

Exploring post-impact reducing greenhouse climates for early Mars with the NASA Ames Mars Global Climate Model

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Abstract

We simulate the early Mars climate response to an impact accounting for water, energy, and H₂ injected into the atmosphere. We utilize the NASA Ames Legacy early Mars Global Climate Model (eMGCM) to assess whether the post-impact environment would be conducive to the formation of surface fluvial features.

1. Introduction

Reducing greenhouse gases H₂ and CH₄ have been shown to be capable of warming early Mars by increasing opacity due to collision induced absorption (CIA) with CO₂ molecules [1, 2]. Theoretical calculations of CO₂-H₂ and CO₂-CH₄ CIA by Wordsworth et al. [2] show that mean annual surface temperatures could have exceeded 273K for early Mars in 1.25 - 2 bar CO₂ atmospheres with molar concentrations of H₂ and CH₄ between 2 and 10%. Laboratory measurements of CIA by Turbet et al. [4] over a subset of the wavelengths presented in Wordsworth et al. [2] have been shown to be lower by a factor of 1.6 and 1.7 for H₂ and CH₄ respectively. Both [2] and [4] show that CIA between reducing gases and CO₂ is more significant than between those gases and N₂ (as in [1]).

Impacts have been suggested as a potential for degassing H₂ and CH₄ into the early Martian atmosphere [5, 6]. It is thought that impact degassing could have maintained a reducing atmosphere for the early Earth rich in CH₄, H₂, H₂O, N₂, and NH₃ [7, 8]. Haberle et al. [5, 6] calculate the quantities of H₂ 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. [2]. They estimate that the cumulative durations of above-freezing surface temperatures due to impact degassing of H₂

during the mid to late Noachian could have been on the order of 10⁵ – 10⁶ years [6]. The impact hypothesis for warming early Mars has the advantage over other mechanisms 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].

Prior investigations of potential post-impact greenhouse warming for early Mars focus primarily on the water and energy delivered to by impacts. These studies show that although impacts can induce periods of above-freezing temperatures and high rainfall rates, these effects are short lived, on the order of a few years at most [10, 12, 13]. 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 impact delivered H₂ to test whether this extends the duration of warm and wet conditions. We examine the global distributions of rainfall and warm surface temperatures that follow a single impact and assess whether such an environment is consistent with geologic evidence of fluvial activity such as crater degradation [14], valley network formation [15], and/or the formation of nontronite-rich clays [16].

2. 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 H₂. Here we estimate the amount of H₂ that could be produced given a few simple assumptions. We assume the impactor is an iron rich H-type ordinary chondrite that is 30% iron by mass [17] and has a density of 3.4 g/cm³. Assuming all of this iron is used to make H₂ (Fe + H₂O → FeO + H₂), we estimate the

atmospheric molar concentration of H₂ that would be produced by an impact. Other compounds (e.g., CH₄) would likely be degassed during this process, however, for this study we focus exclusively on the maximum amount of H₂ 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 [2]. It is therefore feasible that impactors of the larger sizes explored in Segura et al. [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 100-km diameter impactor in an atmosphere with a surface pressure of 2 bar. Following the post-impact initial conditions described in Segura et al. [12], the simulation is 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 and 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. We also initialize the model with a fixed molecular concentration of hydrogen of 0.05 to represent the quantity produced following a 100-km diameter impactor that is 30% iron by mass. On the timescales over which we run our simulation (10 Mars years), the escape rates of hydrogen from the atmosphere (on the order of 10¹¹ molecules cm⁻¹ s⁻¹ [2, 5]) are negligible.

3. 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 CO₂ and H₂O absorption. We incorporate the Wordsworth et al. [2] coefficients for CO₂-H₂ CIA (adjusted by a factor of 1.6 as per Turbet et al. [4]) into the eMGCM radiation treatment in addition to existing coefficients for CO₂-

CO₂ CIA. The radiative effects of liquid and ice H₂O cloud particles are also accounted for [10]. A bulk H₂O cloud condensation scheme, H₂O precipitation and sedimentation are included [10]. In these simulations, the CO₂ cycle is excluded such that CO₂ does not condense onto the surface nor condense to form clouds. Dust exists as condensation nuclei for H₂O clouds but is not radiatively active, is not lifted from the surface, nor advected through the atmosphere. Mars' present-day topography is used.

4. Expected Results

We will present preliminary 3-D eMGCM simulation results for the post-impact scenario of a 100-km diameter impactor in an atmosphere with a surface pressure of 2 bar. Results from a simulation that only accounts for the H₂O and energy delivered by this impact will be compared with results from a simulation that additionally accounts for the H₂ delivered by this impact. We will explore whether including the CO₂-H₂ CIA extends the duration of warm and wet conditions that follow an impact and examine annual rainfall and surface temperature distributions to assess whether this environment would support the formation of observed Noachian fluvial features.

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