LONG-TERM HYDROLOGICAL CYCLING ON EARLY MARS. V. R. Baker[1], [1]Dept. of Hydrology and Atmospheric Sciences & Lunar and Planetary Laboratory, University of Arizona (baker@email.arziona.edu)

Introduction: Like Earth, Mars is a "water planet" [1], and early Mars was a geologically evolving "ocean world" [2]. This understanding has been evident ever since the global planetary imaging missions of the 1970s first documented geomorphological features [e.g., 3, 4] and other evidence [e.g., 5,6] that could not have originated otherwise than from active hydrological cycling involving liquid water flows and ponding on the planetary surface, subsurface water flow, and land-atmosphere interactions. However, subsequent research has shown that the co-evolution of water and land on Mars has followed a very different evolutionary track than that of Earth [7.8]—a complexity that has led to much misunderstanding about the Mars's watery nature and a history of scientific controversy as to the implications that follow from the geological realities [9]. The controversy is made even more striking by the inability of atmospheric 1-D radiative-convective and 3-D global climate models (GCMs) to predict the surface temperature regime presumed to be necessary to explain extensive fluvial and lacustrine activity on early Mars [10].

The Noachian Icy Highlands (NIH) Paradigm: Mars GCM modeling seeks to predict the surface warming that can be achieved for various combinations of external forcing and boundary conditions. Logical parsimony is achieved by beginning with secure knowledge about the current Martian climate dominated by a CO_2 atmosphere that varies in its water and CO_2 content. The modeling shows that, at the higher CO_2 pressures inferred for Noachian, Mars exhibits a pronounced adiabatic cooling effect [11]. By adding a simplified water cycle with atmosphere–surface interactions and atmospheric transport, and taking into account the radiative effects of gas and clouds, the modeling predicts extensive ice accumulation in Mars's southern and equatorial highlands [10]. Moreover, because the known distribution of valley networks seems to coincide with the northern margin of the predicted zone of ice accumulation, it is proposed that this Noachian Icy Highlands (NIH) hypothesis may provide a "…globally sub-zero…scenario for the late Noachian climate…sufficient to explain most of the fluvial geology without the need to invoke additional long-term warming mechanisms or an early warm, wet Mars" [10].

Employing what is claimed to be "an empirical approach," Wordsworth and colleagues [12, 13] model increased solar luminosity and/or atmospheric infrared opacity for a presumed configuration of early Mars topography and surface water bodies (including a northern plains "ocean" delineated by "putative" shoreline constraints). Because the resulting model output fails to produce precipitation patterns consistent with the known late Noachian distribution of valley networks and crater lakes, Wordsworth (2016) surmises that either (a) something was wrong with the modeling, or (b) "Mars was never warm and wet." Choosing (b), Wordsworth [13] concludes, "…GCM simulations of the early climate and other modeling and analog studies suggest that a water-limited early Mars with episodic melting episodes may be a suitable paradigm for much of the late Noachian and early Hesperian climate."

The NIH paradigm envisions global cycling of ice to the subzero southern highlands of Mars, but basal melting of ice caps and local volcanic or impact heating produced scattered liquid water phenomena [14, 10]. Head and Marchant [15] and successive papers envision the early Mars hydrology as a very cold, "horizontally stratified hydrological system" in which sublimation off frozen lowland lakes transfers water to highland areas, where precipitation occurs as snow, ultimately sustaining glaciers. A thick, ice-cemented permafrost layer separates the deep zone of ground water from interaction with the surface, and transient episodes of surface ice melting then produce fluvial channels. This contrasts with what occurs on Earth today: a "vertically integrated hydrological system" in which water evaporates off lakes and the ocean, and much precipitation falls on the land as rain. Part of the latter becomes runoff that erodes a network of channels and valleys, but much of it also infiltrates to become ground water that moves much more slowly back to the surface.

