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The faint young Sun problem revisited with a 3-D climate-carbon model – Part 1

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Abstract

Considering the weak luminosity of the early Sun, it is generally inferred that high concentrations of greenhouse gases (CO_2, CH_4) are required to prevent the early Earth's surface temperature to drop below the freezing point of liquid water. Conversely, a new controversial assumption based on banded iron formation mineralogy hypothesizes that the Archean atmosphere was potentially characterized by low concentrations of CO_2. To solve the faint young Sun problem, it was suggested that a reduced albedo associated to less reflective clouds was able to prevent the Earth to jump into a snowball state. In this very active debate, we have investigated the early Earth climate using a general circulation model to test this scenario. Our simulations include the ice albedo feedback and specific Archean climatic factors such as a different cloudiness, a faster Earth's rotation rate, and a reduced continental surface. We demonstrate that when larger cloud droplets are accounted for, clouds warm high latitudes and inhibit sea-ice formation. This process limits the ice-albedo feedback efficiency and may prevent a global glaciation. Due to this particular mechanism, low pCO_2 allow maintaining a mild climate during the early Archean. This conclusion will be challenged in the second part of this paper, where the carbon cycle is considered.

1 Introduction

Sagan and Mullen (1972) argued from solar models that, in the early Archean, the Sun, as a relatively young star, would have had a 30 % lower luminosity than it does now. According to climate models, the weakness of the young Sun brightness would have led Earth's surface temperature being well below the freezing point over the first 2 billions of years. However a completely frozen Earth disagrees with evidence of presence of liquid water and life development during the Archean. To solve this problem, known as the "faint young Sun paradox" (hereafter FYSP), the greenhouse gases, and more peculiarly carbon dioxide, quickly appeared to be a good candidate (see Feulner, 2012 for a detailed review). Using a RCM (one vertical dimensional Radiative Convective climate Model), Kasting (1984) has calculated that, for 4 Ga solar luminosity (75 % of its present-day value), a $p\mathrm{CO}_2$ of 0.3 bar or ~ 1000 times the Preindustrial Atmospheric Level (hereafter PAL, i.e. 0.28 mbar or 280 ppm) was needed to maintain a mean global surface temperature of 288 K. In a recent modeling study, Kienert and collaborators (2012) used a 3-dimensional model to demonstrate that the early Archean $p\mathrm{CO}_2$ value probably reached 0.6 bar to maintain the surface temperature close to its present-day value (288 K). This rise of the critical CO_2 partial pressure is due to the ice-albedo feedback associated to a faster Earth's rotation rate existing during the early Archean.

In parallel with the modeling approach, in the mid nineties, carbon dioxide has been semi-quantitatively estimated from Archean paleosols in the mid nineties. Based on absence of siderite in 2.8 Ga old soils, Rye et al. (1995) suggested that the $p\mathrm{CO}_2$ has not exceeded ~ 0.03 bar (or ~ 100 PAL). The mineralogical approach of Rye et al. (1995) has been questioned by Sheldon (2006). Using a mass-balance approach, Sheldon (2006) proposed that the $p\mathrm{CO}_2$ was more probably about 8.5 mbars plus or minus a factor of 3 (i.e. 24 PAL with a range from 72 to 8 PAL) between 2.2 and 1.0 Ga. Recently, Rosing et al. (2010) have further lowered the atmospheric CO_2 concentration. Based on the composition of iron-rich minerals found in Archean Banded Iron Formations (BIF), they argued that the coexistence of magnetite (i.e. $\mathrm{Fe}_3\mathrm{O}_4$, a moderately oxidized mineral) and siderite (i.e. FeCO_3, a reduced mineral) in BIF was dependent on the atmospheric level in di-hydrogen ($p\mathrm{H}_2$). Di-hydrogen (H_2) being a nutrient for methanogenic bacteria, biological constraints impose a minimum $p\mathrm{H}_2$. Using this constraint, Rosing et al. (2010) have defined an upper limit for $p\mathrm{CO}_2$ close to 0.9 mbar (900 ppmv or 3.2 PAL). Such a low $p\mathrm{CO}_2$ has been abundantly discussed notably because BIF was probably formed far from the thermodynamic equilibrium with the atmosphere (Dauphas and Kasting, 2011; Reinhard and Planavsky, 2011). However in a recent study of Driese and collaborators (2011), paleoweathering indictors are used to support the assumption of moderate CO_2 partial pressures, at around 10 mbar.

The fact that all pCO_2 estimated from proxies are clearly below modeling results by one order of magnitude challenges our understanding of the Earth primitive atmosphere and implies that other mechanisms have to be searched to solve the FYSP. This key question motives the present study.

2 How to solve the faint young Sun problem?

If an enhanced greenhouse effect seems the most likely solution to the FYSP, other mechanisms influencing climate have been explored, like changes in cloud properties. The mean forcing of clouds results from two opposite effects. Clouds are highly reflective in the spectrum of visible solar radiation (shortwave radiation) and highly absorbing in the spectrum of thermal terrestrial radiation (longwave radiation). Thus it leads to two well known opposite effects: the reflective effect contributing to the planetary albedo and the longwave absorption contributing to the greenhouse effect. These mechanisms are related to the cloud type, the greenhouse effect being stronger than the albedo effect in case of cirrus clouds, which are quite transparent at visible wavelengths but good absorbers of thermal terrestrial radiation. To compensate their omission in RCM, the surface albedo is increased to yield 288 K for the present day conditions (Kasting et al., 1984, 1987; Haqq-Misra et al., 2008) but this assumption is partially incorrect as demonstrated by Goldblatt and Zahnle (2011).

