ON THE DUSTIEST LOCATIONS ON MARS FROM OBSERVATIONS

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Introduction:

Martian mineral dust is radiatively active and mostly absorbs short-wavelength (solar) radiation and, to a lesser extent, long-wavelength (thermal infrared) radiation. The dust cycle is currently considered to be the key process controlling the variability of the Martian climate at inter-annual and seasonal time scales, as well as the weather variability at much shorter time scales. Dust storms are the effect of strong and extended dust lifting by near-surface winds, and the behavior of dust clouds aloft both depends on and impacts the atmospheric circulation.

Therefore, the spatial and temporal distributions of dust aerosol are essential observables for any fundamental or applied study related to the Martian atmosphere, including weather monitoring and forecast for robotic and possible future human exploration missions.

One of the key physical parameters used to quantify the presence and spatial distribution of mineral dust in the atmosphere is the vertically–integrated, or column, optical depth. The column dust optical depth (CDOD) is the retrieval product when the observations are obtained by nadir-viewing instruments, such as the Thermal Emission Spectrometer (TES) aboard the Mars Global Surveyor (MGS) spacecraft or the Thermal Emission Imaging System (THEMIS) aboard the Mars Odyssey spacecraft. Vertical profiles of extinction opacity (or extinction coefficient) can be derived from radiances measured by limb-viewing instruments, such as the Mars Climate Sounder (MCS) aboard the Mars Reconnaissance Orbiter (MRO) spacecraft. Given opportune assumptions and within defined limits, it is also possible to estimate CDODs from the integrated extinction profiles.

Datasets:

Since the Mariner era, there exist several datasets of retrieved CDOD for Mars, spanning more than 20 Martian years. All these datasets are highly heterogeneous as they are retrieved from different instruments observing at different wavelengths and different geometries. Nonetheless, since March 1999 (L_S~104°, MY 24) we have accumulated a nearly uninterrupted series of global dust (as well as temperature and water ice) observations, now approaching the length of a Martian decade –at the time of writing we are in the second half of MY 33. This unique multi-instrumental dataset provides an excellent opportunity for carrying out dynamical studies of the Martian meteorology on one hand, and statistical studies of the Martian climatology on the other hand.

Within the current Martian decade there are three publicly available datasets –those retrieved from TES, THEMIS and MCS observations- that provide or have provided quantitative information on the dust spatial and temporal distributions at planetary scale with good coverage. This information in the horizontal longitude-latitude plane is specifically presented as CDOD values at infrared wavelengths. Another instrument –the Planetary Fourier Spectrometer (PFS) aboard the Mars Express spacecraft- would have the potential to provide an additional key dataset of CDODs, covering multiple local times. Several other datasets are available, but their coverage is less ideal for providing continuous global quantitative information on the dust distribution (e.g. the CDOD datasets retrieved from observations by the Compact Reconnaissance Imager Spectrometer for Mars –CRISM- aboard MRO, the "Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité" –OMEGA- aboard Mars Express, the PanCam cameras aboard the Mars Exploration Rovers, the MastCam camera aboard the Mars Science Laboratory rover, etc.). Finally, qualitative information on the dust distribution can be directly obtained by visible images taken by orbiting cameras such as the Mars Orbiter Camera (MOC/MGS) and the Mars Color Imager (MARCI/MRO).

Montabone et al. [1] used retrieved TES, THEMIS, and estimated MCS IR CDODs to produce gridded daily maps of the 2D dust distribution from L_S~104° in MY 24 through the end of MY 31. More recently, this publicly available gridded dataset has been extended to MY 32 [2], and work is ongoing to include MY 33.

Study of the dust climatology:

This dataset [1, 2] and its extension to more recent Martian years has the key advantage to homogenize otherwise very different observations. Yet, there exist open questions on the effective degree of homogenization, given the intrinsic different nature of CDODs retrieved from nadir-viewing instruments and estimated from limb-viewing geometries. Some of these open questions have been already reported in [1], particularly in relation to the differences near the southern polar cap edges in southern autumn and winter. MCS dust extinction profiles do not always extend to the ground, particularly when high values of dust opacity saturate the retrieval. Therefore, very low altitude dust could be missed by this instrument. This possibility must be taken into account when looking at inter-annual variability in the dust distribution and/or carrying out climatological studies.

In this work we are drawn by a question related to the climatological distribution of atmospheric dust on Mars, i.e.: What are the locations that experience the dustiest skies overall? As much as rainfall can be used to define climate zones on Earth, dust optical depth could give insights into defining possible climate zones on Mars, if statistical analysis can be applied to consistent sets of multi-annual observations.

