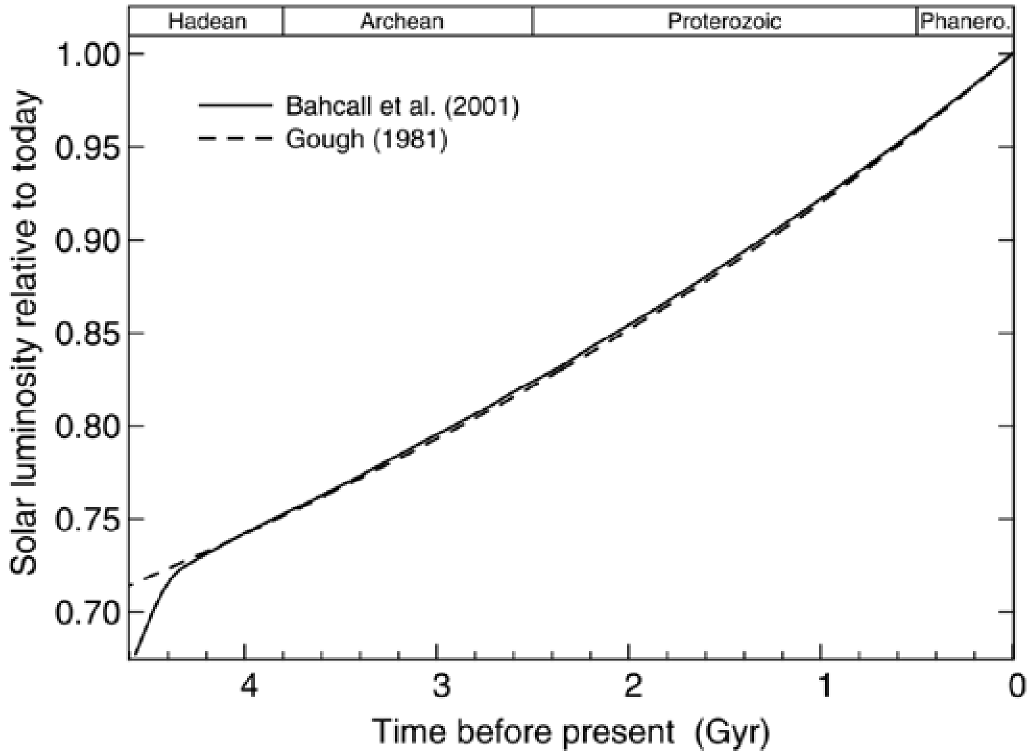
Faint Young Sun Problem of Earth

Long-term trend of solar luminosity



Feulner (2012)

