EXPLORING THE INFLUENCE OF VOLCANISM-INDUCED HEATING ON THE EARLY CLIMATE OF MARS. A. Palumbo[1], J. Head[1], and R. Wordsworth[2], [1]Dept Earth, Environ. & Planetary Sci, Brown Univ, Providence, RI 02912 US, [2]Sch Engin. & App. Sci, Harvard Univ, Cambridge, MA 02138 US, (Ashley_Palumbo@Brown.edu).

Introduction: The nature of the early martian climate remains a compelling scientific problem in our understanding of the planet's evolution. The identification of valley networks (VNs) [1,2], lakes [3–5], and aqueous alteration products [6] suggest that there was abundant liquid water on the surface during the Noachian. This evidence for the presence of liquid water has led to the reasonable deduction that the early climate was "warm and wet", characterized by temperatures >273 K and persistent rainfall [7]. However, climate models have great difficulty in reproducing a sustained background "warm and wet" climate due to the faint young Sun [8,9]. Instead, models suggest that the climate was "cold and icy", characterized by mean annual temperature (MAT) ~225 K, an adiabatic cooling effect, and ice distributed across the southern uplands [9]. In this "Late Noachian Icy Highlands" (LNIH) scenario, VNs are correlated with the distribution of ice accumulation [10] and lakes are distributed near the edge of the ice sheet, where runoff and ponding would be expected if ice melting occurred [11].

Thus, the VNs and lakes are spatially consistent with ice melting, runoff, and ponding in a LNIH climate; however, a transient or punctuated heating mechanism is required to increase temperatures sufficiently for ice melting to occur. One possible way to increase temperatures is through volcanic eruptions releasing sulfur-based gases into the atmosphere [e.g. 12].

Background: SO_2 and H_2S are strong greenhouse gases in the martian atmosphere because they have fundamental absorptions in the IR atmospheric window [13]. Also, it has been suggested that martian magmas are more enriched in sulfur than terrestrial magmas [14], implying that large amounts of sulfur-based gases can be introduced into the atmosphere for relatively small eruption volumes. Further, at least 30% of the surface was covered with basaltic plains by punctuated Late Noachian and Hesperian flood volcanism [15,16], implying that volcanism was an active and important geologic process in earlier martian history. Thus, understanding the influence of volcanism on the climate is critical to interpreting the geologic and climatic history of Mars.

Previous studies have used climate and radiative transfer models to calculate the heating associated with the injection of volcanic gases into the atmosphere, such as SO_2 and H_2S [12,17–20]. Many studies have concluded that these gases cannot produce the necessary climatic change because (1) MAT cannot exceed 273 K for reasonable gas concentrations [19], and (2) the heating may only last up to a few years [20]. Heating is expected to be short-lived because the sulfur-based gases coalesce onto pre-existing atmospheric water vapor and dust to form aerosols, which act as cooling agents. However, recent studies have shown that significant summertime melting can occur in equatorial regions for MAT <<273 K [MAT ~243 K; 21] and, for MAT 273 K, the volume of water required to form the VNs and lakes [22] would be produced in only one year through summertime melting [23]. Thus, we explore whether the warming associated with SO_2/H_2S is sufficient to produce substantial summertime meltwater. The goal of this analysis is to revisit volcanism as a possible mechanism for punctuated heating, ice melting, and VN/lake formation.

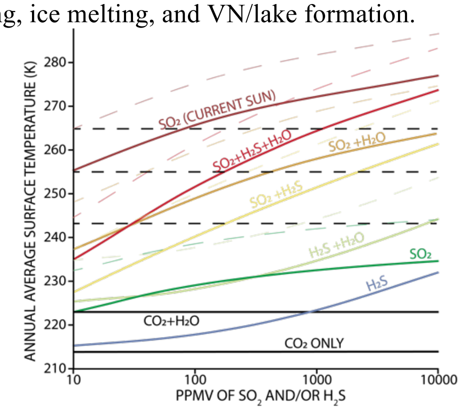

Fig. 1. Adapted from [20]. Horizontal lines at 243 K (**fig. 2**), 255 K and 265 K. (solid) 0.5 bar CO_2 and varying H_2S/SO_2. (transparent dashed) 1 bar CO_2 (+~10 K). Unless specified, the atmosphere is dry, with solar luminosity 75% present value. The range of SO_2/H_2S includes unreasonable values [e.g. >100s ppmv; 20].

