THE DECLINE OF MARS' GREENHOUSE EFFECT CHARTED BY THE CHANGING SPATIAL DISTRIBUTION OF WATER FLOW.

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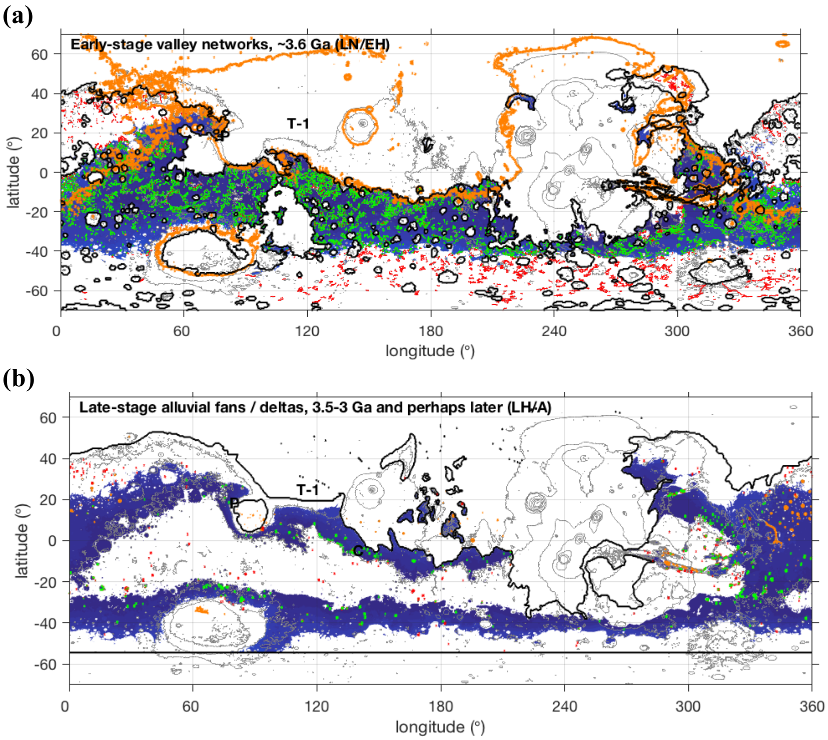

Fig. 1. (a) *Data-model comparison for simplified snowmelt model / GCM output that best matches ~3.6 Ga data (pCO_2 = 150 mbar, τ = 3.1, 45° obliquity, f_{snow} = 43%). Dark blue band: area of predicted snowmelt runoff. Green symbols: true positives. Red symbols: false negatives. Thick black line: border of masked-out region (postfluvial resurfacing), which differs between the two eras. Elevation contour spacing: 3 km. Orange line: 273 K isotherm in annual-average temperature. (Youden's J, 0.30; ROC AUC for varying f_{snow} for this GCM run, 0.68).* **(b)** *As (a), but for the output that best matches 3.5-3.0 Ga data (pCO_2 = 150 mbar, τ = 2.46, 45° obliquity, f_{snow} = 56%). (Youden's J, 0.34; ROC AUC for this GCM, 0.65). LN/EH = Late Noachian/ Early Hesperian, LH/A = Late Hesperian/ Amazonian.*

The Problem: Mars' wet era shows a shifting geographic distribution of rivers over time [1], however these shifts have not previously been compared to quantitative climate models to track changes in Mars' atmospheric greenhouse effect over time.

Our Approach: We used a grid of 54 GCM simulations [2,3] at Early Mars solar luminosity, varying atmospheric pressure (pCO_2), obliquity, and the strength of non-CO_2 greenhouse forcing, which was represented as a gray gas (column optical depth τ) [4,5]. The temperature and potential-sublimation-rate output from the GCM was used to drive a simplified meltwater model, assuming that meltwater runoff occurred where the average temperature exceeded 273 K for a continuous period of 100 sols and snow was relatively stable (we represented the percentage of the planet's surface area with warm-season snow by a free parameter, f_{snow}) [6].

New Results: Our resurfacing-corrected analysis of existing databases of (a) >3.6 Ga valley networks [7], compared to (b) <3.6 Ga alluvial fan (and delta) topographic catchments [8], confirms, for the first time, a down-shift of ~5 km in the preferred elevation of water-worn features between ~3.6 Ga and ~3.0 Ga. (This corresponds to the wettest climates during the two time intervals shown; it is possible that Early Mars was globally dry in most years). When these data are compared on an 8-pixels-per-degree grid to down-sampled MarsWRF GCM output (Fig. 1), the best fits (Fig. 2) are remarkably weakly dependent on pCO_2, but require a decline in the overall greenhouse effect by $\gtrsim$10K. We did not find evidence for changes over time in f_{snow}, which was poorly constrained (best fits ~50%). (Best-fit combinations of {pCO_2 , τ} are the same whether we marginalize over f_{snow} or just consider the best fit). We did not expect our results to be so weakly dependent on pCO_2 [9,10]. Idealized GCM simulations led by B. Fan [11] show that the lapse rate in surface temperature is controlled by greenhouse-effect strength, not pCO_2, consistent with these results.

