THE EFFECT OF VOLCANIC ERUPTIONS ON THE DISTRIBUTION OF WATER ICE ON MARS.

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Introduction: Fundamental processes such as volcanism can influence the surface ice budget on Mars by providing a conduit for volatile gas species to outgas from planetary interiors into the atmosphere. Water vapor is the most abundant volatile species emitted from terrestrial volcanoes [1]. Eruptions on Mars may have similarly released significant amounts of water vapor into the atmosphere over geologic time [2,3]. The balance of meteorological conditions, orbital configurations, and the injection of volcanic gases into the atmosphere may have resulted in periods of surface ice accumulation on Mars in non-equilibrium locations.

To explore this process, we select three volcanoes to represent diverse eruption types and eras and model ice accumulation from these sources in corresponding atmospheric regimes. Apollinaris Mons is a well-preserved Noachian to Hesperian-aged volcano chosen as an example of ancient, explosive eruptions on Mars [4,5,6]. Elysium Mons is a Hesperian to Amazonian-aged shield volcano characterized by the buildup of extensive lava flows [4]. Cerberus Fossae is a geologically young, Amazonian-aged fissure system located in the southeastern edge of the Elysium Volcanic Province [7]. Cerberus Fossae is interpreted to have largely erupted flood basalts indicating that large-scale eruptions occurred recently in martian history [7]. We hypothesize that volatile release during eruptions from Apollinaris Mons, Elysium Mons, and Cerberus Fossae may have contributed significantly to the surface ice budget on Mars.

Methods: Using a global climate model (GCM) developed by the Laboratoire de Météorologie Dynamique (LMD), we simulate the dispersal and deposition of volcanic water from three volcanic sources: Apollinaris Mons, Elysium Mons, and Cerberus Fossae. The GCM functions by calculating the temporal evolution of variables that control or describe the planetary climate at different points on a 3-D grid spanning the atmosphere up to a height of ~32 km [8,9]. The GCM accepts volcanically-driven water vapor as a tracer where it is released at a plume height up to 31 km depending on the atmospheric pressure [10]. As water vapor is released into the GCM, it freezes and is advected by the wind until it finally deposits onto the surface as ice.

A water mass flux of 10^6 kg/s is assumed and the eruption duration is varied from 1–60 sols. We further explore the sensitivity of the model to the atmospheric pressure (6.1 mb– 1 bar), longitude of perihelion (current value and opposite value), eccentricity (0.093 and 0), obliquity (15º–60º), dust opacity (0–5), and the season at the time of eruption (spring–winter).

Results: Our control environmental variables are set to modern Mars conditions: an obliquity of 25.19º, 6.1 mb atmospheric pressure, an eccentricity of 0.093, a longitude of perihelion that coincides with late northern autumn, and trace amounts of non-volcanic water in the atmosphere. We further assume a dust opacity of 0 and a 15-sol volcanic eruption during the spring as our control case. An eruption from Cerberus Fossae is used to explore the parameter space and the sensitivity of ice distribution to environmental variables.

Eruption Duration: The eruption duration in this study is described as the time period in which water vapor is continuously emitted into the martian atmosphere. Following a 1-sol eruption, thin deposits of ice ranging from 1×10^{-4}–1 mm in thickness form near the volcano. As the eruption duration increases, surface ice thickness increases and areal distributions reach near-global coverage. Following a 60-sol eruption, ice deposits reach up to 10 mm in thickness. The thickness of ice is greatest near the confines of the volcano, Hellas Basin, Terra Cimmeria, Argyre Basin, the Tharsis region, and in the northern latitudes above Elysium Planitia. For all durations, the remaining ice injected into the atmosphere following the cessation of an eruption eventually settles onto the surface and creates wider distributions.

Atmospheric Pressure: Apollinaris Mons is used as an example case for the atmospheric pressure sensitivity test to reflect the uncertainty of Mars' atmospheric pressure during the Noachian–Hesperian. A 15-sol volcanic eruption under a 6.1 mb atmospheric pressure results in a wider distribution of ice in comparison to a 1 bar atmospheric pressure with the same duration (Fig. 1). Differences in ice distribution are a function of the atmosphere's holding capacity. Denser atmospheres have a greater holding capacity resulting in a lower rate of ice deposition onto the surface. Conversely, a thinner atmosphere has a lower holding capacity resulting in a greater rate of ice deposition on the surface.

Longitude of Perihelion: The longitude of perihelion indicates the season of closest approach to the Sun [11]. When the longitude of perihelion is reversed (i.e., when the perihelion coincides with the late northern spring as opposed to the late northern autumn), the result is warmer surface temperatures during the northern spring and enhanced surface lifting of ice due to Mars' proximity to the Sun. Higher surface temperatures result in a more energetic atmospheric circulation, a greater degree

of ice accumulation at higher elevations, and an overall wider distribution of surface ice. Under a present-day perihelion, atmospheric circulation is more muted during the northern spring, causing ice to primarily accumulate near the volcanic center.

