Revisiting the radiative impact of dust on Mars using the LMD Global Climate Model

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[1] Airborne dust is the main driver of Martian atmospheric temperature, and accurately accounting for its radiative effect in Global Climate Models (GCMs) is essential. This requires the modeling of the dust distribution and radiative properties, and when trying to simulate the true climate variability, the use of the observed dust column opacity to guide the model. A recurrent problem has been the inability of Mars GCMs to predict realistic temperatures while using both the observed dust radiative properties and column opacity. One would have to drive the model with a tuned opacity to reach an agreement with the observations, thereby losing its self-consistency. In this paper, we show that using the most recently derived dust radiative properties in the LMD (Laboratoire de Météorologie Dynamique) GCM solves this problem, which was mainly due to the underestimation of the dust single scattering albedo in the solar domain. However, an overall warm temperature bias remains above the 1 hPa pressure level. We therefore refine the model by implementing a "semi-interactive" dust transport scheme which is coupled to the radiative transfer calculations. This scheme allows a better representation of the dust layer depth in the model and thereby removes the remaining warm bias. The LMD/GCM is now able to predict accurate temperatures without any tuning of the dust opacity used to guide the model. Remaining discrepancies are discussed, and seem to be primarily due to the neglect of the radiative effect of water-ice clouds, and secondarily to persisting uncertainties in the dust spatial distribution.

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1. Introduction

[2] About 40 years ago, *Gierasch and Goody* [1972] demonstrated that the thermal structure of the Martian atmosphere cannot be accounted for by a purely gaseous CO_2 atmosphere, without the contribution of atmospheric dust. Dust is, indeed, the main driver of the Martian climate, and its radiative properties (extinction efficiency Q_{ext}, single scattering albedo ω_0 and asymmetry parameter g) have to be known in detail to accurately predict the heating rates and temperatures in a Mars Global Climate Model (GCM).

[3] The most appropriate way to simulate the details of the present climate is to drive the GCM with observation-derived dust opacities. However, it has been difficult in the past to obtain realistic temperatures by using the observed dust column opacity. The latter had to be tuned to reach reasonable temperatures, raising some doubts on either GCMs or dust radiative properties used to compute the heating rates.

[4] The dust radiative properties are difficult to retrieve, and are associated with many uncertainties to which GCMs are extremely sensitive. Heating rates are proportional to $(1 - \omega_0)$ in the optically thin limit, and an uncertainty of 5% for a single scattering albedo ω_0 of about 0.9 in the solar domain corresponds to an error on the heating rate of about 50% [*Forget et al.*, 1999]. The asymmetry factor g is also essential, because a decrease in g at solar wavelengths corresponds to a increase in backscattering and hence in the amount of sunlight deposited within the atmosphere [*Pollack et al.*, 1995]. Moreover, the same decrease in g reduces the amount of solar radiation that reaches the surface and impacts on the surface temperature and greenhouse effect [*Wilson and Smith*, 2006].

[5] Thanks to the numerous new missions of the last decade, many improvements have been made in our knowledge of dust radiative properties, ultimately leading to the retrieval of the fundamental refractive index, both in the visible and infrared regions [*Wolff et al.*, 2006, 2009]. This allows us to compute the single scattering parameters for dust particles of different sizes, which is essential to fully account for their effect on GCM temperatures. The goal of this paper is to find the best way to use this new data set, in order to create a self-consistent climate model, i.e. a model in

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Table 1. Main Characteristics of the Three GCM Experiments

Simulation	Dust Single Scattering Properties: Data Set	Spatial Variation	Computation Method	Opacity Profiles[a]
1	Single scattering parameters of *Ockert-Bell et al.* [1997] and *Forget* [1998]	Spatially constant	Direct merging of the two data sets using $\tau_{0.67\mu m}/\tau_{9\mu m} = 2$	Analytical function Modified Conrath profile
2	Refractive index $m = n + ik$ of *Wolff et al.* [2006, 2009]	Spatially constant	T-Matrix generated using m Gamma dist.,[b] $r_{eff} = 1.5$ μm, $\nu_{eff} = 0.3$	Analytical function Modified Conrath profile
3	Refractive index $m = n + ik$ of *Wolff et al.* [2006, 2009]	Space-varying properties based on predicted sizes	T-Matrix generated using m Log-normal dist.,[b] variable r_{eff}, $\nu_{eff} = 0.3$	Model predicted Two-moment scheme