Discussion: Our approach is relatively computationally inexpensive, but has the restriction of assuming a snow/ice water source for rivers – we do not explicitly simulate rainfall [12-13]. It would be interesting to compare 'desert rain' predictions [14] to data. We do not think that the loss of Mars H_2O to space [15] is solely responsible for the decline in the elevation of rivers, because (e.g.) relatively young alluvial fans formed at locally high elevations in the S Highlands, inconsistent with a groundwater source. However, integrating the subsurface hydrology with the surface/atmospheric hydrology of Early Mars at global scale remains an attractive target [16].

Conclusion: Within the framework of our model, river-forming climates on Early Mars were warm and wet first, and cold and wet later. This ≳10 K shift was mainly driven by waning non-CO_2 radiative forcing.

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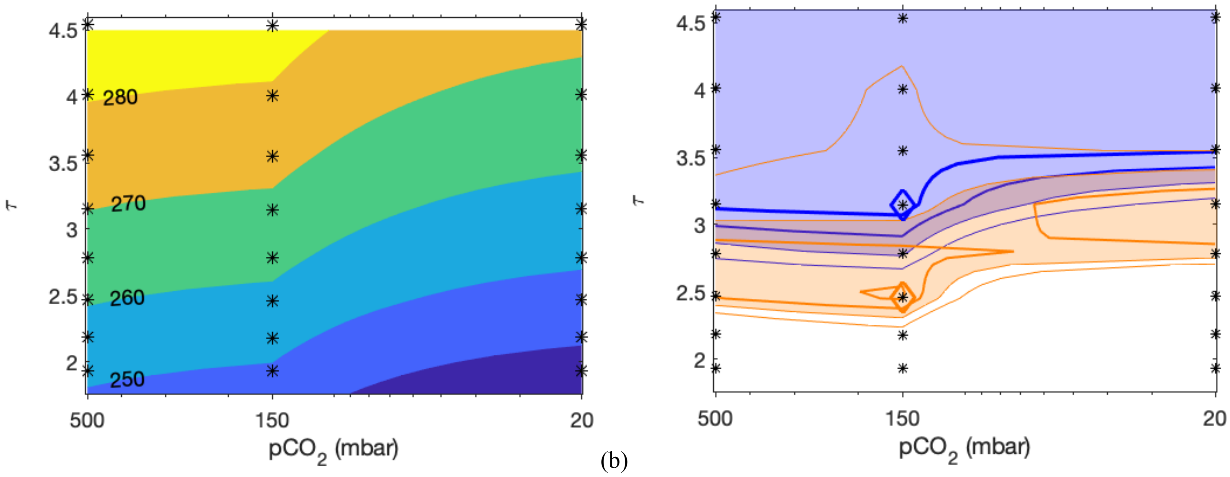

(a)

Fig. 2. (a) *Global annual average temperature (K) as a function of pCO_2 and of gray gas column optical depth, τ. Asterisks correspond to inputs to individual GCMs. Obliquity = 45°.* **(b)** *Goodness of fit of model to data as a function of pCO_2 and of gray gas column optical depth, τ. Blue shaded region corresponds to relatively good fit to >3.6 Ga data, and orange shaded region corresponds to relatively good fit to <3.6 Ga data. The blue diamond is the best-fitting GCM run for >3.6 Ga data (Fig. 1a), and the orange diamond is the best-fitting GCM run for <3.6 Ga data (Fig. 1b). Contours correspond to 0.5, 0.55, 0.6, and 0.65 ROC AUC (thicker lines correspond to better fit).*

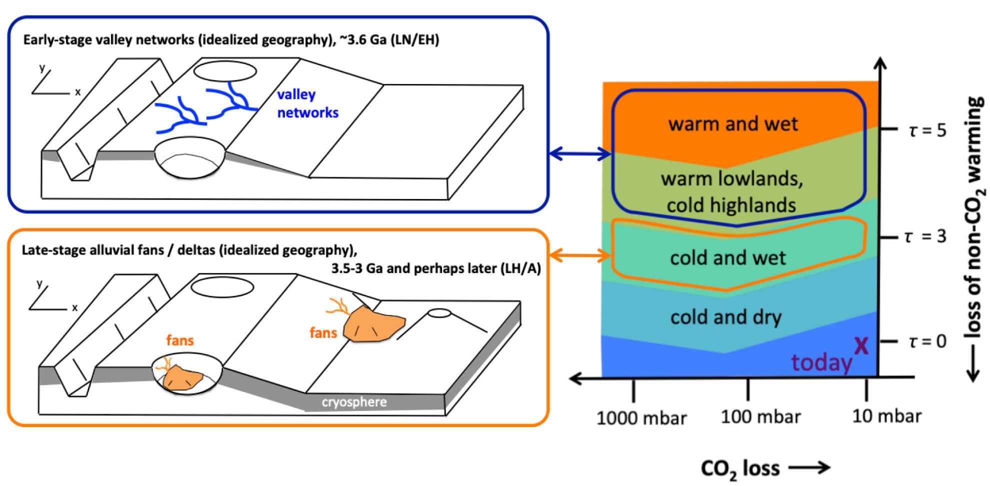

Fig. 3. *Graphical summary of the underlying concept: Why did Mars dry out? (a) Left column shows a simple (geographically idealized) schematic of changes over time, interpreted by analysis of elevation decline in comparison to the ensemble of GCM simulations. Right column: Illustrating that within the framework of our model, shifts can occur with or without changes in pCO_2, but very probably require a decline in non-CO_2 radiative forcing.*