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1 **Martian Year 34 Column Dust Climatology from Mars**
2 **Climate Sounder Observations: Reconstructed Maps and**
3 **Model Simulations**

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11 **Key Points:**

- 12 • We reconstruct sub-daily maps of column dust optical depth for Martian year 34
13 to be used for data analysis and modeling
- 14 • We observe seasonal, daily, and diurnal variability in the column dust, notably dur-
15 ing the global dust event (GDE)
- 16 • Simulations with a global climate model examine the impact of the GDE on the
17 atmospheric circulation and diurnal variability of column dust

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Abstract

We have reconstructed longitude-latitude maps of column dust optical depth (CDOD) for Martian year (MY) 34 (May 5, 2017 - March 23, 2019) using observations by the Mars Climate Sounder (MCS) aboard NASA’s Mars Reconnaissance Orbiter spacecraft. Our methodology works by gridding a combination of standard (v5.2) and novel (v5.3.2) estimates of CDOD from MCS limb observations, using an improved “Iterative Weighted Binning”. In this work, we have produced four gridded CDOD maps per sol, at different Mars Universal Times. Together with the seasonal and daily variability, the use of several maps per sol also allows us to explore the diurnal variability of CDOD in the MCS dataset, which is shown to be particularly strong during the MY 34 equinoctial Global Dust Event (GDE). In order to understand whether the diurnal variability of CDOD has a physical explanation, and examine the impact of the MY 34 GDE on some aspects of the atmospheric circulation, we have carried out numerical simulations with the “Laboratoire de Météorologie Dynamique” Mars Global Climate Model. We show that the model is able to account for at least part of the observed CDOD diurnal variability. This is particularly true in the southern hemisphere where a strong diurnal wave at the time of the GDE is able to displace dust horizontally as well as vertically. The simulations also clearly show the impact of the MY 34 GDE on the mean meridional circulation and the super-rotating equatorial jet, similarly to the effects of the equinoctial GDE in MY 25.

Plain Language Summary

Large dust storms on Mars have dramatic impacts on the entire atmosphere, but may also have critical consequences for robotic and future human missions. Therefore, there is a compelling need to produce an accurate reconstruction of their spatial and temporal evolution for a variety of applications, including to guide Mars climate model simulations. The recently ended Martian year 34 (May 5, 2017 – March 23, 2019) represents a very interesting case because an extreme dust event occurred near the time of the northern autumn equinox, consisting of multiple large dust storms engulfing all longitudes and most latitudes with dust for more than 150 Martian days (“sols”). We have used satellite observations from the Mars Climate Sounder instrument aboard NASA’s Mars Reconnaissance Orbiter to reconstruct longitude-latitude maps of the opacity of the atmospheric column due to the presence of dust at several times in each sol of Martian year 34. These maps allow us to analyze the seasonal, day-to-day, and day-night variability of dust in the atmospheric column, which is particularly intense during the extreme dust event. We have also used simulations with a Mars climate model to show that the strong day-night variability may be partly explained by the large-scale circulation.

1 Introduction

Martian dust aerosols are radiatively active, and the dust cycle — lifting, transport, and deposition — is considered to be the key process controlling the variability of the Martian atmospheric circulations on a wide range of time scales (see e.g. the recent review by Kahre et al., 2017, and references therein). Dust storms are the most remarkable manifestations of this cycle, and one of the most crucial weather phenomena in need of study to fully understand the Martian atmosphere.

Martian dust storms are: 1. a source of strong atmospheric radiative forcing, and alteration of surface energy budget (e.g. Streeter et al., 2019); 2. a major component of the atmospheric inter-annual, seasonal, daily, and diurnal variability (see Kleinböhl et al., 2019, for an example related to the diurnal variability); 3. a way to redistribute dust on the planet via long-range particle transport (as inferred, for instance, using albedo changes: Szwast et al., 2006); 4. a means of producing perturbations of temperature and density, which propagate from the lower to the upper atmosphere, including the lower

68 thermosphere, the ionosphere, and the magnetosphere (e.g. Girazian et al., 2019; Xiao-
 69 hua et al., 2019); 5. a cause of increased loss of chemical species via escape (e.g. Fedorova
 70 et al., 2018; Heavens et al., 2018; Xiaohua et al., 2019); and 6. a source of hazards for space-
 71 craft Entry, Descent and Landing (EDL) manoeuvres, for operations by solar-powered
 72 surface assets, and for future robotic and human exploration (e.g. Levine et al., 2018).
 73 Dust storms on Mars can be studied by using a variety of approaches: analysis of ob-
 74 servations from satellites and landers/rovers, numerical simulations from Global Climate
 75 Models (GCM), and data assimilation techniques.

76 One of the most dramatic and (thus far) unpredictable events linked to Martian
 77 dust storms are the onset of a Global Dust Event — hereinafter GDE. In the literature,
 78 these events are also named “Planet-Encircling Dust Storms” (e.g. Zurek & Martin, 1993;
 79 Cantor, 2007), “Global Dust Storms” (probably the most common name), or “Great Dust
 80 Storms” (e.g. Zurek, 1982). Here we choose the denomination “Global Dust Event” be-
 81 cause 1. even large regional storms can inject dust high enough in the atmosphere, which
 82 eventually encircles the planet, 2. these global dust events are usually characterized by
 83 several storms occurring simultaneously, or one after the other one in rapid succession,
 84 and 3. the GDE denomination was already discussed and used in Montabone & Forget
 85 (2018), and is currently adopted by several authors. However, in this paper we also ar-
 86 gue that the key characteristics of this kind of events is their “extreme” nature, rather
 87 than their “global” nature, for which the denomination “Extreme Dust Events” would prob-
 88 ably be even more appropriate. The Mars scientific community will need in future to de-
 89 fine a consensus-based terminology for dust events, based on scientific arguments and
 90 measurable variables, as it is the case for other kinds of meteorological events (see, for
 91 instance, the distinction among terrestrial tropical depressions, tropical storms, and hur-
 92 ricanes).

93 In the last Martian decade (Martian Year — hereinafter MY — 25 to 34), span-
 94 ning nearly two Earth decades from 2000 to 2019, three GDEs occurred: an equinoctial
 95 event in MY 25, a solstitial event in MY 28, and another equinoctial event in MY 34,
 96 starting only a few mean solar days — sols — after the corresponding onset of the MY
 97 25 event. GDEs inject a large amount of dust particles into the Martian atmosphere, strongly
 98 modify the thermal structure and the atmospheric dynamics over several months (i.e.
 99 several tens degrees of areocentric solar longitude, L_S , see e.g. Wilson & Hamilton, 1996;
 100 Montabone et al., 2005), and impact the Martian water cycle and escape rate (Fedorova
 101 et al., 2018; Heavens et al., 2018). Similar events were previously observed in Martian
 102 Years 1, 9, 10, 12, 15, and 21 (Martin & Zurek, 1993; Cantor, 2007; Montabone & For-
 103 get, 2018; Sánchez-Lavega et al., 2019). The inter-annual variability of GDEs is irreg-
 104 ular, and likely controlled at the first-order by the redistribution of dust on Mars over
 105 the timescale of a few years (Mulholland et al., 2013; Newman & Richardson, 2015; Vin-
 106 cendon et al., 2015).

107 The latest equinoctial GDE had its initial explosive growth in early northern fall
 108 of MY 34 (L_S approximately in the range 185° – 190° , i.e. late May 2018 – early June
 109 2018). A regional dust storm started near the location of the Mars Exploration Rover
 110 “Opportunity”. The visible opacity quickly reached a very high value of 10.8, which led
 111 to the end-of-mission of the Opportunity rover, with last communication received on June
 112 10, 2018. The regional dust storm then moved southward along the Acidalia storm-track,
 113 and expanded both in the northern hemisphere from eastern Tharsis to Elysium (includ-
 114 ing the location of the Mars Science Laboratory “Curiosity” rover and the landing site
 115 of “InSight”), and towards the southern hemisphere (Malin et al., 2018; Kass et al., 2019;
 116 Shirley et al., 2019; Sánchez-Lavega et al., 2019; Hernández-Bernal et al., 2019).

117 The evolution of this MY 34 GDE in summer 2018 has been closely monitored by
 118 three of NASA’s orbiters, including the Mars Reconnaissance Orbiter (MRO) and its Mars
 119 Climate Sounder (MCS) instrument (Kass et al., 2019), two of ESA’s orbiters (Mars Ex-
 120 press and the ExoMars Trace Gas Orbiter), the ISRO’s Mangalyaan orbiter, and ground-

121 based telescopes (Sánchez-Lavega et al., 2019). It has also been observed in detail from
 122 the surface by the Curiosity rover, which could still operate in dust-storm conditions thanks
 123 to its nuclear-powered system. From meteorological observations carried out aboard Cu-
 124 riosity with the Rover Environmental Monitoring Station (REMS), Guzewich et al. (2019)
 125 concluded that the local optical depth reached 8.5, the incident total UV solar radiation
 126 at the surface decreased by 97%, the diurnal range of air temperature decreased by 30
 127 K, and the semidiurnal pressure tide amplitude increased to 40 Pa. Curiosity did not
 128 witness dust lifting within the Gale Crater site, which indicates that the increase in dust
 129 loading at its location is the result of dust transport from outside the crater area.

130 Beyond the undoubtedly interesting GDE, MY 34 also features the development
 131 of an unusually intense and large late-winter regional storm, whose peak value of column
 132 dust optical depth (CDOD) is only rivaled by the late-winter regional storm in MY 26
 133 (reaching 75% of the peak value of the former). It is, however, reminiscent of the two
 134 global events that were successively monitored by the Viking landers in 1977 at $L_S =$
 135 205° and $L_S = 275^\circ$ (Ryan & Henry, 1979; Zurek, 1982). Overall, therefore, MY 34 rep-
 136 resents a unique year for studies linked to the onset/evolution of dust storms, and their
 137 impact on the entire Martian atmospheric system. Consequently, there is a compelling
 138 need to produce an accurate reconstruction of the spatial and temporal evolution of the
 139 dust optical depth in MY 34, particularly covering the GDE, but also putting the un-
 140 precedented weather measurements acquired by the InSight lander during the late-winter
 141 regional storm into global context (Spiga et al., 2018).

142 Montabone et al. (2015) developed a methodology to grid values of CDOD retrieved
 143 from multiple polar orbiting satellite observations, such as NASA’s Mars Global Surveyor
 144 (MGS), Mars Odyssey (ODY), and MRO. Using this methodology (a combination of “It-
 145 erative Weighted Binning” — IWB — and kriging spatial interpolation), they were able
 146 to produce multi-annual datasets of daily CDOD maps extending from MY 24 to MY
 147 33, which are publicly available on the Mars Climate Database (MCD) project webpage
 148 at <http://www-mars.lmd.jussieu.fr/> (look for “Martian dust climatology” on the MCD
 149 webpage). The datasets include both irregularly gridded maps (because of the presence
 150 of missing grid point values after the application of the IWB, where observations are not
 151 available) and regularly kriged ones. The kriged maps can be used as a daily, column-
 152 integrated “dust scenario” to prescribe or guide the evolving atmospheric dust distribu-
 153 tion in numerical model simulations.

154 In this paper we describe how we make use of newly processed dust opacity retrievals
 155 from thermal infrared observations of the MRO/MCS instrument (McCleese et al., 2007)
 156 in order to reconstruct maps of column dust optical depth specifically for MY 34, and
 157 describe aspects of the two-dimensional dust climatology. In Section 2, we discuss the
 158 improvements both to the MCS retrievals and to the gridding methodology described
 159 in Montabone et al. (2015). In Section 3, we analyze in general terms the CDOD vari-
 160 ability at seasonal timescale, and in specific terms the daily evolution of the GDE and
 161 late-winter dust storm. We also address the diurnal variability observed when reconstruct-
 162 ing multiple CDOD maps per sol. In Section 4, we use simulations with the Laboratoire
 163 de Météorologie Dynamique Mars GCM (LMD-MGCM) in order to 1. assess some of the
 164 impacts of the MY 34 GDE on the Martian atmospheric circulation (in this case the model
 165 dust distribution is guided by the kriged maps), and 2. verify that the GCM is able to
 166 reproduce at least part of the diurnal variability observed in the reconstructed multiple
 167 CDOD maps per sol (in this case the model dust distribution is only initiated using the
 168 kriged maps, but is not subsequently guided). Conclusions are drawn in Section 5.

169 2 Building column dust optical depth maps

170 The methodology described in Montabone et al. (2015) to grid CDOD values us-
 171 ing the IWB, and to spatially interpolate the daily maps using kriging, has been applied

172 to observations by MGS/Thermal Emission Spectrometer (TES), ODY/Thermal Emis-
 173 sion Imaging System (THEMIS), and MRO/MCS from MY 24 to MY 32. For MY 33,
 174 because of the progressive change in local time of THEMIS observations, we have intro-
 175 duced a weighting function specific for the THEMIS dataset in order to favor the MCS
 176 dataset (i.e. we simply apply a 0.5 weight to THEMIS CDODs during the first iteration
 177 with the time window of 1 sol, reduced to 0.1 for the subsequent iterations using larger
 178 time windows. The impact of THEMIS observations is therefore reduced to 50% or 10%
 179 with respect to MCS ones). As mentioned in the introduction, version 2.0 (v2.1 for MY
 180 33) of both irregularly gridded maps and regularly kriged ones (we refer to the latter as
 181 the column-integrated “dust scenario” in this paper) are available on the MCD project
 182 website.

183 For the specific case of the MY 34 GDE, the MCS team has updated their retrievals
 184 of temperature, dust and water ice profiles. We have correspondingly updated the grid-
 185 ding/kriging methodology with the aim of producing a more refined and accurate cli-
 186 matology, both for scientific studies and for the use in numerical model simulations. There-
 187 fore, in the following we describe how we reconstruct CDOD maps for MY 34 (currently
 188 version 2.5). We provide some details about the differences between current and previ-
 189 ous versions (i.e. v2.2, v2.3, and v2.4) in Appendix A.

190 2.1 Observational dataset

191 In MY 34, single THEMIS CDOD retrievals are no longer available. Because of the
 192 late local time of THEMIS observations in MY 34, Smith (2019) had to develop a “stack-
 193 ing” algorithm that assesses how a group of THEMIS spectra in a L_S /latitude bin change
 194 as a function of estimated thermal contrast. Therefore, we do not use THEMIS any more
 195 in MY 34, and we completely rely on estimated CDODs from MCS.

196 Dust opacity retrievals from thermal infrared observations of the MCS instrument
 197 aboard MRO are described in Kleinböhl et al. (2009); Kleinböhl et al. (2011), and Klein-
 198 böhl et al. (2017a). The currently standard MCS dataset, based on the v5.2 “two-dimensional”
 199 retrieval algorithm specifically described in (Kleinböhl et al., 2017a), has been reprocessed
 200 by the MCS team for the time of the MY 34 GDE to obtain better coverage in the ver-
 201 tical and, therefore, more reliable estimates of CDOD values during the event (Klein-
 202 böhl et al., 2019). This latest MCS dataset, only available between May 21, 2018 ($L_S \approx$
 203 179°) and October 15, 2018 ($L_S \approx 269^\circ$), and labelled v5.3.2, is an interim version that
 204 includes the use of a far infrared channel for retrievals of dust. The differences between
 205 MCS retrievals version 5.2 and 5.3 are as follows:

- 206 • Use of B1 detectors to extend the dust profile retrieval: the dust extinction effi-
 207 ciency in channel B1 at $32 \mu\text{m}$ is only about half the value of channel A5 at $22 \mu\text{m}$
 208 (Kleinböhl et al., 2017b), which is the primary channel for dust retrievals, allow-
 209 ing profiles to extend deeper by 1 to 1.5 scale heights;
- 210 • Accepting a higher aerosol to CO_2 gas opacity ratio along the line-of-sight in the
 211 temperature retrieval channel A3;
- 212 • Modifications for determining surface temperature when there are no matching
 213 on-planet views (primarily cross-track views) to improve the performance under
 214 high dust conditions when the array is lifted and limb views do not intersect the
 215 surface.

216 CDODs are estimated by integrating the dust opacity profiles after an extrapola-
 217 tion from the lowest altitude at which profile information is available, under the assump-
 218 tion of homogeneously mixed dust (see Fig. 1 of Kleinböhl et al., 2019, as well as Fig. 15
 219 in this paper). For the reconstructed CDOD maps in MY 34, we use MCS v5.3.2 esti-
 220 mated CDODs from $L_S \approx 179^\circ$ to $L_S \approx 269^\circ$, and MCS v5.2 otherwise.

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2.2 Data Quality Control

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A general discussion about the limitations of using CDOD estimates from MCS is included in Montabone et al. (2015), specifically Section 2.1.2. As mentioned in the previous sub-section, the extended vertical coverage in MCS v5.3.2 helps estimate CDODs more accurately. In the present work, therefore, we have improved the definition of the Quality Control (QC) procedure with respect to the one used in Montabone et al. (2015), particularly by allowing a more extensive use of dayside observations. We define dayside observations as those with local times (lt) in the range $09:00 < lt \leq 21:00$, although most of dayside observations at low latitudes have local times close to 15:00. Nightside observations are defined as those outside the dayside range, with most nightside observations at low latitude having local times close to 03:00.

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We need to stress that, despite the improvements in MCS v5.3.2, the main issue for estimating column optical depths using limb observations remains the fact that many opacity profiles have rather high cut-off altitudes (particularly dayside ones, see also right column of Fig.5), due to either dust or water ice opacities that are too large. During the dust storms, cutting off due to dust, and extrapolating over a big altitude range under the assumption of homogeneously mixed dust, provide reasonable CDODs, although increase the uncertainty on the column values. However, when the profile is cut-off due to water ice, the dust column is poorly constrained due to the extrapolation. Because water ice clouds are a dominant source of questionable CDOD values, especially on the dayside, we specifically apply stringent filters when we suspect the dust opacity is likely contaminated by the water ice opacity. Conversely, we relax our filtering for dayside values during the dust storms, when water ice clouds are not likely to be present.

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Note that MCS is also able to observe cross-track, thus providing information within a range of local times at selected positions during the MRO orbits (Kleinböhl et al., 2013). We have also better defined a dust quality flag in MCS v5.3.2 to help filter those observations where a significant number of detectors were excluded in the retrieval of the dust opacity profile, because of radiance residuals exceeding threshold values (Kleinböhl et al., 2009). Each excluded detector corresponds to a truncation of about 5 km in the reported profile compared to the altitude range that was originally selected by the retrieval algorithm based on line-of-sight opacity.

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We apply the following QC procedure to the MCS CDOD values at $21.6 \mu\text{m}$ in extinction:

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- To discard values when they are most likely contaminated by CO_2 ice (i.e. if, at any level below 40 km altitude, the temperature is $T < T_{\text{CO}_2} + 10\text{K}$, and the presumed dust opacity is larger than 10^{-5} km^{-1});
- To discard values when water ice opacity is greater than dust opacity at the cut-off altitude of the corresponding dust profile;
- To discard cross-track CDODs with cut-off altitudes higher than 8 km (i.e. the corresponding dust opacity profiles do not extend down to 8 km altitude or lower), because they are likely to produce questionable CDODs;
- Dayside values are specifically filtered based on a cut-off altitude that depends on the MCS retrieval version and the amount of ice that is present. The threshold cut-off altitude is 8 km during the icy MCS v5.2 prior to $L_S = 179^\circ$. It increases to 16 km during the icy MCS v5.3.2 data period prior to the start of the GDE ($179^\circ < L_S < 186.5^\circ$). There is no threshold cut-off altitude during the GDE with v5.3.2 available ($186.5^\circ \leq L_S \leq 269^\circ$). The threshold cut-off altitude was reinserted at 8 km after the GDE with icy conditions and MCS v5.2 data in the period $269^\circ < L_S \leq 312^\circ$. During the late winter regional dust storm under less icy conditions, the MCS v5.2 data threshold cutoff altitude was again increased to 16 km ($312^\circ <$

- 271 $L_S < 350^\circ$) to return to 8 km after the end of the storm and following possible
 272 presence of the ice clouds ($L_S \geq 350^\circ$);
- 273 • To discard CDODs when more than 1 detector is excluded inside the limits of the
 - 274 MCS v5.3.2 ($179^\circ \leq L_S \leq 269^\circ$) as well as if any detector is excluded in MCS
 - 275 v5.2 during the late-winter dust storm ($312^\circ < L_S < 350^\circ$);
 - 276 • To assign a fixed value of 0.01 to very low values of CDOD < 0.01 having cut-off
 - 277 altitude higher than 4 km.