The most recent studies have explicitly included clouds in RCM and proposed to solve the FYSP by changing the cloud properties. Rondanelli and Lindzen (2010) suggested that a cooling of oceanic surfaces would lead to cirrus formation in the tropics, which would warm the early Earth's surface. This mechanism called the "iris hypothesis" remains controversial. If true, the "iris" mechanism should tend to inhibit the glacial/interglacial cycles. The second hypothesis investigates the influence of cloud properties (Goldblatt and Zahnle, 2011; Rossow et al., 1982). To compensate the weaker solar brightness during the Late Archean, they estimated that clouds must be 3.5 times thicker than at present day, stratus (highly reflective clouds) must be absent and at last the Earth must be entirely cloud-covered. These authors conclude that this scenario is very hypothetical because mechanisms able to change cloud properties in such proportions remain to be found. The last scenario invokes cloud condensation nuclei (i.e. CCN) and the potential existence of clouds with a low albedo during the Precambrian period. In present-day atmosphere, abundant CCN permit the formation of small liquid water droplets leading to optically dense and highly reflective clouds by their direct scattering effect (Charlson et al., 1987). During the Archean, this could have been very different due to the absence of the main biological source of CCN (dimethylsulphide or DMS) produced by planktonic eukaryotic algae (Charlson et al., 1987, and citations therein). Indeed, assuming that sulphate aerosols and sulphuric acid are the only significant contributors to CCN, its amount would reach 10–20 % of its natural present day concentration. As a consequence fewer droplets, but of larger size, should form optically thin clouds characterized by a low scattering of short-wave radiation and shorter lifetime (Kump and Pollard, 2008; Rosing et al., 2010). Testing this assumption using a RCM, Rosing et al. (2010) have shown that a decrease in surface albedo, owing to considerably less continental area and a more transparent atmosphere to shortwave radiation, may have compensated the weak brightness of Sun during the Archean eon.

Because RCM include a detailed radiative scheme, they are well adapted to study the climatic impact of the Archean chemical composition of the atmosphere, in particular the abundances in greenhouse gases. Albeit this approach has permitted to improve our understanding of the early Earth and can be considered to be complex enough to yield a first order climate response to solve the FYSP (Goldblatt and Zahnle, 2010), crucial mechanisms and feedbacks driving the climatic system are not taken into account in these models. Indeed, these one dimensional climate models do not include the dependence of the Earth's surface albedo with temperature (also called ice-albedo feedback) because the surface albedo is fixed. The ice albedo/temperature feedback is a critical parameter of the long-term stability of the Earth climate because it governs the non-linear response of the Earth climatic system. Its lack may bias the climate response, especially when the Earth tends to cool. Indeed without including the ice albedo feedback in models, the Earth can be artificially maintained unfrozen. For this reason, Kasting (2010) considered that a 3-D climate models could help to understand the early Earth's climate because they capture the ice-albedo feedback (Kienert et al., 2012).

To go one step further in the understanding of the FYSP, we propose to use a 3-D climate model, here FOAM, to investigate the validity of the assumption of low $p\text{CO}_2$. To answer this question the study is organized as follows. First a set of experiments has been run to simulate the climate from 3.5 Ga to 1 Ga with a timestep of 250 Ma whereas $p\text{CO}_2$ and $p\text{CH}_4$ have been voluntary kept fixed at the low value of 900 ppmv as in Rosing et al. (2010). The goal of these experiments is not to test the role of the amount of greenhouse gases but rather to investigate the effect of other important forcing factors existing during the Archean: solar constant, paleogeography and amount of continental surface, cloud properties, high salinity of oceans and a faster Earth rotation rate. We then performed a second set of simulations fixing boundary conditions at Early Archean values and we varied $p\text{CO}_2$, our aim being to estimate the minimum value required to balance the solar weakness.

3 Model description and simulations specifications

3.1 Model description

Climate simulations have been run using the General Circulation climate Model (GCM) FOAM 1.5. The atmospheric component of FOAM is a parallelized version of NCAR's Community Climate Model 2 (CCM2) with the upgraded radiative and hydrologic physics incorporated in CCM3 v. 3.2 (Jacob, 1997). All simulations have been performed with an R15 spectral resolution ($4.5 \times 7.5^{\circ}$) and 18 vertical levels. FOAM is used in mixed-layer mode, meaning the atmospheric model is linked to a 50-m mixed-layer ocean with heat transport parameterized through diffusion. The radiative code (extracted from NCAR CCM3) has already shown its validity in atmospheres highly enriched in CO_2 (Pierrehumbert, 2004) and CH_4 (Rosing et al., 2010; Teitler et al., 2013).

