THE WATER CYCLE: DYNAMICS OF RESERVOIR EXCHANGE, TRANSPORT, AND INTEGRATED BEHAVIOUR.

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Mars is replete with evidence suggesting variations in the nature of the water cycle over the planet's history [1]. Indeed, a major goal of Mars exploration, and the Mars Surveyor program in particular, is understanding how the water cycle varied and why. Reconstructing the record of variations in the behaviour of water is within the domain of geology and geochemistry. However, physically-based models of Martian paleoclimate are required to understand these changes, and the development of a mechanistic understanding of the water cycle is one necessary prerequisite for the construction of such models.

Formation of ice clouds in the atmosphere and water ice frost near the Viking Lander 2 site provide evidence for the activity of water in the current climate. However, the best picture of the water cycle to date results from spacecraft and ground based observations of column integrated water vapour. These data sets, and especially that collected by the Viking Mars Atmospheric Water Detector (MAWD), provide information on the spatial and temporal variations of atmospheric vapour [2,3,4]. Zonal and column integrated vapour measurements derived from MAWD [2] are shown in Figure 1. The dominant feature of the data is the large peak in vapour amounts in the northern hemisphere during northern summer. The northern residual water ice cap is exposed during this period, and consequently acts as an important, active water reservoir. The lack of a significant vapour peak during southern summer is consistent with the persistence of a CO_2 ice cap at that pole. However, telescopic data from 1969 suggest a southern summer vapour peak in that year comparable to that seen in the north [3], suggesting that a water ice cap at that pole may become episodically exposed. In all, there appears to be a rough factor of two difference in globally integrated vapour between northern and southern summer, with the vapour mass peaking at roughly 2×10^{15} g in northern summer.

The southern summer MAWD data are significantly affected by atmospheric dust scattering which prevents full sampling of the atmospheric column. The sharp drops in vapour around L_s=210° and 270° correspond to periods of vapour underestimation associated with the two global dust storms of 1977. However, it is clear that some vapour accrues in the southern high latitudes during the summer. Vapour is also observed to accumulate in the northern mid- and high latitudes in northern spring, before the northern residual water ice cap becomes active [5]. These observations suggest additional active reservoirs. Two likely reservoirs are seasonal water ice caps and water adsorbed or frozen within the regolith. Evidence for the existence of a seasonal water ice cap derives from Viking Lander [6] and near-infrared telescopic observations [7], while Jakosky *et al.* (1997) [8] provide equivocal evidence for the observed exchange of water with a regolith reservoir. However, separating the effects of regolith and seasonal ice sources on the observed vapour distributions is made difficult because of the similarity with which both reservoirs are expected to respond to heating and cooling of the surface.

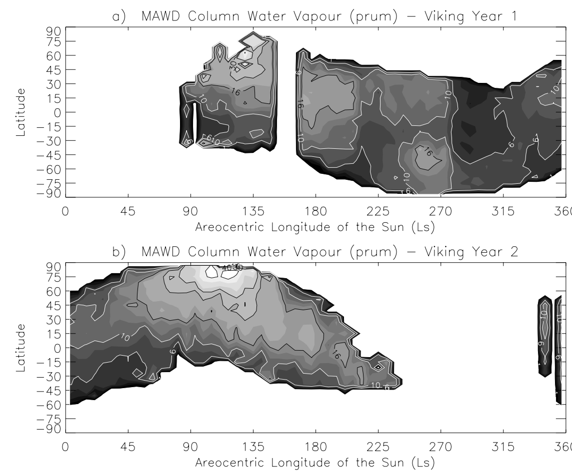

Figure 1: Zonally-averaged and column integrated vapour amounts from Viking MAWD. Increasing vapour amounts run from dark to light shading. Contouring runs from 1 prμm to 90 prμm, where 1 prμm = 10^{-3} kgm^{-2}.

A standard picture of the water cycle has emerged from the vapour observations [9,10]. During northern spring and summer, vapour is injected into the atmosphere from the northern residual ice cap as well as from seasonal water ice deposits and/or the regolith. The vapour amounts decline in mid- to late northern summer as vapour is returned to these reservoirs and/or transported to more southerly latitudes. In the southern hemisphere, vapour accrues in the mid- to high latitudes during late southern spring, as a result of transport, seasonal ice sublimation and/or regolith exchange. By late summer, the southern vapour column has disappeared, presumably by one or a combination of these same three mechanisms. The amount of interhemispheric exchange and net interhemispheric transport is not clear from the data.

