Did Early Mars Self-Regulate As A Desert Planet? New Models Motivated By New Data From Mars Science Laboratory.

E. S. Kite[1], B. Tutolo,[2], M. L. Turner[1], H. B. Franz[3], D. G. Burtt[3], T. F. Bristow[4], W. W. Fischer[5], R. E. Milliken[6], A. A. Fraeman[7], & D. Y. Zhou[1]. 1. *University of Chicago, Chicago, IL, USA (kite@uchicago.edu).* 2. *University of Calgary, Alberta, Canada.* 3. *NASA Goddard Space Flight Center, Greenbelt, MD, USA.* 4. *NASA Ames Research Center, Moffett Field, CA, USA.* 5. *California Institute of Technology, Pasadena, CA, USA.* 6. *Brown University, Providence, RI, USA.* 7. *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.*

Summary: We present results from the first spatially-resolved multi-Gyr atmosphere evolution model for Mars [1]. Assuming that the newly discovered carbonate abundances from Gale crater [2] are globally representative, we model the time evolution of Mars' temperatures from 3.5 Ga onwards while accounting for chaotic orbital forcing, geography, carbonate formation, escape-to-space, and seasonal and diurnal temperature variations. With snowmelt assumed as the water source, this set-up results in intermittent warm episodes during favorable orbital conditions which increase the liquid water availability in oases on the surface. Sedimentary rock formation, which is jumpstarted by the liquid water availability, also results in drawdown of CO_2 from the atmosphere through sequestration as carbonate. This in turn cools the planet [3].

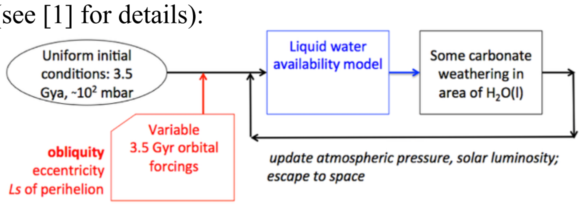
The model has several weaknesses, most importantly the greenhouse effect is over-simplified and does not include water ice cloud and other aerosol feedbacks.

What Caused Mars To Transition From A Climate With Surface Liquid Water To A Dry State?: In principle, Mars' environmental change from more-habitable in the past, to less habitable today (despite increasing solar luminosity), might have been caused by loss of CO_2, loss of non-CO_2 greenhouse agent [4], or loss of H_2O to space (e.g., [5]). In turn, loss of CO_2 could be caused by escape of CO_2 to space, or loss of CO_2 to the subsurface - for example, as carbonate minerals, which are the main store of C in Earth's lithosphere [6]. Carbonate formation has been previously suggested as a reason why Mars lost its habitability (e.g., [3]). Analysis of Mars' isotopic evolution suggests that carbonate formation was the main C loss channel [7-8]. Thus, voluminous carbonate-rich outcrops were expected (e.g., [9-10]). However, prior to 2024, neither global-scale orbital spectroscopy (e.g., [11-12]) nor site-specific initial rover exploration [13] found much carbonate.

The recent discovery of 5-11 wt% siderite (iron carbonate) in sedimentary rocks by the Mars Science Laboratory *Curiosity* rover at Gale crater [2], not anticipated from orbital data [14], has reopened the question of whether young sedimentary rocks were not just a witness, but also a cause, of early Mars' decline in habitability. The *Perseverance* rover at Jezero crater has also recently discovered abundant carbonates [15-16].

Young (post-3.5 Ga) sedimentary rocks are a voluminous (~2 × 10^6 km^3) reservoir, so assuming a density of ~2.5 g/cc and a Fe-carbonate content of 10 wt% leads to a potential drawdown from ~9× the present atmospheric thickness to the modern value. This is enough to make a big difference to evaporitic cooling [17-19] and therefore the likelihood that surface-exposed snow or ice will melt.