278 We plot in Fig.1 the percentage number of CDOD values that are flagged by each
 279 individual filter, together with the total of the filtered values after the application of the
 280 complete QC procedure. The total does not correspond to the sum of each single filter,
 281 as a CDOD value can be flagged by multiple filters. This figure clearly shows that the
 282 presence of water ice in spring and summer strongly affects the number of CDOD val-
 283 ues passing the QC. Dayside values are also problematic because their corresponding dust
 284 profiles usually have rather high cut-off altitudes, compared to nightside values. Cross-
 285 track values have the tendency to exhibit rather high cut-off altitudes as well, and lead
 286 to questionable column dust optical depths. As a consequence, a large number of them
 287 at low- and mid-latitudes are discarded throughout the year. Observations where more
 288 than one detector was excluded in the retrieval are about 20% throughout MCS v5.3.2.
 289 The number of values filtered because of possible carbon dioxide ice contamination is rel-
 290 atively low throughout the year (less than 10%).

291 After QC, the number of available values is plotted in Fig.2, separated into night-
 292 side and dayside values. The aphelion cloud belt and the winter polar hoods are mainly
 293 responsible for the lack of data at equatorial latitudes in the dayside plot, and at high
 294 latitudes in both dayside and nightside plots. The implementation of the new “water ice”
 295 filter is effective in reducing the probability that the lowest levels of the dust profiles are
 296 contaminated by the presence of clouds, but there is a risk of filtering out retrievals that
 297 actually may have been usable, particularly at high latitudes. A refinement of this fil-
 298 ter should be addressed in future work. Vertical bands with no data are periods when
 299 MCS did not observe.

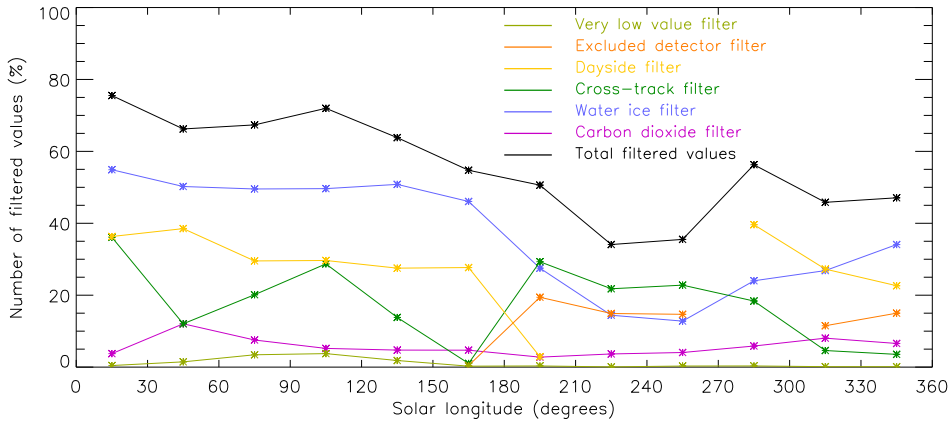


Figure 1. Percentage number of CDOD values flagged by each individual filter in the QC procedure within 30° L_S ranges in MY 34 (color lines), together with the percentage total number of filtered CDODs after the application of the complete QC procedure (black line). The numbers are associated to the middle of each 30° L_S range. Note that the “excluded detector” filter does not apply before $L_S = 179^\circ$ and for $269^\circ < L_S < 312^\circ$, and that the “dayside” filter does not apply during the GDE ($186.5^\circ \leq L_S \leq 269^\circ$).

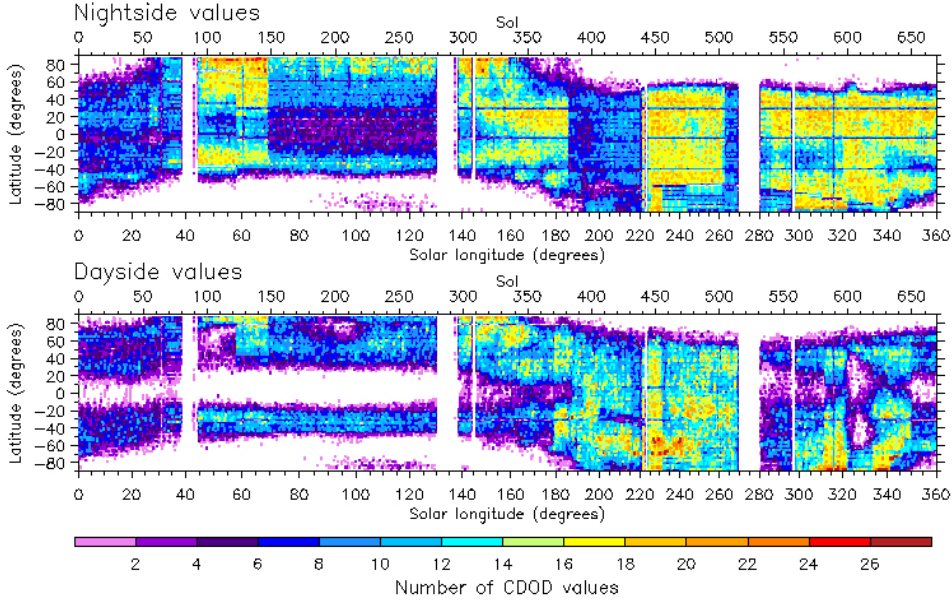


Figure 2. Number of nightside (upper panel) and dayside (lower panel) values of column dust optical depth available for gridding after passing the quality control procedure described in the text. The number of values is summed in $1 \text{ sol} \times 2^\circ$ latitude bins, and plotted as a function of time and latitude, where time is shown both as sol from the beginning of MY 34 and as areocentric solar longitude. Dayside observations are defined to have local times between 09:00 (excluded) and 21:00 (included), whereas nightside observations are defined to have local times between 00:00 and 09:00 (included) as well as between 21:00 (excluded) and 24:00.

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2.3 Data uncertainties and processing

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Together with the QC procedure, we have also revised the empirical method to estimate the uncertainties on the MCS CDOD values at $21.6 \mu\text{m}$ in extinction, with respect to the one used in Montabone et al. (2015). We apply the following relative uncertainties:

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- 10% for CDOD values < 0.01 having cut-off altitude higher than 4 km (i.e. for those values replaced with CDOD=0.01);
- 5% for CDOD values < 0.01 or values with cut-off altitudes lower than 4 km;
- When $\text{CDOD} \geq 0.01$ or cut-off altitude ≥ 4 km, we assign the largest relative uncertainty between the one calculated as a linear function of CDOD ($\frac{15}{1.49} \cdot \text{CDOD} + \frac{7.3}{1.49}$) and the one calculated as a linear function of the cut-off altitude ($\frac{25}{21} \cdot \text{alt} + \frac{5}{21}$). The two functions are defined in such a way that, for instance, the uncertainty is 5% if $\text{CDOD} = 0.01$ or cut-off altitude = 4 km, 20% if $\text{CDOD} = 1.5$, and 30% if cut-off altitude = 25 km.

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As detailed in Montabone et al. (2015), further data processing consists in converting MCS CDODs from $21.6 \mu\text{m}$ in extinction to absorption-only $9.3 \mu\text{m}$ by multiplying by 2.7, to be consistent with the climatologies of the previous Martian years. We then normalize the values to the reference pressure level of 610 Pa, but instead of using the surface pressure value calculated by the MCD `pres0` routine (Forget et al., 2007), we now use the same surface pressure value used for the corresponding MCS retrieval. MCS retrieves pressure at the pointing altitude where it is most sensitive to pressure (typically

20-30 km, see Kleinböhl et al., 2019), from which surface pressure can be extrapolated with an uncertainty estimate based on pointing uncertainty. In conditions where a pressure retrieval is unsuccessful (typically in conditions of high aerosol loading), the MCS algorithm uses pressure derived from the climatological Viking surface pressure (Withers, 2012). In this case, the uncertainty of the surface pressure is derived from the daily root mean squared of surface pressure from the MCD v5.3, interpolated at the specific location and season of an observation using a pre-built $5^\circ L_S \times 5^\circ$ latitude array (as described in Section 2.3 of Montabone et al., 2015).

2.4 Gridding methodology

In this work we closely follow the basic principles of reconstructing CDOD maps, which are detailed in Section 3 of Montabone et al. (2015). Iterative Weighted Binning (IWB) is applied to CDOD values and uncertainties at $9.3 \mu\text{m}$ in absorption, normalized to 610 Pa, to produce gridded values on a 6° longitude \times 5° latitude map. The current criterion to accept a value of weighted average at a particular grid point at any given iteration is that there must be at least one observation within a distance of 200 km from the grid point, otherwise a missing value (“Not-a-Number”, or NaN) is assigned to that grid point. The other used parameters as listed in Table 1 of Montabone et al. (2015) for MCS remain the same.

The application of the IWB for a sol in the growth phase of the GDE when the Mars Universal Time (i.e. the local time at 0° longitude) is $\text{MUT} = 12:00$ (noon) is shown in Fig. 3. In the left column we plot the CDOD observations effectively used for gridding, while in the right column we plot the result of the gridding. The time window (TW) for considering single observations increases from 1 to 7 sols going from the upper to the lower row. All four iterations are applied when reconstructing a map, and each iteration with larger TW only fills NaN grid points left by the previous iterations with smaller TWs. By doing this, each map is always built around the most up-to-date observations, usually provided by the iteration with $\text{TW} = 1$ sol (unless there are missing observations for one or more sols). In general, the value of each valid grid point of a map is assigned using observations within the smallest possible time window. For this reason, daily maps respond to rapidly changing events, such as the onset of a dust storm, as quickly as single observations allow. Obviously, for a polar, Sun-synchronous satellite such as MRO there is an intrinsic limitation to the production of a synoptic map, given by the fixed local times of observations.

The key differences we have introduced in this work with respect to the methodology described in Section 3 of Montabone et al. (2015) are that we now opportunistically separate the contribution of dayside and nightside observations, and we create four gridded maps per sol at four different MUTs. We achieve this by 1. only considering observations with local times within ± 7 hours of the local time of a given grid point, in each TW iteration, and 2. repeating the IWB procedure for observations centered at $\text{MUT} = 00:00, 06:00, 12:00,$ and $18:00$, rather than simply at $\text{MUT} = 12:00$ (this is equivalent to a 6-hour rather than a 24-hour moving average).

The effect of applying a ± 7 h window selection for observations to be gridded at each grid point can be already appreciated in Fig. 3, where the distinction between nightside tracks (positive slope) and dayside ones (negative slope) is evident, at each TW iteration. Because we use a local time window of ± 7 h, there is a superposition of nightside and dayside values at some longitudes, which allows for a smoother transition between the two. In Fig. 4 we show an example of the combined effect of the updated methodology for the same sol of Fig. 3, but only for the last iteration with $\text{TW} = 7$ sol (we stress that all four iterations with increasing TWs are always applied at each MUT, though). In the left column we plot the CDOD observations effectively used for gridding in the four maps of the right column, with $\text{MUT} = 00:00, 06:00, 12:00,$ and $18:00$.

372 The difference in local time between each observation and the map grid point close
 373 to which it is located is plotted in the left column of Fig. 5, using the same observations
 374 of the left column of Fig. 4. Since in Fig. 5 we only show examples with $TW = 7$, there
 375 are multiple orbit tracks with similar local time differences, but belonging to different
 376 sols. For each map with different MUT, there are two longitude ranges (with local times
 377 around 03:00 and 15:00) within which these differences are small, although only one or-
 378 bit track also matches the specific sol. The most current update of CDOD in each map
 379 is therefore confined to these two longitude ranges. The weights on time, distance, and
 380 quality of observation (see details in Section 3.2 of Montabone et al., 2015) eventually
 381 define the contribution of each single observation to the grid point average (plotted in
 382 the right column of Fig. 4 only for the last iteration).

383 It is necessary to discuss the differences among the maps at different MUTs, be-
 384 cause these are the novel result of this work. When looking at the four MUT maps in
 385 the right column of Fig. 4, in fact, a clear diurnal variation of CDOD can be appreci-
 386 ated, particularly pronounced in the latitude band $20^{\circ}\text{S}–70^{\circ}\text{S}$ (see also Section 3 and
 387 Fig. 14). This variation of CDOD has the characteristics of a Sun-synchronous wave with
 388 wavenumber one: smaller optical depths are found at night, larger optical depths occur
 389 during the day. The diurnal variation is already present in the estimated MCS CDODs,
 390 as shown in the left column of Fig. 4, and is not an artefact of the gridding methodol-
 391 ogy, nor is it limited to the sol showed in Fig. 4, as Fig. 14 clearly demonstrates. Fur-
 392 thermore, this strong diurnal variation of CDOD corresponds very well both in L_S (dur-
 393 ing the growth phase of the GDE) and in latitude to the strong diurnal variation of the
 394 MCS dust opacity profiles, as described in Kleinböhl et al. (2019). In that paper, GCM
 395 simulations are used to reproduce the diurnal variability of the dust profiles, and help
 396 explain the likely dynamical effects at the origin of this phenomenon.

397 The question arises, then, whether the diurnal variability observed in estimated MCS
 398 CDOD can also have a dynamical origin, or can be explained otherwise. We address the
 399 possibility of a dynamical origin with GCM simulations in Section 4, while we point out
 400 here that interpreting results from MCS CDODs is particularly challenging, as already
 401 mentioned in Subsection 2.2. The right column of Fig. 5, in fact, shows that the dust
 402 opacity profiles (from which CDODs are estimated) in the latitude band where the di-
 403 urnal CDOD differences are more pronounced have quite different cut-off altitudes above
 404 the local surface between day and night: nightside profiles tend to extend lower in al-
 405 titude, while dayside profiles are generally cut at higher altitudes. This is due to sev-
 406 eral factors, although it is primarily driven by the altitude at which the retrieval algo-
 407 rithm finds the atmosphere too opaque in the limb path. The increase in the amount of
 408 dust or water ice (and their vertical extent) in the dayside profiles causes the profiles to
 409 terminate further from the surface than the nightside ones, on average. As previously
 410 pointed out, the different cut-off altitudes for nightside and dayside retrievals imply that
 411 the uncertainty in the CDOD extrapolation is larger during the day, but it does not nec-
 412 essarily imply that the homogeneously mixed dust assumption is not valid, particularly
 413 during the peak of the GDE. We refer to Section 3 for in-depth discussion on this topic.

414 2.5 Reference MY 34 dust climatology

415 The gridded and corresponding kriged maps of CDOD described in Montabone et
 416 al. (2015) have been used as reference multi-annual dust climatology in several studies
 417 and applications, including the production of MCD statistics. It is, therefore, compelling
 418 to produce a reference MY 34 climatology following the approach established for the pre-
 419 vious Martian years.

420 Although in this work we produce four gridded maps per sol, we calculate the di-
 421 urnal average and we use only one map per sol to build the reference MY 34 climatol-
 422 ogy. We do so because 1. the diurnal variability of MCS CDOD is not yet soundly con-

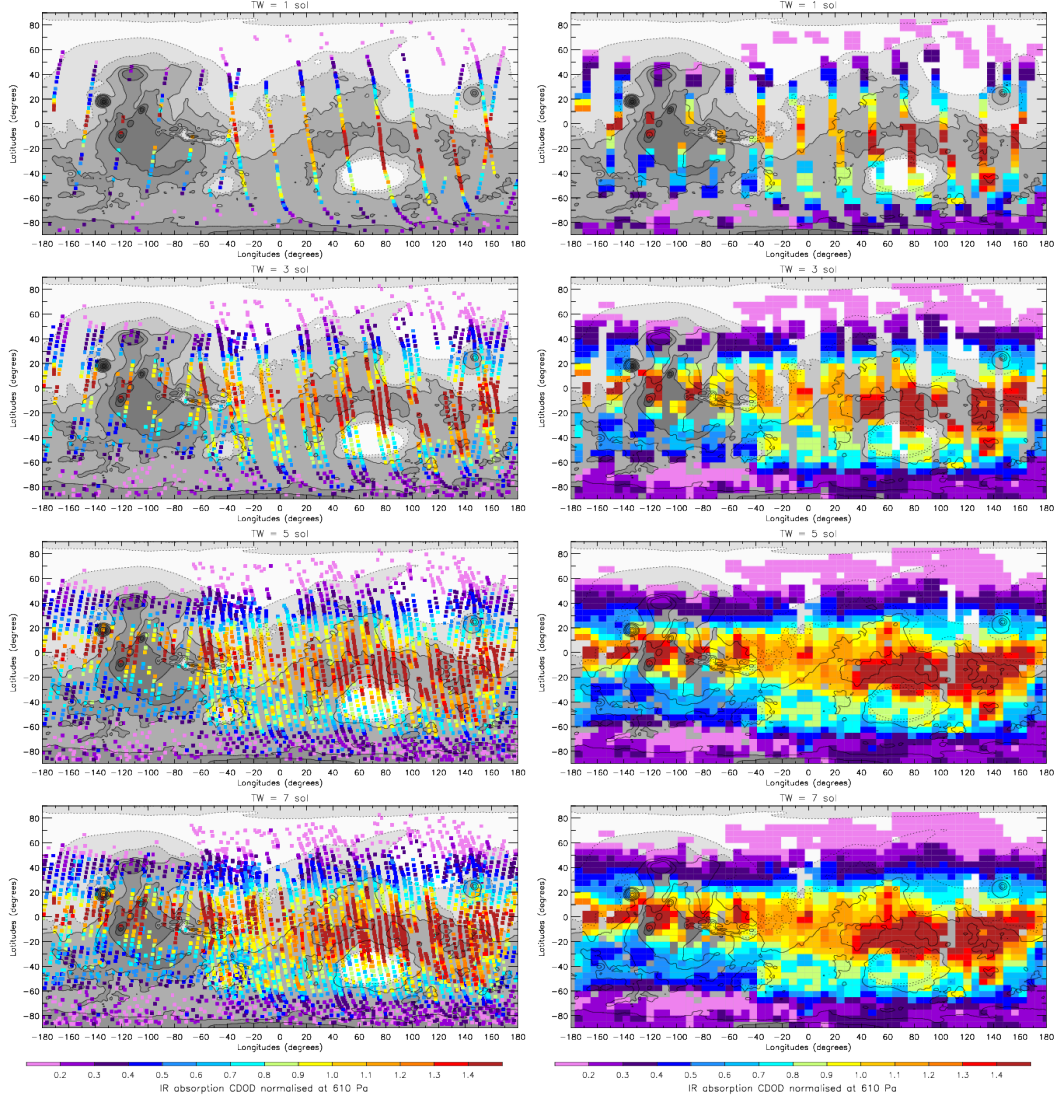


Figure 3. This figure shows longitude-latitude gridded maps (right column) built using CDOD observations (left column) selected within four iterative time windows (TW = 1, 3, 5, and 7 sols, from top to bottom). All maps have MUT = 12:00, and are representative of the sol-of-year (SOY) 400, $L_S \approx 196^\circ$, in the growth phase of the GDE (The SOY is the integer sol number starting from SOY=1 as first sol of the year). The CDODs are IR absorption ($9.3 \mu\text{m}$) values normalized to 610 Pa. The rows from top to bottom illustrate the application of the IWB procedure (including the use of the four subsequent time windows) at a fixed MUT. The final result of the iteration is the map in the bottom right position.

