Reply to RC2: 'Comment on bg-2021-135', Axel Kleidon, 15 Jul 2021

I would like to first thank both the original authors and the reviewers for interesting discussion and for directing my attention to interesting literature that I did not know of before.

I used the Moon for comparison, because I had no Earth without life at hand with which to compare the present vegetated Earth. Life probably did not originate on land, but I shall return to the situation in water. The best proxy for life on land may be what Zang et al. (2013) have described. They compared the albedo of nonpopulated desert sand with that having a biological crust consisting of cyanobacteria, green algae, mosses, lichens, and other organisms. They found that only if the surface was very dry was the albedo higher for the unpopulated sand Fig, 1).

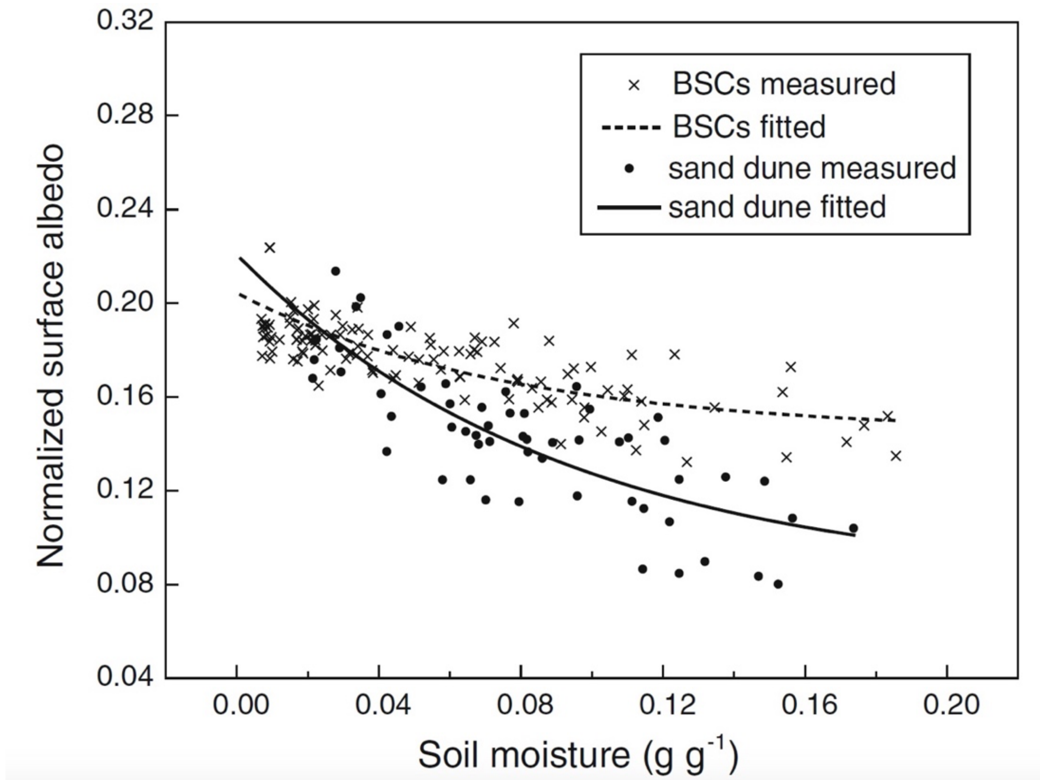


Fig. 1. Albedo for desert dune sand with and without biological soil crust organisms (BSC) at different moisture contents. From Zang et al. (2013).

Kleidon et al. (2000) deal primarily with the land surface. Many researchers believe that life originated in an aquatic environment. In fact, there probably was not much land when life originated; see, e.g., Liu et al. (2021). Kleidon writes (RC2): “Furthermore, it is textbook knowledge that the surface albedo of forests is in most cases darker than bare ground, even though there may be some isolated exceptions.” Again, it is probably not the land surface, and certainly not forests, that are most relevant in a discussion about the origin and early evolution of life. To the situation for early life, the conditions in an aquatic environment are more relevant. For a long time life and photosynthesis probably took place mostly underwater.

For the ocean, algal growth decreases the reflectance at shorter wavelengths, increases it at longer wavelengths (Fig. 2, from Bacour et al. 2020).

