The Climate of Early Mars

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Abstract

The nature of the early martian climate is one of the major unanswered questions of planetary science. Key challenges remain, but a new wave of orbital and in situ observations and improvements in climate modeling have led to significant advances over the past decade. Multiple lines of geologic evidence now point to an episodically warm surface during the late Noachian and early Hesperian periods 3–4 Ga. The low solar flux received by Mars in its first billion years and inefficiency of plausible greenhouse gases such as CO_2 mean that the steady-state early martian climate was likely cold. A denser CO_2 atmosphere would have caused adiabatic cooling of the surface and hence migration of water ice to the higher-altitude equatorial and southern regions of the planet. Transient warming caused melting of snow and ice deposits and a temporarily active hydrological cycle, leading to erosion of the valley networks and other fluvial features. Precise details of the warming mechanisms remain unclear, but impacts, volcanism, and orbital forcing all likely played an important role. The lack of evidence for glaciation across much of Mars's ancient terrain suggests the late Noachian surface water inventory was not sufficient to sustain a northern ocean. Though mainly inhospitable on the surface, early Mars may nonetheless have presented significant opportunities for the development of microbial life.

1. INTRODUCTION

With the exception of Earth, Mars is the Solar System's best-studied planet. Since the first *Mariner* flybys in the 1960s, Mars has been successfully observed by a total of 11 orbiters and 7 landers, four of them rovers. Combined with ongoing observations from Earth, this has allowed a uniquely comprehensive description of the martian atmosphere and surface. However, despite the wealth of data obtained, fundamental mysteries about Mars's evolution remain. The biggest mystery of all is the nature of the early climate: 3–4 Ga Mars should have been freezing cold, but there is nonetheless abundant evidence that liquid water flowed across its surface.

Unlike Earth, Mars lacks plate tectonics, global oceans and a biosphere.[1] One of the happy outcomes of this is that its ancient crust is incredibly well preserved, allowing a window to epochs as early as 3–4 Ga across large regions of the surface (Nimmo & Tanaka 2005). This antiquity is hard to imagine from a terrestrial perspective. By way of comparison, we can imagine the advantages to Precambrian geology if most of Asia consisted of lightly altered terrain from the early Archean, when life was first emerging on Earth. Mars provides us a glimpse of conditions during the earliest stages of the Solar System on a body that had an atmosphere, at least episodic surface liquid water, and, in some locales, surface chemistry conducive to the survival of microbial life (e.g., Grotzinger et al. 2014).

There are many motivations for studying the early climate of Mars. The first is simply that it is a fundamentally interesting unsolved problem in planetary science. Another major motivation is astrobiological—if we can understand how the martian climate evolved, we will have a better understanding of whether life could ever have flourished, and where to look for it if it did. Studying Mars also has the potential to inform us about the evolution of our own planet, because many of the processes thought to be significant to climate on early Mars (e.g., volcanism, impacts) have also been of major importance on Earth. Finally, in this era of exoplanet science, Mars also represents a test case that can inform us about the climates of small rocky planets in general.

The aim of this review is to provide a general introduction to the latest research on the early martian climate. We begin by discussing highlights of the geologic evidence for an altered climate on early Mars, focusing on the extent to which the observations are consistent with episodic warming versus a steady-state warm and wet climate. Next, we discuss the external boundary conditions on the early climate (namely the solar flux and martian orbital parameters) and the constraints on the early atmospheric pressure. We also review previous one-dimensional radiative-convective modeling of the effects of key processes (atmospheric composition, meteorite impacts, and volcanism) on surface temperature. Finally, we discuss recent three-dimensional climate modeling of early Mars by a number of groups that has increased our understanding of cloud and aerosol processes and the nature of the early water cycle. It is argued that future progress will require an integrated approach, where three-dimensional climate models are compared with the geologic evidence on both global and regional scales.

2. GEOLOGIC EVIDENCE FOR LIQUID WATER ON EARLY MARS

With a few important exceptions, all our current information on the early martian climate comes from surface geology. Martian geologic data is derived from a combination of passive and active orbital remote sensing and in situ analysis. The oldest and best studied aspect of martian geology is the surface geomorphology. In recent years, the geomorphic data have been supplemented by

[1] While the possibility of life on Mars today still cannot be ruled out, the absence of a biosphere sufficient to modify the surface substantially is clear.

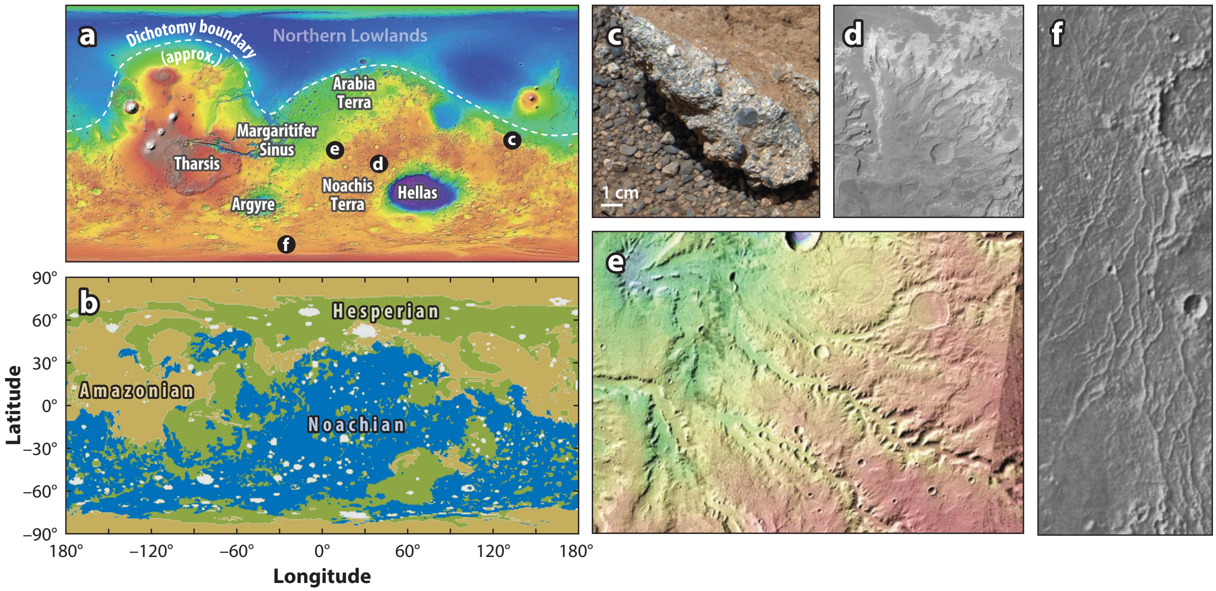

Figure 1

(*a*) Contour plot of the present-day martian topography from Mars Orbiter Laser Altimeter data. Major features of the terrain are indicated. (*b*) Spatial distribution of the three main terrain types on the martian surface (data from Tanaka 1986, Scott & Tanaka 1986, Tanaka & Scott 1987). (*c–f*) Highlights of the geomorphological evidence for an altered climate in the Noachian and Hesperian. (*c*) Fluvial conglomerates observed in situ by the Curiosity rover at Gale Crater (from Williams et al. 2013; reprinted with permission from AAAS). (*d*) Deltaic lake deposits in Eberswalde Crater (from Malin & Edgett 2003; reprinted with permission from AAAS). (*e*) Valley networks in Paraná Valles (from Howard et al. 2005). (*f*) Sinuous ridges in the Dorsa Argentea Formation interpreted as glacial eskers (from Head & Pratt 2001).

global maps of surface mineralogy derived from orbiters and detailed in situ studies of several specific regions by the NASA rover missions.

Figure 1*a* summarizes the basic features of the martian surface. The four most important large-scale features are the north-south dichotomy, the Tharsis bulge, and the Hellas and Argyre impact craters. Because martian topography plays a major role in the planet's climate and hydrological cycle, understanding when these features formed is vital. The relative ages of surface features and regions on Mars can be assessed via analysis of local crater size-frequency distributions (crater statistics) (Tanaka 1986, Tanaka et al. 2014). Absent geochronology data, absolute dating of martian surface units relies on impactor flux models and hence is subject to considerable uncertainty.

It is standard to categorize martian terrain into three time periods (**Figure 2**): the most modern Amazonian (~0–3.0 Ga), which is associated with hyperarid, oxidizing surface conditions and minimal weathering; the Hesperian (~3.0–3.5 Ga), which contains evidence of extensive volcanism and catastrophic flooding; and the ancient Noachian (~3.5–4.1 Ga), when alteration of the martian surface by water was greatest (Werner & Tanaka 2011; also see **Figure 1**). The vast majority of Noachian units are found in the heavily cratered south. The northern hemisphere is dominated by smooth plains that probably result from lava outflow and are dated to the Hesperian and Amazonian (Tanaka 1986). The Noachian period is defined by the Noachis Terra region, which translates evocatively as "Land of Noah." It contains the clearest evidence for an altered early climate and is the primary focus of this article.