Model: The basic idea is shown in the panel below (see [1] for details):



This approach could be implemented using a more sophisticated liquid water availability model, for example a grid of GCMs including H_2O precipitation [20-21]. It could also be implemented using a model of groundwater upwelling as the water source [22], flowing via taliks that open in warm climates. Even though the use of a more sophisticated model or models is probably preferable, we chose to use a snowmelt model because a detailed model is available [23].

The liquid water availability model used is a 2D (latitude-longitude) set of partly coupled 1D temperature-vs-depth column models of surface energy balance for a dusty snowpack (albedo = 0.28). The columns implicitly exchange H_2O, because meltwater is only allowed at cold trap locations, i.e. those that minimize the annually-averaged sublimation rate [24]. At locations where liquid water is predicted by the model, carbonates are allowed to form. The model does not include lateral heat transport by the atmosphere, nor does it explicitly represent precipitation. The model resolves day-night and seasonal thermal cycles. In order to allow many multi-Gyr integrations to be done in a reasonable time, we build two look-up tables of annual averaged sublimation rate, and annual-maximum snowpack temperature, as a function of latitude, longitude, obliquity, longitude of perihelion, eccentricity, and atmospheric pressure. The effect of changing solar luminosity is parameterized as a temperature increase. We specify a fixed areal percentage of the planet that has warm-season snow, f_{snow}. We then integrate the climate system forward at ~1 Kyr resolution (thus resolving all orbital cycles), allowing carbonate formation only when cold traps have warm annual-maximum temperatures.

The rate of carbonate formation in these zones is paced by an assumed aeolian-transported cation input rate, which is in turn based on assignment of rhythmic bedding to orbital forcing [25]. This introduces uncertainty because only in rare cases can we say which orbital forcing is responsible [26]. However, results are qualitatively similar for order-of-magnitude variations in cation input rate.

The Solar System is chaotic and the orbits of the planets cannot be deterministically reverse-integrated over 3.5 Gyr (e.g. [27]). Instead, we carried out many multi-Gyr N-body integrations of the solar system using mercury6 [28] and the obliquity wrapper scripts of [29]. Example results are shown in Fig. 1.

In the model, carbonate formation averages <$10^{-4}\times$ Earth's rate. This is because liquid water availaility is both patchy (concentrated near the equator, in longitudinal patches) and intermittent. In turn, the liquid water is intermittent because carbonate formation reduces CO_2 availability, making evaporitic cooling more severe—a negative feedback. Rising solar luminosity and orbital fluctuations "nudge" the climate system into liquid-water-permitting states, until the climate system approaches the H_2O triple point below which melting cannot occur.

The cation-limited assumption can be justified as follows. Suppose seasonal snow supply of 2 cm/yr meltwater-equivalent, which is plausible [30], and 25 mbar pCO_2. Then the solubility of CO_2 is ~3 g/kg, giving 6 g/yr of CO_2, not including HCO_3^-/CO_3^{2-}. This crude calculation allows up to ~16 g/m^2/yr of $FeCO_3$. In 10 Myr, this is 160 tons/m^2 of $FeCO_3$, or a drawdown of 2 bars. This analysis shows that cations and formation kinetics, and not CO_2 solubility or thermodynamic stability, limit carbonate formation at the relevant sedimentation rates [31-34].

Post-3.5 Ga volcanism and post-3.5 Ga escape-to-space are both assessed but (within our model framework) they are relatively minor [35-37].

The model is motivated in part by the young ages of sedimentary rocks (and many alluvial fans) on Mars, based on crater-statistics analyses corrected for erosion (e.g., [38-39]). These data suggest that some liquid water persisted on Mars, at least intermittently, post-3.0 Ga. The model does not include the valley network era on Mars (~3.6 Ga), which may have been much wetter than the climate modeled here.