Methods: We use the 3D Laboratoire de Météorologie Dynamique General Circulation Model (LMD GCM) for early Mars to estimate the amount of meltwater produced when considering the presence of volcanic SO_2 and H_2S in the atmosphere. We run the model at a spatial resolution of 64×48×18 and collect hourly data. These spatial and temporal resolutions are sufficient to capture the seasonal and regional variation that is necessary to complete our study. Because volcanic eruptions occur at a variety of scales, we explore a range of SO_2 and H_2S concentrations, from 10-10,000 ppmv [20]. The ambient climate is 0.5-1 bar CO_2 [20], ~34 m GEL water [24], 25°-55° obliquity [25], and 0-0.17 eccentricity [25]. For simulations with non-zero eccentricity, we also consider two longitude of perihelion scenarios, L_s=270° and 90° or southern and northern hemispheric summer, to produce conditions most suitable to summertime melting.

Next, we utilize GCM output of temperature and equilibrated ice distribution to perform a positive degree day (PDD) analysis [21,23]. A PDD analysis uses temperature as a proxy for thickness of ice melted in one day; for one day, the PDD value is identified as the average number of degrees above freezing. At each lat/lon model grid point where ice is present and PDD>0, we estimate the thickness of ice melted in one day at that location by multiplying the PDD value by 1.08 mm/PDD [23]. To estimate the global volume of meltwater produced in one day, we sum the thickness of ice melted globally and multiply by the area where ice is present and PDD>0. We repeat this process for every day in one year. Then, we sum over the estimated duration of heating to determine the volume of meltwater produced in one volcanic heating event. We assume that volcanic heating will last for one season, similar to minimum estimates from previous studies which suggest that heating may only last a few months [26]. Thus, for colder scenarios where temperatures will only exceed 273 K in the summer, the eruption must occur near the beginning of summer to produce significant meltwater. We (1) compare the volume of ice melted from one volcanic event with the volume of water required to fill the open-basin lakes, 0.42 Mkm^3 [4], and incise the VNs, 3-100 m GEL [22], and (2) compare the meltwater distribution with VN/lake distribution, to assess whether volcanic heating was an important process for meltwater production and VN/lake formation.

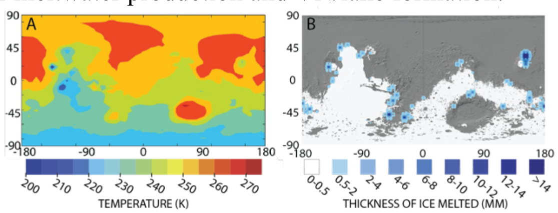

Fig. 2. (A) GCM result, MAT 243 K. Simulation was done by [21] with artificial warming, and we note that warming from SO_2/H_2S absorption may produce a different result. (B) Results from PDD analysis showing thickness of ice melted (mm) per yr for the climate in (A).

Results and Discussion: We have reproduced the simulations of SO_2 and H_2S in the atmosphere at varying concentrations [following 20], for atmospheric pressures of 0.5 and 1 bar (Fig. 1). As shown in Fig. 1, it is difficult to increase MAT to ≥273 K with this mechanism [20,26] and doing so requires unrealistic amounts of SO_2/H_2S or current solar luminosity, both of which are unlikely [14,27]. Producing MAT 273 K in a 1 bar atmosphere would require less SO_2/H_2S than in 0.5 bar, but still requires the unrealistic amount of ~1000 ppmv.

Recent work has shown, however, that significant summertime melting can occur for conditions only slightly warmer (~18 K) than ambient LNIH conditions (MAT 225 K) [21,23], so we have implemented a PDD analysis to determine the amount of summertime melting. Fig. 2 is example output from a PDD analysis for a slightly warmed planet (MAT 243 K) with 25° obliquity and eccentricity of 0. Obliquity is a major control on the distribution of meltwater; low obliquity focuses meltwater at low latitudes. For MAT 243 K, 1.45×10^{-4} m GEL of meltwater is produced annually through summertime melting. Thousands to tens of thousands of summers with these climatic conditions would be required to produce enough meltwater to form the VNs/lakes, less than the duration of one obliquity cycle [25]. For warmer climates, recent work has shown that 0.01-0.03 Mkm^3/yr meltwater is produced in a 255 K MAT climate, and 0.08-0.2 Mkm^3/yr in 265 K MAT climate [23]. These conditions would need to repeat for ~14-42 yrs and ~2-5 yrs to produce enough meltwater to fill the lakes, respectively. If warm climates persisted during periods of low obliquity, meltwater would focus in equatorial regions where VNs/lakes are abundant, implying a possible correlation.

