MODELLING THE MARTIAN WATER CYCLE

M. I. Richardson, *Division of Geological and Planetary Sciences, MC 150-21, California Institute of Technology, Pasadena, CA 91125, USA. (mir@gps.caltech.edu).*

Introduction:

Understanding the water cycle is a major goal of Mars exploration because of the role water plays in connecting some of the most exciting questions we have about the planet. These questions are "exciting" because they focus on aspects of the planet that are more "Earth-like": polar ice sheets, gullies, flow channels, ground ice, and long-term change in these features that can tell us something about climate change. While most of the Mars community are engaged in attempts to decipher such records of change and to map the distribution of water, climate modelling can provide an important bridge to link physical or process insight gained from investigation of the current climate with these records of past climate and volatile behaviour. Physical modelling of the Martian water cycle needs to play a substantial role in aiding the interpretation of these records, and in suggesting future observations. A major building block on the road to that goal is the development of accurate physical models of the current water cycle. This paper will review published work to date on this effort, and suggest where future work needs to be done.

Observations

The most important quantitative target for any modelling study of the water cycle is the spatial and temporal variation of water vapour. To date, most modelling efforts have benefited from the availability of only one atmospheric water vapour data set: that derived from the Mars Atmospheric Water Detector (MAWD) on the twin Viking Orbiters [Farmer *et al.*, 1977; Jakosky and Farmer, 1982]. This instrument provided the first detailed survey of the annual water cycle, which we will describe below. More recently, ingenious and careful work has allowed a high quality water vapour data set to be extracted from the Thermal Emission Spectrometer (TES) aboard the Mars Global Surveyor (MGS), despite the instrument not being optimised for this purpose [Smith, 2002]. The TES data show interesting year-to-year variability that raise new questions and challenges for understanding and modelling.

The MAWD annual cycle includes a peak in water vapour in northern summer, after the seasonal CO_2 ice cap has been removed. This vapour peak is associated with sublimation from the exposed, northern residual water ice cap [Kieffer *et al.*, 1976]. Peak column vapour abundances just equatorward of the polar cap reach 100 prμm (where prμm is the precipitable micron, or a column vapour mass corresponding to 10^{-3} kg/m^2). Figure 1 shows that in northern summer, vapour amounts decrease monotonically from the northern into the southern polar

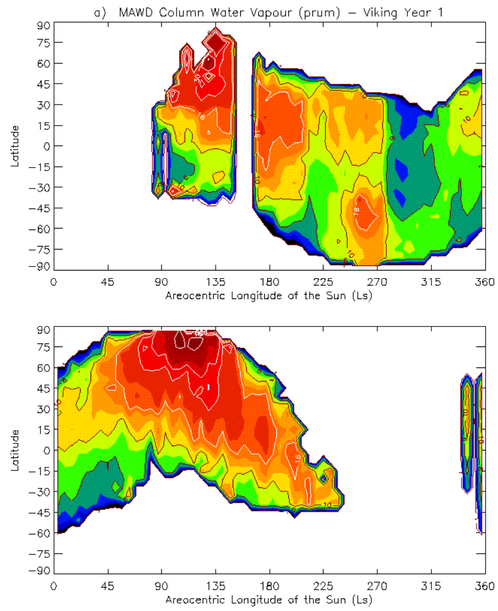

Figure 1. *Zonal-mean MAWD water vapour observations (for two consecutive years - a and b). Colour shading is from small water amounts (<0.1 prμm - blue) to large (100 prμm - deep red).*

regions. As summer wares on, the peak vapour decreases in magnitude and moves to lower latitudes. In late southern spring, the single peaked distribution is replaced by a double peak. The southern peak would appear to result from sublimation from the southern seasonal ice cap or from desorption of regolith water [Jakosky and Farmer, 1982]. The tropical minima and the northern hemisphere peak are argued to be associated with Hadley cell water transport [Richardson and Wilson, 2002]. Moving into northern spring, a single vapour peak reappears, again likely associated with sublimation from the seasonal ice cap or regolith desorption. The MAWD data suggest that this cycle of water vapour between the hemispheres is associated with the annual variation of total water vapour mass between 1-2x10^{12}kg [Jakosky and Farmer, 1982].

The annual cycle of vapour is accompanied by a cycle of cloud. During northern spring and summer, a substantial tropical cloud belt develops [*James et al.*, 1996; Clancy *et al.*, 1996; Pearl *et al.*, 2001]. While there was at one time speculation that the cloud belt structure observed by the Hubble Space Telescope and MGS was not present during the Viking era, it is now known that there has been relatively little change in the cloud belt (or the bulk air temperatures) across the spacecraft observational record [Liu *et al.*, 2002]. These observations suggest a rather repeatable water cycle. However, the TES observations provide the first opportunity to directly examine interannual variability of water vapour, and initial results suggest a noticeable amount of variability, especially in southern spring and summer [Smith *et al*., 2002].