Tharsis bulge: a large region of elevated terrain that dominates the equatorial topography of Mars

Hellas: largest confirmed impact basin on Mars; defines the start of the Noachian period

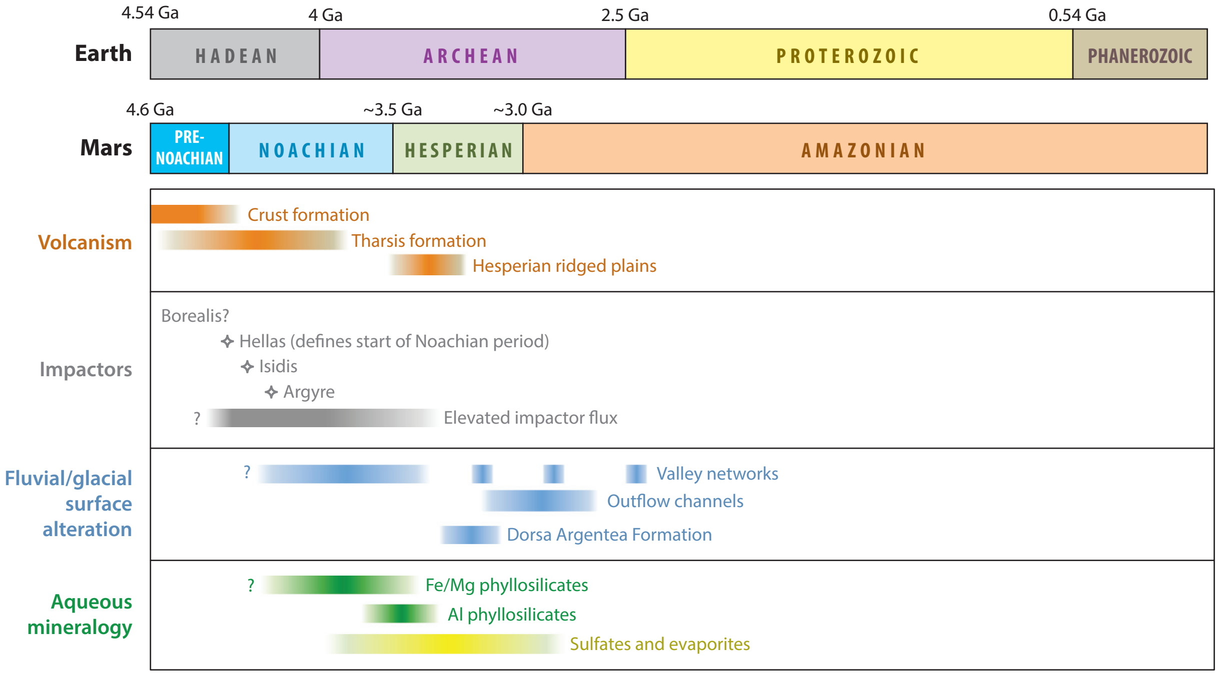

Figure 2

Timeline of major events in Mars history, with the geologic eons of Earth displayed above. In general, the absolute timing of events on Mars is subject to considerable uncertainty, but the sequencing is much more robust. Question marks indicate cases where processes could also have occurred earlier but the geologic record is obscured by subsequent events. Based on data from Werner & Tanaka (2011), Fassett & Head (2011), Ehlmann et al. (2011), and Head & Pratt (2001).

All of the largest scale topographic features on Mars formed during or before the Noachian. The north-south dichotomy is the most ancient surface feature, followed by Hellas and Argyre. The Hellas impact is commonly taken to represent the pre-Noachian/Noachian boundary (Nimmo & Tanaka 2005, Fassett & Head 2011). Although substantial resurfacing and formation of the Tharsis Montes shield volcanoes was ongoing during the Hesperian and Amazonian, the formation of Tharsis likely began early and was mainly complete by the late Noachian (Phillips et al. 2001, Carr & Head 2010, Fassett & Head 2011). To a first approximation, the large-scale topography of Mars in the late Noachian was therefore probably similar to that today.

2.1. Geomorphology

Martian geomorphology has been studied ever since Mariner 4 performed the very first flyby. Today, there are several broad categories of features believed to arise from the action of liquid water on Mars's surface. Here we focus on Noachian geomorphology: Features such as gullies and outflow channels have also been studied in detail but are mainly found in the Hesperian and Amazonian periods.

2.1.1. Valley networks. The valley networks constitute the single most important piece of evidence in favor of a radically different climate on early Mars. Like many drainage basins on Earth and in contrast with the later Hesperian period outflow channels, martian valley networks are dendritic (branching) with tributaries that begin near the peaks of topographic divides. This geomorphology strongly suggests an origin due to a hydrological cycle driven by precipitation (as rain or snow) (Craddock & Howard 2002, Mangold et al. 2004, Stepinski & Stepinski 2005, Barnhart et al. 2009, Hynek et al. 2010, Matsubara et al. 2013) rather than, for example, groundwater sapping (Squyres & Kasting 1994) or basal melting of thick ice sheets (Carr & Head 2003).

Dendritic valley networks are rare on Hesperian and Amazonian terrain but common on Noachian terrain, where they are predominantly seen at equatorial latitudes between 60°S and 10°N (Milton 1973, Carr 1996, Hynek et al. 2010). The largest networks are huge, extending thousands of kilometers over the surface in some cases (Howard et al. 2005, Hoke et al. 2011). Landform evolution models suggest minimum formation timescales for the valley networks of 10^5 to 10^7 years under climate conditions appropriate to arid regions on Earth (Barnhart et al. 2009, Hoke et al. 2011).

Dendritic valley networks: branching networks of channels carved into the ancient martian crust that share many similarities with drainage basins on Earth

2.1.2. Crater lakes. When liquid water carves valley networks on a heavily cratered terrain, ponding and lake formation inside craters is a natural outcome. For sufficiently high flow rates, crater lakes will breach their rims, forming open lakes that are integrated in a larger hydrological network. Both the ratio of watershed area to lake area (drainage ratio) for each lake and the ratio of open- to closed-basin crater lakes in total give important clues as to the nature of the Noachian water cycle. In general, low drainage ratios and a large number of open crater lakes indicate high precipitation rates and a wet climate (Fassett & Head 2008, Barnhart et al. 2009).

As might be expected, analysis of the Noachian southern highlands has revealed abundant evidence for crater lakes interlinked with the valley networks (Cabrol & Grin 1999, Fassett & Head 2008). However, closed-basin lakes greatly outnumber open-basin lakes. This suggests that a very wet climate or periodic catastrophic deluges due, for example, to impact-driven steam greenhouses (see Section 3.4) were not responsible for their formation (Irwin et al. 2005, Barnhart et al. 2009). Open-basin lake drainage ratios strongly vary with location, with wetter formation conditions indicated in Arabia Terra and north of Hellas (Terra Sabaea) (Fassett & Head 2008).

Striking evidence of in situ fluvial erosion was found by NASA's Curiosity rover in the form of conglomerate outcrops at Gale Crater (Williams et al. 2013). Morphologically, the conglomerates are remarkably similar to sediment deposits found on Earth (see **Figure 1**). However, chemical analysis of the outcrops suggested low chemical alteration of the material by water (Williams et al. 2013). Indeed, global analysis of aqueous alteration products on the martian surface suggests a predominance of juvenile or weakly modified minerals (Tosca & Knoll 2009). In addition, most of the minerals in open-basin crater lakes observed from orbit lack evidence of strong in situ chemical alteration (Goudge et al. 2012). This suggests that the flows responsible for eroding the late Noachian and Hesperian surface were relatively short lived.

2.1.3. Northern ocean. The most evocative (and controversial) claim to have come out of geomorphic studies of the ancient surface is that Mars once possessed a northern ocean of liquid water. The original argument proposed to support this is that various geologic contacts in the northern plains resemble ancient shorelines (Parker et al. 1993, Head et al. 1999). Several of the putative shorelines show vertical variations of several kilometers, which is inconsistent with a fluid in hydrostatic equilibrium, although it has been argued that true polar wander could have caused surface deformation sufficient to explain this (Perron et al. 2007). More critically, much of the shoreline evidence was found to be ambiguous in subsequent high-resolution imaging studies (Malin & Edgett 1999).

More recently, it has been argued that many delta-like deposits, which are assumed to be of fluvial origin, follow an isostatic line at −2.54 km from the datum across the surface (di Achille &

Hynek 2010). If this line does represent a Noachian ocean shoreline, the implications are that (*a*) the earlier proposed shorelines are incorrect and martian topography was not modified by a true polar wander event and (*b*) Mars once had a global equivalent layer (GEL) of around 550 m of surface water. The extent to which a warm and wet scenario for early Mars with a northern ocean fits the climate constraints and the other geologic evidence is a major focus of the rest of this article.

Global equivalent layer (GEL): quantity of water expressed as an average depth across the planet's surface

Dorsa Argentea Formation (DAF): mid-Hesperian geologic unit at Mars's south pole interpreted as the remains of a large water ice cap

Lobate debris apron: distinctive volatile-rich, convex martian landform analogous to a terrestrial rock glacier

2.1.4. Glaciation. The evidence for an at least episodically warmer early martian climate is not limited to fluvial landforms. At the south pole, the Dorsa Argentea Formation (DAF), a geologic unit dated to the mid-Hesperian, contains a range of features suggestive of glaciation, including sinuous ridges interpreted as eskers (**Figure 1**) and pitted regions that may have been caused by basal melting of a thick ice sheet (Howard 1981, Head & Pratt 2001). Around the Argyre and Hellas basins, further glacial landforms such as eskers, lobate debris aprons, and possible moraines and cirques are observed (Kargel & Strom 1992). Dynamic ice sheet modeling (Fastook et al. 2012) suggests that polar surface temperature increases of 25–50 K from Amazonian (modern) values are required before wet-based glaciation of the DAF could occur, again suggesting episodically warmer climate conditions on early Mars. Interestingly, however, there is comparatively little evidence for glacial alteration of the surface on Noachian or Hesperian terrain at more equatorial latitudes. This is an important issue that we return to in Section 4.

2.2. Geochemistry

The morphological evidence for liquid water on early Mars, which has been observed in increasing detail from the 1960s onward, has been complemented over the past 10–15 years by a new array of geochemical observations from orbit and rover missions. Iron- and magnesium-rich phyllosilicates (clays) are found extensively over Noachian terrain (Poulet et al. 2005, Bibring et al. 2006, Mustard et al. 2008, Murchie et al. 2009, Carter et al. 2010). To form, these minerals require the presence of liquid water and near-neutral-pH conditions. Other aqueous minerals such as sulphates, chlorides, and silicas are found in more localized regions of the Noachian and Hesperian crust (Gendrin et al. 2005, Osterloo et al. 2010, Carter et al. 2013, Ehlmann & Edwards 2014).

If the phyllosilicates mainly formed on the surface, this would represent evidence in favor of a warm and wet early martian climate (Poulet et al. 2005, Bibring et al. 2006). Recently, however, it has been argued that in most cases their mineralogy may best represent subsurface formation in geothermally heated, water-poor systems (Ehlmann et al. 2011). Many of the sedimentary phyllosilicates observed on the martian surface today may not have formed in situ, but may instead have been transported to their current locations by later erosion of the crust.

