WHY ARE MOUNTAIN-TOPS COLD? — THE DECORRELATION OF SURFACE TEMPERATURE AND TOPOGRAPHY DUE TO THE DECLINE OF THE GREENHOUSE EFFECT ON EARLY MARS.
B. Fan¹, M. F. Jansen¹, M. A. Mischna² and E. S. Kite¹.
1. Department of Geophysical Sciences, University of Chicago, Chicago, IL (bowen27@uchicago.edu). 2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: Mars lost its CO₂-dominated atmosphere over time, from < 2 bar around 4 Ga to 6 mbar today [1-2]. The atmospheric evolution of Mars was accompanied by climate change, which was recorded by shifts in the spatial distribution of rivers and lakes [3]. Consistently, climate models predict shifts in surface temperature pattern with decreasing atmospheric CO₂ [4]. When the CO₂ atmosphere is thick, surface temperature $T_s$ decreases with height (correlated with topography); when the atmosphere is thin, $T_s$ only depends on insolation (decorrelated with topography). Yet the mechanism for this decorrelation remains unknown.

Methods: We use the MarsWRF GCM [5-6] to explore the transition of river-forming climates. We assume the atmosphere is CO₂-only, but allow additional greenhouse warming using a gray gas scheme. To simplify the relation between elevation and surface temperature, we set obliquity to 0° and include simulations with both idealized topography (Fig. 1) and present-day Mars topography. The range of mean surface pressure that we consider is between 0.01 bar and 2 bar.

Results: We use a surface energy budget framework to analyze outputs (Fig. 2):

$$SW + LW_a = LW_s + SH$$

where $SW$ is the net shortwave heating from the sun, $LW_a$ is the longwave heating from the atmospheric greenhouse effect, $LW_s$ is the surface cooling by longwave emission, and $SH$ is the surface cooling by sensible heat flux, respectively. We find greenhouse heating $LW_a$ is the main term balancing the variable surface radiation $LW_s$ (associated with the elevation-dependent temperature) under high $P_{CO_2}$, in contrast to predictions from the previous literature that sensible heat $SH$ was the cause of the regime transition [3-4] ($SH$ is always small, and is not correlated with topography). This conclusion does not change with switching to realistic topography or switching CO₂ radiation to a gray gas scheme. Under low surface pressure $P_s$ but strong gray gas greenhouse effect (high longwave absorption coefficient $\kappa$), the surface temperature still varies with elevation following the adiabatic lapse rate, so the regime transition can be attributed to the evolution of greenhouse gases other than CO₂.

Fig. 1. The idealized Gaussian topography. A 6000-meter-high mountain is placed at the equator (comparable to Tharsis on Mars). The white dash lines are the boundary for tropical averaging in Fig. 2.
Interpretation: Why does high greenhouse effect lead to elevation-dependent temperature while low greenhouse effect leads to uniform temperatures? With low atmospheric greenhouse effect (i.e., low atmospheric emissivity), atmospheric radiation back to the surface \(L_{W_a}\) is negligible. As a result, the surface energy balance becomes dominated by a balance between surface insolation \(SW\) and surface emission \(L_{W_s}\), such that surface temperature (which regulates \(L_{W_s}\)) is purely set by incoming solar radiation and independent of elevation. With high atmospheric greenhouse effect, atmospheric radiation \(L_{W_a}\) becomes important in the surface energy balance, with the leading balance eventually being surface emission \(L_{W_s}\) and \(L_{W_a}\). The surface temperature hence is controlled by the atmospheric temperature, whose vertical structure in turn is tied to the adiabatic lapse rate.

Conclusion: On Earth, mountain-tops are cold and the temperature follows the atmospheric lapse rate, while Mars’s surface temperature decorrelates with topography through its climate change. If wet episodes on early Mars were cold, surface temperature can tell us where the water sources from ice/snowmelt would have been during warming episodes (Rainfall is an alternative scenario when water sources are indirectly connected with surface temperature [7]). Since the surface temperature decorrelation comes from the decline of the greenhouse effect only, changes in Mars’ fluvial patterns may arise from non-CO\(_2\) greenhouse gases (e.g., H\(_2\)) only, rather than the loss of a CO2 dominated atmosphere [8].

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