THE INCORPORATION OF WATER ICE CLOUD MICROPHYSICS IN A MARS GENERAL CIRCULATION MODEL

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Introduction:

The need for incorporating self-consistent models of dust and cloud microphysics into general circulation models of the Martian atmosphere is dictated by the evident impact aerosols provide to the planet's climate, including heat balance, dust, and water cycles. Microphysical processes in aerosols and clouds are usually too complex and diverse, yet obey too different scales in both space and time from the general circulation, which forces researchers to seek simple approximate substitutes describing the macroscopic state of aerosol media in terms of a few parameters. Although such parameterization has been widely used in terrestrial GCMs, it faces serious difficulties in application to the atmospheres of foreign planets where the lack of empirical information precludes reliable verification of such parameterized models. On the other hand, clouds in planetary atmospheres, in particular on Mars, often obey much less diverse and complex microphysics than on the Earth, which gives a hope to implement an *ab initio* model of clouds, which would require moderate computational resources. Usually such non-parameterized, *ab initio* cloud models deal with a size distribution of cloud particles; several generations of comprehensive microphysical models of Martian water ice clouds developed by Michelangeli *et al.* (1993), and by Colaprete *et al.* (2000) operate with size spectrum resolved on a non-uniform grid. These models demonstrate, in particular, that despite the stiffness of the microphysical processes, in most cases the size distribution has single mode and varies smoothly in space and time.

In order to reduce the computational cost of the microphysical model and adapt it to the GCM, we have implemented a spectral approach, based on the method of moments, that allows to drop the dimension of particle sizes in calculation (Rodin *et al.*, 1999). The method is based on the assumption that the essential information on ice crystals population in clouds can be derived from a limited set of lower moments of their size distribution, and the values of these moments may be determined in a self-consistent fashion.

The method of moments:

The moment technique implements a spectral approach to the continuity equation solution that describes the evolution of aerosol particles in large-scale, non-convective clouds. The first practical implication of the moment approach in the hybrid semispectral scheme has been provided by Feingold *et al.* (1980). Each moment of order k is defined as $M_k(\mathbf{x}) = n(\mathbf{x})\int_0^\infty f(r) r^k dr$, where n is number density and f is the size distribution. Individual moments (k = 0-3) may be considered as independent tracers, whose transport is determined by advective and mixing processes common for all tracers, whereas microphysical transformations imply additional sources and sinks. The involved elementary processes are: heterogeneous nucleation on dust particles, condensational growth by direct vapor deposition, sublimation, Brownian coagulation, and sedimentation. The functional forms of the size dependence of some processes are substantially simplified under the condition **Kn**>>1, which applies commonly on Mars. Each ice particle is assumed to have incorporated at least one dust particle as a nucleation core. Owing to the fact that timescales of the microphysical processes in Martian clouds are typically of the order 10^3-10^5 s, i.e. shorter than the dynamical timescale of the general circulation, one could expect these processes to achieve adjustment to a dynamical state of the atmosphere. Therefore, due to distinct timescale separation, the sources applied to particular moments associated with microphysical processes may be formulated by means of the time splitting technique, implying separate time substeps for dynamical terms and microphysical transformations. A limited set of tracers, each characterizing particular moment of the size distribution of ice crystals associated with mineral nucleation core of a given size, have been treated in the GCM to simulate both dust and cloud aerosols. Simulations show that the relationships between different moments, which imply self-consistent size distribution, quickly reach a steady state maintaining balance between inbound and outbound fluxes. It should be noted that this adjusted steady state could be reached far from the equilibrium.

Independent tests of the moment method against traditional gridpoint microphysical schemes and Monte-Carlo simulations, which have been carried out in the framework of 0D and 1D atmospheric models (Rodin, 2002, 2003) show that its relative error, reaching about 30% in worst cases, is of the same order or less than the intrinsic error of the control runs. Fig. 1 presents some examples of equilibrated vertical profiles of ice particles size distribution moments, controlled by condensational growth. In turn the comparison of coagulation process simulation by means of the moment and Monte-Carlo methods (Fig. 2) shows that the accuracy of the first is high within some interval until the breakdown, which duration depends on particular distribution. The moment method loses accuracy when the dynamical range of the particle sizes involved in the microphysical processes differ more than 10^2-10^3, which may happen if large particles were not removed by sedimentation. In that cases it is anticipated that several size categories of condensational aerosols be considered, with each category fitting into acceptable range of sizes.