At several sites, Al-rich clays such as kaolinite are observed alongside or overlying Fe/Mg clays (Poulet et al. 2005, Wray et al. 2008, Ehlmann et al. 2009, Carter et al. 2015). On Earth, the presence of Al-rich clays overlying Fe/Mg clay in a stratigraphic section is a common feature of wet environments, because iron and magnesium cations from the original minerals are preferentially leached (flushed) downward from the topmost layer by water from rain or snowmelt. This is one possible explanation for the presence of Al-rich clays on Mars (Carter et al. 2015). Another interpretation is more acidic and oxidizing local alteration conditions in a mainly cold climate, as suggested by the presence of the sulfate mineral jarosite adjacent to Al clays in several regions (Ehlmann & Dundar 2015).

Sulfate deposits on Mars are particularly interesting because they require a source (most likely volcanic) of sulfur and in some cases indicate acidic and/or saline formation conditions. Sulfates appear primarily, but not exclusively, on Hesperian terrain and may be associated with the volcanic activity that formed the basaltic ridged plains (Head et al. 2002, Bibring et al. 2006). The link between the sulfates, volcanism, and possible changes in the early climate due to sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) is discussed in Section 3.4.2.

One mineral, carbonate, is conspicuous by its low abundance on the martian surface (Niles et al. 2013, Ehlmann & Edwards 2014). This is important, because surface carbonate formation should be very efficient on a warm and wet planet with a basaltic crust and CO_2-rich atmosphere (Pollack et al. 1987). Carbonate formation could have been suppressed by acidic surface conditions caused by dissolution of SO_2 in water (Bullock & Moore 2007, Halevy et al. 2007). However, globally acidic warm and wet conditions are difficult to justify in the presence of a strongly mafic basaltic regolith, which should effectively buffer pH, just like the basaltic seafloor on Earth (Niles et al. 2013). Hence the absence of surface carbonates is a strong indication that early Mars was either only episodically warm, or very dry. Interestingly, carbonates have been discovered in outcrops in the Nili Fossae region by the Compact Reconnaissance Imaging Spectrometer (CRISM) (Ehlmann et al. 2008) and in Gusev Crater by the Spirit rover (Morris et al. 2010). They are also seen in some regions where deep crustal material has been excavated by impacts (Michalski & Niles 2010). This indicates that, regardless of the early surface conditions, the deep crust may still have been a major sink for atmospheric CO_2 over time (see Section 3.1).

Compact Reconnaisance Imaging Spectrometer for Mars (CRISM): a visible-infrared spectrometer onboard the Mars Reconnaissance Orbiter

3. FAINT YOUNG SUN, COLD YOUNG PLANET?

The geologic record is unanimous: Liquid water substantially modified Mars's surface during the late Noachian. The surface processes that could have created this water, however, are far from obvious. Two basic facts conspire to make warming early Mars a fiendish challenge: the martian orbit and the faintness of the young Sun.

With a semimajor axis of 1.524 AU, Mars receives approximately 43% of the solar energy that Earth does. The rapid dissipation of the nebula during terrestrial planet formation and lack of major configurational changes in the Solar System since the late heavy bombardment mean that Mars's orbital semimajor axis cannot have changed significantly since the late Noachian. Mars's orbital eccentricity and obliquity evolve chaotically on long timescales, however, and have probably varied over ranges of 0–0.125 and 10°–60°, respectively (Laskar et al. 2004). Although this has little effect on the net annual solar flux, it still has important implications for the early climate, because the time-varying insolation pattern is a key determinant of peak summertime temperatures and hence the long-term transport and melting of water ice.

The early Sun was less luminous than today because hydrogen burning increases the mean molar mass of the core, causing it to contract and heat up. The rate of fusion is strongly dependent on temperature, so this in turn increases a main sequence star's luminosity over time. This fundamental outcome of stellar physics is supported by detailed solar models and observations of many nearby stars. As a result, the Sun's luminosity 3.8 Ga was approximately 75% of its present-day value (Gough 1981). One possible way to avoid this outcome is if the Sun shed large amounts of its mass early on [over 2% in the first 2 Gyr (Minton & Malhotra 2007)]. Though possible, this is unlikely, because such high mass loss is not observed in any nearby G or K class stars (Minton & Malhotra 2007). The idea that our Sun must be a unique and unusual star solely because Mars once had surface liquid water has not gained widespread acceptance.

If we accept the standard orbital and solar boundary conditions, the early Mars climate problem is now simply understood. Let us assume that in the late Noachian, Mars's received solar flux was $0.75 \times 1{,}366/1.524^2 = 441.1$ W m^{-2}. If the planetary albedo were zero (i.e., every solar photon intersected by Mars was absorbed), the equilibrium temperature would then be $T_e = (441.1/4\sigma)^{1/4} = 210$ K (here σ is the Stefan-Boltzmann constant). This implies a minimum greenhouse effect of 65 K (approximately double that of present-day Earth or nine times that of present-day Mars) to achieve even marginally warm and wet surface conditions. For more realistic planetary albedo estimates, the greenhouse effect required is tens of degrees greater still.

3.1. A Denser Early Atmosphere

One seemingly obvious way to invoke a more potent greenhouse effect on early Mars is via a denser atmosphere. But how thick could the early atmosphere have been? Estimating the total atmospheric pressure in the late Noachian requires consideration of the major sources (volcanic outgassing and impact delivery) and sinks (escape to space and incorporation of CO_2 into the crust).

Carbon dioxide is generally assumed to have been the dominant constituent of the martian atmosphere in the late Noachian, as it is today. The outgassing of CO_2 into the martian atmosphere with time is a function of the rate of volcanic activity and the chemical composition of the mantle (Grott et al. 2011). The rate of volcanism through the pre-Noachian and Noachian is not strongly constrained, but the majority of volatile outgassing in Mars's history almost certainly occurred in these periods (Grott et al. 2011).

Regarding the chemical composition, CO_2 outgassing is strongly dependent in particular on the mantle oxygen fugacity (f_{O_2}). Analysis of martian meteorites suggests Mars has a more reducing mantle than Earth, with an f_{O_2} value between the iron-wüstite and quartz-fayalite-magnetite buffers (Wadhwa 2001). Given this, Hirschmann & Withers (2008) estimated that between 70 mbar and 13 bar of CO_2 could have been outgassed during the initial formation of the martian crust, with the lower estimate for the most reducing conditions. During later events (such as the formation of the Tharsis bulge), they estimate that 40 mbar to 1.4 bar could have been outgassed.

The escape rate of CO_2 to space until the Hesperian is highly uncertain. Escape rates were highest just after Mars's formation, and the isotopic fractionation of noble gases in the atmosphere indicates the majority of the primordial atmosphere was lost very early (Jakosky & Jones 1997). It has also been argued that all of the initially outgassed CO_2 would have been rapidly lost to space by extreme ultraviolet (XUV)-driven escape before the late Noachian (Tian et al. 2010). However, effective loss requires total dissociation of CO_2 into its constituent atoms. The chemistry of this process has not been extensively studied and may be somewhat model dependent (Lammer et al. 2013). Meteorite impacts during accretion remove CO_2 but also deliver it, with the balance dependent on the model used. In contrast, escape processes occurring from the Hesperian onward appear unambiguously ineffective: Ion escape, plasma instability, sputtering, and nonthermal processes combined could not have removed more than a few 100 mbar at most since 4 Ga (Chassefière & Leblanc 2004, Lammer et al. 2013). Although further insights into these processes will be supplied by NASA's ongoing MAVEN mission, it currently appears that a dense late Noachian atmosphere could only have been removed subsequently by surface processes.

The most efficient potential sink for atmospheric CO_2 at the surface is carbonate formation. As we have discussed, surface carbonates are rare on Mars. However, the discovery of carbonates in exhumed deep crust suggests that the possibility of a large subsurface reservoir cannot be discounted (Michalski & Niles 2010). Recently, it has been argued based on orbital observations that this reservoir is unlikely to allow more than a 500 mbar CO_2 atmosphere during the late Noachian (Edwards & Ehlmann 2015). However, sequestration by hydrothermal circulation of CO_2 in deep basaltic crust is a very poorly understood process even on Earth (e.g., Brady & Gíslason 1997), so caution is still required when extrapolating the known carbonate reservoirs. It will be hard to constrain the late Noachian carbon budget definitively until we can send missions to Mars (robotic or human) that are capable of drilling deep into the subsurface.

Finally, one independent constraint on atmospheric pressure comes from the size distribution of craters on ancient terrain. In a thick atmosphere smaller impactors burn up before they reach the surface, so observation of the smallest craters leads to an upper limit on atmospheric pressure. Recent analysis of the Dorsa Aeolis region near Gale Crater using this technique has led to an approximate upper limit of 0.9–3.8 bar on atmospheric pressure 3.6 Ga (Kite et al. 2014).

To summarize, many aspects of Mars's atmospheric evolution are highly uncertain. It is likely that Mars had a thicker CO_2 atmosphere in the late Noachian. This atmosphere could have been as dense as 1–2 bar, but likely no more than this. If the early atmosphere was denser than approximately 0.5 bar, it cannot have all escaped to space and the difference will now be buried in the deep crust as carbonate. Several recent studies have suggested that this reservoir may be small, but the observational search for carbonate deposits on Mars should continue, along with theoretical study of the interaction between atmospheric CO_2 and pore water in deep martian hydrothermal systems.