Early Global Water Cycle Models

For computational and developmental reasons, the first models applied to understanding the water cycle used a simplified, diffusion description of meridional water transport [Davies, 1981; Jakosky, 1983a,b; James, 1985]. These models were designed to address the dominant questions arising from the MAWD data: Why is the water cycle biased to the northern hemisphere? And, what roles do surface ice and regolith adsorbed water play in supplying vapour?

Davies [1981] and James [1985] concentrated on the former question, examining the importance of increased meridional "transport" during the southern summer, and the seasonal biases in the CO_2 condensation flow. Neither model included a regolith exchange parameterisation. While the models showed that the water cycle will be sensitive to these variations in the circulation, the Davies [1981] model came closest to "fitting" the observed vapour cycle. However, the required diffusivity (meridional transport) during southern summer was excessively high.

Jakosky [1983a,b] examined the role of regolith exchange within a diffusion-based global water model. Using regolith activity and meridional diffusivity as a free parameters, and a southern polar cap water cold trap, Jakosky [1983b] was able to obtain a reasonable fit to the observations without requiring excessive southern summer diffusivities. Analysis of the cycle obtained within the model prompted Jakosky [1983b] to suggest that the northern polar cap was the primary driver of the water cycle, with the regolith and seasonal caps being driven into equilibrium with it.

Explicit Circulation Models

Coupling the water cycle with a prognostic model of atmospheric circulation was desirable so as to eliminate meridional diffusivity as a free parameter. In addition, as argued by Haberle and Jakosky (1990), there exist situations in the real atmosphere where transport is "up" the meridional vapour gradient. The first published attempt to address the Martian water cycle with a prognostic model used and adapted version of the Haberle *et al.* [1982] axisymmetric model [Haberle and Jakosky, 1990]. The main focus was the degree to which the northern polar cap can supply the northern summer atmosphere with water vapour - and hence the requirement, if any, for supply from the northern mid-latitude regolith. In this way, the model was used to examine the role of the regolith, while the model itself did not contain (and hence was not sensitive to uncertainty in) a regolith exchange scheme. The model showed that the main limitation in supply of water vapour was in the transport of water from the cap edge to the mid-latitudes. Water was rapidly moved off the residual cap by a vigourous "sea-breeze" circulation, but then stalled near that location, backing-up atmospheric vapour and limiting sublimation from the cap. On

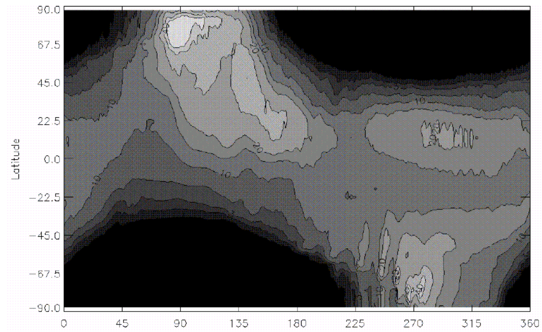

Figure 2. *The zonal and seasonal distribution of water vapour as modelled by the GFDL Mars GCM [Richardson and Wilson, 2002]. Contours are in units of prμm (note the scale is non-uniform).*

this basis, it was suggested that the regolith may play a substantial role in supplying the northern hemisphere water vapour peak [Haberle and Jakosky, 1990].

Full three-dimensional dynamics were first brought to bear on the global water cycle problem by Houben *et al.* [1997]. This model used a simplified three-dimensional circulation or "climate" model based on a spectral core [Haberle *et al.,* 1997], and included atmospheric water condensation, atmospheric vapour and ice transport, and exchange with surface ice and subsurface adsorbed and frozen water. While a somewhat "sluggish" transport circulation was reported in the summer high-latitudes, the Houben *et al*. [1997] model had very little difficulty in supply water to the global atmosphere from the northern polar cap. The model showed a vigourous transport between the northern and southern polar caps, suggesting a truly global water cycle, in contrast to inferences from the Haberle and Jakosky [1990] model. The model also highlighted interesting details in water behaviour, including cloud formation, and the interaction between water vapour and the trailing edge of the seasonal ice cap.

The Houben *et al.* [1997] model results suggested that a regolith is essential for matching the MAWD vapour record, but for the opposite reason discussed by Haberle and Jakosky [1990]. While the latter model required a regolith vapour source in northern summer to explain the observations, the former required a regolith to act as a "sponge" to prevent the model from "flooding" with water and developing extensive surface ice deposits.

