GLACIATION ESCAPE ON EARTH-LIKE PLANETS LIMITED BY CO_2 CONDENSATION

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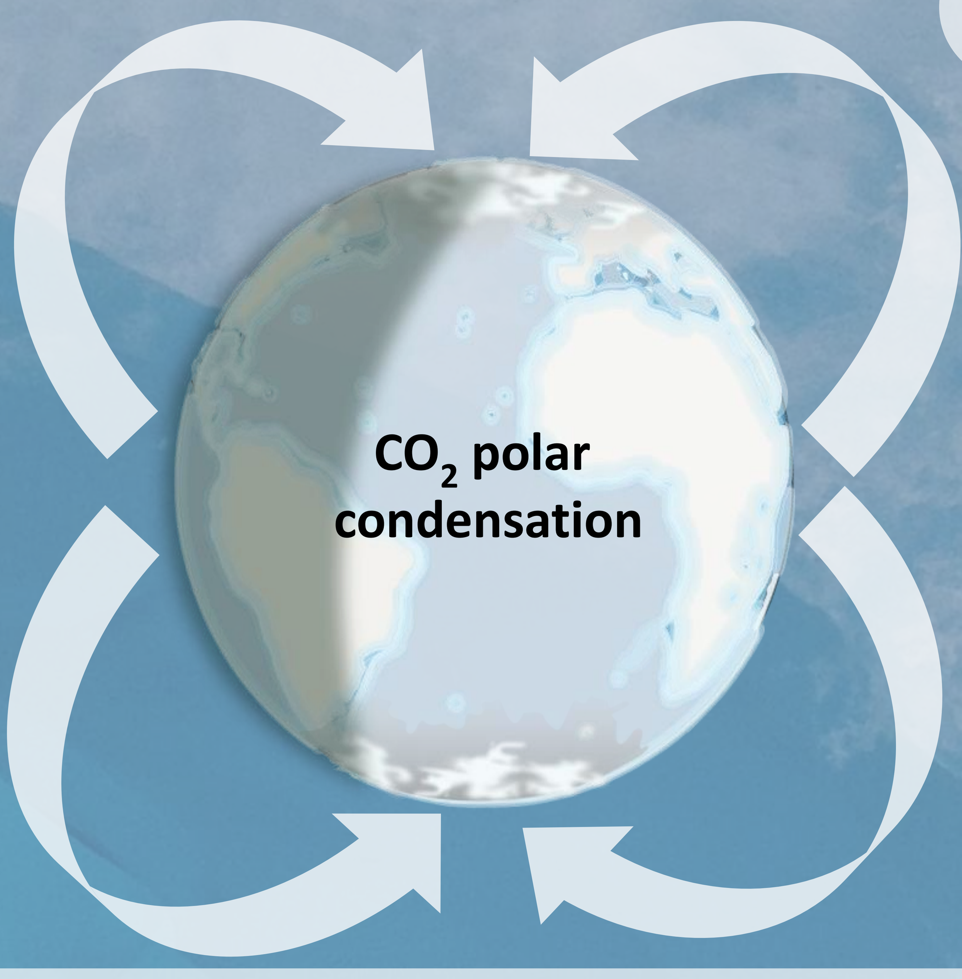
CONTEXT

It is widely considered that the carbonate–silicate cycle is the main agent – through volcanism - to trigger deglaciation by CO_2 greenhouse warming on Earth and by extension on Earth-like planets when they get in frozen state.



METHOD

We use the LMD 3D Global Climate Model – with both CO_2 and water cycles - to simulate the ability of Snowball planets to escape from glaciation by accumulating enough gaseous CO_2.

RESULTS

We find that Earth-like planets orbiting a Sun-like star may never be able to escape from glaciation, if their orbital distance is > 1.27 AU (62 % of the Solar constant) because CO_2 would condense at the poles (cold traps), forming permanent CO_2 ice caps. For planets with a significant water ice cover, we find that CO_2 ice deposits (1.6 x denser than H_2O) should be gravitationally unstable and get buried beneath the water ice cover in geologically short timescale. This would considerably increase the amount of CO_2 trapped and further reduce the probability of deglaciation.

