed in section 2.5. We conclude that a warming by NH_3 , N_2 - H_2 or a higher atmospheric pressure probably did not operate during the Archean. The situation might have been different during the Hadean. In particular, the partial pressure of N_2 was likely higher in the Hadean when nitrogen fixation was limited to abiotic processes [Stüeken et al., 2015, 2016]. An episodic reduced H_2 -rich atmosphere could also have been formed for 10-20 Myrs after giant impacts caused during the late veneer, by reduction of water by a molten iron impactor [Benmer et al., 2020].

3.4 A lower albedo due to less continent and cloud feedbacks

A lower planetary albedo due to a change in the cloud cover and emerged land has been suggested several times as a potential contributor to solve the faint young Sun problem [Jenkins et al., 1993; Rosing et al., 2010]. To fully compensate for a 20-25% lower insolation, the planetary albedo would have to be ~ 0.05 -0.1 (similar to Mercury or the Moon) compared to 0.29 for the present-day Earth [Wild et al., 2013]. Even by removing of all emerged land and all clouds, such a low value would not be reached because of atmospheric Rayleigh scattering. Still, a change in the cloud cover or thickness and fraction of emerged land could have been part of the solution to the faint young Sun problem.

As explained before, the fraction of emerged land is expected to have been lower during the Archean, likely between 2 and 12 % of Earth's surface [Flament et al., 2008]. Furthermore, what emergent continents did exist were likely barren of vegetation, and probably were composed of dark basalts, before gradually changing into the lighter-colored soils we see today as they aged. A reduction of surface albedo would give a maximal radiative forcing of $\sim +5$ W/m^2 [Goldblatt and Zahnle, 2011b].

Clouds have a strong impact on the terrestrial radiative budget by reflecting solar radiation and by absorbing thermal radiation. The albedo effect (cooling ef-

fect) dominates for lower clouds, such as stratus clouds while the greenhouse effect (warming effect) dominates for upper clouds, such as cirrus clouds. *Rondanelli and Lindzen* [2010] suggested that the amount of tropical cirrus formed by detrainment from convective clouds would increase under a fainter Sun, enhancing their greenhouse effect and maintaining a clement climate. Such a negative feedback, called the "Iris hypothesis" [*Lindzen et al.*, 2001], remains debated [*Goldblatt and Zahnle*, 2011a; *Mauritsen and Stevens*, 2015] and could also be compensated or dominated by other positive cloud feedbacks [*Bony and Dufresne*, 2005; *Bony et al.*, 2015]. A more plausible hypothesis is that lower clouds were optically thinner during the Archean, owing to the lack of cloud condensation nuclei (CCN) from biological sources. Such a decrease of CCN yields larger cloud particles which are less effective at scattering and precipitate faster, resulting in a decrease of the planetary albedo [*Rosing et al.*, 2010]. The removal of all lower clouds compared to the present-day cover would lead to a radiative forcing of $\sim 25 \text{ W/m}^2$ [*Goldblatt and Zahnle*, 2011a].

Lessons from recent studies:

3D GCMs have shown that plausible reductions to the surface albedo and emerged land fraction could have increased the global mean surface temperature by up to +4 K [*Wolf and Toon*, 2013; *Charnay et al.*, 2013]. They also suggest that a reduction in CCN results in an increase of the cloud radiative forcing of up to $\sim +12 \text{ W/m}^2$, and an increase in the global mean surface temperature of up to 10 K [*Charnay et al.*, 2013; *Wolf and Toon*, 2014]. A similar temperature change by CCN was found for the Neoproterozoic by *Feulner et al.* [2015]. Independent of the CCN effect, GCMs indicate that a reduced cover of lower clouds and an increased cover of higher clouds for enhanced CO_2 and weaker insolation, providing an additional radiative forcing of $\sim +5 \text{ W/m}^2$ (see section 4.2 and *Wolf and Toon* [2013]; *Charnay et al.* [2013]). In conclusion, a change in the land and cloud cover together cannot compensate more than 60% of the deficit of radiative forcing due to the weaker Archean Sun. A higher amount of greenhouse gases (i.e. CO_2 and CH_4) is still required. However, a reduction to the cloud and surface albedos may have meaningfully contributed to warming the early Earth, and thus less CO_2 and CH_4 may have been otherwise required.

4 New insights from 3D climate models

4.1 Testing the proposed warming solutions with 3D GCMs

While 3D GCMs are notoriously computationally expensive to run, recent gains in computing availability and parallel processing now allow GCMs to be run with sufficient speed to facilitate a wide variety of planetary modelling studies. As such, atmospheric GCMs with simplified ocean/sea-ice components have now been used to thoroughly explore the climate history of the ancient Earth, from the early Archean up through recent snowball Earth epochs [*Jenkins and Smith*, 1999; *Pierre-humbert*, 2004; *Charnay et al.*, 2013; *Wolf and Toon*, 2013, 2014; *Le Hir et al.*, 2014; *Kunze et al.*, 2014; *Teitler et al.*, 2014; *Charnay et al.*, 2017; *Wolf et al.*, 2018]. The use of such 3D climate models has allowed us to explore the numerous alternative climatological mechanisms for warming the early Earth despite the faint young Sun and described in section 3.

As explained in the former section, these models have shown that enhanced CO_2 likely played the major role and could have compensated the fainter Sun with $\text{pCO}_2 \sim 40 \text{ mbar}$ at 2.5 Ga. Such a concentration is above the limits from *Sheldon* [2006] and *Driese et al.* [2011] but compatible with the constraints from *Kanzaki and Murakami* [2015] (see Fig. 2). Note that the case of a warm early Earth with a mean surface temperature of $60\text{-}80^\circ\text{C}$ is achievable with high levels of CO_2 around 0.5-1 bar [*Charnay et al.*, 2017]. However, the pCO_2 required in that case is only compatible with one data point from *Kanzaki and Murakami* [2015] (i.e. $\text{pCO}_2 = 22\text{-}700 \text{ mbar}$ at 2.75 Ga). CH_4 could have been a significant contributor to warm the Archean Earth, increasing the global mean surface temperature by up to +14 K for $\text{pCH}_4 = 1 \text{ mbar}$ (see Fig. 3 and [*Wolf and Toon*, 2013]).

Plausible reductions to the surface albedo or emerged land fraction could have warmed the planet by up to +4 K [*Charnay et al.*, 2013; *Wolf and Toon*, 2014]. A reduction of emerged land fraction does not necessarily imply a lower planetary albedo because cloud cover tends to decrease above continents compared with over oceans. But this cooling effect is compensated by a stronger evaporation leading to an increase in the amount of water vapour in the atmosphere and thus a stronger greenhouse effect [*Charnay et al.*, 2013].

GCMs suggest that increases in the global mean surface temperature of up to +10 K are possible due to reductions in CCN and the resulting feedbacks on clouds. The models predict that there are globally less low clouds (i.e., lower than 5 km), which are in addi-

tion optically thinner, for low and middle latitudes with less CCN. However, there are also more low clouds at high latitudes and more high clouds (i.e., higher than 5 km), because of the warmer climate with a more extended Hadley cell. According to *Wolf and Toon* [2013] and *Charnay et al.* [2013], the warming is dominated by the decrease of low clouds and the shortwave forcing (albedo effect). In the model by *Le Hir et al.* [2014], the cloud feedback is dominated by the increase of high clouds and the longwave radiative forcing (greenhouse effect). We note that *Le Hir et al.* [2014] used a parametrisation for the precipitation rate more sensitive to cloud particle size than *Wolf and Toon* [2013] and *Charnay et al.* [2013], which may explain the difference.

If the background N_2 partial pressure of the Archean was 2 to 3 times greater than today, as postulated by *Goldblatt et al.* [2009], then the Archean may have been warmed by +5 to +10 K for a given amount of CO_2 according to these 3D models. However and as explained in section 2.5, some geological/geochemical analyses indicate that the total nitrogen content of the Archean atmosphere should have been similar or smaller than the present day [*Som et al.*, 2012; *Marty et al.*, 2013; *Som et al.*, 2016].

The early Earth had a faster rotation rate than the present-day Earth, with a diurnal period possibly as short as 10 hours [*Zahnle and Walker*, 1987; *Williams*, 2000; *Bartlett and Stevenson*, 2016]. Changing the rotation would subtly affect horizontal heat transports. A faster rotation rate limits the size of eddies as well as the latitudinal extension and the strength of the Hadley cells. All these changes reduce the efficiency of meridional transport. Under such conditions, the equator-pole thermal gradient is enhanced with a warmer equator and cooler poles, sea ice is more extended and zonal jets are closer to the equator. However this has been shown not to have a significant effect on the overall climate state, with just a small warming of $\sim +1$ K [*Charnay et al.*, 2013; *Wolf and Toon*, 2014; *Le Hir et al.*, 2014]. Note that these studies use simple ocean models, with no sea-ice transport and with a fixed oceanic heat diffusivity. *Charnay et al.* [2013] use a 2-layer ocean model with Ekman transport coupled to surface winds. This allows to more properly simulate meridional heat transport at low latitude, but the model still misses the sea-ice transport. In contrast, simulations by *Kienert et al.* [2012] with a 3D oceanic model and a simplified 2D atmospheric model suggest a strong cooling for a fast rotation rate. This is caused by a reduced atmospheric and oceanic heat transport as well as by a change in cloud cover and lapse rate. The latter is likely an artefact of the parametrisation used in the 2D atmospheric model and the cooling is likely overestimated

(see the discussion in *Le Hir et al.* [2014]). However, the change in ocean dynamics may have a non-negligible impact on the global mean surface temperature. This has to be explored with a full 3D atmosphere-ocean GCM.