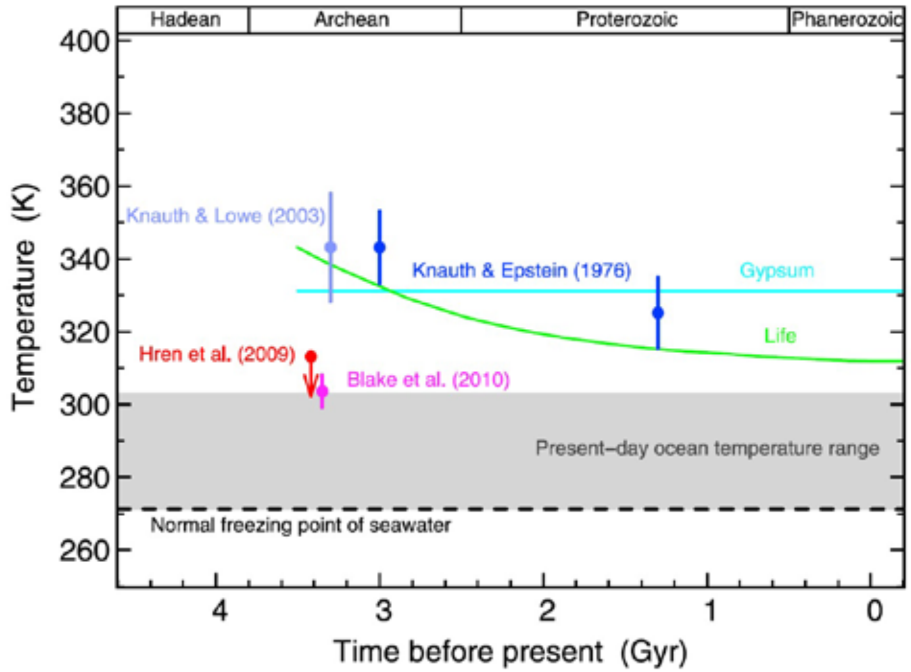
from Wikipedia

"THE FAINT YOUNG SUN PROBLEM"

Feulner (2012, Reviews of Geophysics)

- For the early Earth, models of stellar evolution predict a solar energy input to the climate system that is about 25% lower than today. This would result in a completely frozen world over the first 2 billion years in the history of our planet if all other parameters controlling Earth's climate had been the same.
- Yet there is ample evidence for the presence of liquid surface water and even life in the Archean (3.8 to 2.5 billion years before present), so some effects must have been compensating for the faint young Sun.

Constraints on ocean temperatures



Feulner (2012)

Figure 2. Constraints on ocean temperatures during the Archean. The existence of diverse life since about 3.5 Gyr and the typical ranges of temperature tolerance of living organisms suggest the upper limit indicated by the green line [*Walker*, 1982]. Evaporate minerals are present since about 3.5 Gyr, and the fact that many were initially deposited as gypsum sets an upper limit at 58°C (cyan line) [*Holland*, 1978]. The comparatively high (but controversial; see the text for discussion) temperatures derived from oxygen isotope ratios in cherts are shown in blue [*Knauth and Epstein*, 1976; *Knauth and Lowe*, 2003]. More recent estimates based on a combination of oxygen and hydrogen isotope ratios [*Hren et al.*, 2009] and the oxygen isotope composition of phosphates [*Blake et al.*, 2010] are shown in red and magenta, respectively. The range of present-day ocean temperatures is indicated in gray [*Locarnini et al.*, 2010], and the freezing point of seawater at normal pressure and for present-day salinity is indicated by the dashed line. Modified and updated after *Walker* [1982].