I. When glaciation escape fails

We find that, depending on the CO_2 partial pressure and the stellar flux, the climate simulations of frozen planets can evolve in 3 different climate regimes, each being depicted in the diagram (on right):

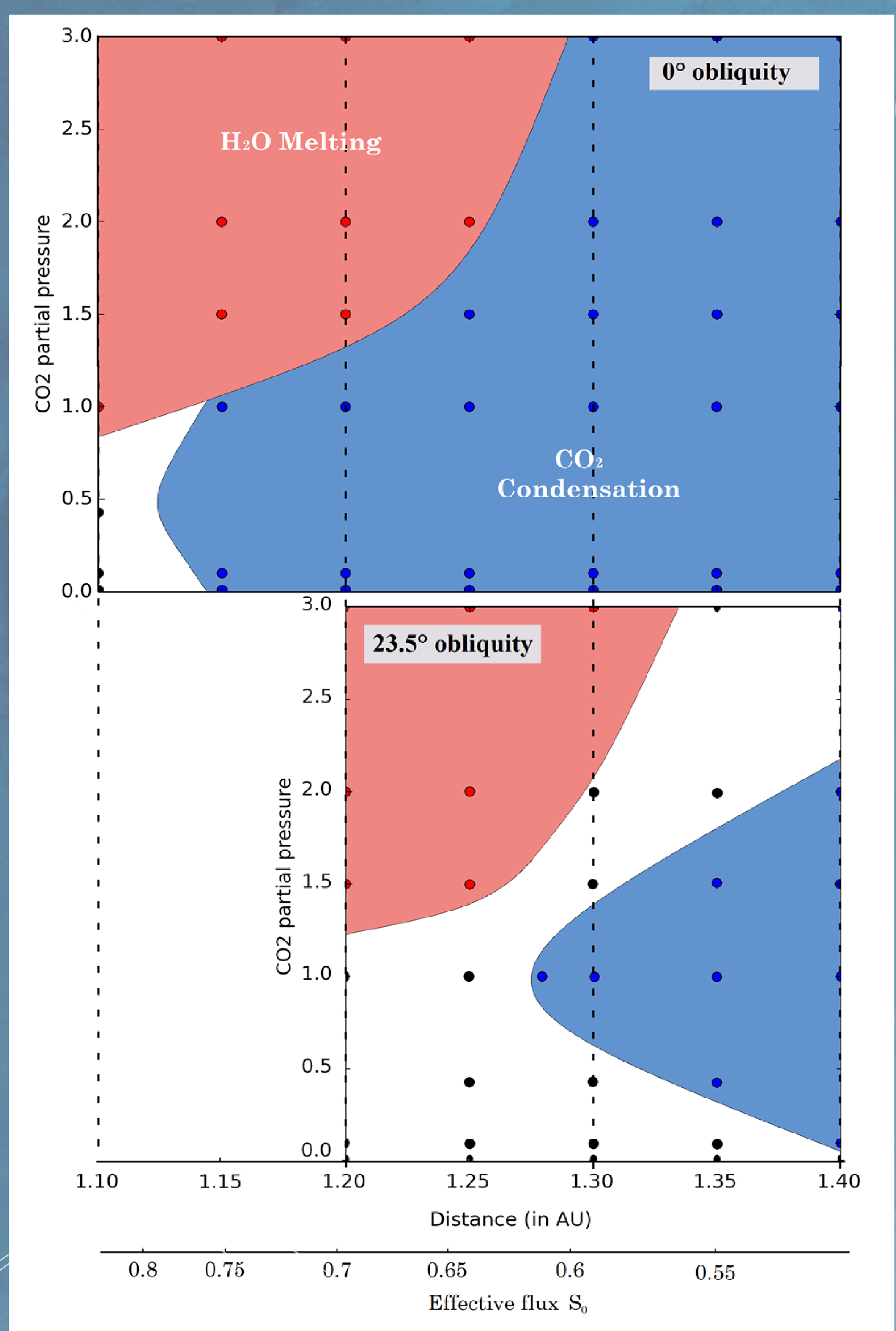
1. In ***red***, the planet is partially or totally deglaciated.
2. In ***white***, the planet is entirely frozen.
3. In ***blue***, the planet is entirely frozen and gaseous CO_2 has permanently collapsed at the poles. This occurs when winter CO_2 frost formation rate exceeds CO_2 ice summer sublimation.