3.2. The Failure of the CO_2 Greenhouse

Constraining the early atmospheric CO_2 content is necessary to build a complete picture of the Noachian climate, but it is not sufficient. In a seminal paper, Kasting (1991) demonstrated that regardless of the atmospheric pressure, a clear-sky CO_2-H_2O atmosphere alone could not have warmed early Mars. There are two reasons for this. First, CO_2 is an efficient Rayleigh scatterer, so in large quantities it significantly raises the planetary albedo. In addition, CO_2 condenses into clouds of dry ice at low temperatures. As surface pressure increases this leads to a shallower atmospheric lapse rate, reducing the greenhouse effect (**Figure 3**). At high enough CO_2 pressures, the atmosphere collapses on the surface completely. This conclusion, which was reached by Kasting using a one-dimensional clear-sky radiative-convective climate model, has recently been confirmed

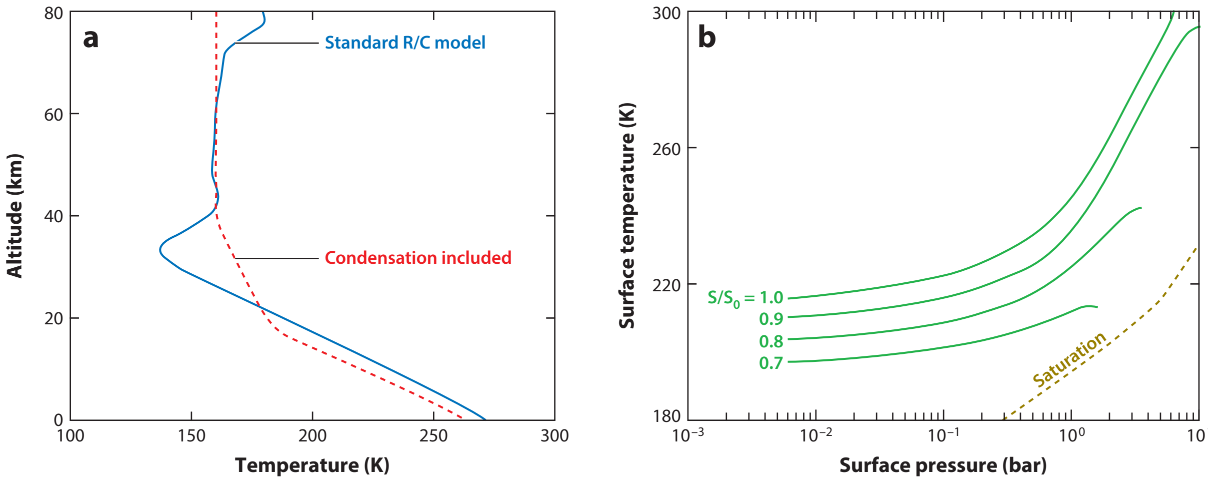

Figure 3

The two plots that began the modern era of research on the early martian climate (from Kasting 1991). (*a*) Temperature-pressure profile for the early martian atmosphere assuming a surface pressure of 2 bar. The dashed line shows the case where CO_2 condensation is (correctly) included, leading to a weaker greenhouse effect. (*b*) Surface temperature versus pressure produced from a clear-sky one-dimensional radiative-convective climate model for several values of solar luminosity relative to present day. The dashed line shows the saturation vapor pressure of CO_2. Note that these surface temperatures are now regarded as overestimates, due to the problems in representation of the CO_2 collision-induced absorption described in Halevy et al. (2009) and Wordsworth et al. (2010).

by three-dimensional climate models that include cloud effects (Forget et al. 2013, Wordsworth et al. 2013).

CIA: collision-induced absorption

Although uncertainty remains, the infrared radiative effects of dense CO_2-dominated atmospheres are now fairly well understood. CO_2 is opaque across important regions of the infrared because of direct vibrational-rotational absorption, particularly due to the ν_2 667 cm^{-1} (15 μm) bending mode and associated overtone bands. In dense atmospheres, CO_2, like most gases, also absorbs effectively through collision-induced absorption (CIA). CIA is a collective effect that involves the interaction of electromagnetic radiation with pairs (or larger numbers) of molecules. For CO_2, it occurs due to both induced dipole effects in the 0–250 cm^{-1} region (Gruszka & Borysow 1997) and dimer effects between 1,200 and 1,500 cm^{-1} (Baranov et al. 2004) (see **Figure 4**). Further complications arise from the fact that the sub-Lorentzian nature of absorption

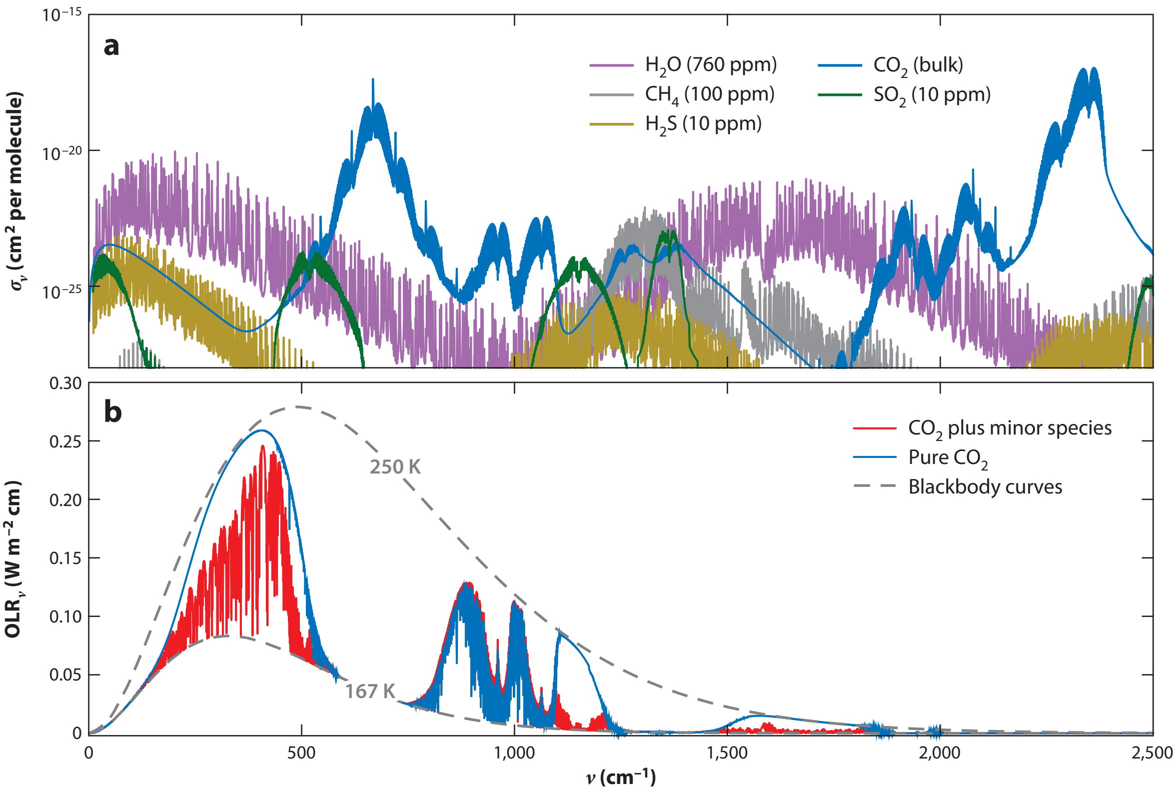

Figure 4

The greenhouse effect on early Mars. (*a*) Absorption cross sections per molecule of background gas versus wavenumber at 1 bar and 250 K, for various greenhouse gases in the early martian atmosphere, with the gas abundances given in the legend. Results were produced using the open-source software *kspectrum*. (*b*) Outgoing longwave radiation (OLR) versus wavenumber from early Mars calculated using a line-by-line calculation assuming surface pressure of 1 bar, surface temperature of 250 K, and a 167 K isothermal stratosphere. Blackbody emission at 250 K and 167 K is indicated by the gray dashed lines. The blue line shows OLR for a pure CO_2 atmosphere, and the red line shows OLR with all the additional greenhouse gases in the top plot included. Results were produced using the HITRAN 2012 database, the Clough et al. (1992) approach to solving the infrared radiative transfer equation, and the CO_2 collision-induced absorption parameterization from Wordsworth et al. (2010). Based on data from Gruszka & Borysow (1997) and Baranov et al. (2004).

lines far from their centers must also be taken into account for accurate computation of CO_2 absorption in climate models (Perrin & Hartmann 1989).

Figure 4*a* shows the absorption coefficient of CO_2 and other gases at standard temperature and pressure computed using the CIA and sub-Lorentzian line broadening parameterization described by Wordsworth et al. (2010), with the two regions of CIA indicated. In **Figure 4*b***, the outgoing longwave radiation (OLR) computed assuming a 1 bar dry CO_2 atmosphere with surface temperature of 250 K is shown. As shown, the CIA causes significant reduction in OLR, but important window regions remain, particularly around 400 and 1,000 cm^{-1}. The most effective minor greenhouse gases on early Mars are those whose absorption peaks lie in these CO_2 window regions. Water vapor absorbs strongly at low wavenumbers and around its ν_2 band at 1,600 cm^{-1}, but its molar concentration is determined by temperature, so it can only cause a feedback effect on the radiative forcing of other gases. At low temperature, this feedback is weak. Hence for pure clear-sky CO_2-H_2O atmospheres under early martian conditions, modern radiative-convective models obtain mean surface temperatures of 225 K or less (Wordsworth et al. 2010, Halevy & Head 2014, Ramirez et al. 2014).

OLR: outgoing longwave radiation

Radiative-convective model: climate model that resolves atmospheric vertical structure and calculates radiative transfer accurately but lacks horizontal resolution

Line-by-line: computationally costly approach to radiative transfer that resolves individual spectral lines

Correlated-*k*: computationally efficient approach to radiative transfer that calculates distributions of line intensity in large spectral bands, at some cost to accuracy

3.3. Alternative Long-Term Warming Mechanisms

The popular notion that Mars was once warm and wet combined with the impossibility of warming early Mars by CO_2 alone has motivated investigation of many alternative warming mechanisms. For the most part, researchers have used one-dimensional radiative-convective models [either line-by-line or correlated-*k* (Goody et al. 1989)] to investigate the early climate. Radiative-convective models allow for temperature variations with altitude only and parameterize or neglect the effects of clouds, which limits their accuracy and predictive power. Nonetheless, their speed and robustness make them invaluable tools for constraining parameter space and investigating novel effects.

Over the years, researchers have investigated various greenhouse gas combinations to achieve a warm and wet early martian climate (Sagan 1977, Postawko & Kuhn 1986, Kasting 1997, Haberle 1998, von Paris et al. 2013, Ramirez et al. 2014). Methane might appear to be a promising martian greenhouse gas given its strong radiative forcing on the present-day Earth. However, it is not an effective warming agent on early Mars because its first significant vibration-rotation band absorbs around 1,300 cm^{-1}—a region too far from the peak of the Planck function in the 200–270 K temperature range to cause much change to OLR (see **Figure 4**). Gases such as ammonia and carbonyl sulfide have greater radiative potential but lack efficient formation mechanisms and are photochemically unstable in the martian atmosphere, so they cannot have been present long term in large quantities.

