

TESTING THE LATE NOACHIAN “COLD AND ICY HIGHLANDS” MODEL: GEOLOGICAL PREDICTIONS FOR EQUILIBRIUM ENVIRONMENTS AND MELTING SCENARIOS. J. W. Head¹, R. Wordsworth², F. Forget³, J.-B. Madeleine³, and I. Halevy⁴, ¹Dept. Geol. Sci., Brown Univ., Providence RI 02912 USA (james_head@brown.edu), ²Dept. of Geosci., Univ. Chicago, Chicago IL 60637 USA, ³Lab. de Météorolog Dynamique du CNRS, Université Paris 6, Paris, France, ⁴Weizmann Inst. Sci., Rehovot, Israel.

I. Introduction: Forget et al. [1] and Wordsworth et al. [2,3] recently presented improved 3D global simulations of the early martian climate performed assuming a faint young Sun and denser CO₂ atmosphere, including a self-consistent representation of the water cycle [2], with atmosphere–surface interactions, atmospheric transport, and the radiative effects of CO₂ and H₂O gas and clouds taken into account. They found that for atmospheric pressures greater than a fraction of a bar, atmospheric-surface thermal coupling takes place and the adiabatic cooling effect (ACE) causes temperatures in the southern highlands to fall significantly below the global average. Long-term climate evolution simulations indicate that in these circumstances, water ice is transported to the highlands from low-lying regions for a wide range of orbital obliquities and that an extended water ice cap forms on the southern pole (Fig. 1). Conditions are too cold to allow long-term surface liquid water. Punctuated events, such as meteorite impacts and volcanism, could potentially cause intense episodic melting under such conditions. Because ice migration to higher altitudes is a robust mechanism for recharging highland water sources after such events, Wordsworth et al. [2,3] suggested that this globally sub-zero, Late Noachian ‘icy highlands’ (LNIH) climate scenario may be sufficient to explain much of the fluvial geology without the need to invoke additional long-term warming mechanisms, or an early “warm and wet” Mars. Here we explore the predictions for geologic settings and processes in both equilibrium and non-equilibrium climate states [4-6] as first steps in the comprehensive testing of the “icy highlands” model.

II. Geology of the “icy highlands” equilibrium environment: **1) Global permafrost:** With mean annual temperature (MAT) consistently well below 0°C [2], LNIH Mars is characterized by a global permafrost layer that forms a shallow perched aquifer [7,8] composed of a dry active layer whose thickness is defined by vapor diffusive equilibrium with the atmosphere. Permafrost thickness is determined by local and regional geothermal heat flux and mean surface temperatures, is thinner than today and varies with altitude and latitude, likely averaging several km thick [9,10]. **2) Surface hydrological cycle:** The LNIH climate is dominated by an expanded south polar cap,

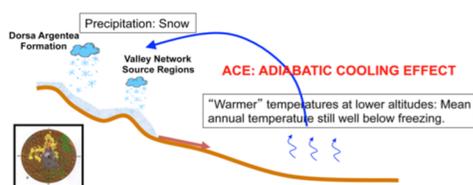


Fig. 1. Noachian icy highlands climate regime; snow at high elevations, a MAT well below 0°C, and a horizontally stratified hydrologic system.

snow and ice accumulation in the highlands, and a global cryosphere; H₂O at lower elevations will be mobilized and transported to the highland cold traps (Fig. 1). Altitude-dependent distribution of snow and ice is further modulated by both latitude dependence and atmospheric circulation patterns [2,3]. **3) Thickness and continuity of snow and ice:** To a first order, mean thickness will be determined by total water inventory and the percentage of the inventory available at and near the surface, neither value being well constrained for the Late Noachian [11]. We assume the current polar/near-surface water ice inventory (~5 M km³; ~30 m Global Equivalent Layer (GEL)) and thus that available ice is *supply limited* [12]. Snow and ice will occur in several highlands environments: a) Snow patches and continuous snow cover: These will vary with seasonal and short term climate change, and locally with wind patterns and insolation shadowing as seen in Antarctica [13]. b) Non-Flowing Ice Deposits: Accumulations in excess of a few meters will occur as firn/ice deposits [14] but will not be thick enough to flow [15]. c) Flowing Glacial Ice Deposits: Where ice thickness exceeds hundreds of meters and has an appropriate basal slope [15], it will flow, but still be cold-based unless it is thick enough (unlikely in the supply limited scenario) to raise the local melting geotherm into the base of the ice [16]. **4) LNIH global distribution of snow and ice:** Based on typical conditions simulated by the GCM [1,2] we assume a plausible Equilibrium Line Altitude (ELA) of +1 km; Fig. 2 portrays the LNIH. a) Poles: There is no north polar cap under nominal obliquity and the south polar cap is much larger [2,3], approximately the size of the Dorsa Argentea Formation (DAF), interpreted to be an ice-sheet remnant [17]. On the basis of glacial flow modeling [18], the thickness of the DAF may have approached 3 km, and involve limited basal melting. b) Hellas hemisphere: Snow and ice are focused on the rim of Hellas, across the southern midlands, and in the Elysium rise; ice deposit margins are very closely coincident with the distribution of valley networks (VN), open-basin lakes (OBL) and closed-basin lakes [6]. c) Tharsis hemisphere: The LNIH Tharsis rise, a region thought to be characterized by an elevated geothermal gradient, is covered with snow and ice, a phenomenon that may help explain the charging of the Tharsis aquifer to source the outflow channels [19,20]. Classic VN (Warego Valles) are also near the margins of the ice accumulation [21].