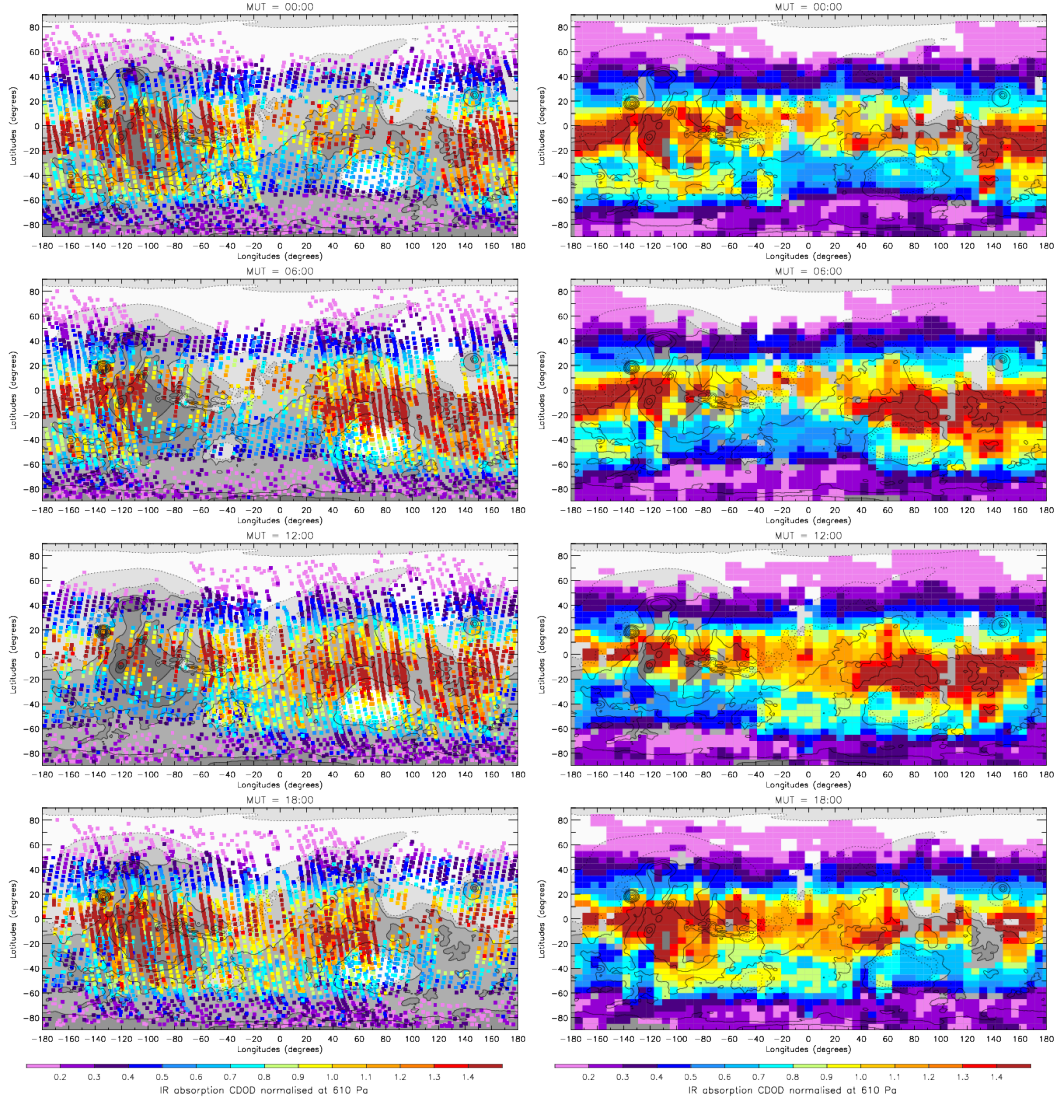


Figure 4. This Figure shows longitude-latitude gridded maps (right column) built using CDOD observations (left column) selected within a time window of 7 sols (after the iterative application of time windows of 1, 3, and 5 sols, as in Fig. 3) at four different Mars Universal Times: MUT = 00:00, 06:00, 12:00, and 18:00, from top to bottom. These maps are representative of the four different MUTs in sol-of-year (SOY) 400, $L_S \approx 196^\circ$, in the growth phase of the GDE (This is the same SOY shown in Fig. 3 only for MUT = 12:00). The CDODs are IR absorption ($9.3 \mu\text{m}$) values normalized to 610 Pa. Each row of this figure illustrates how the last iteration of the IWB procedure is applied to eventually produce one map every 6 hours.

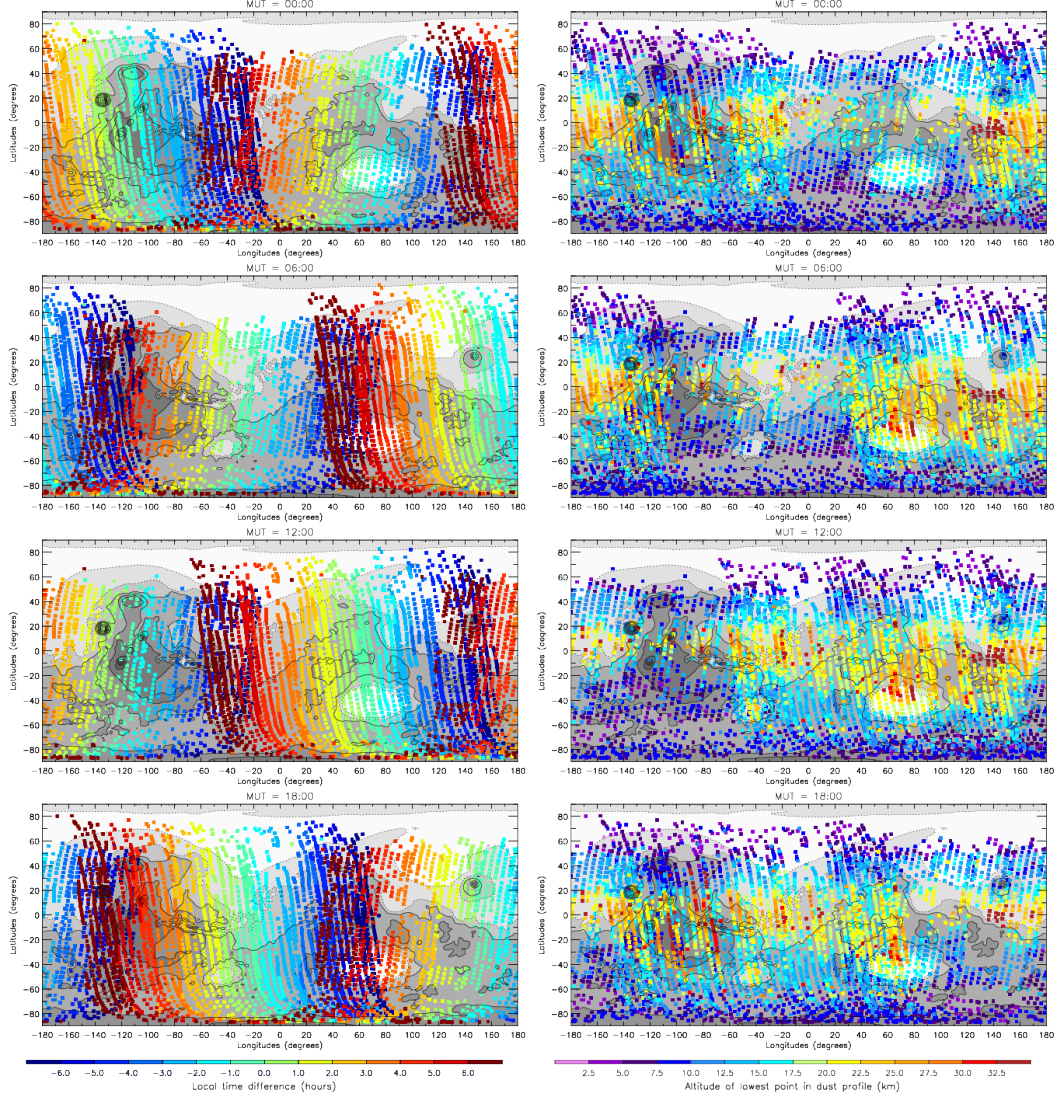


Figure 5. In this Figure we plot the same observations shown in the left column of Fig. 4 for $MUT = 00:00, 06:00, 12:00,$ and $18:00$, color coded according to: (left column) the difference in local time between each observation and the map grid point around which it is located, and (right column) the cut-off altitude above the local surface of the dust opacity profile corresponding to each estimated CDOD observation.

423 firmed by independent observations, 2. it is not clear whether using a column-integrated
 424 dust scenario with diurnal variability in model simulations would not trigger spurious
 425 effects, e.g. erroneously forcing the tides, and 3. we would like to be consistent with cli-
 426 matologies from previous Martian years. There is also a technical issue complicating the
 427 production of diurnally-varying gridded maps, which is the fact that some of the sub-daily
 428 gridded maps have many missing values, particularly when the water ice opacity affects
 429 the dust opacity.

430 We show in Fig. 6 an example of the diurnally-averaged gridded map and corre-
 431 sponding kriged one, for the same sol as in Fig. 3. The diurnally-averaged maps are more
 432 complete than any single MUT map, and rather spatially smooth. The transition to maps
 433 at previous and subsequent sols is also rather smooth (see e.g. Figs. 11 and 13). We should
 434 mention that, in contrast to Montabone et al. (2015), we no longer modify the values of
 435 the gridded maps in a latitude band around the southern polar cap edge before apply-
 436 ing the kriging interpolation. This was previously done to artificially introduce clima-
 437 tological “south cap edge storms” and balance TES and MCS years in term of dust lifted
 438 at the south cap edge. The use of MCS v5.3.2 retrievals extending to lower altitudes, and
 439 the fact that TES CDOD retrievals at the south cap edge are being revised (M. Smith,
 440 personal communication) alleviate the need for such correction.

441 The MY 34 daily maps of gridded and kriged IR absorption CDOD normalized to
 442 610 Pa are included in NetCDF files together with maps of several other variables, as
 443 mentioned in Appendix B of Montabone et al. (2015). We note here that the number
 444 of observations, the time window, and the reliability value for valid grid points are cal-
 445 culated as diurnal averages. The uncertainty is calculated as combined uncertainty of
 446 the four sub-daily values with equal weights. The combined RMSD is calculated as the
 447 square root of the average of the squared RMSDs of the four sub-daily values (also with
 448 equal weights). We separately provide the RMSD of the diurnally averaged values, which
 449 is an indicator of the diurnal variability. We also note that, following the Montabone et
 450 al. (2015) sol-based Martian calendar (see their Appendix A for a description), MY 34
 451 has 668 sols, therefore we provide 668 gridded maps — MY 34 new year’s L_S is 359.98° .
 452 The column-integrated dust scenario, though, has always 669 kriged maps for practical
 453 reasons, hence the last sol of the MY 34 dust scenario is the first sol of MY 35. Both grid-
 454 ded and kriged maps version 2.5 for MY 34 are publicly available at the dedicated “Mar-
 455 tian dust climatology” webpage on the MCD project website hosted by the LMD at the
 456 URL: <http://www-mars.lmd.jussieu.fr/>. They are also available on the “Institut Pierre-
 457 Simon Laplace” (IPSL) data repository at the URL: <https://data.ipsl.fr/catalog/>.
 458 For completeness, we have also made the diurnally-varying gridded maps (identified as
 459 version 2.5.1) available on both sites. See the “Data availability” section at the end of
 460 this paper for detailed access information.

461 2.6 Validation

462 An important aspect of producing a reference dataset for the dust climatology is
 463 its validation with independent observations. The Opportunity rover entered safe mode
 464 right at the onset of the GDE, while the Curiosity rover took measurements of visible
 465 dust optical depth throughout the GDE using its MastCAM camera (Guzewich et al.,
 466 2019). Hence, we use measurements from Curiosity for validation, together with pub-
 467 licly available visible images taken by the Mars Color Imager (MARCI) camera aboard
 468 MRO.

469 Figure 7 show the comparison between the time series of the dust optical depth (sol-
 470 averaged and normalized to 610 Pa) observed by Curiosity in Gale crater during the GDE
 471 (Guzewich et al., 2019), and the time series of CDOD extracted from the gridded maps
 472 and averaged in a longitude-latitude box centered on Gale crater (after conversion to equiv-
 473 alent visible values). The gridded maps are able to fairly well reproduce the timing and

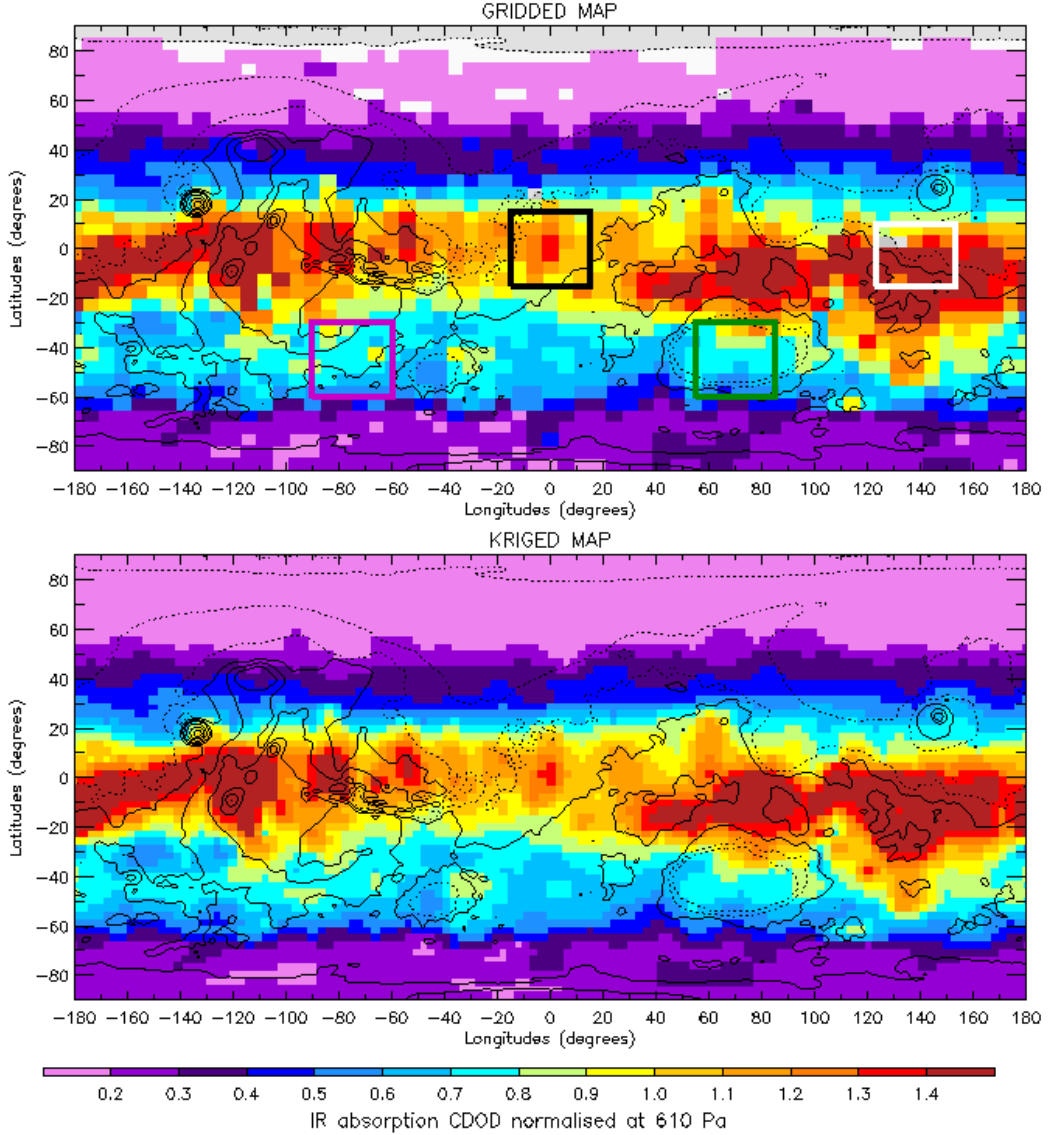


Figure 6. Diurnally-averaged gridded map (upper panel) and corresponding kriged map (lower panel) of $9.3 \mu\text{m}$ absorption column dust optical depth for SOY 400, $L_S \approx 196^\circ$, in the growth phase of the GDE. The gridded map showed here is the diurnal average of the four maps in the right column of Fig. 4. The spatial resolution of the gridded map is 6° longitude \times 5° latitude, whereas the resolution of the kriged one is 3° longitude \times 3° latitude. The white rectangle in the gridded map highlights the averaging area around Gale crater used in Fig. 7 for comparison with the CDOD measured by the Curiosity rover. The other colored squares highlight the averaging areas in Aonia Terra (magenta), Meridiani Planum (black) and Hellas Planitia (green) used in Fig. 14

474 decay of the GDE around Gale, but they underestimate the peak of the event. Further-
 475 more, they overestimate the decay between $L_S \approx 205^\circ$ and $L_S \approx 215^\circ$, although within
 476 the uncertainty limit. Spatial inhomogeneity in the CDOD field, even during the ma-
 477 ture phase of the GDE, may account for some of the differences. Looking within the white
 478 box over Gale Crater in the gridded map of Fig. 6 (which is at $L_S \approx 196^\circ$, i.e. at the
 479 opacity peak for Curiosity), the northern third of the box has substantially lower opac-
 480 ity values. Regional (especially latitudinal) gradients can, therefore, be one of the causes
 481 of the peak difference. Also note that Gale crater is a challenging location for MCS to
 482 observe due to MRO providing relay services to the Curiosity rover. In particular the
 483 number of in-track profiles is limited and may be geographically biased. See also further
 484 comments about the comparison with Curiosity data in Section 4 when discussing Fig. 16.
 485 Finally, we note that the time series using the kriged maps is nearly identical to that us-
 486 ing the gridded ones (i.e. the magenta line in Fig. 7), although we do not show this here.

487 We show the comparison between one of our gridded CDOD maps and a MARCI
 488 image in Fig. 8. The comparison is done for June 6, 2018, at the onset of the GDE, which
 489 corresponds to SOY 387 in our dataset. The extension of the dust cloud in both the MARCI
 490 image and the CDOD map is similar, with both showing intense activity around Meridi-
 491 ani, an eastward progression of the storm, and relatively clear skies over the Tharsis vol-
 492 canoes. This specific CDOD map fails to show the onset of the south polar cap edge dust
 493 activity, but maps at subsequent sols do.