Other researchers have looked at hydrogen as a greenhouse gas (Sagan 1977, Ramirez et al. 2014). Wordsworth & Pierrehumbert (2013) showed that N_2-H_2 CIA can cause significant warming on terrestrial planets even when H_2 is a minor atmospheric constituent, because broadening of the CIA spectrum at moderate temperatures causes absorption to extend into window regions. In a thought-provoking paper, Ramirez et al. (2014) proposed that CO_2-H_2 absorption could have caused warming on early Mars in a similar fashion, perhaps sufficiently to put the climate into a warm and wet state. Hydrogen readily escapes from a small planet such as Mars, so to work, this mechanism requires rapid hydrogen outgassing, which means a very reducing mantle and high rate of volcanism. It also requires a high atmospheric CO_2 content, which as discussed in Section 3.1 may be inconsistent with a highly reducing mantle (Hirschmann & Withers 2008). Finally, a long-lived highly reducing atmosphere is not obviously consistent with evidence for oxidizing surface conditions during the Noachian (Chevrier et al. 2007). Nonetheless, the

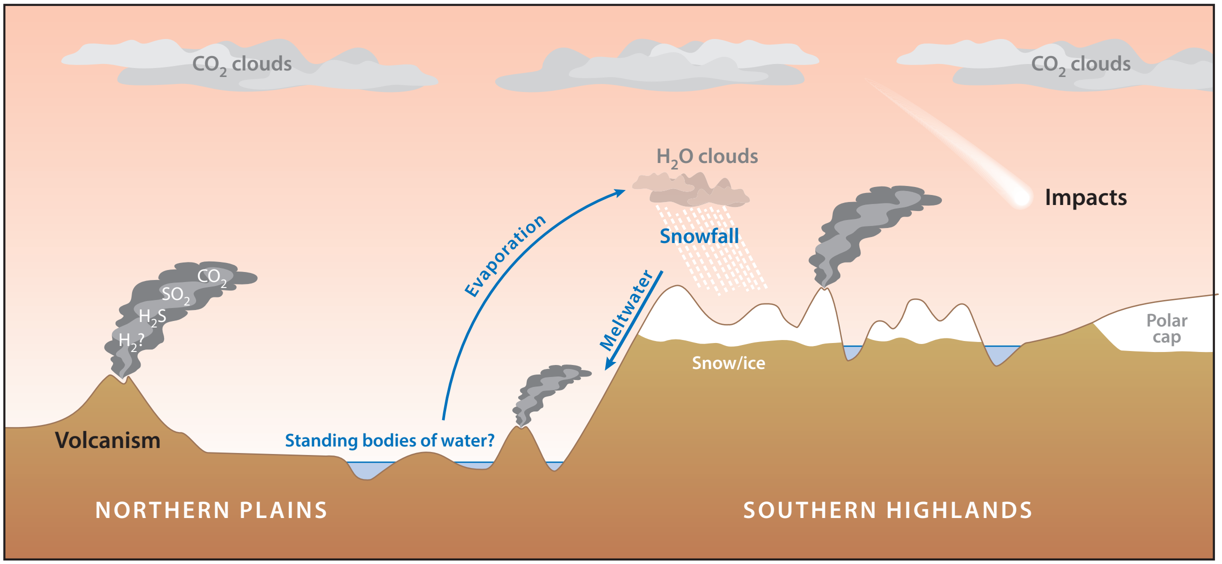

Figure 5

Schematic of the major climate processes on Mars in the Noachian and early Hesperian periods. This cartoon assumes an episodically warm scenario for the early climate with long-term transport of snow to the southern highlands interrupted by episodic melting events.

contribution of reducing species to the early martian climate and atmospheric chemistry is an interesting subject that requires further research.

The radiative forcing of clouds and aerosols was certainly also important to the early martian climate, but it is challenging to constrain. One novel feature of cold CO_2 atmospheres is that condensation at high altitudes leads to CO_2 cloud formation (**Figure 5**)—an effect that is observed in the martian mesosphere today (Montmessin et al. 2007). Forget & Pierrehumbert (1997) proposed that infrared scattering by CO_2 clouds in the high atmosphere could have led to significant, long-term greenhouse warming on early Mars. However, to be effective this warming mechanism requires cloud coverage close to 100%. Recent three-dimensional global climate modeling (Forget et al. 2013, Wordsworth et al. 2013) has shown that this level is never reached in practice. In addition, recent multiple-stream scattering studies have indicated that the two-stream methods used previously to calculate CO_2 cloud climate effects tend to overestimate the strength of the scattering greenhouse (Kitzmann et al. 2013). Hence the net warming effect of CO_2 clouds is likely to have been fairly small in reality. Nonetheless, the infrared scattering effect is still an important term in their overall radiative budget. This means that they at least do not dramatically cool the climate via shortwave scattering, as was thought to be the case in the earliest studies of CO_2 condensation on early Mars (Kasting 1991).

Recent studies have also investigated the role of H_2O clouds. In a three-dimensional climate model study, Urata & Toon (2013) found high-altitude water clouds formed that substantially decreased the OLR. They proposed that this could have caused transitory or long-lived warm climate states on early Mars. However, another three-dimensional climate study published just before Urata & Toon's work found much less effective upward transport of water vapor, resulting in mainly low-lying H_2O clouds that cooled the planet by increasing the albedo (Wordsworth et al. 2013). It is not unduly surprising that two three-dimensional models of early Mars produce such different results on cloud forcing, given the uncertainty on this issue for the present-day

Earth (Forster et al. 2007). Nonetheless, the discrepancy highlights the need for future detailed study of this issue.

3.4. Episodic Warming

The geologic evidence that Mars once had large amounts of surface liquid water is conclusive, but geomorphic constraints on the duration for which that water flowed are much weaker. In addition, much of the geochemical evidence points toward surface conditions that were not warm and wet for long time periods. This is important, because if repeated transient melting events are capable of explaining the observations, the theoretical possibilities for warming become greater.

3.4.1. Impact-induced steam atmospheres. The late Noachian is coincident with the early period of intense impactor flux known as the late heavy bombardment (e.g., Hartmann & Neukum 2001). Meteorite impacts were hence unquestionably a major feature of the environment during the main period of valley network formation. Based on this, several proposals for impact-induced warming have been put forward. Segura et al. (2002, 2008) suggested that large impactors could have evaporated up to tens of meters of water into the atmosphere, which would then have caused erosion when it rained back down to the surface. Later, Segura et al. (2012) proposed that impact-induced atmospheres could be very long lived due to a strong decrease in OLR with surface temperature in a steam atmosphere, which would give rise to a climate bistability.

Despite the appealing temporal correlation, impact-induced steam atmospheres are not compelling as the main explanation for valley network formation. There are two main reasons for this. First, for transient impact-driven warming, there is a large discrepancy between the estimated valley network erosion rates (Barnhart et al. 2009, Hoke et al. 2011) and the amount of rainfall produced postimpact (Toon et al. 2010). Second, the runaway greenhouse bistability argument does not seem physically plausible, at least for clear-sky atmospheres, because it relies on the occurrence of extreme supersaturation of water vapor in the low atmosphere (Nakajima et al. 1992). If impacts played a role in carving the valley networks, therefore, they must have done so by a more indirect method.

3.4.2. Sulfur-bearing volcanic gases. Another idea that has seen intensive study over the past few decades is the SO_2/H_2S greenhouse. The martian surface is sulfur rich (Clark et al. 1976), and sulfates are abundant on Hesperian and Noachian terrain (Bibring et al. 2005, Gendrin et al. 2005, Ehlmann & Edwards 2014). This suggests that volcanic emissions of sulfur-bearing gases (SO_2 and H_2S) could have had a significant effect on early climate (Postawko & Kuhn 1986, Yung et al. 1997, Halevy et al. 2007).

SO_2 is a moderately effective greenhouse gas. The 518 cm^{-1} (19.3 μm) vibrational-rotation band associated with its ν_2 bending mode absorbs close to the peak of the blackbody spectrum at 250–300 K, but sufficiently far from the CO_2 ν_2 band at 667 cm^{-1} to cause a fairly large reduction in the OLR if SO_2 is present at levels of 10 ppm or above (**Figure 4**). SO_2 absorption bands in the 1,000–1,500 cm^{-1} region also contribute but partially intersect with CO_2 CIA at high pressure. H_2S, which would also have been outgassed in significant quantities by the martian mantle if it was reducing, is a far less effective greenhouse gas on early Mars due to the intersection of its main absorption bands with those of H_2O and CO_2 (**Figure 4**).

Like NH_3 and CH_4, SO_2 is photolyzed in the martian atmosphere. Photochemical modeling under plausible early martian conditions has suggested that this limits its lifetime to under a few hundred years (Johnson et al. 2009). More importantly, SO_2 photochemistry leads to rapid formation of sulfate aerosols (Tian et al. 2010). These scatter incoming sunlight effectively, raising the albedo and cooling the planet. Similar climate effects have been observed in stratovolcano eruptions on Earth, such as that of Pinatubo in 1991 (Stenchikov et al. 1998).

GCM: general circulation model

Halevy & Head (2014) argued that intense episodic volcanic SO_2 emissions associated with the formation of Hesperian ridged plains could have caused significant greenhouse warming. Using a line-by-line radiative-convective climate model, they found subsolar zonal average temperatures of 250 K for SO_2 concentrations of 1–2 ppm in a clear-sky CO_2-H_2O atmosphere. Based on this, they argued that peak daytime equatorial temperatures would exceed 273 K for several months per year during transient pulses of volcanism and hence significant meltwater could be generated.

Because Halevy & Head (2014) used a one-dimensional column model, they did not account for horizontal heat transport by the atmosphere. In contrast to their result, recent three-dimensional general circulation model (GCM) studies have found that in concentrations of less than 10 ppm, SO_2 warming cannot cause significant melting events on early Mars (Mischna et al. 2013, Kerber et al. 2015). Indeed, the dramatic cooling effects of sulfate aerosols together with the timing of the Hesperian flood basalts led Kerber et al. (2015) to suggest an opposite conclusion: The onset of intense sulfur outgassing on Mars may have ended the period of episodically or continuously warm conditions in the late Noachian.

