CO_2 Cycle Dampened by the Radiative Effect of Water Ice Clouds in the Late Amazonian: Implications for the Formation of Gullies

L.Lange , *NASA Postdoctoral Program Fellow, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91011, USA. (lucas.lange@jpl.nasa.gov)*, **F.Forget, J.Naar, E.Vos, J.B.Clément, E.Millour,** Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace (LMD/IPSL), Sorbonne Université, Centre National de la Recherche Scientifique (CNRS), École Polytechnique, École Normale Supérieure (ENS), Paris, France Institut Pierre Simon Laplace Université Paris 6, France., **E.David**, Department of Earth \& Planetary Sciences, Weizmann Institute of Science, Rehovot, Israel.

Introduction:
The formation of Martian gullies remains one of the most enigmatic topics that has captivated the scientific community since their discovery in the early 2000s [1]. Given the young age of gullies (less than 5 million years, [2]) and the strong morphological similarity between Martian gullies and terrestrial ones, their presence initially implied the existence of liquid water during the late Amazonian period. Since then, many models have proposed that the melting of surface [1, 3-7] or subsurface [8-10] water ice could have driven gully formation. Notably, most of these models suggest that gullies formed during periods of high obliquity, when the Martian climate was wetter and more favorable to mid-latitude ice accumulation and subsequent melting.

However, as shown by [11-14], melting of water ice at the surface or shallow subsurface in the recent past appears impossible due to significant latent heat removal during sublimation, which prevents the temperature from reaching the melting point.

If melting cannot account for gully formation, what could be the triggering mechanism?

Based on observations of present-day gully activity [15,16], numerous models [e.g., 16-22] have proposed that CO_2 sublimation may play a key role. Yet, considering the limited number of observed active sites relative to the total number of gullies, these models often suggest that gully activity peaked during high-obliquity periods, assuming that CO_2 condensation and sublimation were enhanced under such conditions. Indeed, during higher obliquity, mid-latitudes receive less annual insolation, increasing the extent of seasonal CO_2 ice caps and the amount of CO_2 condensing, thereby favoring gully formation [e.g., 23].

The radiative effect of water ice clouds:
Models predicting an enhanced extent of seasonal CO_2 ice caps at high obliquity generally neglect a key factor: the radiative effect of water ice clouds. On present-day Mars, tropical clouds tend to warm the surface at night via infrared (IR) emission [24] . Madeleine et al. [25] showed that this effect is significantly amplified during periods of high obliquity. The sublimation of northern perennial glaciers increases atmospheric water vapor, which in turn leads to the formation of water ice clouds. These clouds warm the atmosphere, allowing it to hold even more water vapor, creating a positive feedback loop. This leads to the formation of thick clouds that can emit substantial IR radiation toward the surface, inhibiting nighttime cooling.

Preliminary simulations by [26] suggest that this greenhouse effect could become strong enough to prevent surface temperatures from falling below the CO_2 frost point, thereby suppressing the formation of seasonal CO_2 ice caps -see Figure 1-. This discovery challenges our understanding of the past CO_2 cycle on Mars (see Forget et al., this issue).

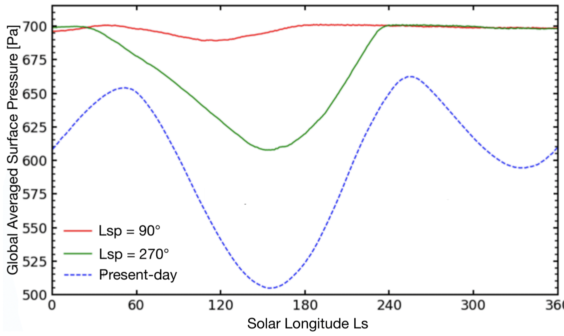

Figure 1: CO_2 cycle at 35° obliquity vs present-day CO_2 cycle. From [26]. Note that [26] assumes that the CO_2 budget between present day orbit and the 35° obliquity is similar. In this work, we modify the value of the total CO_2 available as a function of obliquity to simulate the sublimation of the CO_2 reservoirs buried beneath the South Pole [27].

Impacts on gully activity:
If the CO_2 cycle is indeed dampened during high obliquity by the radiative effect of water ice clouds, this raises concerns about the validity of all CO_2-driven gully formation mechanisms. Yet, no straightforward conclusion can be drawn. A slope "sees" less of the sky than a flat surface; the downward IR flux from clouds is reduced by the sky-view factor, which is proportional to the cosine of the slope angle. Therefore, if a slope is steep enough, it may still allow CO_2 frost to accumulate during high obliquity, potentially allowing CO_2-driven gully activity.

