The ebb of rivers – the paleo-river elevation transition due to the decline of greenhouse effect on early Mars

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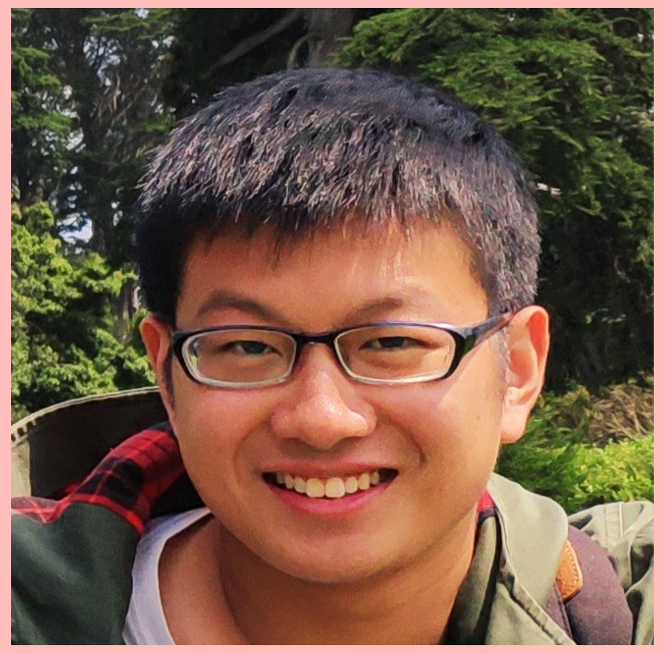
November 26, 2022

Abstract

Long term climate change on early Mars is characterized by a shift in the spatial distribution of rivers and lakes. Geological datasets suggest earlier paleo-rivers prefer higher surface elevations compared to rivers that formed later (Kite, 2019). On the other hand, modeling work also suggest a transition of surface lapse rate that comes with atmospheric escape throughout the Martian history (Wordsworth, 2016). The surface lapse rate follows the atmospheric lapse rate, which is close to dry adiabatic, when the CO_2 atmosphere is thick, but decouples when the atmosphere is thin. Figuring out the surface temperature distribution on early Mars is critical, because it tells us where the water sources from ice/snowmelt would have been during warming episodes. We use the MarsWRF GCM to explore the transition of river-forming climates. We assume the atmosphere is CO_2-only, but allow additional greenhouse warming by a gray gas scheme. To simplify the relation between elevation and surface temperature, we set 0 obliquity and include simulations with both idealized topography and real topography. The range of surface pressure is between 0.01 bar and 2 bar. We use a surface energy budget framework to analyze outputs (Fig. 2). Under the framework, variations in surface emission $\mathrm{LW_s}$ correspond to surface temperature variations. We find greenhouse heating $\mathrm{LW_a}$ is the only term that scales with surface temperature under high $\mathrm{P_{CO2}}$, in contrast to predictions from the previous literature that sensible heat SH was the cause of the regime transition (Wordsworth, 2016). This conclusion does not change with switching to realistic topography or switching CO_2 radiation to a gray gas scheme. Under the low $\mathrm{P_s}$ but high-optical-depth $\varkappa$ gray gas case, the surface lapse rate still follows the atmosphere, so the regime transition can be attributed to the evolution of greenhouse gases other than CO_2. In future, we will add a surface liquid water potential algorithm to link the surface energy balance to paleo-river observations. Assuming surface liquid water is formed during transient ice-melting period, surface liquid water potential can be calculated from the $\mathrm{T_s}$ and $\mathrm{P_s}$ distributions. The output will be compared with different historical epochs to find the best-fit scenario with both CO_2 and non-CO_2 greenhouse forcing.



Why are Mountain-Tops Cold?