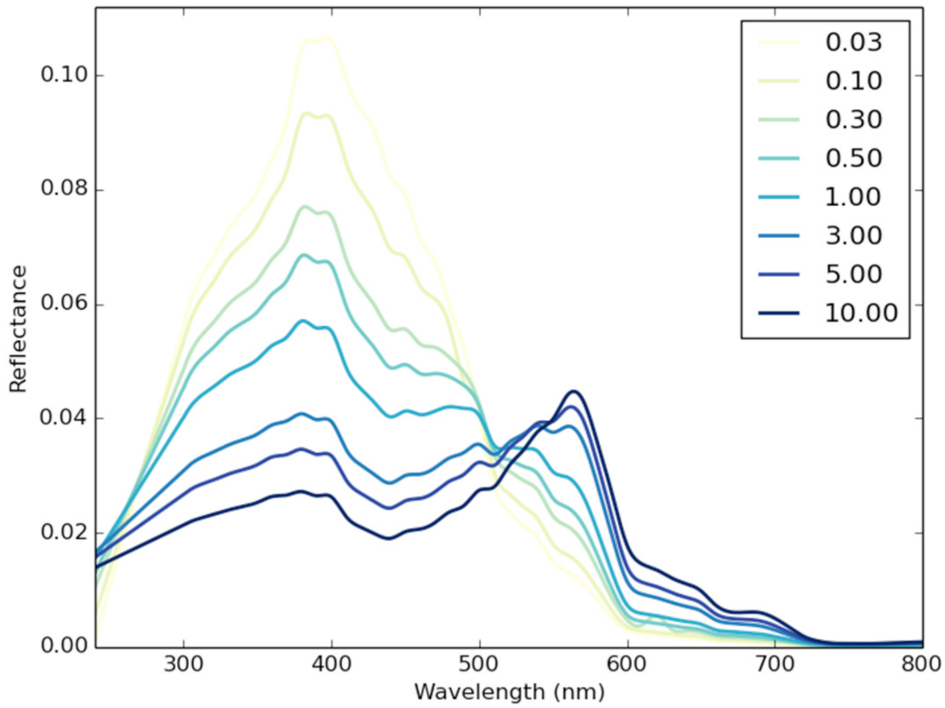


Fig. 2. Ocean column reflectance for eight values of the chlorophyll concentration (0.03, 0.1, 0.3, 0.5, 1, 3, 5, 10 mg.m^{-3}) computed by the Coupled Ocean and Atmosphere Radiative Transfer (COART) bio-optical model (https://cloudsgate2.larc.nasa.gov/jin/coart.html, accessed on 15 March 2020; see also https://cloudsgate2.larc.nasa.gov/jin/rtnote.html). From Bacour et al. (2020). It should be noted that spectral reflectance graphs published by Li et al. (2021), although similar, differ quantitatively from these, with a single peak for 10 mg m^{-3} chlorophyll *a*. Note that the values shown in Fig. 6 of Li et al. (2021) should be multiplied by 2π (conversion from reflectance over 1 radian to reflectance over 2π radians) to be comparable with the values in this Figure.

Similar results are given by Li et al. (2021) (Fig. 3), although the spectral and angular coverage is not quite sufficient for reliable computations of solar energy reflectance or entropy changes. Algae in the ocean decrease reflectance below 510 nm, increase reflectance at wavelength longer than 510 nm. Higher reflectance in this case means lower entropy production. These reflectance spectra should be compared to Archaean daylight (Fig. 5). It is not quite certain whether reflectance increases or decreases with increasing amount of photosynthetic plankton. This partly depends on what early photosynthetic pigment we assume. The integrated reflected radiant powers for 0.03 mg chlorophyll per m^3 of Bacour et al. (2020), i.e. 2.66 W m^{-2}, and Li et al. (2019), 2.77 W m^{-2}, do not differ significantly from each other. In the values for 10 mg chlorophyll per m^3, however, the two publications differ. Bacour et al. (2020) give 2,87 W m^{-2}, a somewhat higher value than for 0.03 mg chlorophyll per m^3, and Li et al. (2019) 2,18 W m^{-2}, i.e. lower than for 0.03 mg chlorophyll per m^3. Using the reflectances of Jin et al. (2011) the values are 1.02 W m^{-2} for 0 mg chlorophyll per m^3 and 1.32 W m^{-2} for 10 mg chlorophyll per m^3, i.e. more reflected power with phytoplankton. Also these spectra are a bit truncated, and it is likely that the difference would be larger with wider spectral coverage. In conclusion it can be said that at present we cannot conclude whether the presence of phototrophs in the ocean in general increased or decreased reflected power from the sun during the Archaean.

