Seasonal and Perennial Carbon Dioxide Deposits on Mars in the Early Amazonian

M. A. Kreslavsky, *Earth and Planetary Sciences, University of California – Santa Cruz, Santa Cruz, California, USA (mkreslav@ucsc.edu).*

Introduction:

Although the nature of martian past climate is a topic of ongoing debates, there is a firm consensus that for most of the Amazonian period the climate system was "more or less like now", except perhaps for several spatially and/or temporarily localized episodes. [e.g. Wordsworth 2016 and references therein]. Currently, Mars has a thin CO_2-dominated atmosphere, a substantial part of which condenses in winter and sublimates in summer forming seasonal deposits of solid CO_2.

Being "more or less like now", the martian climate is nonetheless changing significantly in response to variations in spin and orbit parameters. In addition, loss of volatiles to space or to the crust (conversion of CO_2 to carbonates) has outpaced the replenishment of volatiles through volcanic degassing and meteoroid impacts suggesting much larger volatile inventory in the past. In this presentation I provide an overview of how climate – and especially the CO_2 cycle – could have looked in the Early Amazonian, given all the possible variability. Recently, Watanabe et al. [2024] addressed this problem, however, that work focused on entirely different aspects of it.

Conditions in the Ealy Amazonian.

Climate is driven by the insolation regime, which is controlled by three changing spin / orbit parameters: obliquity θ of spin axis with respect to the orbital plane, orbit eccentricity e, and season of perihelion quantified as areocentric longitude of the Sun at the perihelion L_P. Due to the dynamic chaos in the Solar System changes of these parameters cannot be accurately calculated more than ~5 Ma back in time [Laskar et al. 2004]; however, it is understood that θ varies between ~10° and ~60°, e varies between ~0 and ~0.15, and L_P is uniformly distributed. There are no indications that the semimajor axis of martian orbit could change during the Amazonian, although some exotic scenarios changing it cannot be completely excluded; I assume here that the semimajor axis did not change.

The Sun was dimmer in the past; it brightened approximately linearly with time from ~75% of the present-day luminosity at the beginning of the Amazonian. Presently, solar energy flux is very stable with variations well below 0.1%. In the Hesperian and Early Amazonian, when solar spin rate was higher, variations at ~1% level through the solar cycle and at ~1% level due to large solar spots are possible. Thus, the expected level of Sun variability is small in comparison to systematically lower luminosity in the past and cannot temporarily offset its effects.

Toy model:

To assess the nature of the CO_2 cycle I used simple physical considerations and a toy model of CO_2 condensation and sublimation. The model includes the energy balance of incoming solar irradiation, outgoing thermal radiation, and latent heat of CO_2 phase transition. The model parameters (albedo and emissivity of solid CO_2 and simple parameterization of scattered light) were tuned to quantitatively reproduce the observed pressure cycle on Mars under the present-day conditions. The model can account for topographic roughness by introducing slope distributions of tilted surface facets. It is somewhat similar to the model of [Bierson et al. 2016]. The model was successfully applied in [Kreslavsky & Head 2005] to study atmospheric collapse at low obliquity in the recent past. The model is certainly oversimplified, and there is no hope for quantitatively accurate results, however, it helps to understand the nature of the processes and their dependence on a variety of parameters, because its computational efficiency enables extensive exploration of the parameter space. All calculations reported here are performed for 75% solar luminosity.

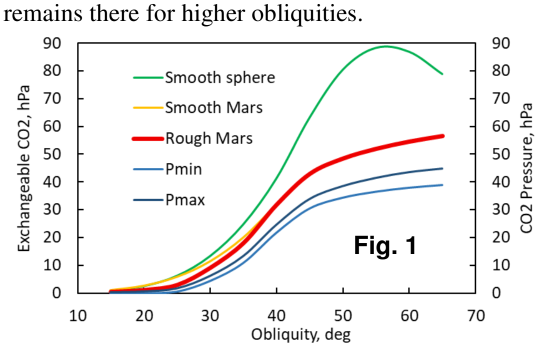
Atmospheric collapse and perennial carbon dioxide deposits

Accurate calculations with detailed global climate models have shown that thick CO_2 atmosphere cannot provide sufficiently strong greenhouse effect and sufficiently intensive latitudinal mixing to prevent CO_2 condensation in winter at high latitudes [e.g. Wordsworth 2016 and references therein]. Condensation can potentially lead to atmospheric collapse, if CO_2 amount condensed during a colder season exceeds its amount that can sublimate during a warmer season: solid CO_2 will be accumulated year by year, until the pressure – and therefore condensation rate – falls below a certain threshold.

This threshold strongly depends on obliquity. The toy model results illustrating this dependence are shown in **Fig. 1**. They are obtained for 75% solar luminosity and zero eccentricity. It is instructive to start with an ideal model of smooth sphere without elevation differences. The uppermost **green** curve in **Fig. 1** shows the collapse-threshold CO_2 inventory expressed as effective pressure. It increases from nearly complete collapse at 15° obliquity to a maximum at ~55°. For obliquity below ~40°, perennial CO_2 deposits form at both poles. For higher obliquities, the placement of perennial deposits shifts toward lower latitudes reaching ~35° latitude at 55° obliquity and ~10° latitude at 65°, the maximum probable obliquity.