III. LNIH melting scenarios: **1) Equilibrium top-down heating and melting:** Under some climate equilibria, extreme orbital parameter-induced seasonal top-down melting might occur, producing daily or seasonal temperatures above 0°C [2]. This could produce transient melting conditions, as observed in the McMurdo Dry Val-

leys [7]. **2) Punctuated top-down melting:** a) *Impact:* Impacts [22] are predicted to produce a runaway greenhouse atmosphere, rain and short-term flooding. Local ejecta deposits and impact-generated widespread dust could change surface albedo and influence melting [23]. b) *Volcanism:* Gases (SO₂, H₂S, CO₂) released by punctuated volcanism [4,5]; such punctuated phases may be constantly recurring, but warming may only last for decades [5], and may be regional [24]. Local to regional dispersed volcanic ash [23,25] could alter melting patterns. c) *Direct ice melting:* Lava flows emplaced on or against ice deposits can induce melting and flooding [26]. **3) Sustained top-down heating:** Should top-down heating be maintained long enough (10¹-10² yrs), water in the upper permafrost would begin to melt at the top of the ice table. Longer sustained heating (10⁴-10⁶ yrs) could melt through the permafrost, first locally, then regionally. **4) Bottom-up heating and melting:** Accumulation of ice to thicknesses exceeding hundreds of m [15] could raise the global mean melting geotherm to the base of ice but on a regional scale ice thickness may be supply-limited. In enhanced heat flow areas (e.g., Tharsis), basal melting may occur [19]. **5) Combinations of factors:** Any one (or more) of these can combine with orbital parameters already favoring melting. **6) Timescales to penetrate cryosphere:** Starting with a nominal LNIH climate scenario [2,3] and heat flux [18], we calculate that it would take of order 10⁴ to 10⁶ yrs for the nominal global cryosphere to be breached and for the hydrological cycle to change from horizontally stratified (with a perched aquifer) to influent and vertically integrated with the groundwater system. The difficulty in sustaining MAT above 0°C for sustained periods [2] makes this scenario unlikely globally; local regions of elevated heat flux (e.g., Tharsis, Elysium) will be exceptions [19]. **7) The role of impacts in cryosphere penetration:** Impacts of sufficient size (in excess of ~25 km) can penetrate the cryosphere and potentially form a short term connection to a groundwater reservoir [27]; effects depend on global groundwater budget and regional hydrostatic pressure.

IV. Nominal Late Noachian Icy Highlands (LNIH) climate model and geological process predictions: For most of the Late Noachian, an icy highlands caused by atmospheric-surface coupling and the adiabatic cooling effect appears to be the nominal equilibrium state (Fig. 1). Orbital parameter variations cause regional redistribution of ice, with limited melting only under extreme circumstances; any local meltwater rapidly freezes and returns to the highlands. Non-equilibrium conditions that could raise MAT above 0°C can be reached through punctuated events such as impact crater formation and high rates of volcanic outgassing, but the duration of the warming effects of individual events is very short geologically. This leads to some predictions for processes that can be used to test the LNIH model: **1) Global cryosphere:** For most top-down melting scenarios, the global cryosphere remains intact. **2) Altitude dependence of melting:** Melting should preferentially occur around the lower margins

