ICARUS 18, 120–125 (1973)

Exchange of Water Vapor Between the Atmosphere and Surface of Mars

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Received June 8, 1972

A model for exchange of water from the atmosphere to condensing CO_2 caps is developed. The rate of water condensation in the caps is assumed to be proportional to the meridional heat flux. It follows that the amount of water condensed in the caps varies inversely with the amount of CO_2 condensed. The seasonal phase of the release of water from the caps is not consistent with observed variations in the abundance of atmospheric water. Seasonal variations of atmospheric water abundance are most consistent with vapor exchange between the atmosphere and permafrost in the subtropics. Although water condensation in semipermanent caps is normally very slow, it may take place at a much faster rate at unusually high atmospheric temperatures, such as those produced by absorption of solar radiation by airborne dust.

Introduction

The behavior of water vapor on Mars is likely to be an important key to understanding the evolution of both the surface and atmosphere of the planet. Escape of hydrogen, presumably resulting from the photodissociation of water, has been observed (Anderson and Hord, 1971) and a plausible explanation for an equivalent rate of loss of the oxygen produced has been proposed (McElroy, 1972). The equivalent depth of water loss, if extended over 4×10^9 years, amounts to 2–3 m and is quite consistent with the observed amount of CO_2 in the atmosphere, if it is assumed that the ratio of H_2O to CO_2 outgassed on Mars is about the same as that on the Earth (McElroy, 1972). On the other hand, it is quite possible that considerable water may be stored as permafrost, and both water and CO_2 may be permanently stored in the polar regions.

The transfer of water to and from the polar caps has been considered by Leighton and Murray (1966) on the basis of a random walk model of meridional transport, with a fixed time constant of 5 days for the local removal rate. They concluded that the annual storage in the polar cap should be very small, amounting to only about $40\,g/cm^2$ over the precessional cycle ($\sim 5 \times 10^4$ years). This represents a total amount of water which is probably less than that removed and stored as permafrost over the same period (Leighton and Murray, 1966). The problem of water transport to the polar caps is reconsidered here from a different point of view.

Water Vapor Transfer Model

The meridional transport of water should be closely related to the transport of heat, at least whenever heat transport is by eddies[1] rather than by zonal mean circulations (such as a Hadley circulation, for example). This is the case on the earth, largely because, to a first approximation, both sensible heat and moisture behave as passive scalars in the transport process. Because of the saturation constraint, sensible heat and mixing ratio are highly

[1] "Eddy" is used here to denote flow components which are departures from zonal averages.

correlated. The total energy transport across latitude ϕ, $F_E(\phi)$, is given by

$$F_E(\phi) = \int_0^\infty \int_0^{2\pi} [a\rho v \cos\phi \cdot (C_p T + gz)]\, d\lambda\, dz, \quad (1)$$

where a is the planetary radius, ρ the air density, v the meridional velocity (positive toward the pole); $(C_p T)$ is the sensible heat content per unit mass, and (gz) is potential energy per unit mass. Integration is over longitude, λ, and height, z. The moisture flux, $F_w(\phi)$, is:

$$F_w(\phi) = \int_0^\infty \int_0^{2\pi} a\rho v \cos\phi \cdot q\, d\lambda\, dz, \quad (2)$$

where q is the mass mixing ratio of water. At middle and high latitudes on Mars, the dominant contribution to F_E and F_w is probably from the eddies, just as it is on the Earth (Lorenz, 1966). This predominance of the eddy flux is a property of the solutions of simulation models of Mars (Leovy and Mintz, 1969). The Mariner 9 television pictures provide direct evidence that baroclinic eddies are indeed a major component of the flow at middle latitudes (Leovy *et al.*, 1972). With this assumption, the potential energy transport vanishes, and (1) reduces to

$$F_E \simeq \frac{2\pi a C_p p_s}{g} \cos\phi \cdot \int_0^{p_s} \langle v' T' \rangle\, d\left(\frac{p}{p_s}\right), \quad (3)$$

where $\langle v' T' \rangle$ is the covariance between temperature and meridional velocity on latitude ϕ, and P_s is the surface pressure (P_s/g is the mass of a unit column of air). A similar approximation applies to F_w. A further plausible assumption concerning the moisture flux can be made. The departure of the mixing ratio from its zonal average, q', is assumed to be closely related to the temperature departure, T'; that is

$$q' \sim \left(\frac{\Delta q_s}{\Delta T}\right)_\phi \cdot rT', \quad (4)$$

where Δq_s is the change in mixing ratio over the finite temperature range ΔT corresponding to both the temperature variance and the mean temperature at latitude ϕ. The quantity r is a mean relative humidity, which will be taken to be unity. Thus, transport of water in condensed form will be neglected. This is an excellent approximation on the Earth, but may be very rough at the low saturation vapor pressures prevailing on Mars. The moisture flux can now be expressed in terms of the heat flux,