For a more realistic model with topography and topographic roughness (**red bold** curve in **Fig. 1**), the threshold is lower than for the smooth sphere on two reasons. First, at lower obliquities (<~35°) pole-facing slopes at high latitudes are more effective cold traps than the poles themselves [Kreslavsky and Head, 2005], which reduces the collapse threshold. In Fig. 1, this is illustrated with the **orange** curve, which shows the model results without topographic roughness and therefore without slope-related cold traps. Second, higher pressure at lower elevations makes condensation more effective, which lowers the threshold, especially for high obliquities.

At the lowest obliquities perennial deposits form at the North pole (which lies at a much lower elevation than the South pole). From ~25° obliquity the locus of perennial deposits shifts southward through the lowermost region of Vastitas Borealis toward northern Acidalia Planitia. At ~45° obliquity the locus of perennial CO_2 deposition switches to Hellas Planitia – the lowermost region of Mars – and remains there for higher obliquities.



Since part of the exchangeable CO_2 inventory is always present in a condensed form of seasonal deposits, the atmospheric pressure is always lower than the exchangeable inventory. A pair of **blue** curves in **Fig. 1** show year-maximum and year-minimum pressure at the mean surface elevation at the threshold CO_2 inventory. According to the model, at high obliquities, the modeled pressure may exceed 40 hPa (1 hPa = 1 mbar), ~7 times higher than the present-day pressure. At such pressure the toy model is a far extrapolation; omission of important atmospheric physics means that the estimates of absolute pressure values are unreliable. However, the overall nature of the dependence on obliquity is likely correctly predicted, as well as locations of perennial deposits, which are directly controlled by the insolation pattern. For the present-day Sun the calculated threshold pressure is too high, and the model is certainly not applicable.

Eccentricity and season of perihelion have little effect on the atmospheric collapse threshold. This modeling result is reasonable because the total annual solar irradiation energy at a given latitude on smooth planet does not depend on eccentricity. For the smooth sphere model, second-order nonlinear effects make the hemisphere of warmer summer and longer winter preferable for CO_2 perennial deposition. For the present-day season of perihelion, this would be the Southern hemisphere. However, for real Mars, the effect of topography supersedes the effect of eccentricity.

Under dim early Sun, CO_2 transport through the atmosphere is rather sluggish. I used the model to figure out how fast CO_2 deposits can migrate from Hellas to Vastitas Borealis and back. When obliquity changes from 50° to 40°, the model predicted thinning Hellas deposits by ~10 cm per (Earth) year. The putative Noachian ~1 bar of CO_2 deposited in Hellas makes ~1.6 km-thick solid CO_2 layer. It would take ~16 kyr (1 kyr = 1000 Earth years) to transfer it with the rate given by the model. Obliquity chaotically oscillates with a characteristic period of ~ 100 kyr, that is the characteristic time scale of obliquity change is the same as the time scale of solid CO_2 transport. This means that the deposits do not follow the obliquity and their distribution and transport are complicated. Due to the confined, highly localized nature of Hellas basin and the much wider unconfined Vastitas Borealis, transport in the opposite direction – toward Hellas – is more effective. As a result, when obliquity oscillates around 45°, the majority of CO_2 would remain in Hellas.

Implications for carbon sequestration.

Obliquity in the Early Amazonian cannot be predicted; however, Laskar's [2004] calculations show that persistence of obliquity above 40° for tens to hundreds of Myr is rather probable. If this indeed occurred, almost all the hypothesized large inventory of CO_2 on early Mars would have ended up in a thick deposit of solid CO_2 in Hellas. It is reasonable to expect a high (compared to the present day) geothermal flux on Mars in the Early Amazonian; in Hellas the flux could be even higher due to residual heat from the Hellas impact. For our order-of-magnitude estimates I use 80 mW m^{-2}. Under such a flux, basal melting would begin at a thickness of ~350 m of pure solid CO_2. Basal melting would cause a range of intensive and complex processes and phenomena (such as cryovolcanism) that are difficult to predict in detail. One inevitable outcome is the percolation of liquid CO_2 down into the crustal pore space. Percolating liquid CO_2 would reach deep aquifers, dissolve in groundwater, and interact with ambient rocks to form carbonates.

Surface of solid CO_2 deposits is a cold trap for water vapor. This likely would lead to the admixture of H_2O ice into perennial CO_2 deposits, possibly, in large amounts. In an H_2O-dominated CO_2 – H_2O ice mixture, CO_2 melting would occur at a depth of ~1.8 km. Formation of clathrate hydrates in thick CO_2 –

H_2O ice mixture layers is plausible; a high clathrate hydrate concentration would reduce thermal conductivity and, therefore, lower the depth to the melting horizon. Possible effects of CO_2 melting in the presence of H_2O ice are even more interesting, complicated, and difficult to accurately predict. However, the higher density of liquid CO_2 relative to H_2O ice or an ice + clathrate mixture favors percolation downward and disfavors cryovolcanism, thus making eventual percolation into crustal pore space even more plausible.