[a]Opacity profiles are always linearly scaled to match the column dust opacity measured by TES.
[b]Randomly oriented oblate cylinder with an axial ratio of 1.

which temperatures and dust opacities are both consistent with observations.

[6] For this, the following questions will be addressed:

[7] 1. What are the effects of the new dust radiative properties on the LMD/GCM?

[8] 2. What is the impact of the dust layer properties (thickness and particle sizes) on the simulated temperatures?

[9] 3. What can we learn from radiatively active dust experiments about the spatial distribution and size of the dust particles?

[10] To answer these questions, we make extensive use of the TES (Thermal Emission Spectrometer onboard Mars Global Surveyor) measurements to constrain our model, as well as to compare the simulated temperatures with the retrieved profiles. TES is a thermal infrared spectrometer (5.8–50 μm) which also includes two broadband visible/near-IR (0.3–2.9 μm) and thermal (5.1–150 μm) channels [*Christensen et al.*, 2001]. We use in this paper the retrievals of atmospheric temperature (using the 15 μm CO_2 band), dust column opacity (9.3 μm) and water-ice cloud column opacity (12.1 μm), which are described by *Conrath et al.* [2000], *Smith et al.* [2000] and *Pearl et al.* [2001], respectively. The MGS mapping mission covers Mars Years 24–27. Martian years are defined by *Clancy et al.* [2000], and the first Martian year begins on April 11, 1955.

[11] Three simulations are carried out, and the corresponding model configurations are described in section 2. Temperatures predicted by the LMD/GCM when using the dust radiative properties of *Ockert-Bell et al.* [1997] and *Forget* [1998] on the one hand, and the more recent optical indices of *Wolff et al.* [2006, 2009] on the other, are analyzed in section 3 and compared to the TES temperature measurements [*Smith*, 2004]. These two simulations are later referred to as case 1 and case 2 simulations. The GCM radiative scheme is then connected to a dust transport model, which computes the dust spatial distribution and particle size. The predicted spatial distribution is used to compute the 3D opacity field, and each opacity profile is then multiplied by a constant to match the dust column opacity observed by TES [*Smith*, 2004]. The particle sizes are also used to compute spatially and temporally variable radiative properties. This simulation is referred to as case 3 simulation, and is analyzed in section 4. Both Martian years 25 and 26 are simulated, to evaluate the model under the relatively clear conditions of MY26, and the dusty conditions of MY25, during which the 2001 global dust storm occurred. It is worth noting that MY25 and MY26 are actually quite similar for the bulk of the annual cycle, with major differences occurring between $L_s = 180°$ and $L_s = 260°$. The radiative effect of water-ice clouds is not included in the model to focus on dust alone, and will be the subject of another article in the near future.

2. Modeling Approach

[12] The three simulations described in this paper are summarized in Table 1. They have a resolution of 5.625 × 3.75° in the horizontal, and 25 levels in the vertical, from the ground to ~100 km. The two first simulations use a modified Conrath profile (see the next section and equation (2) for further details) to describe the vertical distribution of dust (as was the case in the work of *Forget et al.* [1999]) and spatially uniform radiative properties. The last simulation uses interactive dust profiles and varying radiative properties, based on a dust transport model which predicts the shape of the dust vertical profile and the size of the dust particles. Each of the three simulations is further described below.