In the context of an active carbonate-silicate cycle :

A Snowball planet has initially a low CO_2 atmospheric content. It lies in the lower part of the diagram. As CO_2 is outgassed by volcanoes and accumulates in the atmosphere, the CO_2 partial pressure increases and the planet moves up in the diagram until:

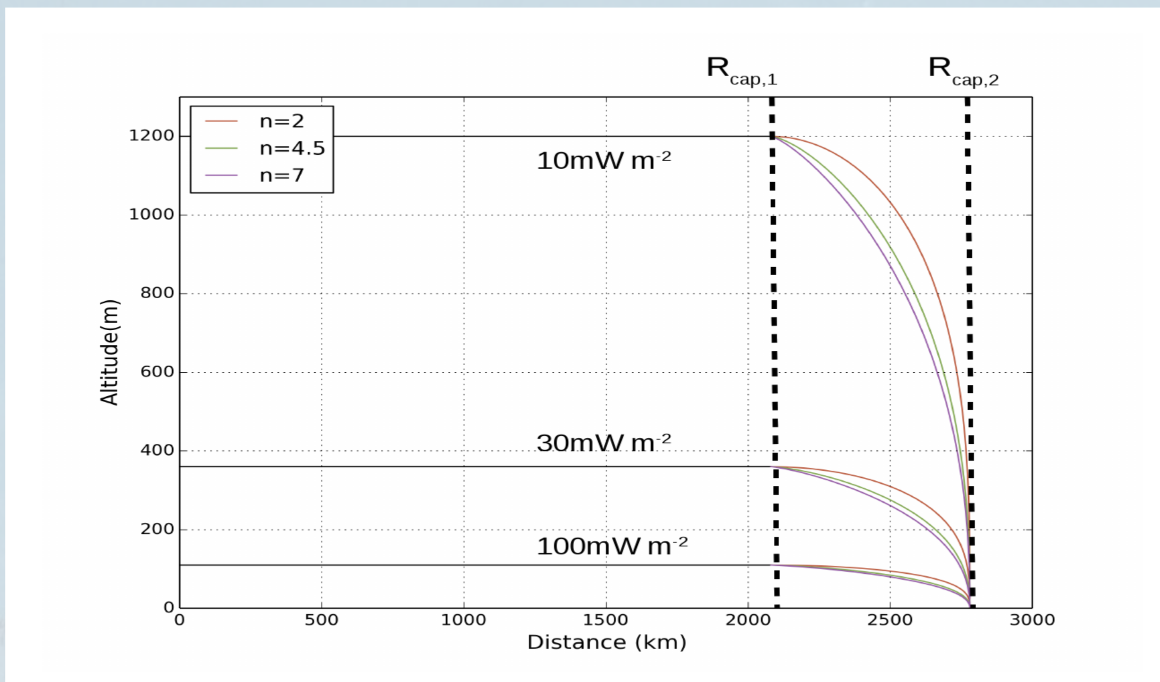
1. the planet reaches the ***red*** zone first. The planet is able to escape glaciation.
2. the planet reaches the ***blue*** zone first. All the extra CO_2 possibly outgassed by volcanoes condenses at the poles and the planet is locked in a perpetual glaciation state.

For an obliquity of 0° (resp. 23.5°), we find that this limit occurs for planets located at more than d_{cond}=1.13 AU (resp. 1.27 AU) from a Sun-like star.