$$\begin{aligned} F_w &\simeq \frac{2\pi a p_s}{g} \cos\phi \cdot \int_0^{p_s} r \left(\frac{\Delta q_s}{\Delta T}\right)_\phi \times \langle v' T' \rangle\, d\left(\frac{p}{p_s}\right) \\ &\simeq \frac{2\pi a p_s r}{g} \left(\frac{\Delta q_s}{\Delta T}\right)_\phi \cos\phi \int_0^{p_s} \langle v' T' \rangle\, d\left(\frac{p}{p_s}\right) \\ &= \frac{r}{C_p} \left(\frac{\Delta q_s}{\Delta T}\right)_\phi F_E. \end{aligned} \quad (5)$$

Since heat storage is negligible on Mars, the divergence of energy flux must equal the heat gained by radiation, R, and the heat gained by release of latent heat in CO_2 condensation, $L\dot{m}_c$, where L is the latent heat of sublimation of CO_2, and $\dot{m}_c$ is the rate of condensation of CO_2 per unit area. Thus,

$$\dot{m}_c = -\frac{1}{L}\left\{R - \frac{C_p p_s}{a g \cos\phi} \cdot \frac{\partial}{\partial\phi}[F_T \cos\phi]\right\}, \quad (6)$$

where

$$F_T \equiv \int_0^{p_s} \langle v' T' \rangle\, d\left(\frac{p}{p_s}\right).$$

Similarly the water condensation rate, $\dot{m}_w$, is equal to the convergence of the moisture flux. Making use of Eq. (5),

$$\dot{m}_w \simeq -\frac{r p_s}{a g} \cos\phi \cdot \frac{\partial}{\partial\phi}\left[\left(\frac{\Delta q_s}{\Delta T}\right)_\phi \cdot F_T \cos\phi\right]. \quad (7)$$

The rates at which CO_2 and water condense at all latitudes poleward of a specific latitude, $\dot{M}_c(\phi)$ and $\dot{M}_w(\phi)$, respectively, are obtained by integrating (6) and (7):

$$\dot{M}_c(\phi) = -\frac{2\pi a^2}{L} \int_\phi^{\pi/2} R \cos\phi\, d\phi - \frac{2\pi a C_p p_s}{Lg} F_T \cos\phi. \quad (8)$$

$$\dot{M}_w(\phi) = \frac{2\pi a r p_s}{g} \left(\frac{\Delta q_s}{\Delta T}\right)_\phi \cdot F_T \cos\phi. \quad (9)$$

It follows that the rate of condensation of water in the cap is a decreasing function of the rate of CO_2 condensation. F_T can be eliminated from (7) and (8), to give

$$\dot{M}_w(\phi) \simeq \frac{2\pi a^2 r}{C_p}\left(\frac{\Delta q_s}{\Delta T}\right)_\phi \int_\phi^{\pi/2} R\cos\phi\cdot d\phi - \frac{rL}{C_p}\left(\frac{\Delta q_s}{\Delta T}\right)_\phi \dot{M}_c(\phi). \quad (10)$$

An upper limit for the rate of deposition of water with CO_2 in a polar cap can be obtained by letting the rate of CO_2 condensation vanish. In this limit,

$$\dot{M}_w(\phi) \lesssim \frac{2\pi a^2 r}{C_p}\left(\frac{\Delta q_s}{\Delta T}\right)_\phi \int_\phi^{\pi/2} R\cos\phi\, d\phi \quad (11)$$

and the heat transport just balances radiative losses. Since condensed CO_2 controls the temperature of the south polar cap to at least latitude 60° near the season of maximum cap extent (Sharp *et al.*, 1971), it is probably an unrealistically high upper limit.

As an example of the application of this model, temperatures and heat fluxes obtained in Mars circulation-simulation experiments (Leovy and Mintz, 1969) were used as the basis for estimating moisture condensed onto the polar cap. The computed rate of condensation at winter solstice is shown in Fig. 1. Also shown is the upper limit condensation rate based on Eq. (11). Almost all of the condensation takes place close to the periphery of the cap as a consequence of the very strong dependence of the saturation vapor pressure on the temperature.

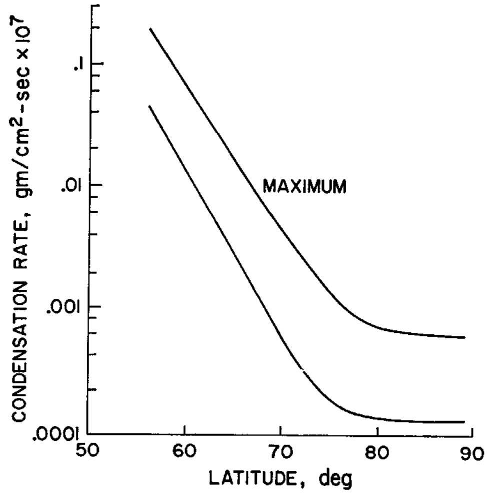

FIG. 1. Mass condensation poleward of latitude ϕ using heat flux from the numerical simulation model of Leovy and Mintz (left), and using the upper limit given by Eq. (11) (curve labeled "maximum," right).