The Decorrelation of Surface Temperature and Topography Due to the Decline of Greenhouse Effect on Early Mars

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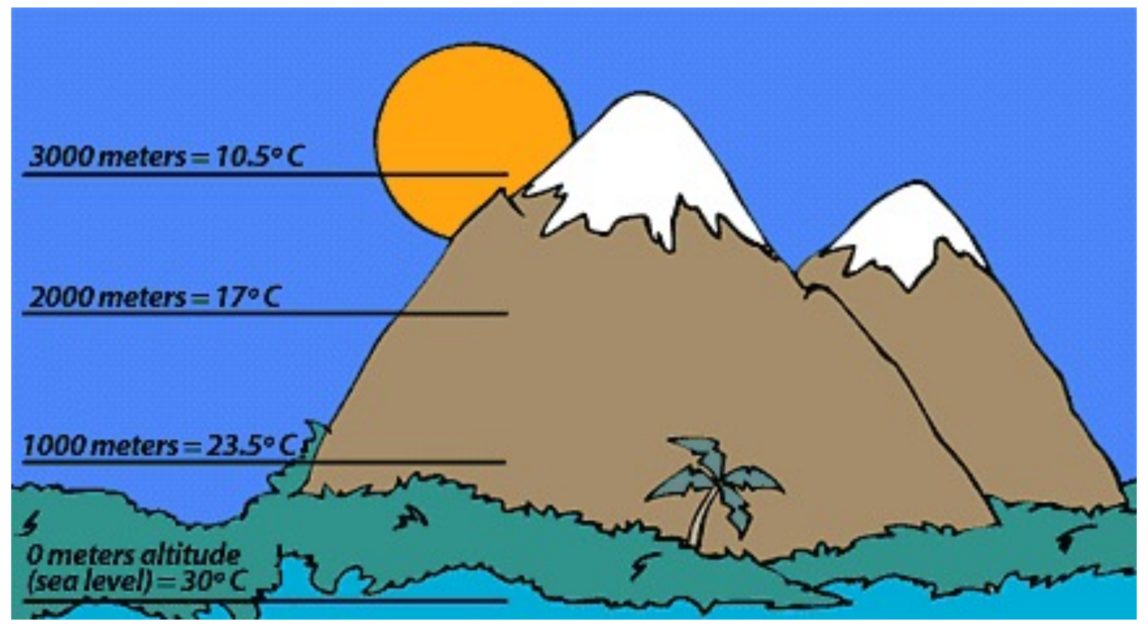
Poster ID: P45B-2434

1 Motivation

On Earth, mountain-tops are cold because the temperature follows atmospheric lapse rate.



What about Mars?

- Mars lost its CO_2-dominated atmosphere over time, from ≤2 bar around 4 Ga to 6 mbar today (Jakosky et al., 2018; Warren et al., 2019).
- The atmospheric evolution of Mars was accompanied by climate change, which was recorded by shifts in the spatial distribution of rivers and lakes (Kite, 2019).
- Climate models find shifts in surface temperature pattern with decreasing atmospheric CO_2 (Wordsworth, 2016). When the CO_2 atmosphere is thick, T_s decreases with height (correlated with topography); when the atmosphere is thin, T_s only depends on insolation (decorrelation with topography).
- **Question: What mechanism is responsible for this decorrelation? What are the implications for Mars' climate change?**

2 Methods

- Model: MarsWRF Mars GCM (Richardson et al., 2007; Toigo et al., 2012).
- Solar luminosity: 85% of the modern value.
- Obliquity and eccentricity set to zero.
- Ice-albedo feedback disabled.
- Atmospheric thickness varied from 0.01 bar to 3 bar.
- Radiation: CO_2 (correlated-k scheme) or gray gas (absorption in the IR wavelength).
- Topography: 2-D Gaussian topography (Fig. 1)

