Water at the Surface of Ancient Mars. A. Soto[1] and M. I. Richardson[1], [1]Division of Geological and Planetary Sciences, California Institute of Technology, M/C 150-21, Pasadena, CA 91125, asoto@caltech.edu.

Introduction: Under what circumstances in an ancient Mars climate would standing bodies of water be possible? Whether the liquid water interface exists above the surface (as standing water) or within the fracture regolith (as a ground water horizon) has profound implications for the global water cycle. These implications place a particular premium on finding unambiguous evidence for standing water.

In this abstract, we investigate constraints on the location of the liquid water interface (above or beneath the surface) for putative early Martian climate states. The constraints on the vertical interface location depends upon the surface energy balance, the diffusion of heat within the subsurface, and the abundance of vapor in the atmosphere.

Data from MER, MRO, and Mars Express depicts a Martian paleoclimate with multiple transitions. The general trend appears to be one from relatively wet to relatively dry [1,2]. But "wet" and "dry" here are still relative terms. Can we envision sustained standing bodies of water in either case?

Definition of Aridity: In examining the stability of surface liquid water, aridity is an important concept. So what is *aridity*? Even when discussing terrestrial deserts, the definition of an arid climate is not universal. Many criteria are available for defining aridity, including rates of precipitation, the difference between precipitation and evaporation, and geologic conditions. Furthermore, on Earth, the relative humidity of deserts, though low, is highly variable and driven by the overall humidity of the Earth's climate, which is generally over 50% on a global scale.[3]

An arid location on Earth tends to be an exception where either the flow of water vapor to the location is blocked (rain shadow), negligible (due to low sea temperatures), or due to persistent regional downwelling of air (suppressing the upward motion needed for cloud and rain generation). Suffice it to say, special circumstances are needed. The special circumstances are needed because in the presence of vast oceans as water sources, the atmosphere is relatively wet, as mentioned above.

What about aridity of ancient Mars? The existence of surface water reservoirs largely determines this. There is thus something of a chicken-and-egg aspect to the problem, which is probably better thought of as a global state transition point. If Mars had extensive surface water deposits, it would require a background vapor abundance in balance with those surface deposits. Indeed, that energy balance would set the global mean humidity. If the global humidity were perturbed low, the relative dryness would drive a net evaporative flux back into the atmosphere until balance were achieved. This balance would only fail when the required global atmospheric vapor abundance required for deposit stability could not be achieved, as for example would be the case of exposed tropical or mid latitude water on Mars today. The tropical / mid-latitude ice would require a vapor abundance much greater than that required over the seasonal ice caps or the northern polar ice cap. As a result, the tropical / mid-latitude water would continue to evaporate "trying" to humidify the atmosphere, while the northern cap (seeing a higher humidity than in balance with its temperature) would continue to draw water from the atmosphere. The end state is the complete removal of our hypothetical tropical / mid-latitude surface water.

The same balance physics will apply at any climate state for Mars. The equilibrium humidity will be set by the maximum temperature of the coldest water reservoir. We don't know the initial water inventory. But if we were to play a conceptual game increasing the initial inventory in a series of experiments, the result is that as the initial inventory is increased, the coldest reservoirs become saturated and the water is forced to reside in progressively warmer reservoirs. Being warmer, the reservoirs maintain a progressively larger mean atmospheric humidity. Any particular location on Mars is therefore coupled to the global climate system by the definition of this global mean humidity. As for the Earth, there is still the possibility of yielding places much drier than this global mean via the same processes of shadowing and mean down-welling motion. It is much more difficult to maintain anomalously humid conditions, since the atmosphere will tend to mix humidity away on geologically rapid timescales.

Surface Water and Evaporation: Let's think about a location on the surface of an ancient Mars in which liquid water is plausible. That is, temperatures above 273 K or appropriate eutectic for brine. If water is delivered to the surface by rain, snowmelt, or ground water flow, then a necessary condition is that the ground is saturated (admittedly trivial if groundwater flow was the supply). In this case, water can't simply percolate into the regolith. Will water stand on the surface in a sustained deposit?