of ice deposits, where closest to melting point. **3) Water recycling:** During and following any melting events, water returns to the uplands, constantly recharging the source region. **4) Relative constancy of source region locations:** Because of the general constancy of LN topography, meltwater returns to the same place, providing automatic recharge of source areas. **5) Character of ice source regions:** Variations in topography, altitude, slope and insolation geometry will govern ice accumulation and melting particularly near ice margins. **6) Melting rates and recharge:** Raising MAT to >0°C will provide significant volumes of meltwater from top-down melting to form VN and create OBL. **7) Likelihood of multiple events:** Top-down melting scenarios favor multiple events; transition to equilibrium returns water to icy source regions. **8) LNIH hydrological cycle model:** Long-term equilibrium icy highlands climate alternating with multiple episodic, but widely spaced short pulses of top-down melting; cycle favors immediate recharge of ice in same source regions. **9) Valley network formation:** Caused by multiple episodic melting events (number, duration and intensity currently unknown) of snow/ice in icy highlands; presence of shallow ice table during melting events influences infiltration and channel shape and enhances erosion rates [8]. Stream/network geometry controlled by cold-based ice patterns [8]. **10) Tharsis and Elysium:** Areas with elevated geotherms are favored for basal melting and aquifer recharge [19]. These predictions provide a basis for further analysis and testing of the LNIH model [2,8,14-16].

References: 1. F. Forget *et al.*, *Icarus*, 222, 81 (2013); 2. R. Wordsworth *et al.*, *Icarus*, 222, 1 (2013); 3. R. Wordsworth *et al.*, *5th Mars Atmos.* (2014); 4. J. Head, L. Wilson, *LPSC 42*, #1214 (2011); 5. I. Halevy, J. Head, *3rd Conf. Early Mars*, #7043 (2012); *5th Mars Atmos.* (2014); 6. J. Head, *LPSC 44*, #1523 (2013); *5th Mars Atmospheres Workshop* (2014); 7. J. Head and D. Marchant, *Antarctic Science*, in review (2013); 8. J. Head *et al.*, *LPSC 45* (2014); 9. S. Clifford, *JGR* 98, 10973 (1993); 10. M. Mellon *et al.*, *JGR* 102, 19357 (1997); 11. M. Carr, J. Head, *LPSC 45* (2014); 12. J. Fastook, J. Head, *PSS*, in press (2013); 13. D. Marchant, J. Head, *Icarus* 192, 187 (2007); 14. J. Cassanelli, J. Head, *LPSC 45* (2014); 15. J. Fastook, J. Head, *LPSC 45* (2014); 16. M. Carr, J. Head, *GRL* 30, 2245 (2003); 17. J. Head, S. Pratt, *JGR* 106, 12275 (2001); 18. J. Fastook *et al.*, *Icarus* 219, 25 (2012); 19. P. Russell, J. Head *PSS* 55, 315 (2007); 20. J. Cassanelli, J. Head, *LPSC 45* (2014); 21. K. Scanlon *et al.*, *GRL* 40, 4182 (2013); 22. T. Segura *et al.*, *Icarus* 220, 144 (2012); 23. L. Wilson, J. Head, *JVGR* 185, 290 (2009); 24. L. Kerber *et al.*, *5th Mars Atmos.* (2014); 25. L. Kerber *et al.*, *Icarus* 219, 358 (2012); 26. J. Head, L. Wilson, *Ann. Glaciol.*, 45, 1 (2007); 27. P. Russell, J. Head, *GRL* 29, 1827 (2002).

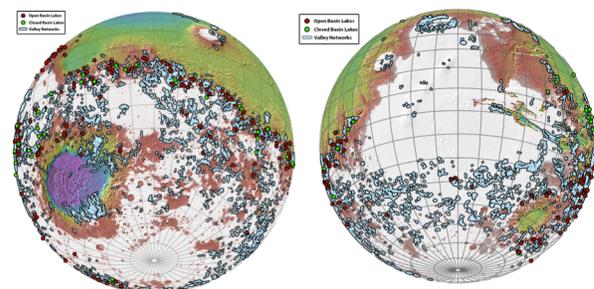


Fig. 2. Global view of the Noachian icy highlands (white areas above the surface ice stability line). Left) Hellas hemisphere: km-thick Dorsa Argentea Formation ice cap near bottom; 10-100s m thick ice cover (white) extends to the vicinity of the dichotomy boundary. Right) Tharsis hemisphere. Valley networks (blue), closed-basin lakes (green dots), and open-basin lakes (red dots) are well-correlated with margins of ice sheets.