Results: The model shows orbitally-paced liquid water events over a typically multi-Gyr time span, with long time gaps of globally dry conditions during this time span (Fig. 1). Liquid water availability is spatially restricted to oases (Figs. 2-3). Oases host carbonate formation which consumes carbon dioxide, and carbon dioxide drawdown leads to increased evaporitic cooling of snow. This leads to reduced liquid water availability - a negative feedback. When inspected in detail, the time distribution of habitability is fractal (statistics summarized in Fig. 2). At least some liquid water is probably required to explain the formation of sedimentary rocks. The model predicts liquid water near the equator, at low elevations, and only at high obliquity. Thick accumulations of post-3.5 Ga sedimentary rocks are only mapped near the equator, at low elevations. The model broadly overpredicts the spatial distribution of sedimentary rocks, which may be due to post-depositional erosion.

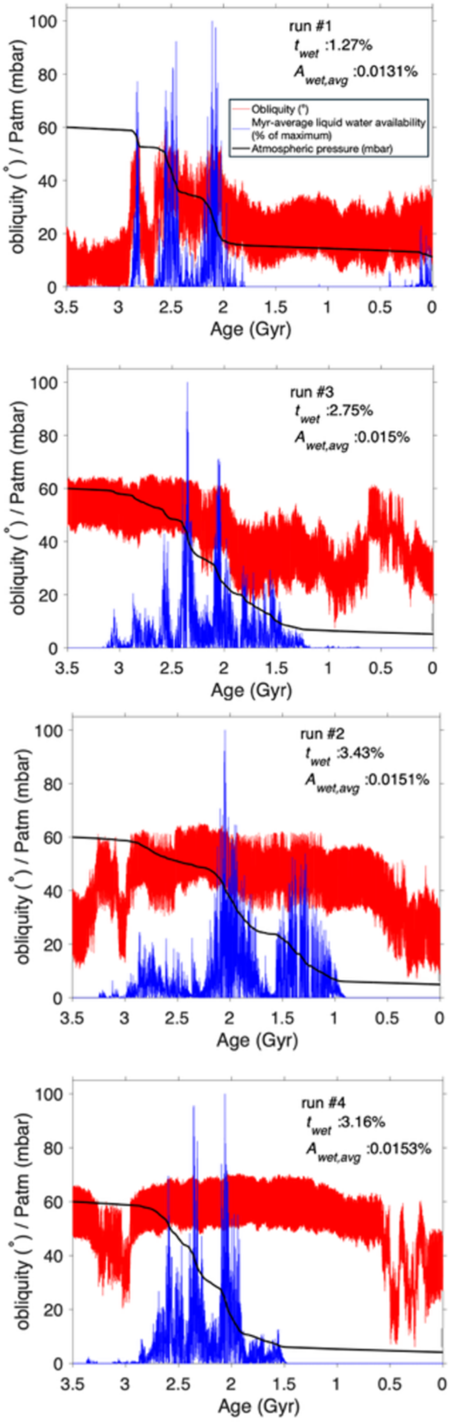


Fig. 1. Examples of climate evolution modeled with varying orbital forcing. *Red line: obliquity. Black line:* pCO_2*. Blue line (1 Myr average) % of the maximum area of (seasonal) surface liquid water availability (which is ~5% of planet area).* t_{wet} *: % of time with any liquid water.* $A_{wet,avg}$ *: mean surface liquid water cover. The orbital forcing varies between panels, corresponding to uncertainty in Mars' true past orbital forcing due to Solar System chaos. We infer that Mars'*

geology records an imprint of Solar System chaos on planetary climate. f_{snow} = 5%.

The model has many additional limitations (see [1] for details). From a data perspective, the model does not reproduce the evidence for catastrophic overspills (ice sheet meltback) relatively late in Mars history [40], nor the megalakes in Valles Marineris [41], nor catastrophic outflows from the circum-Chryse region [42]. Overall, the real post-3.5 Ga Mars almost certainly occasionally saw climates that are warmer than any output from our model, for unknown reasons. However, the cumulative-duration lower limit for these warm climate is only 10^3 yr [43-44].