Table 1 summarises the different proposed solutions to the faint young Sun problem, the radiative forcing (computed from 1D or 3D models) and the constraints (geological, geochemical or theoretical). Solutions which are compatible with geological/geochemical constraints are in green, possible solutions for which there is only theoretical constraints are in yellow and solutions which are not compatible with the constraints are in red. While many researchers have sought to find sweeping solutions to the faint young Sun problem, perhaps the paradox is instead solved by a collection of the processes outlined above. Coupled with enhanced CO_2 , increased CH_4 , reductions to the cloud albedo, and a dark surface, all can contribute +4 to +14 K of global mean warming. Note that the cumulated radiative forcing (i.e. global warming) is not necessary equal to the sum of each process taken separately. For instance, gases and high ice clouds can have overlapping greenhouse effects. 3D studies now suggest that there are plausible solutions for maintaining temperate climates within geological constraints on surface temperature and CO_2 , combining these different warming processes. In particular, *Charnay et al.* [2013] and *Wolf and Toon* [2013] using structurally similar but independently constructed 3D climate models with different boundary conditions (i.e. land distribution), both found that mean surface temperatures similar to that of the present day Earth can be maintained at the end of the Archean (2.5 Ga), provided that the atmosphere had: 1) 40 mbar CO_2 , 2) 10-20 mbar CO_2 and 1-2 mbar CH_4 or 3) 5 mbar CO_2 , 0.1 mbar of CH_4 , reduced CCN and dark soil surface. The yellow curve in the figure 2 shows the amount of CO_2 needed to maintain global mean surface temperatures of $15^\circ C$ considering the case where multiple warming mechanisms are factored in (0.1 mbar of CH_4 , reduced CCN and dark soil surface). The combination of all these processes is totally plausible for the Archean. For this optimal case, a temperate Earth can be maintained at all times of the Archean with CO_2 amounts less than 30 mbar, compatible with constraints from *Sheldon* [2006] and *Driese et al.* [2011].

Finally, the similar results obtained from these different 3D GCMs with simplified ocean/sea-ice models, in particular the similar pCO_2 required for temperate climates, suggest that the faint young Sun problem can be solved more easily than initially thought. Even the case of a warm early Earth at $60^\circ C$ is more accessible from a purely climate modelling point of view, although

not compatible with most of geological constraints on pCO₂ and surface pressure.

4.2 Cloud feedbacks

Fig. 1 shows global mean surface temperature as a function of pCO₂ from two 1D models [*Haqq-Misra et al.*, 2008; *von Paris et al.*, 2008] and two GCMs [*Wolf and Toon*, 2013; *Charnay et al.*, 2013] for a 20% weaker Sun (i.e 3 Ga). While all models predict a pCO₂ around 10 mbar for a global mean surface temperature of 0°C, the 3D GCMs show a higher climate sensitivity (~ 1 K/Wm⁻² in 3D versus ~ 0.6 K/Wm⁻² in 1D), reaching a present-day like mean temperature for half the pCO₂ from 1D model. This higher value is mostly due to feedbacks from sea-ice and clouds, not present in 1D models. The climate sensitivity obtained in these 3D studies is similar to the climate sensitivity of GCMs used for the IPCC report, giving a value of 1 ± 0.5 K/Wm⁻² [*Flato et al.*, 2013].

For a similar global mean surface temperature, a high pCO₂ and a fainter Sun result in a weaker equator-pole temperature gradient, a lower surface evaporation rate and a higher tropopause. The evaporation is reduced by around 7% for the Archean Earth with present-day like temperatures [*Wolf and Toon*, 2013]. Moreover, enhanced CO₂ reduces the radiative cooling of low clouds and thus reduces their efficiency to form. Both the weaker evaporation rate and the weaker radiative cooling lead to a reduced fraction of low clouds for the Archean Earth [*Wolf and Toon*, 2013; *Charnay et al.*, 2013]. In addition, 3D GCMs predict an increase of the cover and altitude of high clouds, due to a more extended troposphere and a colder tropopause for a CO₂-rich atmosphere with no ozone. The decrease of low clouds and the increase of high clouds increases the net cloud radiative forcing. Fig. 4 and Fig. 5 illustrates the change in cloud cover and temperature for the Archean Earth. 3D models predict a net cloud radiative forcing increased by around +15 W/m² for a temperate Archean Earth with 60 mbar of CO₂ [*Wolf and Toon*, 2013]. This increase also takes into account the reduction of the insolation in the past and cannot be added directly to other forcings to compensate for the deficit of absorbed solar radiation. A more proper calculation can be done using the insolation at 3.8 Ga for the shortwave forcing for both the early Earth and the present-day Earth. In this case, the change in the cloud cover increases the net cloud radiative forcing by around +5 W/m². This means that the cloud feedbacks enhance the CO₂ warming by $\sim 11\%$. If we use instead the current insolation for the shortwave forcing (what will be useful for the following comparison with IPCC

simulations), we found an increase of the net cloud radiative forcing by around +7 W/m², or $\sim 16\%$ of the CO₂ warming.

A similar positive cloud feedback due to high clouds and a reduced cover of low clouds for increasing pCO₂ is present in most of 3D GCMs used for climate change (see *Boucher et al.* [2013] and references therein). To compare the cloud feedbacks for the Archean Earth (for which the reduced insolation is balanced by enhanced CO₂) to GCMs used for current climate change, it is appropriate to consider rapid adjustments, that is after the CO₂ is increased but before the ocean temperatures have fully adjusted. This avoids to include contributions due to the change in the sea surface temperature. *Zelinka et al.* [2013] found that the net cloud forcing increases by ~ 1.1 W/m² in simulations from 5 GCMs after an abrupt quadrupling of CO₂. Since the forcing for 4×CO₂ is around 7.4 W/m² [*Boucher et al.*, 2013], cloud feedbacks enhance the CO₂ warming by $\sim 15\%$, similar to our estimate for the Archean Earth using current insolation. We conclude that the cloud feedbacks in 3D simulations of the Archean Earth are similar and consistent with 3D simulations for anthropogenic climate change. Note that the spread between different climate models is large, in particular for the cloud forcing which remain one of the largest sources of uncertainty in climate modelling.

The effects of cloud feedbacks is particularly strong for warm/hot climates. Archean climates with mean surface temperature around 60°C are obtained with ~ 1 bar of CO₂ according to the 3D model of *Charnay et al.* [2017]. This is 3 times less than predictions from the 1D model of *Kasting and Howard* [2006]. This discrepancy mostly comes from the strong decrease of lower clouds for high levels of CO₂. The net cloud forcing is increased by $\sim +10-15$ W/m² for a warm climate (pCO₂=1 bar) compared to a temperate climate (pCO₂=0.1 bar) [*Charnay et al.*, 2017]. This corresponds to an increase of $\sim +25$ W/m² compared to the present-day cloud forcing. Under high pCO₂, increasing the size of cloud particles has a limited effect ($< +3$ W/m²), suggesting that the planet has almost reached the maximal cloud forcing related to the reduction of low clouds.

4.3 The case of cold climates with waterbelts

With fairly small CO₂ amounts (< 1 mbar), 3D models with simplified ocean predict that the early Earth would have been cold ($T < 0^\circ\text{C}$) but would have avoided complete glaciation, instead maintaining an equatorial ice-free waterbelt [*Charnay et al.*, 2013; *Wolf and Toon*, 2013; *Le Hir et al.*, 2014; *Kunze et al.*, 2014; *Teitler et al.*, 2014]. For these cold climates, the mean surface

Solutions to the FYS problem	Maximal radiative forcing	Constraints (paleosols or theoretical)	References for constraints
Elevated CO ₂	+26 Wm ⁻² (for pCO ₂ =10 mbar) +44 Wm ⁻² (for pCO ₂ =60 mbar) [<i>Wolf and Toon, 2013</i>] [<i>Le Hir et al., 2014</i>] [<i>Byrne and Goldblatt, 2014</i>]	pCO ₂ =3–15 mbar (2.69 Ga) pCO ₂ =3–25 mbar (2.5 Ga)	[<i>Driese et al., 2011</i>] [<i>Sheldon, 2006</i>]
		pCO ₂ =24–140 mbar (2.77 Ga) pCO ₂ =22–700 mbar (2.75 Ga) pCO ₂ =45–140 mbar (2.46 Ga) CO ₂ >70% (2.7 Ga)	[<i>Kanzaki and Murakami, 2015</i>] [<i>Kanzaki and Murakami, 2015</i>] [<i>Kanzaki and Murakami, 2015</i>] [<i>Lehmer et al., 2020</i>]
Elevated CH ₄	+9 Wm ⁻² (for pCH ₄ =1 mbar) [<i>Byrne and Goldblatt, 2014</i>] [<i>Le Hir et al., 2014</i>]	pCH ₄ =0.01-10 mbar CH ₄ >0.5% (~3.5 Ga) CH ₄ :CO ₂ ~0.2 (~2.6 Ga)	[<i>Sauterey et al., 2020</i>] [<i>Zahnle et al., 2019</i>] [<i>Zerkle et al., 2012</i>]
Less emerged land	+5 Wm ⁻² (with almost no land) [<i>Goldblatt and Zahnle, 2011a</i>]	Fraction=2-12% (2.5 Ga) Crust volume=60-80% (3 Ga)	[<i>Flament et al., 2008</i>] [<i>Hawkesworth et al., 2019</i>]
Faster rotation	~+0 Wm ⁻² (for P=14h) [<i>Charnay et al., 2013</i>]	Length of day=21.9±0.4h (620 Ma) Length of day~13h (3.8 Ga)	[<i>Williams, 2000</i>] [<i>Bartlett and Stevenson, 2016</i>]
Cloud feedbacks and less CCN	~+5 Wm ⁻² (cloud feedbacks*) ~+12 Wm ⁻² (for r=17 μm) [<i>Charnay et al., 2013</i>] [<i>Wolf and Toon, 2013, 2014</i>]	Larger droplets (r~17 μm)	[<i>Rosing et al., 2010</i>]
High surface pressure	+12.2 Wm ⁻² (for 2×PAL N ₂) [<i>Goldblatt et al., 2009</i>]	P=0.23±0.23 bar (2.74 Ga) P<0.53-1.1 bar (2.7 Ga)	[<i>Som et al., 2016</i>] [<i>Som et al., 2012</i>]
N ₂ -H ₂ warming	+24 Wm ⁻² (for 3×PAL N ₂ , 10%H ₂) [<i>Wordsworth and Pierrehumbert, 2013</i>]	pN ₂ <1.1 bar (3.5-3 Ga) pN ₂ <1 bar (3.3 Ga) pH ₂ <10 mbar H ₂ <1%	[<i>Marty et al., 2013</i>] [<i>Avice et al., 2018</i>] [<i>Kadoya and Catling, 2019</i>] [<i>Kuramoto et al., 2013</i>]
Elevated NH ₃	+33 Wm ⁻² (for pNH ₃ =10 ⁻² mbar) [<i>Byrne and Goldblatt, 2014</i>]	pNH ₃ ~10 ⁻⁵ mbar Higher values if organic hazes	[<i>Kasting, 1982</i>] [<i>Wolf and Toon, 2010</i>]