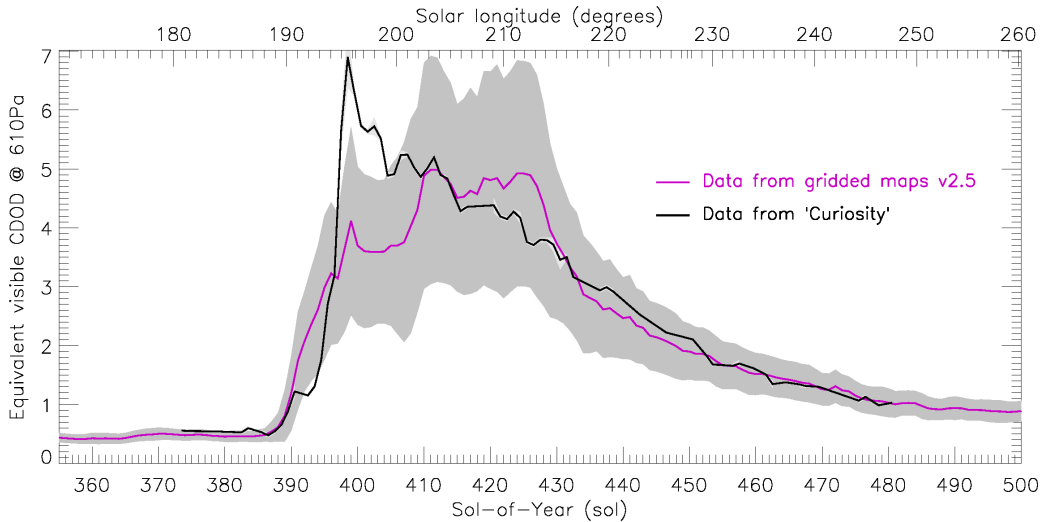


Figure 7. Time series of equivalent visible column dust optical depth calculated from the $9.3 \mu\text{m}$ absorption CDOD normalized to 610 Pa, extracted from the diurnally-averaged gridded maps in an area around Gale crater (magenta line), compared to the time series of visible column optical depth measured by MastCAM aboard NASA’s “Curiosity” rover (black line). Curiosity observations (Guzewich et al., 2019) have been diurnally-averaged and normalized to 610 Pa (using the surface pressure from the Mars Climate Database `pres0` routine). Both time series are shown between Sol-of-Year 355 and 500, i.e. $L_S \approx 170^\circ - 260^\circ$. We used a factor of 2.6 to convert $9.3 \mu\text{m}$ absorption CDODs into equivalent visible ones. Data from gridded maps are averaged in the area shown by a white rectangle in Fig. 6 (i.e. longitudes $123^\circ\text{E} - 153^\circ\text{E}$, latitudes $15^\circ\text{S} - 10^\circ\text{N}$) centered around Curiosity landing site at longitude 137.4°E and latitude 4.6°S . Light and dark grey shades show the uncertainty envelope (1-sigma) respectively for Curiosity’s time series and the time series extracted from the gridded maps.

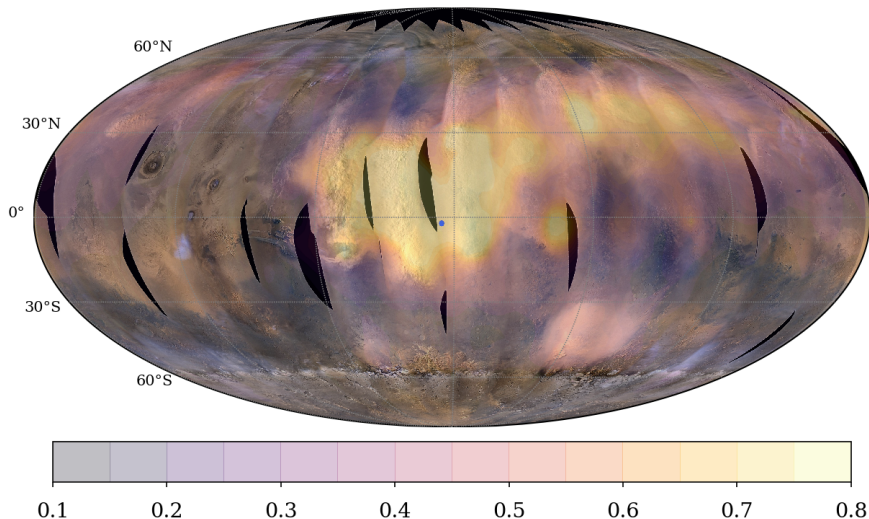


Figure 8. The background global image of Mars in this Figure is referenced PIA22329 in the NASA photojournal (credits: NASA/JPL-Caltech/MSSS). We wrapped this map on a Mollweide projection. It shows the growing MY 34 GDE as of June 6, 2018. The map was produced by the Mars Color Imager (MARCI) camera on NASA’s Mars Reconnaissance Orbiter spacecraft. The blue dot shows the approximate location of the Opportunity rover. We overlay on this image the column dust optical depth kriged map for the corresponding sol (sol-of-year 387), which we have reconstructed from MCS observations. The IR absorption ($9.3 \mu\text{m}$) CDOD map (not normalized to 610 Pa) is plotted as filled colored contours.

494 3 Seasonal, daily, and diurnal variability of column dust

495 In this Section we analyze the variability at different temporal scales, which is in-
 496 cluded in the MY 34 dust climatology reconstructed from MCS CDODs. In particular,
 497 we look at the seasonal, daily, and diurnal variability, as shown in Figures 9 to 15.

498 Starting from the seasonal variability, Fig. 9 shows the latitude vs time plot of the
 499 zonally and diurnally averaged CDOD obtained from both the gridded maps and the kriged
 500 ones. This comparison shows that the kriged maps have the advantage of being complete
 501 (i.e. CDOD values are assigned at every grid point) while preserving the overall prop-
 502 erties of the dust distribution. Montabone & Forget (2018) noted that Martian years show
 503 two distinctive seasons with respect to the atmospheric dust loading, when a compar-
 504 ison of multi-annual zonal means of CDOD is carried out: a “low dust loading” (LDL)
 505 season between $L_S \approx 10^\circ$ and $L_S \approx 140^\circ$, and a “high dust loading” (HDL) season at
 506 other times, when regional dust storms and global dust events are most likely to occur
 507 — commonly referred to as the “dust storm season”. MY 34 does not differ, as dust started
 508 to increase above the 0.15 level (IR absorption at $9.3 \mu\text{m}$) after $L_S \approx 160^\circ$, following
 509 a quiet LDL season (see Fig. 10 as well, which is the time series obtained from the lat-
 510 itude vs time plot by averaging also in the latitude band $60^\circ\text{S} - 40^\circ\text{N}$).

511 Nevertheless, the optical depth abruptly increased after $L_S \approx 186^\circ$ due to the on-
 512 set of the GDE, which rapidly grew to the west of Meridiani Planum, expanded eastwards
 513 and southwards, and spread a large amount of dust at all longitudes within approximately

514 a latitude band 60°S–40°N (see its daily evolution over 12 sols in Fig. 11), then slowly
 515 decayed over about 130 sols, as can be observed from the tail of the GDE peak in Fig. 10.

516 MY 34 also featured two other maxima in CDOD that are climatologically consist-
 517 ent with all other 10 previously observed years: one at southern polar latitudes centered
 518 at $L_S \approx 270^\circ$, and the other in the latitude band 60°S – 40°N peaking at $L_S \approx 325^\circ$.
 519 These maxima are linked respectively to a regional dust storm occurring over the ice-
 520 freed southern polar region, and to a particularly intense late-winter regional storm (see
 521 its daily evolution over 12 sols in Fig.13). The latter has the characteristics of a flush-
 522 ing storm following the Acidalia-Chryse storm track, although its precise origin cannot
 523 be easily tracked in the gridded maps of CDOD. Finally, the absence of the onset of sig-
 524 nificant storms in a range of areocentric solar longitude $250^\circ - 310^\circ$ is also climatolog-
 525 ically consistent with what observed in previous years, except for the solstitial planetary-
 526 scale event of MY 28 (see the so-called “solstitial pause” mentioned in, e.g., Montabone
 527 et al., 2015; Kass et al., 2016; Lewis et al., 2016; Montabone & Forget, 2018; Xiaohua
 528 et al., 2019).

529 Before moving to the analysis of the CDOD diurnal variability, we must consider
 530 one last point about the variability of dust storms. When comparing the daily evolution
 531 of the GDE and the late winter storm at their early stage in Figs. 11 and 13, they look
 532 pretty similar both in intensity and extension. Furthermore, the shapes of the CDOD
 533 peaks in the time series of Fig. 10 are also comparable (both positively skewed, with sharp
 534 increase and long decreasing tail). What really does make the difference is the fact that
 535 a GDE such as the one in MY 34 took about 35 sols of continuous dust injection into
 536 the atmosphere to reach a peak in average CDOD that is more than twice as high than
 537 the one reached by the (rather intense) late-winter regional storm. This includes a much
 538 larger spatial variability during the GDE, as indicated by the root mean square devia-
 539 tion in Fig. 10. An event that was very important in boosting the equinoctial dust storm
 540 into the GDE class was the activation of secondary lifting centers in the Tharsis region,
 541 which seems to have started around SOY 401 in the gridded maps ($L_S \approx 197^\circ$), and
 542 later in the Terra Sabaea region — although one cannot distinguish from the maps whether
 543 the increase of optical depth in this region was the result of eastward transport from Thar-
 544 sis or local dust lifting, or both. Bertrand et al. (2019) highlight this event as well, and
 545 analyze it using simulations with the NASA Ames Mars GCM guided by the kriged maps
 546 described in this paper. When looking at the CDOD daily evolution in Fig. 12, this Thar-
 547 sis event can be considered as a “storm within the storm”, without which we might have
 548 only witnessed a regional storm instead of a GDE. This is one of the reasons why names
 549 such as “global dust storm” or “planet-encircling dust storm” do not seem to capture the
 550 real nature of this type of extreme events, which are not single storms nor uniquely planet-
 551 encircling. Perhaps even “global dust event” is not particularly appropriate, as high lat-
 552 itude regions are mostly free of dust — although indirectly affected by the dust via dy-
 553 namical effects, but this can be true for regional dust storms as well. One possibility is,
 554 therefore, to give these events a name that represents what they really are: “extreme dust
 555 events” (EDE).

556 Another extreme characteristic of the MY 34 equinoctial event is its strong diur-
 557 nal variability, clearly observed by MCS in the vertical expansion of the dayside vs night-
 558 side dusty region (see Kleinböhl et al., 2019), but also featured in the column optical depth
 559 values, as already shown in Fig. 4. The time series at different locations extracted from
 560 the dataset with four MUT maps per sol and shown in Fig. 14 clearly illustrates this phe-
 561 nomenon. The nightside-dayside variability is different at different locations, but is par-
 562 ticularly dramatic in Aonia Terra (to the East of the Argyre Planitia, 90°W–60°W lon-
 563 gitude and 60°S–30°S latitude), which is located in the southern latitude band where
 564 Kleinböhl et al. (2019) observe strong variability in the dust profiles. In Fig. 15, there-
 565 fore, we compare the CDOD values in Aonia Terra at two times during the GDE (i.e.
 566 during its growth phase and near the peak) with the corresponding dust opacity profiles

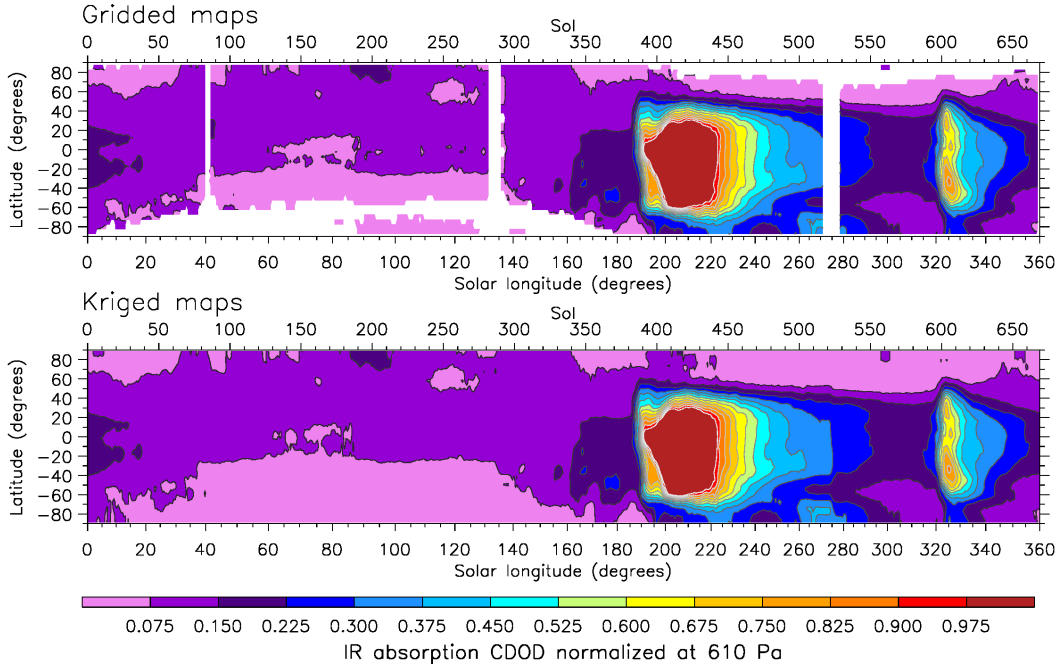


Figure 9. MY 34 latitude vs time plot of the zonally and diurnally averaged gridded maps of 9.3 μm absorption column dust optical depth normalized to the reference pressure level of 610 Pa (upper panel), compared to the same using kriged maps (lower panel). The white color in the upper panel indicates that no valid grid points are available at the corresponding times and latitudes. Kriged maps are complete (all grid points have valid values), therefore no white colour is present in the lower panel.

567 that are extrapolated and integrated in order to estimate the CDODs. The vertical ex-
 568 pansion of about 20 km of the dayside dusty region with respect to the nightside one is
 569 quite spectacular at $L_S \approx 207^\circ$, near the peak of the GDE. Unfortunately, with the rise
 570 in altitude of the dusty region comes the rise in cut-off altitude of the dust profile retrievals.
 571 However, from Fig. 15 one cannot conclude that the homogeneously mixed dust hypoth-
 572 esis at the core of our dust profile extrapolation to the ground does not hold in these cases.
 573 Conversely, there is no evidence that rising dust is replaced by more well-mixed dust in
 574 the missing part of the profile, because we simply have no data there. Furthermore, un-
 575 certainties at the lowest levels of the dust profiles during the GDE tend to be larger (see
 576 e.g. left panel of Fig. 1 in Kleinböhl et al., 2019), hence the real shape of the profile in
 577 the lowest two scale heights could provide some surprises.

578 At this point of the analysis, we can make three hypotheses about the diurnal vari-
 579 ability observed in MCS CDOD:

- 580 1. There is an intrinsic, significant variability of the column dust abundance. In this
 581 case, quite a substantial amount of dust must be supplied in the lowest two scale
 582 heights during the day, which MCS cannot see through. This extra dust must ei-
 583 ther be lifted locally from the ground or supplied via horizontal advection (or both).
 584 Local mesoscale effects might operate at different locations (e.g. katabatic/anabatic
 585 winds, strong convective activity, etc.)
- 586 2. There is no significant variability in the column dust abundance. In this case, at-
 587 mospheric dust is simply moved up and down during the day/night, and the day-

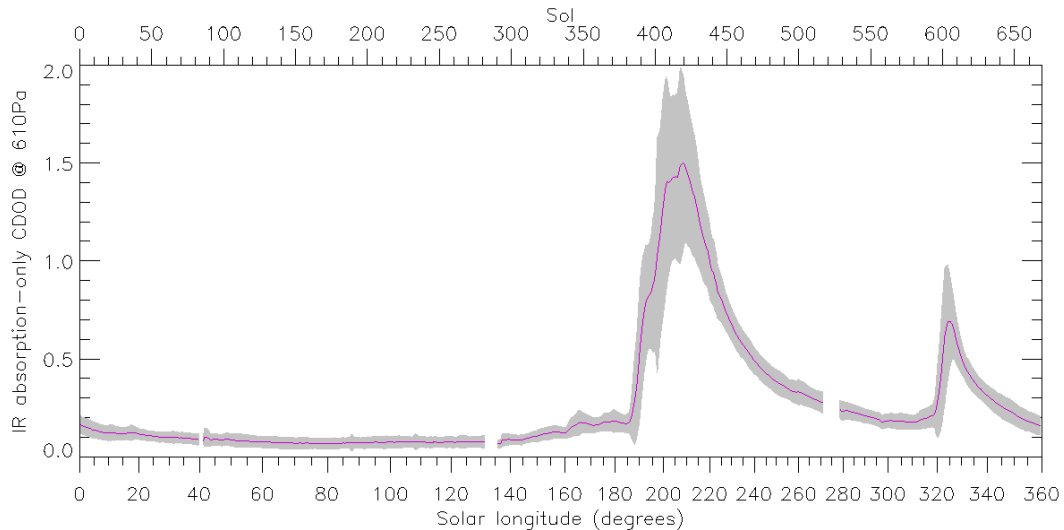


Figure 10. Time series of column dust optical depth ($9.3\ \mu\text{m}$ in absorption, normalized to 610 Pa) extracted from the diurnally averaged gridded maps and averaged at all longitude in the latitude band $60^\circ\text{S} - 40^\circ\text{N}$. The grey shade represents the root mean squared deviation, i.e. the spatial variability within the averaged longitudes and latitudes (note that the diurnal variability is not included).

588 side dust opacities actually decrease with decreasing altitude in the lowest scale
 589 heights, which are not seen by MCS. The diurnal variability of the dust opacity
 590 profiles in the lowest two scale heights during the GDE would then be expected
 591 to be very large, in order to compensate for the vertical expansion of the dust cloud.
 592 3. There is some variability in the column dust abundance. In this case, dust is partly
 593 moved up and down at different local times, and partly lifted locally, or advected
 594 from nearby locations.

595 In order to help clarify which hypothesis is more likely, we have carried out simulations
 596 with the LMD-GCM, which we discuss in the next section.

597 4 Global Climate Model simulations of the MY 34 Global Dust Event

599 The simulations we have carried out using the LMD-MGCM have similar charac-
 600 teristics to those carried out to build the Mars Climate Database version 5.3 (Millour
 601 et al., 2015), except for the model top being set lower (at 100 km compared to 250 km,
 602 with 29 rather than 49 vertical levels) and the thermospheric parameterizations (González-
 603 Galindo et al., 2011) being switched off. The most up-to-date physical parameterizations
 604 are included: interactive dust cycle (explained in the next paragraph, Madeleine et al.,
 605 2011), thermal plume model (a physically-based parameterization for Planetary Bound-
 606 ary Layer —PBL— mixing, Colaïtis et al., 2013), water cycle with radiative effect of clouds
 607 (a key element to account for the measured atmospheric and surface temperatures, Madeleine
 608 et al., 2012; Spiga et al., 2017), and full microphysics scheme (in which the transported
 609 dust particles could serve as condensation nuclei for the formation of water-ice clouds,
 610 Navarro et al., 2014). The “rocket dust storm” parameterization recently built and tested
 611 by Wang et al. (2018) is not included in this version of the GCM. The horizontal grid
 612 features 64×48 longitude-latitude points.

