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Estimating precipitation on early Mars using a radiative-convective model of the atmosphere and comparison with inferred runoff from geomorphology

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ABSTRACT

We compare estimates of atmospheric precipitation during the Martian Noachian–Hesperian boundary 3.8 Gyr ago as calculated in a radiative-convective column model of the atmosphere with runoff values estimated from a geomorphological analysis of dendritic valley network discharge rates. In the atmospheric model, we assume CO_2–H_2O–N_2 atmospheres with surface pressures varying from 20 mb to 3 bar with input solar luminosity reduced to 75% the modern value.

Results from the valley network analysis are of the order of a few mm d^{-1} liquid water precipitation (1.5–10.6 mm d^{-1}, with a median of 3.1 mm d^{-1}). Atmospheric model results are much lower, from about 0.001–1 mm d^{-1} of snowfall (depending on CO_2 partial pressure). Hence, the atmospheric model predicts a significantly lower amount of precipitated water than estimated from the geomorphological analysis. Furthermore, global mean surface temperatures are below freezing, i.e. runoff is most likely not directly linked to precipitation. Therefore, our results strongly favor a cold early Mars with episodic snowmelt as a source for runoff.

Our approach is challenged by mostly unconstrained parameters, e.g. greenhouse gas abundance, global meteorology (for example, clouds) and planetary parameters such as obliquity – which affect the atmospheric result – as well as by inherent problems in estimating discharge and runoff on ancient Mars, such as a lack of knowledge on infiltration and evaporation rates and on flooding timescales, which affect the geomorphological data. Nevertheless, our work represents a first step in combining and interpreting quantitative tools applied in early Mars atmospheric and geomorphological studies.

1. Introduction

Habitability defined as the conditions suitable for life (e.g., Mars Exploration Program Analysis Group, 2005) has become a central concept in both Solar System and exoplanet science. Early Mars is arguably the key environment to study whether habitable conditions could arise away from the Earth.

In this work we apply an atmospheric model to estimate global mean precipitation rates on early Mars. These are then compared with runoff rates as derived from a geomorphological data analysis of a sample of valley networks. Our main aim is not to investigate the formation of individual networks. Rather, we aim to assess (i) the probable strength of the overall hydrological cycle on early Mars in terms of the amount of precipitated water needed to form the networks, and (ii) whether the atmospheric conditions would have allowed for such a hydrological cycle, again in terms of amount of precipitated water, but also in terms of temperature (snow vs. rainfall).

We begin (Section 1.1) by discussing processes affecting atmospheric formation and composition since these are critical for the early Mars climate hence habitability. Then we give an overview of the geomorphological valley features (Section 1.2) observed on Mars which provide key evidence that early Mars was wet. Section 2 presents the tools used and their constraints. Section 3 presents results, comparing precipitation rates from the atmospheric model with those from the geomorphological approach. Section 4 presents a discussion and Section 5 shows conclusions.

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1.1. Background on early Mars atmosphere

Constraints on atmospheric composition and mass for the early Martian atmosphere can be obtained from a combination of outgassing and escape modeling as well as measurements of e.g. isotopic ratios of nitrogen, oxygen and carbon. Degassing during the early magma ocean phase could have led to an atmosphere of tens of bars or more, but this was probably efficiently removed very fast either during the magma-ocean phase or at the latest during the first few hundred million years due to strong solar activity (e.g., Tian et al., 2009; Lammer et al., 2013). Later input by outgassing is likely insufficient to form dense CO_2 atmospheres of the order of a few bars. Model studies suggest a maximum of about 0.5–1.5 bar before 3.8 Gyrs (e.g., Phillips et al., 2001; Grott et al., 2011), with the lower value being more realistic considering the low oxygen fugacity of the Martian mantle and that crustal recycling was inefficient in Mars (e.g., Stanley et al., 2011). However, impacts during the late heavy bombardment may have provided additional atmospheric mass (up to a few bars, e.g., de Niem et al., 2012). Isotopic ratios (e.g., Jakosky and Phillips, 2001; Fox and Hać, 2010; Gillmann et al., 2011) and an in situ analysis of estimated rock trajectories during explosive volcanic eruptions (e.g., Manga et al., 2012) also suggest a denser atmosphere than today. Upper limits on early Mars atmospheric pressure of about 1 bar have been reported recently based on crater analysis (Kite et al., 2014). A key challenge is how to remove considerable amounts of atmosphere in order to arrive at the present, thin atmosphere, since loss processes are not thought to be efficient after the Noachian period (e.g., Lammer et al., 2013).

The early Mars atmosphere is thought to be composed mainly of CO_2, as suggested by outgassing models (e.g., Phillips et al., 2001), although such studies also predict significant H_2O outgassing (e.g., Grott et al., 2011). Trace gases could have been present in the atmosphere, e.g. SO_2 due to volcanic outgassing (e.g., Farquhar et al., 2000; Halevy et al., 2007) or O_3 due to atmospheric photochemistry (e.g., Selsis et al., 2002). Atmospheric N_2 may have been present since its original inventory is relatively large (e.g., McKay and Stoker, 1989). Other radiatively active gases such as CH_4 have also been suggested (e.g., Postawko and Kuhn, 1986). Recent studies investigated the possibility of H_2-induced warming (e.g., Ramirez et al., 2014) because H_2 could have been a major atmospheric constituent due to enhanced outgassing from the reduced early Mars mantle. However, most atmospheric model studies only investigated CO_2–H_2O scenarios, some with the addition of either SO_2, H_2 or N_2, but currently no model has used a combination of all these gases.