Table 1 Table of solutions to the Faint Young Sun Problem. The first column lists the different possible solutions. The second column gives the maximal radiative forcing and the corresponding references based on 1D or 3D models. We remind that the faint young Sun implies a deficit of 44 Wm⁻² at 2.5 Ga and 60 Wm⁻² at 3.8 Ga. For CO₂, we give the forcing for two values of pCO₂ consistent with the different constraints. *The change in the cloud radiative forcing is computed for the insolation at 3.8 Ga, between the Archean cloud cover and the present-day cloud cover. The third and fourth columns show the constraints from paleosols or models for the different solutions with the references (see also table 1 in *Catling and Zahnle [2020]*). We indicate here the prominent recent constraints. Green is for solutions and radiative forcings which are compatible with the constraints, yellow for possible solutions for which there are only theoretical constraints, and red for solutions which are not compatible with the constraints.

temperature is lower than predicted by 1D models (see for instance Fig. 1). Fig. 6 shows the mean latitudinal extent of polar sea ice as a function of pCO₂ from 3D simulations by *Wolf and Toon [2013]* at 3 Ga. Sea ice can extend toward the equator down to 37°N/S without triggering a runaway glaciation. In the model by *Charnay et al. [2013]*, sea ice can extend down to 25°N/S. In this model, equatorial water belts are stabilized by a cloud feedback, with a reduction of tropical low clouds due to a subsidence occurring at the ice line. *Abbot et al. [2011]* also found a stronger subsidence at the tropics in the case of a waterbelt state. In their model, this induces efficient evaporation of the highly reflective snow (albedo~0.8) in the tropics, leaving bare sea ice which is less reflective (albedo~0.4-0.5) and which stabilizes the waterbelt state against runaway glaciation. According to these studies, at least some surface liquid water, and thus habitable conditions, could have been maintained with only a minimal CO₂-CH₄ greenhouse. If real, such a resistance against full glaciation would mitigate the faint young Sun problem.

However, the stability of cold climates with equatorial waterbelts has been questioned by *Voigt and Abbot [2012]*. In the case of the Neoproterozoic glaciations and using a 3D atmosphere-ocean GCM, they showed that sea-ice transport plays a major role in the triggering of full glaciation. Glaciation is initiated with 100 times more CO₂ when sea-ice transport is included. We conclude that 3D GCMs with simple ocean/sea-ice models likely overestimate the stability of waterbelts. Archean cold climates with waterbelts should therefore not be considered as robust solutions to the faint young Sun problem unless their stability is demonstrated with full atmosphere-ocean GCMs.

5 The role of biogeochemical cycles

5.1 The carbon cycle as a key for solving the faint young Sun problem

3D climate modelling with simplified ocean/sea-ice components reveals that temperate climates with present-

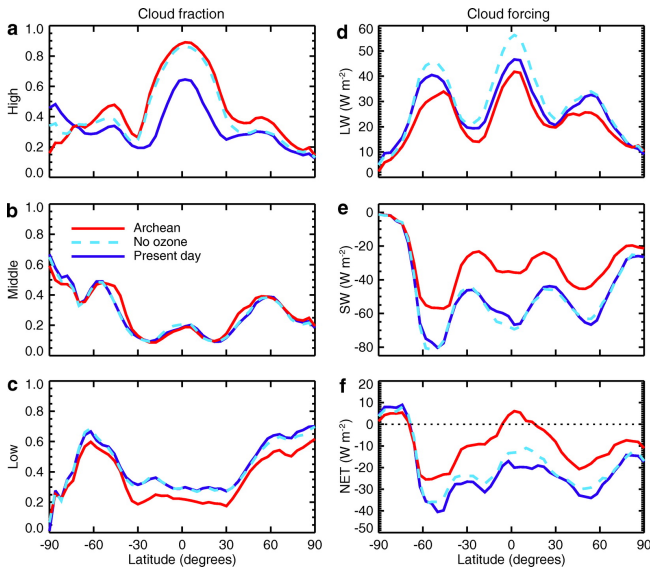


Fig. 4 Zonal mean cloud properties in 3D atmospheric simulations of the Archean (red), present day (purple), and the present-day atmosphere but with oxygen and ozone removed (dashed light blue). (a) Vertically integrated high cloud fraction. (b) Vertically integrated middle cloud fraction. (c) Vertically integrated low cloud fraction. (d) Longwave cloud forcing. (e) Shortwave cloud forcing. (f) Net cloud forcing. Figure from *Wolf and Toon* [2013].

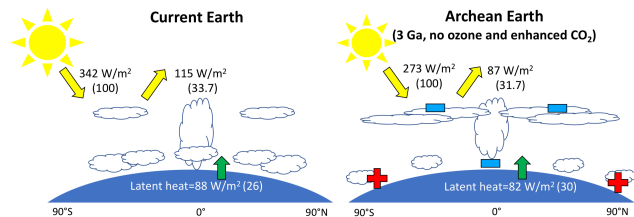


Fig. 5 Illustration of the change in cloud cover for the Archean Earth. The left panel shows the current Earth with global mean insolation at top of the atmosphere and reflected radiation (yellow arrows), latent heat flux (red arrow) and cloud cover. The fluxes in percent of the global mean insolation are given in brackets. The right panel shows the Archean Earth, with the insolation at 3 Ga, no ozone and enhanced CO_2 (i.e. 60mbar) for the same global mean surface temperature as current Earth (287.9 K). Red + indicate the warming of high latitudes and blue - indicate the cooling of equatorial regions and the upper troposphere compared to the current Earth. The Archean Earth has less lower clouds and more upper clouds. Values are taken from *Wolf and Toon* [2013].

day like temperatures can be maintained for the late Archean with enhanced CO_2 , potentially helped by other warming processes. The carbon cycle and its ability to regulate the climate by the carbonate-silicate cycle thus appears to be a key for solving the faint young Sun problem.

Modelling of the carbon cycle of the early Earth by *Sleep and Zahnle* [2001] and *Zahnle and Sleep* [2002] suggested that the Archean was very cold unless an-

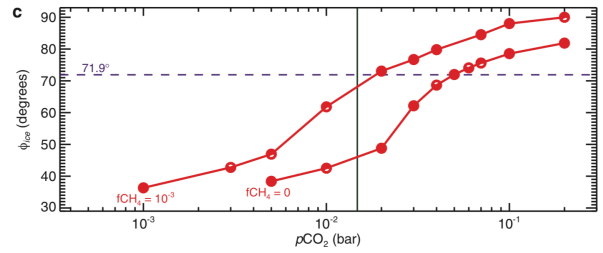


Fig. 6 Annual and hemispheric mean sea ice margin (ϕ_{ice}) as a function of $p\text{CO}_2$ from 3D simulations with present-day continents, the Archean Sun at 3.Ga and with or without methane. Purple dashed lines indicate the sea-ice extent for present-day climate. The green line indicates the $p\text{CO}_2$ estimation by *Driese et al.* [2011]. Figure from *Wolf and Toon* [2013].

other strong greenhouse gas was present. They also suggested that the Hadean was likely fully ice-covered because of the weathering of impact ejecta, particularly during the Late Heavy Bombardment (LHB) [*Gomes et al.*, 2005; *Bottke and Norman*, 2017]. Impact ejecta are indeed easily weathered when falling in the ocean, consuming CO_2 . *Sleep and Zahnle* [2001] and *Zahnle and Sleep* [2002] highlighted the importance of the seafloor weathering, caused by the reaction of seawater with the oceanic crust in low-temperature, off-axis, hydrothermal systems [*Brady and Gislason*, 1997; *Coogan and Gillis*, 2013; *Coogan and Dosso*, 2015]. This CO_2 sink would have been efficient on the early Earth with little emerged land and a high oceanic crust spreading rate. However, calculations of seafloor weathering by *Sleep and Zahnle* [2001] and *Zahnle and Sleep* [2002] did not take into account possible dependence on ocean chemistry, pH and oceanic temperature, and likely overestimated it. Analyses by *Brady and Gislason* [1997]; *Coogan and Gillis* [2013]; *Coogan and Dosso* [2015] suggest that the rate of basalt dissolution and pore-space carbonate precipitation depends on bottom water temperature and/or seawater composition. In addition, reverse weathering induced by authigenic clay formation could have favoured high $p\text{CO}_2$ on the early Earth [*Isson and Planavsky*, 2018].