In summary, no single mechanism is currently accepted as the cause of anomalous warming events on early Mars. Climate models that allow horizontal temperature variations show that, in combination, various atmospheric and orbital effects can combine to create marginally warm conditions and hence small amounts of episodic melting (Richardson & Mischna 2005; Kite et al. 2013; Mischna et al. 2013; Wordsworth et al. 2013, 2015), particularly if the meltwater is assumed to be briny (Fairén et al. 2009, Fairén 2010). Just like the climate of Earth today, the ancient climate of Mars was probably complex, with multiple factors contributing to the mean surface temperature. Nonetheless, further research on this key issue is necessary. The continuing uncertainty with regard to warming mechanisms has recently led some studies to take an empirical approach to constraining the early martian climate (Section 4.2).

4. DECIPHERING THE LATE NOACHIAN WATER CYCLE

Radiative-convective climate models are powerful tools, but they have limitations. One of the most obvious is their inability to capture cloud effects, except in a crude and highly parameterized way. A second major limitation is that they fail to account for regional differences in climate and hence cannot be used to model a planet's hydrological cycle. This is particularly important for Mars, which has large topographic variations and a spatially inhomogeneous surface record of alteration by liquid water.

Whereas three-dimensional GCMs of the present-day martian atmosphere began to be used from the 1960s onward (Leovy & Mintz 1969), development of GCMs for paleoclimate applications has been much slower. An important reason for this is the complexity of dense gas CO_2 radiative transfer, as described above. Nonetheless, in the past five years, several teams have begun three-dimensional GCM modeling of the early martian climate.

Challenges in simulating the martian paleoclimate in three dimensions include a potentially altered topography compared to present day, uncertainty in the orbital eccentricity and obliquity, and the difficulty of calculating radiative transfer accurately and rapidly in an atmosphere of poorly constrained composition. Of all of these, the latter poses the greatest technical challenge. Line-by-line codes such as that used to produce **Figure 4** are impractical for GCM simulations because the number of calculations required makes them prohibitively expensive computationally. Instead, recent three-dimensional simulations have used the correlated-*k* method (Goody et al.

1989, Lacis & Oinas 1991). This technique, which was originally developed for terrestrial radiative transfer applications, replaces the line-by-line integration over spectral wavenumber with a sum over a cumulative probability distribution in a much smaller number of bands.

The first study to apply this technique to three-dimensional martian paleoclimate simulations was carried out by Johnson et al. (2008), who looked at the effect of SO_2 warming from volcanism. Though pioneering in terms of its technical approach, this work used correlated-*k* coefficients that were later found to be in error (Mischna et al. 2013). As a result, it predicted unrealistically high warming due to SO_2 emissions. Since this time, several new three-dimensional GCM studies of early Mars using correlated-*k* radiative transfer have been published, leading to a number of new insights.

As previously discussed, Forget et al. (2013), Wordsworth et al. (2013), and Urata & Toon (2013) investigated the role of CO_2 and H_2O clouds in warming the early climate and found that both cloud fraction and mean particle size were critical factors in their radiative effect. Forget et al. (2013) and Soto et al. (2015) investigated collapse of CO_2 atmospheres due to surface condensation. They found that the process was extremely significant at low obliquities (below 20°) and at pressures above 3 bar. The predictions of Forget et al. (2013) and Soto et al. (2015) differed in detail, however, partly because Soto et al. (2015) neglected the effects of CO_2 clouds and used the present-day solar luminosity. Hence further model intercomparison on this issue is required. In a related study, Kahre et al. (2013) examined CO_2 collapse in the presence of an active dust cycle and found that dust could help to stabilize moderately dense atmospheres (~80 mbar) against collapse at high obliquity. As described in Section 3.4.2, two new three-dimensional studies have also investigated the role of SO_2 warming in the Noachian climate (Mischna et al. 2013, Kerber et al. 2015).

4.1. Adiabatic Cooling and the Icy Highlands Hypothesis

Another outcome of recent three-dimensional GCM modeling has been an improved understanding of the processes governing Mars's early surface water cycle. On a cold planet, the water cycle is dominated by the transport of surface ice to regions of enhanced stability (cold traps). Ice stability is a strong function of the sublimation rate, which depends exponentially on surface temperature via the Clausius-Clayperon relation. In practice, this means that the regions of the planet with the lowest annual mean surface temperatures are usually cold traps. Figuring out the cold trap locations on early Mars is critical, because this tells us where the water sources were during warming episodes.

Mars today has an atmospheric pressure of around 600 Pa and obliquity of 25.2°. The majority of surface and subsurface water ice is found near the poles (Boynton et al. 2002). Mars's obliquity has varied significantly throughout the Amazonian, however (Laskar & Robutel 1993), and at high obliquities ice migration to equatorial (Mischna et al. 2003, Forget et al. 2006) and mid-latitude (Madeleine et al. 2009) regions is predicted. Obliquity variations may well have also been important to ice stability in the Noachian and early Hesperian. However, in this period the role of atmospheric pressure was probably even more important.

Figure 6 shows the simulated annual mean temperature T_s for Mars given a solar flux 75% of that today (Gough 1981) and surface pressures of (*a*) $p_s = 0.125$ bar and (*b*) $p_s = 1$ bar. At the lowest pressure, mean surface temperatures are primarily determined by insolation, and the main variation of T_s is with latitude. At 1 bar, however, a shift to variation of T_s with altitude occurs. The accompanying scatter plot of surface temperature versus altitude clearly shows a trend toward temperature-altitude anticorrelation as pressure increases. The origin of this effect is the increase in coupling between the lower atmosphere and surface via the planetary boundary layer.

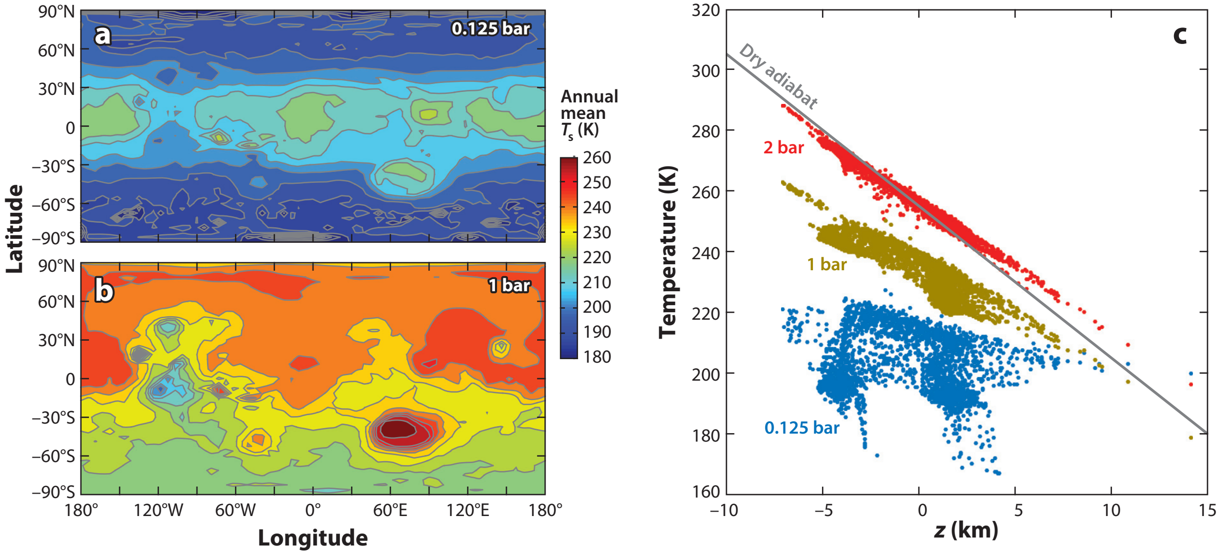

Figure 6

The adiabatic cooling effect on early Mars. (*a*) Annual mean surface temperature from a three-dimensional general circulation model (GCM) simulation with 0.125 bar surface pressure. (*b*) Annual mean surface temperature from a three-dimensional GCM simulation with 1 bar surface pressure. (*c*) Scatter plot of surface temperature versus altitude for simulations with 0.125, 1, and 2 bar surface pressure. The dry adiabat g/c_p is also indicated (*gray line*). Data for the plots were acquired from the 41.8° obliquity, fixed relative humidity simulations described by Wordsworth et al. (2015) (see also Forget et al. 2013).

The surface heat budget on a mainly dry planet can be written as

$$F_{\mathrm{lw},\uparrow} = F_{\mathrm{lw},\downarrow} + F_{\mathrm{sw},\downarrow} + F_{\mathrm{sens}}, \tag{1}$$

where $F_{\mathrm{lw},\uparrow}$ is the upwelling longwave (thermal) radiation from the surface, $F_{\mathrm{lw},\downarrow}$ is the downwelling thermal radiation from the atmosphere to the surface, $F_{\mathrm{sw},\downarrow}$ is the incoming solar flux, and F_{sens} is the sensible heat exchange. The latter term can be written as[2] $F_{\mathrm{sens}} = \rho_a C_D c_p |\mathbf{u}|(T_a - T_s)$, where ρ_a is the atmospheric density near the surface, C_D is the bulk drag coefficient, c_p is the atmospheric specific heat capacity at constant pressure, $|\mathbf{u}|$ is the surface wind speed, and T_a is the temperature of the atmosphere at the surface. Observations and simulations indicate that $|\mathbf{u}|$ generally decreases with ρ_a, but only slowly. Hence the magnitude of F_{sens} will increase with ρ_a unless the temperature difference $T_a - T_s$ simultaneously decreases.

For a planet without an atmosphere (such as Mercury), $F_{\mathrm{lw},\downarrow}$ and F_{sens} equal zero and surface temperature is determined by insolation (with a contribution from geothermal heating in very cold regions). As atmospheric pressure increases, so does heat exchange between the atmosphere and the surface. For a planet with a thick atmosphere (such as Venus or Earth), sensible and radiative atmospheric heat exchange are significant and drive T_s toward the local air temperature T_a. Because the atmospheric lapse rate follows a convective adiabat in the troposphere, surface temperatures decrease with altitude. This is exactly the effect that causes equatorial mountains on Earth such as Kilimanjaro to have snowy peaks despite the tropical temperatures at their bases.

[2]At low atmospheric pressures (<0.2 bar) and surface wind speeds, free convection may also be important (Kite et al. 2013, figure 9), but its relative effect declines at higher pressures.