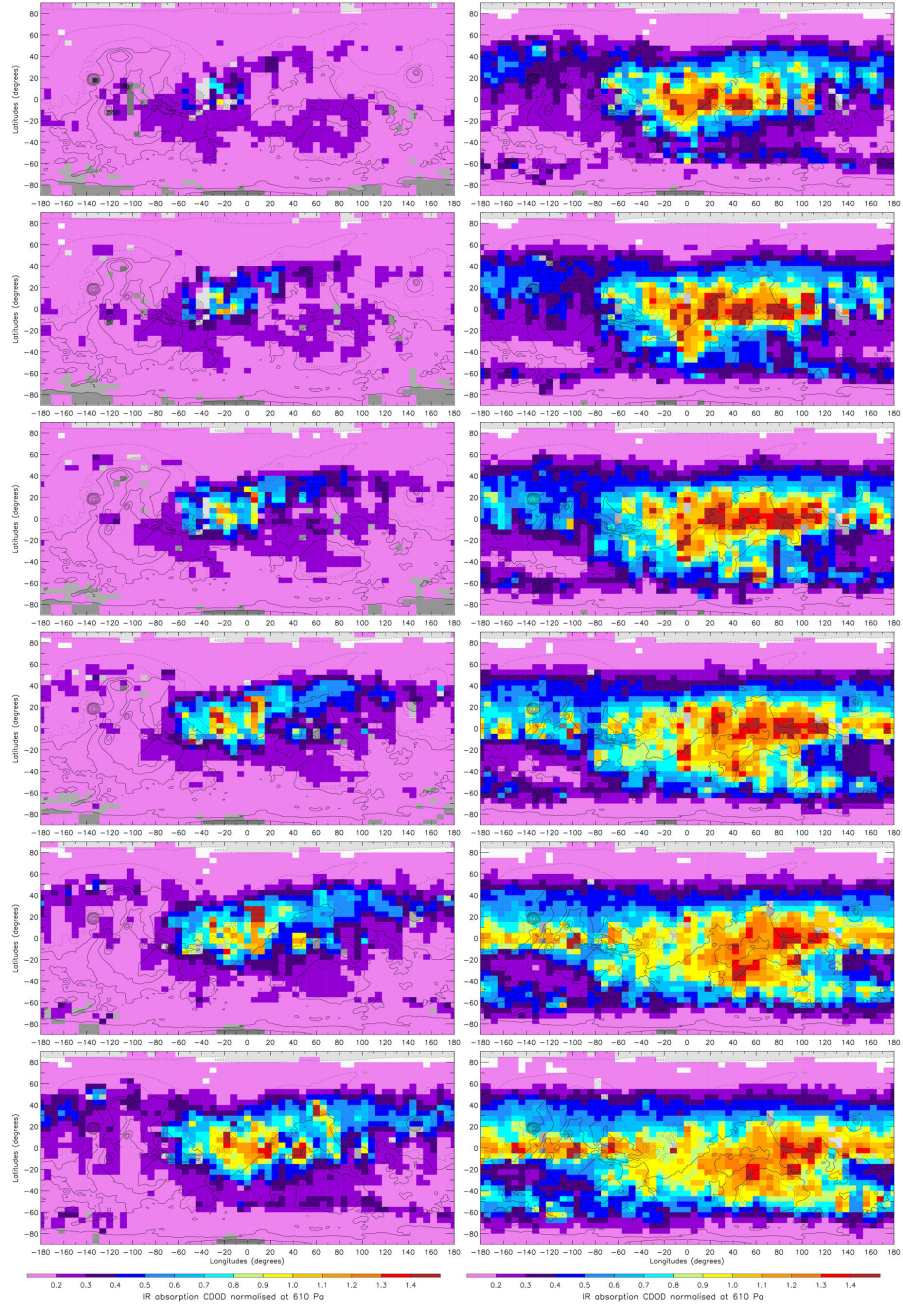


Figure 11. Initial evolution of the MY 34 Global Dust Event. Each panel shows diurnally averaged gridded column dust optical depth (in absorption at $9.3 \mu\text{m}$) normalized to the reference pressure level of 610 Pa. From top left to bottom right, maps are provided for (sol-of-year/ L_S): $383/186.2^\circ$; $384/186.8^\circ$; $385/187.4^\circ$; $386/188.0^\circ$; $387/188.6^\circ$; $388/189.2^\circ$; $389/189.8^\circ$; $390/190.4^\circ$; $391/191.0^\circ$; $392/191.6^\circ$; $393/192.2^\circ$; $394/192.8^\circ$. L_S is calculated at MUT=12:00 of each sol, and rounded to one decimal place. See also Appendix A of Montabone et al. (2015) for the description of the sol-based Martian calendar we use in this paper.

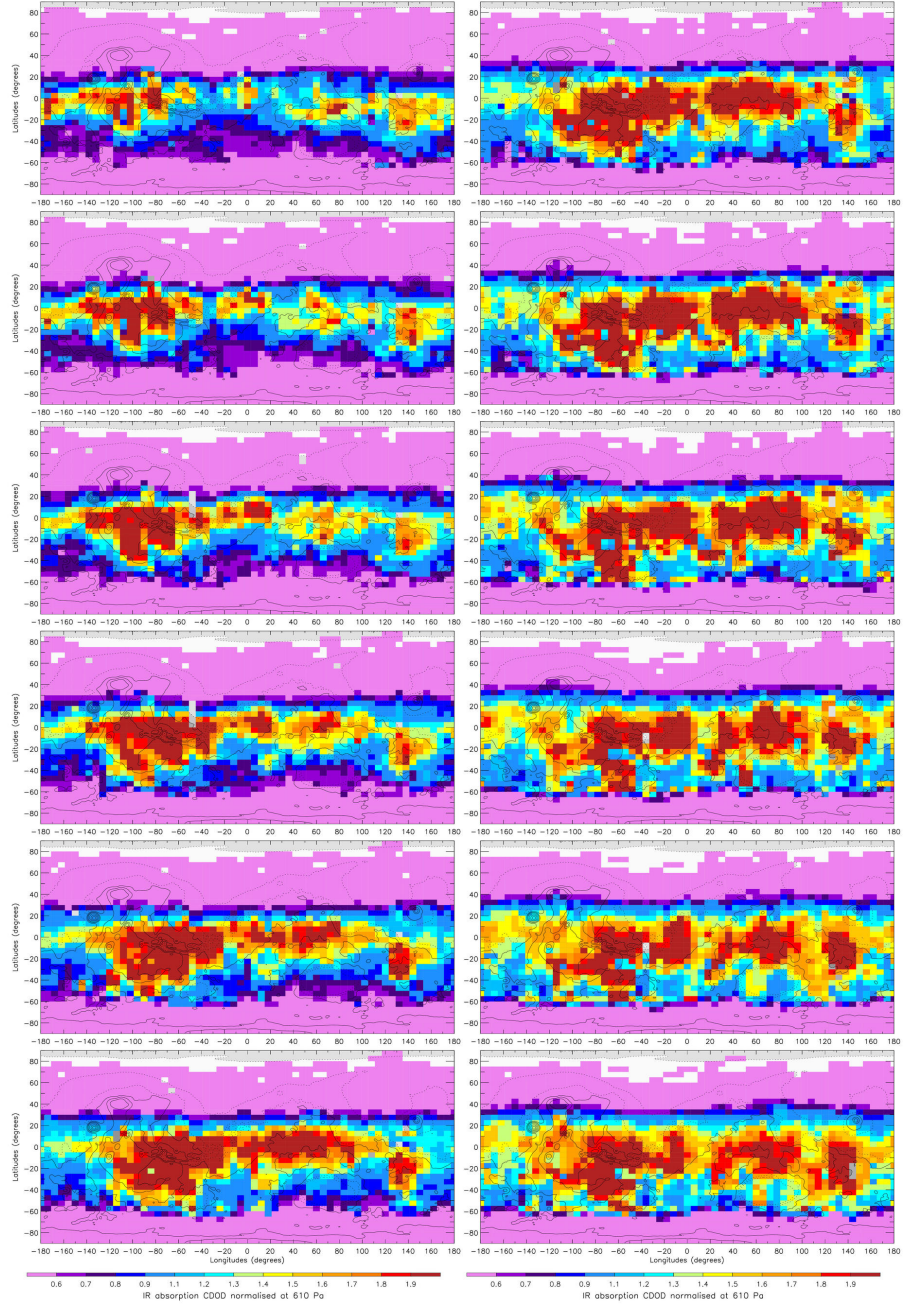


Figure 12. Same as Fig.11 but for the MY 34 secondary storm within the GDE. From top left to bottom right, maps are provided for (sol-of-year/ L_S): 401/197.0°; 402/197.6°; 403/198.2°; 404/198.8°; 405/199.4°; 406/200.0°; 407/200.7°; 408/201.3°; 409/201.9°; 410/202.5°; 411/203.1°; 412/203.7°. L_S is calculated at MUT=12:00 of each sol, and rounded to one decimal place. Note that the scale for the CDOD values has changed with respect to Fig. 11.

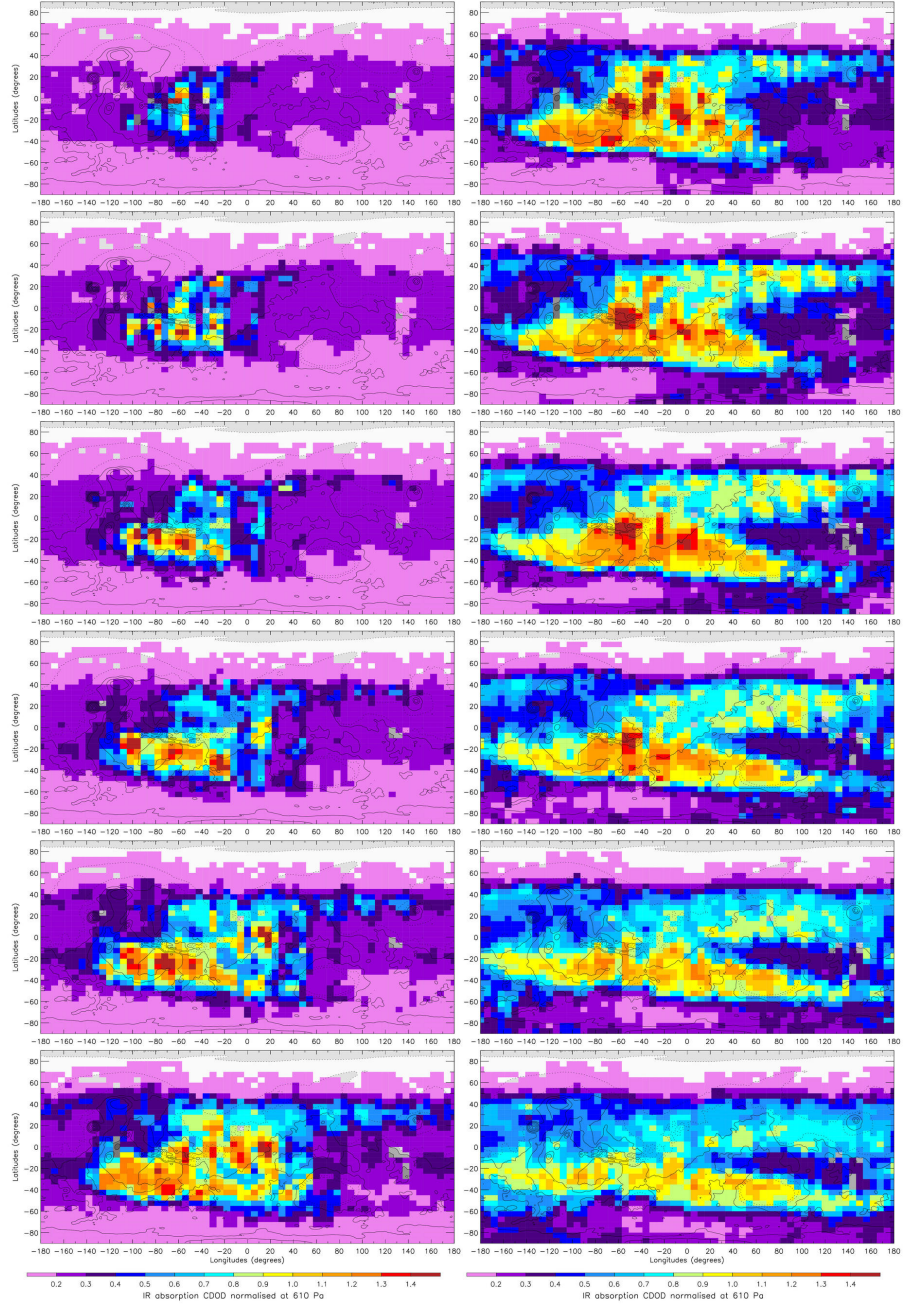


Figure 13. Same as Fig.11 but for the MY 34 late-winter regional storm. From top left to bottom right, maps are provided for (sol-of-year/ L_S): 596/320.0°; 597/320.6°; 598/321.2°; 599/321.8°; 600/322.4°; 601/322.9°; 602/323.5°; 603/324.1°; 604/324.7°; 605/325.2°; 606/325.8°; 607/326.4°. L_S is calculated at MUT=12:00 of each sol, and rounded to one decimal place. The scale for the CDOD value is the same as in Fig. 11.

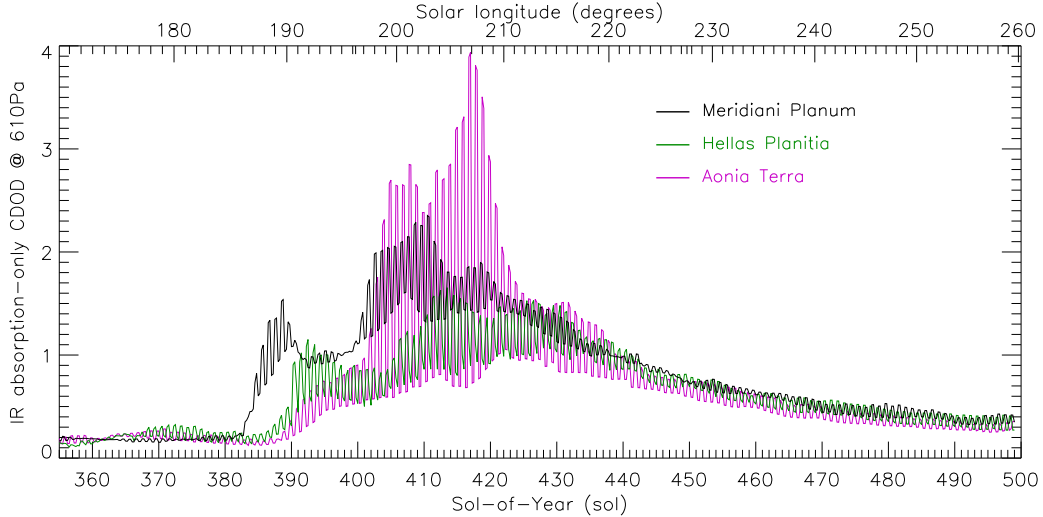


Figure 14. Time series of column dust optical depth ($9.3 \mu\text{m}$ in absorption, normalized to 610 Pa) extracted from the gridded maps with four MUT per sol and spatially averaged in three different areas: Meridiani Planum ($15^\circ\text{W} - 15^\circ\text{E}$ longitude, $15^\circ\text{S} - 15^\circ\text{N}$ latitude), Hellas Planitia ($55^\circ\text{E} - 85^\circ\text{E}$ longitude, $60^\circ\text{S} - 30^\circ\text{S}$ latitude), and Aonia Terra (East of Argyre Planitia: $90^\circ\text{W} - 60^\circ\text{W}$ longitude, $60^\circ\text{S} - 30^\circ\text{S}$ latitude). The boundaries of the three areas can be visualized as colored squares in the upper panel of Fig. 6. The time series are shown between Sol-of-Year 355 and 500, i.e. $L_S \approx 170^\circ - 260^\circ$.

613 A complete description of the interactive dust cycle is included in Madeleine et al.
 614 (2011) and Spiga et al. (2013). To summarize, the transport of dust particles by the re-
 615 solved dynamics is based on a two-moment scheme: the particle size distribution is fully
 616 described by two tracers (mass mixing ratio and number density) assuming a log-normal
 617 distribution of constant standard deviation. When a column-integrated dust scenario (such
 618 as the one described herein for MY34) is used in a LMD-GCM run, the value of total
 619 column dust opacity is normalized at each timestep by the value in the dust scenario.
 620 The vertical distribution of dust particles in the LMD GCM simulation remains a pre-
 621 diction from the model.

622 A run without the normalization of the total column dust opacity by the value pro-
 623 vided in the dust scenario is named a “free-dust” run, since both the column opacity and
 624 the vertical distribution of dust particles are fully predicted by the model. For GCM sim-
 625 ulations guided by the column-integrated dust scenario, spatially uniform lifting rate is
 626 assumed all over the planet, with dust particles being injected in the first layers of the
 627 model PBL (Madeleine et al., 2011). Conversely, our “free-dust” run assumes no lifting
 628 of dust particles from the surface. Only the normalization of the total column dust opac-
 629 ity, and the lifting of dust particles from the surface, are different between a regular GCM
 630 simulation and a “free-dust” simulation. Physical processes such as sedimentation, cloud
 631 scavenging, and small-scale mixing of dust particles, are still included in the “free-dust”
 632 GCM simulation. The goal of the “free-dust” GCM simulation is thus to clearly identify
 633 how the combination of atmospheric dynamics and sinks (sedimentation, cloud scaveng-
 634 ing) is acting to modify the spatial distribution of dust particles in the martian atmo-
 635 sphere. This kind of GCM simulation is appropriate for either the clear season, or the
 636 decaying phase of dust storms (the latter being the case considered here). During 10 to

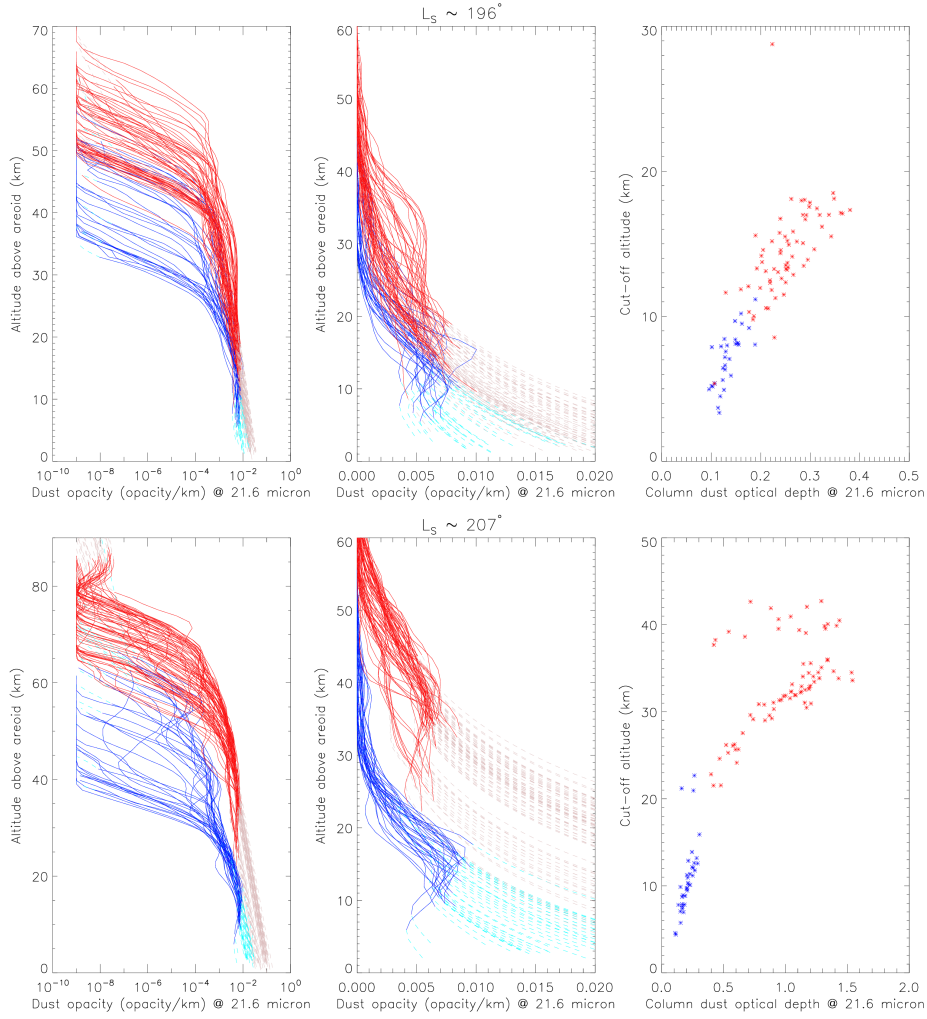


Figure 15. Data plotted in each panel of this figure are for 7 sols centered on either sol-of-year 400 ($L_s \approx 196^\circ$, upper panels) or sol-of-year 418 ($L_s \approx 207^\circ$, lower panels) in Aonia Terra ($90^\circ\text{W} - 60^\circ\text{W}$ longitude, $60^\circ\text{S} - 30^\circ\text{S}$ latitude). Blue indicate nightside data, red is for dayside data. The left and central panels of this figure show the retrieved MCS dust opacity profiles (solid, vivid lines) and the extrapolated sections (dashed, pastel lines) as a function of altitude above the areoid (topography values are interpolated from the MOLA dataset at the corresponding longitudes and latitudes). The x-axis is logarithmic in the left panels, whereas it is linear in the central ones, to better separate the profiles in the lowest scale heights. The right panels show the integrated MCS CDOD in extinction at $21.6 \mu\text{m}$ (not normalized to 610 Pa) as a function of the cut-off altitudes of their corresponding dust opacity profiles. Note that the x-axis and y-axis ranges can be different among the panels.