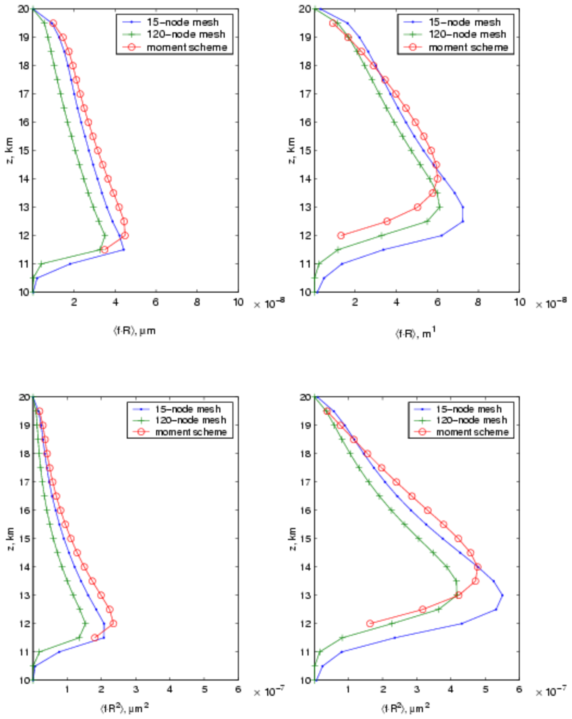


Figure 1. The comparison of relaxed vertical profiles of size distribution moments calculated from the 1D model with size-resolving scheme of various resolution (blue and green curves) and directly by the method of moments (red curve). Eddy mixing is $10^6 cm^2 \cdot sec^{-1}$ (left column) and $10^7 cm^2 \cdot sec^{-1}$ (right)

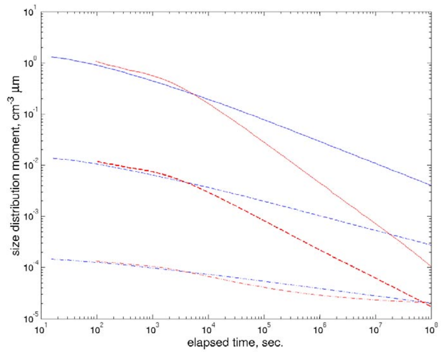


Figure 2. A comparison of a spatially uniform aerosol system evolution by Brownian coagulation, simulated by method of moments (red curves) and in Monte-Carlo experiment (blue curves). Solid line: number density; dashed: first moment (effective radius); dot-dashed: third moment (effective area). Time is scaled by squared density.

Dust and clouds in the MGCM are both treated as radiatively active. The optical properties of ice crystals are based on the second moment of the size distribution, which is proportional to their geometric crossection. Using the interactive estimate of the effective particle size, optical parameters are retrieved from a lookup table built offline and in the assumption of Mie scattering by double-layered particles composed of dusty nucleation core and icy shell.

Simulation of the aphelion cloud belt: The implementation of the cloud microphysics scheme in the MGCM provides simulations of cloud features that are currently observed, and visualization of related dynamical patterns of the general circulation. One of the most spectacular cloud feature on Mars is the prominent tropical cloud belt in the latitude range 10°S-30°N that lasts through the aphelion season from $L_s \approx 60°$ to $L_s \approx 145°$ (Clancy *et al.*, 1996). This coherent tropical cloud system, allegedly maintained by the intense upward motion of the cross-equatorial Hadley cell carrying water vapor from the subliming North polar cap, reveals a wave 2 zonal structure and significant local variations due to the influence of major Tharsis volcanoes (Smith *et al.*, 2000). Simulations of the aphelion cloud belt with the MGCM with moment-based microphysical scheme shown in Fig. 3, demonstrate surprisingly detailed agreement with observations. This indicates that the appearance of clouds on Mars is less sensitive to the details of their microphysics than the underlying dynamical structures. Indeed, the steady state implies a balance between the dynamically determined influx of water vapor to be condensed, and the sedimentary sink, whose bulk intensity is roughly proportional to nr^4. The high stability of particle sizes combines with prominent sensitivity to the number of available nucleation centers. Therefore, the resulting appearance of clouds is more sensitive to the microphysical properties of dust, e.g. number density of small particles, nucleation probability etc., rather than to the details of the cloud microphysics.