Early 1D CO_2–H_2O atmospheric model studies by, e.g., Kasting (1991) suggested mean surface temperatures far below freezing, indicating that sustained rainfall might not be the reason for producing observed fluvial features. One possible mechanism suggested for warming early Mars includes the formation of CO_2 clouds (e.g., Pierrehumbert and Erlick, 1998; Forget and Pierrehumbert, 1997). However, 1D and 3D modeling studies suggested that the cloud cover would have to be nearly 100% (e.g., Mischna et al., 2000), which is unrealistic as found by more detailed, time-dependent 1D or 3D simulations (e.g., Colaprete and Toon, 2003; Wordsworth et al., 2013). Recent radiative transfer modeling studies (Kitzmann et al., 2013) suggested that the overall warming effect might have been strongly overestimated.

Most recent 1D atmospheric modeling studies continue to calculate mean surface temperatures below freezing even when including the presence of additional greenhouse gases such as SO_2 (e.g., Tian et al., 2010) or N_2 (e.g., von Paris et al., 2013a). In contrast, the new study by Ramirez et al. (2014) found mean surface temperatures well above freezing upon simulating dense CO_2–H_2 atmospheres. Kahre et al. (2013) speculate that a highly active dust cycle on early Mars could have warmed the surface. Dust could have warmed the surface by up to 10 K depending on dust opacity (Forget et al., 2013). A reduction in surface albedo (e.g. due to a larger exposure of basaltic bedrock) has been suggested to warm the surface by, e.g., Fairén et al. (2012) and Mischna et al. (2013).

With 3D model studies (e.g., Johnson et al., 2008; Wordsworth et al., 2013; Mischna et al., 2013; Urata and Toon, 2013), the problem of cold global mean surface temperatures could be addressed to some extent: they showed that even for mean surface temperatures below freezing, large areas of the Martian surface could remain much warmer, with annual means of 260–270 K. In addition, 3D global and mesoscale models of the early Mars climate suggest that orography could be an important factor to drive precipitation. In a recent study, Scanlon et al. (2013) show that orography-driven precipitation in the form of snowfall (of the order of about 10^{-2}–10^{-1} kg d^{-1} m^{-2}) coincides roughly with the location of former rivers on early Mars.

1.2. Background on geomorphology: Martian valley networks

The term valley networks denotes fluid-carved systems of incisions on planetary surfaces, interpreted to be former river valleys. Less degraded fluvial valleys may still possess a narrow interior channel along the valley bottom, which represents the riverbed itself (e.g., Jaumann et al., 2005). Valley networks on Mars occur in two generic types, namely "dendritic" and "longitudinal". Each type implies a different hydrological regime. Dendritic patterns are interpreted to be indicative of precipitation-fed surface runoff due to their analogy to terrestrial features (e.g., Craddock and Howard, 2002; Irwin et al., 2005; Barnhart et al., 2009; Ansan and Mangold, 2013). The surface runoff can be either caused by snowmelt or rain whereby recent studies emphasize that episodic snowmelt might be the most favorable process of water release (e.g., Forget et al., 2013; Wordsworth et al., 2013; Scanlon et al., 2013). Longitudinal valleys may represent fluvial channels, but featuring only a few tributaries.

Whereas some authors propose erosion by groundwater seepage (sapping) as the most plausible water release mechanism for these channels (e.g., Malin and Carr, 1999; Goldspiel and Squyres, 2000; Harrison and Grimm, 2005; Jaumann et al., 2010), others have demonstrated that sapping alone does not account for the erosion at analogous terrestrial channels and a significant contribution by overland runoff is required (e.g., Lamb et al., 2008). Valley networks on Mars occur mostly in the heavily cratered southern highlands whereas some isolated fluvial channels have been observed along the flanks of volcanic edifices (e.g., Gulick and Baker, 1990; Carr, 1995; Fassett and Head, 2006; Hynek et al., 2010).

Crater size-frequency analyses of valley network-incised regions show that fluvial activity peaks during the late Noachian and sharply decreases after the early Hesperian (e.g., Fassett and Head, 2008, 2011; Hoke and Hynek, 2009). Nevertheless, recent research has shown that aqueous surface processes continued even after the early Hesperian, though on a less intense level (e.g., Fassett et al., 2010; Howard and Moore, 2011; Hauber et al., 2013; Parsons et al., 2013; Hobley and, 2014). A recent study by Buhler et al. (2014) suggests intermittent (not continuous) fluvial activity of the order of 10^{-3} of the available time to form the networks, based on complex transport and hydrological analyses.

2. Tools and methods

2.1. Atmosphere

We use atmospheric profiles of pressure p, temperature T and water concentrations c_{H_2O} from calculations presented in von Paris