POST-IMPACT CLIMATES ON EARLY MARS: REVISITING 1-D SCENARIOS WITH A 3-D GCM.

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Introduction: Comet and asteroid impacts have been studied as a mechanism for inducing warm and wet conditions on early Mars, given the significant amounts of water vapor and energy they inject into the atmosphere [1, 2, 3, 4]. The 1-D modeling studies of Segura et al. [1, 2, 3] were the first to explore this hypothesis in detail, showing that post-impact climates are capable of producing 10s of cm to 10+ m of rainfall and several days to years of above-freezing temperatures. This work [1, 2, 3] is the foundation on which the Mars community explores and assesses the validity of the impact heating hypothesis for early Mars [5, 6]. We further test this hypothesis by simulating the post-impact climate cases of [1] using a 3-D global climate model (GCM) with a self-consistent hydrologic cycle.

Since the publication of the Segura et al. [1, 2, 3] studies, a new potential paradigm for early Mars known as the icy highlands hypothesis [7] has called the duration of warm and wet periods in the Noachian and early Hesperian into question. GCM modeling work shows that in early Mars climate scenarios with massive CO_2 atmospheres, adiabatic cooling results in significant water ice accumulation in the southern highlands [7]. In the icy highlands scenario, periodic warming from volcanism or impacts could cause snowmelt and runoff in the southern highlands to form valley networks [7]. Whether the geologic evidence supports this hypothesis is a subject of debate. In contrast to the idea of a transiently warm early Mars, Segura et al. [3] suggest it might be possible for impacts to induce a long term, stable, warm runaway climate. Exploring the impact heating hypothesis in this new context of the icy highlands scenario and the greater debate regarding the duration of warm and wet periods provides additional motivation to revisit this work.

The ARC early Mars GCM: The Ames Research Center (ARC) Mars Global Climate Model (MGCM) is a 3-D numerical model that simulates physical and dynamical processes in Mars' atmosphere [8]. The following physics treatments differ from the standard ARC MGCM [8] to more accurately represent Mars during the late Noachian/early Hesperian. We refer to this version of the model as the ARC early Mars GCM. Solar luminosity is decreased to 75% of its current value and surface pressure is increased. An updated correlated-k radiative transfer scheme includes CO_2 far line absorption [9], accounts for CO_2 collisionally induced absorption [10], and extends the temperature range of the radiation code up to 800K. CO_2 clouds and CO_2 surface exchange is not currently included, nor are they in Segura et al. [1]. These simulations do not currently include atmospheric dust or a dust cycle.

Representation of hydrologic cycle. An important difference between the ARC early Mars GCM and the 1-D model described in Segura et al. [1] is that the GCM includes a self-consistent hydrologic cycle. The microphysics code carries three tracers similar to the treatment in Wordsworth et al. [7] (tracers for CO_2 clouds, H_2O vapor, and H_2O clouds). Water clouds condense or evaporate when a region becomes supersaturated or subsaturated respectively, accounting for latent heat exchange [11]. The radiative effects of clouds are accounted for with separate treatments for liquid water particles and ice particles. Segura et al. [1] include some 150-mbar surface pressure cases with radiatively active clouds in which particle sizes are constant at 100 microns or 1 mm. In the ARC Mars GCM, spherical cloud particle sizes are calculated based on the total mass in a grid box and a constant number of cloud condensation nuclei of 10^5 particles per kg of CO_2 [7]. These water cloud particles undergo size-dependent gravitational sedimentation. Precipitation occurs when clouds exceed a mass mixing ratio of 0.001 kg of water per kg of CO_2 [7] after which excess mass is put directly on the ground as precipitation. In Segura et al. [1], precipitation occurs when clouds form near the surface, at which point water from the column is transferred to the surface. A moist convection scheme based on Manabe et al. [11] and Manabe and Wetherald [12] is incorporated in addition to the standard dry convective adjustment [8].

Initial conditions for impact scenarios: We simulate post-impact scenarios from Segura et al. [1] matching the described initial conditions as closely as possible. The main cases in Segura et al. [1] represent 30-km, 50-km, and 100-km diameter impactors in a 150-mbar atmosphere; 50-km and 100-km impactors in a 1-bar atmosphere; and a 50-km impactor in a 2-bar atmosphere. The three impact sizes of 30-km, 50-km, and 100-km inject global equivalent layers of water that are 0.1534, 0.3563, and 1.75 m in depth respectively. This water is distributed globally as vapor. Segura et al. [1] also allow subsurface ice to be melted and then instantaneously brought to the surface where it is available to be evaporated. Most of this subsurface melt is evaporated into the atmosphere fairly quickly, within the first simulated year (Figures 2, 5, and 11 in [1]). We choose to initialize the subsurface melt (1.15 m for scenario in Figs 1-3) as water vapor in our simulations. Initial temperature profiles follow the descriptions in Segura et al. [1] with initial near-surface temperatures of 600K for 30- and 50- km impacts and 700K for a 100-km impact. Profiles then follow the moist adiabat up through the model top. We also incorporate the thick, hot debris layer in our subsurface model, which has a temperature of 1600K and depths of 0.0696, 0.277, and 2.23 m as per Segura et al. [1].