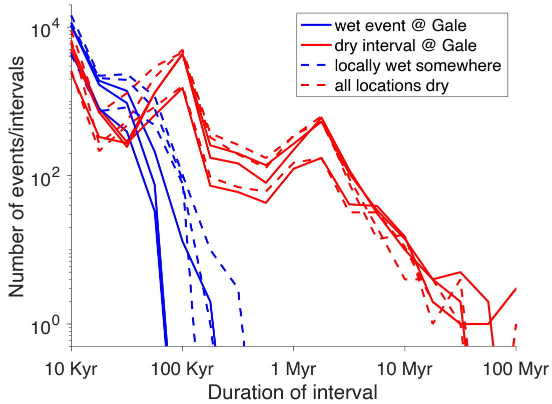


Fig. 2. Intermittency statistics from a model of long term climate evolution including carbonate formation *[1]. Mars is buffered to a fluctuating habitability state, with orbitally paced wet events and long dry intervals. Blue, histograms of the durations of wet events at Gale and globally; red: durations of dry intervals within the time span of wet events. The three different lines of each type correspond to three different random orbital histories. Globally dry periods are sometimes very long and might drive surface life (had it existed) extinct.*

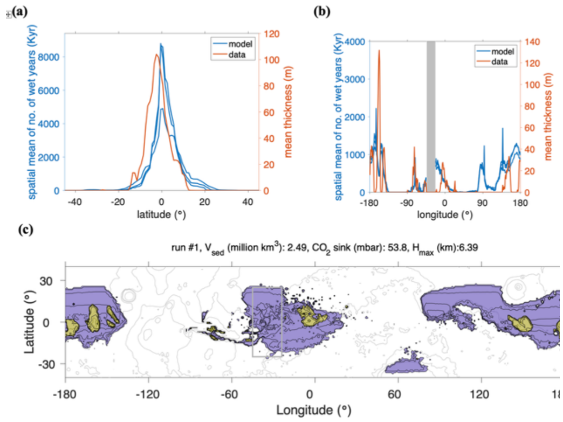


Fig. 3. Spatial patterns. *In panels (a) and (b), three different model runs, corresponding to runs #1-#3 from Fig. 1, are shown.* ***(a)*** *Latitude distribution of sedimentary rock (red) and model-predicted liquid water availability (blue).* ***(b)*** *Longitude distribution of sedimentary rock (red) and model-predicted liquid water availability (blue). The gray zone is masked out due to Middle Amazonian catastrophic outburst erosion [45]. Note that model prediction for longitude is 100% due to topography.* ***(c)*** *Preserved (gold tint) and predicted (purple tint) sedimentary rock distribution. Credit for mound mapping: D. P. Mayer and J. Sneed. Thin gray open contours are topographic contours (2.5 km intervals).*

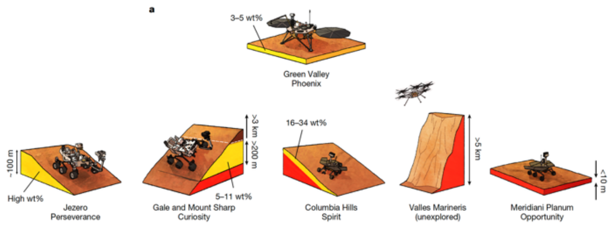


Fig. 4. Distribution of carbonate detections in sedimentary rocks and soil on Mars *[2,16,34,46]. Yellow: abundant carbonates detected; red: no detection; brown: yet to be explored.*