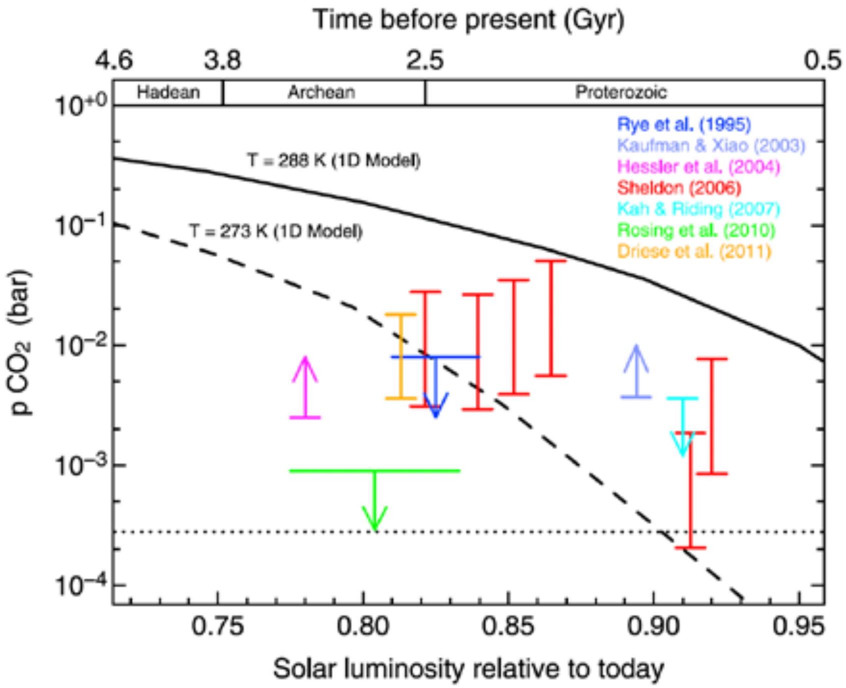


Figure 6. Comparison of empirical estimates of carbon dioxide partial pressures during the Precambrian and climate model results for an average global surface temperature of 288 K assumed to be required to prevent global glaciation as a function of relative solar luminosity (solid black line). The results for a global mean temperature of 273 K are indicated by the dashed black line. Calculations are based on a one-dimensional radiative-convective climate model [*von Paris et al.*, 2008]. Geochemical estimates for atmospheric CO_2 partial pressures at different epochs are indicated [*Rye et al.*, 1995; *Hessler et al.*, 2004; *Sheldon*, 2006; *Rosing et al.*, 2010; *Driese et al.*, 2011]; see the text for details. A temperature of 298 K is assumed in case an explicit dependence of the estimates on environmental temperature is available. In addition to the Archean and Paleoproterozoic estimates, four Mesoproterozoic estimates are shown for comparison: a lower limit derived from a carbon isotope analysis of microfossils dating back 1.4 Ga [*Kaufman and Xiao*, 2003], a ~1.2 Ga upper limit inferred from in vivo experiments of cyanobacterial calcification [*Kah and Riding*, 2007], and two estimates from *Sheldon* [2006]. The dotted line shows the preindustrial CO_2 partial pressure of 2.8×10^{-4} bar. The conversion from solar luminosity (bottom scale) to age (top scale) follows the approximation given in equation (1). Modified and updated after *Kasting* [2010].

Comparison of estimates of carbon dioxide partial pressures and climate model results for an average global surface temperature of 288 K assumed to be required to prevent global glaciation as a function of relative solar luminosity

"Is the Faint Young Sun Problem for Earth Solved?"

Charnay et al. (2020, Space Science Reviews)

- "The faint young Sun problem for Earth has essentially been solved."
- Key processes:
  - Greenhouse effect of CO_2 + CH_4
  - Less land surface area
  - Decreased low clouds due to fewer cloud condensation nuclei (CCN)
  - Increased high clouds due to absence of ozone
  - Lower pressure

Global mean warming by methane

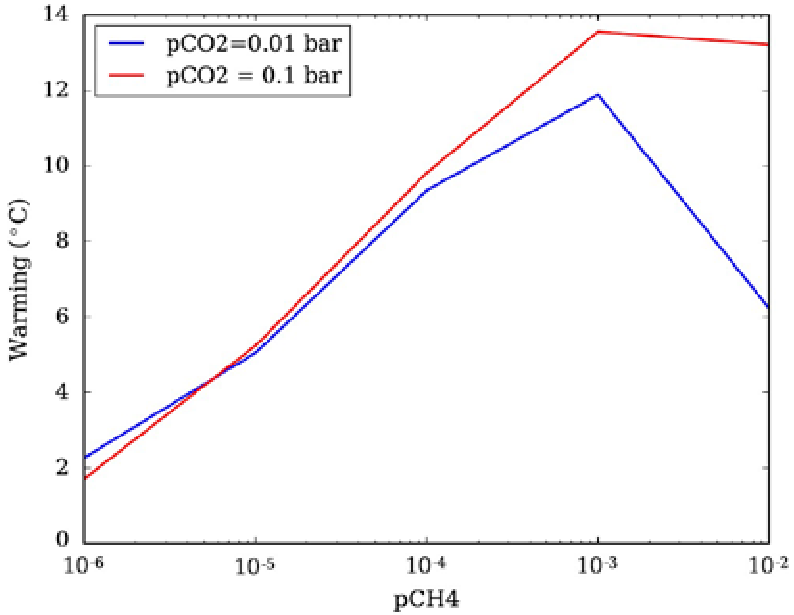


Table 1 Table of solutions to the Faint Young Sun Problem. The first column lists the different possible solutions. The second column gives the maximal radiative forcing and the corresponding references based on 1D or 3D models. We remind that the faint young Sun implies a deficit of 44 Wm^{-2} at 2.5 Ga and 60 Wm^{-2} at 3.8 Ga. For CO_2, we give the forcing for two values of pCO_2 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

