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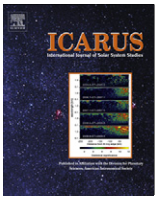

Global modelling of the early martian climate under a denser CO_2 atmosphere: Water cycle and ice evolution

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ABSTRACT

We discuss 3D global simulations of the early martian climate that we have performed assuming a faint young Sun and denser CO_2 atmosphere. We include a self-consistent representation of the water cycle, with atmosphere–surface interactions, atmospheric transport, and the radiative effects of CO_2 and H_2O gas and clouds taken into account. We find that for atmospheric pressures greater than a fraction of a bar, the adiabatic cooling effect causes temperatures in the southern highland valley network regions to fall significantly below the global average. Long-term climate evolution simulations indicate that in these circumstances, water ice is transported to the highlands from low-lying regions for a wide range of orbital obliquities, regardless of the extent of the Tharsis bulge. In addition, an extended water ice cap forms on the southern pole, approximately corresponding to the location of the Noachian/Hesperian era Dorsa Argentea Formation. Even for a multiple-bar CO_2 atmosphere, conditions are too cold to allow long-term surface liquid water. Limited melting occurs on warm summer days in some locations, but only for surface albedo and thermal inertia conditions that may be unrealistic for water ice. Nonetheless, meteorite impacts and volcanism could potentially cause intense episodic melting under such conditions. Because ice migration to higher altitudes is a robust mechanism for recharging highland water sources after such events, we suggest that this globally sub-zero, 'icy highlands' scenario for the late Noachian climate may be sufficient to explain most of the fluvial geology without the need to invoke additional long-term warming mechanisms or an early warm, wet Mars.

1. Introduction

After many decades of observational and theoretical research, the nature of the early martian climate remains an essentially unsolved problem. Extensive geological evidence indicates that there was both flowing liquid water (e.g., Carr, 1995; Irwin et al., 2005; Fassett et al., 2008b; Hynek et al., 2010) and standing bodies of water (e.g., Fassett et al., 2008b) on the martian surface in the late Noachian, but a comprehensive, integrated explanation for the observations remains elusive. As the young Sun was fainter by around 25% in the Noachian (before approx. 3.5 GYa) (Gough, 1981), to date no climate model has been able to produce long-term warm, wet conditions in this period convincingly. Transient warming events have been proposed to explain some of the observations, but there is still no consensus as to their rate of occurrence or overall importance.

The geomorphological evidence for an altered climate on early Mars includes extensive dendritic channels across the highland Noachian terrain (the famous 'valley networks') (Carr, 1996; Fassett et al., 2008b; Hynek et al., 2010), fossilised river deltas with meandering features (Malin and Edgett, 2003; Fassett and Head, 2005), records of quasi-periodic sediment deposition (Lewis et al., 2008), and regions of enhanced erosion most readily explained through fluvial activity (Hynek and Phillips, 2001). Some studies have also suggested evidence for an ancient ocean in the low-lying northern plains. These include a global analysis of the martian hydrosphere (Clifford and Parker, 2001) and an assessment of river delta/valley network contact altitudes (di Achille and Hynek, 2010). However, in the absence of other evidence, the existence of a northern ocean in the Noachian remains highly controversial.

More recent geochemical evidence of aqueous alteration on Mars has both broadened and complicated our view of the early climate. Observations by the OMEGA and CRISM instruments on the Mars Express/Mars Reconnaissance Orbiter spacecraft (Poulet et al., 2005; Bibring et al., 2006; Mustard et al., 2008; Ehlmann et al., 2011) showed widespread evidence for phyllosilicate (∼clay) and sulphate minerals across the central and southern Noachian terrain. Surface aqueous minerals are rarer in Mars' northern lowlands, which are mostly covered by younger Hesperian-era lava

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plains (Head et al., 2002; Salvatore et al., 2010) and outflow channel effluent (Kreslavsky and Head, 2002). However, phyllosilicates have been detected in some large northern impact craters that penetrated through these later deposits (Carter et al., 2010). As these impacts were understood to have excavated ancient Noachian terrain from below the lava plains, it seems plausible that aqueous alteration was once widespread in both hemispheres, on or just beneath the martian surface.

Evidence from crater counting (Fassett and Head, 2008a, 2011) suggests that valley network formation was active during the Noachian but ended near the Noachian-Hesperian boundary (approx. 3.5 GYa in their analysis). Broadly speaking, this period overlaps with the end of the period when impacts were frequent and the Tharsis rise was still forming. Interestingly, however, crater statistics also suggest that the main period of phyllosilicate formation ended somewhat before the last valley networks were created. Few Late Noachian open-basin lakes (Fassett et al., 2008b) show evidence of extensive in situ phyllosilicates on their floors (Goudge et al., 2012) and in those that do, the clays appear to have been transported there from older deposits by way of valley networks (e.g., Ehlmann et al., 2008).