FOAM, as other GCMs, relies on a physical basis which means that mechanisms and feedbacks are explicitly represented. Obviously GCMs still have limitations; one of them consists in the representation of clouds. Goldblatt and Zahnle (2011) challenged the use of GCMs considering that sub-grid scale parameterization of clouds in GCM precludes their use in paleoclimate modeling. If clouds scheme is a driver of GCM differences, these clouds differences are understood and appear only significant in snowball Earth climates (Abbot et al., 2012). Moreover, by their spatial resolution, GCMs represent a powerful tool to improve our understanding of the clouds mechanisms involved in the present day global warming (Abbot et al., 2009) as well as in deep time climate changes (Pollard and Kump, 2008). For all these reasons, authors assume that GCMs remain accurate tools to investigate past climates (Donnadieu et al., 2006, 2009; Le Hir et al., 2009, 2010, 2011; Nardin et al., 2010; Poulsen and Jacob, 2004) because they can capture interplays of clouds with other factors changing with time (paleogeography, rotation rate, . . .).

3.2 Boundary conditions and experimental design

In order to test how solar constant, paleogeography, amount of continental surface, cloud properties, high salinity of oceans and a faster Earth rotation rate, influence the climate during the Archean eon, atmospheric partial pressures of both CO_2 and CH_4 are fixed at 900 ppmv or 0.9 mbar (following the values used by Rosing et al., 2010). To avoid the astronomic influence, orbital parameters are set at their present-day values in all experiments. Because of the quasi-absence of oxygen in the Archean atmosphere (Bekker et al., 2004), the stratospheric ozone layer is removed for all experiments prior to 2.25 Ga and remains at present day value for all experiments of the Proterozoic eon. The absence of ozone layer precludes the formation of a stratosphere. It results in a 40 km thick troposphere (corresponding to the topmost atmospheric grid points in the GCM). The global mean lapse rate between the surface and the 200 hPa level is not significantly affected by the absence of ozone layer, and a mean global cooling of 0.7 °C only at the Earth surface is simulated (Appendix Fig. 1A). The atmospheric thermal structure resulting from the removal of the ozone layer agrees well with previous studies using 1-D climate model, which estimated a cooling in the range of 1 to 2 °C at Earth's surface (Kasting et al., 1984; Khiel and Dickinson, 1987).

We have performed a set of numerical experiments for the period ranging from 3.5 to 1 Ga with a 0.25 Gyr time step. Boundary conditions including solar constant and paleogeography have drastically changed along this period of 2.5 Gyr. Indeed the solar constant increases by as much as 19 % between 3.5 Ga (1053 $\mathrm{W\,m^{-2}}$) and 1 Ga (1258 $\mathrm{W\,m^{-2}}$) (Gough, 1981) (Fig. 1a). The early Earth's surface has varied in response to the growth and emergence of the continental surface, a process which has affected the mean surface albedo ($\alpha_{\text{ocean}} = 0.06$, $\alpha_{\text{bare soil}} = 0.32$). Different scenarios ranging from a progressive formation to a quasi-instantaneous formation of all continental crust have been proposed. Here we considered a gradual continental growth (Fig. 1b), an evolution in agreement with the changes of $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ (Godderis and Veizer, 2000) and $\delta^{34}\mathrm{S}$ throughout the Archean and Early Proterozoic. According to this scenario, the surface of the emerged continents has changed from 4 % at 3.5 Ga to 27,5 % at 1 Ga. The paleogeographic reconstructions are based on the work by Peasonen et al. (2003) (Fig. 1c). The elevation of land points is fixed at 200 m in all experiments.

In order to test the role of clouds, their properties have been modified as suggested by Rosing et al. (2010). Larger liquid water droplets (20 µm), about twice the mean present day size (5 to 10 µm over continents, and 10 µm over oceans), resulting from lower atmospheric concentration in CCN could have helped to solve the FYSP. To quantify how larger liquid droplets influence climate, we have performed a set of experiments using the GCM FOAM in which the mean size of liquid droplet is fixed at 20 µm (over oceans and continents). Larger droplets rain out more rapidly, decreasing the cloud lifetime because of an increased cloud-to-precipitation conversion rates. To take into account this factor omitted in the Rosing et al's study (2010), we have used the dependency established by Kump and Pollard (2008) fixing this ratio at 8 (instead of 1 for current conditions). We have also performed a set of experiments in which clouds are totally removed in order to explore the effect of the surface albedo itself caused by the growth of continental area.

To complete this work, we have undergone an additional set of experiments in order to determine whether a faster Earth rotation rate may affect the previous results. Indeed Paleozoic rythmites, mollusk shells and coral fossils records indicate that the Earth rotated faster in deep past leading to a shorter length of the day (LOD) (Walker and Zahnle, 1986). Between 3.8 and 2.5 Ga, the slowdown of the rotation rate has increased the LOD from 14 to 18 h. Jenkins (1993) has tested the effects of a shorter LOD on the early Earth climate using a GCM. He has demonstrated that a faster rotation (corresponding to a LOD of ~ 14 h) reduces the mean global nebulosity by 20 % and increases the mean global surface temperature by 2 °C. In fact the global warming hides local temperature changes, namely a cooling at the poles and a warming in the tropics due to the weakening of transient eddies carrying the heat from low to high latitudes. Hence faster Earth's rotation may render the Earth more vulnerable to the ice albedo feedback (Kienert et al., 2012). To check this assumption, we run a set of experiments considering a LOD of 16 h which corresponds to a LOD 3.5 Ga ago.