If the atmosphere overlaying the surface water is saturated, then the surface water will be stable. This requires consistent conditions that aren't really plausible even for the Earth. A more realistic case is one in which diurnal and seasonal variations of humidity and temperature yield an precipitation rate that balances evaporation. The need for high precipitation is the same as needing high humidity, and maintaining high humidity average humidity requires the global atmosphere to be relatively humid (again, local humidity extremes tend to be unsustainable).

In most cases, it is plausible to image a situation where the atmosphere overlaying a water deposit on early Mars to be subsaturated. In this case, is surface water sustainable even in the presence of ground water flow delivery? This comes down to a question of rates of potential evaporation compared to rates of reasonable water supply. From recent groundwater hydrology models [4,5], we have an estimate of the upper rate of groundwater delivery to the surface: ~1 mm/yr. (Time will be in Earth units of years unless otherwise noted.)

We can estimate rates of evaporation from consideration of the energy budget. The energy balance at the surface can be expressed by

$$F_{net} = (1-\alpha)S_{\odot} + F_{LW\uparrow} + F_{SH} + F_{LH}$$

where F_{net} is the net radiation, α is the surface albedo, $S_{\odot}$ is the solar flux at Mars, $F_{LW\uparrow}$ is the upward infrared flux from the surface ($F_{LW\uparrow} = \epsilon\sigma T_g^4$), F_{SH} is the sensible heat flux, and F_{LH} is the latent heating flux. In the case of a saturated regolith or a liquid deposit, any small increase in temperature will lead to a significant increase in the require saturation vapor pressure that will tend to fuel more rapid evaporation and hence stronger evaporative cooling. This tends to limit the amount of temperature change for a given input of heat, and thus to first order, we can simply balance the radiative heating of the surface against the evaporative heat loss. This is why wet soil is much cooler on a hot day that dry dirt.

The latent heat flux is related to the evaporation rate by

$$F_{LH} = \rho_w L_v E$$

where ρ_w is the density of water, L_v is the latent heat of vaporization, and E is the evaporation rate. If we set the evaporation rate equal to the groundwater delivery rate then we have an estimate of the amount of latent heat flux required to keep all of the water vaporized. For the upper range of groundwater flow of ~1 mm/yr (from the modeling by Andrews-Hanna et al. [4]) the required latent heat flux is 0.08 W/m^2. Even for flow rates as high as 10 mm/yr, the required latent heat flux is only 0.8 W/m^2. The solar radiation delivered to ancient Mars, when adjusted for the faint young sun and for the range of desert albedos (0.05 to 0.7) [3], is in the range of 100 W/m^2 to 200 W/m^2. Thus there is orders of magnitude more energy available than is needed to evaporate any surface liquid water. For current Mars, much effort is expended at looking at the specific geometry of locations because shadowing effects can create great differences in temperature on very small scales. Unfortunately, as the atmosphere becomes thicker, such thermal heterogeneity is less readily sustained because of sensible heat exchange with the atmosphere becomes much more efficient.

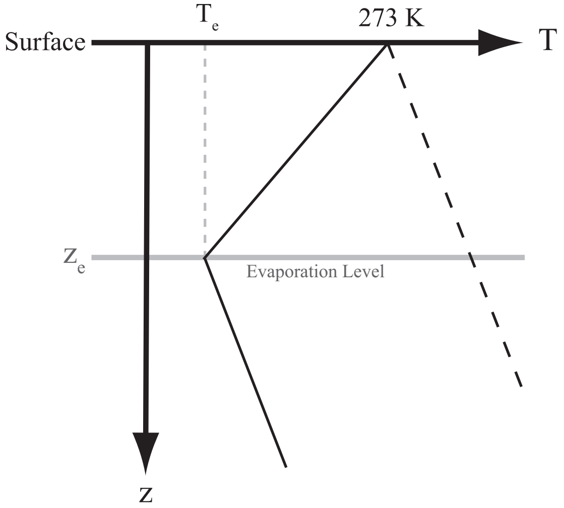

Figure 1. A schematic view of the subsurface cooling profile created by subsurface evaporation. The dashed line represents an idealized temperature profile driven just by geothermal heating. The solid line represents the effect of evaporative cooling on the temperature profile. The gray evaporation level line marks the top of the equilibrium water table.