The most recently published water cycle model is that of Richardson and Wilson [2002] and Richardson *et al.* [2002], who used the Geophysical Fluid Dynamics Laboratory (GFDL) Mars GCM. The model was initially used to test the Houben *et al.*

[1997] requirement for a regolith by running without an active regolith. The model did include exchange with surface water ice, transport of atmospheric water vapour, and water ice cloud. While the model was able to extract much more water from the northern cap than the Haberle and Jakosky [1990] model, the GFDL Mars GCM did not flood with water. Instead, the results suggested that the model would come into near steady-state with an atmospheric vapour abundance a factor of a few (2-3) higher than observed, but with vapour, surface ice, and cloud ice distributions qualitatively similar to those observed (Figure 2).

The difference between the Richardson and Wilson [2002] and Haberle and Jakosky [1990] models was examined by using the GFDL model in an axisymmteric mode. In this mode, the GFDL model produced very similar vapour distributions to that of the Haberle and Jakosky [1990] model. Comparing the 2D and 3D versions of the model, it was found that a significant fraction of transport in the northern mid-to-high latitudes occurs in zonally asymmetric circulations [Richardson and Wilson, 2002].

Discrepancy between the GFDL model and the Houben *et al.* [1997] model was examined (by removing surface property variations from the GFDL model). However, in no case would the GFDL model reproduce the results shown by Houben *et al.* [1997] for an inactive regolith. Indeed, it now seems likely that the inactive regolith simulations described by Houben *et al.* [1997] contained a code error.

Water Reservoir Activity in the GFDL Model

The GFDL Mars GCM water cycle produces a good qualitative fit to the observed vapour, surface ice, and cloud ice seasonal cycles. As such, some insight into the processing of water within the Martian climate system and the component interactions that lead to steady-state may result from examining the modelled water cycle. Richardson and Wilson [2002] were particularly interested in determining what mechanisms drive the model to a steady-state following initialisation from an excessively "dry" or "wet" atmospheric state. In order to highlight the important exchanges, they developed a simplified set of water cycle budgetary components, illustrated in Figure 3a. These components include water ice on the southern residual ice cap, water in the northern polar column (at latitudes greater 75°N, and including ground ice, cloud ice, and water vapour), and an element containing all other water in the system. Based on the trends in these budgets (Figure 3b), Wilson and Richardson [2002] developed a simplified picture of dynamical balance in the water cycle. They argued that the critical exchange interface is between the northern polar water budget and that of the rest of the planet. They further argue that separate variables control fluxes across this interface in northern summer (when the flow is outward from the pole) and at other seasons (when the flow is to the pole). For a given climatology of circulation (transport capacity), the outflow is determined by the pole to equator vapour gradient, which is dominated by the northern polar vapour maximum. Thus, with broad brush strokes, the northern polar cap temperature determines outflow. Return flow is also determined by the meridional vapour gradient, but away from northern summer this gradient is set by the history of accumulation of available water outside of the northern pole. Thus, starting from a dry model initial state, a fixed northern polar outflow will eventually introduce enough water into the non-polar atmosphere to generate a non-summer return flow to balance the summertime outflow. Conversely, an excessively wet initial state will generate return flow that overwhelms outflow until the non-polar water has been reduced to a steady-state level.

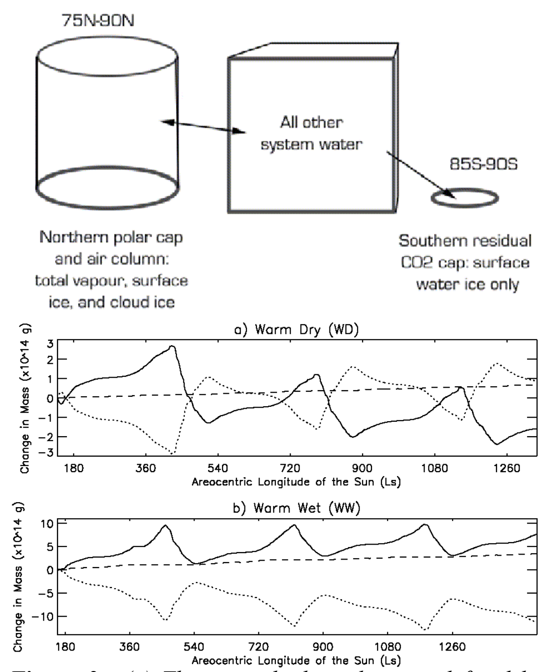

Figure 3. *(a) The water budget elements defined by Richardson and Wilson [2002] and (b) the evolution of these budgets in GCM simulations that were initialised "dry" (upper) and "wet" (lower). The solid line is northern polar water, and the dashed line south polar water. The northern cap operates as a source or sink so as to drive the water cycle towards a steady state that is qualitatively similar to observed.*

The Wet Model Problem

The GFDL Mars GCM generates a steady-state vapour abundance that is 2-3 times higher than observed when using the inactive regolith scheme and the basic cloud ice scheme described in Richardson and Wilson [2002]. This error occurs despite good fits of ground and air temperatures to observations. The role of the regolith was examined by using a two-level scheme based on that of Houben *et al.* [1997]. However, the inclusion of this scheme was found to worsen the fit to observations. Richardson and Wilson [2002] suggest that this is due to the regolith providing additional sites to trap water outside of the northern pole and to release it back into the atmosphere in southern spring and summer. Put another way, the regolith sites allow more water to be extracted from the northern pole during summer, and hence for higher return flow and higher vapour amounts in the southern spring and summer.