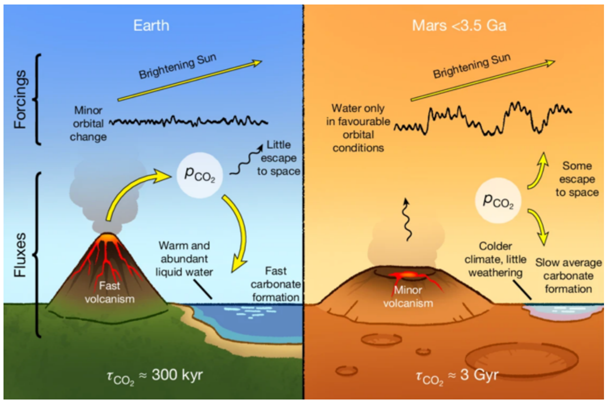


Fig. 5. *Fluxes and feedbacks for climate and habitability regulation on post-3.5 Ga Mars and Earth, according to [1]. On Earth, temperature increase from vigorous volcanic outgassing of CO_2 is balanced by fast carbonate formation. On Mars, in the ref. [3] hypothesis, slow temperature increase from solar brightening is balanced by slow (time-averaged) carbonate formation. The locally high rate of carbonate formation once liquid water is available assures that on Mars the climate has only infrequent liquid-water oases (during orbital optima). This model does not account for pre-3.5 Ga valley networks. τ_{CO_2}, residence time in (atmosphere + surface water) reservoir. Figure: D. Zhou.*

The feedback mechanism that (in our model) keeps Mars as a desert planet with infrequent oases is temperature-dependent carbonate formation. This is the same mechanism that maintains Earth as a clement ocean planet (rather than a moist greenhouse or an ice-covered planet) [6,47]. The reasons for the different outcome for Mars, in our model, is that Mars is a stagnant-lid planet with relatively minor volcanism (Fig. 5). Thus, carbonates that form post 3.5 Ga are not recycled by metamorphism (subduction and orogeny). Rising solar luminosity drives warming, which causes liquid water availability, which allows carbonate formation and thus cooling.

Tests and implications for future research: We have presented a testable idea rather than definitive evidence. One key test will come from the ongoing extended mission of Mars Science Laboratory through the paleoclimate-sensitive [48] deposits of Gale crater: do carbonates persist uphill along the traverse, as predicted by this model? Because Gale crater is a low spot close to the equator, it should have relatively good conditions for carbonate formation according to this model. Moreover, MSL isotopic data for carbonates (which so far has been unexpectedly enriched; [49]) may constrain the relative contributions of escape to space versus carbonate formation to habitability's end [7,50].

In situ exploration of other sedimentary rock mountains (for example, Valles Marineris) will ultimately be necessary to test if the fate of Mars' ancient atmosphere was to be entombed in the rocks.

Returned samples will allow radiogenic age-dating of young aqueous minerals, testing the time span of surface liquid water.

Acknowledgements: We thank M. A. Mischna, D. P. Mayer, J. Sneed, M. A. Kahre, I. Halevy, J. Frydenvang, J. Schieber and A. Yen. We thank D. P. Mayer and J. Sneed for the mound mapping. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). Funding: NASA-NNX16AG55G, 80NSSC20K0144, 80NSSC22K0731.