If upwelling groundwater evaporates at the surface, at what depth will the groundwater table balance with the evaporation? Let's assume a rather arid atmosphere of about 10% relative humidity (RH). Evaporation cools the level of the regolith at which the water is evaporating (the top of the water table). This cooling can only be balanced by conduction. If the evaporative cooling can be provided entirely by the geothermal heat flux, then the regolith will continue to dessicate (ground water table will fall) until either the horizontal ground water transport increases or the atmosphere becomes more humid (decreasing evaporation potential and/or increasing precipitation rates).

If geothermal heat flux cannot balance the evaporative cooling, then the ground water table can thermally stabilize at some depth. By determining the subsurface temperature profile induced by the evaporative cooling, we can estimate this depth. Using a linear heat conduction relation

$$q = -K\frac{\partial T}{\partial z}$$

where q is the heat flux which we are setting equal to the latent heat flux and K is the thermal conductivity, we solve for $\frac{\partial T}{\partial z}$. The thermal conductivity for desert rocks has a range of 0.2 to 5.0 W/m/K, including the type of basaltic rocks found on Mars [3,6]. Using the lowest thermal conductivity, ~0.2 W/m/K, and the highest latent heat flux, ~0.8 W/m^2, the steepest subsurface thermal gradient is about -4 K/m.

Using the calculated thermal gradient and the Clausius-Clapeyron equation, we can determine the depth at which the groundwater table balances the evaporation for a 10% relative humidity. In meteorology, the Clausius-Clapeyron equation is often written as

$$e = 6.112 \exp\left(\frac{17.67T_e}{T_e + 243.5}\right)$$

where e is the vapor pressure. We want to calculate the temperature, T_e, for a vapor pressure of $e = 0.1e_s$, where e_s is the surface saturation vapor pressure. Since we are assuming a minimum surface temperature of 273 K then $e_s = 6.112$ mbar and $0.1e_s = 0.6112$ mbar for our calculation. Thus, we solve for T_e and find $T_e = 270\ K$. With the -4 K/m thermal gradient calculated above, then the depth of the water table is about 0.75 m.

Under the conditions of this example, surface liquid water is not sustainable. Instead the liquid water interface occurs three quarters of a meter into the subsurface, based on the values we used. Heterogeneity in thermal conductivity and groundwater flow rates lead to a range in the actual depth of the groundwater from the surface to about 1m.

Analogy with Earth's Oases: On the Earth, surface liquid water is quickly removed by run-off, ground infiltration, and evaporation. Similar to Mars analysis above, evaporation rapidly removes the water, leading to a desiccated surface with high sensible heat.

Additionally, desert surfaces exhibit a vapor barrier in the near subsurface. As the surface and then near surface dry out, the hydraulic diffusivity, which is a function of humidity, decreases. Thus, the pathway for water in the near subsurface becomes restricted. The vapor barrier thus has a low latent heat flux to the atmosphere. Coupled with the low thermal conductivity of the near subsurface, the vapor barrier results in the termination of evaporation of subsurface groundwater into the atmosphere.

A similar process should occur on an arid Mars. Thus, due to the aridity, surface liquid water evaporates from the surface. This evaporation surface migrates into the near subsurface, until a vapor barrier forms that essentially cuts off evaporation of the groundwater into the atmosphere. This cut off continues until the hydraulic head of upwelling water pushes past the vapor barrier and the process repeats itself. An area to be investigate is the lifetime of surface liquid water under these arid conditions.

An important difference between a terrestrial desert and an arid Mars is the global humidity. The Earth is clearly in a relatively high global humidity regime such that surface deposits of liquid are stable. Even in terrestrial deserts, surface water is recharged by the global hydrology. On Mars, if the global humidity is not sufficiently high, the tropical and mid-latitude water is driven to and trapped in the polar regions. Only if there is sufficient humidity on a global scale will surface liquid what be persistent.

Conclusion: Even on a warm ancient Mars, two very different climate states are possible. These two climate states depend on the global relative humidity conditions: relatively low global humidity leads to a dry Mars with no stable surface water while relatively high global humidity leads to a climate that can potentially sustain surface liquid water. In the former case, the high evaporation rates possible at the surface suggest that even in locations of net ground water convergence, the water table is extremely unlikely to reach the surface.

While evidence for liquid water on or beneath the surface is interesting, there is a huge premium to be placed on unambiguous evidence of water residing on the surface – for such observations place uniquely strong constraints on the nature of the global water cycle and climate.

References:

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