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)	$pCO_2 = 3$–15 mbar (2.69 Ga)	(Driese et al. 2011)
	$+44\ Wm^{-2}$ (for $pCO_2 = 60$ mbar)	$pCO_2 = 3$–25 mbar (2.5 Ga)	(Sheldon 2006)
		$pCO_2 = 24$–140 mbar (2.77 Ga)	(Kanzaki and Murakami 2015)
	(Wolf and Toon 2013)	$pCO_2 = 22$–700 mbar (2.75 Ga)	(Kanzaki and Murakami 2015)
	(Le Hir et al. 2014)	$pCO_2 = 45$–140 mbar (2.46 Ga)	(Kanzaki and Murakami 2015)
	(Byrne and Goldblatt 2014)	$CO_2 > 70\%$ (2.7 Ga)	(Lehmer et al. 2020)
Elevated CH_4	$+9\ Wm^{-2}$ (for $pCH_4 = 1$ mbar)	$pCH_4 = 0.01$-10 mbar	(Sauterey et al. 2020)
	(Byrne and Goldblatt 2014)	$CH_4 > 0.5\%$ (~ 3.5 Ga)	(Zahnle et al. 2019)
	(Le Hir et al. 2014)	CH_4:CO_2~0.2 (~2.6 Ga)	(Zerkle et al. 2012)
Less emerged land	$+5\ Wm^{-2}$ (with almost no land)	Fraction = 2-12% (2.5 Ga)	(Flament et al. 2008)
	(Goldblatt and Zahnle 2011a)	Crust volume = 60-80% (3 Ga)	(Hawkesworth et al. 2019)
Faster rotation	$\sim +0\ Wm^{-2}$ (for P = 14 h)	Length of day = 21.9 ± 0.4 h (620 Ma)	(Williams 2000)
	(Charnay et al. 2013)	Length of day $\sim$ 13 h (3.8 Ga)	(Bartlett and Stevenson 2016)
Cloud feedbacks and less CCN	$\sim +5\ Wm^{-2}$ (cloud feedbacks*)	Larger droplets ($r \sim 17$ μm)	(Rosing et al. 2010)
	$\sim +12\ Wm^{-2}$ (for $r = 17$ μm)		
	(Charnay et al. 2013)		
	(Wolf and Toon 2013, 2014)		

Charnay et al. (2020)

Suggestions from a 3-D GCM (Charnay et al. 2013)

Continents

- The continental crust volume was lower and has increased during the Archean
- Since continents have lower albedos than oceans, the smaller continental area would have increased the temperature

Clouds

- On the modern Earth, an important fraction of CCN comes from biological activity
- The smaller amount of CCN during the Archean leads to a smaller number of larger droplets, which means optically-thinner clouds, lowering the planetary albedo.

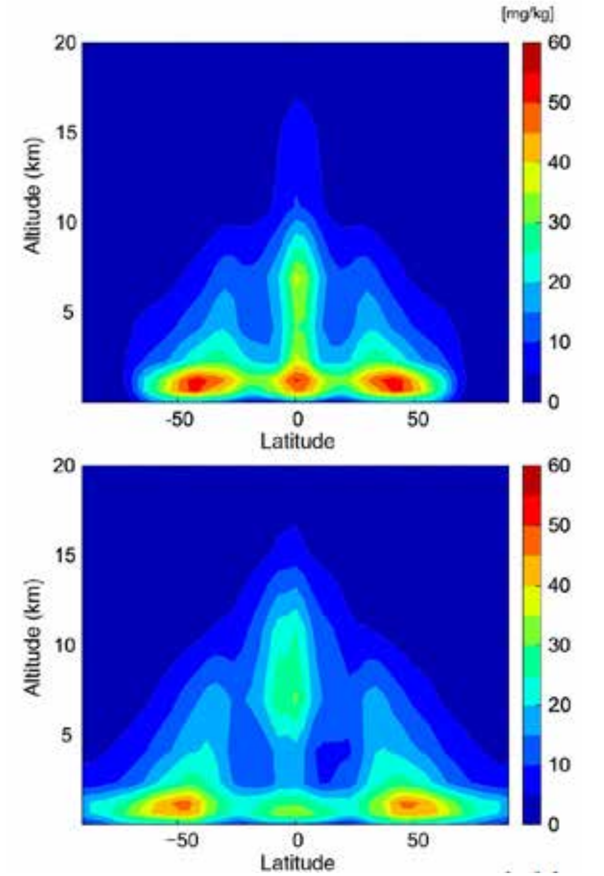
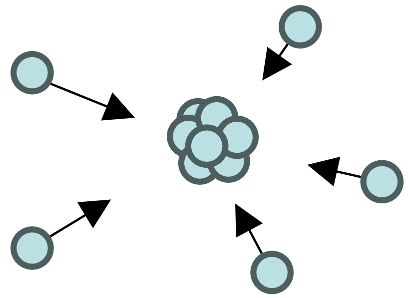