More recent modelling works by *Charnay et al.* [2017] and *Krissansen-Totton et al.* [2018a], using updated climate models and parametrizations of seafloor weathering with composition/temperature dependence, revealed an efficient regulation of the carbon cycle maintaining temperate conditions for the early Earth (see Fig. 7). Seafloor weathering flux in these models is of a similar magnitude or higher than continental weathering flux. According to these studies, warm early oceans at 60°C can not be maintained because of the strong negative temperature feedback. *Charnay et al.* [2017] re-

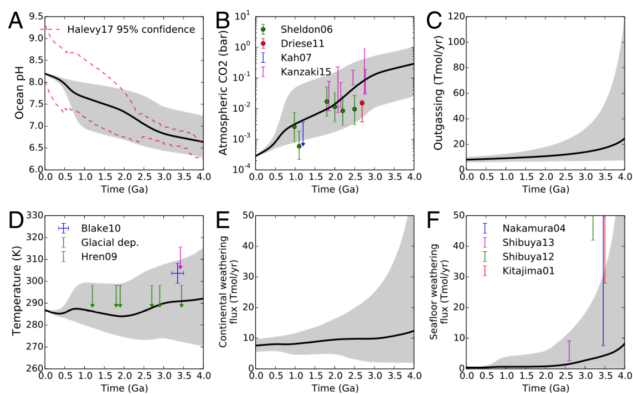


Fig. 7 Evolution of pH (A), $p\text{CO}_2$ (B), global outgassing flux (C), mean surface temperature (D), continental silicate weathering flux (E) and seafloor weathering flux (F) over Earth’s history. Gray shaded regions represent 95% confidence intervals, and black lines are the median outputs of the carbon-cycle model from *Krissansen-Totton et al.* [2018a]. Some geological/geochemical proxies for temperature, $p\text{CO}_2$ and seafloor weathering are indicated. Figure from *Krissansen-Totton et al.* [2018a].

evaluated the long-term effect of impacts on the carbon cycle during the Late Heavy Bombardment (whose existence is still debated, see for instance *Boehnke and Harrison* [2016]). They found that the weathering of ejecta would have strongly decreased the partial pressure of CO_2 leading to cold climates but not necessary to a snowball Earth during all that period.

In conclusion, these recent modelling studies suggest that the early Earth’s climate was likely temperate, except during the Late Heavy Bombardment, and regulated by the carbon-cycle, without necessary requiring additional greenhouse gas or warming process.

5.2 The biosphere and life feedbacks

A fascinating topic is the role that life played in the maintenance of Earth’s habitability. Some researchers have speculated that the long-term stability of Earth’s climate is aided by feedbacks involving life itself [*Love-lock and Margulis*, 1974; *Schwartzman and Volk*, 1989; *Lenton*, 1998; *Lenton and von Bloh*, 2001]. In particular, several possible solutions to the faint young Sun problem rely on the biosphere and life feedbacks, for instance the production of CH_4 by methanogens or the reduction of CCN from biological sources. In contrast, metabolic or ecological evolution could destabilize the carbon cycle or the radiative balance, inducing glacial events and mass extinctions. For instance, the Huronian glaciations, the Neoproterozoic glaciations and the

Ordovician glaciations could be related to the development of new species (i.e. cyanobacteria, algae, fungi and plants respectively) [*Heckman et al.*, 2001; *Lenton et al.*, 2012; *Feulner et al.*, 2015]. The C isotopic fractionation from ancient rocks suggests the presence of a productive biosphere, likely due to the early emergence of photosynthesis (oxygenic or anoxygenic) [*Nisbet and Sleep*, 2001; *Krissansen-Totton et al.*, 2015]. This potentially implies a significant impact of the early biosphere on the carbon cycle, but also on the nitrogen cycle (affecting the surface pressure, see *Stüeken et al.* [2016]) and other biogeochemical cycles (in particular sulfur and phosphorous). The question about life feedbacks is also fundamental for exoplanets, concerning the habitability and the search for biosignatures [*Chopra and Lineweaver*, 2016]. To be tested, it requires global planet models simulating the interaction between ecosystems, biogeochemical cycles and the climate.

A recent modelling work following this approach by *Sauterey et al.* [2020] points to the efficient methane production by primitive methanogenic ecosystems. They appear as a robust contributor to solve the faint young Sun problem. However, the methane greenhouse effect enhances rock and seafloor weathering, decreasing $p\text{CO}_2$. At equilibrium, this negative feedbacks by the carbon cycle compensates for around 50% of the methane warming. For some conditions, the decrease of $p\text{CO}_2$ by the carbon cycle feedback can lead to the formation of organic hazes (for $\text{CH}_4:\text{CO}_2 \geq 0.2$), cooling the Earth and triggering glaciations [*Kanzaki and Murakami*, 2018]. Finally, the late appearance of methanotrophs, consuming methane once $p\text{CO}_2$ was reduced, could also have triggered glacial events [*Sauterey et al.*, 2020]. These are examples of climate destabilization by life with primitive ecosystems. Additional work is needed to investigate all the possible implications of the early biosphere on the climate at different ages.

6 Conclusions and perspectives

A few years ago, the faint young Sun problem appeared to be very challenging despite the various proposed solutions: “All of these solutions present considerable difficulties, however, so the faint young Sun problem cannot be regarded as solved.” [*Feulner*, 2012]. 1D atmospheric models failed to produce present-day like mean surface temperate when satisfying the geological/geochemical constraints on CO_2 . In addition, carbon cycle models were not able to maintain temperate climates during the Archean and the Hadean with only CO_2 as greenhouse gas.

Major progress concerning the faint young Sun problem has been made during the last decade, in particu-

lar with 3D atmospheric GCMs coupled to simplified ocean/sea-ice models which have allowed comprehensive testing of a variety of proposed solutions [Charney *et al.*, 2013; Wolf and Toon, 2013, 2014; Le Hir *et al.*, 2014; Kunze *et al.*, 2014; Teitler *et al.*, 2014; Charney *et al.*, 2017]. These 3D models overcame the limitations inherent to previous 1D models, taking into account fundamental climate feedbacks (clouds and sea-ice), atmospheric/oceanic heat transport and land distribution, although they do not capture the dynamics of sea-ice and the oceans. They suggest that a temperate early Earth is easier to achieve than previously thought. More precisely, around 200 mbar of CO₂ is required at 3.8 Ga to reach present-day mean temperate and 40 mbar at 2.5 Ga, assuming no change in Earth's continents and rotation rate. This is around half of that estimated by 1D models. This discrepancy is mostly due to cloud feedbacks with a reduction of low clouds and an increase of high clouds for enhanced CO₂ and reduced insolation. Similar cloud feedbacks are predicted with 3D models used for climate future projections [Boucher *et al.*, 2013; Schneider *et al.*, 2019]. Unfortunately, the cloud response which may have helped to warm the early Earth, may worsen the current anthropogenic climate change.

3D studies also revealed that temperate climates can be reached for the late Archean with modest levels of CO₂ (down to 5 mbar), if combined with realistic levels of CH₄, reduced CCN and less emerged lands. CH₄ appears as an excellent complement to CO₂, although its warming effect saturates at pCH₄~1 mbar (corresponding to a warming of ~+14 K). Ecosystem models coupled to atmospheric models suggest that CH₄ concentration of the order of 0.1-1 mbar could have been reached during the Archean [Ozaki *et al.*, 2018; Sauterey *et al.*, 2020]. The reduction of CCN appears as another robust mechanism producing optically thinner low clouds and a significant global warming (up to ~+10 K). The reduction of the fraction of emerged land has a modest but non-negligible effect (up to ~+4 K). All these changes (biogenic CH₄, reduced CCN and emerged land) are plausible for the Archean Earth. In addition, recent geological constraints suggest higher levels of CO₂ for the late Archean, generally ~20-140 mbar [Kanzaki and Murakami, 2015] or potentially higher [Lehmer *et al.*, 2020]. Such higher values of CO₂ mitigate the faint young Sun problem, since enhanced CO₂ alone can then be a sufficient solution. According to recent modelling studies, these levels of CO₂ could have been maintained by the carbon cycle, producing an efficient climate regulation [Charney *et al.*, 2017; Krissansen-Totton *et al.*, 2018a]. Finally, constraints of the barometric pressure and the N₂ abundance suggest that the

surface pressure was likely lower than today during the Archean, ruling out solutions involving a higher surface pressure and N₂-H₂ CIA.

In conclusion, the 3D atmospheric GCMs combined with carbon-cycle models suggest that the faint young Sun problem can be solved with higher levels of CO₂, consistent with the most up to date constraints on pCO₂, potentially help by additional warming processes (i.e. biological CH₄, less emerged land and less CCN). The case of a temperate early Earth does not appear very problematic anymore. The case of a warm (~60-80°C) early Earth, which is heavily debated, remains challenging. 3D models showed that it requires less greenhouse gases than previously thought, but still exceeding most of the recent constraints on CO₂ and on the barometric pressure.

Although we believe that the faint young Sun problem has essentially been solved, new geological and geochemical constraints on the atmospheric composition, pressure and surface temperature are required to get a clear picture of the early Earth's climate. Additional modelling work is also needed, in particular for quantifying the impact of ocean transport and for testing the stability of cold waterbelt states, with atmospheric GCMs fully coupled to 3D oceanic models including sea-ice transport. Such 3D atmosphere-ocean GCMs for the early Earth are a great challenge in term of modelling but would have numerous applications for past climates and for exoplanets. New simulations for low atmospheric surface pressures are also necessary to analyse the changes in terms of heat transport and cloud cover, and to estimate the pCO₂ required to avoid glaciation. More generally, a major challenge is to understand the co-evolution of life and the environment on Earth. In terms of modelling, this requires to simulate the biogeochemical cycles and the couplings between the different components of the Earth system (ocean, atmosphere, biosphere, land and interior). Recent modelling studies show promising perspectives for the early Earth in this context (see for instance Stüeken *et al.* [2016]; Krissansen-Totton *et al.* [2018a]; Sauterey *et al.* [2020]).

Finally, the faint young Sun problem has stimulated a lot of research and new ideas in the fields of solar physics, geology, climate science, planetary science, biology, in particular concerning the interactions between the different components of the Earth system. With its different stellar flux, rotation rate, land distribution, atmosphere and biosphere, we can view the early Earth has another habitable world or even multiple habitable worlds different from our modern Earth. The early Earth appears as a fantastic laboratory to study processes controlling the climate, the atmospheric evolu-

tion and the habitability of exoplanets. We can dream that in return, the characterization of terrestrial exoplanets will shed light on these processes and on the environmental conditions which allowed the emergence of life on Earth.

Acknowledgements We thank the two anonymous reviewers for comments that improved the manuscript. B. Charnay acknowledges financial support from the Programme National de Planétologie (PNP) of CNRS/INSU, co-funded by CNES.

