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VOLATILES ON MARS

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I. Introduction

The long-term evolution of both the atmosphere and the surface of Mars can be understood by examining the history of volatiles in the Mars atmosphere, their non-atmospheric reservoirs, and the processes of exchange between the two. Clearly, we can only see the present state of both the surface and the atmosphere, so that any inferences about the evolution of the climate system are just that--inferences. The processes which control the atmosphere and surface on a seasonal basis, however, are the same processes which can act on longer timescales; only the specific solar and atmospheric forcing will differ. Once the ability of each process to affect the seasonal behavior is understood, the long-timescale forcing may be applied to the various processes in order to clearly identify the ability of the processes to act over the entire history of Mars.

The observational evidence suggests a significant previous influence of volatiles on the martian environment. Flowing water on the surface, the enrichment of N^{15} relative to N^{14}, and the evidence for a quasi-periodic variation of ice and dust transport within the polar regions all suggest a significant exchange of volatiles between the surface and atmosphere at some time in the past (e.g., Carr, 1981). Observations of the seasonal behavior of the martian polar caps suggest a significant exchange of CO_2 between the surface and atmosphere (Leighton and Murray, 1966; Paige and Ingersoll, 1985), in a manner which varies significantly depending on the epoch (Toon et al., 1980). The behavior of water vapor in the atmosphere over the course of a season also suggests a significant exchange of water between the atmosphere and regolith (Leovy, 1973; Jakosky and Farmer, 1982; Jakosky, 1985), and simple quantitative models of the exchange process support that hypothesis (Jakosky, 1983a,b).

These areas of surface-atmosphere interaction on Mars are addressed in our ongoing research. The climate system on Mars is controlled by processes involving the exchange between the surface and atmosphere, so it is important to understand the current behavior of those processes. This is especially so in light of the current interest in understanding Mars; the upcoming Mars Observer mission and the potential for a future sample-return or human-exploration mission will focus emphasis on this area of Mars science.

II. Progress to date

In the past year, we have made significant progress in several of the areas we originally proposed, and several papers have been submitted for publication. Progress is summarized below.

We have completed modelling of the sublimation of water from the residual north polar cap of Mars during the summer season and of the ability of the atmosphere to transport the water away from the polar region. These calculations were done because several features of the Viking MAWD observations suggested that the residual cap is a major source for atmospheric water during northern summer, and that the water it supplies to the atmosphere is transported equatorward to low northern latitudes by summers' end. We have explored the role of the north residual cap in the current water cycle by constructing models to assess the ability of the cap to supply water to the atmosphere and the ability of the atmosphere to transport it out of the polar regions. The models take two forms. First, we calculate the sublimation from the cap using observed temperatures as a boundary condition; unknowns such as the surface emissivity, wind speed, and small-scale properties are varied to get a range of possible water sublimation amounts. Second, we use the axisymmetric circulation model of Haberle et al. (1982) to calculate the summertime transport through the atmosphere; this model is thought to be appropriate due to the lack of wave activity or other evidence of non-axisymmetric behavior.

From our sublimation model, we conclude that the residual cap can sublime the 7×10^{14} g of water that appears in the atmosphere after $L_s = 80°$ provided that the surface winds are high (10 m/s), the cap emissivity is low (0.9), or the exposed soil in polar regions contains ice that is accessible to the atmosphere. In our view, these requirements seem unlikely and we are drawn to the conclusion that other sources for water exist. This conclusion is further supported by the results of the 2D transport simulations which show that most of the water sublimed from the cap remains at high latitudes. The polar circulation simply lacks the intensity and scale to move water very far. A weak circulation places additional constraints on cap sublimation rates since abundant clouds and significant ice deposits would form just equatorward of the cap edge, according to the model, if the cap is allowed to sublime the 7×10^{14} g of water. Such predictions are inconsistent with available data. We suggest that the nature of the additional source is water desorbing from the non-polar regolith.

