MODELING A VOLCANIC ERUPTION COLUMN ON MARS: A 4D SOLUTION.

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Introduction and background: Current models for explosive volcanic eruptions on Mars are thought to overestimate the maximum sustainable plume height by tens of kilometers [1], a consequence of the simplifying assumptions behind their 1D formulations. Since an actual volcanic eruption on Mars has not been observed, the exact extent of disparity between true and modeled rise heights remains unclear. This has potentially significant impacts on the distribution of Martian primary tephra deposits. Buoyant Martian volcanic plume models [e.g., 2-6] are based on a 1D entrainment hypothesis, which states that the mixing velocity of the ambient atmosphere in a buoyant plume is proportional to its vertical velocity [7]. The underlying assumptions that govern this entrainment hypothesis are invalid when a plume rises or expands radially faster than the speed of sound, the plume expands radially faster than it rises, or if the plume is much wider than it is high [1]; these limitations inherent in the 1D models are likely to result in overestimation of plume height [1]. The maximum plume height produced by an explosive volcanic eruption on Mars has implications for not only interpreting surface deposits, but also on the evolution of the Martian climate. We present results of a new 4D, Navier-Stokes based Martian eruption simulation created by adapting the terrestrial Active Tracer High-resolution Atmospheric Model (ATHAM) [8,9]. These results can then be applied to atmospheric mixing and particulate dispersal [e.g., 10] during eruptions at suggested regions of explosive volcanism on Mars (Fig. 1).

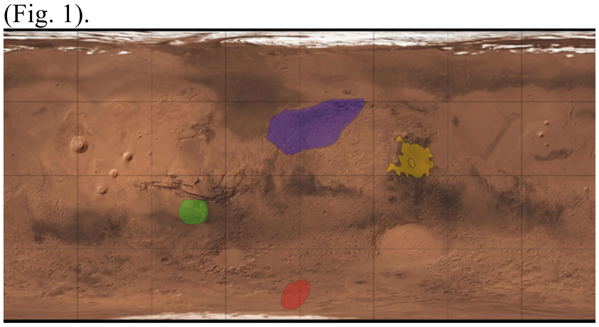

Figure 1. *Martian surface with zones of possible explosive volcanism. Green: Thaumasia Planum [11]; Red: Sisyphi Montes [12]; Blue: N. Arabia Terra [13]; Yellow: Syrtis Major Planum [14].*

Model: ATHAM was developed for terrestrial use with volcanic eruptions and large fires [8,9]. It solves the Navier-Stokes equations using a Large Eddy Simulation closure, employs phase changes within the plume, and allows direct control over plume constituents at the vent. It solves all of these over three-dimensional space plus time [15], bypassing the simplifying model assumptions from the 1D models [1-7]. We developed a new Martian module for ATHAM, collectively referred to as M-ATHAM, to adjust planetary and atmospheric conditions including gravity, atmospheric density, and thermal lapse rate.

Explosive eruptions on Mars would have occurred under different atmospheric conditions than at present. The actual conditions are unknown, so we used four different atmospheric models from the literature (Table 1) [1,16-18]. Grain sizes used were 1, 3, and 5 Φ.

Maximum plume heights are determined based on 0m/s vertical rise associated with the 0.01 ash fraction. While the arbitrary limit may be too low, increasing up to 0.1 only results in interpreted plume heights ~5% lower (e.g., Fig 2); the sensitivity to the plume height decision threshold is small relative to the impact of vent or atmospheric conditions.

Table 1. *Atmospheric conditions used in M-ATHAM. Scale height is used to calculate pressure change with altitude in atmosphere.*

	Atmo1 [1]	Atmo2 [16]	Atmo3 [17]	Atmo4 [18]
Composition (dry)	100% CO_2	100% CO_2	99.5% CO_2 0.5% SO_2	85% CO_2 15% SO_2
Relative humidity (%)	0	100	100	100
Surface temperature (K)	225	268	278	278
Climate	Cold & dry	Cold & wet	Warm & wet	Warm & wet
Surface pressure (Pa)	10^5	10^5	10^5	10^5
Scale height (km)	8	10.4	12.8	25.3
Tropopause (km)	42	38	37	55

Maximum plume rise: As anticipated, M-ATHAM plumes rise to significantly greater maximum heights than their terrestrial counterparts, which are often limited by the tropopause. Surprisingly, maximum M-ATHAM plumes are also taller than 65 km, the previously calculated tallest achievable plume via 1D modeling (Table 2), despite concerns that the 1D approach might greatly overestimate possible plume rise [1]. This is due to M-ATHAM explicitly accounting for heat exchange and resulting buoyancy changes not handled by the 1D model, as well as the varying atmospheric conditions.

