CLIMATIC CONSEQUENCES OF EPISODIC ERUPTIONS ON EARLY MARS.

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Introduction: An abundance of geomorphological, mineralogical and geochemical evidence suggests widespread aqueous activity on the surface or early Mars [1-3]. However, recent studies of Mars' early climate, using sophisticated three-dimensional climate models, find average surface temperatures too low to explain the observations [4,5]. It seems likely, therefore, that Mars' early climate was, on average, cold and dry, implying that winds easily lifted fine-grained particles and that the atmosphere was dusty, much like the present atmosphere in which the average visible dust optical depth is approximately 0.5 [6].

Volcanic sulfur-bearing gases have been suggested as a possible solution to the early climate problem [7,8]. However, scattering of incoming solar radiation by sulfuric acid (H_2SO_4) aerosols has been suggested to result in net cooling as SO_2 levels increase [9,10]. In addition, we argue here that even in the absence of H_2SO_4 aerosols, reasonable long-term average volcanic outgassing rates are unable to sustain climatically important atmospheric concentrations of SO_2. This is a consequence of the reactivity of SO_2 and its sensitivity to ultraviolet photodissociation [9,11].

Here, on the basis of morphological similarity to terrestrial flood basalts, we suggest that early martian eruptions were highly episodic, and characterized by exceptionally rapid emission rates during short bursts of activity, separated by long quiescent periods. We show that volcanic emission rates during brief and strong ("punctuated") eruptions were enough to sustain climatically important SO_2 levels, and that the net effect of injection of SO_2 into a dusty atmosphere is warming, despite the formation of H_2SO_4-bearing aerosols. We discuss probable climate feedbacks associated with the above scenario, and the possible existence of multiple climate states.

Methods:

A flood basalt analog to plains volcanism. A long maximum in volcanic activity during the transition between the Noachian and Hesperian [12] appears coeval with widespread evidence for aqueous activity [1-3, 13]. The Hesperian Ridged Plains (Hr) on Mars appear to have effused rapidly from wide fissures, rather than central cones or calderas [14,15]. This, in addition to their occurrence as laterally extensive plains, suggests an analogy with terrestrial flood basalts.

Individual flows in the Columbia River Flood Basalts and the Deccan Traps [16,17] imply instantaneous sulfur outgassing rates up to several hundred times the total global rate. Considering the higher sulfur content of martian magmas [18], the sulfur outgassing rate during similar eruptions on Mars could be thousands of times the terrestrial rate. Finally, plains basalts on Mars are larger in volume and area than any known terrestrial flood basalts, suggesting that Hr emplacement involved a greater number of eruptions and lasted for a longer time than is typical on Earth.

A coupled aerosol microphysics-radiative transfer model. We developed a model of aerosol microphysics, which treats the formation, growth and transport of pure H_2SO_4 and mixed dust-H_2SO_4 aerosols. Model inputs are a size distribution of newly lofted dust [6], and a volcanic emission rate. Sulfur photochemistry is parameterized using full photochemical model results [9,10]. Model output is a time-dependent size distribution of aerosols composed of a dust core and a H_2SO_4 coating, which we use in a line-by-line radiative transfer model [19] to calculate radiation fluxes.

Results and Discussion:

The background climate state. With a solar constant 75% its present value, we calculated global mean annual surface temperatures (MAST) of 207 and 206 K for a 0.5 and 1 bar clear-sky CO_2 atmosphere, at 80% relative humidity (Figure 1). Dust decreases MAST by ~10 and ~12 K, respectively in these cases. Tropical

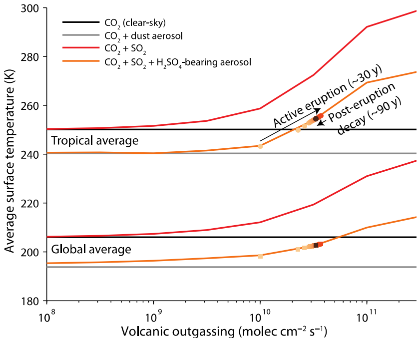

Figure 1: Global and tropical MAST as a function of the volcanic outgassing rate. Lines show the steady-state MAST, and markers show the MAST during a lengthy punctuated eruption. Without sulfur species, the steady-state global MAST with a dusty atmosphere (gray lines) is ~12 K cooler than the clear-sky case (black lines). Adding only SO_2 causes strong warming (red lines), but even with the effect of H_2SO_4-bearing aerosols, volcanic emission of SO_2 results in relatively strong net warming (orange lines).