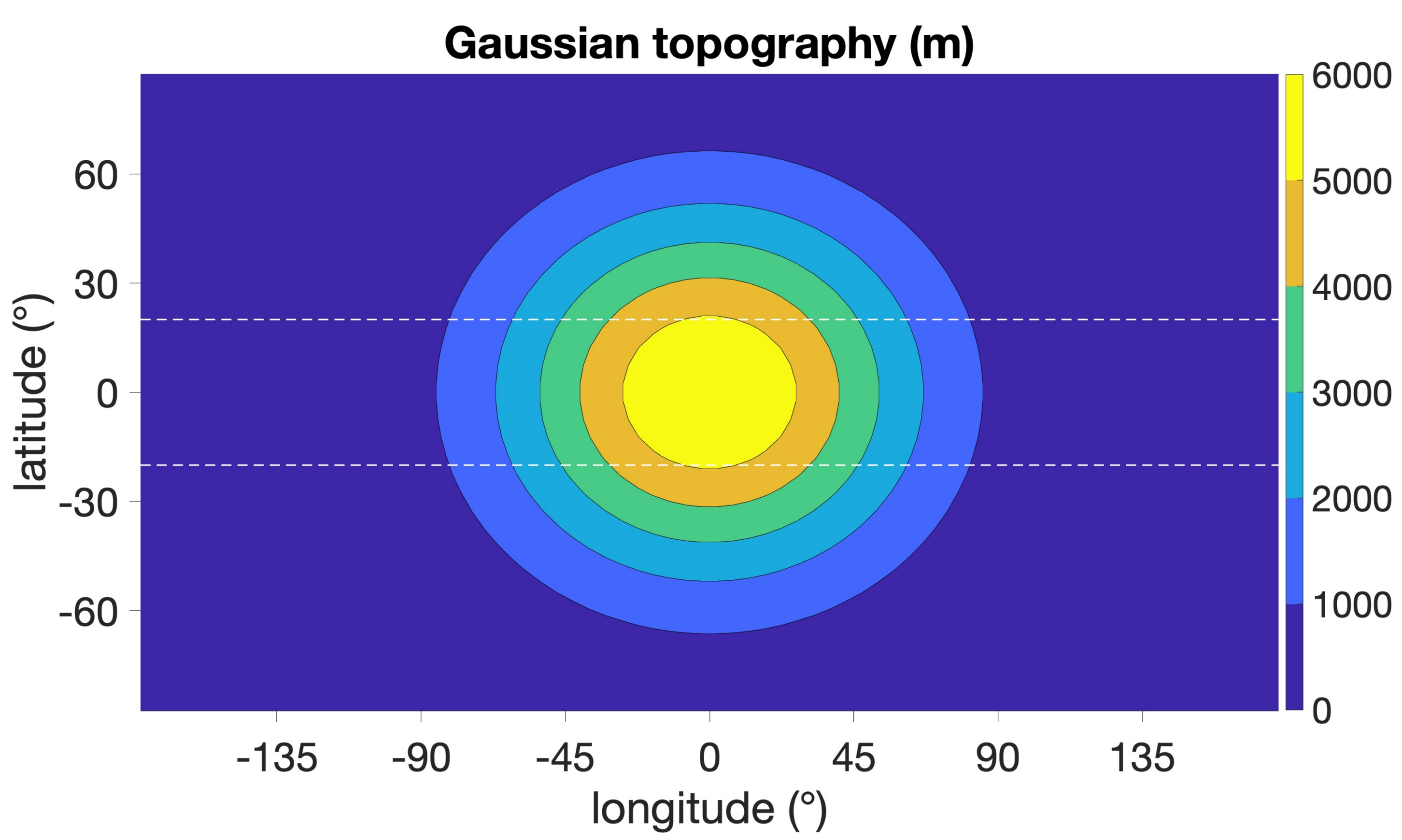


Fig. 1: The idealized Gaussian topography. A 6000-meter-high mountain is placed at the equator (comparable to Tharsis on Mars). The white dash lines are the boundary for tropical averaging in Fig. 2. This topography is labelled as "Gaussian" in Fig. 3 (represents the case when highlands only cover a small fraction of the surface). We also simulated with "iGaussian" topography, which means the surface elevation is "Gaussian × -1". The "iGaussian" case represents when lowlands only cover a small fraction of the surface.

3 Surface Energy Budget Indicates that the Greenhouse Effect Controls the Decorrelation

$$SW + LW_a = LW_s + SH$$

- Under steady state, the surface energy budget is the balance between shortwave heating from the sun (SW), longwave heating from the atmosphere (LW_a), surface cooling by emission (LW_s), and the cooling by sensible heat flux (SH).
- For the 1st time, we find that **the decorrelation of T_s (scales with emission) with topography is due to the decrease of CO_2 greenhouse effect**, not due to the sensible heat flux as proposed by Wordsworth (2016) and Kite (2019).