Simulation	Orbital Parameters	Total pressure	Dust opacity	Location of the water ice reservoirs
35° obliquity	Lsp = 90°; Eccentricity = 0.12 Lsp = 270°; Eccentricity = 0.12 Lsp = 0°; Eccentricity = 0.	2x present-day value	2; 0.2 (at 610 Pa)	North Pole South Pole (CO_2 residual cap is assumed to deseapear)
30° obliquity	Lsp = 90°; Eccentricity = 0.12 Lsp = 270°; Eccentricity = 0.12 Lsp = 0°; Eccentricity = 0.	1.5x present-day value	2; 0.2 (at 610 Pa)	One set of simulations with ice at the NorthPole, one set with ice at high latitudes (LDM)
Present-day	Current Lsp, current eccentricity	1x present-day value	Dust Climatology of Montabone et al. (2015)	North Pole
20° obliquity	Lsp = 90°; Eccentricity = 0.12 Lsp = 270°; Eccentricity = 0.12 Lsp = 0°; Eccentricity = 0.	Atmospheric collapse: the model is still reaching equilibrium	0.2 (at 610 Pa)	North Pole
15° obliquity	Lsp = 90°; Eccentricity = 0.12 Lsp = 270°; Eccentricity = 0.12 Lsp = 0°; Eccentricity = 0.	Atmospheric collapse: the model is still reaching equilibrium	0.2 (at 610 Pa)	North Pole

Table 1: Simulations performed in this study. For each simulation, one is performed with radiative active clouds (RAC) and one without.

Model:

To leverage this question, we extend the work from [26] using the Mars Planetary Climate Model and its slope parameterization [28] to simulate slope microclimates where gullies are formed. We ran paleoclimate simulations at various orbital parameters (see Table 1). We also check the sensitivity of our results by activating /removing the effects of water ice clouds, increasing the dust opacity, and adding some water reservoirs at the South Pole/ high latitudes. Models are run until equilibrium, i.e., when the difference in the yearly average global water content in the atmosphere is less than 1% between two years. As slope microclimates are sensitive to the presence of water ice with a high inertia in its subsurface [29], we introduce subsurface ice with a large thermal inertia in the subsurface and compute its position based on its equilibrium depth [30].

Preliminary Results:

A preliminary result at 35° obliquity, Lsp = 90°, and a dust opacity of 0.2 is presented in Figure 2. Despite viewing a more limited portion of the sky, steep slopes are still strongly impacted by the radiative effects of water ice clouds. The formation of CO_2 ice is inhibited because of this effect between 20°S and 35°S. The thickness of the CO_2 frost is also significantly reduced, from more than 150 mm between 40 and 45°S without RAC to less than 10 mm with it. Preliminary simulations also show that CO_2 condensation is inhibited when the dust opacity is set to 2. We will present at the conferences all of our simulations and discuss whether or not some CO_2-driven gully activity is favored in the recent past of Mars.

Discussion: If neither water ice melting nor CO_2 sublimation can trigger the formation of gullies, how can these features form? [31] recently detected water ice with a few dust impurities (less than 1%) within gullies alcoves. They proposed that gullies could have been formed by the melting of this ice. Indeed, all studies that showed that melting was impossible [11-14] assumed that the solar energy was deposited at the surface only and not within the ice. While this assumption might be valid for fresh snow, the solar radiation should penetrate deep into the ice. If these radiation encounters dust impurities, then the dust would be heated and create a solid-state greenhouse effect within the ice. [6,32] showed that such an effect could be strong enough to allow the melting of water ice at depth. Current work by [34] aims to determine whether this mechanism is still valid for snow, snow transforming into glacier ice, or glacier ice. Yet, as noted by [22], the quantity of liquid water generated by the mechanism proposed by [6, 32] might be too low to trigger the formation of gullies. Hence, 25 years after their discovery, the formation of gullies during the recent past of Mars remains mysterious!

Acknowledgments: LL's research was supported by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, administered by Oak Ridge Associated Universities under contract with NASA. LMD authors have received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No 835275, project "Mars Through Time").