This research has been carried out in collaboration with R. M. Haberle of NASA/Ames Research Center, and has been submitted for publication.

We have also modelled the behavior of the south polar cap, both in order to understand the differences between the two caps and to try to explain the observed water-vapor behavior. Observations of water made in 1969 suggested that the seasonal CO_2 frost covering may have disappeared that year to reveal an underlying water-ice cap, yet the CO_2 frost remained all year when viewed by Viking (Jakosky and Barker, 1984). We modelled the energy balance of the cap to determine if it was possible for all of the CO_2 frost to disappear one year yet to remain throughout the summer during another year. Our model suggests that the cap has two stable states in which it may reside at the current epoch: One, observed by Viking, was covered year round by CO_2 frost; the other, which has in fact been predicted by previous models, has the CO_2 frost disappearring at about mid-summer to reveal an underlying surface (either regolith or water ice). The difference between the two states depends on the amount of energy conducted into the subsurface during summer; thus, if CO_2 frost was present year round last year, there is little or no conducted energy to affect the surface energy balance and CO_2 frost will be stable year round again. If the frost disappeared last year, conducted energy will be important and will be of sufficient magnitude to sublime all of the CO_2 frost by midsummer again this year. The cap may jump between the two states depending on subtle atmospheric effects on the energy balance--a change in the dust content of the atmosphere or surface or the additional transport of a clean, fine-grained water frost to the cap. This work has significant implications for understanding the long-term behavior of the martian climate. This work has been submitted for publication by Jakosky and Haberle.

We have also modelled the evolution of martian water based on the recent measurement of D/H in the Mars atmosphere. Owen et al. (1988) suggested that the enhancement was due to preferential escape of H relative to D in an early, thick, wet atmosphere, owing to the large amounts of water which must be photodissociated and escaped to produce the large enrichment. Yung et al. (1988) calculated the current escape rate and suggested that, if the current atmospheric conditions prevailed for 4.5 billion years, Mars must have a non-atmospheric reservoir equivalent to 0.2 m of water with which the atmospheric water exchanges. We point out that this latter number is inconsistent with polar volatile theory (which predicts about 100 times this amount of water in an exchangeable non-atmospheric reservoir). Rather, we suggest that the current D/H could result from escape from an atmosphere whose time-averaged water content is larger than the current value, and that such a situation may result based solely on the expected solar forcing of the polar caps over the 10^5- and 10^6-year timescales of the obliquity oscillations. An early, wet atmosphere is not required. A manuscript based on these results has been submitted for publication by Jakosky.

Finally, we have completed analysis regarding the uncertainties in the measurements of the column water abundance in the martian atmosphere. Such results provide constraints on the interpretation of the seasonal water cycle, and are important in not over-interpreting the data. We are in the process of modelling the role of scattering by atmospheric dust (see below), and will publish the results together in the future.

III. Plans for the coming year

During the coming year, we intend to continue modelling the role of scattering by atmospheric aerosols in determining the observed water-vapor abundances, modelling the interplay between regolith exchange and atmospheric transport of water in the seasonal cycle, and modelling the basic physics of the polar caps in order to understand the long-term evolution of the martian climate. These tasks are described below.

A. Modelling of water-vapor observations. We will also model the role of dust in scattering sunlight, and use this information to invert the Viking MAWD measurements simultaneously for the water vapor column abundance and the effective pressure and temperature of line formation. Although the individual raster-level data are too noisy to allow this analysis, averaging data together can reduce the random uncertainties and allow an inversion. Preliminary modeling suggests that averaging together of about 400 data points will produce sufficiently small errors. The use of 400 data points precludes an analysis with the same spatial and temporal resolution as earlier analyses (10° in latitude and longitude, and 15° of L_s), but will still allow significant seasonal and spatial information to be obtained.

