EPSC Abstracts
Vol. 11, EPSC2017-313, 2017
European Planetary Science Congress 2017

CO_2 condensation can seriously limit the deglaciation of Earth-like planets

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Context

It is widely believed that the carbonate silicate cycle [1,2,3] is the main agent (through volcanism, and when weathering ceases) 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 a 3D Global Climate Model (the LMD Generic Model) to simulate the ability of planets initially completely frozen to escape from glaciation episodes by accumulating enough gaseous CO_2 [4]. The model includes CO_2 condensation and sublimation processes and the full water cycle.

Results

We find that initially completely frozen planets that accumulate CO_2 through volcanism can evolve in three different climate regimes:

1) The greenhouse effect of CO_2 is too weak to trigger a deglaciation. The planet stays in a snowball state but keep accumulating CO_2 in the atmosphere.

2) The greenhouse effect of CO_2 is sufficient to raise the surface temperatures in equatorial regions above the melting temperature of water ice. The planet escape from glaciation.

3) The greenhouse effect of CO_2 is too weak to raise the surface temperatures of the poles above the condensation temperature of CO_2 . In this case, the gaseous CO_2 collapses and the planet is locked in a global glaciated state, with two permanent CO_2 polar ice caps.

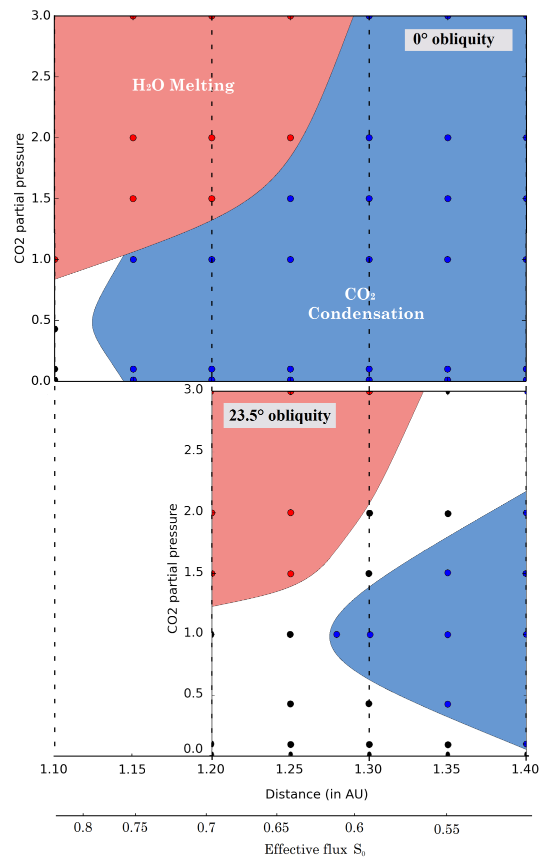

Figure 1: Climate regimes reached as function of the equivalent distance from a Sun-like star (in AU) and the CO_2 partial pressure, assuming a cold start (i.e. snowball state without permanent CO_2 ice deposits). Figures correspond to Earth-like planets with 0° (top panel) obliquity or 23.5° obliquity (bottom panel). The red color roughly 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.

Quantitatively, and as illustrated on Fig. 1, we find that planets with Earth-like characteristics (size, mass, obliquity, rotation rate, ...) orbiting a Sun-like star may never be able to escape from a glaciation era if their orbital distance is greater than ∼ 1.27 Astronomical Units (Flux < 847 W m^{-2} , S_{eff} < 0.62), because CO_2 would condense at the poles – here the cold traps – forming permanent CO_2 ice caps. This limits the amount of CO_2 in the atmosphere and thus its greenhouse effect.

Furthermore, our results indicate that for (1) high planetary rotation rates ($P_{rotation}$ < 24 h), (2) low obliquity (< 23.5°), (3) low background gas partial pressures (< 1bar), and (4) high water ice albedo (> 0.6), the CO_2 polar condensation could occur for significantly lower orbital distance.

For each possible configuration, we show that the amount of CO_2 that can be trapped in the polar caps depends on the efficiency of CO_2 ice to flow laterally as well as its gravitational stability relative to subsurface water ice. The flow of CO_2 ice from polar regions to the equator is mostly controlled by the bottom glacier temperature, and hence by the internal heat flux of the planet. We find that a frozen Earth-like planet located at 1.30 AU of a Sun-like star could store as much as 1.5/4.5/15 bars of dry ice at the poles, for internal heat fluxes of 100/30/10 mW m^{-2}.

But these amounts are in fact lower limits. For planets with a significant water ice cover, we show that CO_2 ice deposits should be gravitationally unstable. They get buried beneath the water ice cover in very short timescales of 10^2-10^3 yrs, mainly controlled by the viscosity of water ice. For water ice cover exceeding ~ 300 meters (or geothermal heat flux lower than ~ 0.4 W m^{-2}, respectively), we show that the CO_2 would 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.

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