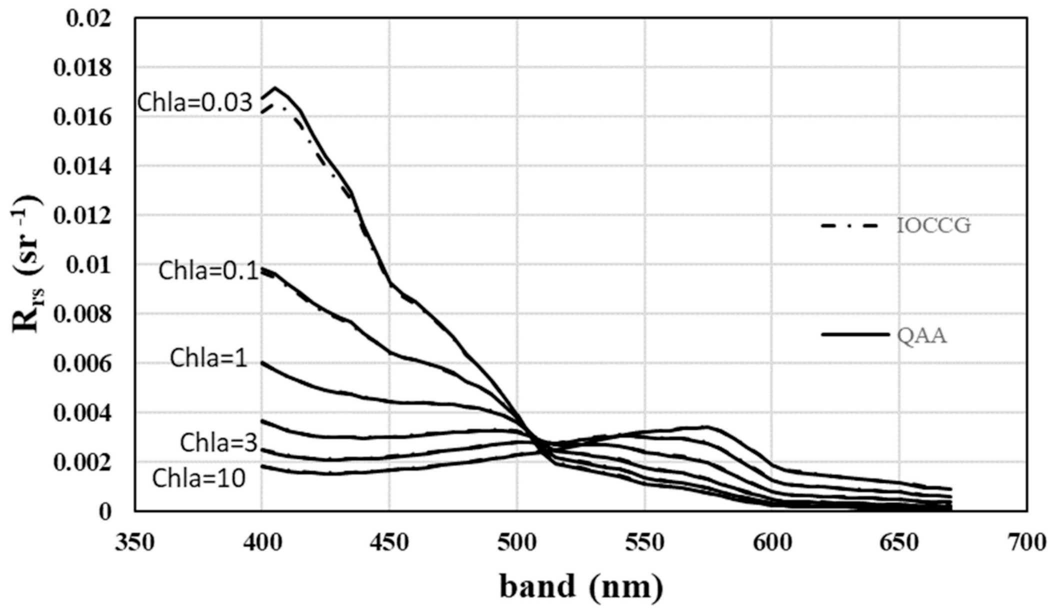


Fig. 3. Ocean reflectance over 1 radian according to Li et al. (2021) for various concentrations of chlorophyll *a*-containing organisms.