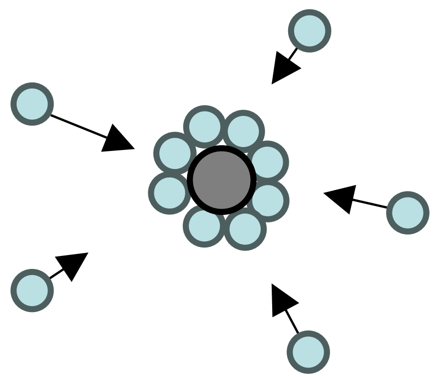
Figure 11. Zonally averaged mixing ratio (in mg/kg of air) of condensed water (liquid and icy clouds) at 2.5 Ga (atmospheric composition: 10 mbar of CO_2 and 2 mbar of CH_4) for liquid droplet radius of (top) 12 μm and (middle) 17 μm. (bottom) The difference between both (17 μm minus 12 μm).

Homogeneous nucleation
vs. Heterogeneous nucleation

- Homogeneous nucleation
  - Liquid or solid particles form directly from vapor without the presence of pre-existing particles (cloud condensation nuclei, CCNs)
  - It generally requires significant supersaturation of the vapor, i.e., a vapor pressure higher than the saturation vapor pressure.



- Heterogeneous nucleation
  - Liquid or solid particles form on the surface of existing aerosol particles (CCNs).
  - It generally requires relatively small supersaturation.



Atmospheric Pressure

- The surface pressure was higher in the past. About 2 bars of nitrogen were likely initially present in the atmosphere and later fixed by surface organisms and incorporated into the mantle by subduction.

- An increase in the atmospheric pressure increases the moist adiabatic lapse rate (going closer to the dry adiabatic lapse rate $-g/c_p \approx 9.8$ K), leading to warming

Moist adiabatic lapse rate

$$\Gamma_s = -\left(\frac{\mathrm{d}T}{\mathrm{d}z}\right)_S = \frac{g}{c_p}\left(\frac{1+\frac{L_V x_S}{R_d T}}{1+\frac{L_V^2 x_S}{c_p R_d T^2}}\right)$$

Dry adiabatic lapse rate

- An increase in atmospheric pressure reinforces the effect of other greenhouse gases through pressure broadening, leading to warming