The Wet Early Mars (WEM) Working Hypothesis: Another response to what has been termed the "Early Mars Climate Conundrum" is to relax the usual *a priori*, parsimonious assumptions that are made for physical climate modeling (Mars is under no obligation to be simple), and consider forcing mechanisms and boundary conditions that are very different from those of today. The system to be modeled should conform to ancient Mars conditions, which involved prolonged episodes of relatively warm, wet conditions. These ancient conditions become, in effect, the inspiration for working hypotheses [16, 17], and the modeling becomes the means for elucidating the consequences of these working hypotheses. This methodology contrasts with the more common, though trivial, use of geological observations for testing models, a procedure subject to a number of logical flaws [18].

As exemplified by Earth, large-scale surface-water ponding on a planetary surface is critical to the operation of a dynamic hydrological cycle. Though this kind of cycle was long recognized as a critical component for understanding early Mars hydrology [19], its importance was obscured by the protracted debate over the early Mars northern plains water body, provocatively named “Oceanus Borealis” (OB) [19]. It is now recognized that the prolonged debate over “shoreline” evidence for this water body was clouded by Mars’s unique history of deformation [20, 21] and by the role of mega-tsunami events [22, 23]. Early Mars was not “water-limited” and the immense volume of the Mars hydrosphere is evident in the volume of the late Hesperian manifestation of OB, which held about 130-m global equivalent layer (GEL) of water. An earlier Noachian OB [24] probably held a GEL of 550 m [25]. This was the water body associated with the valley networks, which formed in the heavy rainfall zone surrounding the southern OB margins, exactly where expected at the land-sea margin, at a time when Tharsis was not yet a factor influencing atmospheric circulation, as assumed by Wordsworth et al. [10].

As Mars evolved from its late NoachianOB phase, the very high infiltration capacity of the Martian land surface, something ignored in the NIH paradigm, resulted in the sequestering of water into the subsurface, where it subsequently developed a thick cap of ice-rich permafrost [26, 7]. After a long period of quiescence , this reservoir of subsurface water was disrupted by volcanism during the Hesperian, resulting in massive outbursts of water that ultimately drained to the northern plains, thereby producing the late Hesperian OB.

Global Mars Hydrology and the need for a Mars System Model (MSM): While the primary applications of basic physical principles are impressive for the GCM model simulations that underpin the NIH paradigm, the secondary geological assumptions are not. More specifically, atmosphere-focused models do not properly capture the long-term hydrological cycle on Mars. As has been learned in the development of Earth System Models (ESMs), a GCM framework provides an incomplete system representation of a dyanamic hydrological cycle on an earthlike planet. A major failing of the GCM-centered modeling approach is its lack of consideration of the role of ground water. During much of Mars’s history. Particularly from the latest Noachian onward, much of Mars’s hydrosphere was sequestered in the subsurface, both as ground water and as ground ice. For this reason a huge volume of planetary water was isolated from mechanisms that would otherwise have induced its loss to space

A key function of a MSM would be to account for the feedbacks and interactions among climate, geology, and hydrology. Instead of trying to predict surface temperatures from purely external factors (solar radiation, radiatively active gases, etc.), the hydrological component of a MSM emphasizes all aspects of the hydrological cycle. Water in channels originates not just from precipitation, but also from the amount (and rate) of infiltration, the flow path of the watercourse, the amount evaporation, and other factors. These, in turn, depend on different geological and geomorphological constraints. Topography dictates flow paths; permeability dictates infiltration; and so on. Feedbacks and interactions between the climate, geology, and hydrology act over geological timescales to modify the geological and geomorphological constraints. Water flows cause bank erosion, channel incision, sedimentation, etc. Sedimentation can decrease soil porosity at the surface, thereby reducing infiltration. The amount of water evaporating back to the atmosphere depends on geological (e.g. surface resistance) and atmospheric/climatic (e.g. vapor pressure deficit, temperature) factors. Changes in fluxes and patterns of evaporation lead to changes in the fluxes and patterns of precipitation. It is important, therefore, to account for both the current state of these feedbacks and interactions, but also how they have coevolved over time. Because none of this can be effectively accomplished by GCMs alone, it is premature to invoke a paradigm of early Mars hydroclimatic conditions from their predictions.

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