MAST is only ~240 K with 1 bar of CO_2, too low for the sustained existence of liquid water.

The effect of punctuated eruptions. Both at the atmospheric steady state and during episodes of strong volcanic eruption, we find that injection of SO_2 into a dusty martian atmosphere causes net warming, even when scattering by H_2SO_4-bearing aerosols is included. The reason is mostly that the atmosphere already scatters an appreciable fraction of the incident solar radiation due to the presence of dust aerosols. The increase in the fraction of scattered radiation as SO_2 is photochemically converted to H_2SO_4 is minor. The major greenhouse effect by SO_2 then results in net warming.

Global average MAST do not exceed 220 K even for long-term average volcanic emission rates more than 300 times the global terrestrial rate (Figure 3), consistent with recent climate model results [10]. However, tropical MAST exceed 273 K for long-term average volcanic emission rates ~200 times the terrestrial rate. Such rates are unlikely over long periods, even given the higher sulfur content of the martian mantle. However, on the basis of the analogy between martian plains volcanism and terrestrial flood basalts, rates such as these and even higher are sustainable for years to a few decades. This implies that during punctuated eruptions, summer daytime temperatures exceed 273 K in the tropics. These conditions last well after the eruption ceases due to the relatively slow destruction of atmospheric SO_2, which has a lifetime of centuries if its atmospheric mixing ratios exceed 10 ppb [11]. Warm tropical summers may thus last up to a few centuries after exceptionally strong volcanic eruptions, consistent with growing evidence for transient rather than sustained wet conditions on the surface of early Mars [e.g., 1,2], and with the low-latitude bias in the spatial distribution of valley networks and open-basin lakes [2,3].

Climate feedbacks? The mechanism we propose suggests the existence of climate feedbacks. A positive feedback involves the scavenging of atmospheric particles as warmer conditions invigorate the hydrological cycle. When conditions become warm enough to melt ice in tropical regions, hydrological activity increases both on the surface and in the atmosphere. An increase in precipitation rates results in more rapid scavenging of atmospheric particles and a moister surface results in less efficient lofting of new dust aerosols. The decreasing optical depth of atmospheric aerosols results in less scattering of solar radiation, while greenhouse warming by SO_2 continues, leading to further warming and invigoration of the hydrological cycle.

The return to a dusty atmosphere only occurs once SO_2 levels decrease to a threshold value below which the climate becomes too cold and dry to prevent efficient lofting of dust. Due to the cleanliness of the atmosphere, this threshold value is lower than the SO_2 levels needed to trigger warmer and wetter conditions in a pre-eruption dusty atmosphere (Figure 2).

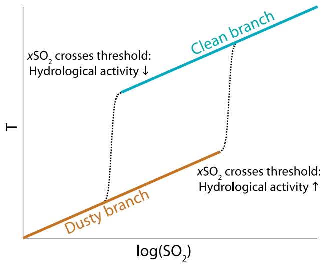

Figure 2: Hysteresis between a dusty and clean atmosphere. Episodic eruptions push a dusty atmosphere to the clean branch by causing the scavenging of atmospheric particles. After the cessation of eruptions the atmosphere returns to the dusty branch.

A negative feedback involves the influence of the liquid hydrosphere volume on atmospheric SO_2 levels. As the climate warms due to increasing atmospheric SO_2 concentrations, the volume of aqueous solutions on the surface increases. As SO_2 is highly soluble, an increasing size of the aqueous reservoir makes it harder to saturate the surface of the planet with SO_2. Consequently, rather than rapidly reaching equilibrium with atmospheric levels of SO_2 [7], the surface acts as a sink for depositing SO_2. The resulting decrease in atmospheric SO_2 concentrations causes cooling, which leads to a decrease in the size of the aqueous reservoir and releases dissolved SO_2 back into the atmosphere.

Conclusions: We suggest episodically warmer and wetter conditions due to emission of SO_2 into the martian atmosphere during punctuated volcanic eruptions with outgassing rates hundreds to thousands of times the terrestrial global average rate. The cooling effect by H_2SO_4-bearing aerosols is minor when these aerosols form in an already dusty atmosphere, such as the one expected on early Mars. For decades after punctuated eruptions, tropical summer daytime temperatures reach and even exceed 273 K, consistent with the low-latitude distribution of most known valley networks, open-basin lakes and sedimentary rock deposits.

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