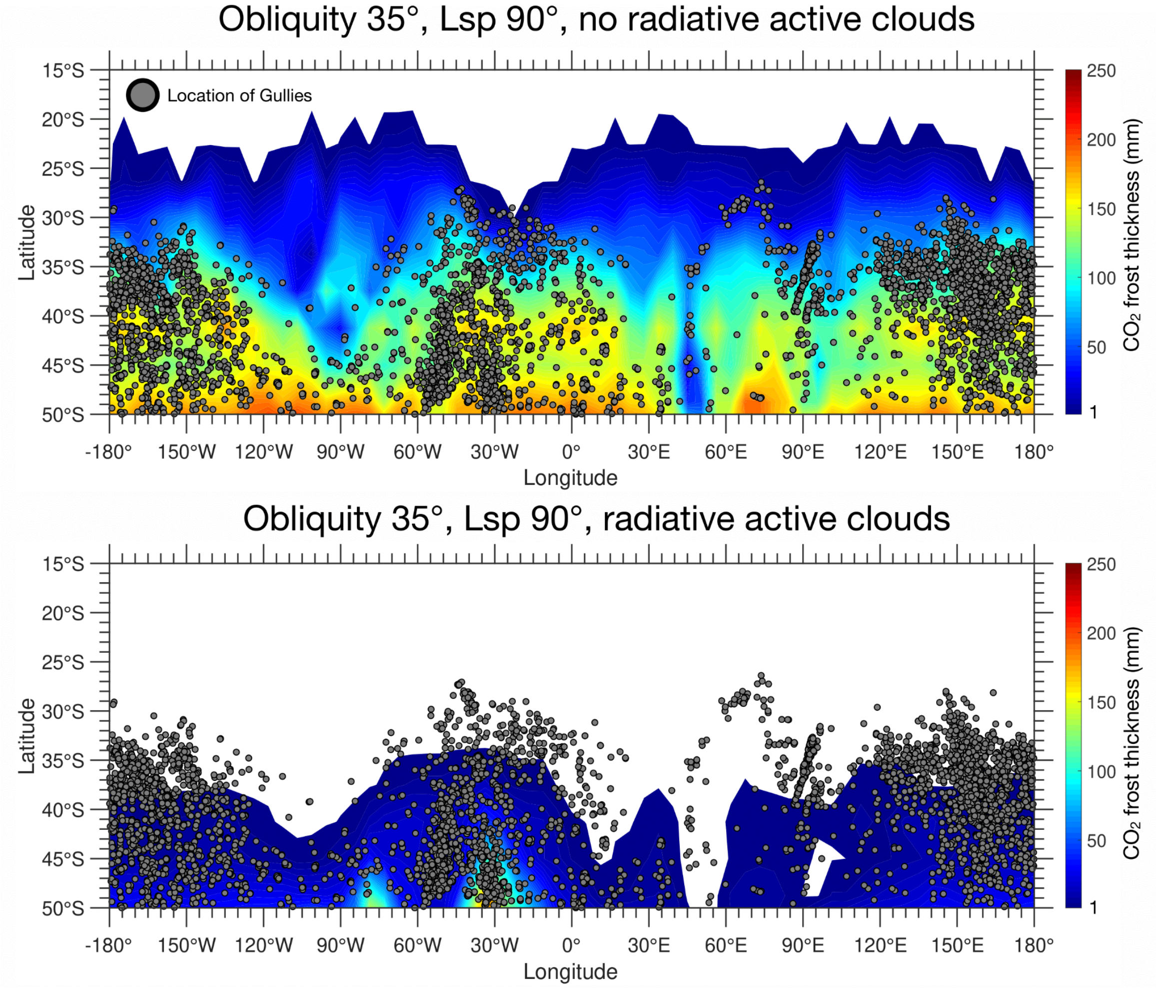

Figure 2: CO2 ice thickness on a 30° pole-facing slope at 35° obliquity, Lsp = 90°, dust opacity of 0.2, with and without radiative active clouds. Grey dots point to the location of gullies.

References: [1] Malin et al. (2000), *Science*, 302(5652); [2] de Haas et al. (2017), *Geological Society, London, Special Publications*, 467(1); [3] Hecht (2002), *Icarus* , 156 (2); [4] Christensen (2003); *Nature*, 422(6927); [5] Kossacki et al. (2004); *Icarus*, 171(2); [6] Williams et al. (2008), *Icarus*, 196(2); [7] Dickson et al. (2023), *Science*, 380(6652); [8] Costard et al. (2002), *Science*, 295(5552); [9] Kreslavsky & Head (2003), *GRL*, 30(15); [10] Morgan et al. (2010), *Icarus*, 208(2); [11] Ingersoll (1970), *Science*, 168(3934); [12] Schorghofer (2020), *The Astrophysical Journal*, 890(1); [13] Khuller & Clow (2024), *JGR-Planets*, 129(4); [14] Lange & Forget, (2025), submitted to *GRL*; [15] Malin et al. (2006), *Science*, 314(5805); [16] Dundas et al. (2022), *Icarus*, 386, 115133; [17] Hoffmann (2002), *Astrobiology*, 2(3):313-23; [18] Diniega et al. (2010), *Geology*, 38, 1047–1050, [19] Dundas et al. (2010), *GRL*, 37(9); [20] Pilorget & Forget (2016), *Nature Geoscience*, 9, 65-69; [21] Roelofs et al. (2024), *Communications Earth and Environment,* 5; [22] Dundas et al. (2025), *GRL*; [23] Forget et al. (2017), *The Atmosphere and Climate of Mars*; [24] Wilson et al. (2008), *GRL*, 35; [25] Madeleine et al. (2014); GRL; 41(14); [26] Naar, J. *Phd Dissertation, Sorbonne University*; [27] Bulher & Piqueux (2021), *JGR-Planets,* 126; [28] Lange et al. (2023), *JGR-Planets*, 129(10); [29] Vincendon et al. (2010); *GRL*; 37(1); [30] Schorghofer & Aharonson (2005), *JGR-Planets*, 110(E5); [31] Khuller & Christensen (2021), *JGR-Planets*, 126(2) ; [32] Clow (1987), *Icarus*, 45 (2); [33] Khuller et al. (2024), *Communications Earth and Environment*, 5