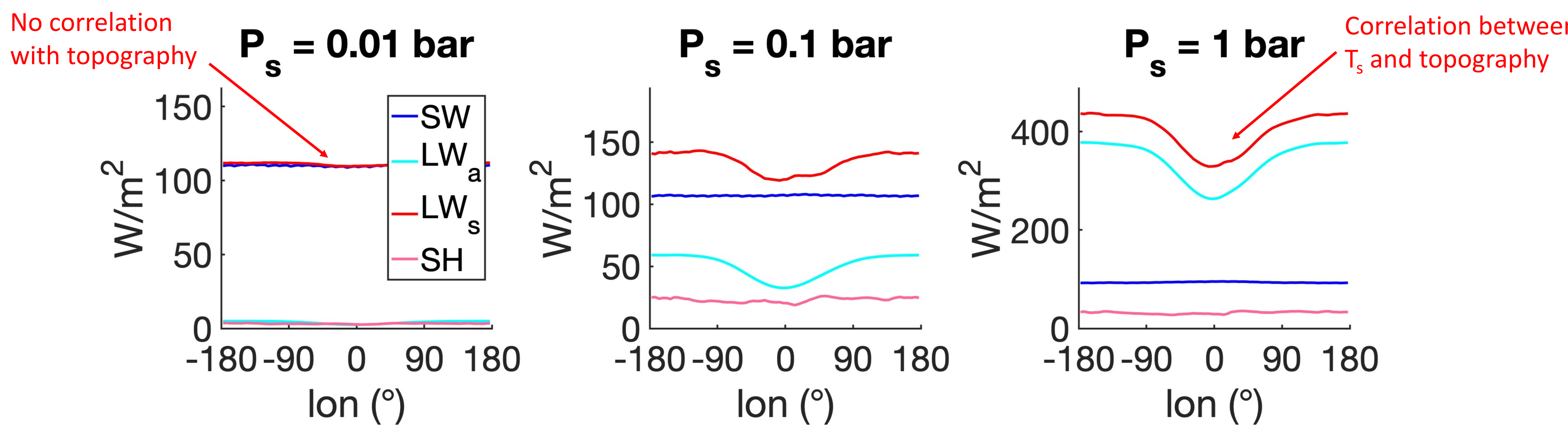


Fig. 2: Time-averaged surface energy budgets in runs. Each term is averaged within the tropics (20°N - 20°S). The red curve with a dip represents the correlation between T_s and topography (lower T_s/emission over the mountain), which is controlled by the decrease of greenhouse heating. These examples are performed with Gaussian topography, correlated-k CO_2 scheme, and diurnal-mean insolation, but changing topography, radiation scheme, or diurnal cycle do not change our conclusion (Fig. 3).

4 Reducing the Complexities from GCM

- The decorrelation can be reproduced by decreasing IR opacity under the gray scheme, without changing atmospheric thickness.

→Changes in Mars' fluvial/temperature patterns may arise from changes in non-CO_2 GH gases (e.g., H_2), rather than the lost of CO_2-dominated atmosphere.

- A 3D model is necessary to determine the correct strength of GH forcing for the decorrelation.

→ Atmospheric circulation is important to redistribute the energy between highlands and lowlands.

- Other factors (diurnal cycle, topography) do not matter within our idealized simulations.
- Next step: a conceptual framework to explain the decorrelation.