References

- Abbot, D. S., A. Voigt, and D. Koll, The Jormungand global climate state and implications for Neoproterozoic glaciations, *Journal of Geophysical Research (Atmospheres)*, 116(D18), D18103, doi:10.1029/2011JD015927, 2011.
- Abramov, O., and S. J. Mojzsis, Microbial habitability of the Hadean Earth during the late heavy bombardment, *Nature*, 459, 419–422, doi:10.1038/nature08015, 2009.
- Allegre, C. J., and D. Rousseau, The growth of the continent through geological time studied by Nd isotope analysis of shales, *Earth and Planetary Science Letters*, 67(1), 19–34, doi:10.1016/0012-821X(84)90035-9, 1984.
- Arney, G., S. D. Domagal-Goldman, V. S. Meadows, E. T. Wolf, E. Schwieterman, B. Charnay, M. Claire, E. Hébrard, and M. G. Trainer, The Pale Orange Dot: The Spectrum and Habitability of Hazy Archean Earth, *Astrobiology*, 16(11), 873–899, doi:10.1089/ast.2015.1422, 2016.
- Asplund, M., N. Grevesse, A. J. Sauval, and P. Scott, The Chemical Composition of the Sun, *Annual Review of Astronomy & Astrophysics*, 47(1), 481–522, doi:10.1146/annurev.astro.46.060407.145222, 2009.
- Avice, G., B. Marty, R. Burgess, A. Hofmann, P. Philippot, K. Zahnle, and D. Zakharov, Evolution of atmospheric xenon and other noble gases inferred from Archean to Paleoproterozoic rocks, *Geochimica et Cosmochimica Acta*, 232, 82–100, doi:10.1016/j.gca.2018.04.018, 2018.
- Bartlett, B. C., and D. J. Stevenson, Analysis of a Precambrian resonance-stabilized day length, *Geophysical Research Letters*, 43(11), 5716–5724, doi:10.1002/2016GL068912, 2016.
- Belousova, E. A., Y. A. Kostitsyn, W. L. Griffin, G. C. Begg, S. Y. O’Reilly, and N. J. Pearson, The growth of the continental crust: Constraints from zircon Hf-isotope data, *Lithos*, 119, 457–466, doi:10.1016/j.lithos.2010.07.024, 2010.
- Benner, S. A., et al., When did life likely emerge on earth in an rna-first process?, *ChemSystemsChem*, 2(2), e1900,035, doi:10.1002/syst.201900035, 2020.
- Blake, R. E., S. J. Chang, and A. Lepland, Phosphate oxygen isotopic evidence for a temperate and biologically active Archean ocean, *Nature*, 464, 1029–1032, doi:10.1038/nature08952, 2010.
- Boehnke, P., and T. M. Harrison, Illusory Late Heavy Bombardments, *Proceedings of the National Academy of Science*, 113, 10,802–10,806, doi:10.1073/pnas.1611535113, 2016.
- Bony, S., and J.-L. Dufresne, Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models, *Geophysical Research Letter*, 32(20), L20806, doi:10.1029/2005GL023851, 2005.
- Bony, S., et al., Clouds, circulation and climate sensitivity, *Nature Geoscience*, 8(4), 261–268, doi:10.1038/ngeo2398, 2015.
- Bottke, W. F., and M. D. Norman, The Late Heavy Bombardment, *Annual Reviews of Earth and Planetary Sciences*, 45, doi:10.1146/annurev-earth-063016-020131, 2017.
- Boucher, O., et al., Clouds and Aerosols, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.*, 2013.
- Bousseau, B., S. Blanquart, A. Necselea, N. Lartillot, and G. Manolo, Parallel adaptations to high temperatures in the Archean eon, *Nature*, 456, 942–945, doi:10.1038/nature07393, 2008.
- Brady, P. V., and S. R. Gíslason, Seafloor weathering controls on atmospheric CO₂ and global climate, *Geochimica et Cosmochimica Acta*, 61, 965–973, doi:10.1016/S0016-7037(96)00385-7, 1997.
- Budyko, M. I., The effect of solar radiation variations on the climate of the earth., *Tellus*, 21, 611–619, 1969.
- Buldgen, G., S. Salmon, and A. Noels, Progress in global helioseismology: a new light on the solar modelling problem and its implications for solar-like stars, *Frontiers in Astronomy and Space Sciences*, 6, 42, doi:10.3389/fspas.2019.00042, 2019.
- Byrne, B., and C. Goldblatt, Radiative forcings for 28 potential Archean greenhouse gases, *Climate of the Past*, 10, 1779–1801, doi:10.5194/cp-10-1779-2014, 2014.
- Caffau, E., H. G. Ludwig, M. Steffen, T. R. Ayres, P. Bonifacio, R. Cayrel, B. Freytag, and B. Plez,

- The photospheric solar oxygen project. I. Abundance analysis of atomic lines and influence of atmospheric models, *Astronomy and Astrophysics*, *488*(3), 1031–1046, doi:10.1051/0004-6361/200809885, 2008.
- Caffau, E., H. G. Ludwig, P. Bonifacio, R. Faraggiana, M. Steffen, B. Freytag, I. Kamp, and T. R. Ayres, The solar photospheric abundance of carbon. Analysis of atomic carbon lines with the CO5BOLD solar model, *Astronomy and Astrophysics*, *514*, A92, doi:10.1051/0004-6361/200912227, 2010.
- Cammack, J., M. Spicuzza, A. Cavosie, M. Van Kranendonk, A. Hickman, R. Kozdon, I. Orland, K. Kitajima, and J. Valley, "sims microanalysis of the strelley pool formation cherts and the implications for the secular-temporal oxygen-isotope trend of cherts", *Precambrian Research*, *304*, 125 – 139, doi:10.1016/j.precamres.2017.11.005, 2018.
- Catling, D. C., and K. J. Zahnle, The archean atmosphere, *Science Advances*, *6*(9), doi:10.1126/sciadv.aax1420, 2020.
- Charnay, B., F. Forget, R. Wordsworth, J. Leconte, E. Millour, F. Codron, and A. Spiga, Exploring the faint young Sun problem and the possible climates of the Archean Earth with a 3-D GCM, *JGR*, *118*, 10,414, doi:10.1002/jgrd.50808, 2013.
- Charnay, B., G. Le Hir, F. Fluteau, F. Forget, and D. C. Catling, A warm or a cold early Earth? New insights from a 3-D climate-carbon model, *Earth and Planetary Science Letters*, *474*, 97–109, doi:10.1016/j.epsl.2017.06.029, 2017.
- Chopra, A., and C. H. Lineweaver, The Case for a Gaiian Bottleneck: The Biology of Habitability, *Astrobiology*, *16*(1), 7–22, doi:10.1089/ast.2015.1387, 2016.
- Coogan, L. A., and S. E. Dosso, Alteration of ocean crust provides a strong temperature dependent feedback on the geological carbon cycle and is a primary driver of the Sr-isotopic composition of seawater, *Earth and Planetary Science Letters*, *415*, 38–46, doi:10.1016/j.epsl.2015.01.027, 2015.
- Coogan, L. A., and K. M. Gillis, Evidence that low-temperature oceanic hydrothermal systems play an important role in the silicate-carbonate weathering cycle and long-term climate regulation, *Geochemistry, Geophysics, Geosystems*, *14*, 1771–1786, doi:10.1002/ggge.20113, 2013.
- de Wit, M. J., and H. Furnes, 3.5-Ga hydrothermal fields and diamictites in the Barberton Greenstone Belt–Paleoarchean crust in cold environments, *Science Advances*, *2*(2), e1500,368–e1500,368, doi:10.1126/sciadv.1500368, 2016.
- Dhuime, B., C. J. Hawkesworth, P. A. Cawood, and C. D. Storey, A Change in the Geodynamics of Continental Growth 3 Billion Years Ago, *Science*, *335*(6074), 1334, doi:10.1126/science.1216066, 2012.
- Driese, S., M. Jirsa, M. Ren, S. Brantley, N. Sheldon, D. Parker, and M. Schmitz, Neoproterozoic paleoweathering of tonalite and metabasalt: Implications for reconstructions of 2.69 ga early terrestrial ecosystems and paleoatmospheric chemistry, *Precambrian Research*, *189*, 1–17, doi:10.1016/j.precamres.2011.04.003, 2011.
- Feulner, G., The faint young Sun problem, *Reviews of Geophysics*, *50*, RG2006, doi:10.1029/2011RG000375, 2012.
- Feulner, G., C. Hallmann, and H. Kienert, Snowball cooling after algal rise, *Nature Geoscience*, *8*(9), 659–662, doi:10.1038/ngeo2523, 2015.
- Fichtinger, B., M. Güdel, R. L. Mutel, G. Hallinan, E. Gaidos, S. L. Skinner, C. Lynch, and K. G. Gayley, Radio emission and mass loss rate limits of four young solar-type stars, *Astronomy & Astrophysics*, *599*, A127, doi:10.1051/0004-6361/201629886, 2017.
- Flament, N., N. Coltice, and P. F. Rey, A case for late-Archean continental emergence from thermal evolution models and hypsometry, *Earth and Planetary Science Letters*, *275*, 326–336, doi:10.1016/j.epsl.2008.08.029, 2008.
- Flato, G., et al., Evaluation of Climate Models., *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013.*
- Forget, F., R. Wordsworth, E. Millour, J. B. Madeleine, L. Kerber, J. Leconte, E. Marcq, and R. M. Haberle, 3D modelling of the early martian climate under a denser CO₂ atmosphere: Temperatures and CO₂ ice clouds, *Icarus*, *222*(1), 81–99, doi:10.1016/j.icarus.2012.10.019, 2013.
- Foriel, J., P. Philippot, P. Rey, A. Somogyi, D. Banks, and B. Ménez, Biological control of Cl/Br and low sulfate concentration in a 3.5-Gyr-old seawater from North Pole, Western Australia, *Earth and Planetary Science Letters*, *228*(3-4), 451–463, doi:10.1016/j.epsl.2004.09.034, 2004.
- Fralick, P., and J. Carter, Neoproterozoic deep marine paleotemperature: Evidence from turbidite successions, *Precambrian Research*, *191*, 78–84, doi:10.1016/j.precamres.2011.09.004, 2011.
- Gaillard, F., and B. Scaillet, A theoretical framework for volcanic degassing chemistry in a comparative planetology perspective and implications for planetary atmospheres, *Earth and Planetary Science*

