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Key Points:

- Dust field is reconstructed from its thermal signature only
- Inclusion of detached dust layers in model produces better temperature
- Dust improves Martian temperature data assimilation

Correspondence to:

T. Navarro,
Thomas.Navarro@lmd.jussieu.fr

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Detection of detached dust layers in the Martian atmosphere from their thermal signature using assimilation

T. Navarro¹, F. Forget¹, E. Millour¹, and S. J. Greybush²

¹Laboratoire de Météorologie Dynamique, CNRS/UPMC/IPSL, Paris, France, ²Department of Meteorology, Pennsylvania State University, University Park, Pennsylvania, USA

Abstract Airborne dust modifies the thermal structure of the Martian atmosphere. The Mars Climate Sounder (MCS) first revealed local maxima of dust mass mixing ratio detached from the surface, not reproduced by global climate models (GCM). In this paper, the thermal signature of such detached layers is detected using data assimilation, an optimal combination of a GCM and observations. As dust influences the atmospheric temperatures, MCS temperature profiles are used to estimate the amount of dust in the atmosphere. Data assimilation of only MCS temperature information reproduces detached dust layers, independently confirming MCS's direct observations of dust. The resulting analyzed state has a smaller bias than an assimilation that does not estimate dust. This makes it a promising technique for Martian data assimilation, which is intended to support weather forecasting and weather research on Mars.

1. Introduction

Airborne dust is a major forcing of the Martian atmosphere [Gierasch and Goody, 1972], and modeling its spatial distribution and its temporal evolution is a challenge for Mars global climate models (MGCM). The vertical dust distribution long has been assumed to be the result of a balance between large-scale motions and sedimentation [Conrath, 1975]; however, the observations of dust by the Mars Climate Sounder (MCS) [McCleese et al., 2007] have revealed unexpected detached layers of dust [McCleese et al., 2010; Heavens et al., 2011a] above the planetary boundary layer and up to 40 km. This seems incompatible with the previous assumptions of Conrath [1975]. Detached dust layers have been confirmed by the Thermal Emission Spectrometer (TES) [Guzewich et al., 2013a] and the Compact Reconnaissance Imaging Spectrometer [Smith et al., 2013]. Heavens et al. [2011b] give a list of possible physical processes that could fully account for the existence of these detached dust layers. Among them, Rafkin [2012] tried to explain their existence by upslope topographic winds, their source being located on significant topography variations such as volcanos [Rafkin et al., 2002]. Using a mesoscale atmospheric model, Spiga et al. [2013] showed how the radiative heating of dust in the solar wavelengths in local and regional dust storms could produce a convective motion that rapidly transports dust vertically, thus forming detached dust layers. Navarro et al. [2014], using a MGCM, showed that scavenging of dust by water ice clouds cannot account for the existence of detached dust layers.

The modeling of dust in MGCM traditionally used an idealized analytical function for the dust vertical profile based on "Conrath" assumptions [e.g., Forget et al., 1999]. More recently, free-evolving dust schemes have been used on the same assumptions [Madeleine et al., 2011; Kahre et al., 2006] without being able to reproduce detached dust layers. Guzewich et al. [2013b] forced the dust distribution of a MGCM to the one observed in order to assess its impact on temperature. However, the inclusion of detached layers in a global atmospheric model as a self-consistent and predicted phenomenon remains unachieved.

Another way to include a given dust distribution in a MGCM is by the use of assimilation. The goal of data assimilation is the reconstruction of the whole state of the atmosphere at a given time, and the lessons learned in the process in improving Martian data assimilation and its end product are of great value for weather research and forecasting on the red planet. In this paper we tackle the issue of dust distribution in a MGCM with the use of an assimilation framework, by assimilating only atmospheric temperature profiles of MCS during a regional dust storm into the Laboratoire de Météorologie Dynamique (LMD) MGCM with an ensemble Kalman filter (EnKF). By doing so, we estimate the airborne dust amount without any prescription on its column opacity or vertical shape, by taking advantage of the ability of the LMD MGCM to transport dust as a free-evolving tracer [Madeleine et al., 2011]. Other studies have assimilated temperature or dust

(see section 5), but none so far has tackled the issue of reconstructing dust from temperature alone and without the “Conrath” assumption on the dust vertical distribution.