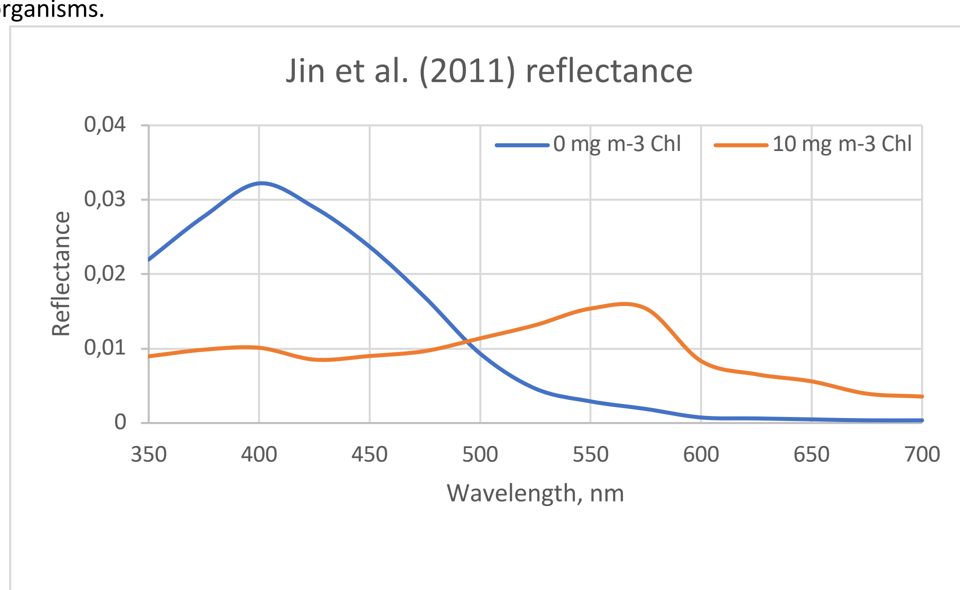


Fig 4. Ocean reflectance without and with phytoplankton with chlorophyll according to Jin et al. (2011).

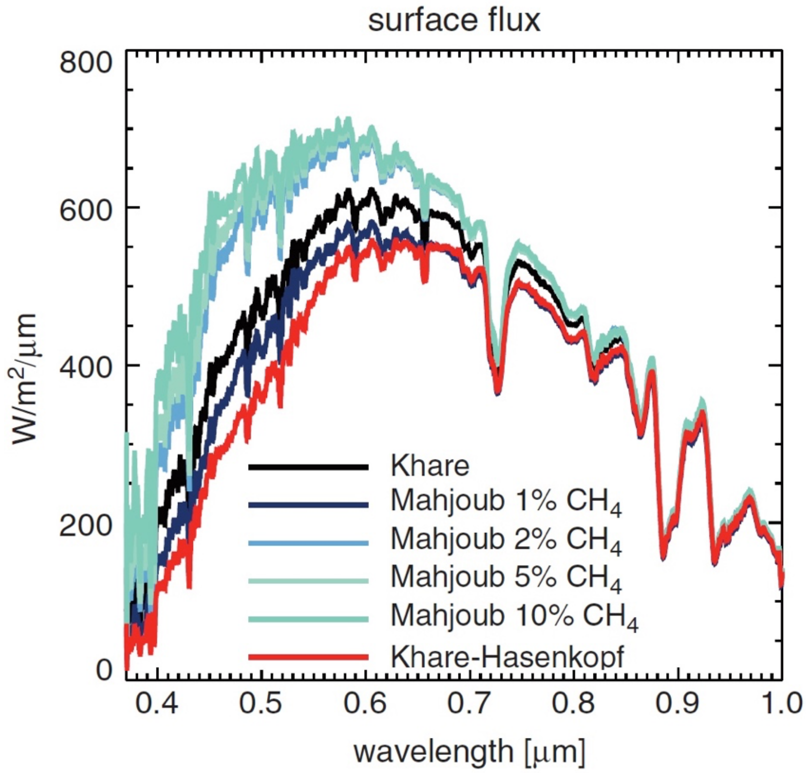


Fig. 5. Daylight spectrum at ground level in the Archaean according to various estimates compiled by Arney et al. (2016). I have used the data marked "Khare-Hasenkopf" (red curve) for my calculations of reflected specteal power in the Fig. 5.