Obliquity: Changes in obliquity cause the planet to spin in a different orientation with respect to the Sun. As a result, there are variations in planetary heating and slight changes in the distribution of ice. Higher obliquities result in less ice at the poles and a shift in distribution of ice towards the equator. Lower obliquities result in a broadening of the ice deposit, while higher obliquities cause the ice to become more concentrated toward the volcano.

Eccentricity: When the eccentricity is set to 0, (i.e., circular orbit) the durations of each season are equal. The total mass of surface ice increases linearly with time in a circular orbit. Ice deposition follows a similar pattern under an eccentric orbit until perihelion is reached. At this time, ice begins to sublime and deposit on a diurnal cycle due to Mars' close proximity to the Sun. Changes in Mars' eccentricity have an overall small impact on the surface ice distribution.

Seasons: The distribution of ice is sensitive to variances in the season and is heavily dependent on the latitude of the eruption. Assuming a 15-sol eruption occurs under a present-day eccentricity, eruptions that occur at a higher latitude (i.e., Elysium Mons and Cerberus Fossae) during the northern spring, summer, and autumn results in ice deposition primarily near the poles. Eruptions near the equator (i.e., Apollinaris Mons) produce ice deposits that generally remain confined to that region. For the northern winter, eruptions from each volcano result in an eastward ice distribution. In all cases, deposition and sublimation occur at a slower rate during the northern spring and autumn equinoxes and are the fastest during the summer and winter solstices.

Dust: We vary the dust opacity from 0 (no dust), to 1 (moderately dusty atmosphere), to 5 (extreme global dust storm). Due to the downwelling radiative impacts of dust [12], higher dust loading in the atmosphere can lead to an increase in surface and atmospheric temperatures. As the amount of dust loading in the atmosphere increases, zonal circulation is intensified and the distribution of ice narrows in the latitudinal direction.

Surface Ice Survival: A 10-year simulation was run after the cessation of the control eruption to test the survival time of surface water ice. The greatest rate of sublimation occurs during the northern autumn–winter months as they coincide with perihelion. When the ice sublimates, it lingers in the atmosphere as water ice clouds before depositing back down to the surface. Ice deposition increases as the northern spring approaches and remains stagnant until the autumn equinox. Ice deposition is interpreted to be at its greatest when Mars reaches aphelion just before the northern summer solstice. Surface ice undergoes a cycle of sublimation and increasingly higher deposition each year as ice is slowly exhausted from the atmosphere over time.

Conclusions: We tested the sensitivity of model results to various parameters describing planetary conditions at the time of an eruption from Apollinaris Mons, Elysium Mons, and Cerberus Fossae. The distribution of ice is highly sensitive to the season of eruption, the atmospheric pressure, eruption duration, obliquity, the longitude of perihelion, and the presence of dust in the atmosphere. Ice distributions are less sensitive to variances in eccentricity. Under a present-day atmospheric pressure, ice can survive on the surface for at least 10 years. Future, longer simulations following an eruption will allow us to further track the survival time of surface ice.

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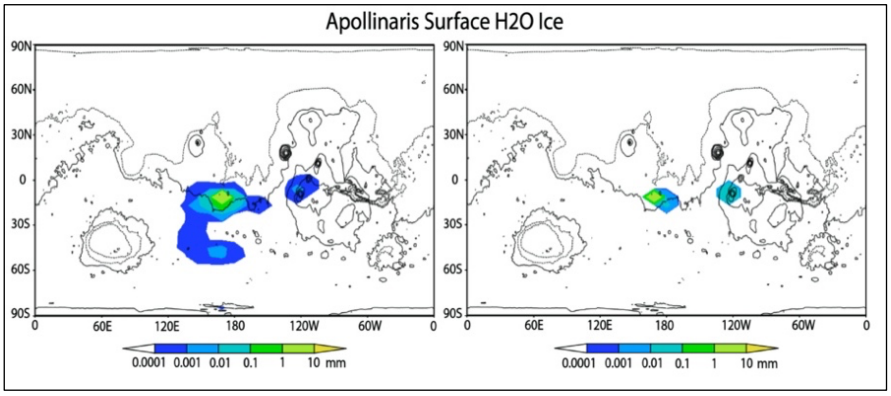

Figure 1: The total accumulation of surface ice is inversely proportional to the atmospheric pressure. A 15-sol volcanic eruption from Apollinaris Mons under a 6.1 mb atmospheric pressure (left) is compared to a 1 bar atmospheric pressure (right).