It is widely considered that the carbonate–silicate cycle is the main agent – through volcanism - to trigger deglaciation by CO₂ greenhouse warming on Earth and by extension on Earth-like planets when they get in frozen state.

We use the LMD 3D Global Climate Model – with both CO₂ and water cycles - to simulate the ability of Snowball planets to escape from glaciation by accumulating enough gaseous CO₂.

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 CO₂ would condense at the poles (cold traps), forming permanent CO₂ ice caps. For planets with a significant water ice cover, we find that CO₂ ice deposits (1.6 x denser than H₂O) should be gravitationally unstable and get buried beneath the water ice cover in geologically short timescale. This would considerably increase the amount of CO₂ trapped and further reduce the probability of deglaciation.

I. When glaciation escape fails

We find that, depending on the CO₂ 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 blue, the planet is entirely frozen.
3. In blue, the planet is entirely frozen and gaseous CO₂ has permanently collapsed at the poles. This occurs when winter CO₂ frost formation rate exceeds CO₂ ice summer sublimation.

In the context of an active carbonate-silicate cycle:

A Snowball planet has initially a low CO₂ atmospheric content. It lies in the lower part of the diagram. As CO₂ is outgassed by volcanoes and accumulates in the atmosphere, the CO₂ 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 CO₂ possibly outgassed by volcanoes condenses at the poles and the planet is locked in a perpetual glaciation state.

For an equilibrium at 0°C (resp. 23.5°C), we find that this limit occurs for planets located at more than 1.13 AU (resp. 1.27 AU) from a Sun-like star.

II. Maximum thickness of CO₂ ice caps

At first sight, the main limit of the trapping of CO₂ as ice instead of greenhouse gas is the size of the solid CO₂ reservoirs. As CO₂ is outgassed by volcanoes, the size of CO₂ polar caps grows, forming glaciers that can flow efficiently toward equatorial regions, get sublimated and re injected in the atmosphere. The maximum size of the CO₂ polar ice cap is controlled by 3) sliding (through basal melting) or 2) flowing. We simulate both processes and find, after integration of steady state CO₂ ice radial profiles (see below), that the maximum amount of CO₂ 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.

III. Gravitational instability and CO₂ sequestration

Gravitational instabilities can occur in all CO₂ ice sheets. This is the case when the CO₂ ice sheet is destabilized by convective instabilities. Depending on internal heat flux/water content, CO₂ could be melted/ Led to form clathrate hydrate, and potentially be trapped permanently ...

IV. CO₂ 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 CO₂. We explored this possibility for the recently discovered TRAPPIST-3 planets (Gillon et al. 2017) and show that the 4 outer planets of the system are highly sensitive to CO₂ atmospheric collapse, for a wide range of background gas atmospheric pressures (see diagram below). In blue, CO₂ has permanently collapsed on the nightside. In red, CO₂ is stable in the atmosphere. If the planet initially starts with a thick CO₂ 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 CO₂ atmospheric content or no CO₂ at all and progressively accumulates additional CO₂ in the atmosphere (e.g. by volcanic outgassing), all the extra CO₂ should keep condensing on the nightside (blue color). The planet would thus be permanently locked with a cold, thin CO₂ atmosphere.

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More details can be found in :