An attempt was made to extrapolate this calculation over a Mars year. The Mars circulation calculations were carried out for only two seasons: a winter solstice, when the polar cap extended to latitude 50°, and mid-spring, when the cap extended to only 70°. The average temperature, the

TABLE I

ESTIMATED ANNUAL DEPOSITION OF H_2O WITH CO_2 IN THE SOUTH CAP, BY LATITUDE BELT, AND ASSUMED RELEASE DATE

Latitude range	Total mass (g) ($\times 10^{14}$)	Mass/unit area (g/cm^2) ($\times 10^{-2}$)	H_2O/CO_2 ratio, using the peak solid CO_2 amount of Leighton and Murray ($\times 10^{-3}$)	Equivalent abundance for uniform distribution in the atmosphere (precipitable μm)	Aereocentric longitude of release, relative to the vernal equinox (L_s)
50–60	72	10	3	52	170
60–65	36	12	2	26	205
65–70	9	4	0.5	6	230
70–75	4	2.3	0.24	3	245
75–80	1.1	0.8	0.08	0.7	260
80–85	0.4	0.4	0.03	0.3	300
85–90	0.1	0.4	0.03	0.1	—

derivative of temperature with respect to the sine of the latitude, and the temperature variance all had values at the cap edge which were about the same in the two cases. Thus, each of these quantities was scaled with respect to the position of the cap edge. These two cases also suggested scaling of the magnitude of the heat flux with the square of the cosine of the latitude of the cap edge and scaling its distribution with the position of the edge. The time variation of cap latitude thus determined the moisture flux. Eccentricity of Mars' orbit was not taken into account. Time variation of the south cap was obtained by combining the observed cap decay (Slipher, 1964) with the cap development computed by Leighton and Murray. Results are insensitive to the cap model used except within 10° of the latitude of maximum annual extent. Results of this calculation are given in Table I. Also given in Table I is the ratio of water condensed to the maximum amount of CO_2 condensed, as calculated by Leighton and Murray.

Discussion

It can be seen that the bulk of the moisture is concentrated in the cap periphery. This result is not sensitive to the details of the model. Even if relative humidities up to 200% were incorporated, to allow for possible transport of condensed water, and even if the upper limit heat flux, consistent with occurrence of CO_2 condensation were assumed, the mass condensed in the inner zone (poleward of 75°) would not increase by more than a factor of 10.

A consequence of this result is that the release of moisture from the cap, which would take place at the time of disappearance of the CO_2, is quite out of phase with the observed seasonal variation in atmospheric moisture. In Fig. 2, the release of the amounts of moisture given in Table I is plotted against the value of L_s corresponding to the date at which the cap disappears in the southern hemisphere. The computed moisture release is compared with data of Barker *et al.* (1970). Although no specific calculations were made, a similar curve would apply to the northern cap, with a 180° shift in L_s. The indicated moisture abundances correlate closely with the seasonal variation of the frequency of white clouds (Smith and Smith, 1972). Since these clouds are believed to be water ice clouds, their behavior supports the reality of the indicated moisture variatiôn. Even allowing for a substantial lag in the atmospheric response to this input, it is obvious that the phase of the observed moisture variation is quite different from that expected from the seasonal input from the caps. The behavior of the global dust storm of 1971 indicates that the time scale for global mixing in the atmosphere is only about 15 days, corresponding to a lag in L_s due to atmos-

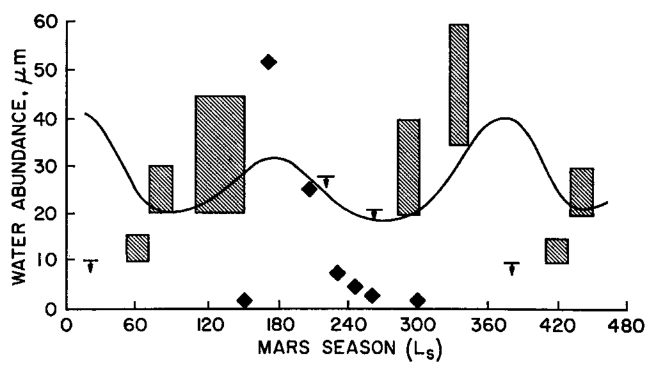

FIG. 2. Water vapor abundance measurements and upper limits, shown by the hatched areas and arrows (Barker *et al.*, 1972). Computed quantities of moisture released from the solid cap (diamonds). Moisture abundance assuming equilibration with the disk average temperature calculated by Leighton and Murray, for a depth of 135cm (curve).

pheric response of $L_s \sim 6°$ (Capen and Martin, 1971). Basically, the phase difficulty arises from the fact that, regardless of the rate of storage of water in the cap as a whole, much more water must be stored in the periphery of the cap than in the interior, and moisture released from the cap periphery would appear in the atmosphere much earlier than observed.

