

THE MARGINAL CASE FOR SULFUR-DRIVEN WARMING IN THE EARLY MARTIAN ATMOSPHERE. L. Kerber¹, F. Forget², R. Wordsworth³, ¹Jet Propulsion Laboratory (4800 Oak Grove Dr. Pasadena, CA 91109, kerber@jpl.nasa.gov), ²Laboratoire de Météorologie Dynamique du CNRS, Université Paris 6, Paris, France, ³Harvard School of Engineering and Applied Sciences, 29 Oxford Street Cambridge, MA 02138

Introduction: A successful working model for the early Martian atmosphere and hydrosphere must be able not only to produce conditions suitable for liquid water at the surface, but also to explain how the nature of this aqueous activity changed over time and eventually diminished. There are two major end-member hypotheses: first, that early Mars was wet and warm, with a sustained greenhouse that made it possible for liquid water to be stable on the surface for extended periods [e.g., 1, 2-4], and second, that early Mars was generally cold, and that most of the aqueous alteration took place underground [5,6] or during transient warm periods tied to impact cratering [7], or volcanism [8]. In both cases, volcanic gases (especially SO₂) have been suggested as a possible way of creating either a sustained or transient greenhouse. Several researchers have tested the addition of SO₂ to climate models in order to assess whether it would provide an adequate amount of greenhouse warming to allow liquid water to flow across the surface [9-12], with differing results.

Here we reconsider the efficacy of a sulfur-induced greenhouse in early Noachian history using the LMD (Laboratoire de Météorologie Dynamique) 3-D Generic Climate Model (LMD-GCM), exploring the effects of SO₂, H₂S gases and sulfate and sulfur aerosols on the surface temperature. We expand upon earlier works, using improved CO₂ spectroscopy, radiatively active CO₂ ice clouds, and more complete S₈ optical properties. The goals for this work are to determine:

(1) Whether (and by how much) SO₂ and H₂S were capable of warming the early Martian surface.

(2) How SO₂-derived warming varies depending on location on the planet, and how that compares to the spatial distribution of valley networks and aqueous mineral deposits.

(3) Whether (and by how much) sulfate and elemental sulfur aerosols were capable of cooling the Martian surface.

Methods: The GCM used in this study was developed for general planetary applications, and includes generalized radiative transfer and cloud physics [e.g., 13]. The model was adapted specifically to early Mars conditions and used by Forget et al. [14] to explore the effects of a CO₂ atmosphere from 0.1 to 7 bars, including the effects of different obliquities, orbital parameters, cloud microphysical parameters, atmospheric dust loading, and surface properties (see also [13]).

Control simulations were run at 0.5 bars with a 32x32x15 grid, corresponding to a resolution of 11.25° longitude by 5.625° latitude in the horizontal

with 15 vertical levels from the surface to ~50 km. Simulations with H₂O were run with a relative humidity profile derived from the full, self-consistent water cycle (including CO₂ and water ice clouds) used in [13]. The relative humidity in this profile is 45% near the surface with the hygro-pause near 8 km.

Results: Sulfur-bearing gases do significantly warm the surface given high enough concentrations. Even in the cases where large amounts of SO₂ and H₂S (and H₂O) are added to the atmosphere, however, the annual global average surface temperature does not rise above freezing (given a faint young Sun). H₂S provides significantly less warming than SO₂ (Fig. 1)

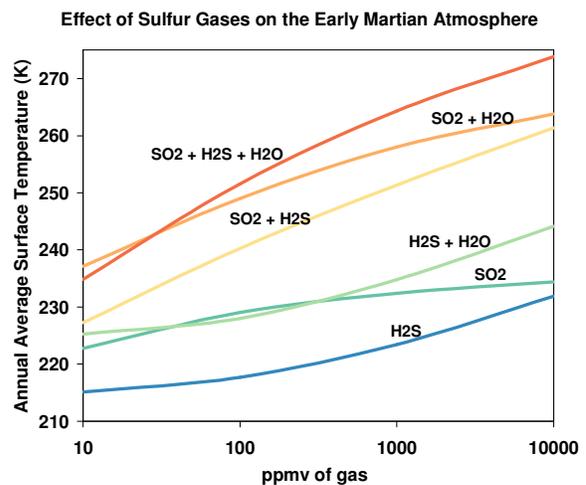


Figure 1.

The Effect of Pressure

The pressure of the Martian atmosphere during this time is not well known, so a default value is usually selected either because it is “reasonable” based on the limited constraints available, or because it maximizes warming. However, the choice of background pressure can affect the result significantly, to the same order as a difference between 0 and 10000 ppm of SO₂. We modeled a large range of atmospheric pressures, from 5 mbars to 2 bars. Within this range, higher pressures yield higher temperatures, although annual average temperatures still did not exceed 273 K for the tested cases. A given temperature can be reached with a much lower SO₂ mixing ratio in a high pressure atmosphere, though a given mixing ratio actually requires more SO₂ in a thick atmosphere compared to a thin one.

