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# DIURNAL AND ANNUAL CYCLES OF $H_2O$ IN THE MARTIAN REGOLITH;

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1. ***Atmospheric Heat Engines on Earth and Mars.*** A terrestrial micrometeorologist is constantly aware of the intimate connection between the surface fluxes of $H_2O$ and of sensible heat. This connection is ubiquitous evidence of the Earth's atmospheric heat engine in action. Its character depends, *inter alia*, on the tightness of the linkage between the energy cycle and the cycle of $H_2O$. $H_2O$ is an important component of the working fluid because the temperature and pressure at the Earth's surface are such that $H_2O$ is always present there in at least one condensed phase as well as vapor; and because the surface air's latent heat content is relatively large compared to its sensible heat capacity, with consequent correlation between energy transport and $H_2O$ transport.

The same micrometeorologist finds however, that the latent heat capacity of surface air on Mars is only about one ten-thousandth that on Earth. $H_2O$-based latent heat fluxes represent only a trivial fraction of total energy fluxes on Mars: the linkage between $H_2O$ and energy fluxes is extremely weak [1]. Unlike on Earth, $H_2O$ on Mars is an ineffective component of the working fluid. $CO_2$ is the dominant component.

Can we make these considerations quantitative? Equation [1] defines $\Theta$, which we propose as an index of the relative importance of latent heat transport by a particular component under particular surface conditions:

$$\Theta = \frac{\rho_V L}{\rho c_p} \qquad [1]$$

Here $\rho$ is the density and $c_p$ the specific heat at constant pressure of the surface air, $\rho_V$ the surface vapor density of the component, and L its latent heat of phase change (evaporation or sublimation).

The quantity $\Theta$, with the dimensions of temperature, is the excess of surface equivalent temperature (2) for the particular component, over the surface air temperature. We may call it the *equivalent temperature excess*. A tight linkage between energy flux and the mass flux of a component will give large values of $\Theta$ under given surface conditions; and conversely.

Figure 1 graphs evaluations of $\Theta$ for $H_2O$ on Earth and for $H_2O$ and $CO_2$ on Mars. On Earth $\Theta$ decreases from 93 K for a surface dewpoint of 310 K to 0.1 K for a frostpoint of 225 K. On Mars $\Theta$ for $H_2O$ decreases from 6.2 K for a frostpoint of 220 K to $10^{-5}$ K for one of 150 K. Contrast the very large value for $CO_2$ on Mars, $\Theta = 692$ K. The latitudinal distribution of $\Theta$ on the two planets signalizes vividly their different meteorology. Earth's atmospheric heat engine is most effective and active in the tropics and least so at the poles. On the other hand, the Martian heat engine is most effective over the polar $CO_2$ caps, with $\Theta$ there more than 10 times that of tropical Earth; but it is ineffective elsewhere.

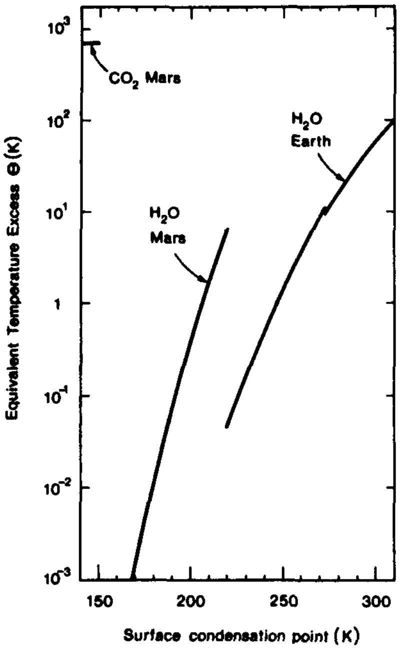

Figure 1.

Variation of Θ with surface condensation point for $H_2O$ on Earth and for $CO_2$ and $H_2O$ on Mars.

2. ***Diurnal and Annual Cycles of $H_2O$ in the Martian Regolith.*** The looseness of the atmospheric linkage of energy and $H_2O$ surface fluxes enables analysis of the equilibrium and flux of $H_2O$ in the Martian regolith with the atmosphere entering only through surface boundary conditions on temperature, T, and $H_2O$ vapor density. The regolith is so cold that we need consider only the processes of sublimation, vapor diffusion, and thermal conduction. In such systems ice behaves as a "wetting" capillary substance. Many of the concepts of terrestrial soil-water physics (e.g. 3,4) with appropriate modification, carry over. Details are given in (5,6), where this approach was used to investigate model diurnal and annual $H_2O$ cycles. The vector flux density of $H_2O$, q, is described by the equation

$$q = -D_\theta \nabla\theta - D_T \nabla T \qquad [2]$$

where the coefficients $D_\theta$, $D_T$ are strongly nonlinear functions of both T and of the regolith volumetric ice content $\theta$.