Section 2 introduces the MGCM, the assimilation method, and the observations used in this study. Section 3 gives details about the assimilation setup and explains how dust can be dynamically estimated from temperature in an ensemble data assimilation. Section 4 shows results and how the assimilation can be improved using 4-D estimation of dust. Section 5 puts these results in the broader context of Martian assimilation. Section 6 gives concluding remarks and implications for future efforts of Martian assimilation.

2. Methods

2.1. MCS

The MCS is an atmospheric sounder [McCleese *et al.*, 2007] on board the Mars Reconnaissance Orbiter (MRO) that uses nine channel in the infrared bands, with 21 detectors for each channel. It performs limb observations at roughly 3 P.M. and 3 A.M. local time, given the Sun-synchronous orbit of MRO. Retrievals of MCS are profiles of pressure, temperature, and dust and water ice opacity [Kleinböhl *et al.*, 2009], taking into account aerosol scattering [Kleinböhl *et al.*, 2011] with estimated associated errors for each retrieved quantity. The ability to retrieve vertical profiles of dust revealed the presence of unsuspected maxima of dust [Heavens *et al.*, 2011a, 2011b] at altitudes from 15 to 40 km.

2.2. MGCM

The MGCM used in this study is the Laboratoire de Météorologie Dynamique (LMD) MGCM, a finite-difference model on a latitude-longitude grid [Forget *et al.*, 1999], the resolution employed for this study being 3.75° in latitude and 5.625° in longitude. It includes the sublimation-condensation cycle of CO_2 and the radiative effects of CO_2 gas and two aerosols: dust and water ice [Madeleine *et al.*, 2011, 2012; Navarro *et al.*, 2014]. The radiatively active airborne dust is dynamically advected, and a two-moment scheme is used [Madeleine *et al.*, 2011]: both mass mixing ratio (in kg/kg of air) and the number of particles (per kg of air) are transported as tracers in the MGCM, accounting for space and time variation of dust particle-size distribution.

2.3. Local Ensemble Transform Kalman Filter

The local ensemble transform Kalman filter (LETKF) [Hunt *et al.*, 2007] is an EnKF [Evensen, 1994] with efficient formulation for parallel computing. In particular, it has been used for the assimilation of the Thermal Emission Spectrometer (TES) data with a MGCM [Greybush *et al.*, 2012], and is used for this study. As an ensemble Kalman filter, the LETKF estimates both the mean and covariance of the atmospheric state vectors (which are composed of selected variables on the grid of the model for a MGCM simulation, e.g., temperature or winds) from an ensemble of MGCM simulations. In other words, 20 simulations with slightly different initial states (and in particular different dust loadings) are run in parallel. This notably provides information on the relationship between dust loading and temperature at a given location and time. During an assimilation cycle over a time window, the background mean state and covariance of the MGCM are compared to the instrumental observations and error, respectively, to compute an analyzed mean state and covariance. This analysis serves as new initial condition for the MGCM integration, and the output of this simulation is the background state for the next assimilation window. Because of the strong diurnal cycle on Mars, we use here the 4-D LETKF, where the background is compared to the observations as if it were the exact same time throughout the assimilation window.

The analysis state can be expressed as a local linear combination of the members. It is constructed based on the local correlations in the background error covariance matrix, making possible the extrapolation of information given by an observation in space, time, and to other state variables that are not observed (e.g., winds and dust). See Hunt *et al.* [2007] for more details about the LETKF, its algorithm, and implementation.

In this study, the assimilation window is 6 Martian hours long (3699 s), and the analysis is produced using background data 3 Martian hours before and 3 Martian hours after the time of the analysis, as in Greybush *et al.* [2012]. An adaptive inflation [Miyoshi, 2011] is used with a prior inflation variance of 0.05^2 , which account for model deficiencies and ensemble finite size.