2.1. Ockert-Bell et al. Model (Case 1 Simulation)

[13] The dust layer is characterized by the amount and spatial distribution of dust, as well as the radiative properties of the dust particles. The amount of dust in the atmosphere is indirectly given by its dust optical depth:

$$d\tau_\lambda = \frac{3}{4}\frac{Q_{ext,\lambda}\, q}{\rho_p r_{eff}\, g}\, dp, \tag{1}$$

where Q_{ext} is the dust extinction efficiency, q the mass mixing ratio, ρ_p the dust particle density (2500 kg m^{-3}), and r_{eff} the effective radius. In the case 1 and case 2 simulations, we assume a homogeneous size and extinction efficiency of the dust particles. Consequently, the opacity in each layer is directly proportional to the amount of dust q and the pressure differential dp. Since dust is not carried explicitly by the model in these simulations, a modified Conrath vertical profile is assumed [*Conrath*, 1975; *Forget et al.*, 1999], and the dust opacity differential obeys the relation:

$$d\tau_\lambda(p) \propto dp \exp\left\{0.007\left[1 - \left(\frac{p_{ref}}{p}\right)^{70/z_{max}}\right]\right\}, \tag{2}$$

where $p < p_{ref}$, with p_{ref} the reference pressure (6.1 hPa). When the atmospheric pressure p is larger than p_{ref}, the dust opacity is assumed constant. The dust layer depth z_{max} is given by an analytical function that fits the measurements of z_{max} achieved by *Jaquin et al.* [1986] (see *Montmessin et al.* [2004, section 2.1] for further information). The variation of this function at the equator is represented in Figure 5c (black sinusoid). The variations in z_{max} are identical from one Martian year to another, and cannot capture the interannual variability of the dust layer thickness. The opacity profile given by equation (2) is then linearly scaled so that the dust column opacity in the model matches the observed TES column opacity at 9.3 μm (see Figure 5b and *Smith* [2004]). It is worth remembering that TES column opacity is an absorption opacity, and it has to be converted to an extinction opacity, which is the opacity actually needed by the GCM. As discussed in detail by *Wolff and Clancy* [2003, section 7.2.1], this conversion can be done without large error using a factor of 1.3, assuming the canonical $r_{eff,dust}$ = 1.5 μm (see section 2.2 and *Wolff et al.* [2009]). Consequently, τ_{GCM} (9.3 μm) = τ_{TES} (9.3 μm) × 1.3, and the GCM is constrained by the observed and untuned dust column opacity. This is true for all the simulations presented in this paper.

[14] Once the opacity in each layer is known, the model needs the dust single scattering parameters, which will be used by the radiative transfer scheme. The radiative transfer codes at solar wavelengths and outside the 15 μm CO_2 band are both based on the two stream algorithm of *Toon et al.* [1989]. Their channels include two solar bands (0.1–0.5 μm and 0.5–5 μm), the silicate band (5–11.5 μm), and the rest of the IR domain (20–200 μm). The net exchange formulation [*Dufresne et al.*, 2005] is used in the 15 μm CO_2 band (11.5–20 μm), where dust scattering is neglected [*Forget et al.*, 1999, section 4.2.2]. In this band, only absorption by dust is taken into account, and added to that of CO_2 by using $Q_{abs} = Q_{ext} (1 - \omega_0)$ [*Forget et al.*, 1999; *Wolff and Clancy*, 2003].

[15] Providing dust radiative properties covering the entire solar and thermal infrared spectral range for climate modeling required long-term efforts. Several data sets have been available since Mariner 9 in 1972. The first general circulation models including a comprehensive radiative transfer model [*Pollack et al.*, 1990; *Haberle et al.*, 1993, 1997, 1999; *Hourdin et al.*, 1993, 1995; *Wilson and Hamilton*, 1996] used solar spectrum averaged single scattering properties derived from Viking lander studies by *Pollack et al.* [1979] at solar wavelength and from Mariner 9 IRIS observations by *Toon et al.* [1977]. This dust was relatively "dark" (solar averaged single-scattering albedo and asymmetry parameter were 0.86 and 0.79, respectively) and yielded warm atmospheric temperatures.