References: [1] Kite, E.S., et al., 2025. Nature, 643(8070), 60-66. [2] Tutolo, B. M. et al. Science 388, 292–297 (2025). [3] Kahn, R. Icarus 62, 175–190 (1985). [4] Kite, E.S., et al., 2022. Science Advances, 8(21), p.eabo5894. [5] Mahaffy, P.R., et al., 2015. Science, 347(6220), pp.412-414. [6] Lee, C.-T. A. et al. in *Deep Carbon: Past to Present* (eds Orcutt, B. N. et al.) 313–337 (Cambridge Univ. Press, 2020). [7] Hu, R., et al. Nat. Com-mun. 6, 10003 (2015). [8] Thomas, T. B., Hu, R. & Lo, D. Y. Planet. Sci. J. 4, 41 (2023). [9] McKay, C. P. & Nedell, S. S. Icarus 73, 142–148 (1988). [10] Catling, D. C. JGR Planets 104, 16453–16469 (1999). [11] Bibring, J. P. et al. Science 312, 400–404 (2006). [12] Edwards, C. S. & Ehlmann, B. L. Geology 43, 863–866 (2015). [13] Thorpe, M. T. et al. JGR Planets 127, e2021JE007099 (2022). [14] Sheppard, R.Y., et al., 2025. Frontiers in Astronomy and Space Sciences, 12, p.1549242. [15] Horgan, B. H., et al. Icarus 339, 113526 (2020). [16] Clavé, E. et al. in Tenth Intl. Conference on Mars Vol. 3007, 3161 (Lunar and Planetary Institute, 2024). [17] Schorghofer, N., 2020. Astrophysical Journal, 890(1), 1-9. [18] Hecht, M.H., 2002. Icarus, 156(2), pp.373-386. [19] Forget, F., et al. 2024. LPI Contributions, 3007, p.3511. [20] Clément, J.B., et al.., 2024. in Tenth Intl. Conference on Mars (LPI-Contribution). [21] Kuroda, T., Kamada, A., Kobayashi, M., Karyu, H., Kodama, T. and Sugimoto, N., 2025, EPSC/DPS Meeting (No. EPSC-DPS2025-769). [22] Andrews-Hanna, J. C., et al. JGR Planets 115, E06002 (2010). [23] Kite, E. S., et al. Icarus 223, 181–210 (2013). [24] Wordsworth, R. D., et al. JGR Planets 120, 1201–1219 (2015). [25] Lewis, K. W. & Aharonson, O. JGR Planets 119, 1432–1457 (2014). [26] Lewis, K.W., et al., 2008. Science, 322(5907), pp.1532-1535. [27] Laskar, J. et al. Icarus 170, 343–364 (2004). [28] Chambers, J. E. Mon. Not. R. Astron. Soc. 304, 793–799 (1999). [29] Armstrong, J. C., Leovy, C. B. & Quinn, T. Icarus 171, 255–271 (2004). [30] Madeleine, J.-B. et al. Icarus 203, 390–405 (2009). [31] Booth, M. C. & Kieffer, H. H. JGR Solid Earth 83, 1809–1815 (1978). [32] Stephens, S. K. PhD dis-sertation, California Institute of Technology; https://doi.org/10.7907/PSFY-MZ22 (1995). [33] Bristow, T. F. et al. Proc. Natl Acad. Sci. USA 114, 2166–2170 (2017). [34] Boynton, W. V. et al. Science 325, 61–64 (2009). [35] Ramstad, R., et al. JGR Planets 123, 3051–3060 (2018). [36] Stanley, B. D., et al. Geochim. Cosmochim. Acta 129, 54–76 (2014). [37] Kite, E. S. & Conway, S. Nat. Geosci. 17, 10–19 (2024). [38] Holo, S. J., et al. Planet. Sci. J. 2, 210 (2021). [39] Li, A. Y., et al. Planet. Sc. J. 3, 246 (2022). [40] Warren, A. O., et al. Planet. Sci. J. 5, 174 (2024). [41] Warner, N. H., et al. Geology 41, 675–678 (2013). [42] Salvatore, M. R. & Christensen, P. R. Geology 42, 423–426 (2014). [43] Kite, E.S., et al., 2019. Science Advances, 5(3), p.eaav7710. [44] Stucky de Quay, G., Kite, E.S. and Mayer, D.P., 2019. JGR Planets, 124(11), pp. 3119-3139. [45] Rodriguez, J. A. P. et al. Icarus 257, 387–395 (2015). [46] Morris, R. V. et al. Science 329, 421–424 (2010). [47] Walker, J. C., Hays, P. B. & Kasting, J. F. JGR Oceans 86, 9776–9782 (1981). [48] Milliken, R. E., Grotzinger J. P. & Thomson B. J. Geophys. Res. Lett. 37, L04201 (2010). [49] Burtt, D.G., et al., 2024. Proceedings of the National Academy of Sciences, 121(42), p.e2321342121. [50] Franz, H. B. et al. Nat. Astron. 4, 526 (2020).