- Letters*, 403, 307–316, doi:10.1016/j.epsl.2014.07.009, 2014.
- Gallet, F., and J. Bouvier, Improved angular momentum evolution model for solar-like stars, *Astronomy and Astrophysics*, 556, A36, doi:10.1051/0004-6361/201321302, 2013.
- Gaucher, E. A., S. Govindarajan, and O. K. Ganesh, Palaeotemperature trend for Precambrian life inferred from resurrected proteins, *Nature*, 452, 704–707, doi:10.1038/nature06510, 2008.
- Genda, H., and Y. Abe, Enhanced atmospheric loss on protoplanets at the giant impact phase in the presence of oceans, *Nature*, 433(7028), 842–844, doi:10.1038/nature03360, 2005.
- Goldblatt, C., and K. J. Zahnle, Clouds and the Faint Young Sun Paradox, *Climate of the Past*, 7, 203–220, doi:10.5194/cp-7-203-2011, 2011a.
- Goldblatt, C., and K. J. Zahnle, Faint young Sun paradox remains, *Nature*, 474, doi:10.1038/nature09961, 2011b.
- Goldblatt, C., T. M. Lenton, and A. J. Watson, Bistability of atmospheric oxygen and the Great Oxidation, *Nature*, 443(7112), 683–686, doi:10.1038/nature05169, 2006.
- Goldblatt, C., M. W. Claire, T. M. Lenton, A. J. Matthews, and A. J. Watson, Nitrogen-enhanced greenhouse warming on early Earth, *Nature Geoscience*, 2, 891–896, 2009.
- Gomes, R., H. F. Levison, K. Tsiganis, and A. Morbidelli, Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets, *Nature*, 435, 466–469, doi:10.1038/nature03676, 2005.
- Goosmann, E. A., D. C. Catling, S. M. Som, W. Altermann, and R. Buick, Eolianite Grain Size Distributions as a Proxy for Large Changes in Planetary Atmospheric Density, *Journal of Geophysical Research (Planets)*, 123(10), 2506–2526, doi:10.1029/2018JE005723, 2018.
- Gough, D., Solar interior structure and luminosity variations, *Solar Physics*, 74, 21–34, doi:10.1007/BF00151270, 1981.
- Guzik, J. A., and K. Mussack, Exploring Mass Loss, Low-Z Accretion, and Convective Overshoot in Solar Models to Mitigate the Solar Abundance Problem, *Astrophys. J.*, 713(2), 1108–1119, doi:10.1088/0004-637X/713/2/1108, 2010.
- Guzmán-Marmolejo, A., A. Segura, and E. Escobar-Briones, Abiotic Production of Methane in Terrestrial Planets full access, *Astrobiology*, 13(6), 550–559, doi:10.1089/ast.2012.0817, 2013.
- Haberle, R. M., D. C. Catling, M. H. Carr, and K. J. Zahnle, *The Early Mars Climate System*, pp. 497–525, doi:10.1017/9781139060172.017, 2017.
- Haqq-Misra, J. D., S. D. Domagal-Goldman, P. J. Kasting, and J. F. Kasting, A Revised, Hazy Methane Greenhouse for the Archean Earth, *Astrobiology*, 8, 1127–1137, doi:10.1089/ast.2007.0197, 2008.
- Hawkesworth, C., P. Cawood, and B. Dhuime, Rates of generation and growth of the continental crust, *Geoscience Frontiers*, 10(1), 165 – 173, doi:https://doi.org/10.1016/j.gsf.2018.02.004, 2019.
- Heckman, D. S., D. M. Geiser, B. R. Eidell, R. L. Stauffer, N. L. Kardos, and S. B. Hedges, Molecular evidence for the early colonization of land by fungi and plants, *Science*, 293(5532), 1129–1133, doi:10.1126/science.1061457, 2001.
- Hoffman, P. F., et al., Snowball Earth climate dynamics and Cryogenian geology-geobiology, *Science Advances*, 3(11), e1600,983, doi:10.1126/sciadv.1600983, 2017.
- Hren, M. T., M. M. Tice, and C. P. Chamberlain, Oxygen and hydrogen isotope evidence for a temperate climate 3.42 billion years ago, *Nature*, 462, 205–208, doi:10.1038/nature08518, 2009.
- Isson, T. T., and N. J. Planavsky, Reverse weathering as a long-term stabilizer of marine pH and planetary climate, *Nature*, 560(7719), 471–475, doi:10.1038/s41586-018-0408-4, 2018.
- Jaffrés, J. B. D., G. A. Shields, and K. Wallmann, The oxygen isotope evolution of seawater: A critical review of a long-standing controversy and an improved geological water cycle model for the past 3.4 billion years, *Earth Science Reviews*, 83, 83–122, doi:10.1016/j.earscirev.2007.04.002, 2007.
- Jenkins, G. S., and S. R. Smith, GCM simulations of snowball earth conditions during the Late Proterozoic, *Geophysical Research Letters*, 26(15), 2263–2266, doi:10.1029/1999GL900538, 1999.
- Jenkins, G. S., H. G. Marshall, and W. R. Kuhn, Precambrian climate: The effects of land area and Earth’s rotation rate, *Journal of Geophysical Research*, 98, 8785–8791, 1993.
- Kadoya, S., and D. C. Catling, Constraints on hydrogen levels in the Archean atmosphere based on detrital magnetite, *Geochimica et Cosmochimica Acta*, 262, 207–219, doi:10.1016/j.gca.2019.07.041, 2019.
- Kanzaki, Y., and T. Murakami, Estimates of atmospheric CO₂ in the Neoproterozoic-Paleoproterozoic from paleosols, *Geochimica et Cosmochimica Acta*, 159, 190–219, doi:10.1016/j.gca.2015.03.011, 2015.
- Kanzaki, Y., and T. Murakami, Effects of atmospheric composition on apparent activation energy of silicate weathering: II. Implications for evolution of atmospheric CO₂ in the Precambrian, *Geochimica et Cosmochimica Acta*, 240, 314–330, doi:10.1016/j.gca.2018.08.020, 2018.

- Kasting, J. F., Stability of ammonia in the primitive terrestrial atmosphere, *Journal of Geophysical Research*, 87(C4), 3091–3098, doi:10.1029/JC087iC04p03091, 1982.
- Kasting, J. F., and T. M. Howard, Atmospheric composition and climate on the early Earth, *Phil. Trans. R. Soc.*, 361, 1733–1742, doi:10.1098/rstb.2006.1902, 2006.
- Kasting, J. F., and S. Ono, Palaeoclimates: the first two billion years, *Phil. Trans. R. Soc.*, 361, 917–929, doi:10.1098/rstb.2006.1839, 2006.
- Kasting, J. F., J. B. Pollack, and D. Crisp, Effects of high CO₂ levels on surface temperature and atmospheric oxidation state of the early earth, *Journal of Atmospheric Chemistry*, 1, 403–428, 1984.
- Kasting, J. F., M. T. Howard, K. Wallmann, J. Veizer, G. Shields, and J. Jaffres, Paleoclimates, ocean depth, and the oxygen isotopic composition of seawater, *Earth and Planetary Science Letters*, 252, 82–93, doi:10.1016/j.epsl.2006.09.029, 2006.
- Kavanagh, L., and C. Goldblatt, Using raindrops to constrain past atmospheric density, *Earth and Planetary Science Letters*, 413, 51–58, doi:10.1016/j.epsl.2014.12.032, 2015.
- Kharecha, P., J. Kasting, and J. Siefert, A coupled atmosphere-ecosystem model of the early Archean earth, *Geobiology*, 3(2), 53–76, doi:10.1111/j.1472-4669.2005.00049.x, 2005.
- Kiehl, J. T., and R. E. Dickinson, A study of the radiative effects of enhanced atmospheric CO₂ and CH₄ on early Earth surface temperatures, *Journal of Geophysical Research*, 92, 2991–2998, doi:10.1029/JD092iD03p02991, 1987.
- Kienert, H., G. Feulner, and V. Petoukhov, Faint young Sun problem more severe due to ice-albedo feedback and higher rotation rate of the early Earth, *Geophysical Research Letters*, 39(23), L23710, doi:10.1029/2012GL054381, 2012.
- Knauth, L. P., and D. R. Lowe, High Archean climatic temperature inferred from oxygen isotope geochemistry of cherts in the 3.5 Ga Swaziland Supergroup, South Africa, *Geological Society of America Bulletin*, 115, 566–580, doi:10.1130/0016-7606(2003)115(0566:HACTIF)2.0.CO;2, 2003.
- Krissansen-Totton, J., and D. C. Catling, Constraining climate sensitivity and continental versus seafloor weathering using an inverse geological carbon cycle model, *Nature Communications*, 8, 15423, doi:10.1038/ncomms15423, 2017.
- Krissansen-Totton, J., R. Buick, and D. C. Catling, A statistical analysis of the carbon isotope record from the Archean to Phanerozoic and implications for the rise of oxygen, *American Journal of Science*, 315(4), 275–316, doi:10.2475/04.2015.01, 2015.
- Krissansen-Totton, J., G. N. Arney, and D. C. Catling, Constraining the climate and ocean pH of the early Earth with a geological carbon cycle model, *Proceedings of the National Academy of Science*, 115(16), 4105–4110, doi:10.1073/pnas.1721296115, 2018a.
- Krissansen-Totton, J., S. Olson, and D. C. Catling, Disequilibrium biosignatures over Earth history and implications for detecting exoplanet life, *Science Advances*, 4(1), eaao5747, doi:10.1126/sciadv.aao5747, 2018b.
- Kunze, M., M. Godolt, U. Langematz, J. L. Grenfell, A. Hamann-Reinus, and H. Rauer, Investigating the early Earth faint young Sun problem with a general circulation model, *Planetary and Space Science*, 98, 77–92, doi:10.1016/j.pss.2013.09.011, 2014.
- Kuramoto, K., T. Umemoto, and M. Ishiwatari, Effective hydrodynamic hydrogen escape from an early Earth atmosphere inferred from high-accuracy numerical simulation, *Earth and Planetary Science Letters*, 375, 312–318, doi:10.1016/j.epsl.2013.05.050, 2013.
- Le Hir, G., Y. Teitler, F. Fluteau, Y. Donnadieu, and P. Philippot, The faint young Sun problem revisited with a 3-D climate-carbon model - Part 1, *Climate of the Past*, 10, 697–713, doi:10.5194/cp-10-697-2014, 2014.
- Lehmer, O. R., D. C. Catling, R. Buick, D. E. Brownlee, and S. Newport, Atmospheric CO₂ levels from 2.7 billion years ago inferred from micrometeorite oxidation, *Science Advances*, 6(4), eaay4644, doi:10.1126/sciadv.aay4644, 2020.
- Lenton, T. M., Gaia and natural selection, *Nature*, 394(6692), 439–447, doi:10.1038/28792, 1998.
- Lenton, T. M., and W. von Bloh, Biotic feedback extends the life span of the biosphere, *Geophysical Research Letters*, 28(9), 1715–1718, doi:10.1029/2000GL012198, 2001.
- Lenton, T. M., M. Crouch, M. Johnson, N. Pires, and L. Dolan, First plants cooled the Ordovician, *Nature Geoscience*, 5(2), 86–89, doi:10.1038/ngeo1390, 2012.
- Lindzen, R. S., M.-D. Chou, and A. Y. Hou, Does the Earth Have an Adaptive Infrared Iris?., *Bulletin of the American Meteorological Society*, 82, 417–432, doi:10.1175/1520-0477(2001)082(0417:DTEHAA)2.3.CO;2, 2001.
- Lovelock, J. E., and L. Margulis, Atmospheric homeostasis by and for the biosphere: The Gaia hypothesis, *Tellus*, 26, 2, 1974.
- Lyons, T. W., C. T. Reinhard, and N. J. Planavsky, The rise of oxygen in Earth's early ocean and atmosphere, *Nature*, 506, 307–315, doi:10.1038/nature13068, 2014.