637 20 sols of simulation, the global column opacity predicted by the model does not depart
638 significantly from the global column opacity reported in the dust scenario.

639 The initial state for the MY 34 run at $L_S = 0^\circ$ uses the “climatological” column-
640 integrated dust scenario typical of MYs devoid of global dust events. Then, two simu-
641 lations for MY 34 are carried out:

- 642 1. a simulation using the reference MY 34 dust scenario v2.5 (i.e. the maps kriged
643 from the diurnally averaged gridded maps, as discussed in Section 2.5) to guide
644 the column dust field throughout the GDE period;
- 645 2. a simulation using the MY 34 dust scenario until $L_S = 210^\circ$ (around the peak
646 of the GDE), then continuing as a “free-dust” run for a few sols, with no more ex-
647 ternal guidance on the column dust field and no more regular injection of dust par-
648 ticles at the bottom of the model, as explained in the previous paragraph.

649 The LMD-MGCM simulations for MY 34 are also used in Kleinböhl et al. (2019)
650 to discuss the diurnal cycle of the vertical distribution of dust observed by MCS. We use
651 the two types of simulations for two different purposes: 1. the forced run is used to anal-
652 yse some of the impacts of the MY 34 GDE on the local and global atmospheric dynam-
653 ics, thus verifying that the use of a diurnally averaged dust scenario produces reason-
654 able results; 2. the “free-dust” run is used to identify possible diurnal variability of the
655 column dust in the model, which could corroborate one of the three hypotheses provided
656 at the end of the last section.

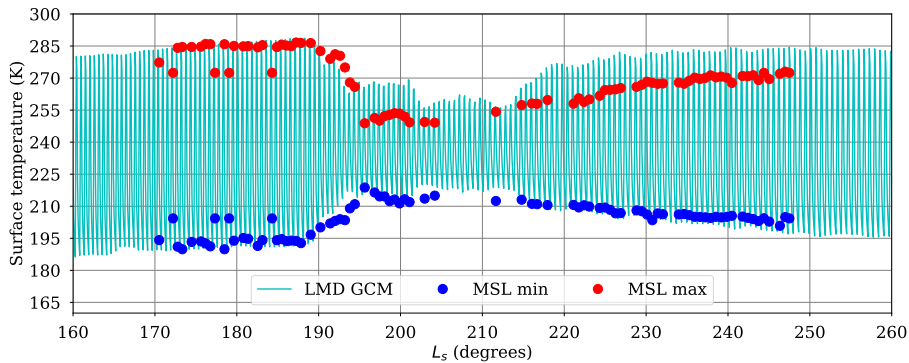


Figure 16. Comparison of surface temperature simulated by the LMD-MGCM model ver-
sus surface temperature measured by the Rover Environmental Monitoring Station (REMS)
on board MSL “Curiosity” rover (diurnal minimum in blue and diurnal maximum in red). Data from
MSL are provided as supplementary material of Guzewich et al. (2019). The model simulation is
guided by the column-integrated dust scenario.

657 Figure 16 shows a comparison between the surface temperature measured by Cu-
658 riosity (Guzewich et al., 2019) and the surface temperature computed by the LMD-MGCM.
659 When the MY 34 global dust event starts, the diurnal amplitude of temperature is re-
660 duced: daytime temperatures are lower as a result of visible absorption of incoming sun-
661 light being more efficient in a dustier atmosphere, and nighttime temperatures are higher
662 as a result of increased infrared radiation emitted towards the surface in a dustier at-
663 mosphere. The temporal variability of temperature (absolute and relative values) is well
664 reproduced for the nighttime minimum temperature, but less so for the daytime tem-
665 peratures (although the qualitative behaviour is correct). There might be three reasons

666 for this: 1. thermal inertia is not well represented in the LMD-MGCM for daytime con-
 667 ditions in Gale Crater; 2. the CDOD observed by MCS in the region of Gale crater is un-
 668 derestimated with respect to the one observed by Curiosity from $L_S \approx 195^\circ$ to $L_S \approx$
 669 202° , and by consequence the corresponding gridded and kriged maps are low-biased at
 670 those times (see Fig. 7 in Section 2.6); 3. the accuracy of the calculations by the model
 671 radiative transfer could decrease under extreme dust loading conditions, or could be af-
 672 fected by an inaccurate distribution of particle sizes.

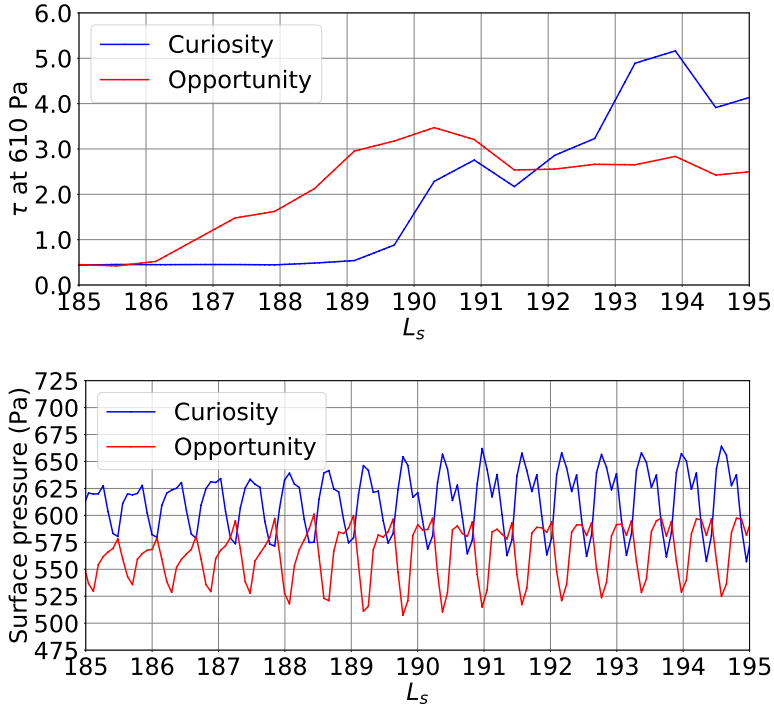


Figure 17. Time series of equivalent-visible column dust optical depth at 610 Pa (upper panel) and surface pressure (lower panel) as simulated by the LMD Mars GCM guided by the MY 34 column-integrated dust scenario. The focus of the figure corresponds to the onset of the GDE. This is showing the simulated fields at the Opportunity (red curves) and Curiosity (blue curves) landing sites.

673 An important test of the dynamical behavior of our LMD-MGCM simulation forced
 674 by the MY 34 column-integrated dust scenario is how thermal tides react to the global
 675 increase of dust opacity following the onset of the GDE. Figure 17 shows several diurnal
 676 cycles of surface pressure at the time of the GDE onset. Both the amplitude of the
 677 diurnal pressure cycle, and its morphology, are modified by the GDE at its onset. The
 678 diurnal pressure cycle is dominated by the diurnal tide before the GDE takes place. When
 679 the GDE starts to build up and the column optical depth increases, the diurnal mode
 680 increases slightly in amplitude while the semi-diurnal mode increases significantly com-
 681 pared to the other modes, as already described in previous studies (Zurek & Martin, 1993;
 682 Wilson & Hamilton, 1996; Lewis & Barker, 2005, their Figure 5). The reinforcement of
 683 the semi-diurnal tide with increased column opacity is due to the fact that this tide com-
 684 ponent is dominated by a Hough mode with a large vertical wavelength (Chapman &
 685 Lindzen, 1970). As a result, this Hough mode is very sensitive to forcing extended in al-
 686 titude such as the absorption of incoming sunlight by dust particles during a dust storm.

687 Those major changes in the tidal modes take only a couple of sols to react to the
 688 MY34 GDE onset, and the simulations show that those changes are global. This is true
 689 for both the Opportunity site, located close to the regional storm that initiated the MY34
 690 GDE, and the Curiosity site, at which dust opacity started to increase about 5° later than
 691 at the Opportunity site. Hence, at the Curiosity site, both the amplification of the di-
 692 urnal and semi-diurnal modes in the simulated surface pressure are predicted to occur
 693 before dust opacity increases locally. This is in agreement with the observations by Cu-
 694 riosity of the diurnal pressure amplitude, which is found to react about 4 sols before the
 695 increase of dust opacity observed by Curiosity in Gale Crater (Viúdez-Moreiras et al.,
 696 2019).

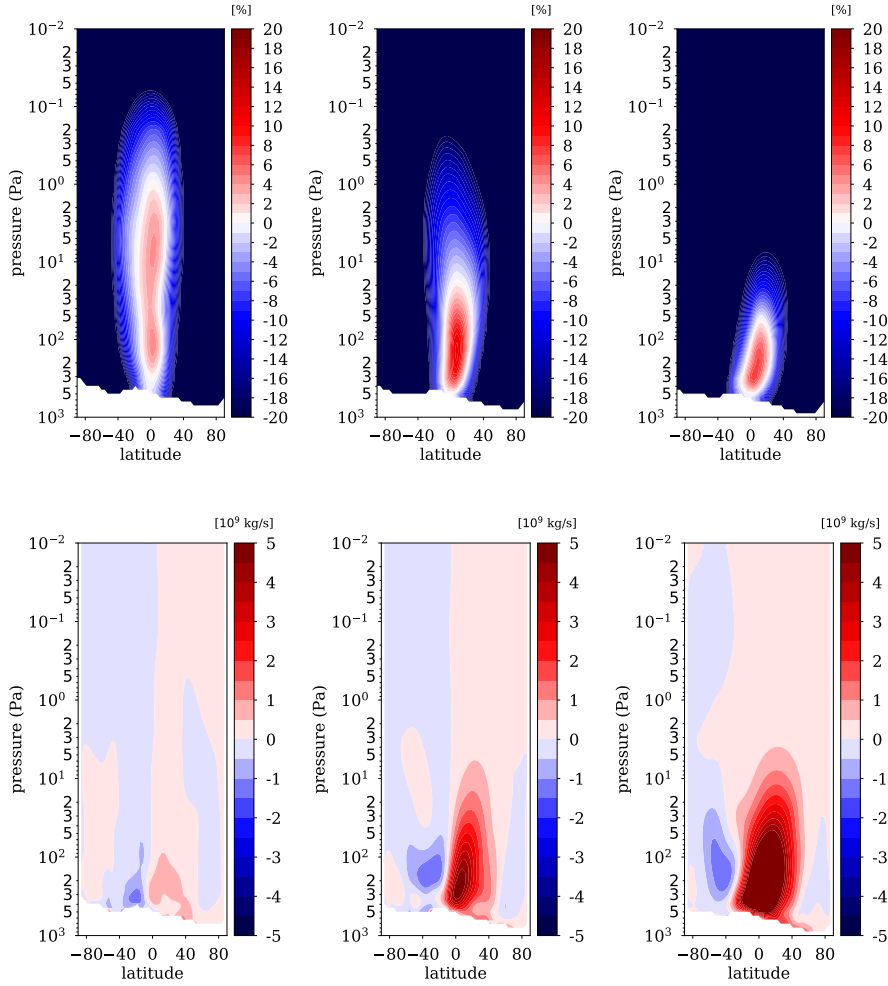


Figure 18. The impact of the MY 34 GDE on the zonally-averaged global circulations on Mars is shown from left to right, averaged on the L_S intervals 150° – 180° (pre-GDE conditions), 180° – 210° (onset of the GDE), and 210° – 240° (mature phase of the GDE). [Top] Super-rotation index s computed according to Lewis & Read (2003) with positive values denoting regions where eastward jets are super-rotating i.e. exceeding the solid-body rotation of the planet. [Bottom] Mass streamfunction with blue regions corresponding to counterclockwise circulation and red regions corresponding to clockwise circulation.

697 The increase in column dust optical depth associated with the MY 34 GDE has a
698 profound impact on the large-scale circulation. Lewis & Read (2003) evidenced an equa-
699 torial low-troposphere super-rotating jet in the atmosphere of Mars, and emphasized the
700 strong positive impact of the atmospheric dust loading on this jet. Our LMD-MGCM
701 forced simulation for MY 34 shows that the intensity of this super-rotating jet, diagnosed
702 by the super-rotation index as in Lewis & Read (2003), is indeed increased following the
703 onset of the GDE from a 5% super-rotation index to a 15% super-rotation index. We
704 also find that this jet becomes confined closer to the surface as the GDE develops (Fig-
705 ure 18, top panels). The mean meridional circulation is also deeply impacted by the large
706 dust loading following the onset of the MY 34 GDE: the intensity of this mean merid-
707 ional circulation is enhanced by a factor of 10 following the onset and mature phase of
708 the GDE (Figure 18, bottom panels). This behaviour is similar to the evolution of the
709 mean meridional circulation simulated under MY 25 GDE conditions (see e.g. Montabone
710 et al., 2005).

711 Finally, we discuss the use of a “free dust” simulation to gain some insights on the
712 diurnal variability of CDOD in the GCM model. GCM simulations show that large-scale
713 circulation components (i.e. the mean meridional circulation, planetary waves, and the
714 polar vortex) cause the vertical distribution of dust to undergo diurnal variations both
715 in equatorial and extratropical regions (Kleinböhl et al., 2019). Figure 19 shows the col-
716 umn dust optical depth simulated in the free-dust LMD-MGCM run after $L_S = 210^\circ$
717 (i.e. near the peak of the MY 34 storm). The total column optical depth freely evolves
718 in the simulation without being normalized using the values in the MY 34 column-integrated
719 dust scenario. As observed in the MCS CDOD values, and by consequence in the grid-
720 deded/kriged maps reconstructed following the method described in this paper, the col-
721 umn optical depth in the “free dust” model run varies significantly on a diurnal basis in
722 some regions. Figure 20 shows that the modeled diurnal anomalies in visible column dust
723 optical depth can reach about $\bar{\tau} \pm 1.5$ in specific regions – particularly Aonia Terra, as
724 observed in the estimates for MCS CDODs. It also clearly shows that a strong wavenumber-
725 1 wave is present at mid-latitudes in the southern hemisphere, which coincides with what
726 is observed for instance in Fig. 5. Furthermore, when looking at anomaly maps for more
727 than one sol, they also show that baroclinic waves are present at low latitudes in the north-
728 ern hemisphere, thus explaining the variability at other locations (not shown here).

The diurnal variability of the CDOD reproduced by the model results from hor-
horizontal transport by the large-scale circulation. To diagnose this, and to rule out the in-
influence of sinks of dust particles still included in the “free dust” GCM simulation, such
as sedimentation and cloud scavenging, the temporal change $\partial q / \partial t$ of dust mass mix-
ing ratio q can be compared to the divergence $\nabla \cdot (q\vec{v})$, which represents the horizon-
tal flux of dust particles transported by the horizontal wind \vec{v} . Under the assumption
that the wind transport of dust particles dominates the sinks, the two terms should be
strongly correlated since the horizontal transport is simply governed by a conservation
law, which states:

$$\frac{\partial q}{\partial t} + \nabla \cdot (q\vec{v}) = 0.$$

729 Figure 21 provides a mapping of the two terms, along with wind vectors, at an altitude
730 where the diurnal contrasts in dust mixing ratio are particularly strong (see Figure 15).
731 At every local time in a sol, the divergence term and the temporal term are closely re-
732 lated. Especially in the southern hemisphere, the diurnal cycle of atmospheric circula-
733 tions — notably the thermal tides amplified by the dust storm conditions — cause a sig-
734 nificant diurnal cycle of horizontal transport of dust particles, hence an overall diurnal
735 cycle of the column opacity at particular locations (such as Aonia Terra exemplified pre-
736 viously). Through the horizontal transport of dust particles, daytime regions are a “source”
737 of dust particles, while nighttime regions are a “sink” of dust particles. Hence, in this study,
738 we show that a diurnal cycle of column opacity is associated with the diurnal cycle of
739 vertical distribution of dust particles evidenced in Kleinböhl et al. (2019).

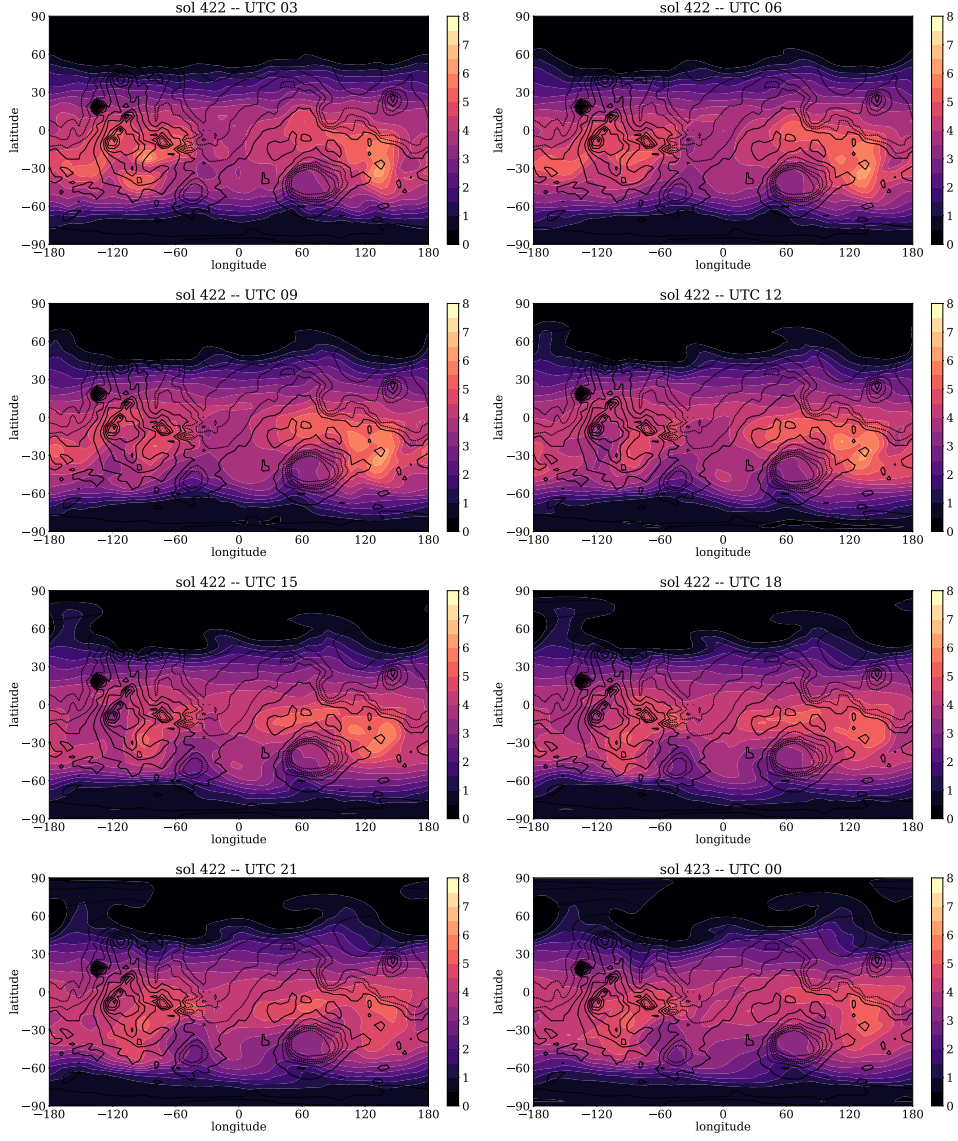


Figure 19. Sequence of column dust optical depth maps separated by 3 hours over one sol in a LMD-MGCM “free dust” simulation where, contrary to the simulation guided by the MY 34 column-integrated dust scenario, the dust mass mixing ratio in the model is not normalized to match the total column dust optical depth of the scenario. This “free dust” simulation was restarted from the simulated state of the atmosphere at $L_S = 210^\circ$ in a regular LMD-MGCM simulation guided by the MY 34 dust scenario.