$D_T$ increases very strongly (approximately exponentially) with T, so that an harmonic temperature wave imposed at the surface produces a net downward flux due to the temperature field. For equilibrium over the year this must be balanced by a net upward flux due to $\theta$ increasing with depth. These considerations yield the equilibrium ice content profile. In principle, this profile is perturbed by diurnal and annual oscillations in surface boundary layers. These perturbations, in fact, prove to be trivial.

The earlier work produced ice tables (regolith saturated with ice) at depths below the surface which were very sensitive to the surface humidity cycle. In the light of later information, the humidities used then were unrealistically high. The present calculations are for conditions approximating the mid-latitudes. They are: mean surface temperature 200 K with diurnal and annual semi-amplitudes of 30 K; and daytime surface frostpoint (DSF) from 190 to 200 K. The solutions give $\theta$ in the range 0.02 - 0.03, with a slow increase with depth down to about 12 m. There the areothermal heat flux becomes important, reversing the gradient of $\theta$. See Table 1.

Table 1. Equilibrium Ice Content Profiles

| Daytime Surface Frostpoint (K) | 190 | 195 | 200 |
|---|---|---|---|
| Depth (m) | Ice Content $\theta$ | | |
| 0 | 0.02497 | 0.02569 | 0.02648 |
| 0.1 | 0.02630 | 0.02719 | 0.02819 |
| 1 | 0.02803 | 0.02924 | 0.03090 |
| 2 | 0.02883 | 0.03034 | 0.03246 |
| 6 | 0.03074 | 0.03319 | 0.03994 |
| 12 | 0.03122 | 0.03455 | 0.04209 |

Figure 2 shows the annual cycles of $H_2O$ flux into and from the regolith for DSF's of 190, 195, and 200 K. Figure 3 shows, for a DSF of 195 K, the diurnal $H_2O$ cycles for 12 representative sols. The notable point about these results is the very small value of the $H_2O$ fluxes. Even for the largest DSF, 200 K, the total annual variation of condensed $H_2O$ in the regolith is only 120 x $10^{-6}$ m. This corresponds to variations of $\theta$ of only $\pm$ 0.00006 distributed over the top 1 m of the regolith. The largest diurnal change in ice content (DSF = 200 K, sol 167) is 1.2 × $10^{-6}$ m, corresponding to a change in $\theta$ of only 0.00003 distributed over the top 0.04 m of the regolith.

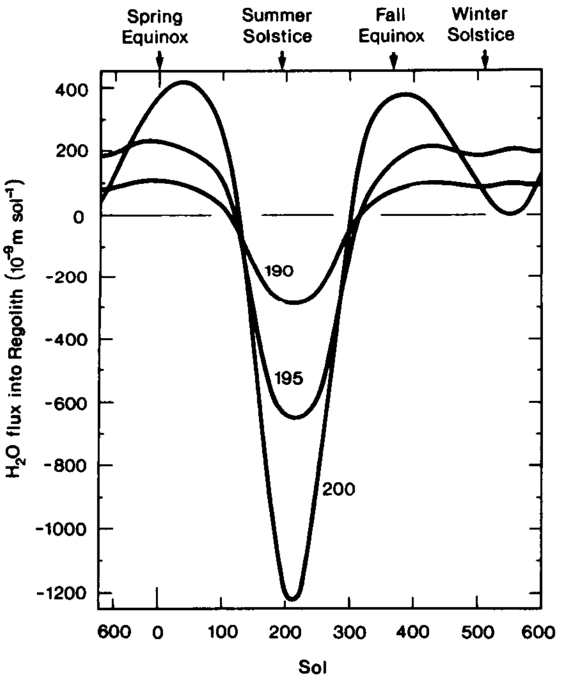

Figure 2.

Annual cycles of $H_2O$ exchange with the Martian regolith. Illustrative examples with DSF = 190, 195, 200 K.