The amount of SO_2/H_2S required to produce MAT 243 K, 255 K, or 265 K are reasonable (only a few 100 ppmv; Fig. 1) and the number of years, or number of eruptions spanning a single summer, is also reasonable when considering one or more active volcanoes [e.g. 28]. It is likely that volcanism was an abundant and active process earlier in martian history, as evidenced by significant volcanic resurfacing [15,16]. Thus, a combination of volcanic eruptions at various scales could have contributed to the production of significant meltwater through punctuated, modest duration events. It is important to note that the number of eruptions estimated here is a lower limit because it is likely that many eruptions will occur outside of the summer season and winter temperatures would be too cold to produce significant melting in the equatorial region, especially for relatively high eccentricity and obliquity conditions. We are currently assessing the amount of meltwater produced for the full range of simulations produced in this analysis.

Conclusions: In order to form the VNs and lakes in a "cold and icy" climate, punctuated heating events are required to melt ice, producing runoff and ponding. In this contribution, we consider the climatic influence of volcanically-released gases. Reasonable concentrations of SO_2/H_2S cause a transient temperature perturbation. As a result, summertime temperatures increase above 273 K in the equatorial region, permitting significant seasonal ice melting. Our preliminary analysis shows that this effect can produce sufficient meltwater for VN/lake formation. Thus, it is possible that a continuous "warm and wet" climate is not required to form the VNs and lakes, and that they instead were formed through punctuated heating in a "cold and icy" climate.

Acknowledgements: This work was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program for AMP; Grant 90NSSC17K0487.

References: [1] Hynek, B. et al. (2010) *JGR Planets*, *115*, E09008. [2] Hoke, M. et al. (2011) *EPSL*, *312*, 1–12. [3] Cabrol, N. & Grin, E. (1999) *Icarus*, *142*, 160–172. [4] Fassett, C. & Head, J. (2008) *Icarus*, *198*, 37–56. [5] Goudge, T. et al. (2015) *Icarus*, *260*, 346–367. [6] Bibring, J. et al. (2006) *Science*, *312*, 400–404. [7] Craddock, R. & Howard, A.(2002) *JGR Planets*, *107*, 5111. [8] Forget, F. et al. (2013) *Icarus*, *222*, 81–99. [9] Wordsworth, R. et al. (2015) *JGR Planets*, *120*, 1201–1219. [11] Head, J. & Marchant, D. (2014) *Antarct. Sci.*, *26*, 774–800. [12] Halevy, I. & Head, J. (2014) *Nat. Geosci.*, *7*, 865–868. [13] Postawko, S. & Kuhn, W. (1986) *JGR Solid Earth*, *91*, 431–438. [14] Gaillard, F. & Scaillet, B. (2009) *EPSL*, *279*, 34–43. [15] Head, J. et al. (2002) *JGR Planets*, *107*, 3–1. [16] Tanaka, K. et al. (2014) *PSS*, *95*, 11–24. [17] Johnson, S. et al. (2008) *JGR 113*, E08005. [18] Johnson, S. et al. (2009) *JGR Planets*, *114*, E11011. [19] Mischna, M. et al. (2013) *JGR Planets*, *118*, 560–576. [20] Kerber, L. et al. (2015) *Icarus*, *261*, 133–148. [21] Palumbo, A. et al. (2018) *Icarus*, *300*, 261–286. [22] Rosenberg, E. et al. (2015) *PSS*, *117*, 429–435. [23] Fastook, J. & Head, J. (2015) *PSS*, *106*, 82–98. [24] Carr, M. & Head, J. (2015) *GRL*, *42*, 2014GL062464. [25] Laskar, J. et al. (2004) *Icarus*, *170*, 343–364. [26] Tian, F. et al. (2010) *EPSL*, *295*, 412–418. [27] Gough, D. (1981) *Sol. Phys.*, *74*, 21–34. [28] Wilson, L. & Head, J. (2009) *JVGR*, 290–297.