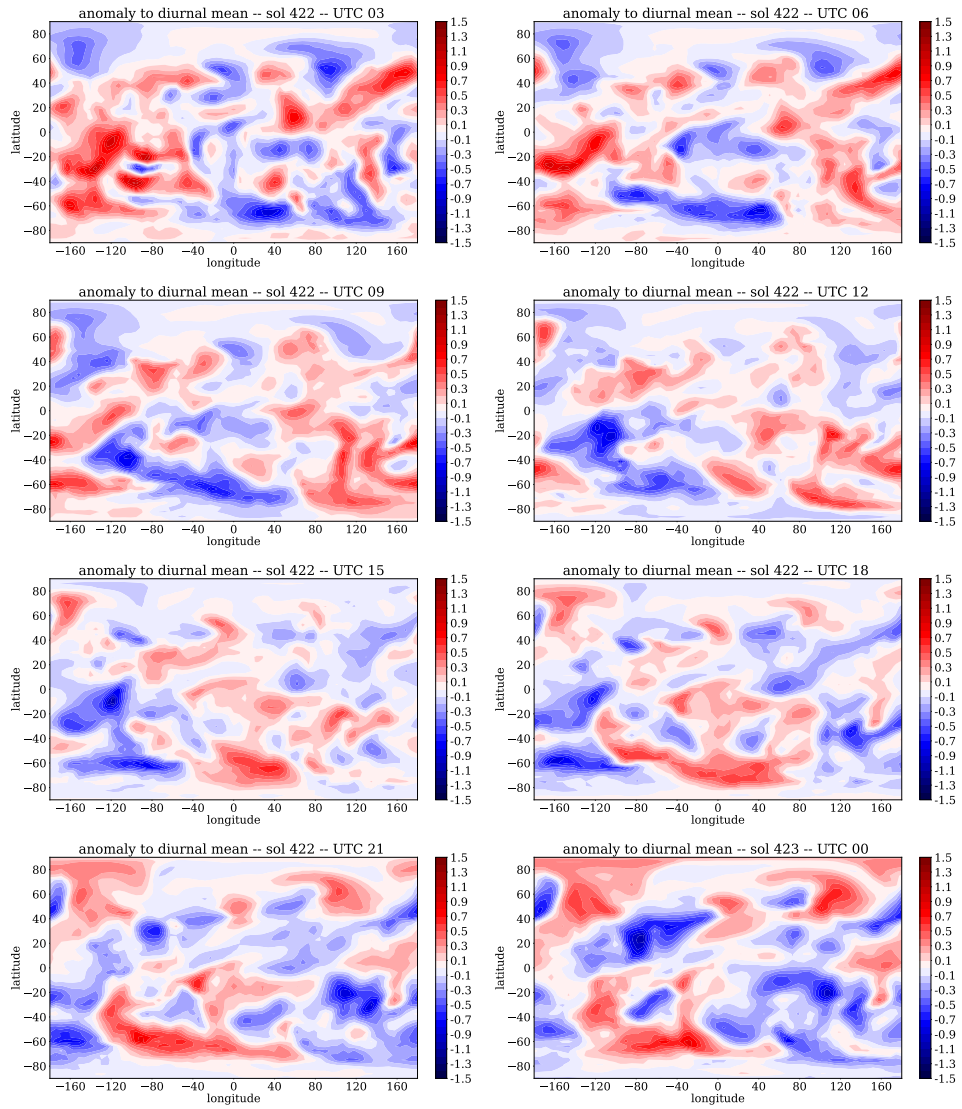


Figure 20. Same as Figure 19 except that the anomaly relative to the diurnal mean is shown.

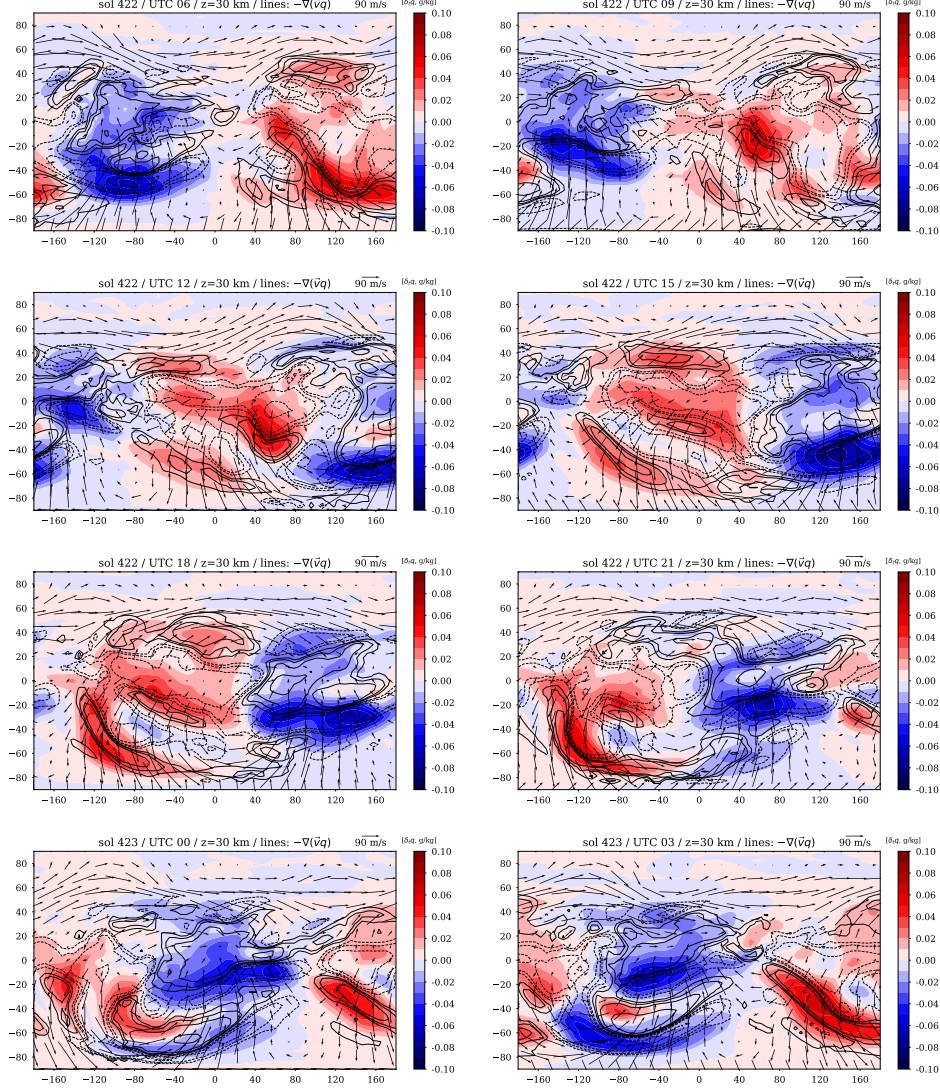


Figure 21. Sequence of maps separated by 3 hours over one sol in a LMD-MGCM “free dust” simulation (see the caption of Figure 19). Colors depict the temporal variation of dust mass mixing ratio q within a time interval corresponding to the considered local time ± 3 hours. Lines depict the horizontal divergence of dust flux $q\vec{v}$, i.e. the horizontal transport of dust particles. The horizontal wind vectors \vec{v} are superimposed. Note that the first panel (top left) is at 06:00 MUT because the temporal derivative uses data from the previous output at 03:00 MUT.

740 While it is not possible to rule out the other possible interpretations for the ob-
 741 served diurnal variability of column dust optical depth as discussed at the end of Sec-
 742 tion 3, the LMD-MGCM results in Figure 19 strongly suggest that this variability has
 743 a physical basis, and at least part of it is likely related to the large-scale horizontal trans-
 744 port. Vertical transport also likely plays a central role, as discussed in Kleinböhl et al.
 745 (2019). What our GCM simulation cannot tell, however, is how much specific mesoscale
 746 phenomena, including dusty deep convection (i.e. “rocket dust storms”, Spiga et al., 2013),
 747 or PBL processes, contribute to the stronger diurnal variability observed by MCS.

748 5 Conclusions and remarks

749 The work described in this paper was devoted to 1. reconstructing maps of column
 750 dust optical depth for MY 34 from Mars Reconnaissance Orbiter/Mars Climate Sounder
 751 observations, 2. analyzing the seasonal, daily, and diurnal variability of column dust showed
 752 by the maps, and 3. using numerical simulations with the Laboratoire de Météorologie
 753 Dynamique Mars Global Climate Model, forced by or simply initiated with the recon-
 754 structed CDOD maps, in order to examine some aspects of the impact of the MY 34 global
 755 dust event on local and global scale atmospheric dynamics, including the diurnal vari-
 756 ability of column dust.

757 The reconstructed maps for MY 34 follow the work by Montabone et al. (2015) and
 758 extend the publicly available multi-annual, multi-instrument climatology of column dust
 759 optical depth to 11 Martian years. An important difference of the present work with re-
 760 spect to Montabone et al. (2015) is that we now reconstruct diurnally-varying maps of
 761 column dust, which provides access to the analysis of the diurnal variability of this quan-
 762 tity. This is made possible by using novel retrievals (version 5.3.2) of dust opacity pro-
 763 files from MCS observations during the period May 21, 2018, to October 15, 2018 ($L_S =$
 764 $179^\circ - 269^\circ$ in MY 34), which extend lower in altitude than standard version 5.2 retrievals.
 765 In general, therefore, the estimated column dust optical depth values during the global
 766 dust event of MY 34 are more accurate, within the intrinsic limitations of estimating CDODs
 767 from limb observations.

768 The analysis of the MY 34 column dust variability at different temporal scales us-
 769 ing the reconstructed maps highlights that:

- 770 • MY 34 reproduces the dichotomy observed in the 10 previous years between the
 771 “low dust loading” and the “high dust loading” seasons. Note that MY 35, which
 772 started in March 2019, features an unusual regional dust storm during the LDL
 773 season at $L_S \approx 35^\circ$ (D. Kass, personal communication). However, its intensity
 774 and duration, preliminarily estimated from CDOD maps using MCS observations,
 775 are still compatible with the concept of a “low dust loading” season;
- 776 • It also features other typical characteristics of the seasonal evolution of CDOD,
 777 such as large values at southern polar latitudes peaking at $L_S \approx 270^\circ$, a solsticial
 778 pause in a L_S range $250^\circ - 310^\circ$, and large values peaking again at $L_S \approx 325^\circ$
 779 during the evolution of an intense late-winter regional dust storm;
- 780 • The key distinction of MY 34 is undoubtedly the equinoctial global dust event (start-
 781 ing at $L_S \approx 186^\circ$ only a few sols after the equivalent event in MY 25), which seems
 782 to feature a “storm within the storm” at $L_S \approx 197^\circ$, boosting its growth to at-
 783 tain extreme characteristics, typical of GDEs;
- 784 • The MY 34 GDE seems also to feature very large CDOD diurnal variability at se-
 785 lected locations, particularly at southern mid- and high-latitudes, as already ob-
 786 served in the corresponding MCS dust opacity profiles by Kleinböhl et al. (2019).

787 While the diurnal variability in dust opacity profiles comes from direct MCS re-
 788 trievals, and could be explained by global climate model simulations invoking the effects
 789 of the large-scale circulation (Kleinböhl et al., 2019), the diurnal variability in the in-

810 directly estimated column dust optical depth values poses more challenging questions.
 811 Is the diurnal variability intrinsic to the column dust, or should we expect that the shape
 812 of the dust profile in the lowest one or two scale heights not directly observed by MCS
 813 (particularly in dayside observations) is not compatible with a homogeneously mixed as-
 814 sumption? Whether the answer leans towards the former or the latter, or a bit of both,
 815 it would provide new knowledge on how dust is three-dimensionally distributed within
 816 Martian dust storms.

817 It is not the purpose of this paper to provide a definite answer to the aforemen-
 818 tioned question. Nevertheless, we have resorted to numerical simulations with the LMD-
 819 MGCM to provide us with some hints. Using a “free dust” model run, initiated at $L_S =$
 820 210° with the reconstructed CDOD field, the model is able to reproduce some diurnal
 821 variability in column dust at selected locations. Despite the fact that both the range of
 822 the variability and the precise locations do not coincide with what is estimated from MCS,
 823 this result provides physical evidence that some degree of diurnal variability can be ex-
 824 pected not only in the upper portion of the dust profiles but also in the whole columns.
 825 Furthermore, the dust lifting and PBL parameterizations of the global model might ac-
 826 tually miss some of the important features that lead to an accurate description of the
 827 three-dimensional dust distribution. The model result might, therefore, underestimate
 828 the real variability of the column dust.

809 What the model simulations clearly show when forced with diurnally averaged CDOD
 810 maps, however, is that the impact of the MY 34 GDE on the atmospheric dynamics is
 811 as large as for the MY 25 GDE. Key features of the local and global dynamics (such as
 812 tides, mean meridional circulation, and equatorial winds) respond to the equinoctial dust
 813 events in a very similar manner. This is also an indirect validation of the MY 34 refer-
 814 ence column-integrated dust scenario based on the diurnally averaged CDOD maps from
 815 MCS, which is currently used in several modeling studies of the 2018 GDE.

816 Future work should address the possibility of producing diurnally-varying (com-
 817 plete) kriged maps from the diurnally-varying (incomplete) gridded ones, and making
 818 them publicly available. As mentioned in Subsection 2.5, we consider that this option
 819 is not currently viable, mainly because the CDOD diurnal variability is not yet indepen-
 820 dently confirmed, and because it is not yet clear whether model simulations forced by
 821 a diurnally-varying, column-integrated dust scenario are free of spurious effects. Current
 822 Mars GCMs might need to be adapted to handle diurnally varying CDODs in a stable
 823 and sensible fashion, if the degree of variability is proved to be as large as the one shown
 824 in this paper. A further technical issue that complicates the production of diurnally-varying
 825 kriged maps is that some of the gridded maps have many missing values (particularly
 826 when the water ice opacity affects the dust opacity), hence some assumptions are required
 827 before applying the spatial interpolation. In the present work, we have bypassed this is-
 828 sue by diurnally averaging the gridded maps before producing the kriged ones. A future
 829 option could also be the production of fully three-dimensional maps, based on the val-
 830 ues of dust opacity at different pressures rather than on the column-integrated values.

831 Strong emphasis should also be put on obtaining future observations of column-
 832 integrated dust as well as dust profiles with diurnal frequency. The Planetary Fourier
 833 Spectrometer (PFS) aboard Mars Express, and the Atmospheric Chemistry Suite (ACS)
 834 aboard Trace Gas Orbiter currently provide the capability to retrieve CDOD at multi-
 835 ple local times, and could help in the comparison with the estimated MCS day-night vari-
 836 ability of column dust. Future observations from the forthcoming Emirates Mars Mis-
 837 sion (EMM) might provide even stronger evidence of the presence or absence of diurnal
 838 variability, due to the spacecraft coverage of multiple local times at once at apoapsis (when
 839 the spacecraft is able to observe the full Martian disk).

840 Moreover, novel approaches should be taken in the future, in order to fully char-
 841 acterize the diurnal cycle of dust and accurately monitor the evolution of dust storms
 842 on Mars. These include:

- 843 • the use of satellites in Mars-stationary orbits (also called “areostationary”), which
 844 are equatorial, circular, planet-synchronous orbits equivalent to geostationary ones
 845 for the Earth (see e.g. Montabone et al., 2018);
- 846 • the use of instruments that allow observation of the vertical distribution of the dust
 847 in the Martian PBL, such as lidars. This is particularly important during dust storms
 848 when IR spectrometers/radiometers (both nadir- and limb-looking) fail to produce
 849 reliable retrievals because of the large atmospheric opacity and the reduced tem-
 850 perature contrast. In this paper we have in fact shown that it would be quite crit-
 851 ical to know whether the assumption of homogeneously mixed dust still holds in
 852 the lowest scale heights in the midst of a dust storm.

853 Appendix A MY 34 dust climatology versioning

854 MCS version 5.3.2 is an interim, experimental version of retrievals, leading to a pos-
 855 sible future improved version of the whole MCS dataset. As a consequence, the MY 34
 856 gridded and kriged datasets should be considered work in progress, as should the datasets
 857 related to other Martian years. It is our intention to regularly update the multi-annual,
 858 multi-instrument dust climatology with new observations, novel retrievals of past obser-
 859 vations, and updated gridding methodologies/features. The updates are likely to be made
 860 publicly available on the Mars Climate Database project webpage at the URL [http://](http://www-mars.lmd.jussieu.fr/)
 861 www-mars.lmd.jussieu.fr/. There exist, therefore, multiple versions of these reference
 862 dust climatologies, notably for MY 34, and we would like to provide in this appendix some
 863 details about the main differences.

864 As mentioned in Section 2, the reference version of the current maps from MY 24
 865 to 32 is v2.0. For this version, the used gridding/kriging methodology is precisely the
 866 one described in Montabone et al. (2015). Version 2.1 is a specific version only for MY
 867 33, where we have used an additional weight for THEMIS observations, in order to ac-
 868 count for THEMIS retrievals being provided at progressively later local times (i.e. we
 869 apply a 0.5 weight to THEMIS CDODs during the first iteration with the time window
 870 of 1 sol, reduced to 0.1 for the subsequent iterations using larger time windows). Since
 871 v2.1 we have also started using MCS v5.2 “two-dimensional” retrievals (Kleinbühl et al.,
 872 2017a) instead of v4.3 “one-dimensional” retrievals used for previous years 28 to 32.

873 For MY 34, we have produced three intermediate versions (v2.2, v2.3, and v2.4)
 874 and the v2.5 described in this paper, which should be considered as the reference ver-
 875 sion. All three intermediate versions use MCS v5.3.2 retrievals for the available period,
 876 and MCS v5.2 for the rest of the time, but do not use the two distinctive features de-
 877 scribed in Subsection 2.4, namely the local time cut-off window of ± 7 hours for obser-
 878 vations considered for the weighted average at each grid point, and the 6 hour moving
 879 average producing 4 maps per sol. Instead, they use observations at all local times for
 880 each grid point (except in v2.3 and v2.4 during the GDE, see below), and the 24 h mov-
 881 ing average produces only one map per sol, centered at MUT=12:00, as described in Montabone
 882 et al. (2015).

883 Within the intermediate versions, the differences are as following:

- 884 • v2.2: This version still uses the same data QC and gridding methodology as in Montabone
 885 et al. (2015). The use of dayside values is limited by the application of the “day-
 886 side” filter with 8 km cut-off altitude threshold at any time. Apart the use of MCS
 887 v5.3.2 retrievals, the only other difference with respect to v2.0 is in the kriged maps,
 888 where we have artificially introduced climatological south cap edge “storm” only

889 for areocentric solar longitude earlier than 180° , as in MY 25. This version also
 890 uses MCS observations only until end of September 2018 ($L_S \approx 260^\circ$), stopping
 891 at SOY 501.

