**EXAMINING THE POTENTIAL FOR HABITABILITY IN A POST-IMPACT REDUCING GREENHOUSE CLIMATE ON EARLY MARS.**
K. E. Steakley[1], M. A. Kahre[1], R. M. Haberle[1], K. J. Zahnle[1], [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035, kathryn.e.steakley@nasa.gov.

**Introduction:** Surface geologic evidence implies that liquid water altered Mars's surface in various ways during the Late Noachian and Early Hesperian eras (roughly 3.6 - 3.8 Gya) [1]. There is debate within the community regarding what mechanism(s) may have induced warmer, wetter periods during the first billion years of Mars's history and the timescales over which they were active.

Collision induced absorption (CIA) between $CO_2$ molecules and reducing greenhouse gases such as $H_2$ and $CH_4$ are one potential mechanism for inducing at least a temporary warm and wet climate on early Mars [2, 3, 4]. However, it remains to be shown what could have produced reducing greenhouse gases in the quantities required to raise surface temperatures above freezing (molar mixing ratios of a few to 10% of a $CO_2$ atmosphere depending on surface pressure; [3, 4]). Haberle et al. [5, 6] propose that asteroids could have been capable of delivering reducing greenhouse gases to early Mars via impact degassing. It has been suggested that impact degassing could have maintained a reducing atmosphere for the early Earth rich in $CH_4$, $H_2$, $H_2O$, $N_2$, and $NH_3$ [7, 8, 9]. Haberle et al. [5, 6] calculate the quantities of $H_2$ that could be delivered to early Mars by impacts and show that for large impactors (>100 km), they exceed quantities required to support above-freezing mean annual surface temperatures in a 1-bar atmosphere according to Wordsworth et al. [3]. They estimate that the cumulative durations of above-freezing surface temperatures due to impact degassing of $H_2$ during the mid to late Noachian were of the order of $10^5 – 10^6$ years [6]. The impact hypothesis has the advantage over other mechanisms in that there is ample evidence of crater formation during the Noachian, but is problematic for explaining some geologic observations because the largest craters pre-date the end of valley network activity and the formation of alluvial fans [10].

Previous assessments of potential post-impact greenhouse warming for early Mars focused only on the water and energy delivered by impacts and show that – although capable of inducing periods of above-freezing temperatures and high rainfall rates – these effects are short lived, on the order of a few years at most following an individual impact [10, 11, 12, 13]. The introduction of $H_2$ to an already warm and wet environment following an impact is an ideal way to prolong warm and wet climate conditions on early Mars. Here, we use a 3-D global climate model (GCM) to simulate post-impact scenarios similar to those explored in Steakley et al. [10], now accounting for $H_2$ delivered by these impacts to test whether this extends the duration of warm and wet conditions. We examine reducing greenhouse post-impact climate conditions including global distributions of rainfall and warm surface temperatures and their evolution over time and assess metrics of fractional habitability in these climates.

**Initial Conditions:** In the early, extremely hot stage of a post-impact environment, reduced iron from an impactor and water (from both an impactor and water that is excavated from the planet subsurface during crater formation) can react to produce FeO and $H_2$. Here we estimate the amount of $H_2$ that could be produced from Fe and $H_2O$ given a few simple assumptions. We assume the impactor is an iron rich H-type ordinary chondrite that is 30% iron by mass [14] and has a density of 3.4 g/cm$^3$. Assuming all the iron is used to make $H_2$ ($Fe + H_2O \rightarrow FeO + H_2$), we estimate that the atmospheric molar concentration of $H_2$ produced by an impact. Other compounds (e.g., $CH_4$) could be generated during this process, however, for this study we focus exclusively on the maximum amount of $H_2$ that could be produced. Given these assumptions, minimum impact diameters of roughly 83 km and 101 km in 2- and 1- bar atmospheres respectively could produce molar concentrations (of 0.03 in a 2-bar atmosphere and 0.1 in a 1 bar atmosphere) high enough to maintain surface temperatures > 270K [3]. It is therefore feasible that impactors of the larger sizes explored in Segura et al. [11, 12] and Steakley et al. [10] could have delivered planetwide warming quantities of hydrogen if they impacted atmospheres with large enough surface pressures.

