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# Daily dust variation from the PFS MEx observations

by

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29 **Abstract**

30

31 We collected over 7 Martian years (MY) of data observed by the Planetary Fourier Spectrometer  
32 (PFS) to present a daily variation of dust content in the Martian atmosphere. We found three typical  
33 behaviors of dust opacities with LT (local time). The most peculiar variation was observed when  
34 global dust storms (MYs 28 and 34) or particularly strong regional storms (MY 29) occurred on Mars.  
35 Here, large dust opacities were measured at 10 LT (MY 34) and 11 LT (MY 28). Then, relatively  
36 small values of dust opacities were found in the evening (20 LT). The non-dusty season, particularly  
37 near northern summer solstice, was characterized by a deep minimum of the total dust opacity at late  
38 night/early morning, while small variations around the mean value were observed during daytime.  
39 The clear trend of dust was observed over both hemispheres during early morning. We noted elevated  
40 dust opacities in the second half of the year compared to the non-dusty season in all Martian years  
41 without global dust storms. The daily variation of three types of storms occurring in moderately dusty  
42 conditions was also investigated. Dust in A storms was present in the atmosphere at all LTs and was  
43 mostly confined to the southern hemisphere. The maximum of dust opacities in B storms was found  
44 at 15 – 17 LT, close to the South Pole. C storms were mainly constrained to southern latitudes and  
45 occurred from the late morning to midday.

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## 58 1. Introduction

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60 Thanks to elliptical orbits by the Mars Express spacecraft (MEx), Planetary Fourier Spectrometer  
61 (PFS) is able to investigate a daily cycle of atmospheric components such as dust or water-ice. Dust  
62 is a strongly variable constituent of the Martian atmosphere. A seasonal variation of dust with  $L_s$   
63 (solar longitude) has been widely documented, based on data acquired from past and present missions:  
64 Viking (Martin et al., 1979), Mariner 9 (Santee and Crisp, 1993; Fenton et al., 1997), Mars Global  
65 Surveyor (Smith, 2004), Mars Odyssey (Smith, 2009), Mars Reconnaissance Orbiter (McCleese et  
66 al., 2010; Kass et al., 2016), and Mars Express (Zasova and Formisano, 2007; Määttänen et al., 2013).  
67 The spatial and seasonal behavior of dust in the atmosphere depends on the occurrence of global dust  
68 storms (Haberle, 1986). Based on the analysis of 4 years of pressure, temperature and wind from the  
69 Viking meteorological station by Leovy et al. (1985), Haberle (1986) found that the weather on Mars  
70 was governed by two different regimes during southern summers. The first regime was associated  
71 with the occurrences of global dust storms in which dust was transported from the southern  
72 hemisphere by a cross-equator Hadley circulation (Haberle, 1986). Near perihelion, over the southern  
73 subtropics, insolation was strong and mean upward vertical atmospheric motions dominated (Haberle,  
74 1986). In years without the global dust storms, in the second regime, dust was lifted from the northern  
75 hemisphere by relatively active mid-latitude storm systems (Haberle, 1986). From numerical  
76 simulations when the northern dust haze diminished, its contribution to the surface stress decreased  
77 in the southern hemisphere and prevented the development of a global dust storm (Haberle, 1986).  
78 The two circulations in the opposite hemispheres compete between each other (Haberle, 1986), and  
79 as a result they could give some indications about when a global dust storm occurs. For example,  
80 stronger southern circulation favored the occurrence of a global dust storm. However, the origin of  
81 global dust storms is still unknown.

82 PFS is the instrument which enables observations of the diurnal variation of suspended dust. Previous  
83 missions had a limited coverage of local times. However, some analysis at the variation of dust  
84 opacity during daytime from the IRTM (Infrared Thermal Mapper) Viking measurements was  
85 presented by Martin and Tamparri (2007). They found that dust increased in the atmosphere at 10 -  
86 12 LT and then gradually decreased in the late afternoon around 16 LT. The MCS (Mars Climate  
87 Sounder) MRO (Mars Reconnaissance Orbiter) instrument also detected a diurnal variation of dust  
88 opacity around the northern summer solstice over the northern tropics (Heavens et al., 2011). The  
89 high altitude dust maximum (HATDM) varied 3 times over the course of a 24-hour day (Fig.2b, d in  
90 Heavens et al., 2011, Heavens et al., 2014). Recently, MCS vertical dust distributions during the

91 global dust storm in MY 34 showed differences between day and night (Kleinboehl et al., 2020).  
92 These differences depended on the fact that the vertical extent of dust was higher during day than  
93 night, especially during a mature phase of the global dust storm. The top altitude of the dust changed  
94 over the course of the 24-hour day particularly at the high southern latitudes (Kleinboehl et al., 2020).  
95 This means that the total dust amount in the atmosphere varies during a 24-hour day.