- 892 • v2.3: This version uses only dayside values during the GDE ($186.5^\circ < L_S < 269^\circ$,
 893 SOY 383 to 515). It has also an improved data QC with respect to v2.2: we in-
 894 troduced the “water ice” filter, the “cross-track” filter, and we did not apply the
 895 “dayside filter” with 8 km cut-off altitude threshold during the GDE and the late
 896 winter regional storm ($L_S > 312^\circ$). This allowed to use many more dayside val-
 897 ues during the two major dust events of MY 34, increasing the overall optical depth
 898 to levels observed by, e.g., the Opportunity rover. We also redefined the estima-
 899 tion of uncertainties according to the scheme that was later adopted in v2.5 (but
 900 with slightly lower uncertainties overall). Furthermore, we changed a couple of pa-
 901 rameters in the IWB methodology: the criterion to accept a value of weighted av-
 902 erage at a particular grid point at any given iteration became that there must be
 903 at least one observation within a distance of 200 km from the grid point. We started
 904 using the same surface pressure recorded in the MCS dataset to normalize CDOD
 905 to 610 Pa, instead of the MCD surface pressure. If MCS surface pressure is not
 906 retrieved, we associated a 10% uncertainty by default. We stopped using the ar-
 907 tificial modification of a latitude band around the southern polar cap at all times.
 908 This version also uses MCS observations only until end of February 2018 ($L_S \approx$
 909 349°), stopping at SOY 647.
- 910 • v2.4: This version is quite similar to v2.3. The only differences are in the refined
 911 data QC, which is the one we also use in v2.5 (see Subsection 2.2). It also extends
 912 until the end of MY 34.

913 Refer to the two Figures in the Supplementary Information for a comparison of re-
 914 sults using versions 2.2, 2.3, 2.4 and 2.5.

915 Data availability

916 The maps of gridded and kriged CDOD produced in this work are publicly avail-
 917 able on the “Institut Pierre-Simon Laplace” (IPSL) data repository (accessible via the
 918 URL <https://doi.org/10.14768/20191217001.1>). The available datasets include the
 919 diurnally-averaged gridded and kriged maps (reference column dust climatology, version
 920 2.5), and the sub-daily gridded maps (version 2.5.1). The same maps are available un-
 921 der the Mars Climate Database project webpage (at the current URL http://www-mars.lmd.jussieu.fr/mars/dust_climatology/). Mars Climate Sounder data is publicly
 922 available on NASA’s Planetary Data System (<https://pds-atmospheres.nmsu.edu/>).
 923 Data from Curiosity rover obtained by the Rover Environmental Monitoring Station (REMS)
 924 instrument is publicly available as supplementary material of Guzewich et al. (2019). GCM
 925 outputs and supporting Python scripts used to produce the figures related to modeling
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947 References

- 948 Bertrand, T., Wilson, R. J., Kahre, M. A., Uratal, R., & Kling, A. (2019). Simu-
949 lation of the 2018 global dust storm on mars using the nasa ames mars gcm: A
950 multi-tracer approach. *Journal of Geophysical Research - Planets*, 125(7). doi:
951 10.1029/2019JE006122
- 952 Cantor, B. A. (2007). MOC observations of the 2001 Mars planet-encircling dust
953 storm. *Icarus*, 186, 60-96. doi: 10.1016/j.icarus.2006.08.019
- 954 Chapman, S., & Lindzen, R. (1970). *Atmospheric tides. Thermal and gravitational*.
955 Dordrecht: Reidel, 1970.
- 956 Colaïtis, A., Spiga, A., Hourdin, F., Rio, C., Forget, F., & Millour, E. (2013). A
957 thermal plume model for the Martian convective boundary layer. *Journal of Geo-*
958 *physical Research (Planets)*, 118, 1468-1487. doi: 10.1002/jgre.20104
- 959 Fedorova, A., Bertaux, J.-L., Betsis, D., Montmessin, F., Korablev, O., Maltagliati,
960 L., & Clarke, J. (2018). Water vapor in the middle atmosphere of Mars during the
961 2007 global dust storm. *Icarus*, 300, 440-457. doi: 10.1016/j.icarus.2017.09.025
- 962 Forget, F., Spiga, A., Dolla, B., Vinatier, S., Melchiorri, R., Drossart, P., ...
963 Gondet, B. (2007). Remote sensing of surface pressure on Mars with the Mars
964 Express/OMEGA spectrometer: 1. Retrieval method. *Journal of Geophysical*
965 *Research (Planets)*, 112(E11), 8-+. doi: 10.1029/2006JE002871
- 966 Girazian, Z., Luppen, Z., Morgan, D. D., Chu, F., Montabone, L., Thiemann,
967 E. M. B., ... Némec, F. (2019). Variations in the ionospheric peak altitude at
968 mars in response to dust storms: 13 years of observations from the mars express
969 radar sounder. *Journal of Geophysical Research - Space Physics*, accepted.
- 970 González-Galindo, F., Määttänen, A., Forget, F., & Spiga, A. (2011). The mar-
971 tian mesosphere as revealed by co2 clouds observations and general circulation
972 modeling. *Icarus*, 216, 10-22.
- 973 Guzewich, S. D., Lemmon, M., Smith, C. L., Martínez, G., de Vicente-Retortillo,
974 Á., Newman, C. E., ... Zorzano Mier, M.-P. (2019). Mars Science Laboratory
975 Observations of the 2018/Mars Year 34 Global Dust Storm. *Geophysical Research*
976 *Letters*, 46(1), 71-79. doi: 10.1029/2018GL080839
- 977 Heavens, N. G., Kleinböhl, A., Chaffin, M. S., Halekas, J. S., Kass, D. M., Hayne,
978 P. O., ... Schofield, J. T. (2018). Hydrogen escape from Mars enhanced
979 by deep convection in dust storms. *Nature Astronomy*, 2, 126-132. doi:
980 10.1038/s41550-017-0353-4
- 981 Hernández-Bernal, J., Sánchez-Lavega, A., del Río-Gaztelurrutia, T., Hueso, R.,
982 Cardesín-Moinelo, A., Ravanis, E. M., ... Wood, S. (2019). The 2018 martian
983 global dust storm over the south polar region studied with mex/vmc. *Geophysical*
984 *Research Letters*, 46(17-18), 10330-10337. doi: 10.1029/2019GL084266
- 985 Kahre, M. A., Murphy, J. R., Newman, C. E., Wilson, R. J., Cantor, B. A., Lem-
986 mon, M. T., & Wolff, M. J. (2017). The Mars Dust Cycle. In *The atmosphere*
987 *and climate of mars, edited by r.m. haberle et al. isbn: 9781139060172. cambridge*

- 988 *university press, 2017, p. 229-294* (p. 229-294). doi: 10.1017/9781139060172.010
- 989 Kass, D., Schofield, J., Kleinböhl, A., McCleese, D., Heavens, N., Shirley, J., &
990 Steele, L. (2019). Mars climate sounder observation of mars' 2018 global dust
991 storm. *Geophysical Research Letters*, *0*(ja). doi: 10.1029/2019GL083931
- 992 Kass, D. M., Kleinböhl, A., McCleese, D. J., Schofield, J. T., & Smith, M. D.
993 (2016, Jun). Interannual similarity in the Martian atmosphere during the
994 dust storm season. *Geophysical Research Letters*, *43*(12), 6111-6118. doi:
995 10.1002/2016GL068978
- 996 Kleinböhl, A., Chen, L., & Schofield, J. T. (2017b, January). Far Infrared Spectro-
997 scopic Parameters of Mars Atmospheric Aerosols and their Application to MCS
998 Retrievals in High Aerosol Conditions. In F. Forget & M. Millour (Eds.), *The*
999 *mars atmosphere: Modelling and observation* (p. 2230).
- 1000 Kleinböhl, A., John Wilson, R., Kass, D., Schofield, J. T., & McCleese, D. J. (2013,
1001 May). The semidiurnal tide in the middle atmosphere of Mars. *Geophysical Re-*
1002 *search Letters*, *40*(10), 1952-1959. doi: 10.1002/grl.50497
- 1003 Kleinböhl, A., Schofield, J. T., Abdou, W. A., Irwin, P. G. J., & de Kok, R. J.
1004 (2011). A single-scattering approximation for infrared radiative transfer in limb
1005 geometry in the Martian atmosphere. *J. Quant. Spectrosc. Rad. Transfer*, *112*,
1006 1568-1580.
- 1007 Kleinböhl, A., Schofield, J. T., Kass, D. M., Abdou, W. A., Backus, C. R., Sen, B.,
1008 ... McCleese, D. J. (2009, October). Mars Climate Sounder limb profile retrieval
1009 of atmospheric temperature, pressure, and dust and water ice opacity. *Journal of*
1010 *Geophysical Research (Planets)*, *114*, 10006. doi: 10.1029/2009JE003358
- 1011 Kleinböhl, A., Spiga, A., Kass, D. M., Shirley, J. H., Millour, E., Montabone, L., &
1012 Forget, F. (2019). Diurnal variations of dust during the 2018 global dust storm
1013 observed by the mars climate sounder. *Journal of Geophysical Research - Planets*,
1014 accepted. doi: 10.1029/2019JE006115
- 1015 Kleinböhl, A., Friedson, A. J., & Schofield, J. T. (2017a). Two-dimensional radiative
1016 transfer for the retrieval of limb emission measurements in the martian atmo-
1017 sphere. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *187*, 511 -
1018 522. doi: <https://doi.org/10.1016/j.jqsrt.2016.07.009>
- 1019 Levine, J. S., Winterhalter, D., & Kerschmann, R. L. (2018). *Dust in the atmo-*
1020 *sphere of mars and its impact on human exploration*. Cambridge Scholars Publish-
1021 ing, UK.
- 1022 Lewis, S. R., & Barker, P. R. (2005). Atmospheric tides in a Mars general circula-
1023 tion model with data assimilation. *Advances in Space Research*, *36*, 2162-2168.
1024 doi: 10.1016/j.asr.2005.05.122
- 1025 Lewis, S. R., Mulholland, D. P., Read, P. L., Montabone, L., Wilson, R. J., &
1026 Smith, M. D. (2016). The solsticial pause on Mars: 1. A planetary wave re-
1027 analysis. *Icarus*, *264*, 456-464. doi: 10.1016/j.icarus.2015.08.039
- 1028 Lewis, S. R., & Read, P. L. (2003). Equatorial jets in the dusty Martian atmo-
1029 sphere. *Journal of Geophysical Research (Planets)*, *108*, 5034+. doi: 10.1029/
1030 2002JE001933
- 1031 Madeleine, J.-B., Forget, F., Millour, E., Montabone, L., & Wolff, M. J. (2011,
1032 November). Revisiting the radiative impact of dust on Mars using the LMD
1033 Global Climate Model. *Journal of Geophysical Research (Planets)*, *116*, 11010.
1034 doi: 10.1029/2011JE003855
- 1035 Madeleine, J.-B., Forget, F., Millour, E., Navarro, T., & Spiga, A. (2012). The
1036 influence of radiatively active water ice clouds on the Martian climate. *Geo-*
1037 *phys. Res. Lett.*, *39*, 23202. doi: 10.1029/2012GL053564
- 1038 Malin, M. C., Cantor, B. A., & W., B. A. (2018). *Mro marci weather report for the*
1039 *week of 4 june 2018 - 10 june 2018*. Malin Space Science Systems Captioned Im-
1040 age Release, MSSS-534, http://www.msss.com/msss_images/2018/06/13/.
- 1041 Martin, L. J., & Zurek, R. W. (1993). An analysis of the history of dust activity on

- 1042 Mars. *J. Geophys. Res.*, 98(E2), 3221-3246.
- 1043 McCleese, D. J., Schofield, J. T., Taylor, F. W., Calcutt, S. B., Foote, M. C., Kass,
1044 D. M., ... Zurek, R. W. (2007). Mars Climate Sounder: An investigation of
1045 thermal and water vapor structure, dust and condensate distributions in the atmo-
1046 sphere, and energy balance of the polar regions. *Journal of Geophysical Research*
1047 (*Planets*), 112(E11), 5-+. doi: 10.1029/2006JE002790
- 1048 Millour, E., Forget, F., Spiga, A., Navarro, T., Madeleine, J.-B., Montabone, L.,
1049 ... MCD/GCM development Team (2015). The Mars Climate Database (MCD
1050 version 5.2). *European Planetary Science Congress 2015, 10*, EPSC2015-438.
- 1051 Montabone, L., & Forget, F. (2018). Forecasting Dust Storms on Mars: a Short
1052 Review. In *Dust in the atmosphere of mars and its impact on human exploration*
1053 (p. 000). Cambridge Scholars Publishing, Ed. Levine, G. S. and Winterhalter, D.
1054 and Kerschmann, R. L. doi: doi_tbd
- 1055 Montabone, L., Forget, F., Millour, E., Wilson, R. J., Lewis, S. R., Cantor, B., ...
1056 Wolff, M. J. (2015). Eight-year climatology of dust optical depth on Mars. *Icarus*,
1057 251, 65-95. doi: 10.1016/j.icarus.2014.12.034
- 1058 Montabone, L., Forget, F., Smith, M., Cantor, B., Wolff, M., Capderou, M., & Van-
1059 Woerkom, M. (2018, Jul). Mars Aerosol Tracker (MAT): An Areostationary
1060 SmallSat to Monitor Dust Storms and Water Ice Clouds. In *42nd cospar scientific*
1061 *assembly* (Vol. 42, p. B0.2-16-18).
- 1062 Montabone, L., Lewis, S. R., & Read, P. L. (2005). Interannual variability of Mar-
1063 tian dust storms in assimilation of several years of Mars global surveyor observa-
1064 tions. *Advances in Space Research*, 36, 2146-2155. doi: 10.1016/j.asr.2005.07.047
- 1065 Mulholland, D. P., Read, P. L., & Lewis, S. R. (2013). Simulating the interannual
1066 variability of major dust storms on Mars using variable lifting thresholds. *Icarus*,
1067 223, 344-358. doi: 10.1016/j.icarus.2012.12.003
- 1068 Navarro, T., Madeleine, J.-B., Forget, F., Spiga, A., Millour, E., Montmessin, F.,
1069 & Määttänen, A. (2014). Global Climate Modeling of the Martian water cycle
1070 with improved microphysics and radiatively active water ice clouds. *Journal of*
1071 *Geophysical Research (Planets)*. doi: 10.1002/2013JE004550
- 1072 Newman, C. E., & Richardson, M. I. (2015). The impact of surface dust source
1073 exhaustion on the martian dust cycle, dust storms and interannual variability, as
1074 simulated by the MarsWRF General Circulation Model. *Icarus*, 257, 47-87. doi:
1075 10.1016/j.icarus.2015.03.030
- 1076 Ryan, J. A., & Henry, R. M. (1979). Mars atmospheric phenomena during major
1077 dust storms as measured at surface. *J. Geophys. Res.*, 84, 2821-2829.
- 1078 Shirley, J., Kleinböhl, A., Kass, D., Steele, L., Heavens, N., Suzuki, S., ... McCleese,
1079 D. (2019). Rapid expansion and evolution of a regional dust storm in the acidalia
1080 corridor during the initial growth phase of the martian global dust storm of 2018.
1081 *Geophysical Research Letters*, 0(ja). doi: 10.1029/2019GL084317
- 1082 Smith, M. D. (2019). Themis observations of the 2018 mars global dust storm. *Jour-
1083 nal of Geophysical Research - Planets*, accepted.
- 1084 Spiga, A., Banfield, D., Teanby, N. A., Forget, F., Lucas, A., Kenda, B., ...
1085 Banerdt, W. B. (2018). Atmospheric Science with InSight. *Space Science Re-
1086 views*, 214, 109. doi: 10.1007/s11214-018-0543-0
- 1087 Spiga, A., Faure, J., Madeleine, J.-B., Määttänen, A., & Forget, F. (2013, April).
1088 Rocket dust storms and detached dust layers in the Martian atmosphere. *Journal*
1089 *of Geophysical Research (Planets)*, 118, 746-767. doi: 10.1002/jgre.20046
- 1090 Spiga, A., Hinson, D., Madeleine, J., Navarro, T., Millour, E., Forget, F., &
1091 Montmessin, F. (2017). Snow precipitation on Mars driven by cloud-induced
1092 nighttime convection. *Nature Geoscience*, 10, 652-657. doi: 10.1038/ngeo3008
- 1093 Streeter, P. M., Lewis, S. R., Patell, M. R., Holmes, J. A., & Kass, D. M. (2019).
1094 Surface warming during the 2018/Mars Year 34 Global Dust Storm. *Geophysical*
1095 *Research Letters*, 0(ja). doi: 10.1029/2019GL083936

- 1096 Szwest, M. A., Richardson, M. I., & Vasavada, A. R. (2006). Surface dust re-
 1097 distribution on Mars as observed by the Mars Global Surveyor and Viking
 1098 orbiters. *Journal of Geophysical Research (Planets)*, *111*(E10), 11008. doi:
 1099 10.1029/2005JE002485
- 1100 Sánchez-Lavega, A., del Río-Gaztelurrutia, T., Hernández-Bernal, J., & Delcroix, M.
 1101 (2019). The onset and growth of the 2018 martian global dust storm. *Geophysical*
 1102 *Research Letters*, *46*(11), 6101-6108. doi: 10.1029/2019GL083207
- 1103 Vincendon, M., Audouard, J., Altieri, F., & Ody, A. (2015). Mars Express mea-
 1104 surements of surface albedo changes over 2004-2010. *Icarus*, *251*, 145-163. doi: 10
 1105 .1016/j.icarus.2014.10.029
- 1106 Viúdez-Moreiras, D., Newman, C. E., de la Torre, M., Martínez, G., Guzewich,
 1107 S., Lemmon, M., ... Gómez-Elvira, J. (2019). Effects of the my34/2018
 1108 global dust storm as measured by msl rems in gale crater. *Journal of Geo-*
 1109 *physical Research: Planets*, *124*(7), 1899-1912. Retrieved from [https://](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JE005985)
 1110 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JE005985 doi:
 1111 10.1029/2019JE005985
- 1112 Wang, C., Forget, F., Bertrand, T., Spiga, A., Millour, E., & Navarro, T. (2018).
 1113 Parameterization of Rocket Dust Storms on Mars in the LMD Martian GCM:
 1114 Modeling Details and Validation. *Journal of Geophysical Research (Planets)*, *123*,
 1115 982-1000. doi: 10.1002/2017JE005255
- 1116 Wilson, R. W., & Hamilton, K. (1996). Comprehensive model simulation of thermal
 1117 tides in the Martian atmosphere. *J. Atmos. Sci.*, *53*, 1290-1326.
- 1118 Withers, P. (2012, Sep). Empirical Estimates of Martian Surface Pressure in Sup-
 1119 port of the Landing of Mars Science Laboratory. *Space Science Reviews*, *170*(1-4),
 1120 837-860. doi: 10.1007/s11214-012-9876-2
- 1121 Xiaohua, F., Ma, Y., Lee, Y., Bougher, S., Liu, G., Benna, M., ... Jakosky, B.
 1122 (2019). Mars dust storm effects in the ionosphere and magnetosphere and im-
 1123 plications for atmospheric carbon loss. *Journal of Geophysical Research - Space*
 1124 *Physics*, accepted.
- 1125 Zurek, R. W. (1982). Martian great dust storm, an update. *Icarus*, *50*, 288-310.
- 1126 Zurek, R. W., & Martin, L. J. (1993). Interannual variability of planet-encircling
 1127 dust storms on Mars. *J. Geophys. Res.*, *98*(E2), 3247-3259.