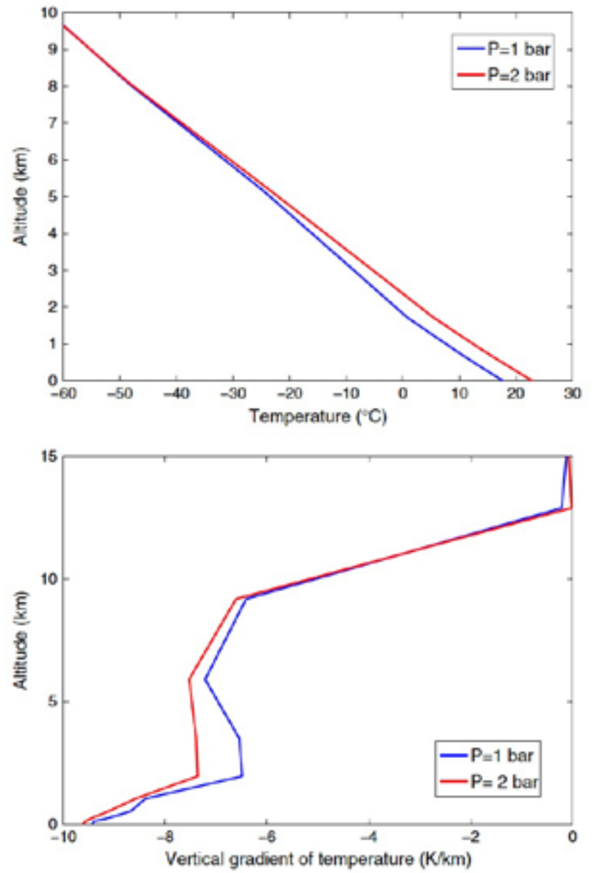


Figure 14. Zonally averaged (top) vertical temperature profiles and (bottom) temperature lapse rate at the equator at 2.5 Ga (atmospheric composition: 10 mbar of CO_2 and 2 mbar of CH_4) with an atmospheric pressure of 1 bar (blue) and 2 bars (red).

Absorption line shape

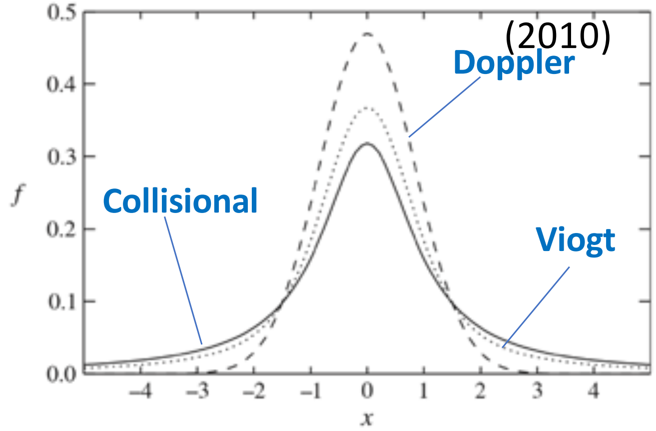
Extinction coefficient

line-shape function

$$k_\nu = \sum_n S_n f_n(\nu - \nu_n)$$

line strength

Andrews (2010)



Illustrating the Lorentz (solid), Doppler (dashed) and Voigt (dotted) line shapes as a function of $x = (\nu - \nu_0)/\alpha$, where α is the half-width at half maximum appropriate for each shape. The curves are normalised such that the area under each is the same.

Collisional broadening

$$f(\nu - \nu_n) = \left(\frac{\gamma_L}{\pi}\right) \frac{1}{(\nu - \nu_n)^2 + \gamma_L^2}$$

$$\gamma_L \propto p T^{-1/2}$$

Dominant in the lower atmosphere

Doppler broadening

$$k_\nu = \frac{S}{\gamma_D \sqrt{\pi}} \exp\left(-\frac{(\nu - \nu_0)^2}{\gamma_D^2}\right)$$

