GLACIATION ESCAPE ON EARTH-LIKE PLANETS LIMITED BY CO_2 CONDENSATION.
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Introduction: It is widely considered that the carbonate-silicate cycle [1] is the main agent - through volcanism - to trigger deglaciations by CO_2 greenhouse warming on Earth and by extension on Earth-like planets, when they get in frozen state. We use the LMD-G 3D Global Climate Model (with both CO_2 and H_2O cycles) to simulate the ability of planets initially completely frozen to escape from glaciation episodes by accumulating enough gaseous CO_2 [2,3].

Around a Sun-like star: We find that planets that are initially completely frozen and which accumulate CO_2 through volcanism can evolve in different climate regimes depending on their insolation and obliquity. Initially the greenhouse effect of CO_2 is too weak to trigger a deglaciation. The planet stays in a snowball state but keeps accumulating CO_2 in the atmosphere. Then, if CO_2 continues to accumulate, two outcomes are possible 1) The greenhouse effect of CO_2 is sufficient to raise the surface temperatures in equatorial regions above the melting temperature of water ice and the planet escapes from glaciation. 2) The greenhouse effect of CO_2 is too weak to raise the surface temperatures of the poles above the condensation temperature of CO_2 and CO_2 collapses there. The planet is locked in a global glaciated state, with two permanent CO_2 polar ice caps. Quantitatively, we find (see Fig. 1) that planets with Earth-like characteristics orbiting a Sun-like star may never be able to escape from glaciation if their orbital distance is greater than 1.27 AU (62% of the Solar constant), because CO_2 would condense at the poles (the cold traps) forming permanent CO_2 ice caps [2].

Furthermore, for planets with a significant water ice cover, we find that CO_2 ice deposits (1.6x denser than H_2O) should be gravitationally unstable [2,3]. They get buried beneath the water ice cover in geologically short timescale ~10^4 yr, mainly controlled by the viscosity of water ice. CO_2 could then be permanently sequestered underneath the water ice cover, in the form of CO_2 liquids, CO_2 clathrate hydrates and/or dissolved in subglacial water reservoirs. This would considerably increase the amount of CO_2 trapped and further reduce the probability of deglaciation.

Around a M-dwarf: The water ice bolometric albedo is considerably reduced around cool stars [4], making the scenario of CO_2 polar condensation less efficient. However, planets orbiting M-dwarfs are subject to tidal locking. The temperature on the nightside of a synchronous planet can be extremely low, favoring CO_2 condensation. This possibility, already explored in [3], will be presented at the Habitable Worlds 2017 conference.

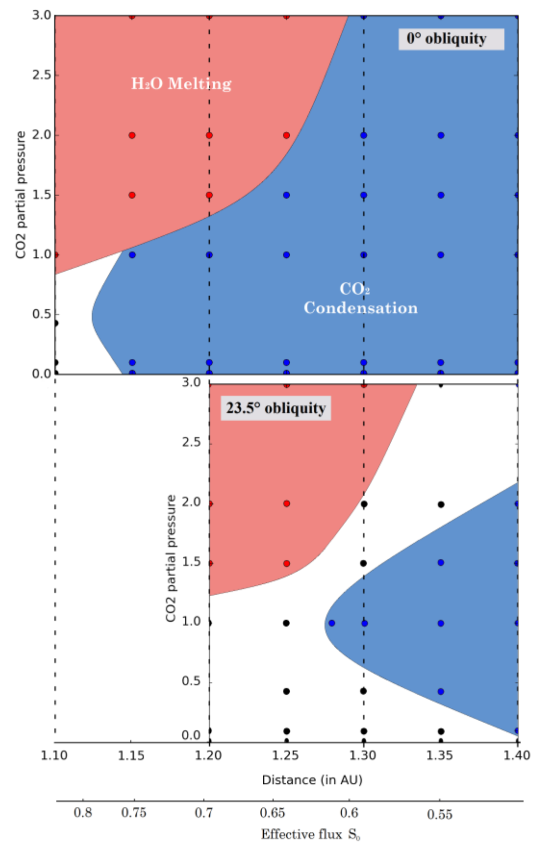

Figure 1: Climate regimes reached as function of the distance from a Sun-like star and the CO_2 partial pressure, assuming a cold start [2]. Figures correspond to Earth-like planets with 0/23.5° obliquity (for upper/lower panels, respectively). The red color depicts the region where deglaciation is observed. The blue region represents glaciated states where CO_2 collapses permanently. The white region describes cases where none of this two previous conditions were reached.

References: [1] Walker, J.C.G. et al. (1981) *J. Geophys. Res.*, 86:9776–9782. [2] Turbet M. et al (2017) accepted for publication in *EPSL* [ArXiv:1703.04624]. [3] Turbet M. et al. (2017) submitted to *A&A* [arXiv:1707.06927]. [4] Joshi M.M. & Haberle R.M. (2012) *Astrobiology* vol. 12.