Here, we simulate a 2-bar $CO_2$ atmosphere following an impact by a 100-km diameter object in which only the water and energy injected into the atmosphere by that impact are considered (Case A), and a simulation in which Fe delivered by a 100-km impact reacts with the $H_2O$ injected into the atmosphere to form $H_2$ (Case B). Following the post-impact initial conditions described in Segura et al. [12], the simulations are initialized with a vertical atmospheric temperature profile following the moist adiabatic lapse rate with a near-surface temperature of 700K. Initially, there is a hot (1500K) subsurface layer that is 2.23 m deep to represent a global debris layer formed from the impact. Case A is initialized with a well-mixed atmospheric water vapor content equivalent to a 1.75-m thick layer of water if it were evenly distributed on the surface. For case B, we initialize the simulation with a well-mixed water vapor content equivalent to a global layer 0.5566 m thick and a fixed molecular concentration of hydrogen of 0.054 to account for the quantities of $H_2O$ lost and $H_2$ produced following a 100-km diameter impactor that is 30% iron by mass. On the timescales over which we run our simulation (15 Mars years), the escape rates of hydrogen from the atmosphere (on the order of $10^{11}$ molecules $cm^{-1}$ $s^{-1}$ [3, 6]) are negligible.

**Early Mars Global Climate Model:** We utilize the NASA Ames Legacy early Mars Global Climate Model (eMGCM), which is supported by the Agency's Mars Climate Modeling Center. This version of the model uses an Arakawa C-grid dynamical core: ARIES version 2 [10]. A 2-stream radiative transfer scheme with correlated-k's accounts for gaseous $CO_2$ and $H_2O$ absorption. We incorporate the Wordsworth et al. [3] coefficients for $CO_2$-$H_2$ CIA (adjusted by a factor of 1.6 as per Turbet et al. [15]) into the eMGCM radiation treatment in addition to existing coefficients for $CO_2$-$CO_2$ CIA. The radiative effects of liquid and ice $H_2O$ cloud particles are also accounted for [10]. Physical treatments of water cloud microphysics in the eMGCM include bulk $H_2O$ cloud condensation and sublimation when the atmosphere is supersaturated or sub-saturated (with condensed cloud mass distributed equally between a constant number of spherical particles; $10^5$ condensation nuclei per kg of $CO_2$), precipitation when cloud mass mixing ratios exceed 0.001 kg of $H_2O$ per kg of $CO_2$, gravitational sedimentation, and moist convection [10]. In these simulations, the $CO_2$ cycle is excluded such that $CO_2$ does not condense onto the surface nor condense to form clouds. Dust exists as condensation nuclei for $H_2O$ clouds but is not radiatively active, is not lifted from the surface, nor advected through the atmosphere. To represent the faint young Sun approximately 3.8 Gya, solar flux is decreased to 75% of its present day value [16]. Constant values are used for surface thermal inertia (250 J $m^{-2}$ $s^{-1/2}$ $K^{-1}$ ) and surface albedo (0.2 for regolith, 0.5 if surface ice is present, 0.07 if liquid surface water is present). Mars' present day topography is used.

**Preliminary Results:** We will present preliminary 3-D eMGCM simulation results examining post-impact environments which account for $H_2$ impact degassing and those in which it is absent and will evaluate the potential habitability of these climates. We will specifically examine annual rainfall and surface temperature distributions in this assessment. Our preliminary eMGCM simulation results suggest that in the aftermath of a 100-km diameter impact in a 2-bar CO2 atmosphere with impact-degassed $H_2$, surface temperatures initially cool rapidly but can equilibrate to warm conditions above 273 K (as also shown in [3, 4]). A clear potential issue for habitability in these environments is the extremely high temperatures from the impact itself. If these initial conditions could be survived, the resulting long-term conditions may be suitable for life. We will examine simulation results for their potential to produce habitable environments, including annual surface temperature variations, annual rainfall patterns, and fractional habitability metrics with respect to time and planet surface area as in Spiegel et al. [17].

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