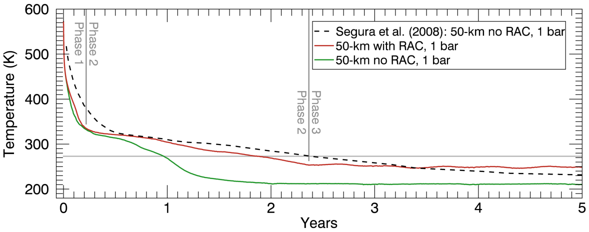

Figure 1: Global average surface temperature in K with time for 50-km, 1-bar post impact scenarios with (red line) and without (green line) radiatively active clouds (RAC). Horizontal gray line is at 273K and vertical gray lines mark transitions between Phases 1, 2, and 3 for the RAC case.

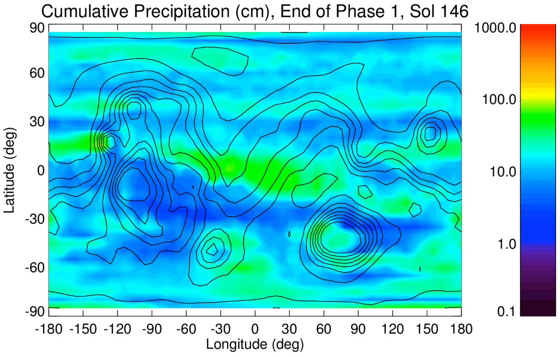

Figure 2: Cumulative precipitation in cm through the end of Phase 1 (Sol 146) for the 50-km, 1-bar post impact scenario with radiatively active clouds.

Results: Temperature behavior in the post-impact scenarios can generally be distinguished in three phases. Figure 1 shows global average surface temperature with time for the 50-km, 1-bar post-impact scenarios to illustrate this. In Phase 1, the atmosphere rapidly cools until cloud formation becomes significant, slowing this cooling. Figure 2 shows the cumulative precipitation in cm as a function of latitude and longitude at the end of Phase 1 for the 50-km, 1bar case with radiatively active clouds. In Phase 2, temperatures still decline, but widespread cloud formation releases latent heat, keeping temperatures relatively warm. The majority of precipitation occurs during this phase as cloud opacities are highest. Radiatively active clouds approximately double the duration of Phase 2 in the 50-km, 1-bar case (Fig 1). Higher surface pressures, larger impacts, and radiatively active clouds all extend the duration of this phase and ultimately result in more precipitation. Despite the warming boost from cloud formation, cooling does continue and eventually, surface temperatures drop below freezing. These simulations account for albedo feedback from the rocky Martian surface (0.2), liquid water (0.07), and water ice (0.5). Therefore, once surface ice layers are thick enough, the albedo increases and this accelerates cooling. Eventually temperatures level out and remain stable, which we define as Phase 3. Scenarios with radiatively active clouds retain warmer surface temperatures in this phase than those without (Fig 1). Figure 3 shows the cumulative precipitation at the end of Phase 2. Although significant amounts of precipitation (up to ~10 m) can result from impacts (Fig 3), ultimately this warm and wet period is relatively short lived (on the order of years at most) compared to timescales of valley network formation (~10^4-10^7 years [13]). Thus far, results indicate that inducing prolonged periods (hundreds to thousands of years) of warm and wet conditions following an impact is unlikely.

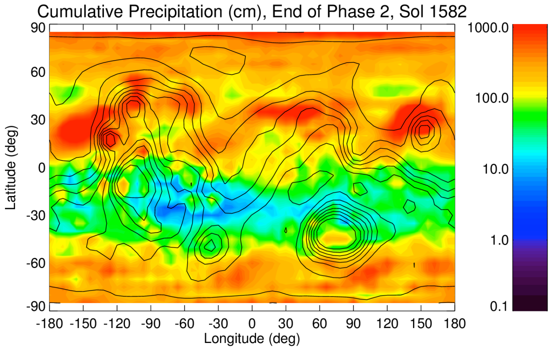

Figure 3: Cumulative precipitation in cm through the end of Phase 2 (Sol 1582) for the 50-km, 1-bar post impact scenario with radiatively active clouds.

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