The influence of an observation is limited in space: we use a vertical localization of $0.2 \ln(p)$ and an horizontal localization of 600 km, with a cut-off at 900 km. MCS data below an altitude of 11 km (corresponding to a pressure of 100 to 300 Pa) are not assimilated, as there is a systematic difference between model and

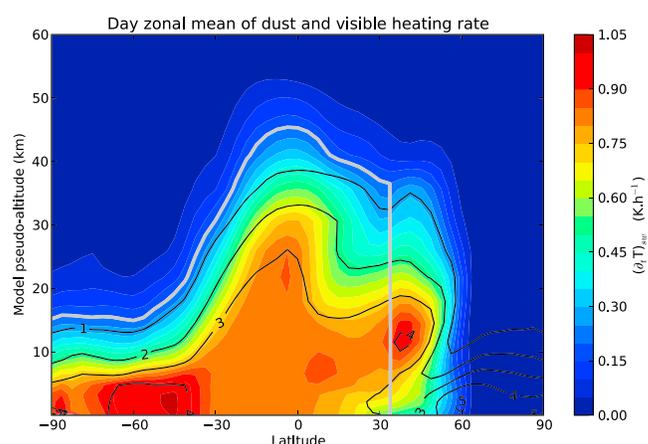


Figure 1. Example of a dayside zonal mean of dust mass mixing ratio (black contoured, ppm) and heating rate in the visible band (colors, K h^{-1}) at the beginning of the assimilation at $L_s = 300^\circ$. The criterion for temperature observations to be considered for dust update in the analysis is illustrated with the region below the gray thick line.

observations near the surface. This bias close to the surface is due to the widening of the $15 \mu\text{m CO}_2$ band, which impacts on the retrieval algorithm given the bandpass of the MCS channels [see Kleinböhl et al., 2009]. Also, there is a bias between MCS and MGCM surface temperature that affects the planetary boundary layer, which mostly comes from the position of the seasonal CO_2 and H_2O ice caps and surface properties that are not fully accounted for in the MGCM (uniformity of thermal inertia inside a mesh, varying albedo of ice, subsurface properties, etc.). On the whole, this discrepancy is out of the scope of the present study.

3. Setup

The MCS temperature profiles are assimilated with the LMD MGCM using the

LETKF framework from solar longitude (L_s) = 300° to $L_s = 330^\circ$ (Martian solar days (= 24.6 h) (sols) 562 to 613) of Martian Year (MY) 29. Two different runs are performed

1. An assimilation named the *dust predicted by GCM* case, in which the atmospheric state vector contains the atmospheric temperature, the latitudinal and meridional components of the wind, surface pressure, but not the dust field.
2. A similar case, named the *dust retrieved from temperature* case, with the exception that the mass mixing ratio of dust is also added in the atmospheric state vector.

In addition to these, a free run is performed, in which no data is assimilated to serve as a baseline for comparing the performance of each case. For the sake of simplicity, the radiative effects of clouds [Madeleine et al., 2012] are not taken into account in the MGCM. Even if there is a minimum of water ice opacity at this season, clouds are present in the middle atmosphere [McCleese et al., 2010] with infrared heating and cooling comparable to the visible heating of dust [Heavens et al., 2010]. The initial states were obtained from the same climatological state at $L_s = 270^\circ$ and integrated over 1 month for 20 different uniform dust opacities ranging from 0.05 to 3 (geometric spread).

3.1. Dust Predicted by GCM

In the dust predicted by GCM case, temperature, winds, and surface pressure are corrected in the analysis at each assimilation cycle on the basis of the observations of temperature. Winds and surface pressure, however, are not observed and are modified on the basis of their correlations with temperatures constructed with the ensemble of MGCM simulations over the last assimilation cycle. A source of dust is set on the surface to simulate lifting, and the vertical profile is repeatedly rescaled to match the column-integrated dust optical depth of a predefined dust scenario, as in Madeleine et al. [2011]. In other words, at each grid point of the model, the shape of the dust vertical profile is free to evolve with the physical processes implemented in the MGCM (advection by winds, sedimentation, etc.), but its column-integrated value follows a prescription. This prescription is constructed from various observational data sets [Montabone et al., 2014] and depends on latitude, altitude, and time, with a resolution of 5° by 5° every sol, for 8 years, from MY24 to MY31.