Another peculiar feature of the Archean Earth is the hypersaline ocean. Hay et al. (2006) revealed large-scale salinity changes over the course of the Phanerozoic, due to fluctuations in the total salt content of oceans. Knauth (2005) has suggested a long-term decline of ocean salinity throughout the Precambrian in parallel with the development of sedimentary basins and climatic conditions able to form and preserve halite (NaCl) deposits. In consequence the Archean oceans could have been enriched in Na^+ leading to a mean salinity close to 60 ‰ at that time (in comparison to 35 ‰ at the present day) (Knauth, 2005; Foriel et al., 2009). Because a higher salinity lowers the seawater freezing temperature (Millero and Poisson, 1981), sea ice formation could have been delayed and potentially limited the influence of ice albedo feedback. Because the GCM FOAM is coupled with a slab ocean, a higher salinity cannot be taken into account. To mimic this feature, we have fixed the seawater freezing point at

−3.3 °C following the equation of state of seawater proposed by Millero and Poisson (1981). As for the LOD experiments, the influence of hypersaline ocean is only tested for 3.5 Ga, which represents the most drastic conditions to solve the FYSP.

4 Influence of Archean factors

Figure 2 shows the global mean surface temperature (Fig. 2a) and the mean planetary albedo (Fig. 2b), each square representing a simulation. Each run lasts several tens of years until a steady state is reached for a decade or more. Climatic variables are averaged over the last decade.

4.1 Influence of the solar constant

Figure 2a (blue curve) represents the evolution of the global mean surface temperature (i.e. Ts) from 3.5 to 1 Ga simulated using the present-day cloud parameterization. The mean temperature is as low as −75 °C at 3.5 Ga and increases linearly up to −65 °C at 2.5 Ga. The planetary albedo always exceeds 0.65 (Fig. 2b, blue curve) because the Earth is entirely frozen. An abrupt climatic transition expressed by temperature and albedo shifts is observed between the 2.5 and 2.25 Ga experiments. The global mean surface temperature reaches −20 °C in the 2.25 Ga run and the albedo falls to 0.45. It corresponds to a partially frozen Earth; sea ice spreads up to 30° latitude in both hemispheres. Between 2.25 and 1.75 Ga, we observe a slight global warming of about 5 °C followed by a marked transition of some 24 °C between 1.75 and 1.25 Ga and a final slight warming of 4 °C between the two last runs at 1.25 and 1 Ga, respectively.

Three climate states can be defined: a weakly frozen Earth (1 and 1.25 Ga), a partially frozen Earth (from 1.75 to 2.25 Ga) and a snowball Earth (2.5 Ga and beyond). We notice that the changes in global mean surface temperature during this interval are far from being linear (Fig. 2a) albeit the solar brightness increases almost linearly. The solar brightness at 1 and 1.25 Ga is strong enough to limit the sea ice extent at the

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

latitude of 50–60°. The mean latitudinal surface temperature gradient does not significantly differ from the present day one. Between 1.25 and 1.75 Ga, sea ice spreads towards the equator up to 30° in response to the decrease in insolation. Between 1.75 and 2.25 Ga, sea ice limit remains fixed in the vicinity of 30 °C. Indeed sea ice cannot stretch further towards the equator because of the strong meridional energy transport by atmosphere and ocean driven by a latitudinal gradient of temperature about twice as strong as in the 1 Ga experiment. Finally as the solar brightness still decreases, we jump into a climate state corresponding to an entirely frozen Earth. Hence the solar constant evolution and its interplay with the ice-albedo feedback are the predominant factor governing the Earth's climate. The use of 3-D model (GCM) highlights the non-linear comportment of the climate, notably a jump into a snowball state, results are at odds with the recent work performed by 1-D model (RCM) where abrupt climatic transitions are not observed (Rosing et al., 2010).

4.2 Influence of clouds

To highlight the prevailing role of clouds, new experiments have been performed without the formation of clouds (no-clouds runs, see green lines on Fig. 2). The set of experiments yields two climatic states. The first state corresponds to a snowball Earth (from 3.5 to 2.5 Ga), where the global mean surface temperature is very similar to those simulated with modern clouds. The transition from a snowball state toward a partially ice-free Earth takes place at the same time (between 2.5 and 2.25 Ga). However, we observe that when clouds are removed, the global mean surface temperature at 2.25 Ga is 15 °C warmer and increases quasi-linearly up to reaching 20 °C at 1 Ga. This result agrees with the clouds radiative forcing (CRF) predicting a negative forcing from −10 to −20 W m^{-2} at high and mid latitudes when the modern cloud microphysics is used (Fig. 3b). In consequence the removal of clouds limits sea ice migration beyond the mid latitudes. This result explains the slowdown of global warming after 1.5 Ga obtained with no-clouds runs (Fig. 2a green curve) because sea ice is restricted at very high latitudes and its contribution to planetary albedo becomes unsignificant (Fig. 2b green curve). This mechanism, added to absence of clouds in the p-albedo computation, explains why no-clouds experiments present lowest planetary albedo (p-albedo) before after 2.5 Ga (Fig. 2.b green curve). These simulations show that modern clouds, with their negative CRF in mid and high latitudes, enhance the Earth's climate sensitivity to ice-albedo feedback, which tends to amplify the Earth's cooling.

