CLIMATE OPTIMUM ON MARS INITIATED BY ATMOSPHERIC COLLAPSE?
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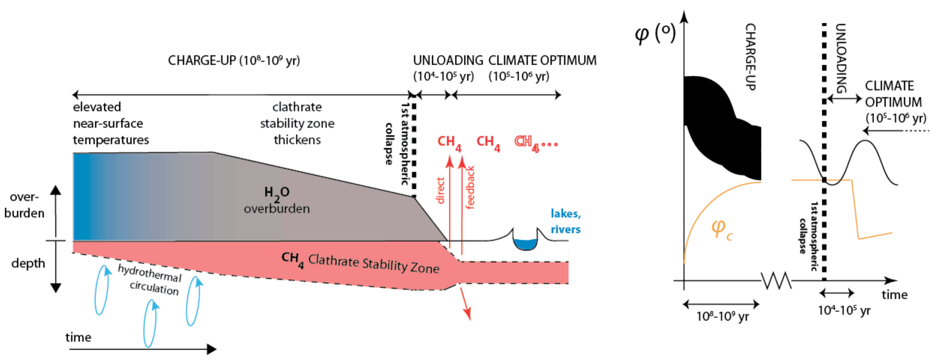
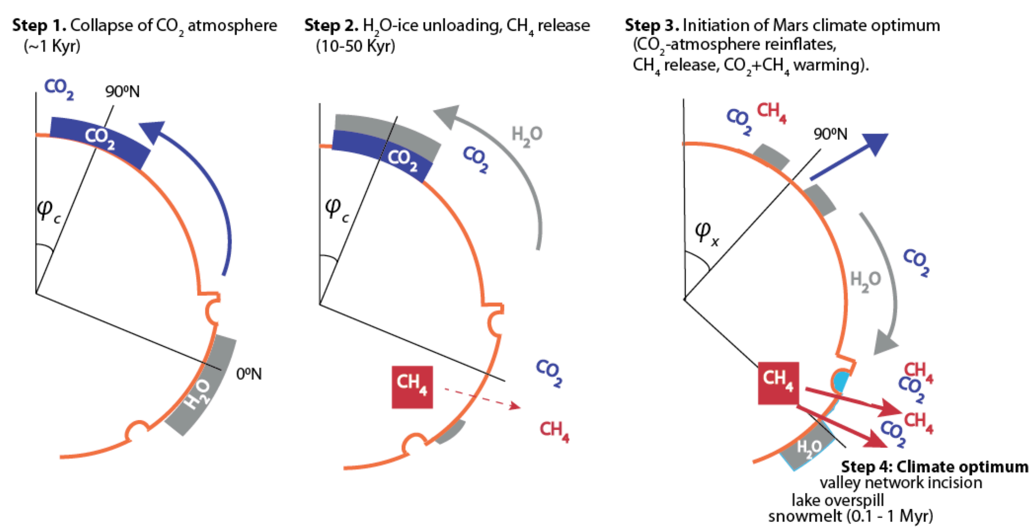
Introduction: The progressive drying-out of Mars' surface was punctuated by a dramatic transient increase in fluvial erosion around the Noachian-Hesperian boundary [1]. Standard explanations of this climate optimum appeal to volcano- or impact-triggered climates and imply that individual runoff episodes were brief, apparently inconsistent with evidence for persistent runoff. We examine a scenario in which the duration, intensity and uniqueness of the Noachian-Hesperian climate optimum result from degassing of CH_4-clathrate consequent to Mars' first atmospheric collapse. Atmospheric collapse causes low-latitude surface H_2O-ice to sublimate , depressurizing and destabilizing CH_4 clathrate in subglacial pore space. Subsequent atmospheric re-inflation leads to further warming and further destabilizes CH_4-clathrate. CH_4-induced warming is efficient, permitting strong positive feedbacks, and possibly raising Mars into a climate optimum. The optimum is brought to a close by photolysis of CH_4, and drawdown of the clathrate reservoir prevents recurrence. This scenario predicts a 10^5-10^6 yr climate optimum, transient connections between the deep hydrosphere and the surface, and strong surface weathering, all of which are consistent with recent observations. Crustal hydrothermal circulation very early in Mars history could yield CH_4 that would be incorporated into clathrate on approach to the cold surface. The scenario explains why regional watershed integration on Mars occurred relatively late and only once, and suggests that the contrasts between Noachian versus Hesperian climate-sensitive deposits on Mars correspond to a transition from a never-collapsed atmosphere to a collapse-prone climate, ultimately driven by slow loss of CO_2 to space.



(a)



(b)

Figure 1. Overview of proposed scenario. (a) *Left*: schematic of the long-term evolution of a column of the Mars highlands. *Right*: obliquity diffusion and slow CO_2 loss lead to polar temperatures dropping below a pressure-dependent critical value for atmospheric collapse initiation, φ_c. (b) Below φ_c, >90% of the atmosphere will condense in 1-10 Kyr (step 1). This unloads high ground (step 2), releasing CH_4 from sub-ice clathrate. Reinflation of the atmosphere leads to climate optimum (steps 3-4).

Overview of the climate optimum scenario.