Spatial Variability of SO₂ Warming

While average temperatures might not allow melting, regional and seasonal temperatures can be much higher. **Figure 2** shows maps of average annual surface temperature for different scenarios: CO₂ only, H₂O+CO₂, CO₂+SO₂ (100 ppmv), and CO₂+H₂O+SO₂ (100 ppmv). Significant warming is observed in Hellas Basin and around 30°N. These locations change depending on assumed orbital parameters such as longitude of perihelion and obliquity.

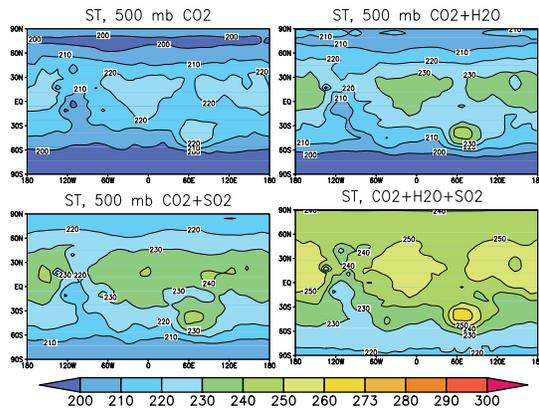


Figure 2.

The Effect of Sulfur and Sulfate Aerosols

Aerosol simulations were first run in a dry CO₂ atmosphere with well-mixed 1 μm H₂SO₄ or S₈ particles with opacities ranging from $\tau = 0.2$ to 10 (at 550 nm). These produced cooling from a few degrees to ~23 K for H₂SO₄ $\tau = 10$. A single layer of H₂SO₄ aerosols of the same opacity produced similar results.

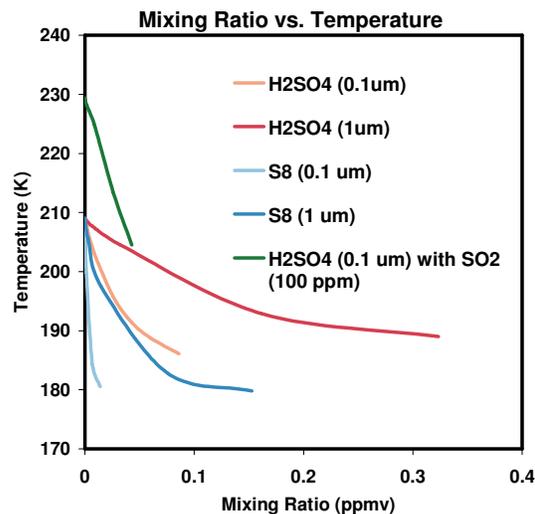


Figure 3.

While a significant amount of SO₂ gas is required to create a moderate amount of surface warming, only a very small amount of aerosol is needed for dramatic cooling. For example, if 100 ppmv of SO₂ was released into the atmosphere, and only 0.04% of it became 0.1-μm H₂SO₄ particles, the entire warm-

ing effect of the SO₂ would be cancelled out. **Figure 3** shows the cooling effects of sulfate and sulfur aerosols versus the mixing ratio in ppmv of equivalent H₂SO₄ or S₈ gas. Each line ends at the mixing ratio which creates an optical depth of 10 (at 550 nm). The green line shows the combined effect of 100 ppmv of SO₂ with rising amounts of H₂SO₄ aerosol. The warming from the SO₂ is quickly canceled out by small amounts of H₂SO₄ aerosol. Large (10 μm), warming aerosols, require larger concentrations in order to arrive at an optical depth of 10 (still less than 5 ppmv).

Conclusions: From these results we can make several conclusions:

- (1) SO₂ and H₂S gases, considered alone, would warm the surface of Mars. A hot, enduring greenhouse is unlikely, but concentrations of SO₂ up to several hundreds to thousands of ppmv would be sufficient to bring temperatures above freezing for certain regions during certain portions of the year. This is true of atmospheres up to 2 bars (the thickest atmosphere tested).
- (2) Depending on assumed orbital parameters, the areas which spend the greatest time above 273K change. For example, using an eccentricity of zero leads to greater warming taking place in the northern lowlands, while a high eccentricity and a modern-day longitude of perihelion leads to greatest warming in the southern highlands close to the equator.
- (3) Even a small amount (<0.05 ppmv) of H₂SO₄ production in common size ranges would cancel out SO₂-derived warming. S₈ would cause cooling in the small particle range, but warming if all of the particles could grow to more than 3 μm.

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