Finally we have investigated the role of low CCN clouds (Fig. 2, red curves). The use of large liquid droplets (20 µm) promotes a climatic transition at 3 Ga, 0.75 Gyr earlier compared to the other sets of experiments. Snowball Earth states characterized by a global mean surface temperature of −70 °C are simulated at 3.5 Ga and 3.25 Ga only, when the incoming solar energy is too weak to prevent Earth's surface from complete freezing. In the 3 Ga experiment, the global mean surface temperature is about 13 °C and then increases linearly approaching 31 °C in the last experiment at 1 Ga. All over Archean and Proterozoic eons, low CCN clouds increase by 20 °C up to 35 °C the global mean surface temperature, respectively at 1 Ga and at 2.25 Ga. Moreover just before the transition toward a snowball state, the predicted climate is temperate, 13 °C in global annual mean (Fig. 2a red curve), a contrasting result regarding others situations (−5° and −20 °C for modern clouds and no-cloud runs respectively, see Fig. 2a blue and green curves). These very warm temperatures and the abrupt transition from an ice-free Earth to a snowball Earth at 3 Ga could appear surprising. For that reason, we regarded how low CCN clouds have affected sea-ice formation and its spreading to understand this very unusual climate behavior.

The clouds radiative forcing (Fig. 3a) shows that net CRF obtained with large droplets (CCN fixed to 20 µm in size) is positive in all experiments except during snowball state (Fig. 3a). More important, with large liquid droplets the CRF is positive at high latitudes (+40 W m^{-2}), favoring a warming and preventing sea-ice formation (Fig. 3b), which is the opposite of results obtained using the normal droplets size of clouds (CCN ranging from 5 to 10 µm) (Fig. 3a, b). This positive CRF, predicted with low CCN clouds, results from the combination of a slightly more negative CRF at short wavelength (scattering effect) and a much more positive CRF at large wavelength (IR trapping) than with normal size droplets (Fig. 3c). As a consequence, even low elevation clouds (the most reflective clouds) have a positive CRF, as already shown by Goldbatt and Zahnle (2011). Because inhibiting sea-ice formation, low CCN clouds limit the ice albedo feedback efficiency, which explains why the p-albedo does not change significantly (Fig. 2b red curve). This process, associated to warming due to low CCN clouds (Fig. 3a), explains relative hot surface temperatures obtained from 1 to 3 Ga. This mechanism also allows to decipher why the transition from an ice-free Earth to a snowball Earth at 3 Ga is so abrupt. Before 3 Ga the incoming solar energy is too weak and the Earth's cooling reduces the amount of water vapor into the troposphere, which inhibits the condensation of large amounts of water vapor to form low CCN clouds. In these conditions, the ice albedo feedback overcomes effects provided by low CCN clouds, leading to the very abrupt transition observed at 3.25 Ga (Fig. 2a).

4.3 Influence of continental surfaces

The mean albedo of the early Earth's surface has changed in response to the growth of the continental surface ($\alpha_{\text{ocean}} = 0.06$, $\alpha_{\text{bare soil}} = 0.32$). The lower albedo due to smaller continental area has been suggested to solve FYSP (Schatten and Endel, 1982; Rosing et al., 2010) and several times dismissed (Walker et al., 1982; Golbatt and Zanhle 2011). Simulations performed without clouds (Fig. 2b, green curve) show that the p-albedo (here equals to surface albedo) was higher at 2.25 Ga than at 1 Ga, so in opposite of the growth of continents. This p-albedo evolution is caused by the increase of ice coverage associated to the Earth's surface cooling (Fig. 2a, green curve). Indeed, a little change in ice-surface ($\alpha_{\text{sea-ice}} = 0.5$) is enough to overcome the influence of smaller continental area ($\alpha_{\text{sea-ice}} = 0.32$). These results demonstrate that the surface albedo is, at the first order, governed by the ice extension, the continental growth is a superimposed factor of second order importance. This result is confirmed with low CCN clouds simulations, which predict a quite stable p-albedo from 3 to 1 Ga (Fig. 2b, red curve), while the ice-albedo feedback is almost shutdown (Fig. 2c, 1 and 3 Ga cases). Hence smaller continental surfaces do not appear to be a mechanism able to solve the FYSP.

We will discuss in the second part of this paper that this conclusion can be challenged when the carbon cycle will be considered (see Part 2 for more details).