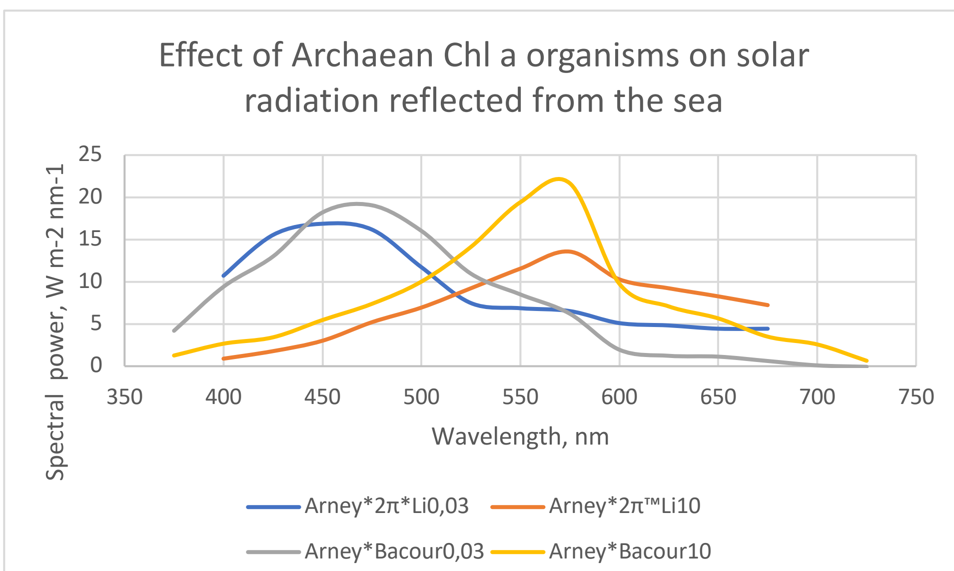
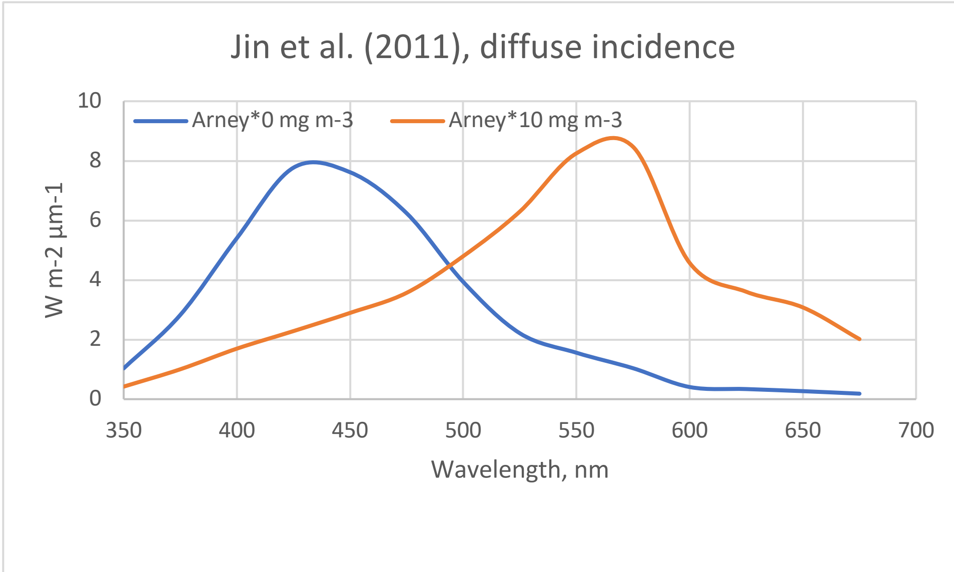


Fig. 6. The convolution of the red curve in Fig. 4 by the spectra in Figs 2 and 3 for 0,03 and 10 mg chlorophyll per m^3. The spectra of Li et al. in Fig. 3 were multiplied by 2π to for adjustment to same angular geometry.



Fig, 7. he convolution of the red curve in Fig. 4 by the spectra in Fig. 4.

It must be assumed that the power that is not reflected, ultimately will give rise to radiation of longer wavelength, mostly heat radiation of the temperature of the Earth surface. I thought at first that for life in water we do not have to consider the liquid to gaseous transition of water when discussing entropy and early life. This is, however, not correct. The presence of pigmented organisms can cause local heating of up to 1.5°C of the ocean surface, and thus probably cause extra evaporation (Kahru et al. 1993).

Michaelian and Simeonov say (bg-2021-135-CC4-supplement, lines 103–104): “Less than 0.1% of the free energy in sunlight goes into carbon bond making, which is how photosynthesis stores free energy [Gates (1980)].” The same is also said by Simeonov in the earlier bgd-12-C1904-2015, also referring to Gates (1980). This may be correct, although I have not been able to find support for it in Gates (1980), who writes (p. 491) “Of the total amount of light energy incident on a plant, only 1 to 7% is converted to useful products”. Zhu et al. (2010) specify “an efficiency of conversion of full-spectrum solar radiation into biomass of approximately 1.5%” for soybean (p. 240), and “The theoretical maximal photosynthetic energy conversion efficiency (εc) is 4.6% for C3 and 6% for C4 plants” (p. 240), although this would perhaps never be realized.

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