THE EARLY CLIMATE HISTORY OF MARS: “WARM AND WET” OR “COLD AND ICY”?

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Examination of the geological record of non-polar ice deposits [1] strongly suggests that the climate of Mars throughout the Amazonian (the last ~66% of Mars history), was much like it is today, a cold and dry climate regime, characterized by the latitudinal migration of surface ice in response to variations in spin-axis/orbital parameters, primarily obliquity [2]. But what of the earlier history of Mars? What characterized the climate regime during the Noachian, the first ~20% of Mars history? Many lines of evidence and reasoning have been cited to support the interpretation of a “warm and wet” early Mars climate [e.g., 3,4], but this evidence has also been challenged [5,6]: 1) Significant parts of the phyllosilicates in the Noachian crust (Fe, Mg clays) appear to be due to hydrothermal (subsurface) alteration [7]; 2) Noachian degradation/erosion rates are very low by terrestrial standards [8]; 3) Poor integration of valley networks and open-basin lakes (despite increased valley network density) [9] could suggest shorter-term fluvial, rather than long-term pluvial activity; 4) Regional ice deposits at all latitudes in the Amazonian [1] provide perspective on the possibility of regional ice deposits in the Noachian; 5) A Late Noachian south circumpolar ice sheet [10] suggests that Noachian and mid-latitude atmospheric mean annual temperatures (MAT) were below freezing [11]; 6) Valley network-related precipitation might be snowfall (nivial), not rainfall (pluvial) [12]; 7) The Mars-like Antarctic Dry Valleys [13] show that meltwater-related fluvial activity can occur when MATs are well below freezing; 8) Punctuated volcanic outpourings can lead to transient atmospheric warming and extensive melting of surface ice [14]; 9) New estimates of water loss rates to space are much lower [15]; 10) Martian meteorites [16] suggest that paleoatmospheric pressures were <400 mbar by 4.16 Ga; 11) Atmospheric modelers have always encountered difficulty in producing and maintaining an atmosphere conducive to Noachian warm and wet pluvial environments due to a faint young Sun and insufficient greenhouse gases [17].

Recently, significant progress has been made in the modeling of the atmosphere on early Mars by Forget, Wordsworth and colleagues. A complete 3-D General Circulation Model (GCM) [18] including revised spectroscopic properties for CO_2, and a full water cycle [19], has been developed. Simulations of an early Mars climate assumed a faint young Sun and a CO_2 atmosphere with surface pressures between 0.1 and 7 bars. One of the most fundamental findings of the model is that for atmospheric pressures greater than a few hundred millibars, surface temperatures vary with altitude because of the onset of atmosphere-surface thermal coupling, and adiabatic cooling and warming of the atmosphere as it moves vertically. This *adiabatic cooling effect* results in the deposition of snow and ice at high altitudes (Fig. 1), in contrast to the conditions at present and throughout the Amazonian. Exploration of parameter space for the Noachian atmosphere-surface thermally coupled climate regime [18,19] found that, in the absence of other warming mechanisms, no combination of parameters could lead to mean annual surface temperatures consistent with widespread melting and flow of liquid water anywhere on the planet. Inclusion of a complete water cycle with clouds and precipitation [18] permitted the modeling of the location and evolution of water and ice on the surface of early Mars. The addition of a water cycle, combined with the adiabatic cooling effect, causes southern highland region temperatures to fall significantly below the global average (Fig. 1). These conditions lead to the scenario of a “Noachian Icy Highlands”: Water is transported to the highlands from low-lying regions due to the adiabatic cooling effect and snows out to form an extended H_2O ice cap at the southern pole, and altitude-dependent snow and ice deposits down to lower southern latitudes [18-19]. Meteorite impacts and volcanism could potentially cause intense episodic melting [19], with ice migration to higher altitudes being a robust mechanism for recharging highland water sources. Could the predictions of this “Noachian Icy Highlands” model (Fig. 3) be consistent with the many lines of evidence traditionally cited for a “warm, wet” early Mars and also address the contradictions cited above?

A simple reconstruction of an icy Noachian Mars [18,19] shows the effects of the adiabatic cooling effect (Fig. 2**):** first, the Dorsa Argentea Formation would surround the south circumpolar region, and snow would concentrate at high altitudes (high southern latitudes) accumulating and forming ice deposits; a value of +1.0 km is adopted for the surface ice stability line (ISL). Below this altitude, snow and ice could accumulate on local highs depending on local and regional topography and atmospheric circulation patterns [12]. In a steady-state situation, any transient low-altitude (equatorial and northern lowlands) surface liquid water would rapidly freeze, sublimate, and be transported to the southern high altitudes (Fig. 1), forming a cover of cold-based ice and snow. Any regolith exposed below the ice stability line would show a dry surface layer over a shallow ice table, the depth of which would be determined by diffusive equilibrium with the atmosphere. Spin-axis/orbital perturbations [2] would modulate, but not radically change, this configuration.