4.4 How much CO_2 is required to solve the FYSP?

Since none of the experiments can entirely solve the FYSP when a $p\mathrm{CO}_2$ of 0.9 mbar (or 900 ppmv or 3.2PAL) is applied, we investigate the minimal amount of CO_2 required to balance the solar weakness 3.5 Ga ago performed by performing a second set of simulations. rogressively increasing the $p\mathrm{CO}_2$, the Fig. 4a shows that a $p\mathrm{CO}_2$ of 1.8 mbar (or 1800 ppmv or 6.4PAL) is high enough to avoid a pan-glaciation at 3.5 Ga when low CCN clouds are considered. Solving the FYSP with 1.8 mbar of CO_2 at 3.5 Ga may appear surprising, however the radiative forcing separating a snowball Earth state (3.5 Ga, Fig. 2.c) and a partially ice-free Earth (3 Ga, Fig. 2.c) does not exceed 9 W m^{-2} (Fig. 1a). The radiative forcing due to the doubling of CO_2 (+4 W m^{-2}) associated to the ice-albedo feedback can easily fulfils the lacking 9 W m^{-2} . In consequence, when the atmosphere is poorly enriched in CO_2, low CCN clouds can prevent the Earth from a global glaciation during the early Archean. The realization that low CCN clouds associated to low $p\mathrm{CO}_2$ can solve the FYSP could be an interesting way to reconcile geochemical and modeling estimates, without invoking additional warming mechanisms, including pressure broadening of CO_2 and H_2O by high atmospheric pressure (Goldbatt et al., 2009) or high concentrations of H_2 (Wordsworth and Pierrehumbert, 2013).

This result also implies that the assumption defended by Rosing et al. (2010) – i.e. that low $p\mathrm{CO}_2$ are compatible with a solved FYSP – appears theoretically possible. However it is important to keep in mind that the $p\mathrm{CO}_2$ threshold value, here 1.8 mbars, can be model-dependent. Indeed the carbon dioxide value could differ according to the model used due to their respective parameterization. Furthermore several processes are lacking in this study. One of them is the absence of chemical reactions within the atmosphere. With a CO_2 minimal value close to 2 mbars and CH_4/CO_2 ratio reaching 0.5, an organic haze should be formed (threshold fixed to 0.2 according to Haqq-Mishra et al., 2008). Since this haze cools the planet, the CO_2 concentration should

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

be slightly higher to solve the FYSP. A second source of uncertainties is the use of a slab-ocean. With heat transport parameterized through diffusion, the GCM cannot intensify the meridional ocean heat transport due to smaller land fraction (Endal and Schatten, 1982). We also acknowledge that oceans with salinity twice higher should lead to a weaker overturning (Williams et al., 2010). These conflicting assessments concerning the ocean circulation, and their respective influence on the FYSP, could be explored using a fully-coupled dynamic ocean model, an investigation which has not been done in this study for reason of time computation limitation.

4.5 Influence of faster Earth rotation rate and saltier oceans

To investigate the sensitivity of the $p\mathrm{CO}_2$ as a function of factors able to warm the early Earth, an additional set of simulations has been performed using: (1) an Earth's rotation rate corresponding to the early Archean (LOD of 16 h, Zahnle and Walker, 1987) and/or (2) an ocean twice saltier (Knauth, 2005; Foriel et al., 2009). Using these new constraints with 3.5 Ga boundary conditions, 900 ppmv of $p\mathrm{CO}_2$ and low CCN clouds, all simulations predict a snowball Earth state (Fig. 4a), which means that none of these factors represent a serious solution for the FYSP. A similar puzzling result is obtained with 1800 ppmv of CO_2, when Earth is not entirely frozen. Runs depicted in Fig. 4a reveal that when faster Earth rotation and saltier ocean are associated, simulations predict a very modest warming (+0.2 °C). It is quite surprising because a faster Earth rotation rate and a lower seawater freezing point tend to warm the Earth's surface by several degrees in present-day conditions. The explanation of this unusual comportment is found in the complex interplay between these factors.

Regarding SST anomalies (Fig. 4b), we observe that the warming associated to a saltier ocean is localized into high latitudes. Delaying sea ice formation, elevated salinity decreases the Earth's sensitivity to the ice albedo feedback, a mechanism very effective in cold climate. More intriguing is the response induced by a faster Earth's rotation rate. In present day conditions, the change of day length from 24 to 16 h warms by about 2 °C the Earth surface (from 14.5 to 16.3 °C, see Fig. A1), in agreement with previous results (Jenkins, 1993). However in detail this warming is inhomogeneous. Due to reduced the latitudinal heat transport and changed clouds pattern, a faster Earth rotation warms low latitudes but cools high latitudes (see Fig. A1). In present-day conditions, the high latitudes cooling and the associated sea-ice extent remain limited. At the global scale the warming in low latitudes overcomes the cooling in high latitudes. The behavior is different during the early Archean because the climate is slightly colder and no emerged land limits the sea-ice spreading. Indeed simulations show that shorter LOD acts in the opposite (Fig. 4b), the sea ice formation at high and mid latitudes is eased, increasing the albedo and amplifying the cooling. Hence a shorter LOD in these particular conditions does not increase SST at the global scale. For all these reasons, when shorter LOD and saltier oceans are associated they balance each other – shorter LOD increases the Earth's sensitivity to the ice-albedo feedback whereas saltier oceans reduce this sensitivity – which explains why they do not affect results of FYSP (Fig. 4b).

If the effect of the faster Earth rotation rate could appear weak compared to result presented in Kienert et al. (2012), it is important to note that their simulations have been performed using a present-day cloudiness parameterization. Since the modern nebulosity tends to amplify the Earth's cooling (see Sect. 3.2), they overestimate the ice-albedo feedback which explains the disagreement between these two studies for $p\mathrm{CO}_2$ able to solve the FYSP.