II. Maximum thickness of CO_2 ice caps

At first sight, the main limit of the trapping of CO_2 as ice instead of greenhouse gas is the size of the solid CO_2 reservoirs. As CO_2 is outgassed by volcanoes, the size of CO_2 polar caps grows, forming glaciers that can flow efficiently toward equatorial regions, get sublimated and reinjected in the atmosphere. The maximum size of the CO_2 polar ice caps is controlled by 1) sliding (through basal melting) or 2) flowing. We simulate both processes and find, after integration of steady state CO_2 ice radial profiles (see below), that the maximum amount of CO_2 ice that can be stored in the two polar caps (distance=1.3 AU, obliquity=23.5°) for geothermal heat fluxes of 100/30/10 mW m-2 is approximately **1.5/4.5/15 bars**.



CO_2 ice glacier radial profiles, for different flow laws and geothermal heat fluxes

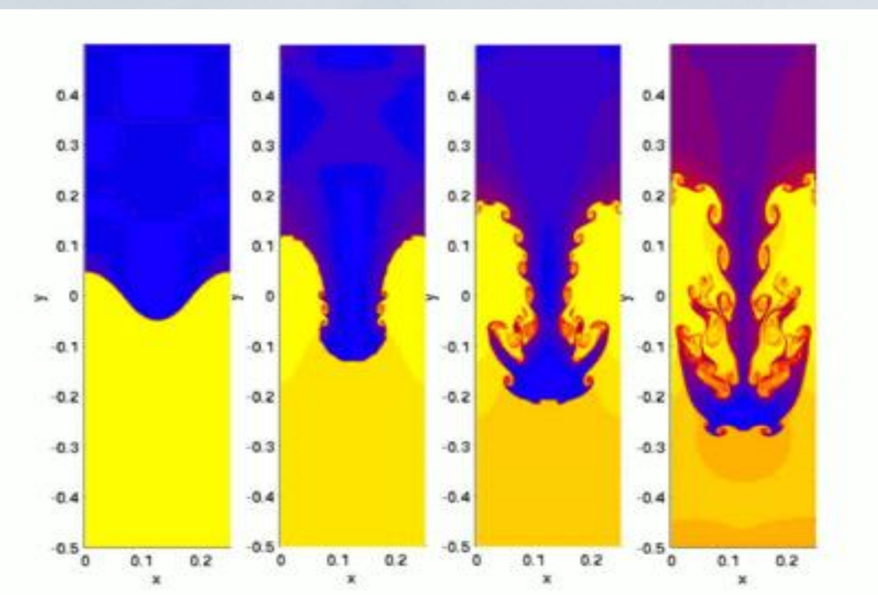
III. Gravitational unstability and CO_2 sequestration

REMINDER : density of CO_2 ice (d=1.5) >> density of water ice (d=0.93 at 200-220 K)

The CO_2 ice deposits are gravitationally unstable and should get burried at the base of the H_2O ice layer. The density contrast should initiate **Rayleigh-Taylor instabilities** at a timescale τ_{RT} roughly equal to (Turcotte & Schubert 2001) :

$$\rightarrow \tau_{RT} = 13\ \eta\ /\ (\Delta\rho g b) \sim 7\times10^3\ \text{yr} \times (\eta/10^{16}\ \text{Pa.s})$$

with $\eta_{water-ice}$~10^{15}-10^{16} Pa s, $\Delta\rho$ the density contrast and b the characteristic size of the domain