- Marin-Carbonne, J., M. Chaussidon, and F. Robert, Micrometer-scale chemical and isotopic criteria (O and Si) on the origin and history of Precambrian cherts: Implications for paleo-temperature reconstructions, *Geochimica et Cosmochimica Acta*, *92*, 129–147, doi:10.1016/j.gca.2012.05.040, 2012.
- Marin-Carbonne, J., M. Chaussidon, and F. Robert, The silicon and oxygen isotope compositions of Precambrian cherts: A record of oceanic paleotemperatures?, *Precambrian Research*, *247*, 223–234, doi:10.1016/j.precamres.2014.03.016, 2014.
- Martens, P. C., The Faint Young Sun and Faint Young Stars Paradox, in *Living Around Active Stars, IAU Symposium*, vol. 328, edited by D. Nandy, A. Valio, and P. Petit, pp. 350–355, doi:10.1017/S1743921317004331, 2017.
- Marty, B., L. Zimmermann, M. Pujol, R. Burgess, and P. Philippot, Nitrogen isotopic composition and density of the archean atmosphere, *Science*, *342*(6154), 101–104, doi:10.1126/science.1240971, 2013.
- Marty, B., G. Avicé, D. V. Bekaert, and M. W. Bradley, Salinity of the Archaean oceans from analysis of fluid inclusions in quartz, *Comptes Rendus Geoscience*, *350*(4), 154–163, doi:10.1016/j.crte.2017.12.002, 2018.
- Mauritsen, T., and B. Stevens, Missing iris effect as a possible cause of muted hydrological change and high climate sensitivity in models, *Nature Geoscience*, *8*(5), 346–351, doi:10.1038/ngeo2414, 2015.
- McKay, C. P., J. B. Pollack, and R. Courtin, The greenhouse and antigreenhouse effects on Titan, *Science*, *253*, 1118–1121, doi:10.1126/science.253.5024.1118, 1991.
- Minton, D. A., and R. Malhotra, Assessing the Massive Young Sun Hypothesis to Solve the Warm Young Earth Puzzle, *Astrophys. J.*, *660*(2), 1700–1706, doi:10.1086/514331, 2007.
- Mojzsis, S. J., T. M. Harrison, and R. T. Pidgeon, Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago, *Nature*, *409*(6817), 178–181, 2001.
- Newman, M. J., and R. T. Rood, Implications of Solar Evolution for the Earth's Early Atmosphere, *Science*, *198*(4321), 1035–1037, doi:10.1126/science.198.4321.1035, 1977.
- Nisbet, E. G., and N. H. Sleep, The habitat and nature of early life, *Nature*, *409*, 1083–1091, 2001.
- Ojakangas, R., V. S. Srinivasan, R. and Hegde, S. M. Chandrakant, and S. V. Srikantia, The talya conglomerate: an archean (~2.7 ga) glaciomarine formation, western dharwar craton, southern india, *Current Science*, *106*(3), 387–396, 2014.
- Owen, T., R. D. Cess, and V. Ramanathan, Enhanced CO₂ greenhouse to compensate for reduced solar luminosity on early Earth, *Nature*, *277*, 640–642, doi:10.1038/277640a0, 1979.
- Ozaki, K., E. Tajika, P. K. Hong, Y. Nakagawa, and C. T. Reinhard, Effects of primitive photosynthesis on Earth's early climate system, *Nature Geoscience*, *11*(1), 55–59, doi:10.1038/s41561-017-0031-2, 2018.
- Pavlov, A. A., J. F. Kasting, L. L. Brown, K. A. Rages, and R. Freedman, Greenhouse warming by CH₄ in the atmosphere of early Earth, *Journal of Geophysical Research*, *105*, 11,981–11,990, doi:10.1029/1999JE001134, 2000.
- Pavlov, A. A., L. L. Brown, and J. F. Kasting, UV shielding of NH₃ and O₂ by organic hazes in the Archean atmosphere, *Journal of Geophysical Research*, *106*, 23,267–23,287, doi:10.1029/2000JE001448, 2001.
- Pierrehumbert, R. T., Thermostats, Radiator Fins, and the Local Runaway Greenhouse, *Journal of the Atmospheric Sciences*, *52*, 1784–1806, 1995.
- Pierrehumbert, R. T., High levels of atmospheric carbon dioxide necessary for the termination of global glaciation, *Nature*, *429*(6992), 646–649, doi:10.1038/nature02640, 2004.
- Pope, E. C., D. K. Bird, and M. T. Rosing, Isotope composition and volume of Earth's early oceans, *Proceedings of the National Academy of Sciences*, *109*(12), 4371–4376, doi:10.1073/pnas.1115705109, 2012.
- Pujol, M., B. Marty, R. Burgess, G. Turner, and P. Philippot, Argon isotopic composition of Archaean atmosphere probes early Earth geodynamics, *Nature*, *498*(7452), 87–90, doi:10.1038/nature12152, 2013.
- Reinhard, C., and N. Planavsky, Mineralogical constraints on Precambrian pCO₂, *Nature*, doi:doi:10.1038/nature09959, 2011.
- Rey, P. F., and N. Coltice, Neoproterozoic lithospheric strengthening and the coupling of Earth's geochemical reservoirs, *Geology*, *36*(8), 635–638, doi:10.1130/G25031A.1, 2008.
- Robert, F., and M. Chaussidon, A palaeotemperature curve for the Precambrian oceans based on silicon isotopes in cherts, *Nature*, *443*, 969–972, 2006.
- Rondanelli, R., and R. S. Lindzen, Can thin cirrus clouds in the tropics provide a solution to the faint young Sun paradox?, *Journal of Geophysical Research (Atmospheres)*, *115*, D02108, doi:10.1029/2009JD012050, 2010.
- Rosing, M. T., D. K. Bird, N. H. Sleep, and C. J. Bjerrum, No climate paradox under the faint early Sun, *Nature*, *464*(7289), 744–747, 2010.
- Rye, R., P. H. Kuo, and H. D. Holland, Atmospheric carbon dioxide concentrations before 2.2 billion years