5 Conclusion

In contrast to recent modeling studies defending high $p\mathrm{CO}_2$ to solve the FYSP, our study explains mechanisms and feedbacks allowing the existence of a temperate climate since 3.5 Ga with low $p\mathrm{CO}_2$. We argue that, in an atmosphere poorly enriched in cloud condensation nuclei (CCN), carbon dioxide pressures in the order of magnitude of around 2 mbars are able to keep the Earth unfrozen. Below this CO_2 threshold, not enough water vapor is maintained into the atmosphere to allow cloud formation, which drives the Earth into a snowball state. Above this threshold, clouds formed by large liquid droplets size warm high latitudes and inhibit sea-ice formation. This process limits the efficiency of the ice-albedo feedback and maintains the Earth's albedo to low values, which prevents the complete freezing of the Earth even with low $p\mathrm{CO}_2$. This complex interplay between clouds and albedo illustrates the importance of the spatial resolution to consider feedbacks, and the value of GCMs to investigate deep-time climates. If this study improves our understanding of the physical processes able to solve the FYSP in term of climate, we assume that these results are not a final answer. In order to have a complete picture of the FYSP, the next step is to test what levels of CO_2 are possible from a climate-carbon cycle point of view, both being necessary at the equilibrium at long-term scale (> 1 Myr).

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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

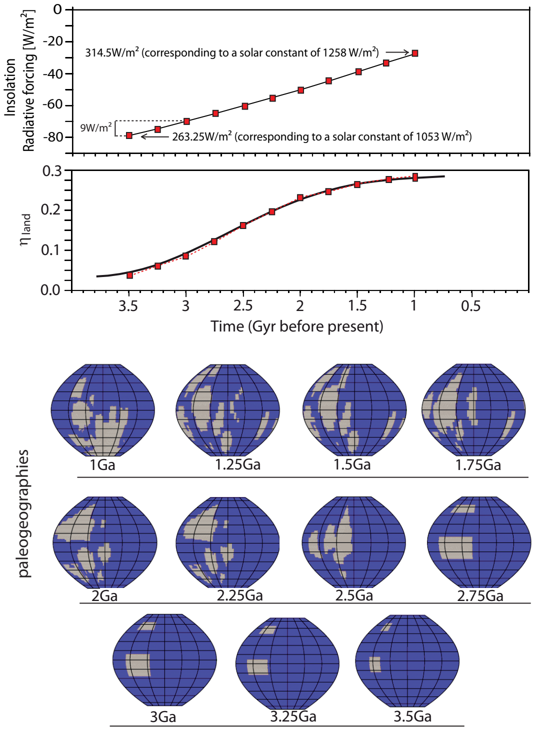


Fig. 1. Boundary conditions for solar constant (upper part) and continental growth (lower part). η_{land} is the emerged surface/Earth surface ratio (present-day surface is 146×10^6 km^2 or 29 % of the Earth surface). Each red square represents boundary conditions used in our sets of simulations.

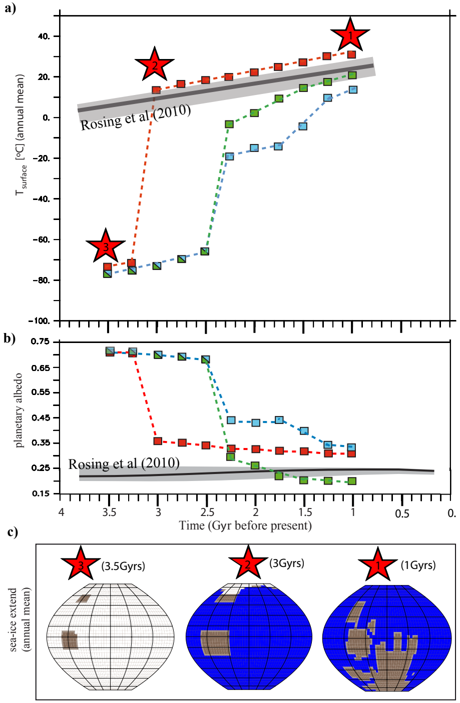


Fig. 2. 3-D climate simulations from 3.5 to 1 Gyr. **(a)** Evolution of surface temperature versus time assuming increasing irradiance, linear continental growth and $p\mathrm{CO}_2$ and $p\mathrm{CH}_4$ of 900 ppmv. Grey line is from Rosing et al. (2010). Blue and red lines were obtained using liquid droplets size of 5 to 10 µm (modern clouds) and 20 µm (optically thinner and short-lived clouds), respectively. Green squares represent the no-clouds scenario. **(b)** Evolution of planetary albedo versus time (α_{ocean} 0.06, $\alpha_{\mathrm{rocky\ desert\ continents}}$ 0.32, α_{seaice} 0.5, α_{snow} 0.8). **(c)** Red starts represent sea-ice extend (white) predicted with runs performed with liquid droplets size of 20 µm (Fig. 2a and b show corresponding temperature/albedo for each simulation).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