96 This daily cycle of dust is still poorly understood, and we are trying to answer the question of how  
97 long dust is suspended in the atmosphere. The current climate models are still doing very poorly to  
98 simulate diurnal variation in the dust distribution. More analysis and comparison to the current GCMs  
99 (global circulation models) are needed for a complete interpretation of PFS observations.

100 Dust can be investigated indirectly by observing brightness temperatures at  $15\ \mu\text{m}$  and atmospheric  
101 temperatures at 25 km (0.5 mb). The brightness temperatures allow us to study a deep layer of the  
102 atmosphere centered at roughly 0.5 mb, corresponding to an elevation of 25 km (Wilson and  
103 Richardson, 2000). A significant seasonal variation of the global mean temperature was found by  
104 Leovy (1985) and Clancy et al. (1996) due to a large seasonal modulation in atmospheric dust content  
105 (Zurek et al., 1992). Global brightness temperatures at  $15\ \mu\text{m}$  rapidly rose up along with the onset of  
106 each of the two 1977 global dust storms (Wilson and Richardson, 2000). These brightness  
107 temperature increases were due to a direct heating of the atmosphere by dust (Wilson and Richardson,  
108 2000). Aerosol affected atmospheric temperatures leading to diurnal variations presented by Wilson  
109 and Richardson (2000). Data from Mariner 9 Infrared Interferometer Spectrometer (IRIS) during the  
110 1971 global dust storm revealed the 30 K difference (peak-to-peak), extending to at least 40 km  
111 (Hanel et al., 1972). The similar diurnal temperature variations at 25 km were observed in the IRTM  
112 brightness temperatures at  $15\ \mu\text{m}$  when the onset of two global dust storms occurred (1977a and  
113 1977b) (Martin and Kieffer 1979).

114 In this work, we present three typical daily variations of dust opacities observed by PFS in non- and  
115 dusty seasons. The zonally averaged dust as a function of latitude and LT is illustrated. We  
116 characterize the LT variation of seasonal types of storms defined by Kass et al. (2016).

117

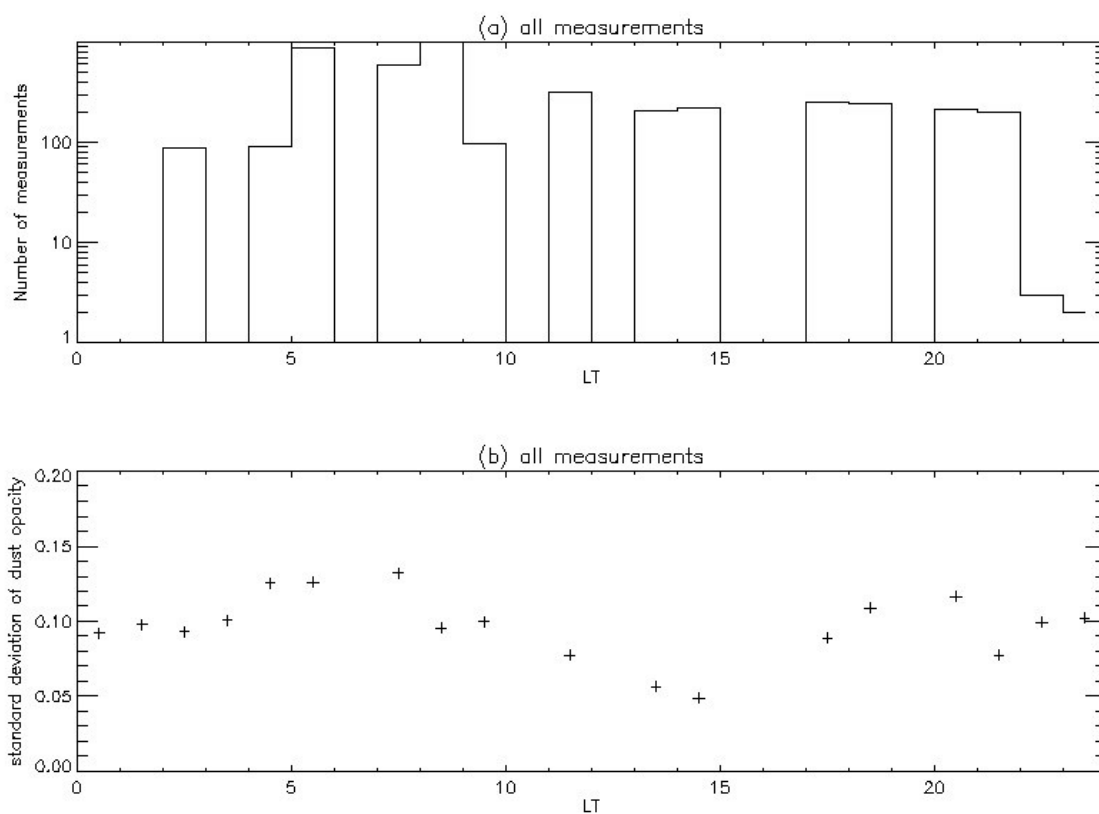
## 118 **2. Typical behaviors of dust activity with LT**