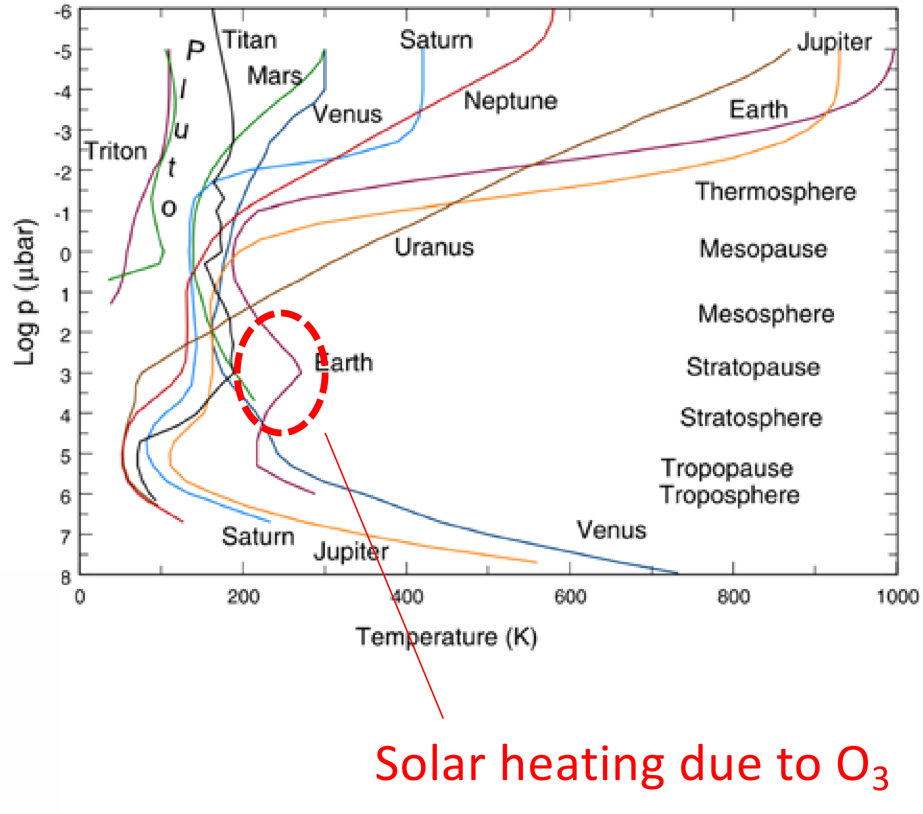
$$\gamma_D = \frac{\nu_0}{c} \left(\frac{2 k_B T}{m}\right)^{1/2}$$

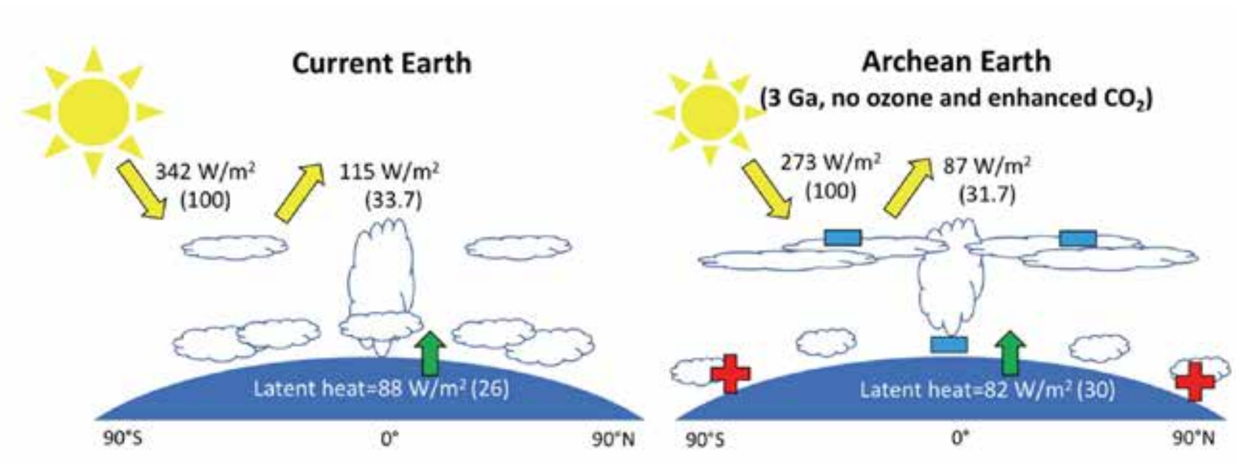
Dominant in the upper atmosphere

(Mueller-Wodarg et al.)

Atmospheric ozone (O_3)

- The absence of ozone leads to a colder higher troposphere, which could result in a increase of the amount of cirrus clouds, increasing their greenhouse effect.





less lower clouds and more upper clouds