Modeling of the scattering by atmospheric dust has been done previously by Davies (1979). We will develop a scattering model which will be significantly improved over that used by Davies in the following ways: First, our model will incorporate more-realistic estimates of the dust scattering phase function, based on measurements at the 1.4-μm wavelength of the MAWD instrument. Although the data do not go to high enough phase angles to show the entire high-phase-angle peak of scattered light, models of the light scattering by dust can be checked for consistency with the properties deduced from measurements made in the visible and near-infrared from the Viking landers (Pollack et al., 1977; Kahn et al., 1981). Second, we will include the vertical variation of pressure and temperature within the atmosphere, rather than using a fixed pressure and temperature as Davies (1979) did.

Inclusion of scattering by dust will introduce two additional variables into the analysis - the dust opacity and the vertical distribution of the dust within the atmosphere (e.g., the dust scale height). Additional information on the dust opacity is available from Viking lander measurements (Pollack et al., 1977, 1979), from Viking IRTM infrared measurements (Martin et al., 1979; Martin, 1986), and, on a more global scale, based on atmospheric tide information (Zurek, 1981). Information on the vertical distribution of dust is available from Viking lander observations (Pollack et al., 1977, 1979; Kahn et al., 1981). Although we probably cannot uniquely solve for dust as well as water-vapor properties from the MAWD data set alone (although dust scattering effects on the individual lines may, indeed, allow a unique determination of dust opacity), we can check for consistency with the other data sets and solve, for instance, for the ratio of the water vapor scale height to the dust scale height.

As a result of this analysis, we hope to gain information on the effective pressure of the water vapor absorption lines, equivalent to learning the vertical distribution of the water vapor. Such information is valuable in understanding the seasonal transport of water (Haberle, 1986), the microphysics of cloud formation and the consequent radiative and dynamical phenomena (see, for instance, Kahn, 1984), and the seasonal exchange of water with the regolith (Jakosky, 1983b). Unfortunately, the vertical distribution of the water within the atmosphere has not been well-determined, and limited information is available at only a small number of locations and seasons (Davies, 1979; Farmer et al., 1977; Jakosky, 1985).

Even if it turns out to not be possible to uniquely determine the vertical water vapor distribution from the MAWD data due to the scattering by dust, we can determine the vertical distribution of the water relative to the dust using the same technique of multiple viewing angles used by Davies (1979) on a more global and seasonal basis. Over one hundred observational sequences like the one he used are available at a large number of locations and spread in time throughout the year. Each one consists of observations by both the MAWD and IRTM instruments of a location on the surface at a variety of emission angles over a short time interval. Also, we will be able to estimate the effects of dust scattering on the previously derived water vapor column abundances in a more realistic manner than was done by Davies (1979).

The work described in this section of the proposal will constitute the bulk of a doctoral dissertation by Helen M. Hart at the University of Colorado.

B. The seasonal water cycle. The dominant process involved in the seasonal cycle of water, along with sublimation and condensation in the polar regions and transport within the atmosphere, is exchange with the global near-surface regolith. Models by Jakosky (1983a,b) suggest that this exchange, driven by the seasonally varying surface and subsurface temperatures, can be important in driving the seasonal cycle of atmospheric water. This result is not as contradictory with the previous discussion as it might appear: The north residual polar cap appears to be responsible for about half of the water which appears in the martian atmosphere during the spring and summer seasons, and for most of the water which appears after L_s=80° (e.g., Jakosky, 1985). The other half of the water comes from either the retreating seasonal polar cap or from the regolith. We are planning additional modelling of the efficacy of the exchange with the regolith, in order to better understand the role of the regolith in the seasonal cycle.

We will construct a one-dimensional model of the martian atmosphere and near-surface regolith in order to examine the vertical exchange of water between the surface and atmosphere on both diurnal and seasonal timescales. The model will significantly improve that by Flasar and Goody (1976) for the diurnal cycle and by Jakosky (1983a) for the seasonal cycle by inclusion of an improved boundary layer model of the atmosphere. This model has been recently developed by R. M. Haberle, and will be coupled to a surface and subsurface model to be developed by the P.I.