Mars has a lower surface gravity than Earth does, which decreases its dry adiabatic lapse rate ($\Gamma_d = -g/c_p$, with g gravity and c_p the specific heat capacity at constant volume). However, this is more than compensated for by its large topographic variations. The altitude difference between Hellas Basin and the southern equatorial highlands is approximately 12 km, or just over one atmospheric scale height. In three-dimensional GCM simulations, the corresponding drop in annual mean temperature is approximately 30 K at 1 bar atmospheric pressure, or approximately 40 K at 2 bar (**Figure 6**).

Firn: a partially compacted form of solid H_2O intermediate in density between snow and ice

As a result of this adiabatic cooling effect, for moderate values of martian obliquity and atmospheric pressures above around 0.5 bar, the equatorial Noachian highlands (where most valley networks are observed) become cold traps, confirming a prior prediction by Fastook et al. (2012). Long-term three-dimensional climate simulations coupled to a simple ice evolution model (Wordsworth et al. 2013) have demonstrated that, as a result, ice migrates to the valley network source regions regardless of where it is initially located on the surface.

The adiabatic cooling effect led Wordsworth et al. to propose the so-called icy highlands scenario for the early climate (**Figure 5**). In essence, the idea is that if the valley network source regions were cold traps, the early martian water cycle could have behaved somewhat like a transiently forced, overdamped oscillator. Episodic melting events (the perturbing force) would have transported H_2O to lower-altitude regions of the planet on relatively short timescales. Over longer timescales, adiabatic cooling (the restoring mechanism) would have returned the system to equilibrium.

Recent modeling and observational work has used the icy highlands hypothesis as a framework for testing various predictions about the early martian climate. For example, Scanlon et al. (2013) used an analytical model combined with the three-dimensional GCM of Wordsworth et al. (2013) to study orographic precipitation over Warrego Valles and were able to match local precipitation patterns with the valley network locations. Head & Marchant (2014) discussed the analogies between the icy highlands scenario for early Mars and the Antarctic Dry Valleys, which have long been considered one of the most Mars-like regions on Earth.

Fastook & Head (2014) used a glacial flow model to study how the buildup of large ice sheets would have affected the geomorphology of the Noachian highlands. Assuming a thermal conductivity appropriate to ice without a blanketing effect from snow or firn, they found that if the Noachian water inventory was less than $5\times$ the present-day GEL (i.e., 170 m), equatorial highland glaciers would have been cold based and hence would not have left traces on the surface in the form of cirques, eskers, or other glacial landforms. This conclusion was broadly confirmed by Cassanelli & Head (2015), who studied the influence of snow and firn thermal blanketing on ice sheet melting under a H_2O-limited scenario only. The relative lack of glaciation in the equatorial highlands and the total water inventory are key pieces of the Noachian climate puzzle that we return to in Section 4.4.

4.2. The Hydrological Cycle on a Warm and Wet Planet

The icy highlands scenario provides a useful working model for thinking about the early martian climate and fits many aspects of the geologic evidence. Nonetheless, because some observations are still interpreted as supporting long-term warm and wet conditions, it is also interesting to model alternative scenarios for the early martian climate. As discussed above, no climate model based on realistic assumptions currently predicts warm and wet conditions for early Mars.[3] To

[3]Ramirez et al. (2014) argued that the CO_2-H_2 CIA mechanism can come close. However, in their model, it still requires more atmospheric H_2 than they can produce, even using their most generous outgassing estimates.

study the hydrological cycle on a warm and wet planet, therefore, it is necessary to use an empirical approach. There are two basic ways to do this: increasing the solar luminosity or increasing the atmospheric infrared opacity.

Wordsworth et al. (2015) tried both these approaches to study precipitation patterns on a warm and wet early Mars. As a starting condition, they assumed that Mars had a global northern ocean and smaller bodies of water in Argyre and Hellas, based on the putative delta shoreline constraints of di Achille & Hynek (2010). For simplicity, they also neglected the destabilizing effects of ice-albedo feedback on the early martian climate (Section 4.3).

In general, Wordsworth et al. (2015) found that the precipitation patterns in the warm and wet case were not a close match to the valley network distribution. In particular, the presence of Tharsis caused a dynamical effect on the circulation that led to low rainfall rates in Margaritifer Sinus, where some of the most well-developed valley networks on Mars are found. This indicates that either (*a*) something was missing from their model or (*b*) Mars was never warm and wet and the martian valley networks formed through transient melting events. The opinion of this author is that the second possibility is the correct one. Future work testing the influence of poorly constrained effects such as cloud convection parameterizations, changes in surface topography, and possibly true polar wander on this result will allow the first possibility to be tested further. In any case, it is clear that systematic empirical investigation of different scenarios using three-dimensional models provides a new way to constrain the early climate.

4.3. Snowball Mars

An additional impediment to the warm and wet scenario for early Mars that has not yet been extensively considered is the ice-albedo feedback (Budyko 1969). This process is an important player in the ongoing loss of sea ice in the Arctic on Earth due to anthropogenic climate change (Stroeve et al. 2007). It was also responsible for the Snowball Earth global glaciations that occurred in the Neoproterozoic (Kirschvink 1992, Hoffman et al. 1998, Pierrehumbert et al. 2011).

Even with a northern ocean at the di Achille & Hynek (2010) shoreline, Mars would possess a far higher land-to-ocean ratio than Earth does, making the physics of a snowball transition quite different. Unlike on Earth, where runaway glaciation occurs through freezing of a near-global ocean, on Mars transport of H_2O to high-altitude regions as snow would play the key role. Because of the presence of Tharsis at the equator, the topography of Mars is particularly conducive to an ice-albedo instability of this kind. As discussed in Section 2, most of the formation of Tharsis was probably complete by the late Noachian (see also **Figure 2**). Thanks to the adiabatic cooling effect under a thicker atmosphere, Tharsis is an effective cold trap for water ice even if most of Mars is assumed to be warm and wet.

To put numbers to this idea, we can define sea level as −2.54 km from the datum following di Achille & Hynek (2010) and take the summit of Tharsis [neglecting the peaks of the Tharsis Montes volcanoes, which are Amazonian-era (Tanaka et al. 2014)] to be approximately $z = 8$ km. Then the sea level–to–summit adiabatic temperature difference is $\Gamma_d z = -gz/c_p \approx 38$ K. At 1 bar surface pressure the surface temperature gradient with altitude is still somewhat below the adiabatic value, so we can conservatively estimate a temperature difference of 30 K. To a first approximation, seasonal temperature changes at the equator can be neglected, so an annual mean sea-level temperature of approximately 30°C is required to avoid the buildup of snow and ice on Tharsis.

The high altitude of Tharsis means that the atmospheric radiative effects above it (both scattering and absorption) are reduced. This increases its radiative forcing due to surface albedo changes compared to lower-lying regions. Because of its equatorial location, an ice-covered Tharsis also increases the planetary albedo regardless of Mars's obliquity.

No three-dimensional climate simulation has yet addressed the impact of a snowy Tharsis on the stability of a warm and wet early Mars. This is an important topic for future study. It may be that marginally warm global mean temperatures are insufficient to stop Mars from rapidly transitioning to a cold and wet state.

4.4. The Periglacial Paradox and the Noachian Surface Water Inventory

As discussed in Section 2, there is little evidence for glaciation during Mars's Noachian period in the equatorial highlands. At first glance, this seems like a potential drawback of the icy highlands scenario for the early climate (Grotzinger et al. 2015). If snow and ice buildup in high-altitude regions was the source of the water that carved the valley networks, should we not see a more widespread record of glacial and fluvioglacial alteration across the Noachian highlands?

The trouble with this line of thinking as an argument against the icy highlands scenario is that it equally applies to a warm and wet early Mars. If Mars was once warm and wet, it must have subsequently become cold, because it is cold today. Once it did, liquid water would freeze into ice and migrate to the cold trap regions of the surface. This implies the buildup of ice sheets in the equatorial highlands unless the martian atmospheric pressure immediately decreased to low values *and* obliquity was continually low in the period following the warm and wet phase. The quantity of surface water sufficient to fill a northern ocean to the di Achille & Hynek (2010) shoreline implies a GEL of approximately 550 m, so in the immediate post–warm and wet phase these ice sheets could be several kilometers thick. As shown by Fastook & Head (2014), this would lead to wet-based glaciation (and hence fluvioglacial erosion) even under very cold climate conditions, and even without the insulating effects of a surface snow layer.

If a warm and wet Mars should leave abundant evidence of glaciation in its subsequent cold and wet phase, how can the equatorial periglacial paradox be explained? Most likely, the resolution lies in early Mars's total surface H_2O inventory. In a supply-limited icy highlands scenario with episodic melting, snow and ice deposits are cold based. Then, the only significant alteration of terrain comes from fluvial erosion during melting events.

Many studies have investigated the evolution of Mars's surface H_2O inventory through time. The deuterium-to-hydrogen (D/H) ratio can be used to constrain the early martian water inventory (Greenwood et al. 2008, Webster et al. 2013, Villanueva et al. 2015), although our lack of knowledge of the dominant escape process in the Noachian/Hesperian and of the cometary contribution to Mars's surface water (Marty 2012) complicates the analysis. Villanueva et al. (2015) recently used Earth-based observations of martian D/H and estimated the late Noachian water GEL to be 137 m. In contrast, Carr & Head (2015) recently calculated the H_2O loss/gain budget in the Hesperian and Amazonian and concluded that the late Noachian water GEL was as low as 24 m. Although the uncertainty is considerable, most estimates place the early martian water inventory below a few hundred meters GEL. This low inventory compared to Earth's is consistent with Mars's low mass and likely significant loss of atmosphere to space (see sidebar).

Continuing our previous line of thought to its logical conclusion, we can construct an idealized two-dimensional phase diagram for the early martian climate, with surface temperature on one axis and the total surface H_2O inventory on the other (**Figure 7**). Each quadrant in **Figure 7** represents a different end-member state for the long-term climate and surface hydrology of early Mars. The warm and wet state with a northern ocean is disfavored for the geochemical and climatological reasons discussed previously. Because of the ice-albedo feedback, it also readily transitions to a cold and wet state. The cold and wet state implies extensive wet-based glaciation across Noachian terrain, in conflict with the geomorphological record. The cold and (relatively) dry state (water GEL <200 m) is essentially the icy highlands scenario, which in combination with the right

MARS, THE RUNT PLANET

Mars is fascinating to study in its own right, but also because of the insight it can give us into planetary evolution and habitability in general. Several potentially rocky exoplanets and exoplanet candidates that receive approximately the same stellar flux as Mars have now been discovered (e.g., Udry et al. 2007, Quintana et al. 2014). Can we derive lessons from martian climate evolution studies that are generalizable to a wider context?