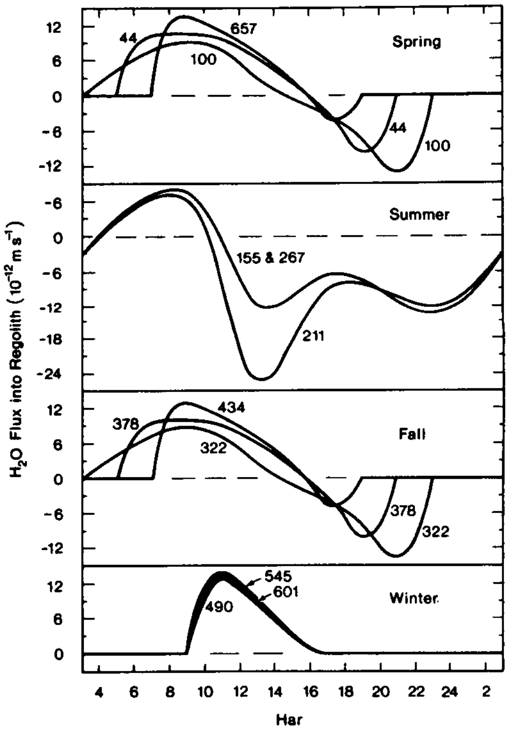

Figure 3.

Diurnal cycles of $H_2O$ exchange with the Martian regolith. Illustrative example with DSF = 195 K. Note that 24 hars (Martian hours) = 1 sol. Numerals on curves show sol number, with sol 0 at vernal equinox.

3. ***Influence of Areothermal Heat Field on Regolith $H_2O$.*** We have already noted that the areothermal heat field interacts with the damped surface temperature waves in the unsaturated regolith leading to a maximum value of $\theta$ at about 12 m. Below this $\theta$ decreases slowly to negligible values in depth.

Interest attaches to the possibility of liquid water in the regolith at great depths. The depth to the 273 K isotherm,

$$z_{273} = \frac{\bar{\lambda}}{Q}(273-\bar{T}_0)\ , \qquad [3]$$

with $\bar{T}_0$ the mean annual surface temperature (at $z = 0$), $\bar{\lambda}$ the mean thermal conductivity in $0 < z < z_{273}$, and $Q$ the areothermal heat flux density. We adopt $Q = 0.025\ \mathrm{W\ m^{-2}}$ and take $\bar{\lambda} = 0.728\ \mathrm{W\ m^{-1}\ K^{-1}}$, consistent with the profiles of $\theta$ of the examples discussed above. We thus find, for $\bar{T}_0 = 200$ K, the value $z_{273} = 2126$ m. Typically, the possibility of liquid $H_2O$ in the regolith arises only at depths of the order of kilometers.

If the regolith $H_2O$ is in equilibrium with the present Martian atmosphere, its $H_2O$ content below the 273 K isotherm seems likely to be so small that the $H_2O$ may exist primarily in an adsorbed phase.

Matters would be different, of course, if a mass of fossil ice-saturated regolith were connected to the 273 K isotherm. In the unlikely circumstance where the region below 273 K was undrained, one would then have water-saturated regolith underlying the ice-saturated mass. Underdrainage seems the more likely possibility. In this case the final profile of $H_2O$ beneath the ice-saturated mass would be established by $H_2O$ vapor equilibration in the areothermal heat field.

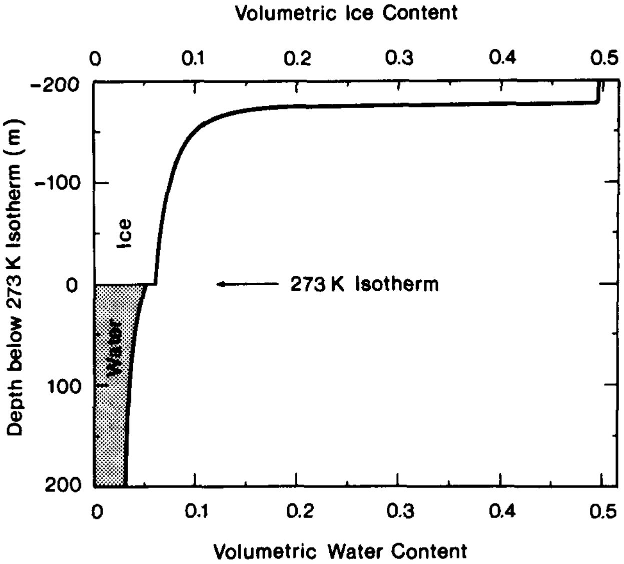

Figure 4.

Case of ice-saturated regolith with ice extending to 273 K isotherm. Volumetric ice and water content profiles above and below isotherm.

Figure 4 shows the profile of ice and water content for an illustrative example. For a regolith with underdrainage, we see that, even granted the existence of fossil ice-saturation above 273 K, liquid $H_2O$ can occur only at a depth of order of kilometers, in minor concentrations.

## 4. *References*

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