3.2. Dust Retrieved From Temperature

In the dust retrieved from temperature case, dust amount is modified in the analysis using its correlation with temperature, drawn from the ensemble of simulations, as for winds and surface pressure. The dust is neither prescribed nor lifted during the integration of the MGCM. Instead, dust is updated during the analysis steps of the assimilation (every 6 Martian hours), thus creating three-dimensional sources and sinks of dust in the atmosphere to match the aerosol heating implied by the temperature profiles. During the subsequent forecast steps (in between each analysis step), dust can freely evolve in the model; that is,

Table 1. Bias Between Observations and the Mean Background State From the Surface to 0.5 Pa for Different Cases, Interpolated to the Same Location, and Its Error Standard Deviation in Parenthesis in Kelvins

Case	Sols 570 to 579 (No Dust Storm)	Sols 580 to 590 (Regional Dust Storm)
Free run	5.33 (5.11)	8.78 (6.30)
Dust predicted by GCM	1.13 (5.39)	2.67 (6.25)
Dust retrieved from temperature	0.45 (5.42)	1.19 (5.99)

it is advected by the model horizontal winds but not added or removed with explicit parameterized sources and sinks. The typical timescale for the settling of dust is a few tens of sols, a period much longer than the assimilation period of 6 Martian hours. So the major physical process during the MGCM integration is the horizontal transport of dust rather than the vertical one. The upward vertical motion of dust is presumably on the same timescale as horizontal transport but is not implemented in the MGCM. The MCS profiles of temperature play the role of the prescription for dust. At each analysis step, the dust field is modified, using the same ensemble weights of the linear combination used for the temperature. However, dust is only modified where it directly controls the temperature because of its absorptions of solar radiation. A criterion is applied for considering if an observation of temperature is used to update the analysis' dust field. Two empirically defined thresholds are applied (as illustrated in Figure 1)

1. A lower limit of 100 W m^{-2} for the daily-averaged insolation at the top of the atmosphere. This threshold prevents from considering locations where dust solar heating is negligible or where it is not the major source of temperature change. This is especially true for the season considered here, when a strong subsidence resulting in adiabatic warming dominates the northern midlatitudes during northern winter.
2. A lower limit of 0.2 K h^{-1} for the local heating rate in the solar wavelength of the mean background state. Below this threshold, dust is not modified, so that dust is only modified during daytime and at altitudes where it is already present.

Dust opacity is the quantity that controls the local heating rate. As said above, we choose to put the dust mass mixing ratio, which is proportional to the dust opacity, in the state vector. Since dust in the MGCM is represented using both its mass mixing ratio and number of particles, a correction must be applied to the particle number tracer when the mass mixing ratio tracer is updated in the analysis. We choose to not modify the particle radius r , and thus the particle number tracer N is adjusted to match the mass mixing

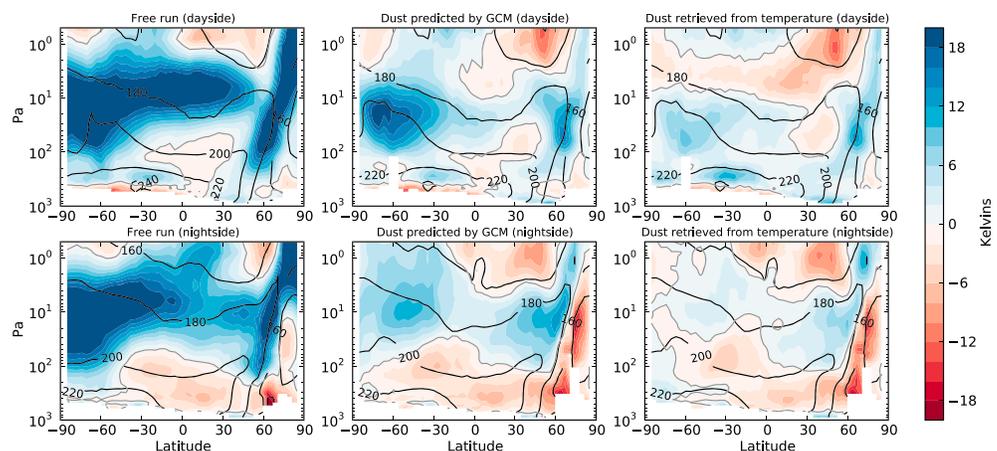


Figure 2. Bias at MY29 for sols 585 to 590 on the (top) dayside and the (bottom) nightside of the orbit, (left) for the free run, (middle) the assimilation with dust predicted by the GCM with a prescribed dust scenario, and (right) the assimilation with dust retrieved from temperature without any prescribed scenario. Blue indicates that the GCM is colder than MCS.