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120 Dust opacities are obtained from PFS radiance measurements in a spectral range around  $1075\ \text{cm}^{-1}$   
121 ( $9.3\ \mu\text{m}$ ) where the dust absorption band is observed. In our analysis we also use vertical temperature  
122 profiles retrieved from radiance measurements performed in a spectral range corresponding to the

123 main CO<sub>2</sub> absorption band at 667 cm<sup>-1</sup> (15 μm). All retrieved parameters with surface temperatures  
124 are obtained using the optimal estimation method with the Bayesian approach (Grassi et al., 2005).

125 The error analysis presented in Wolkenberg et al. (2018) showed that the mean values of uncertainties  
126 for dust opacities were 0.06 and 0.11 for surface temperatures greater than 220 K and less than 220  
127 K, respectively. In this study, a dataset of ~ 5000 selected retrievals of dust opacity, spanning all  
128 combinations of Ls, LT and location was gathered to demonstrate a histogram of dust opacity standard  
129 deviations as a function of LT. The same retrievals were applied in Wolkenberg et al. (2018) and  
130 collected from MY 28. Standard deviations of dust opacity vary with LT within 0.06 – 0.13 (Fig.1a,  
131 b). We obtained a similar result for two populations of surface temperatures greater than and less than  
132 220 K, respectively. The maximum values are observed from 4 LT to 8 LT and then the standard  
133 deviation progressively decreases with LT down to 0.05 (Fig.1b).

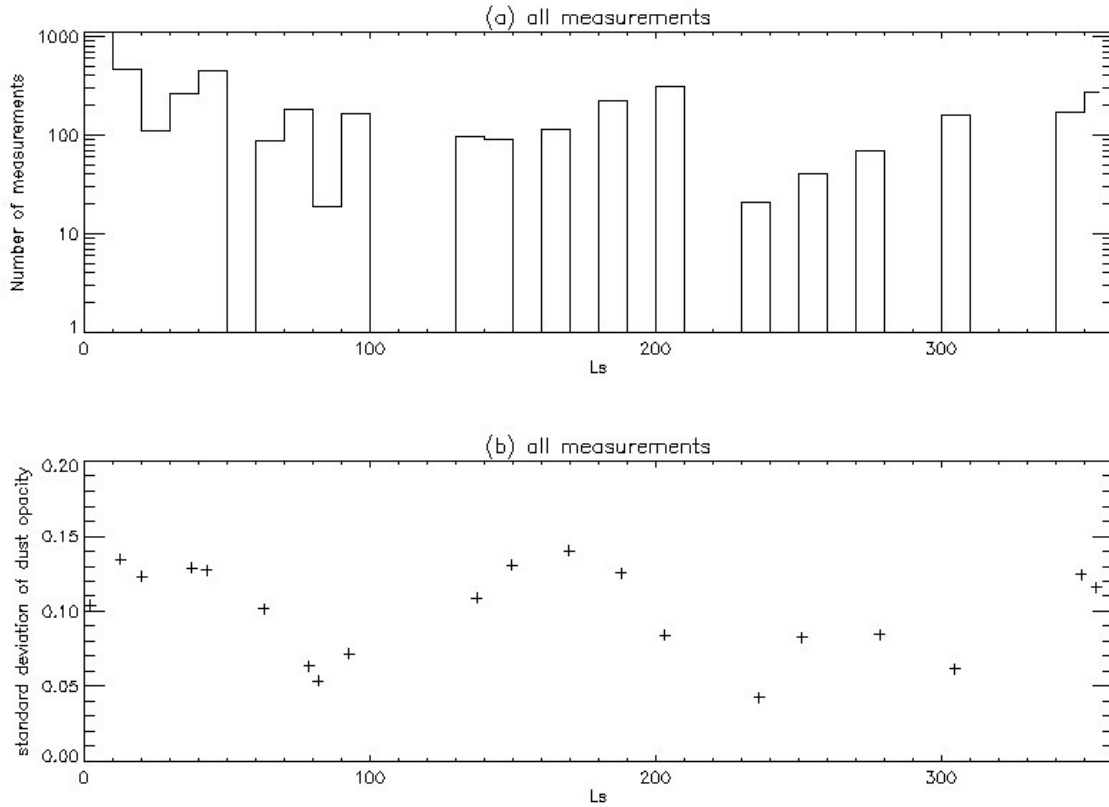


134

135 Fig. 1. Histogram of standard deviations for dust opacity: (a) number of measurements as a function  
136 of LT, (b) standard deviations of dust opacity as a function of LT. Gaps in Fig.1b mean no  
137 measurements.