Perturbing this predominant Noachian environment with punctuated impacts and volcanism/greenhouse gases would lead to the raising of global surface temperatures toward the melting point of water. Four factors would be important: 1) the adiabatic cooling effect would control the distribution of snow and ice (the surface ice stability line); 2) the greenhouse effect would determine the level and duration of temperature changes; 3) latitude dependent insolation would modulate temperatures (cold at the south pole, ‘warmer’ toward equator); 4) general circulation patterns further influence air temperatures and local ice accumulation. To investigate further the effects of punctuated global warming, we assume current topography, spin-axis/orbital parameters, atmospheric circulation patterns, and a Noachian icy highlands climate [18-19]. Raising Noachian Mars equatorial MAT to +5°C (typical of central Canada and Scandinavia on Earth today) would produce the following consequences (Fig. 2): 1) ice above the surface ice stability line would undergo rapid altitude/latitude dependent warming during each Mars summer (about 6 Earth months); 2) meltwater runoff from the continuous ice sheet would drain and flow downslope to the edge of the ice sheet, where meltwater channels would encounter Noachian cratered terrain topography and flow around and into craters, forming closed-basin and open-basin lakes and extensive, but poorly integrated fluvial drainage systems; 3) local snow and ice accumulations below the ISL also undergo melting, producing a more integrated drainage system controlled by the presence of snow; sometimes these two systems integrate; 4) seasonal top-down heating and melting of the top tens of meters of continuous ice would produce a volume of water well in excess of the total volume interpreted to have occupied open-basin/closed basin lakes [20]; 5) this meltwater would initially erode into the dry regolith down to the top of the ice table, producing a perched aquifer and more efficient erosion than infiltration alone; 6) time periods above 0°C would be long enough to cause extensive melting and runoff, but too short to cause significant differences in the depth to the top of the ice table; 7) at the end of the annual melting period, temperatures would return to below 0°C, meltwater would freeze and sublime, returning to the high altitudes as snowfall to replenish the snow and ice deposit (Fig. 1); 8) this Noachian icy highlands, adiabatic cooling effect-dominated water cycle would persist until MAT dropped to below 0°C; 9) once MAT returned to normal values well below 0°C at the end of punctuated warming, lower altitude snow and ice would return to high altitudes to reestablish the nominal Noachian icy highlands climate.

In summary, the icy Noachian highlands and punctuated volcanism scenario (Figs. 1,2) appears to be able to account for: 1) the source and volume of water required for valley networks; 2) the presence of closed-basin lakes and open-basin lakes; 4) evidence for recurring phases of activity over millions of years; 5) the generally small amounts of net erosion; 6) areas of both significant trunk streams and more distributed runoff; 7) relatively poor stream integration and lower order than typical of pluvial activity on Earth; 8) abrupt cutoff in valley networks and open-basin lake activity based on delta characteristics; 9) apparent short duration of individual phases of activity; 10) the presence of a surface hydrological cycle that can replenish the source area and cause recurring activity with a small total budget of water; and 11) the presence of melting and runoff in a Late Noachian climate compatible with other constraints (e.g., faint young Sun, low atmospheric pressure).

As outlined here, the contrasting “warm and wet” and “cold and icy” Noachian climate regime models make important predictions that can be tested with current and future data, experiments and missions and point out key locations for the return of samples.

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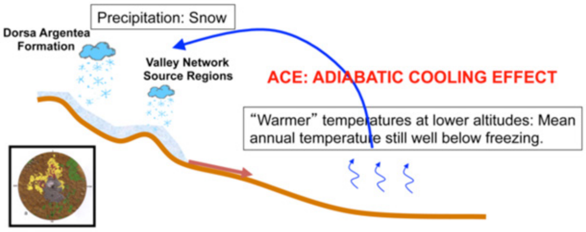

Fig. 1. *Noachian icy highlands climate regime* (*18-19*); snow at high elevations, a MAT well below 0°C, and a horizontally stratified hydrologic system. Inset map: extensive Dorsa Argentea Formation south polar cap.

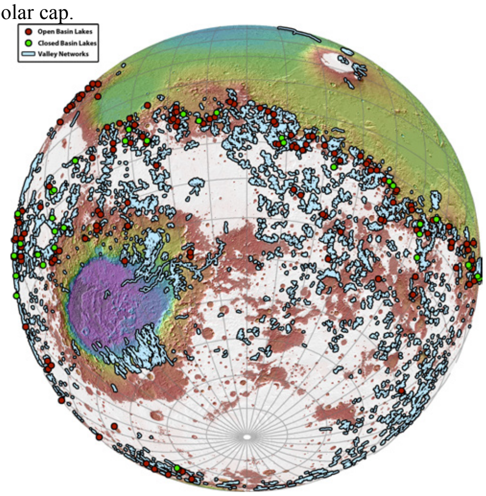

Fig. 2. Global view of the *Noachian icy highlands* (white areas above the surface ice stability line). Kilometers-thick Dorsa Argentea Formation ice cap near bottom; tens to hundreds of meters thick ice cover (white) extends to the vicinity of the dichotomy boundary. The distribution of valley networks (blue), closed-basin lakes (green dots), and open-basin lakes (red dots) are shown. Punctuated volcanism is predicted to cause global warming and transient melting of the icy highlands (white) creating sufficient meltwater to form valley networks and associated lake systems.