To answer this question, the first step is to calculate annual mean and standard deviations of CDODs in the [2] dataset –including the available part of MY33- at each grid point. We have also tested the use of other measures of central tendency, such as median and mode. MY 25 and MY 28 include planet-encircling dust storms. It is interesting to observe that the annual means in MCS-covered MY 29, 30, 31 and 32 are very similar, and generally more quiescent than all other years, even those without planet-encircling dust storms (not shown here). Overall, a clear dichotomy appears when comparing years covered by TES and THEMIS observations (MY 24 to MY 27) with those covered by MCS and THEMIS observations (MY 28 through the current MY 33). Such dichotomy can be summarized by the two multi-annual means presented here in Figs. 1 and 2. In particular, Fig. 1 shows the multi-annual mean and standard deviation of MY 24, 25 and 26 (TES-observed years) while Fig. 2 shows the equivalent for MY 28 through 32 (MCS-observed years). We did not include MY 27 in the multi-annual means because it is mostly covered by sparse THEMIS observations, nor we included MY 33, which is not complete yet at the time of writing.

TES years have larger mean and standard deviation values overall (the global mean value is 0.21 while it is 0.14 for MCS years). But the most striking features are the large values of the multi-annual TES mean in both Hellas and Argyre basins, as well as the northern and southern polar regions. According to the TES climatology, these are the overall dustiest locations on Mars, followed by a band of ~20° latitude centered around 45°S as well as by the western Meridiani Planum (Xanthe and Margaritifer Terrae) and the area around Valles Marineris. The above mentioned latitude band is characterized by dust being lifted by southern baroclinic waves during southern autumn and winter, while the western Meridiani Planum area lies within the Acidalia-Chryse storm track. The least dusty places on Mars are the northern mid-high latitudes between 45° and 75°N. These locations are also those that experience the smallest variability, together with a ~15° latitude band centered around 70°S. Locations at several longitudes in the southern "tropical" region (0°<lat<25°) have large variability, but one has to remember that a good part of such variability originates from the large values of CDODs during the MY 25 planet-encircling dust storms, which is included in the multi-annual analysis presented here.

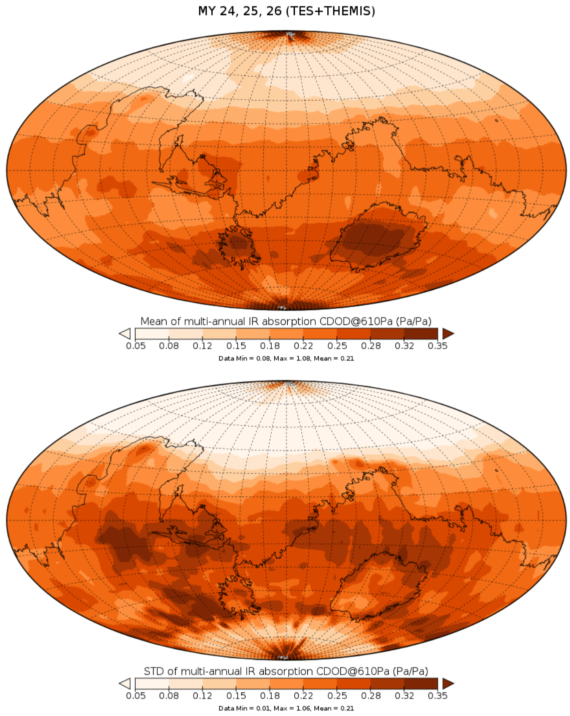

Figure 1: The upper panel shows the grid-point mean of multi-annual (MY 24 through 26) 9µm absorption CDODs normalized to the reference 610 Pa pressure level. The lower panel shows the corresponding grid-point standard deviation of the multi-annual observations. Observations are from TES and THEMIS (only for MY 26). CDOD values are extracted from the [2] dataset, produced as described in [1]. We have filtered the data and used values at a grid point only if the recorded time window is TW=1 sol and the reliability value is cdodrel > 5 (see definitions for these dataset variables in [1], Appendix B). The used map projection is "Aitoff".

Moving to the maps for the years observed by MCS and THEMIS, there is no sign of large values in the Argyre and Hellas basins. Furthermore, generally speaking, the mid-high southern latitudes are among the least dusty locations in contrast to what observed in the map produced with TES/THEMIS data. The map built with MCS data generally agrees with that produced with TES data in the equatorial/tropical regions as well as in the mid-high northern latitudes, except for the northern polar region. In particular, both datasets agree in defining the Xanthe, Margaritifer and Valles Marineris areas as dusty locations. MCS dataset also highlights the Elysium-Terra Tyrrhena-Syrtis Major area as particularly dusty. Note that this area is located in the Utopia storm track.