[16] After the late 1990s, a second generation of models [*Forget et al.*, 1999; *Hartogh et al.*, 2005; *Takahashi et al.*, 2006] used the improved data set achieved by *Ockert-Bell et al.* [1997] in the solar range, and by *Forget* [1998] in the infrared range. It is this data set which is used in the case 1 simulation, and referred to as the Ockert-Bell et al. data set.

[17] *Ockert-Bell et al.* [1997] extended Viking Lander data corrected by *Pollack et al.* [1995] to all solar wavelengths (0.2–4.2 μm), by using different spectra of bright surfaces under low dust conditions, acquired by the Orbiting Astronomical Observatory in the UV [*Wallace et al.*, 1972] and by Phobos-2 ISM and earth-based telescopes in the visible and near-infrared range [*Mustard and Bell*, 1994]. The infrared data set (5–50 μm) was built on the work by *Toon et al.* [1977], who fitted IRIS/Mariner 9 spectra by using a sample of clay called Montmorillonite 219b. This data set was adapted for GCMs by *Forget* [1998], who removed the 20 μm absorptions of this mineral which are not observed on Mars.

[18] These first properties thus merge information from different instruments looking at different locations and times in the solar and thermal domains. Consequently, the dust particle size distributions (which control the balance between dust absorption at solar wavelengths and emission in the infrared region) are different from one observation to another, and thus different for the two domains. Consequently, the ratio of the extinction efficiency (and thus opacity) in the visible to the one in the infrared (later called the "solar over infrared ratio") is specified to correct for this bias and merge both data sets. Here, we use $Q_{ext,GCM}$(0.67 μm)/$Q_{ext,GCM}$(9 μm) = 2 [*Forget*, 1998; *Toigo and Richardson*, 2000]. The resulting single scattering parameters are shown in Figure 1 (grey line), and the corresponding values in the five channels of the GCM are reported in Table 2. These properties are assumed constant in space and time.

[19] It is worth adding that in the time between the retrieval of the aforementioned radiative properties and the second unified data set of *Wolff et al.* [2006, 2009], different values have been adopted for use in climate models. The measurements of *Clancy and Lee* [1991] have been used in many GCMs [*Forget et al.*, 1999; *Montabone et al.*, 2006; *Richardson et al.*, 2002; *Basu et al.*, 2004, 2006], but with caution due to the unusually low value of the asymmetry factor *g*. More recently, *Hinson and Wilson* [2004], *Wilson et al.* [2007], and *Wilson et al.* [2008a] have used ω_0 = 0.92 and *g* = 0.75 in the GFDL model, and the IR properties derived by *Wolff and Clancy* [2003].

2.2. Wolff et al. Model (Case 2 Simulation)

[20] The second unified data set comes from MGS (Mars Global Surveyor) and MRO (Mars Reconnaissance Orbiter) overflights of the MERs (Martian Exploration Rovers), which enabled the simultaneous observation of dust both from the surface and from space by instruments having similar spectral windows.

[21] *Wolff et al.* [2006, 2009] combined the "best parts" of each data set in order to effectively isolate the average scattering properties of the suspended dust particles. More specifically, using the total column optical depth and surface reflectance properties from MER with the multiangle, multispectral MGS (TES) and MRO (CRISM) observations, they constructed a self-consistent retrieval algorithm which returned the single scattering albedo and associated refractive indices. At the same time, the combined analyses minimized the typical model uncertainties generally encountered in atmospheric remote sensing analyses, i.e., surface reflectance/emission properties, consistent aerosol scattering with respect to wavelength and particle size, etc. Ultimately, the MER-MGS analyses constrain the 7.5–30 μm region while that for MER-MRO cover 0.26–3 μm. *Wolff et al.* [2009] extend this latter coverage to 4 μm through the MEX-OMEGA observations of *Määttänen et al.* [2009].

[22] The resulting refractive indices are used to compute the single scattering parameters of the dust population, which is described by a Gamma size distribution of effective