Effects of atmosphere: The four proposed atmospheres have significant effects on maximum plume height. Wet atmospheres result in higher rise heights, with Atmo4 having the highest maximum plume rise for stable eruption columns (Fig. 3). In terrestrial plumes, this is a result of heat released back as they cool during rise. This magnifies the increases in maximum rise driven by M-ATHAM treating the heat exchange. In all cases, the maximum height plume breached the tropopause into the stratosphere (Table 2), thereby facilitating global distribution of gases and fine-grained particulates.

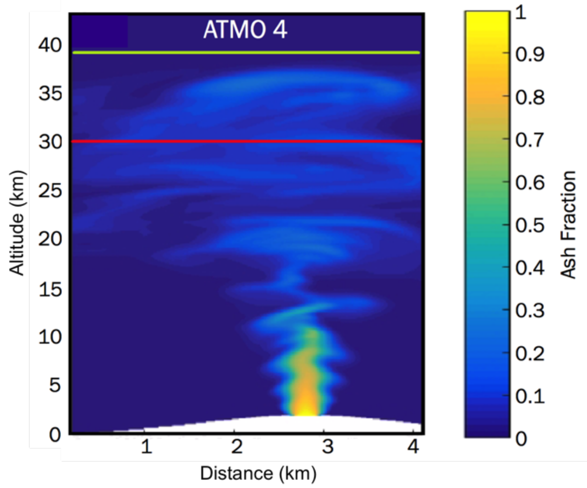

Figure 2. *Single frame snapshot of MATHAM output for vent velocity of 230 m/s and vent radius 50 m. Green horizontal line marks maximum M-ATHAM plume height; red line marks 1D plume height for the same vent conditions [1].*

Table 2. *Maximum M-ATHAM stable plume heights.*

	Max. height (km)	MER (kg/s)
Atmo1	69.2	$2.5x10^9$
Atmo2	75.8	$5.1x10^9$
Atmo3	74.6	$4.5x10^9$
Atmo4	84.8	$7.7x10^9$

Plume collapse: Plume collapse, generating pyroclastic density currents instead of a stable buoyant plume, is common in the M-ATHAM output; for simplicity, we have not included it here in detail. Plume collapse happens when the rising plume loses vertical momentum while it is still negatively buoyant. This can occur due to low vent velocities (ie, “boiling over”) or with narrow vent diameters paired with relatively fast vent velocities, in which the restricted plume cross-sectional perimeter inhibits mixing and consequent density decrease. Thus, the stability fields for Martian plumes, like terrestrial plumes, are complex and will be reported in a later manuscript.

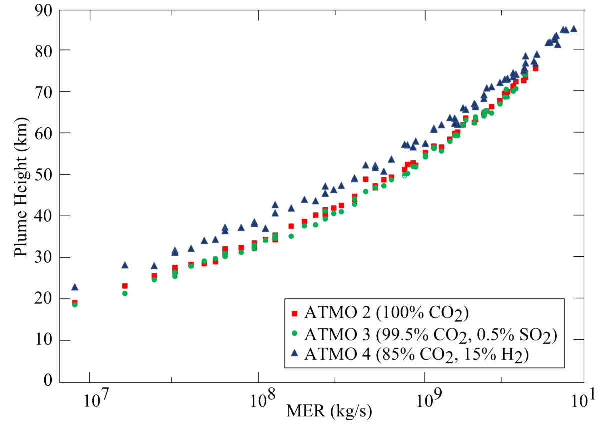

Figure 3. *Maximum plume rise height for stable plumes as a function of Mass Eruption Rate (MER) in Atmo2-4. Note: collapsed plumes not included.*

Conclusions: Contrary to expectations, use of a Navier-Stokes based plume simulator for Martian eruption plumes results in maximum feasible rise heights greater than those calculated using 1D models. This is true in all four proposed Martian atmospheres evaluated here, with the largest plumes associated with warm, wet ambient conditions. The increased maximum plume heights are a result of explicit treatment of heat exchange and changes in the assumed atmospheric conditions. This has significant implications for primary tephra distribution on Mars and differentiation of clastic deposits [10].

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