Richardson *et al.* [2002] examined the effect of cloud precipitation rate on the global water cycle. The results show strong sensitivity, but that excessively large ice particles (~10μm) would be needed to bring the model into a good quantitative agreement with observed global vapour amounts. Interestingly, the same large particle sizes tend to bring the predicted cloud ice belt structure into very good agreement with observations [Richardson *et al.,* 2002]

The Role of Water Condensation and Clouds

Kahn [1990] suggested that during late summer, when the northern polar atmosphere is rapidly cooling, 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 with the GFDL model show that this role for clouds is indeed important, and that if neglected, substantial qualitative disagreement exists between the model and observations [Richardson *et al.,* 2002].

The role of clouds in modifying the modelled vapour distribution was mentioned above. The mechanism of modification in this case is through the interference of the Hadley cell transport of water in northern spring and summer by the formation of the tropical cloud belt. The idea that clouds cloud limit interhemispheric water transport was first raised by Clancy *et al.* [1996] following from the realisation that the Martian atmosphere is substantially cooler at mid-levels (10-30km) in northern spring and summer than previously suspected, and from observations of the thick cloud belt in Hubble Space Telescope images. While the cloud belt can dramatically influence inter-hemispheric water transport, it should be noted that in order to fit southern spring and summer vapour observations, substantial water transport to the southern hemisphere is necessary in northern summer, and thus it is not useful to think of the clouds as "trapping" or "sealing" water in the northern hemisphere - the cycle is global.

Cap Stability

Both Houben *et al.* [1997] and Richardson and Wilson [2002] examined the hypothetical existence of a residual water ice cap at the southern pole. In both cases, the southern cap was found to be a net source of water and to decrease in mass over time. This is equivalent to saying that a southern water cap would be unstable relative to a northern cap, and/or that the equilibrium global vapour abundance demanded by a southern water cap is higher than that demanded by the northern cap. These simulations occurred for current spin and orbital parameters, which produce a warmer southern pole. Richardson and Wilson [2002] further investigated the stability issue by prescribing peak southern cap temperatures to be lower than those in the north, changing the thermal bias in favour of the south. However, the southern cap was still found to lose mass to the north, potentially due to inherent biases in the interhemispheric circulation [Richardson and Wilson, 2002b].

The Future

The Houben *et al.* [1997] and Richardson and Wilson [2002] models provide the first integrated examination of the water cycle inside of the full GCM framework, but do so with very crude representations of many of the physical processes. As a result, substantial scope exists to improve these parameterisations and assess the degree to which their augmentation improves the model prediction of observables. Already underway in several GCM models is incorporation of cloud ice microphysical schemes to self-consistently calculate particle nucleation and growth rates, and to couple these to radiation. Coupling between dust and water in the atmosphere is also beginning to be investigated. Diffusion and sequestration of water in the subsurface provides another substantial opportunity for improvement, employing schemes such as that described by Zent *et al.* [1993]. Initial unpublished work by different groups on improved cloud and improved regolith parameterisations suggest that one or both of these augmentations may help with the "wet model problem."

Observations provide the focus for modelling work, with understanding usually resulting only from the partnership. New TES observations are providing the first look at interannual variability of water vapour [Smith *et al*., 2002] not substantially affected by observational biases. Initial indications suggest significant variability in southern spring and summer water vapour. Such variability is either the slave of another climate system component (such as varied insolation associated with southern hemisphere dust activity) or requires some form of memory within the cycle (such as that associated with the distribution and thickness of surface ice deposits). In either case, this provides fresh motivation for climate-system coupling and longer-term simulations.

To return to the initial theme of this paper, it is important that improved understanding of water cycle - and more broadly climatic - processes are brought to bear on questions that are central to exploration of Mars: water distribution and paleoclimate. The models developed by Houben *et al.* [1997] and Richardson and Wilson [2002] represent a substantial jump in capability compared to the diffusion models of the 1980's. In the same way that those early models were used to provide an initial exploration of paleoclimatic variability [Jakosky *et al*., 1993; 1995], the next generation of models offers the opportunity to explore paleoclimate in a more rigourous and self-consistent manner. The challenge is to use the models in a physically valid way and to attack problems where the improved representation has greatest impact.

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