138 As expected, large standard deviations occur during the night and early morning when surface  
139 temperatures are less than 220 K. They then gradually decrease to around 0.05 with surface  
140 temperatures larger than 220 K and again reach a large value in the evening. The largest values of

141 standard deviations are encountered during rapid changes of insolation in the early morning, 5 - 7 LT,  
 142 and in the evening, 18 – 20 LT. We also investigated the seasonal variation of dust opacity standard  
 143 deviations. Fig.2 presents a histogram of standard deviations as a function of season ( $L_s$ ).



144  
 145 Fig.2. Histogram of standard deviations for dust opacity, (a) number of measurements as a function  
 146 of  $L_s$ , (b) standard deviations of dust opacity as a function of  $L_s$ . Gaps in Fig.2b mean no  
 147 measurements.

148 The seasonal variation of dust opacity standard deviations is different than for LT. We observe almost  
 149 two minima of standard deviations of dust opacity at around  $L_s = 80^\circ$  and  $L_s = 230^\circ$ . The two minima  
 150 coincide approximately with the aphelion and perihelion seasons. The largest standard deviations are  
 151 found at the beginning of the year at  $L_s = 10^\circ$  to  $40^\circ$  then from  $140^\circ$  to  $180^\circ$  and from  $350^\circ$  –  $360^\circ$ .  
 152 Thus the maxima coincide with the equinox seasons. However, standard deviations are within 0.04 –  
 153 0.14 during the whole year, consistent with results by Wolkenberg et al. (2018).

154 We also performed tests on sensitivity of retrieval for column integrated dust opacities using the  
 155 different vertical dust distributions as an ‘a priori’ profile. The results of total dust opacities were  
 156 compared with the original obtained by using vertical dust distributions derived from the EMCD v4.2  
 157 database (Forget et al., 1999a,b) and derived from an analytical formula given by Heavens et al.  
 158 (2011, eq.15). We find a negligible effect of different vertical distributions on retrieved total dust

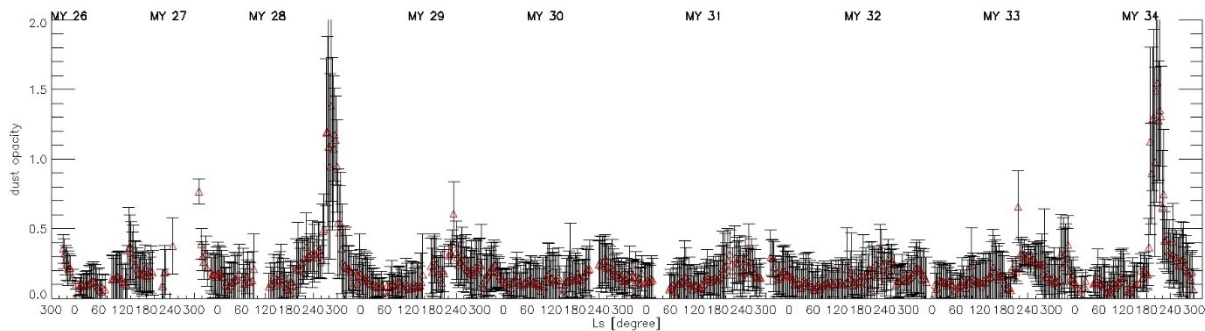
159 opacities during daytime and nighttime. We only observe a relative difference of 10% in the total dust  
160 opacities (for example 1.72 vs. 1.52) when high dust loadings occur in the atmosphere. A detailed  
161 analysis can be found in Appendix A.

162

## 163 2.1. Diurnal dust activity during global dust storms in MY 28 and MY 34 and the regional dust 164 storm in MY 29

165

166 **Fig.3** presents seasonal variations of zonal mean dust opacities averaged for a region from 40.5°S to  
167 40.5°N. The most striking features are very large dust opacities during dusty seasons in MY 28 and  
168 MY 34. Moderate-to-large dust activities are also observed a year before and after MY 28 and a year  
169 before MY 34. The regional, planet-encircling dust storm observed in MY 29 had a moderate-to-  
170 large dust opacity around 0.5. Dust opacities around 0.3 are observed in dusty seasons of other years.  
171 After an analysis of dust activity from  $L_s = 331^\circ$  of MY 26 to  $L_s = 300^\circ$  of MY 34, we selected data  
172 for intervals when the global dust storms occurred (i.e. in MY 28 and MY 34).