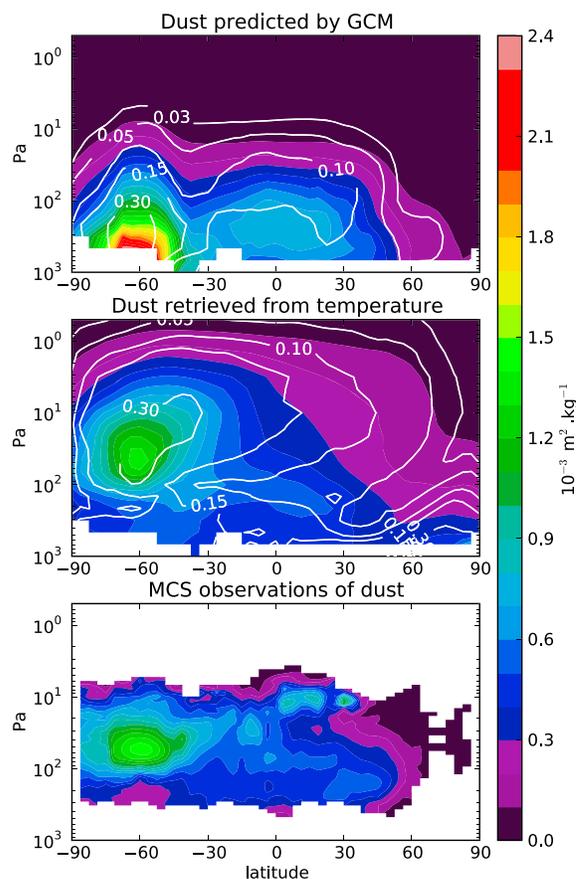


Figure 3. Background density-scaled dust opacity (colors) and its ensemble standard deviation (contours) at MY29 for sols 587 to 590 in the assimilation with a (top) prescribed dust scenario, (middle) retrieved dust, compared to (bottom) nighttime MCS observations.

clearly improved with temperature assimilation in the dust predicted by GCM case. However, a strong cold bias still persists between 100 and 10 Pa in the Southern Hemisphere, by a magnitude of 20 K on the dayside, and 10 K on the nightside. This bias is greatly reduced in the dust retrieved from temperature case, with a maximum of 8 K on the dayside and less than 2 K on the nightside. The strongest biases now lie in the northern polar regions due to a misrepresentation of the polar warming.

The reason why the cold remaining bias between 100 and 10 Pa is improved when using retrieved dust is due to the resulting vertical profile of dust. Figure 3 compares the mean background state of density-scaled opacity of dust in the two assimilations (see *Heavens et al.* [2011a] for the relevance of density-scaled opacity when comparing model and observation). The dust predicted by GCM case exhibits a monotonous decreasing density-scaled opacity with altitude and fails to reproduce the maximum of dust. On the contrary, the dust retrieved from temperature produces a maximum of dust at the location of the cold bias obtained in the dust predicted by GCM case. When compared to the MCS retrievals of density-scaled opacity of dust at the same period, the structure of the dust field in the Southern Hemisphere is in better agreement when assimilation uses a retrieved dust scheme, with a similar amount at the maximum of dust. This proves that this bias has been corrected on the basis of the dust that has been added during the analysis step. Nevertheless, detached, thinner dust layers close to equator and in Northern Hemisphere can be observed by MCS at altitudes between 30 Pa and 10 Pa and are not reproduced by the assimilation, the reason being that their thermal signature is not apparent.

5. Discussion

So far, most of the Martian data assimilation efforts have focused on assimilating the TES data with the use of a nudging scheme [Lewis et al., 2007] or an EnKF [Lee et al., 2011; Greybush et al., 2012]. In all these studies,

ratio tracer q using equation (1):

$$q = \frac{4}{3} \pi r^3 \rho N \quad (1)$$

with ρ the density of dust (2500 kg m⁻³).