This scenario is a new possibility to solve the problem of missing carbonates on Mars: the total inventory of carbonates in sedimentary rocks observed spectrally at the surface is well below the amount that would be produced from the putative massive Noachian atmosphere. Under this scenario the missing carbonates are hidden deep in the upper crust below the Hellas basin. The peculiar deep bowl-shaped Hellas topography plays a key role in this scenario. A similar scenario would be less plausible for perennial CO_2 deposits in the northern plains: the absence of lateral confinement would enable lateral escape of liquid CO_2 and further evaporation; the absence of confinement would also increase the area of the deposit and decrease its thickness, which may prevent basal melting; geothermal flux would likely be lower, etc.

Seasonal carbon dioxide deposits.

When obliquity is moderately low and / or the atmosphere is thin, the seasonal CO_2 cycle is generally similar to the present day: seasonal frost condenses in the polar areas in the autumn and early winter and sublimates in spring and summer.

Of course, wintertime condensation and summertime sublimation occur for a thick atmosphere and high obliquity too, however, the cycle has less similarity to the present-day pattern. **Fig. 2** shows snapshots of the seasonal frost thickness map in the simple cylindrical projection cut at 180° longitude. The frost thickness (assuming a solid layer) was calculated with the toy model for obliquity $\theta = 55°$, eccentricity $e = 0.12$, perihelion at the northern winter solstice ($L_P = 270°$), and an accessible CO_2 amount equivalent to 62 hPa – very close to the perennial deposit formation threshold for this obliquity, just below the red curve in Fig. 1. Almost the same seasonal CO_2 cycle is expected in the presence of perennial deposits in Hellas. Values of L_S, the areocentric longitude of the Sun, quantify the season in Fig. 2; $L_S = 0$ corresponds to the northern spring equinox.

While under a thin atmosphere, seasonal frost appear only at high latitudes (at lower obliquity) and high- and midlatitudes (at higher obliquity), in the case shown in Fig. 2, seasonal frost periodically appears almost everywhere; the only exception is a relatively small area of the highest elevations in Tharsis Regio. In the equatorial zone the frost layer is always thinner than ~20 cm; it reaches ~1 m in the polar regions and in Hellas. Another difference is that the seasonal frost persists through a significant part of the year and disappears only for a relatively short period annually.

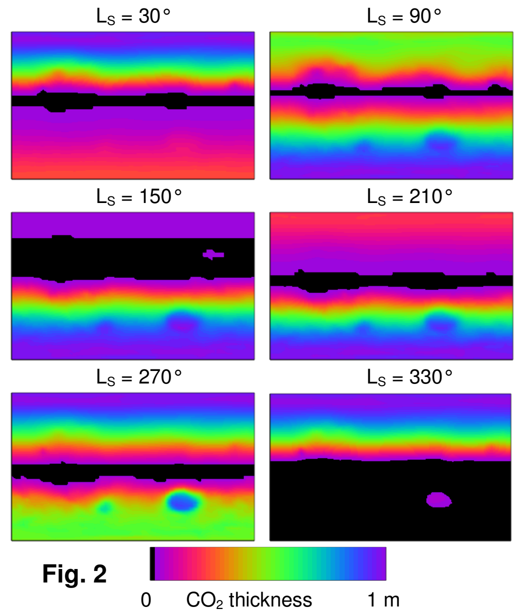


Fig. 2

Implications for Amazonian glaciation.

Extensive coverage with seasonal frost under high-obliquity thick-atmosphere conditions leads to suppression of water vapor transport by the atmosphere. The frost-covered surface maintained at frost temperature (~160 K for relevant pressure levels) plays the role of cold traps for H_2O vapor. The potential for water vapor transport is limited to high latitudes and short late summer seasons; it is inhibited in the equatorial zone. This situation substantially differs from the Late Amazonian, when high obliquity and increased atmospheric pressure favored water vapor transport and therefore glacial processes in the tropics. The difference is due to the proximity of the atmospheric conditions to the collapse threshold in the Early Amazonian, a result of the lower Sun luminosity. This contributes to the absence of observed glacial features of Early Amazonian age in the martian tropics.

References.

[Bierson et al. 2016] Stratigraphy and evolution of the buried CO2 deposit in the Martian south polar cap. https://doi.org/10.1002/2016GL068457

[Kreslavsky & Head 2005] Mars at very low obliquity: Atmospheric collapse and the fate of volatiles. https://doi.org/10.1029/2005GL022645

[Laskar et al. 2004] Long term evolution and chaotic diffusion of the insolation quantities of Mars https://doi.org/10.1016/j.icarus.2004.04.005

[Watanabe et al. 2024] Behaviors of Martian CO2-driven dry climate system and conditions for atmospheric collapses. https://arxiv.org/abs/2411.06871