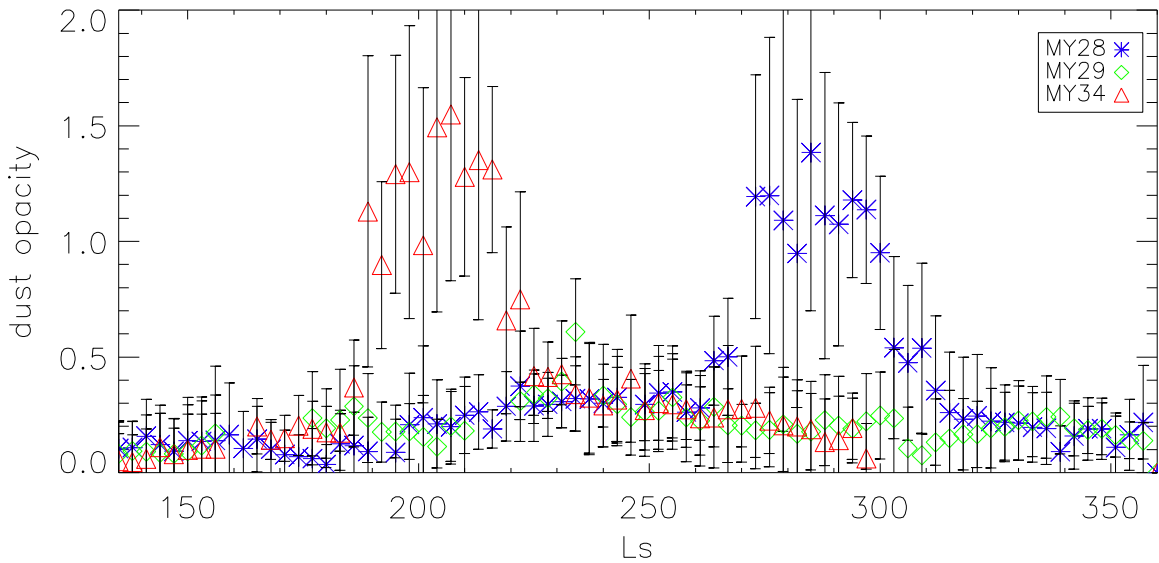


173

174 **Fig.3.** Zonal mean dust opacity averaged for a region from 40.5°S to 40.5°N as a function of  $L_s$ . The  
175 data are binned in  $L_s$  of  $3^\circ$ . Dust opacity is normalized to the reference pressure 6.1 mbar. Standard  
176 deviations contain variabilities of dust opacity within each bin. An “error bar” represents the standard  
177 deviation of each averaged value and provide an indication of the observed zonal and meridional  
178 variations.

179

180 Data was separated based on the particular behavior, which was not observed in the other MYs, of  
181 dust opacities with LT in MY 28, MY 29 and MY 34.



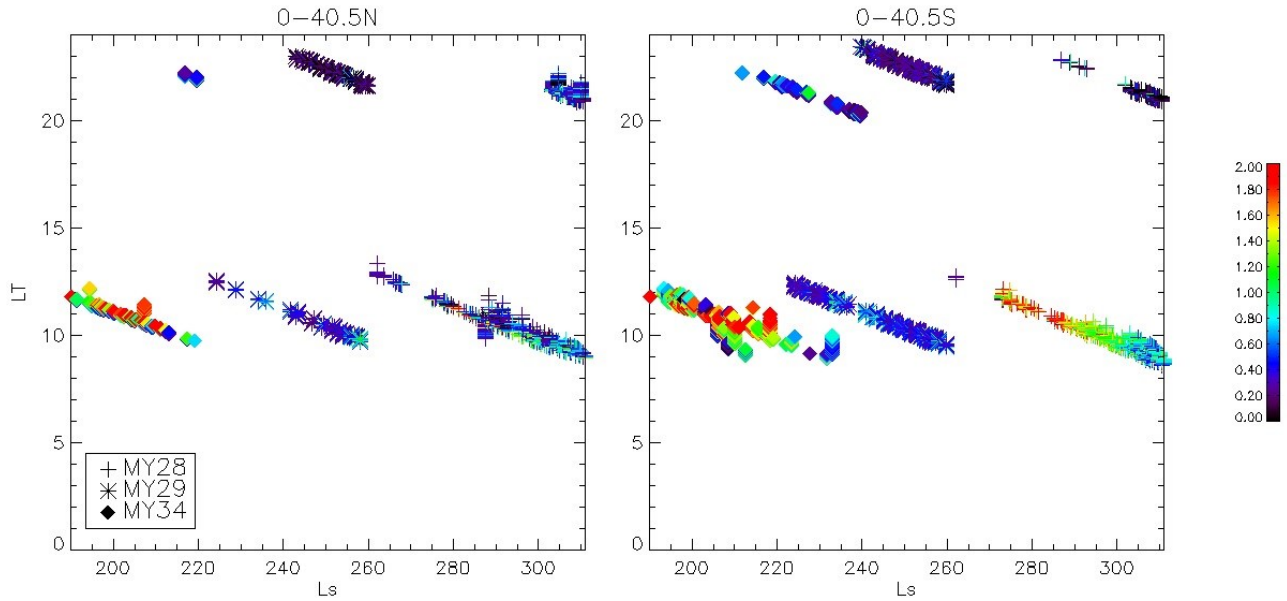
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183 Fig.4. Zonal mean dust opacities averaged for the region from 40.5°S to 40.5°N in MY 28, 29 and  
 184 34. The data are binned in  $L_s$  of 3°. Dust opacities are normalized to the reference pressure 6.1 mbar.  
 185 Standard deviations contain variabilities of dust opacity within bin. The “error bars” represent the  
 186 standard deviation of each averaged value and provide an indication of the observed zonal and  
 187 meridional variations.