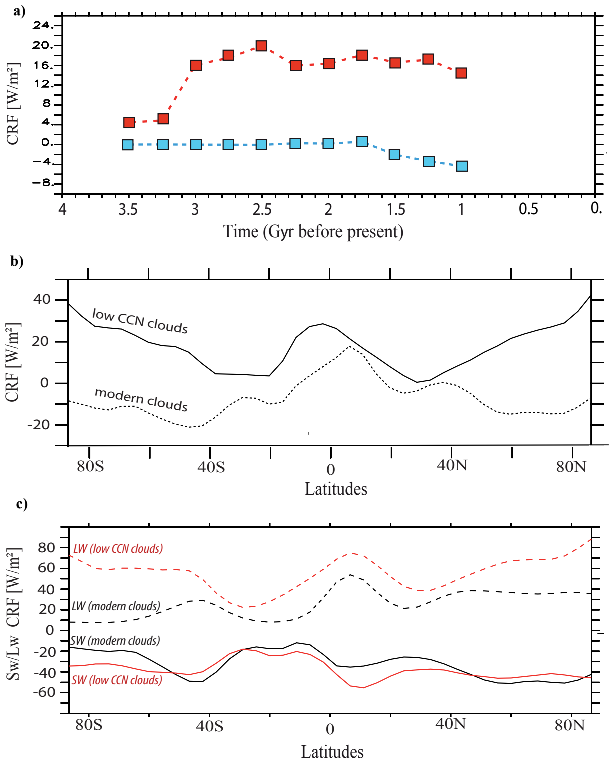
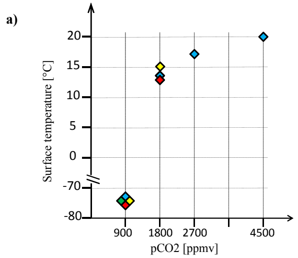
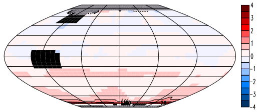
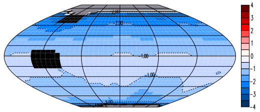


Fig. 3. **(a)** Net cloud radiative forcing (CRF, unit W m^{-2}) versus time. Optically thinner and short-lived clouds (red squares) result in a positive forcing because the effect of infra-red trapping overcomes that of scattering **(b)** CRF as a function of latitude for simulations performed at 1 Ga. The black line represents low CCN clouds (liquid droplets size of 20 µm), dashed line the modern clouds parameterization (liquid droplets size of 5 to 10 µm). **(c)** Simulations performed using 1 Ga boundary conditions. Dashed lines represent long-wave (LW) budget of clouds (greenhouse effect), continuous lines their short wave budget (albedo effect).

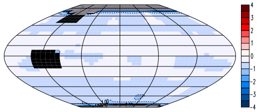




Annual SST anomalies [°C]
Standard - LOD 16h



Annual SST anomalies [°C]
Standard - Saltier ocean



Annual SST anomalies [°C]
Standard - (Saltier ocean and LOD 16h)

Fig. 4. **(a)** Faster rotation rate (16 h of LOD), saltier ocean and $p\mathrm{CO}_2$ impacts on the FYSP 3.5 Ga ago. Red diamonds represent simulations with standard conditions ($p\mathrm{CH}_4$ fixed at 900 ppmv, low CCN clouds), yellow diamond (standard cond. + saltier ocean), green diamond (standard cond. + 16 h of LOD), blue diamond (standard cond. + saltier ocean + 16 h of LOD). At 1800 ppmv of CO_2 the surface temperature reaches 14.2 °C, 15.0 °C, 14.2 °C, 14.4 °C, respectively. **(b)** The sea surface temperature (SST) response to a faster rotation rate (LOD) and saltier ocean at a fixed $p\mathrm{CO}_2$ (1.8 mbar or 1800 ppmv or 6.4 PAL).

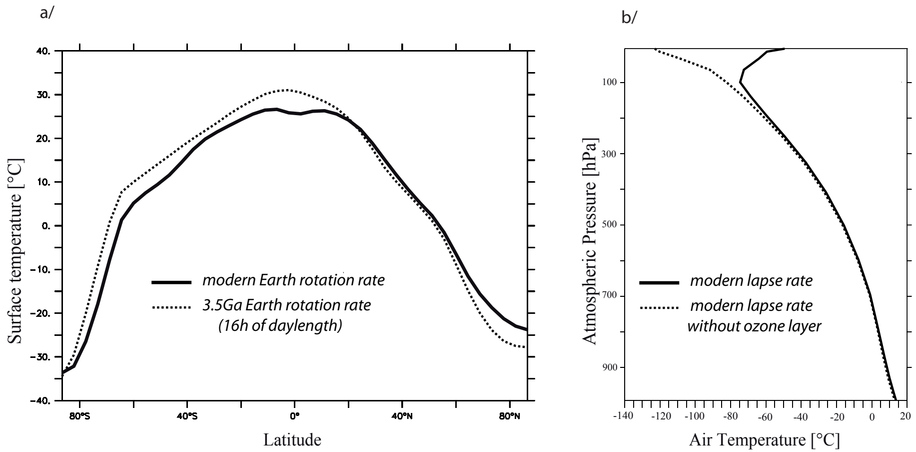


Fig. A1. **(a)** Temperature gradient as a function of Earth rotation rates. **(b)** Atmospheric lapse rate of function of ozone layer presence/removing. Simulations performed using present day boundary conditions.