Interpreting the surface conditions necessary to form the observed phyllosilicates on Mars remains a key challenge to understanding the Noachian climate. It is clear that there is substantial diversity in the early martian mineralogical record, which probably at least partially reflects progressive changes in environmental conditions over time (Bibring et al., 2006; Mustard et al., 2008; Murchie et al., 2009; Andrews-Hanna et al., 2010; Andrews-Hanna and Lewis, 2011). Nonetheless, the most recent reviews of the available geochemical evidence suggest that the majority of phyllosilicate deposits may have been formed via subsurface hydrothermal alteration (Ehlmann et al., 2011) or episodic processes, as opposed to a long-term, warm wet climate.

While it is likely that Mars once possessed a thicker CO_2 atmosphere than it has today, it is well known that CO_2 gaseous absorption alone cannot produce a greenhouse effect strong enough to allow liquid water on early Mars at any atmospheric pressure (Kasting, 1991). Various alternative explanations for an early warm, wet climate have been put forward. Two of the most notable are additional absorption by volcanically emitted sulphur dioxide (Halevy et al., 2007), and downward scattering of outgoing infrared radiation by CO_2 clouds (Forget and Pierrehumbert, 1997). However, both these hypotheses have been criticised as insufficient in later studies (Colaprete and Toon, 2003; Tian et al., 2010). Sulphur-induced warming is attractive due to the correlation between the timing of Tharsis formation and the valley networks and the abundance of sulphate minerals on the martian surface. However, Tian et al. (2010) argued that this mechanism would be ineffective on timescales longer than a few months due to the cooling effects of sulphate aerosol formation in the high atmosphere. CO_2 clouds are a robust feature of cold CO_2 atmospheres that have already been observed in the mesosphere of present-day Mars (Montmessin et al., 2007). They can cause extremely effective warming via infrared scattering if they form at an optimal altitude and have global coverage close to 100%. However, our 3D simulations of dry CO_2 atmospheres (Forget et al., 2012) suggest that their warming effect is unlikely to be strong enough to raise global mean temperatures above the melting point of water for reasonable atmospheric pressures.

Given the problems with steady-state warm, wet models, other researchers have proposed that extreme events such as meteorite impacts could be capable of causing enough warming to explain the observed erosion alone (Segura et al., 2002, 2008; Toon et al., 2010). These authors proposed that transient steam atmospheres would form for up to several millenia as a result of impacts between 30 and 250 km in diameter. They argued that the enhanced precipitation rates under such conditions would be sufficient to carve valley networks similar to those observed on Mars, and hence that a long-term warm climate was not necessary to explain the geological evidence. This hypothesis has been questioned by later studies – for example, landform evolution modelling of the Parana Valles region (−20°N, 15°W) (Barnhart et al., 2009) has suggested that the near-absence of crater rim breaches there is indicative of a long-term, semi-arid climate, as opposed to intermittent catastrophic deluges. Other researchers have argued that with realistic values of soil erodability, there is a significant discrepancy (of order 10^4) between the estimated Noachian erosion rates and the total erosion possible due to post-impact rainfall (Jim Kasting, private communication). Hence impact-generated steam atmospheres alone still appear unable to explain key elements of the geological observations, and the role of impacts in the Noachian hydrological cycle in general remains unclear.

Most previous theoretical studies of the early martian climate have used one-dimensional, globally averaged models. While such models have the advantage of allowing a simple and rapid assessment of warming for a given atmosphere, they are incapable of addressing the influence of seasonal and topographic temperature variations on the global water cycle. Johnson et al. (2008) examined the impact of sulphur volatiles on climate in a 3D general circulation model (GCM), but they did not include a dynamic water cycle or the radiative effects of clouds or aerosols. To our knowledge, no other study has yet attempted to model the primitive martian climate in a 3D GCM.

Here we describe a range of three-dimensional simulations we have performed to investigate possible climate scenarios on early Mars. Our approach has been to study only the simplest possible atmospheric compositions, but to treat all physical processes as accurately as possible. We modelled the early martian climate in 3D under a denser CO_2 atmosphere with (a) dynamical representation of cloud formation and radiative effects (CO_2 and H_2O), (b) self-consistent, integrated representation of the water cycle and (c) accurate parameterisation of dense CO_2 radiative transfer. We have studied the effects of varying atmospheric pressure, orbital obliquity, surface topography and starting H_2O inventory. In a companion paper (Forget et al., 2012), we describe the climate under dry (pure CO_2) conditions. Here we focus on the water cycle, including its effects on global climate and long-term surface ice stabilization. Based on our results, we propose a new hypothesis for valley network formation that combines aspects of previous steady-state and transient warming theories.

In Section 2, we describe our climate model, including the radiative transfer and dynamical modules and assumptions on the water cycle and cloud formation. In Section 3, we describe the results. First, 100% relative humidity simulations are analysed and compared with results assuming a dry atmosphere (Forget et al., 2012). Next, simulations with a self-consistent water cycle and varying assumptions on the initial CO_2 and H_2O inventories and surface topography are described. Particular emphasis is placed on (a) the long-term evolution of the global hydrology towards a steady state and (b) local melting due to short-term transient heating events. In Section 4 we discuss our results in the context of constraints from geological observations and atmospheric evolution theory, and assess the probable effects of impacts during a period of higher flux. Finally, we describe what we view as the most likely scenario for valley network formation in the late Noachian and suggest a few directions for future study.

2. Method

To produce our results we used the LMD Generic Climate Model, a new climate simulator with generalised radiative transfer and