The ambiguity of the picture that can be extracted directly from the data has prompted the use of models to constrain aspects of the problem. For example, if models of atmospheric transport and water exchange with a single reservoir are assumed to accurately represent processes acting on Mars, differences between the data and model output may provide evidence for the action of other reservoirs. Major questions that remain open and which have been addressed by modeling of the data include: How important is the northern residual cap as a source/sink (what capacity must other reservoirs provide)? Also, is the water 'cycle' truly a cycle, or is there net loss to the south? Additional and related questions include: How important is transport of water versus local exchange in explaining the vapour distribution? What role does the atmospheric vapour holding capacity play? And, what role does atmospheric ice transport play?

1 Water Transport During Northern Summer

Early studies of the water cycle employed a simple 'down-gradient' approximation to represent atmospheric transport [5,11]. However, transport in the terrestrial atmosphere is not well approximated by a uniform diffusion model and there is no reason to believe things should be different for Mars. Numerical circulation models based on the primitive equations of atmospheric motion better simulate the Earth's atmosphere, and those which have been adapted to Mars are reasonably able to reproduce most observations of the Martian atmosphere available to date (limited in number as they may be). While the circulation might be approximated by a diffusion model with spatially and temporally varying diffusivity (including negative values), a full circulation model would be needed to prescribe these values.

Haberle and Jakosky (1990) [12] (henceforth HJ90) published the first results of vapour transport studies with a circulation model. Using an axisymmetric (2D) model, they investigated the maximum supply capacity of the northern residual cap during late northern spring and summer. The study found significant deviations from the diffusion approximation. In particular, a strong, off-cap flow was found at low levels which moved vapour from above the cap to the cap periphery, in agreement with the observed latitude of peak vapour (70°-80°N). This ''sea-breeze'' circulation was found to result from the strong gradient in surface temperature across the cap-edge boundary.

South of the vapour accumulation zone, the circulation was found to become extremely ''sluggish'', limiting the equatorward flow of vapour from the high northern latitudes. Houben *et al.* (1997) [13] (henceforth H97), used a 3D circulation model and reported similar ''sluggish'' transport out of the northern summer hemisphere, but did not examine the circulation in detail. However, a 3D General Circulation Model (GCM) used by M.I. Richardson and R.J. Wilson [14] (henceforth RW) was found to produce rather vigorous equatorward transport in the northern mid-latitudes relative to the two previous models.

To elucidate the reasons for differences in modeled transport behaviour, RW examined the dependence of transport circulation on 2D versus 3D dynamics, the inclusion of a diurnal cycle, and the prescription of 'Mars-like' topography and surface thermophysical properties (albedo and thermal inertia). The 2D version of the GCM was found to produce results very similar to those described by HJ90. The ''sluggish'' circulation equatorward of 70°N was found to result from a time-mean circulation cell located between 65° and 75°N with poleward surface level winds, the upwelling branch being located over a latitudinal surface temperature maxima at 75°N. In 3D mode, with the diurnal cycle and surface property variations eliminated (as with the H97 model), the GCM allowed somewhat more transport across the 65°-75°N belt, due to the action of weak eddies.

However, RW found a major increase in transport when topography and surface property variations were included. Longitudinally confined, north-south trending ''currents'' were found to provide a significant equatorward flux of vapour in the 65°-75°N belt, despite the presence of a low level, zonal and time mean poleward flow at these latitudes. Further, evidence for the currents was found in the MAWD data. The importance of longitudinal variations in the Martian circulation for the transport of tracers suggests that explicit treatment of the full 3D circulation is necessary.

2 Water Reservoir Activity

While the northern residual cap is clearly implicated as an active water reservoir, the degree of activity relative to other reservoirs is poorly constrained by the data alone. Most efforts to extract information from the data via modeling have attempted to ''fit'' the annual cycle of vapour observed by MAWD (Figure 1) [5,11,13]. However, such an approach requires high fidelity in the simulation of all aspects of the cycle. Further, the MAWD data does not uniquely constrain the modeled water cycle, such that errors in one aspect of the model may be compensated by errors in another, thereby allowing a good match to data. The 'good fit' to data found by studies which differ greatly in conclusion as to the mechanics of the water cycle attests to this [5,11,13].