Rayleigh-Taylor instability

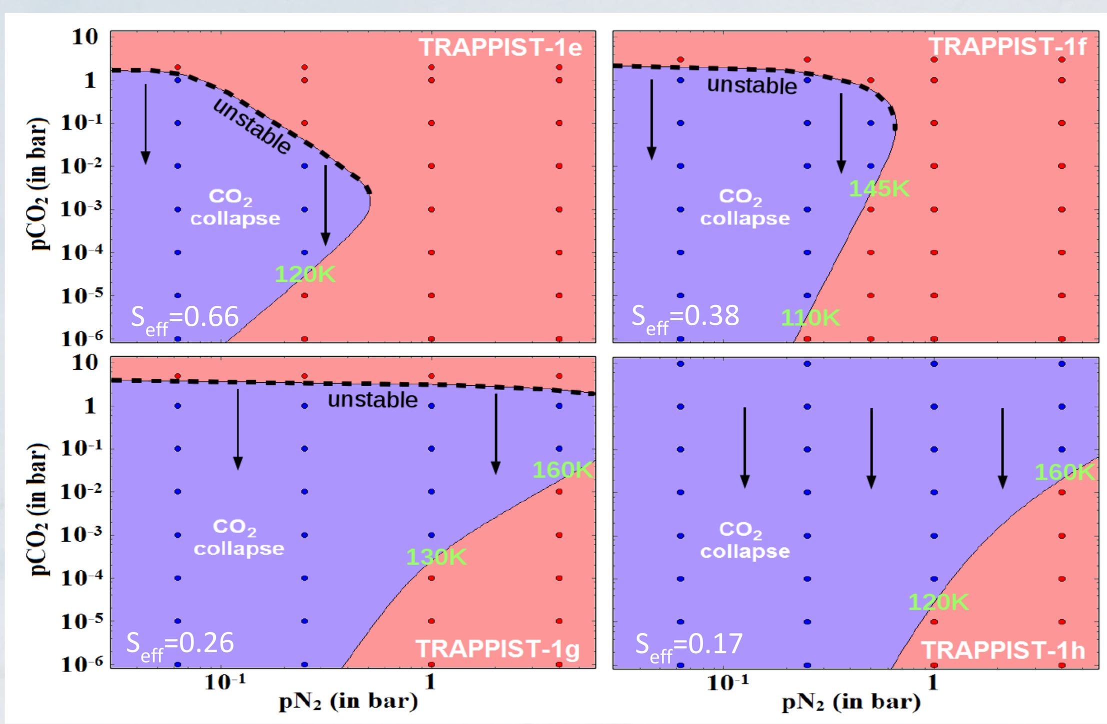
Once gravitationally destabilized, the CO_2 ice would sink toward the base of the water ice shell at a rate determined by the Stokes velocity U_s (Ziethe & Spohn, 2007):

$$\rightarrow U_s = 2\ \Delta\rho g\ (r^2/\eta) \sim 10\ \text{cm/yr}$$
(or 1km/10^4yrs) for a 100-m diapir.

Depending on internal heat flux/water content, CO_2 could be melted /could interact with H_2O to form clathrate hydrate, and potentially be trapped permanently …

IV. CO_2 condensation on tidally locked planets

Planets orbiting in the Habitable Zone of low mass stars are subject to tidal locking. The surface temperature of the nightside of a synchronously rotating planet can be extremely low, favoring the condensation of CO_2. We explored this possibility for the recently discovered TRAPPIST-1 planets (Gillon et al. 2017) and show that the 4 outer planets of the system are highly sensitive to CO_2 atmospheric collapse, for a wide range of background gas atmospheric pressures (see diagram below). In ***blue***, CO_2 has permanently collapsed on the nightside. In ***red***, CO_2 is stable in the atmosphere. If the planet initially starts with a thick CO_2 atmosphere (e.g. 10 bars), the greenhouse effect and the heat redistribution are efficient enough for such atmosphere to be stable (*red color*).



Conversely, if the planet initially starts with a low CO_2 atmospheric content or no CO_2 at all and progressively accumulates somehow additional CO_2 in the atmosphere (e.g. by volcanic outgassing), all the extra CO_2 should keep condensing on the nightside (*blue color*). The planet would thus be permanently locked with a cold, thin CO_2 atmosphere.

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More details can be found in :

1) Turbet et al. 2017, EPSL vol. 476.
2) Turbet et al. 2017, submitted to A&A [arXiv 1707.06927].