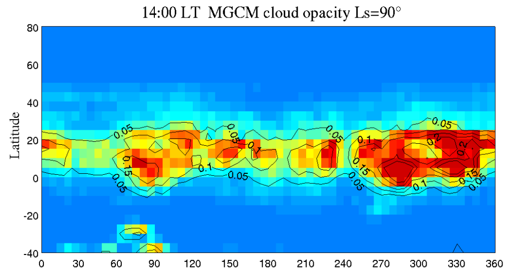


Figure 3. The aphelion cloud belt as simulated by the MGCM. Ls = 90°, fixed local time 2 p.m.

The prominent wave 2 zonal structure of the cloud belt represents a stationary wave generated in the midlatitudes in the aphelion season. One of the counterparts of this wave 2 structure is associated with Tharsis plateau, the region dominated by the divergent near-surface flows that induces intense cloud formation. In contrast with observations, which show localized cloud lids over each major volcano, the MGCM with 5°×6° resolution only represents large-scale features. However, it appears sufficient not only for the global-scale structures like the aphelion cloud belt, but also for mesoscale cloud activity.

Other cloud types:

An example of such evolving cloud feature is shown in upper panel of Fig. 4, corresponding to shortly after the onset of the polar vortex during the Northern fall season. The high regularity of such features revealed in the simulations despite variable microphysical parameters of the model argues that the position, shape, bulk water contents and the visible opacities are determined by external processes, namely the influx of water vapor by the general circulation. Moreover, these features are consistent with recent MOC imagery (James and Cantor, 2002), although they do not match all the details of the observations. Evidently, such circumpolar mesoscale clouds are under strong dynamical control, and given their short lifetime, sedimentation also has minor effect on their shape. For such short-lived clouds, the MGCM suggests the microphysical processes provide rapid adjustment to the evolving thermodynamical conditions. In the case where water vapor influx is not dramatically strong, the moment relationships generated by the model are consistent with a narrow size distribution with mean particle radius of about 2 μm. A similar size distribution is indicated for optically thin clouds that appear north of the tropical cloud belt at the end of the aphelion season (see Fig. 4a). By contrast, due to the high influx of supersaturated water vapor by the Hadley cell circulation, estimates of size distribution in the aphelion cloud belt suggest ice particles with radii of 3-4 μm. Such a distinction is presumably a result of the very strong (by orders of magnitudes) difference between the water supply regimes in these cloud systems, damped by the forth-power dependence of the sedimentary sink on particle size.

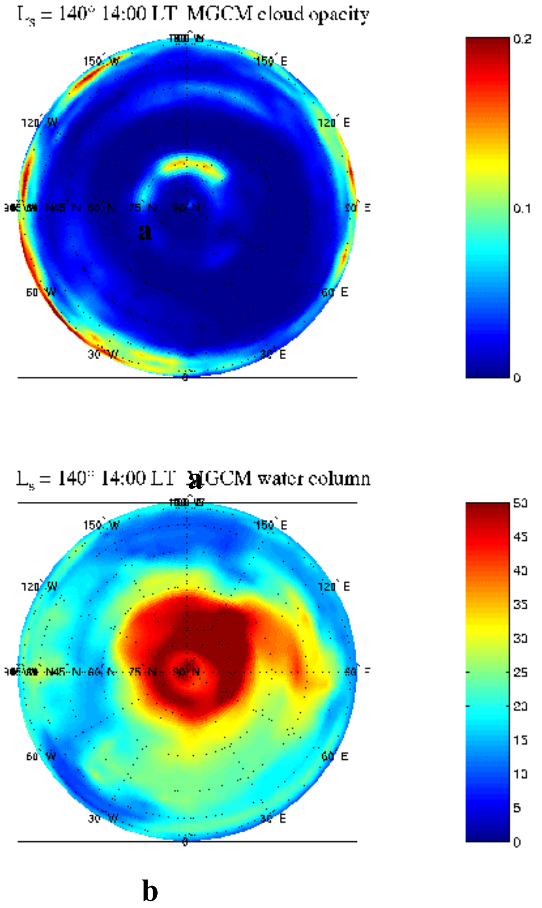
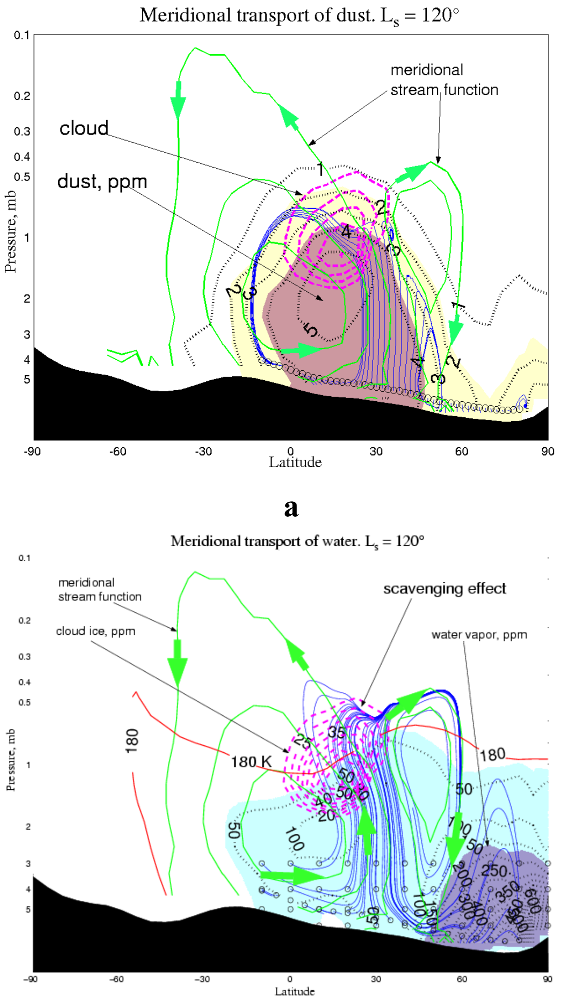