The HJ90 study [12] of vapour supply in northern summer employed a far more robust approach. In that study, a northern cap sublimation model was coupled to a 2D transport model. The aim of the study was to establish the maximum amount of vapour that the residual cap may reasonably supply, and through comparison with MAWD data, seek evidence of other active water reservoirs. The cap was found able to supply all the observed vapour increase if the atmosphere were perpetually dry and the winds above the cap strong. However, the efficiency of sublimation is closely related to the efficiency with which vapour is transport from above the cap (which keeps the relative humidity low). The 'sluggish' transport of vapour away from the polar region, mentioned above, was found to limit the residual cap role to less than roughly 35% of the total northern spring and summer vapour increase. The remaining fraction must be provided by a combination of seasonal ice or regolith. The behaviour or participation of regolith was not directly addressed by HJ90, but comparison of the results with MAWD data do suggest a role for the regolith [10]. The 'spur' of vapour seen in the MAWD data (Figure 1) which appears to correspond to southward vapour transport between L_s=135° and 200°, cannot be supplied with vapour from the polar regions according to the 2D model transport results. As the seasonal cap cannot be responsible, it has been suggested that vapour is being supplied by the regolith at successively lower latitudes during this season [10].

A similar study with the RW GCM [14] found equivalent supply capacity for the residual cap and evidence of a regolith role, but with opposite behaviour to that found by HJ90.

The 3D GCM circulation differs from that generated in a 2D model, as discussed above, and generates much greater off-cap transport. Sublimation into an initially dry atmosphere, as in HJ90, results in the residual cap being able to supply all the observed vapour increase. RW instead used MAWD data as the model initial vapour state, which greatly decreases (to a more realistic level) the cap sublimation capacity. Interestingly, the residual cap was found able to supply a rough maximum of 40% of the vapour increase, which is similar to estimates by both HJ90 [12] and Jakosky (1983) [5]. The greater transport capacity allowed the model to easily transport vapour equatorward during the L_s=135°-200° period. In fact, excess vapour was found throughout the tropics and northern mid-latitudes, which strongly suggests a vapour sink. The model included the seasonal cap as a vapour sink during late summer, so this sink must be the regolith.

A simplified picture of the northern spring and summer water cycle may be constructed from the RW results. During spring, vapour is released by the regolith at progressively higher latitudes throughout the northern hemisphere, and by the retreating edge of the seasonal cap. After the exposure of the residual cap, sublimation from the cap greatly increase northern polar vapour amounts, and the global vapour mass peaks by mid-summer. Much of the water injected into the atmosphere from the residual cap condenses back onto the residual or seasonal ice caps during mid- to late summer. However, some equatorward transport of vapour occurs. As this vapour moves equatorward, it resupplies the regolith with vapour lost the previous spring. This model of the northern water cycle closely resembles that suggested by Jakosky and Farmer (1982) [2] and Jakosky (1985) [9] from inspection of the data. The validity of the picture, however, depends on the validity of the GCM transport predictions, and the behaviour of the modeled residual cap.

3 The Role of Water Condensation and Clouds

The most basic question relating to atmospheric condensation of water is whether saturation limits the amount of vapour that the atmosphere can hold. Davies (1979) [15] used Viking radio occultation and infrared observations to suggest that nighttime saturation does generally limit vapour amounts. However, other observations suggest a rather uniform profile of vapour [16,17] which requires a rather contrived atmospheric temperature profile to fully saturate. In fact, Davies' conclusion relies on Viking Infrared Thermal Mapper estimates of the diurnal cycle of atmospheric temperature, which have now been show to be too large [18]. The data therefore suggest column integrated saturation values of less than 30% at most non-polar latitudes, and these values are readily produced by models.

The distribution of clouds have been assessed from Viking camera and Hubble Space Telescope observations [19,20]. Cloud distributions provide a constraint on model dynamics and vapour distributions, and consequently provide an important constraint on models. RW [14] found that a GCM will produce ice hazes at most locations on the planet for at least some portion of the diurnal cycle. However, the haze was found to be far from uniform, and if the regions of thickest haze correspond to the observed clouds, then comparison with the data suggests rough agreement both in the instantaneous spatial distribution, and in the evolution of the latitudinal distribution through northern spring and summer. The water content of the haze was found to be sensitive to assumed cloud particle properties.

The uniform distribution of vapour with height results from the superior efficiency of vertical diffusion of vapour relative to precipitation [21]. A simplified picture emerging from the data suggest that the uniform vapour column is capped by ice hazes where the saturation temperature profile intersects the environmental temperature profile. In the haze region, precipitation balances vertical vapour diffusion and significant further upward transport of water is checked. Kahn (1990) [22] suggested that during late summer, when the northern polar atmosphere is rapidly cooling, the precipitation of ice near the rapidly descending saturation level allows water to be concentrated near the surface and more rapidly removed from the atmosphere than if vertical diffusion alone was acting on the vapour. Simulations undertaken by RW find significant disagreement with the MAWD data if this mechanism is eliminated.

