COMPARISON OF WARM, WET AND COLD, ICY SCENARIOS FOR LATE NOACHIAN MARS IN A 3D GENERAL CIRCULATION MODEL

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Introduction: Despite decades of research, deciphering the nature of Mars' early climate remains a huge challenge. Although Mars receives only 43% of the solar flux incident on Earth, and the Sun's luminosity was likely 20-30% lower 3-4~Ga, there is extensive evidence for aqueous alteration on Mars' late Noachian and early Hesperian terrain. Key features of the observations include dendritic valley networks that are distributed widely across low to midlatitudes over the Noachian/Hesperian terrain (Hynek et al., 2010), lacustrine deposits (Malin and Edgett, 2003), in-situ observations of conglomerates in Gale Crater (Williams et al., 2013), and geochemical observations of phyllosilicate and sulphate minerals in many regions where the geomorphology suggests fluvial erosion (Ehlmann et al., 2011). All of these features strongly suggest the presence of liquidwater on the early Martian surface, at least episodically. Based on these geological observations, many researchers have previously argued that the Martian climate passed through a warm, wet phase in the late Noachian and early Hesperian (Pollack et al., 1987; Craddock and Howard, 2002). This conclusion is not universally accepted; the phyllosilicate observations, in particular, have instead recently been interpreted as primarily due to subsurface hydrothermal processes, rather than alteration at the surface (Ehlmann et al., 2011). Nonetheless, elements of the geomorphology, particularly the valley networks, are difficult to explain in scenarios where the early Martian surface was always extremely cold.

The icy highlands hypothesis for the late Noachian climate: Previously, we performed the first 3D simulations of the early Martian climate with accurate multiband radiative transfer, and showed that even with cloud radiative effects taken into account, a CO2/H2O greenhouse would have been insufficient to raise early Martian mean surface temperatures above the freezing point of liquid water alone (Wordsworth et al., 2013; Forget et al., 2013). However, we also found that due to the increase in adiabatic surface cooling by the atmosphere at high pressure, H2O would have migrated towards the highland equatorial regions where most valley networks are observed, even when annual mean temperatures were far below the freezing point of water. This led us to propose the ‘icy highlands’ hypothesis for early Mars (Wordsworth et al., 2013), where transport of H2O as ice/snow to the valley network source regions occurs in a cold climate on long timescales, and melting occurs episodically on shorter timescales due to transient or episodic heating events. This hypothesis circumvents the need for H2O transport to the valley network source regions as rain during warm periods, as is necessary for e.g. postimpact steam atmosphere scenarios. However, to cause fluvial erosion, transient warm periods of some duration are clearly still required.

Climate and hydrology in warm, wet and cold, icy late Noachian scenarios: We have performed a range of simulations at $64\times48\times18$ spatial resolution where we assume a) a faint young Sun and realistic radiative transfer (the standard cold scenario) and b) increased solar flux and/or atmospheric opacity due to exotic climate or solar physics (the warm, wet scenario). In the cold simulations, we have broadly confirmed our previous results on the icy highlands effect. We have also developed a new diagnostic, the *annual potential sublimation*, that closely correlates with snow/ice migration in long-term simulations with a water cycle but can be calculated much more rapidly. Snow migration is a function of both obliquity and surface pressure. At surface pressures just above those required to avoid atmospheric collapse (~0.5 bar) and moderate to high obliquity, snow is transported to the equatorial highland regions where the concentration of valley networks is highest (Figure 1). Snow accumulation in the Aeolis quadrangle is high, indicating an ice-free northern ocean is not required to supply water to Gale Crater. At lower surface pressures and obliquities, both H2O and CO2 are trapped as ice at the poles and the equatorial regions become extremely dry.

In our warm, wet simulations where Hellas contains an ocean, significant precipitation is observed across most of the southern terrain, including some regions where few valley networks are observed. However, in the Margaritifer Sinus quadrangle, where the valley network drainage density is high, our simulations exhibit low precipitation rates. Via modified topography experiments, we have determined the origin of this effect to be a planetary-scale rain shadow caused by the Tharsis bulge. At elevated pressure the atmosphere adiabatically cools the surface of Tharsis; conversely, Tharsis heats the atmosphere. The resulting large-scale dynamics can be idealized in terms of the classical Gill solution, with modifications due to topographic wind effects that give rise to the rain shadow (Figure 3). The effect is not sensitive to obliquity. Magnetic field observations and geodynamics modelling (Phillips et al. 2001) suggests the bulk of Tharsis was already in place by the time of valley network formation. Hence erosion due to precipitation in a warm, wet climate may not be the explanation for VN formation in Margaritifer Sinus.

