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Eight-year climatology of dust optical depth on Mars

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ABSTRACT

We have produced a multiannual climatology of airborne dust from martian year 24–31 using multiple datasets of retrieved or estimated column optical depths. The datasets are based on observations of the martian atmosphere from April 1999 to July 2013 made by different orbiting instruments: the Thermal Emission Spectrometer (TES) aboard Mars Global Surveyor, the Thermal Emission Imaging System (THEMIS) aboard Mars Odyssey, and the Mars Climate Sounder (MCS) aboard Mars Reconnaissance Orbiter (MRO). The procedure we have adopted consists of gridding the available retrievals of column dust optical depth (CDOD) from TES and THEMIS nadir observations, as well as the estimates of this quantity from MCS limb observations. Our gridding method calculates averages and uncertainties on a regularly spaced spatio-temporal grid, using an iterative procedure that is weighted in space, time, and retrieval quality. The lack of observations at certain times and locations introduces missing grid points in the maps, which therefore may result in irregularly gridded (i.e. incomplete) fields. In order to evaluate the strengths and weaknesses of the resulting gridded maps, we compare with independent observations of CDOD by PanCam cameras and Mini-TES spectrometers aboard the Mars Exploration Rovers "Spirit" and "Opportunity", by the Surface Stereo Imager aboard the Phoenix lander, and by the Compact Reconnaissance Imaging Spectrometer for Mars aboard MRO. We have statistically analyzed the irregularly gridded maps to provide an overview of the dust climatology on Mars over eight years, specifically in relation to its interseasonal and interannual variability, in addition to provide a basis for instrument intercomparison. Finally, we have produced regularly gridded maps of CDOD by spatially interpolating the irregularly gridded maps using a kriging method. These complete maps are used as dust scenarios in the Mars Climate Database (MCD) version 5, and are useful in many modeling applications. The two datasets for the eight available martian years are publicly available and distributed with open access on the MCD website.

1. Introduction

The dust cycle is currently considered to be the key process controlling the variability of the martian climate at seasonal and interannual time scales, as well as the weather variability at much shorter time scales. The atmospheric thermal and dynamical structures, and the transport of aerosols and chemical species, are all strongly dependent on the dust spatio-temporal distribution, particle sizes, and optical properties.

After the first systematic observations of a planet-encircling dust storm by ground-based telescopes in the late 1950s, the study of dust has been one of the main objectives of many spacecraft missions to Mars over more than 40 years. Recent and ongoing missions, such as Mars Global Surveyor (MGS), Mars Odyssey (ODY), Mars Express, Mars Exploration Rover (MER), Mars Reconnaissance Orbiter (MRO), Phoenix, and Mars Science Laboratory, have included spectrometers, radiometers, imagers, cameras, and

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one LIDAR to measure radiances at wavelengths sensitive to dust. See Smith (2008) for an extensive review of spacecraft instruments sensitive to dust prior to the Surface Stereo Imager (SSI) and the LIDAR aboard the Phoenix lander (Smith et al., 2008), and the Mastcam camera aboard the Mars Science Laboratory rover (Grotzinger et al., 2012).

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 (also called optical thickness). It is related to how much radiation at a specific wavelength would be removed from the vertical component of a beam during its path through the atmosphere by absorption and scattering (i.e. extinction) due to airborne dust. The column optical depth is the product of dust retrievals when the radiance observations are obtained by nadir-viewing instruments. Vertical profiles of extinction opacity (or extinction coefficient) can be derived from radiances measured by limb-viewing instruments, providing important information on the vertical extension of the dust. Although relative variations of optical depth can be readily obtained from remote observations, absolute values are much trickier to obtain because they require accurate knowledge of important properties related to dust, such as the particle size distribution and the optical parameters. These properties are difficult to retrieve from direct measurements of radiances (Clancy et al., 2003; Wolff and Clancy, 2003; Wolff et al., 2006, 2009).

Dust climatology is a terminology generally adopted to indicate dust data (e.g. observed horizontal and vertical distributions) that characterize specific times and locations, but can be assumed as valid at other times and locations in a statistical sense. Because there are relatively few observations of dust on Mars, which do not cover all times and locations, the use of dust climatologies as "dust scenarios" is common practice in modeling studies of the martian atmosphere. Dust climatologies are also commonly used as input values for atmospheric species and surface quantity retrievals, e.g. atmospheric ozone (Clancy et al., 2014), surface albedo (Vincendon et al., 2014), and surface thermal inertia (Putzig and Mellon, 2007), to cite only a few.