Figure 4. Polar projection of cloud opacity (a) and water vapor column in precipitable microns (b) in the late aphelion season at L_s = 140° suggest significant impact of planetary-scale atmospheric waves on the Martian water cycle.

Implication for dust and water cycles:

A significant aspect of the climate impact of water ice clouds on Mars is scavenging of dust, as well as water, from supersaturated regions, due to increased sedimentation rates. The comprehensive study of the dust and water cycles remains a principal motivation for the development of the microphysical scheme for water ice clouds and its implementation in the MGCM. Simulations of the current Martian climate with the coupled microphysical model suggests that the impact of clouds on both transport cycles mainly consists of sealing off the Southern hemisphere across the Hadley cell upper branch by the tropical cloud belt in the aphelion season, consistent with the conclusion of Clancy *et al.* (1996). Figure 5 (a,b) demonstrates the streamline analysis of dust and water transport affected by the cloud scavenging effect. A depression of meridional flow, coinciding with the level of clouds, is a signature of the enhanced sedimentation, which in the case of dust, results in confinement of the streamlines below 1 mbar and North to equator. For water transport, the effect is more dramatic: the depression at the cloud level redirect the meridional water flow into the polar branch of the Hadley cell, effectively preventing cross-equatorial transport of water. The apparent contrast from the perihelion season implies that the aphelion cloud system is a significant component of the Martian water cycle (Clancy *et al.*, 1996). However, the exact contribution of this mechanism is hard to examine on short time scales, since it has the same impact as the prominent cross-equatorial topographic slope noted by Richardson and Wilson (2002). The moment scheme provides a crucial parameter related to dust and water cycles – sedimentation flux – self-consistently with basic thermal and dynamical state of the model. Richardson *et al* (2002)



a

b

Figure 5. Streamline plots of the meridional transport of dust (a) and water (b) in the aphelion season. Clouds are shown by pink dashed contour; all densities are given in ppm.

implemented a more simplistic bulk-continuity cloud scheme with a fixed sedimentation rate and arrived at a reasonable simulation of the annual cloud and water cycle. It is anticipated that for cases using a prescribed climatology, the microphysical scheme may be further simplified without substantial loss of accuracy.

There is evidence for a significant impact of complex dynamical phenomena, e.g. planetary-scale wave activity, on the transport cycles, as illustrated by the zonal distribution of water column in Fig. 4(b). Taking into account the lack of direct measurement of the atmospheric motion on Mars, microphysical models coupled with MGCM become a valuable diagnostic tool, employing cloud structures for visualization of underlying dynamical patterns by comparison of model output with observations.

Conclusions:

The implementation of the moment-based microphysical model of water ice clouds in the MGCM demonstrates the practical reliability of simplified non-parameterized *ab initio* schemes. The strong dynamical control over the shape and water contents of clouds suggests the limited relevance of the details of microphysical processes for the large-scale water ice clouds in the Martian atmosphere. A range of microphysical schemes of various degree of complexity may be employed in the framework of MGCMs to study different aspects of clouds, from quantitative comparison with observations to long-term climate simulations. Increasing complexity of adopted cloud scheme implies increasingly strict requirements to the accuracy of other blocks of the model, in particular, surface boundary conditions participating in dust and water cycles.

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