Step 1. Collapse of an initially-thick CO_2 atmosphere. As Mars' atmosphere is thinned by escape-to-space and carbonate formation, the remaining atmospheric CO_2 becomes increasingly vulnerable to collapse. Collapse is triggered if polar CO_2-ice caps grow from year to year. Cap growth occurs below a critical polar temperature. Polar temperature is set by insolation, which increases with obliquity, and by heating from the CO_2 atmosphere (both the greenhouse effect, and equator-to-pole heat transport, increase with atmospheric pressure). Given secular atmospheric-pressure decline, obliquity variations will eventually lower insolation below the threshold for perennial CO_2-ice caps. Once nucleated, caps grow in <10^4 yrs [2] and typically sequester >90% of the planets' CO_2. Post-collapse pCO_2 is in equilibrium with polar-CO_2-ice-cap surface temperature. Cap thickness is ~1200 m/bar CO_2 . Atmospheric collapse involves a hysteresis, but obliquity rise will eventually trigger rapid re-sublimation of CO_2. Cooling of the surface due to loss of the greenhouse effect helps to stabilize CH_4-clathrate, outweighing the destabilizing effect of loss of the weight of the atmosphere. Cold post-collapse conditions are unfavorable for liquid water.

Step 2: H_2O-ice unloading of low latitudes triggers CH_4 release. Following Mars' first-ever atmospheric collapse, the atmosphere can longer provide much heat to the poles; these are now the stable location for H_2O ice. H_2O ice condenses at the poles, and sublimates away from low-latitude highlands for the first time in Mars history. The low-latitude ice sublimates in <10^5 yr (the scenario assumes a net rate of ~10 mm/yr; e.g. [3]). On this timescale H_2O-ice glacial flow is negligible [3]. This latitudinal shift in ice overburden is the first such shift in Mars history, and (in the collapse trigger scenario) it has an effect on CH_4 -clathrate decomposition that is unsurpassed. Unloading of the highlands due to removal of H_2O-ice causes irreversible decomposition of sub-ice within-regolith pore-space CH_4 clathrate. The corresponding CH_4(g) release can be very large. The clathrate is charged up with CH_4 produced by water-rock reactions over >10^8 yr. It is released in <10^3 yr. Once in the atosphere CH_4 is photolyzed at a rate of 0.1 mbar/Kyr [4]. CH_4 is ineffective at warming Mars at this stage because CH_4's principal greenhouse band at 7.7 μm is mismatched with the cold-Mars Planck function, and CH_4-CO_2 Collision-Induced Absorption (CIA) is also ineffective because the collapsed-atmosphere pCO_2 is low [5]. The collapsed-atmosphere CH_4/CO_2 ratio may exceed the threshold for forming haze, which will scatter sunlight and further suppress temperatures.

Step 3. CO_2-atmosphere reinflation and further CH_4 *release.* Mars's first atmospheric collapse occurs at the bottom of a (20° amplitude) quasi-periodic obliquity cycle. As the obliquity cycle continues, pCO_2 initially rises in vapor-pressure equilibrium with polar temperature, and with most CO_2 sequestered in ice. pCO_2 rises in equilibrium with CO_2-ice temperature because, although stiff H_2O-ice may enshroud the CO_2-ice, flow of thick, soft CO_2-ice opens crevasses. When obliquity rises to the point where no value of pressure yields a polar temperature below the condensation point, the remaining polar CO_2 -ice caps rapidly (10^3 year) and completely sublimate. Because the duration of quasi-periodic orbital cycles is known for the post-4.0 Ga solar system, the time between Mars' first atmospheric collapse and reinflation is 1-5 × 10^4 yr for reasonable parameter choices. Loss of H_2O-ice overburden exposes clathrate to the CO_2 -greenhouse warming associated with reinflation, and clathrate irreversibly decomposes, releasing CH_4. The wait time for CH_4 clathrate decomposition is (reinflation time + subsurface conductive-warming time + decomposition time) = (10^3 yr + ~10^2 yr + <10 yr) = 10^3 yr. This is much quicker than the 10^4-10^5 yr needed for H_2O ice to return to the low latitudes. In the simulations, the amount of CH_4 released at this point is larger than in Step 2. For methane clathrate stability zone occupancy fractions larger than a few percent, the atmosphere now contains abundant CO_2, with 1-5% CH_4. These are ideal conditions for strong CH_4-CO_2 CIA warming [5].

Step 4. CH_4+CO_2 = Mars climate optimum. The cocktail of circumstances enabled by Mars' first atmospheric collapse (a massive CH_4 pulse, a thick CO_2 atmosphere, low-latitude water ice) now permits low-latitude rivers and lakes. H_2O snow falling on the equator (plus any H_2O ice that did not have time to sublimate) encounters high insolation and high greenhouse forcing. Seasonal snowmelt runoff forms valleys that drain into perennial ice-covered lakes, which overspill to form valley networks. High lake-bottom temperatures destabilize sub-lake methane clathrates. CH_4-induced warming is strong to destabilize additional CH_4 in the regolith (and under some circumstances this positive feedback can produce a runaway).

Step 5. CH_4 loss shuts down of wet climate in 10^5-10^6 yr. The wet climate ends when atmospheric CH_4 is photolyzed. So long as CH_4-induced warming persists, atmospheric re-collapse is unlikely. As CH_4 is destroyed without resupply, eventually the rivers dry up. Wet conditions persist for 10^5-10^6 yr, consistent with geomorphic estimates of the number of wet years needed to form the VNs and reconciling the geomorphic data with mineralogic upper limits on the interval of surface liquid water (e.g., Ref. 6).

Possible tests will be discussed at the conference.

Acknowledgements. C. Goldblatt, R. Wordsworth, F. Forget, A. Howard, R. Irwin, and A. Soto.

References. (Many excellent references omitted due to space constraints). [1] Irwin et al., JGR 2005. [2] Soto et al., Icarus 2015. [3] Fastook & Head, P&SS 2015. [4] Kite et al. arXiv:1611.01717. [5] Wordsworth et al. arXiv:1610.09697. [6] Olsen & Rimstidt, Am. Min. 2007.