The choice of dust scenarios has a significant impact on martian model simulations. The knowledge of the dust spatio-temporal distribution is essential to produce quantitative estimates of dust mass mixing ratios, and calculate the atmospheric heating rates due to absorption and scattering of solar and infrared (IR) radiation by airborne particles. These calculations are the basis for describing the thermal forcing in Mars atmospheric models, such as global climate models (GCM), and producing accurate predictions of the atmospheric state. Model studies have often been carried out with analytical specifications of dust distributions, both in the horizontal and in the vertical (see e.g. Forget et al., 1999; Montmessin et al., 2004; Kuroda et al., 2008). More recently, modeling groups have been carrying out simulations with more realistic horizontal dust distributions, tied to TES observations. A non-exhaustive list of examples includes Guzewich et al. (2013a), Wang and Richardson (2015), Kavulich et al. (2013), Greybush et al. (2012), Madeleine et al. (2011, 2012). Steele et al. (2014b) use an horizontal dust distribution derived from MCS observations in martian year (MY) 30, which is an early version of the MY 30 dust scenario presented in this paper.

We propose in this paper to create a well-documented, multiannual, 2D dust climatology of the column dust optical depth (CDOD), as well as a set of dust scenarios to be used in model experiments. Although we focus our attention on the column-integrated dust distribution, it should be noted that the spatial variation of the vertical distribution of dust also plays a significant role in thermal response (see e.g. Guzewich et al., 2013a). There are a number of approaches to represent this vertical structure (e.g. Madeleine et al., 2011; Greybush et al., 2012), all of which are based on the constraint of observed dust optical depths.

To date, there exist several datasets of retrieved CDOD for Mars, spanning more than 20 martian years since the Mariner era (e.g. Fenton et al., 1997). These datasets are highly heterogeneous, as they have been created using data from different instruments having different geometric views, spatial and temporal coverage, as well as different observing wavelengths. Nonetheless, we show in this paper that at least some of these datasets can be appropriately used to quantitatively reconstruct the recent dust climatology on Mars, and characterize the variability over many seasonal cycles. This paper seeks to produce a continuous, multiannual climatology of CDOD from early March 1999 (solar longitude $L_s \sim 104^\circ$ in MY 24) to the end of July 2013 ($L_s = 360^\circ$ in MY 31). During this period of time, the Thermal Emission Spectrometer (TES, Christensen et al., 2001) aboard MGS, the Thermal Emission Imaging System (THEMIS, Christensen et al., 2004) on ODY, and the Mars Climate Sounder (MCS, McCleese et al., 2007) on MRO provided global coverage of radiance observations at IR wavelengths, from which Smith et al. (2003), Smith (2004, 2009), Kleinböhl et al. (2009) obtained direct retrievals of CDOD or estimates of this quantity from the integrated extinction profiles.

While images from orbiting spacecraft can provide information over large areas on the planet at any given time, observations of IR radiances from orbiting instruments have a very discrete coverage in longitude and local time due to the choice of orbit geometry. MGS and MRO, for instance, have Sun-synchronous, nearly 2-h polar orbits, which provide good latitude coverage but only sample about a dozen longitudes per day, usually at close to two fixed local times except when crossing the poles. Because dust storms on Mars have a wide range of spatial and temporal scales (Cantor, 2007; Wang et al., 2003, 2005), these discrete observations can affect the space–time representation of dust storm activity. Extrapolating the data collected along orbit tracks to a broader range of local time and longitude introduces even more biases. Global maps produced using simple average binning may alter the representation of rapidly evolving dust distribution.

We have developed a gridding methodology that is specifically adapted to heterogeneous observations, and to the discrete longitudinal/temporal coverage typical of spacecraft data acquisition. The ultimate objective is to produce regularly gridded maps of absorption CDOD at 9.3 μm for several consecutive martian years (dust optical depth in absorption is less dependent on the particle size than in extinction). To achieve this goal, we have adopted a two-step procedure. The first step consists in iteratively calculating averages of observations and related uncertainties on a regularly spaced spatio-temporal grid, after having binned the data using time windows of different size, and applied appropriate weighting functions in space, time, and retrieval quality at each iteration. The lack of observations at certain times and locations introduces missing grid points in the maps, which are therefore likely to result as incomplete, or irregularly gridded. We have used this first product to statistically study the dust variability over almost eight complete martian years. The second step consists in producing regular maps of CDOD by spatially interpolating and/or extrapolating the irregularly gridded maps, using a kriging method (see e.g. Journel and Huijbregts, 1978, for a general introduction on the technique). This multiannual series of complete maps of CDOD is used for the dust scenarios in the GCM simulations that produce the current version of the Mars Climate Database (MCD version 5, Millour et al., 2014).

We provide open access to both the irregularly gridded and regularly kriged datasets, to foster scientific analyses and applications of the long-term martian dust climatology. The most up-to-date version of these products (currently v2.0) can be downloaded in