- ago, *Nature*, *378*, 603–605, doi:10.1038/378603a0, 1995.
- Sagan, C., and G. Mullen, Earth and Mars: Evolution of Atmospheres and Surface Temperatures, *Science*, *177*, 52–56, doi:10.1126/science.177.4043.52, 1972.
- Sauterey, B., B. Charnay, A. Affholder, S. Mazevet, and R. Ferrière, Co-evolution of primitive methane-cycling ecosystems and early Earth's atmosphere and climate, *Nature Communications*, *11*(2705), doi:https://doi.org/10.1038/s41467-020-16374-7, 2020.
- Schneider, T., C. M. Kaul, and K. G. Pressel, Possible climate transitions from breakup of stratocumulus decks under greenhouse warming, *Nature Geoscience*, *12*(3), 163–167, doi:10.1038/s41561-019-0310-1, 2019.
- Schwartzman, D. W., and T. Volk, Biotic enhancement of weathering and the habitability of Earth, *Nature*, *340*(6233), 457–460, doi:10.1038/340457a0, 1989.
- Schwieterman, E. W., C. T. Reinhard, S. L. Olson, K. Ozaki, C. E. Harman, P. K. Hong, and T. W. Lyons, Rethinking CO Antibiosignatures in the Search for Life Beyond the Solar System, *Astrophys. J.*, *874*(1), 9, doi:10.3847/1538-4357/ab05e1, 2019.
- Sellers, W. D., A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System., *Journal of Applied Meteorology*, *8*(3), 392–400, doi:10.1175/1520-0450(1969)008<0392:AGCMBO>2.0.CO;2, 1969.
- Sengupta, S., and A. Pack, Triple oxygen isotope mass balance for the Earth's oceans with application to Archean cherts, *Chemical Geology*, *495*, 18–26, doi:10.1016/j.chemgeo.2018.07.012, 2018.
- Sheldon, N., Precambrian paleosols and atmospheric CO₂ levels, *Precambrian Research*, *147*, 148–155, doi:10.1016/j.precamres.2006.02.004, 2006.
- Sleep, N. H., and K. Zahnle, Carbon dioxide cycling and implications for climate on ancient Earth, *Journal of Geophysical Research*, *106*, 1373–1400, doi:10.1029/2000JE001247, 2001.
- Sleep, N. H., K. Zahnle, and P. S. Neuhoff, Inaugural Article: Initiation of clement surface conditions on the earliest Earth, *Proceedings of the National Academy of Science*, *98*(7), 3666–3672, doi:10.1073/pnas.071045698, 2001.
- Som, S. M., D. C. Catling, J. P. Harnmeijer, P. M. Polivka, and R. Buick, Air density 2.7 billion years ago limited to less than twice modern levels by fossil raindrop imprints., *Nature*, *484*(7394), 359–362, doi:10.1038/nature10890, 2012.
- Som, S. M., R. Buick, J. W. Hagadorn, T. S. Blake, J. M. Perreault, J. P. Harnmeijer, and D. C. Catling, Earth's air pressure 2.7 billion years ago constrained to less than half of modern levels, *Nature Geoscience*, *9*, 448–451, doi:10.1038/ngeo2713, 2016.
- Spalding, C., W. W. Fischer, and G. Laughlin, An Orbital Window into the Ancient Sun's Mass, *Astrophys. J. L.*, *869*(1), L19, doi:10.3847/2041-8213/aaf219, 2018.
- Stüeken, E. E., R. Buick, B. M. Guy, and M. C. Koehler, Isotopic evidence for biological nitrogen fixation by molybdenum-nitrogenase from 3.2 Gyr, *Nature*, *520*(7549), 666–669, doi:10.1038/nature14180, 2015.
- Stüeken, E. E., M. A. Kipp, M. C. Koehler, E. W. Schwieterman, B. Johnson, and R. Buick, Modeling pN₂ through Geological Time: Implications for Planetary Climates and Atmospheric Biosignatures, *Astrobiology*, *16*(12), 949–963, doi:10.1089/ast.2016.1537, 2016.
- Tartese, R., C. M., A. Gurenko, F. Delarue, and F. Robert, Warm Archean oceans reconstructed from oxygen isotope composition of early-life remnants, *Geochemical Perspective letters*, *3*, 55–65, doi:10.1126/science.aad5513, 2016.
- Teitler, Y., G. Ler Hir, F. Fluteau, P. Philippot, and Y. Donnadieu, Investigating the paleoproterozoic glaciations with 3-d climate modeling, *Earth and Planetary Science Letters*, *395*, 71 – 80, doi:https://doi.org/10.1016/j.epsl.2014.03.044, 2014.
- Tian, F., O. B. Toon, A. A. Pavlov, and H. De Sterck, A Hydrogen-Rich Early Earth Atmosphere, *Science*, *308*, 1014–1017, doi:10.1126/science.1106983, 2005.
- Tian, F., J. F. Kasting, and K. Zahnle, Revisiting HCN formation in Earth's early atmosphere, *Earth and Planetary Science Letters*, *308*, 417–423, doi:10.1016/j.epsl.2011.06.011, 2011.
- Trainer, M. G., A. A. Pavlov, H. L. Dewitt, J. L. Jimenez, C. P. McKay, O. B. Toon, and M. A. Tolbert, Inaugural Article: Organic haze on Titan and the early Earth, *PNAS*, *103*, 18,035–18,042, doi:10.1073/pnas.0608561103, 2006.
- Turck-Chièze, S., L. Piau, and S. Couvidat, The Solar Energetic Balance Revisited by Young Solar Analogs, Helioseismology, and Neutrinos, *Astrophys. J. L.*, *731*(2), L29, doi:10.1088/2041-8205/731/2/L29, 2011.
- Urata, R. A., and O. B. Toon, Simulations of the martian hydrologic cycle with a general circulation model: Implications for the ancient martian climate, *Icarus*, *226*, 229–250, doi:10.1016/j.icarus.2013.05.014, 2013.
- van den Boorn, S., M. van Bergen, W. Nijman, and P. Vroon, Dual role of seawater and hydrothermal fluids in Early Archean chert formation: Evidence from silicon isotopes, *Geology*, *35*, 939, doi:10.1130/\

- %\$2FG24096A.1, 2007.
- Voigt, A., and D. S. Abbot, Sea-ice dynamics strongly promote Snowball Earth initiation and destabilize tropical sea-ice margins, *Climate of the Past*, *8*(6), 2079–2092, doi:10.5194/cp-8-2079-2012, 2012.
- von Paris, P., H. Rauer, J. Lee Grenfell, B. Patzer, P. Hedelt, B. Stracke, T. Trautmann, and F. Schreier, Warming the early earth—CO₂ reconsidered, *Planetary and Space Science*, *56*, 1244–1259, doi:10.1016/j.pss.2008.04.008, 2008.
- Walker, J. C. G., P. B. Hays, and J. F. Kasting, A negative feedback mechanism for the long-term stabilization of the earth’s surface temperature, *Journal of Geophysical Research*, *86*, 9776–9782, doi:10.1029/JC086iC10p09776, 1981.
- Whitmire, D. P., L. R. Doyle, R. T. Reynolds, and J. J. Matese, A slightly more massive young Sun as an explanation for warm temperatures on early Mars, *Journal of Geophysical Research*, *100*(E3), 5457–5464, doi:10.1029/94JE03080, 1995.
- Wild, M., D. Folini, C. Schär, N. Loeb, E. G. Dutton, and G. König-Langlo, The global energy balance from a surface perspective, *Climate Dynamics*, *40*(11-12), 3107–3134, doi:10.1007/s00382-012-1569-8, 2013.
- Wilde, S. A., J. W. Valley, W. H. Peck, and C. M. Graham, Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4Gyr ago, *Nature*, *409*(6817), 175–178, 2001.
- Williams, G. E., Geological constraints on the Precambrian history of Earth’s rotation and the Moon’s orbit, *Reviews of Geophysics*, *38*, 37–60, doi:10.1029/1999RG900016, 2000.
- Wolf, E. T., and O. B. Toon, Fractal Organic Hazes Provided an Ultraviolet Shield for Early Earth, *Science*, *328*(5983), 1266–1268, doi:10.1126/science.1183260, 2010.
- Wolf, E. T., and O. B. Toon, Hospitable Archean Climates Simulated by a General Circulation Model, *Astrobiology*, *13*, 656–673, doi:10.1089/ast.2012.0936, 2013.
- Wolf, E. T., and O. B. Toon, Controls on the Archean Climate System Investigated with a Global Climate Model, *Astrobiology*, *14*, 241–253, doi:10.1089/ast.2013.1112, 2014.
- Wolf, E. T., J. Haqq-Misra, and O. B. Toon, Evaluating Climate Sensitivity to CO₂ Across Earth’s History, *Journal of Geophysical Research (Atmospheres)*, *123*(21), 11,861–11,874, doi:10.1029/2018JD029262, 2018.
- Wood, B. E., H.-R. Müller, G. P. Zank, and J. L. Linsky, Measured Mass-Loss Rates of Solar-like Stars as a Function of Age and Activity, *Astrophysical Journal*, *574*(1), 412–425, doi:10.1086/340797, 2002.
- Wood, B. E., H. R. Müller, G. P. Zank, J. L. Linsky, and S. Redfield, New Mass-Loss Measurements from Atmospheric Ly α Absorption, *Astrophys. J. L.*, *628*(2), L143–L146, doi:10.1086/432716, 2005.
- Wood, S. R., K. Mussack, and J. A. Guzik, Solar Models with Dynamic Screening and Early Mass Loss Tested by Helioseismic, Astrophysical, and Planetary Constraints, *Solar Physics*, *293*(7), 111, doi:10.1007/s11207-018-1334-1, 2018.
- Wordsworth, R., and R. Pierrehumbert, Hydrogen-Nitrogen Greenhouse Warming in Earth’s Early Atmosphere, *Science*, *339*(6115), 64, doi:10.1126/science.1225759, 2013.
- Zahnle, K., and N. H. Sleep, Carbon dioxide cycling through the mantle and implications for the climate of ancient Earth, *Geological Society of London Special Publications*, *199*, 231–257, doi:10.1144/GSL.SP.2002.199.01.12, 2002.
- Zahnle, K., and J. C. G. Walker, A constant daylength during the precambrian era?, *Precambrian Research*, *37*, 95–105, 1987.
- Zahnle, K. J., Photochemistry of methane and the formation of hydrocyanic acid (HCN) in the earth’s early atmosphere, *Journal of Geophysical Research*, *91*, 2819–2834, doi:10.1029/JD091iD02p02819, 1986.
- Zahnle, K. J., M. Gacesa, and D. C. Catling, Strange messenger: A new history of hydrogen on Earth, as told by Xenon, *Geochimica et Cosmochimica Acta*, *244*, 56–85, doi:10.1016/j.gca.2018.09.017, 2019.
- Zank, G. P., Interaction of the solar wind with the local interstellar medium: a theoretical perspective, *Space Science reviews*, *89*, 413–688, doi:10.1023/A:1005155601277, 1999.
- Zelinka, M. D., S. A. Klein, K. E. Taylor, T. Andrews, M. J. Webb, J. M. Gregory, and P. M. Forster, Contributions of Different Cloud Types to Feedbacks and Rapid Adjustments in CMIP5*, *Journal of Climate*, *26*(14), 5007–5027, doi:10.1175/JCLI-D-12-00555.1, 2013.
- Zerkle, A. L., M. W. Claire, S. D. Domagal-Goldman, J. Farquhar, and S. W. Poulton, A bistable organic-rich atmosphere on the Neoproterozoic Earth, *Nature Geoscience*, *5*, 359–363, doi:10.1038/ngeo1425, 2012.