188

189 We also analyzed the northern and southern hemispheres within 40.5°N and 40.5°S latitudes,  
 190 respectively. The evolution of global dust storms and the regional dust storm in MY 29 during  $L_s =$   
 191 135° - 360° are plotted in **Fig.4**. We distinguish the onset, core and decay phases in each global storm.  
 192 Each storm starts at a different  $L_s$ . For example, in MY 34, the storm begins at  $L_s = 190^\circ$  and its core  
 193 has a duration of 30°  $L_s$  approximately (**Fig.4**). The MY29 regional storm starts as a flushing storm  
 194 around  $L_s = 230$ , peaking at  $L_s = 238$  as it spreads southward and westward. It gradually decays  
 195 afterwards. The global dust storm in MY 28 starts later in the year, at  $L_s = 262^\circ$ , and continues until  
 196  $L_s = 311^\circ$ .

197 Our main purpose was to show a variation of dust content during daytime and nighttime for high dust  
 198 activity periods (global dust storms). We plotted dust opacities as a function of LT and  $L_s$  during the  
 199 storms for each year considered (**Fig.5**).



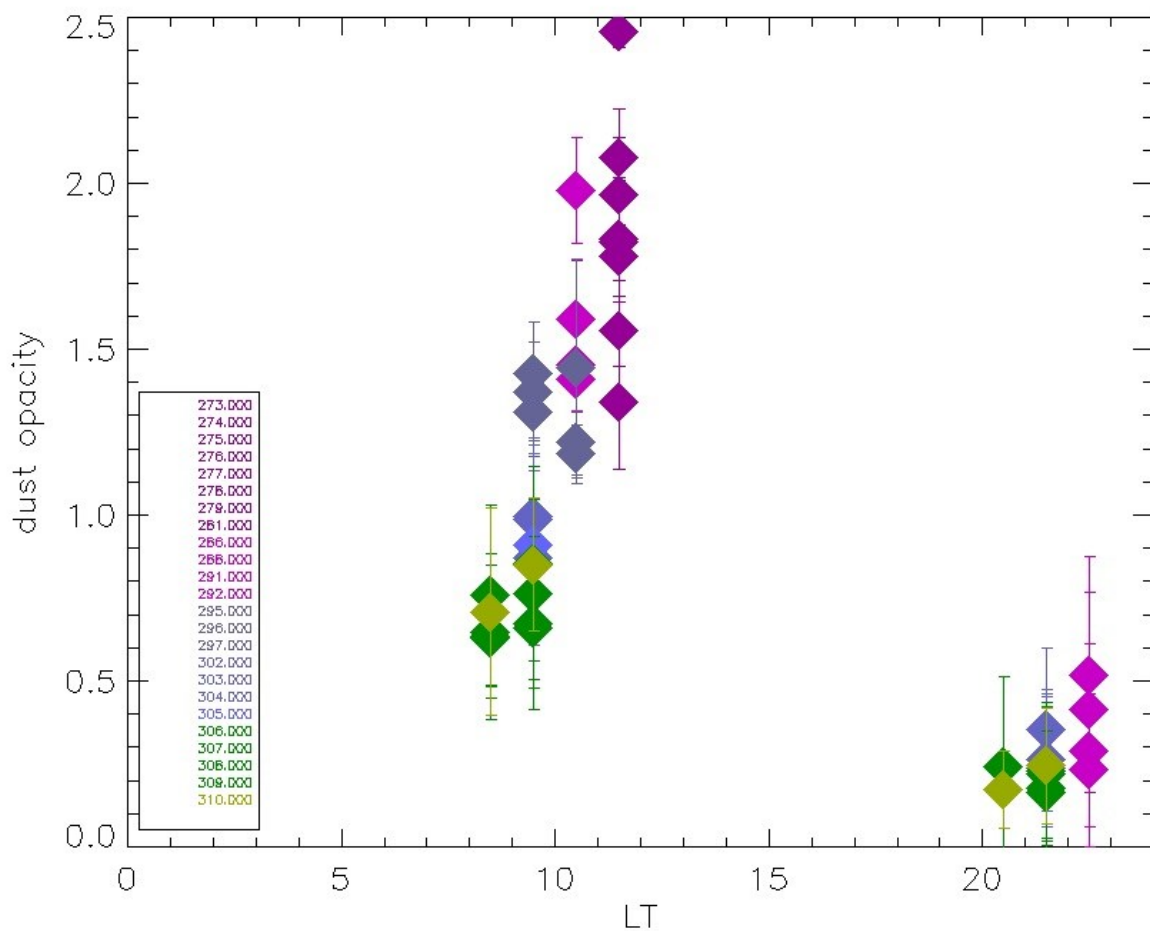
200

201 Fig.5. Dust opacities as a function of LT and Ls for the northern hemisphere (left panel) and the  
 202 southern hemisphere (right panel) during global storms in MY 28 and 34 and the regional storm in  
 203 MY 29. Some values of dust opacities can exceed 2.

204

205 All column-integrated dust opacities retrieved by PFS are presented separately for the northern (0-  