4. Detection of Detached Dust Layer

From sols 570 to 579, there is no significant difference between the two cases that assimilate temperature, when comparing observations and model forecast (Table 1). When compared to the free run, assimilation clearly improves the 5.33 K bias. From sols 580 to 595, a regional dust storm occurs in the Southern Hemisphere. The performance of the free run has a higher bias and error standard deviation. When compared to the free run, the error standard deviation of the two assimilation runs is improved as well, the dust retrieved from temperature being best.

In order to have an insight on these global values, Figure 2 shows the difference between observations and model as a function of latitude and altitude during the regional dust storm. Above 100 Pa, the free run exhibits a substantial cold bias of the model. In the northern polar region, the so-called “polar warming,” a purely dynamical feature, is not well represented and also causes a cold bias. The temperature bias is

dust was prescribed, whether by its column opacity [Lewis *et al.*, 1997; Greybush *et al.*, 2012], by its vertical distribution when dust column was assimilated along with temperature [Lewis and Barker, 2005; Montabone *et al.*, 2005, 2006; Lewis *et al.*, 2007] or by radiances [Lee *et al.*, 2011]. Greybush *et al.* [2012] also used dust column opacity as a fixed forcing varying among an ensemble, similarly to ensemble assimilation with different physics of the model [e.g., Houtekamer *et al.*, 2009].

However, Rogberg *et al.* [2010] showed that the lack of a realistic distribution of aerosols in a MGCM is the major cause of error in Martian assimilation, due to imperfections in the modeling of dust. In particular, it concluded that Martian assimilation is “extremely demanding on the accuracy of the model” and suggested to reduce systematic errors in MGCM, and among them aerosol distribution. This work provides the same arguments to underline the importance of a forcing like dust, and that substantial improvement in the overall assimilation can be achieved when accounting for the source of the forcing on temperature, in this case, dust.

The effects of water ice clouds were not considered in this first study because of the minimum of water ice column opacity in the Martian atmosphere during northern winter [Smith, 2004]. The signature of an aerosol on temperature has been implicitly attributed to dust alone, and future assimilations will need to differentiate dust from water ice. Although dust is observed by MCS, it is not used in this study. We have assimilated temperature to estimate dust. One reason for this is that an accurate observation operator still needs to be designed for dust opacity, especially regarding the assumptions made on the dust distribution and radiative properties for the retrieval [Kleinböhl *et al.*, 2011] that can still impact the density-scaled opacity. Another reason is that applying only this technique can improve representation of the dust field, even when dust retrievals are not available. All in all, dust estimation based on temperature observations and correlations among the ensemble gives meaningful information on the dust distribution, which should not be neglected in future assimilations, whether dust observations are assimilated or not. This is especially true as this information is very likely to be independent of dust observations for any instrument, as long as the preferential bands to retrieve temperature and dust measurements are different. For instance, MCS mainly uses its A1, A2, and A3 channels (595 to 665 cm^{-1}) for temperature whereas dust is mostly based on its A5 channel (400 to 500 cm^{-1}).

6. Summary

We have coupled the local ensemble transform Kalman filter with the Laboratoire de Météorologie Dynamique Mars global climate model (MGCM). An assimilation of the temperature retrievals of the Mars Climate Sounder (MCS) during the period from $L_s = 300^\circ$ to $L_s = 330^\circ$ for MY29 was performed with the use of a prescribed dust scenario for the MGCM. An assimilation with dust retrieved from MCS temperature retrievals proved to improve the assimilation during a regional dust storm in the Southern Hemisphere. The reason is that the retrieved dust allows the update of the dust field during the analysis step of the assimilation from temperature observations only, by taking advantage of the correlations among the ensemble of simulations. Thus, the vertical profile of dust is improved, reproducing a maximum in altitude not simulated by a MGCM alone, and the resulting temperature field predicted by the MGCM. From this example over a limited period, this technique is shown to be useful for both improving Martian data assimilation and the understanding of detached dust layers on Mars, including their modeling in MGCM.

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