Transient melting events: We are currently testing various mechanisms to cause transient melting and runoff in a mainly cold early Martian climate. Unlike in the warm, wet simulations, we work within known constraints on solar evolution and use physically realistic absorption and scattering properties for gases and aerosols. We find a moderate warming effect by SO2 / H2S, although less than that found by Halevy & Head (2014). Even when the effects of SO2 destruction by photolysis and cooling by aerosol formation are neglected, the maximum plausible warming effect at 0.5 bar CO2 pressure is insufficient alone to cause significant melting of ice deposits. Other effects such as increased levels of atmospheric dust, a reduced ice surface albedo, increased eccentricity and a slightly increased solar constant all cause small (< 5 K) perturbations to the baseline climate state at 0.5 bar in isolation. Because of the nonlinearity in the climate system due to effects such as the H2O vapour feedback, however, in combination these mechanisms can cause warming sufficient to raise summertime mean temperatures above 273 K in the valley network regions and hence significant melting (Fig. 2). Explaining how such a scenario could emerge self-consistently remains an important challenge. Nonetheless, the key to explaining the late Noachian Mars in future most likely lies in untangling how multiple effects interact in 3D, in the full climate system.

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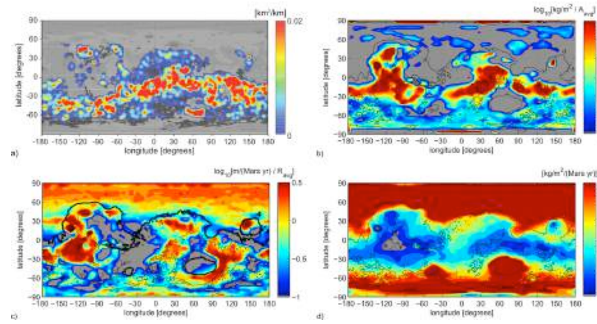

Figure 1: (top left) Valley network drainage density using data from Hynek et al. (2010). (bottom left) Annual precipitation in a 1-bar early Mars simulation assuming a solar flux of 1.3×present-day and a liquid H2O ocean below altitudes of -2.54 km. (top right) Simulated yearly surface ice accumulation assuming a 0.6 bar CO2 atmosphere and polar H2O sources. (bottom right) Annual potential sublimation for the same case. In all simulations the spatial resolution is 64×48×18 and an obliquity of 41.8° [the most probable value 3.8 Ga; Laskar et al. (2004)] is used.

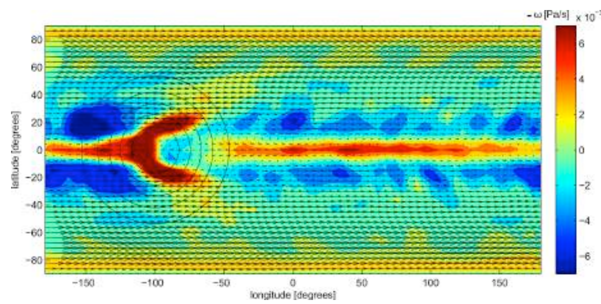

Figure 3: Idealized effect of Tharsis on dynamics at high pressure: Annual mean vertical velocity (filled contours) and horizontal velocity (black arrows) at the 8th model level (approx. 0.7 bar) in an idealised dry, gray simulation with topography represented by a Gaussian function (black solid lines).

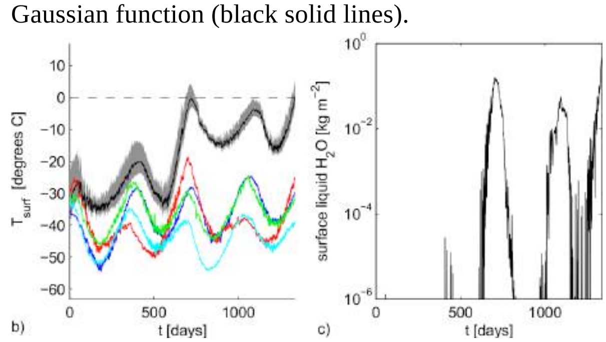

Figure 2: (left) Diurnal mean temperature vs. time, averaged over valley network region for different forcing [reduced surface albedo and dusty atmosphere, blue; *e* = 0.125 and solar constant of F=0.8F_0, red; 10~ppm atmospheric SO2, green; all effects, black]. (right) Surface liquid water amount vs. time for the most extreme forcing case.