 206 40.5°N) and the southern (0-40.5°S) hemispheres (Fig.5). The most spectacular behavior of dust is  
 207 observed before midday in MY 28 and MY 34 in **Fig.5**. The elevated dust opacity is found between  
 208 10 – 12 LT in MY 28 and MY34. We note lower values of dust opacities in the evening/early night  
 209 compared to the dust content before midday for all considered years. Unfortunately, in MY 28 and  
 210 MY 34 in the northern hemisphere our observations of the evening/early night dust opacities occurred  
 211 during a decay phase of the dust storms. Moreover, the contrast, in both years, between midday and  
 212 early night observations is smaller in the northern than southern hemisphere: in the core of the MY  
 213 28 storm and at the beginning of the decay phase at Ls ~ 285, the gap in daytime and nighttime  
 214 activity is more distinct in the southern hemisphere, even late in the decay phase. During the core of  
 215 the dust storm in MY 34, dust opacities are measured from 9 - 12 LT over the southern hemisphere.  
 216 Smaller dust opacities are found at 9 LT compared to values at 10 and 11 LT at around Ls = 210.  
 217 Similarly to the MY28 storm, we observe dust opacities in the late evening at the end of the storm  
 218 core and at the beginning of the decay phase. The contrast between midday and late evening  
 219 observations is greatly pronounced until Ls = 220. This contrast decreases gradually with the  
 220 progressing season. The regional dust storm in MY 29 shows less contrast between midday and late  
 221 evening measurements for both hemispheres.