The subsurface model will combine the thermal aspects of the model of Kieffer et al. (1977) and the water-vapor-diffusion aspects of the model of Jakosky (1983a). It will represent a significant improvement over the earlier subsurface model (Jakosky, 1983a) by including sufficient vertical resolution to simultaneously incorporate both diurnal and seasonal effects, flexibility to allow for various subsurface thermophysical parameters and their variations (as described, for instance, by Jakosky and Christensen, 1986a,b), more-accurate calculation of subsurface temperatures, and a proper boundary condition at the surface.

The atmospheric boundary-layer model developed by R. M. Haberle solves the basic conservation equations in the presence of a background wind profile. Calculations are done with high precision in the vertical, and include an appropriate water-vapor-diffusion boundary condition at the base of the atmosphere.

The coupled one-dimensional model will be applied to the specific problems of the diurnal exchange of water between the regolith and atmosphere, the condensation and sublimation of water and carbon dioxide frost which was observed at the Viking Lander-2 site (and modeled in a preliminary sense by Hart and Jakosky, 1986), the near-surface saturation of the atmosphere observed at the Viking landers (Ryan and Sharman, 1981; Ryan et al., 1982), and the seasonal diffusion and possible loss of water from a high-latitude ground ice deposit (as has been postulated by Leighton and Murray, 1966, and Farmer and Doms, 1979). This model can also be applied to longer-timescale exchange of water between the regolith and atmosphere, updating the simpler models of Fanale et al. (1986) and Zent et al. (1986).

We will also couple this one-dimensional regolith model to the global circulation models which have been and are being developed at Ames by R. M. Haberle. This will allow us to estimate in a more-realistic manner the bulk importance of the regolith in the global and seasonal behavior of martian water. The previous coupled-regolith-and-atmosphere model used eddy diffusion within the atmosphere as the dynamical transport mechanism. The atmospheric transport aspect of the model will consist of one of two different models. The first one will be the same model as described above, the two-dimensional axisymmetric model discussed by Haberle et al. (1982). In this case, an additional quasi-diffusion term would need to be included to take into account sub-grid-scale mixing and transport due to non-axisymmetric waves (such as the winter-hemisphere baroclinic waves or, perhaps, the summer-hemisphere waves which are responsible for the spiral wave clouds which have been described by Gierasch et al., 1979). The second model will be a three-dimensional spectral model currently being developed by R. M. Haberle and R. E. Young at Ames.

The coupling of the regolith model to either of the atmospheric models will involve a number of one-dimensional regolith columns at a variety of latitudes, each able to communicate with the atmosphere at that latitude. In this respect, the model will be similar to that discussed by Jakosky (1983b); only the atmospheric aspect will be different. Unfortunately, computer requirements are probably too severe to couple a regolith-physics model to the three-dimensional general circulation model currently under development by J. B. Pollack and colleagues at Ames.

We will use the coupled atmospheric and regolith physics models to investigate the seasonal exchange of water between the regolith and atmosphere of Mars. We do not currently know the true ability of the regolith to allow exchange of water with the atmosphere. This ability depends primarily on the diffusivity of the material which, although undoubtedly related to other measurable parameters such as the thermal inertia (Jakosky and Christensen, 1986a,b), is not independently known. By running models for a variety of plausible values of the diffusivity and its spatial variations, we can test the hypothesis that exchange with the regolith contributes a significant amount of the seasonal atmospheric water. The key issue is to determine the relative proportions of water coming from the regolith and water coming from the retreating seasonal polar caps; both processes are thermally driven by the advancing seasons, so distinction between the two may be difficult.