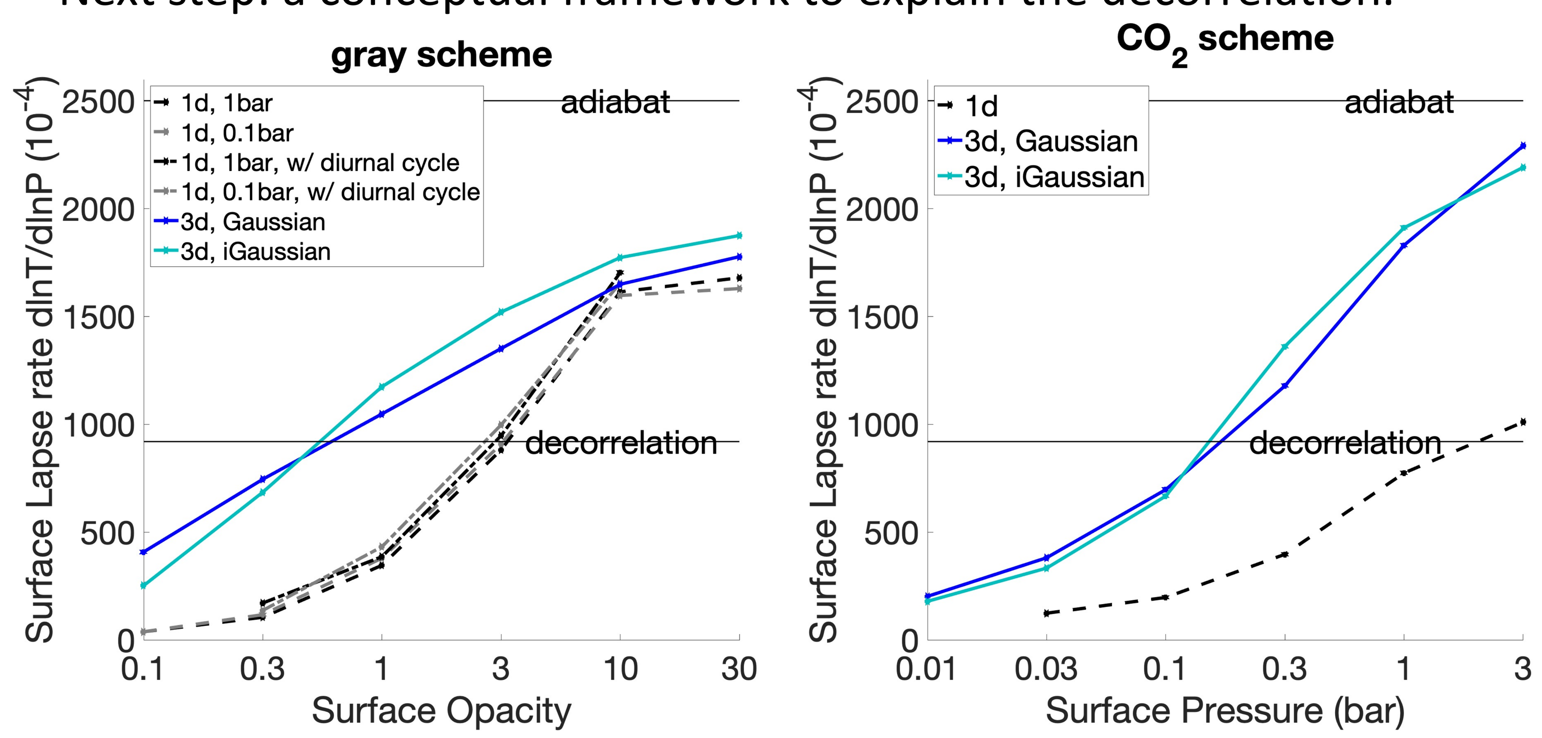


Fig. 3: The relation between T_s and topography in simulations with gray gas scheme (left) and CO_2 scheme (right). The relation is quantified as surface lapse rate $\left(\frac{d\ln T_s}{d\ln P_s}\right)$. When the greenhouse effect is strong, the lapse rate approaches to the atmospheric lapse rate (adiabat); when the greenhouse effect is weak, the lapse rate in T_s approaches to zero. We define the decorrelation point as the adiabat divided by Euler's number *e*.

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Acknowledgements: This research was funded by NASA (80NSSC20K0144+80NSSC18K1476). The simulations were completed with resources provided by the University of Chicago Research Computing Center (RCC). We thank the MarsWRF team for support with the use of the GCM.