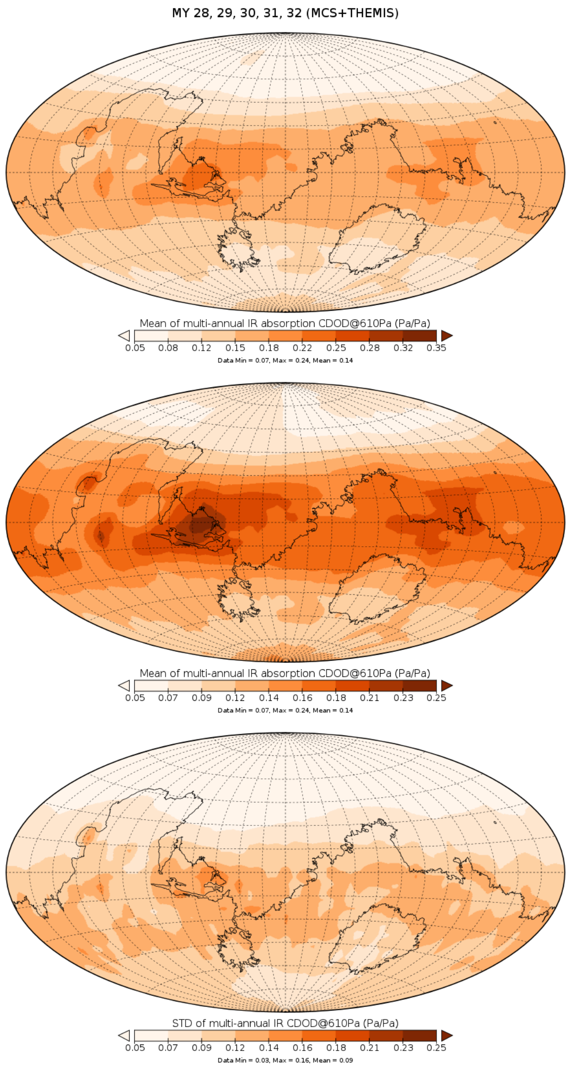

Figure 2: The upper panel shows the grid-point mean of multi-annual (MY 28 through 32) 9µm absorption CDODs normalized to the reference 610 Pa pressure level. The scale range is the same as in Fig. 1. The central panel shows the same variable but using a smaller scale range to make use of the full color table. The lower panel shows the corresponding grid-point standard deviation of the multi-annual observations using the smaller scale range. Observations are from MCS and THEMIS. As in Fig. 1, CDOD values are extracted from the [2] dataset and we have filtered the data using values at a grid point only if the recorded time window is TW=1 sol and the reliability value is cdodrel > 5. The used map projection is “Aitoff”.

Further analysis will involve separating the “largely active dust season” (i.e. 140°<L_S<360° and 0°<L_S<10°) from the “quiescent dust season” (i.e. 10°<L_S<140°) in order to distinguish the southern hemisphere differences between TES and MCS years. Furthermore, analysis of MCS dust extinction opacity profiles at selected locations (e.g. within the Hellas Basin) will provide insights on the reason(s) why they are not seen as dusty as in the TES dataset.

Understanding the differences:

Ultimately, the answer to the aforementioned question can only come from a climatological study using many Martian years of reliable observations and unbiased statistics. Therefore, an important step of this study is to understand whether the significant differences between TES and MCS are a product of inter-annual variability (unlikely) or the effect of biased statistics. If the latter, the causes could be the mentioned vertical cut-off of a significant number of dust extinction profiles, a bias in the distribution of MCS dust observations considered in the gridding of [1], the filtering adopted in the present study, or a combination of these and possibly other causes.

Work is ongoing to specifically compare CDOD values between TES and MCS at the polar cap edge and in the polar regions in general. While MCS is able to provide dust extinction opacities -and therefore estimated CDODs- in the polar regions, publicly available retrieved TES CDOD values are missing in large areas at latitudes where the thermal contrast between the surface and the atmosphere is small (in other words, over cold surfaces). This prevents a precise assessment of the consistency of high CDOD values e.g. at the southern polar cap edge in southern autumn/winter with values at higher latitudes. New retrievals of TES IR observations on cold surfaces are ongoing, using an improved radiative transfer code. Furthermore, retrievals of visible CDOD from TES Emission Phase Function (EPF) observations ([3, 4]) are also ongoing, which should provide an independent validation of the IR CDOD in cold regions. In order to further validate these new TES retrievals, a direct comparison with all available global-scale MOC images is planned. MOC images have been specifically processed and geo-referenced to provide the best testbed for validation.

The MCS team, on the other hand, has future plans to retrieve CDODs from near-nadir observations rather than to estimate them in the current way.

Finally, new observations from future instruments and missions, both short-term and middle-term, have the potential to greatly improve the multi-annual series of global dust observations. The Trace Gas Orbiter (TGO) mission is currently in the preparation phase before aerobraking and science mapping, and its Atmospheric Chemistry Suite (ACS) instrument is designed to provide dust profiles and column opacities when observing in occultation and nadir modes.

The study of dust meteorology and climatology would also greatly benefit from new observational geometries, which have not yet been explored for Mars. Such geometries (e.g. observations from equatorial areostationary orbits) have the potential to provide continuous monitoring of dust distribution – as well as of other atmospheric variables- over large portions of the Martian disks.

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[2] The complete dataset is publicly available on the Mars Climate Database webpage: http://www-mars.lmd.jussieu.fr/mars/dust_climatology

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