Evidently, the seasonal variations in atmospheric water vapor abundance are not due to exchange of vapor with the caps alone. Exchange of vapor with permafrost layers at lower latitudes, a possibility recognized by Barker *et al.* (1970) seems much more likely. In that event, correlation of the observed atmospheric abundance with subsurface temperatures would be observed. The solid curve in Fig. 2 shows the vapor abundance to be expected for vapor in saturation equilibrium with the average disk temperatures would be observed. The solid by Leighton and Murray. Except for the sharp disagreement between the high values predicted by this curve, and the upper limit of 10μm at $L_s = 22°$, the agreement might be considered acceptable. The phase agreement could be improved by postulating equilibration at a more shallow depth, but then the semiannual period disappears (Leighton and Murray, 1966). The phase disagreement is in the wrong sense to be accounted for by diffusion time in the soil.

The disk average temperature heavily weights both the tropics and the subtropics. The phase agreement could be much improved by excluding the tropics, say between ± 20 latitude, and requiring equilibration with permafrost at depths which are reached by the seasonal thermal wave within 1 or 2 months of the surface temperature wave. The subtropics appear to be the region which seasonally exchanges vapor with the atmosphere as a whole. Control of the atmospheric moisture content by surface temperatures in the tropics or subtropics is consistent with adsorption of moisture in the surface material (Pollack *et al.*, 1970).

Condensation of vapor in the caps may correspond to that given by the model, provided that vapor exchanged with the caps is transferred primarily between the cap and the adjacent subtropical region. On the other hand, the model used may seriously overestimate condensation in the caps. It is quite possible that the value of r used is too large, and the heat flux may be overestimated. The condensation rate is unlikely to be an underestimate, unless the actual atmospheric temperatures are significantly higher than those assumed. In particular, the mass of water condensed in the permanent inner caps must be very small for the temperatures assumed. The close agreement of the calculated annual mass condensed in the inner cap with that calculated by Leighton and Murray is fortuitous, but their conclusion of small storage in the permanent cap during the precessional cycle (~40 g/cm^2) is strongly supported by this model, provided that the atmospheric temperatures remain low.

On the other hand, the model is very sensitive to temperature over the cap. Figure 3 shows the variations of condensation rate at latitudes poleward of 70° and 50°, retaining all of the other assumptions used in obtaining Fig. 1, but allowing the temperature to vary. Thus, temperature at the cap edge, and over the cap is the predominant factor controlling water condensation in the cap. Since the atmospheric temperature can vary substantially as a

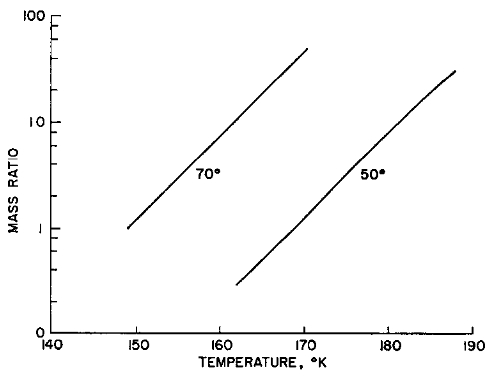

FIG. 3. Variation with temperature at latitude ϕ of the moisture amount condensed poleward of latitude ϕ, for the heat flux from the numerical simulation model. The calculations are for 50° and 70° and correspond to winter solstice conditions.

result of absorption by airborne dust (Hanel *et al.*, 1972; Gierasch and Goody, 1972), the rate of condensation may be controlled by the persistence of dust in the atmosphere. In particular, the storage in the semipermanent inner caps may be controlled by the airborne dust.

Acknowledgment

This work was supported by NASA Grant 48-002-073.

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Discussion

Sagan: There is a possible greenhouse instability in this process. With more water in the atmosphere, infrared opacity will be higher, the heating will be more efficient and even higher water content will result. There is also the possibility that the water may be released from minerals on the surface and that seasonal variations in water content may be explained that way.

Hess: You assumed only large-scale eddy diffusion. For Mars even more so than for the Earth there is also a mean transport.

Leovy: The mean transport apparently is still small.

McElroy: In the flow of water to high latitudes is there any difficulty with the supply? Also, how do you get the water back again?

Leovy: The water will circulate back again, but this circulation problem is not yet well understood.

McElroy: There may also be water production near the poles through reactions between O_3 and hydrogen.