4 The Net Annual Water ''Cycle''

The term ''cycle'' presupposes system-wide conservation of quantity. However, the presence of a residual CO_2 cap at the southern pole guarantees some loss of water from the exchangeable water budget. The lost water may be replenished in years when the CO_2 cap fully sublimes, but it is not clear whether this ever actually occurs. Given that the ''cycle'' is not completely closed, we are faced with two major questions: how much vapour is annually transfered from north to south? And, what mechanisms might allow the maintenance of the large annual average gradient in vapour seen in the MAWD data?

A number of factors suggest that northward transport of water during southern summer should be more vigorous than southward transport around the opposite solstice. Southern summer is associated with greater dust loads and stronger solar insolation, which drive a more vigorous circulation [11]. Additionally, the net transfer of CO_2 between seasonal caps in the two hemispheres is stronger during late spring in the south than in the north [23]. Simulations with the simplified 3D model of Houben $et\ al.$ (1997) [13] (henceforth H97) and the GCM of RW [14] support the notion of much stronger transport during southern spring and summer, but the relative importance of CO_2 flow, eddy transport, and zonal-mean circulation have not been examined.

Differences in the transport vigour alone may not be sufficient to explain the large vapour gradient. When H97 examined the annual cycle of water in a simplified 3D model employing only surface ice reservoirs, the atmosphere was found to drift to a state of saturation ($i.e.$ to a state where the atmosphere contained as much vapour as it could hold).

The predicted vapour amounts were greatly in excess of those observed, leading H97 to conclude that a regolith reservoir must provide primary control over the water cycle.

Annual cycle simulations with the RW GCM employing only surface ice reservoirs were found to produce quasi-equilibrated water cycles which were far from saturated, casting doubt on the H97 claim that the regolith provides dominant control of the water cycle. In fact, the equilibrium global-average vapour masses were generally found to be less than observed. The contrasting model behaviour may result from the inclusion of topography, surface thermal variations, and the diurnal cycle in RW model, which have been shown to affect the style and vigour of atmospheric transport (see above).

The water cycle in the RW model can be reduced to a simplified picture. During northern summer, RW claim that mean cap temperatures primarily determine the polar vapour abundance, which in turn primarily determines the meridional vapour gradient, as the mass mixing ratio of vapour in the polar regions greatly exceeds that in the mid-latitudes. During the rest of the annual cycle, the north polar air mass is nearly dry, and the meridional vapour gradient depends primarily on the amount of vapour located in the tropical and lower mid-latitude atmosphere. RW claim that the observed large gradient in annual average water results from the fact that much less time in the annual cycle is available for transport away from the north polar region and that north to south transport is generally less efficient. The annual average gradient in vapour is compensated by a reverse annual average gradient in transport capacity. In this picture, the regolith plays a somewhat secondary role, altering the spatial distribution of vapour and thereby biasing the quasi-equilibrium global and annual average vapour amount. Within this framework, the saturation of H97 model can be interpreted as a quasi-equilibration in which the non-summer transport was so weak that the saturation holding capacity was reached before the seasonal vapour fluxes could come into balance.

Control of the water cycle and the true net transfer of vapour from north to south remain open questions that future observations can help to address. These questions remain open because they depend upon the integrated behaviour of transport and reservoir exchange processes, and upon representing each process correctly.

5 Interannual Variability

The Viking mission provided us with the most complete picture of the Martian water cycle and climate to date [2]. Thus, MAWD data provides the standard by which models are judged. However, there is some evidence from telescopic observations that, while the general pattern of the vapour cycle observed by MAWD is robust, disk average vapour amounts in some seasons may vary by a factor of 2 or more [3,4]. If this is true, expanding a great deal of effort in 'fitting' the MAWD data is unwarranted. However, disk average measurements can be biased by a number of factors including technique, variations in atmospheric aerosol loading, and by the large longitudinal variation in vapour. Indeed, explaining very large interannual variations in vapour would be challenging given the rather repeatable behaviour of mean atmospheric temperatures and dust away from southern summer dust-storm season [24].

6 Future Observations

Missions within the Mars Surveyor program will provide new data in many key areas. Infrared observations from the orbiter-based PMIRR and TES instruments will provide important constraints on the seasonal evolution of the 3D vapour distribution and on the validity of circulation models [25,26]. Measurements of near surface vapour and soil water content from the lander-based MVACS instrument set [27] should provide evidence for and quantification of water exchange between the atmosphere and the regolith. Additionally, information on boundary layer dynamics should aid in modeling water fluxes between the free atmosphere and surface. Studying the Martian water cycle and/or climate with observational platforms which operate but for a single Mars year has obvious limitations. Continued ground-based monitoring of Martian vapour and atmospheric temperatures is therefore extremely important for investigation of dynamic atmospheric phenomena and interannual variability within the climate system [4,28].

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