Mars formed very rapidly compared to Earth (Dauphas & Pourmand 2011) and is smaller than predicted by standard formation models (Chambers & Wetherill 1998). Current thinking suggests Mars is best understood as a planetary embryo, whose development into a fully fledged terrestrial planet was arrested by some process such as instability in the configuration of the outer planets (Walsh et al. 2011). The Red Planet is not as massive as it could have been, and this factor more than any other has dominated its subsequent evolution.

Mars's low mass relative to Earth led to an early shutdown of the magnetic dynamo (Acuna et al. 1998) and rapid cooling of the interior. If plate tectonics ever initiated at all, it ceased rapidly (Connerney et al. 2001, Solomon et al. 2005). As a result, volatile cycling between the surface and interior was strongly inhibited and the rate of atmospheric loss to space was probably also enhanced. The present-day atmosphere is so thin that liquid water is unstable on the surface. Mars's reddish, hyperoxidized surface, which is extremely inhospitable to life, is a direct result of the escape of hydrogen to space over geologic time (Lammer et al. 2003).

Almost certainly, Mars tells us more about the habitability of low-mass planets than the habitability of planets that are far from their host stars. Indeed, an Earth-mass planet with plate tectonics at Mars's orbital distance would be habitable today, if mainstream thinking on the carbonate-silicate cycle (Walker et al. 1981) and planetary habitability (Kasting et al. 1993) is correct. Radiative-convective calculations using the model described by Wordsworth & Pierrehumbert (2013) indicate that a 1 $M_{\oplus}$ planet at Mars's orbit with an atmosphere dominated by CO_2 and H_2O would have a surface temperature of 288 K for an atmospheric pressure of around 3–5 bar—a small amount in comparison with Earth's total carbon inventory (Sleep & Zahnle 2001, Hayes & Waldbauer 2006).

In the absence of the still-mysterious process that abruptly halted Mars's growth, our more distant neighbor could have been globally habitable to microbial life through much of its history. Given the potential for exchange of biological material on impact ejecta between terrestrial planets (Mileikowsky et al. 2000, Kirschvink & Weiss 2002), biogenesis on Earth (or Mars; Kirschvink & Weiss 2002) would then have led to the development of global biospheres on two planets in the Solar System. A future scenario in which Mars possesses a global biosphere is also possible but will depend on human colonization and subsequent intentional modification of the climate.

amount of episodic melting can explain most of the geologic record. Finally, there is a possible warm and dry scenario in which all the surface water is liquid but the H_2O GEL is below ~200 m. This might also fit many of the geologic constraints on the early martian climate. However, it is climatologically as hard to justify as the warm and wet state. In addition, in such a scenario the low-lying regions where liquid water stabilizes would be so far from the valley network source regions that precipitation there might be limited or nonexistent. Preliminary GCM studies using the model described by Wordsworth et al. (2015) suggest that this is indeed the case. This is yet another important issue that deserves to be studied in detail in the future.

5. OUTLOOK

Although major questions remain on the nature of the early martian climate, recent advances have been significant. The weight of geomorphological and geochemical evidence points toward a late Noachian hydrological cycle that was intermittent, not permanently active. Three-dimensional GCM simulations of the early climate and other modeling and analog studies suggest that a

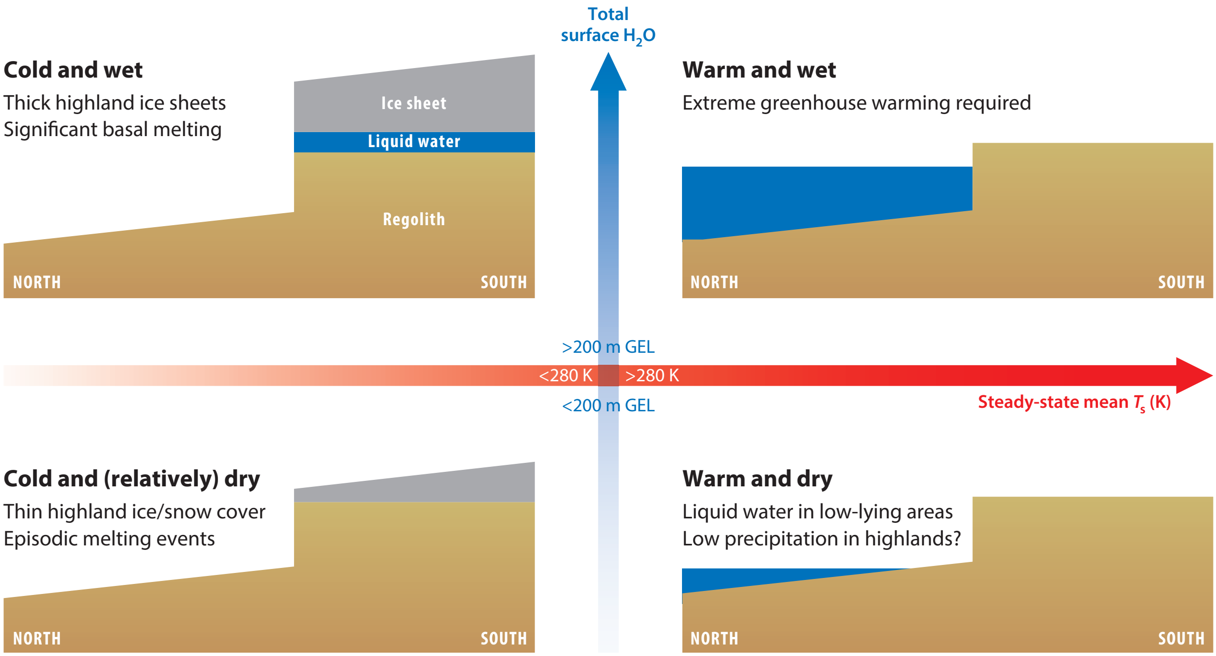

Figure 7

Conceptual phase diagram for the steady-state early martian climate under a denser atmosphere. Given mean surface temperature and the total surface H_2O inventory as x and y axes, respectively, four idealized climate states can be imagined. The cold and wet state leads to large highland wet-based glacial ice sheets, in conflict with the geologic record. The warm and wet state requires extreme greenhouse warming and rapidly transitions to the cold and wet state when surface temperatures decrease. The warm and dry state has not yet been simulated numerically but may lead to little or no rainfall in the equatorial highlands. The cold and relatively dry state, when combined with episodic melting events, appears consistent with the majority of the geologic evidence. Abbreviation: GEL, global equivalent layer.

water-limited early Mars with episodic melting episodes may be a suitable paradigm for much of the late Noachian and early Hesperian climate.

Despite the progress over the past few years, aspects of the early climate remain unclear. Chief among these is the driving mechanism behind the episodic warming events. Previous theories for warming by CO_2 clouds, sulfur volcanism, and impact-induced steam atmospheres have all been shown to possess serious problems. Indeed, as one- and three-dimensional climate models become more accurate, there has been a general trend toward prediction of colder surface temperatures. A successful theory for surface warming must yield valley network erosion rates consistent with the geologic evidence (Hoke et al. 2011) but avoid extensive surface carbonate formation and aqueous alteration of sediments (Tosca & Knoll 2009, Ehlmann et al. 2011).

The climate of early Mars, like that of present-day Earth, almost certainly involved multiple interacting processes. In addition, despite the difficulties with the impact-induced steam atmosphere hypothesis, the timing of the peak period of valley network formation with respect to the late heavy bombardment is suggestive of a causal link. In contrast, the lack of temporal correlation between the valley networks and Hesperian ridged plains argues against a causal link with effusive volcanism.

The key advantage of modeling the early climate as a spatially varying system, rather than studying isolated processes or trying to achieve mean temperatures above 273 K in a globally averaged model, is that it allows tighter intercomparison with the geologic evidence. Future research should work toward close integration of surface geology, three-dimensional climate, and hydrological modeling studies. Specific regions where this approach would be particularly useful include the south pole around the Dorsa Argentea Formation and the Aeolis quadrangle where Gale Crater is located. Issues of specific importance to the three-dimensional climate modeling include better representation of clouds, perhaps through a subgridscale parameterization scheme (e.g., Khairoutdinov & Randall 2001), and coupling with subsurface hydrology models (Clifford 1993, Clifford & Parker 2001).

If Mars never had a steady-state warm and wet climate, does this spell doom for the search for past life on the surface? Probably not: Life on Earth clings tenaciously to almost any environment where we can look for it, including Antarctica's Dry Valleys and deep below the seafloor (Cary et al. 2010, D'Hondt et al. 2004). Indeed, if one view of Earth's climate in the Hadean and early Archean is correct, our own planet may have been in a globally glaciated state when life first formed (Sleep & Zahnle 2001). The search for life on Mars must continue, but to maximize our chances of success, it needs to be informed by our evolving understanding of the early climate.

SUMMARY POINTS

1. Mars underwent an extended period of surface erosion and chemical weathering by liquid water until around 3.5 Ga, during the late Noachian and early Hesperian periods.
2. The weight of the observational evidence favors a mainly cold climate with episodic warming events, rather than permanently warm and wet conditions.
3. If early Mars was once warm and wet, thick wet-based ice sheets would have formed on the Noachian highlands when the warm period ended, causing significant glacial erosion.
4. Constraints on the early solar luminosity, martian orbit, and radiative transfer of CO_2 strongly disfavor a warmer climate due to CO_2 and H_2O only.
5. Under a thicker atmosphere, adiabatic cooling of the surface causes transport of snow and ice to the valley network source regions.
6. Repeated episodic warming events probably caused ice and snowpacks in the Noachian highlands to melt, carving valley networks and other fluvial features.
7. The precise mechanism that caused the warming events is still poorly constrained. The two most likely forcing mechanisms are meteorite impacts and volcanism, although the details remain unclear.

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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