The end results of this task will be a much improved understanding of the ability of water to exchange between the atmosphere and the surface on Mars, and of the processes which control this exchange. Our results will be valid for the diurnal and seasonal cycles, but the results may then be extrapolated to longer timescales because the solar forcing variations are known. These results will also be a valuable aid in planning, obtaining, and interpreting atmospheric data from the Mars Observer mission. Not only will results from that mission directly address the issues discussed here, but the insight gained from modeling and analyzing the currently available data from Viking will increase the value of the MO results.

C. Behavior of the polar caps. Both the seasonal and longer-timescale behavior of the polar caps on Mars depend on processes involving the cycles of carbon dioxide, water, and dust. Direct condensation of carbon dioxide onto the surface during winter accounts for the bulk of the seasonal polar caps (Leighton and Murray, 1966; Paige and Ingersoll, 1985). Transport of water within the atmosphere to and from the residual (and, to some extent, seasonal) polar caps accounts for a significant fraction of the observed cycle of atmospheric water behavior (e.g., Jakosky, 1985). Seasonal transport of dust and water into and out of the polar regions can, over a period of 10^5-10^6 years, account for the formation and evolution of the polar caps and polar layered terrain, as well as the circumpolar dune fields (e.g., Cutts, 1973; Pollack et al., 1979; Toon et al., 1980; Jakosky and Carr, 1985). By examining the individual processes which comprise the entire polar phenomena, we can better understand the interplay between these processes on both seasonal and longer timescales, and thereby better understand the history of martian volatiles and of the martian climate. We will study the seasonal cycles in the polar region, with an eye toward understanding the stability of water and carbon dioxide in the polar regions on several timescales.

We will examine the long-term stability of the polar caps due to both variations in the solar forcing and geophysical influences. Paige (1985) points out that the location of the south polar cap is apparently controlled by topography, but suggests an unrealistic mechanism of control--that the half-degree slopes which are present can shift the center of the cap by up to five degrees of latitude. Rather, we suggest that it is the altitude differences which control the location of the cap, with the cap located in the topographic depression described by Paige (1985). We will model the role of topography in controlling the size, shape, and stability of the polar caps, both at the current and at other epochs.

Murray and Malin (1973) have previously described the role of topographic variations in polar-cap stability, but they did so for the gross case of north- versus south-polar cap. Rather, we will model the effect for spatial variations within a single cap. Relevant processes include the seasonal condensation and sublimation of CO_2, and condensation, sublimation, and atmospheric migration of water ice. We suspect that it is actually the location of the water ice which governs the location of the CO_2 frost, again being guided by the behavior of the retreat of the seasonal cap. Although transport of water vapor from the south cap may not be important at the current epoch, unless the CO_2 frost does indeed disappear in some years, it is clear that the summer behavior of the water will be important at higher obliquity when summer solar heating of the caps is more intense. Therefore, we will expand our polar model to include geographic variability and solar variations.

By examining this aspect of polar behavior on Mars, we anticipate a significant increase in our understanding of the behavior of volatiles, both at the current epoch and over long timescales. Because the polar caps control the behavior of the martian climate (e.g., Jakosky, 1985), we will obtain a better understanding of the variations which have occurred in the climate over long timescales.

D. Volatile inventory on Mars. Finally, we will examine the behavior of volatiles based on measurements of the SNC meteorites. These meteorites are thought to have come from Mars based on gas inclusions, composition, mineralogy, and petrology (McSween, 1985; Pepin, 1985), and they contain significant clues to the evolution of volatiles on the planet. Dreibus and Wanke (1985) made estimates of the water content of the planet based on some of the clues. We are updating their analysis to include the uncertainties in some of the geochemical relationships; this will, essentially, result in error bars on their estimates of water content which are very large. We are also using the observed water and argon abundances in the Mars atmosphere to constrain the outgassing history of the planet, assuming that early outgassing is unlikely (see Zahnle et al., 1988) and that volcanism is the primary source of later outgassing (see Greeley, 1987). This analysis will result in a better understanding of the water content of Mars, its outgassing history, and the role of climate change in the evolution of the planet.

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