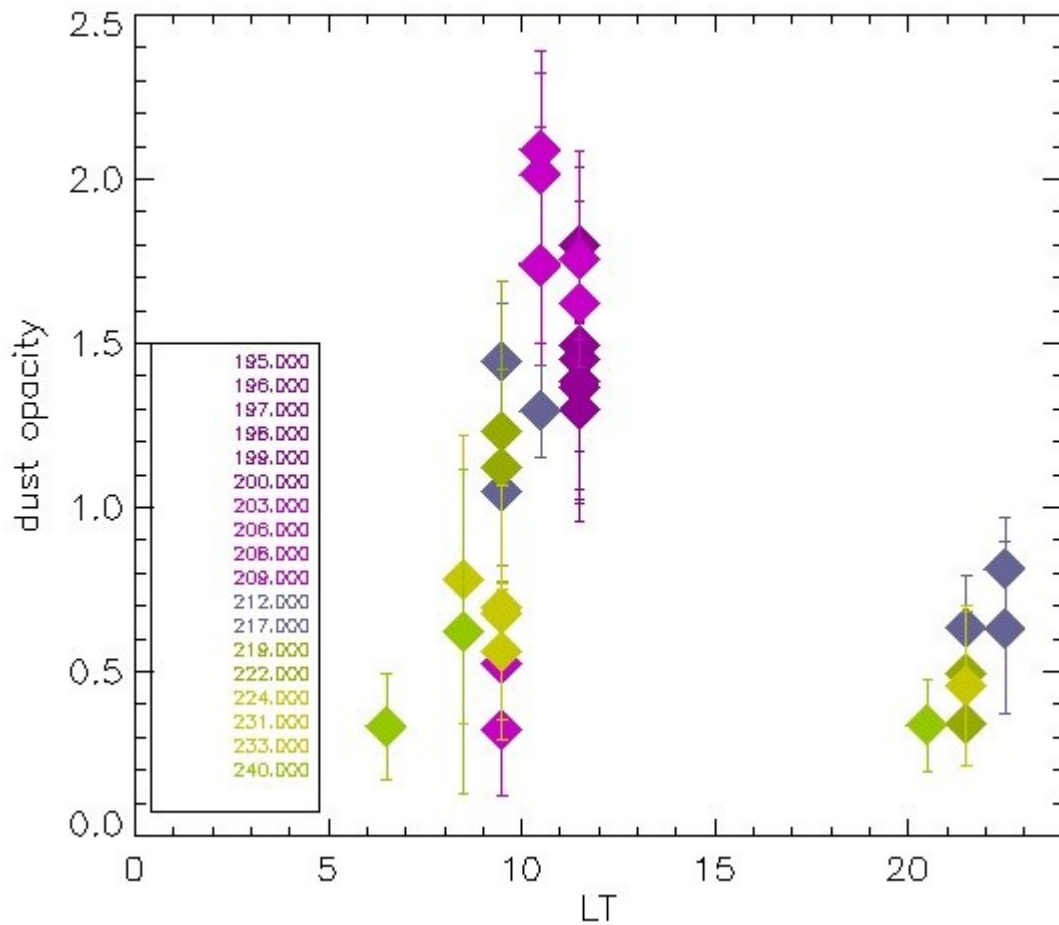
222 To better analyze the LT variation excluding the seasonal effect we made figures with  $L_s$  bin equal to  
 223  $1^\circ$  during the  $L_s$  range of large dust opacities. **Fig.6** presents dust opacities as a function of LT for  
 224 some sols in MY 28. We have binned the data by  $1^\circ$  in  $L_s$ , by  $3^\circ$  in latitude and by 1 hour. Then we  
 225 averaged the binned data from  $40.5^\circ\text{S}$  to the equator and from the equator to  $40.5^\circ\text{N}$ . For our example  
 226 we took the southern latitude range because the storm core mostly appeared over this region. Dust  
 227 opacities available at different LTs were set into groups with similar behaviors. At 11 - 12 LT, dust  
 228 opacities show a large range of values between 1.3 – 2.5, from  $L_s = 273$  to  $L_s = 281$  (first group).  
 229 The maximum values of dust opacities are observed at 11 - 12 LT in our dataset at around  $L_s = 281^\circ$ .  
 230 We also note that dust opacities increase progressively within the first group at 11-12 LT, but this is  
 231 due to a seasonal effect.



232  
 233 Fig.6. Dust opacities as a function of LT for  $L_s$  bin ( $1^\circ$ ) shown in the legend in MY 28 for the southern  
 234 hemisphere ( $0 - 40.5^\circ\text{S}$ ). Some gaps are evident in  $L_s$  bins. The “error bars” represent the standard  
 235 deviation of each averaged value and provide an indication of the observed zonal and meridional  
 236 variations. As expected, such variations are particularly large during a global dust storm.

237

238 The second group is characterized by the largest differences in dust opacities at 10 - 11 LT and 22 -  
 239 23 LT. This group contains observations in the core of this storm and at the beginning of the decay  
 240 phase from  $L_s = 286$  to  $L_s = 292$ . The next group is from  $L_s = 295$  to  $L_s = 297$ . Within this group,  
 241 observations are taken only in the morning from 9 to 11 LT and show 1.2 - 1.5 of dust opacities. In  
 242 the decay phase, from  $L_s = 302$  to  $L_s = 304$ , the differences in dust opacities are observed between  
 243 the morning (9 - 10LT) and the evening (21 - 22 LT). The differences then gradually diminish but  
 244 they are still evident even at  $L_s = 310^\circ$ . There are several gaps in  $L_s$  bins but it is clear that dust  
 245 opacities from 8 - 11 LT are larger than in the evening at around 20 - 22 LT. The most interesting  
 246 behavior is found at 9 LT when the dust opacities vary from 0.4 to 1.4 during most available later  $L_s$   
 247 bins ( $295^\circ - 310^\circ$ ). Dust opacity starts changing from 1.4 at  $L_s = 295^\circ$  and gradually decreases with  
 248 season at this LT. Unfortunately, we are not able to claim that dust activity grows with LT for each  
 249 day during morning hours. We observe a seasonal effect. Only observations at  $L_s = 310^\circ$  show dust  
 250 increasing from 8 to 9 LT and the difference in dust opacities between morning and evening hours.  
 251 In **Fig.6** dust opacities at LT 12 are not plotted because not enough measurements were taken during  
 252 the onset of the storm for  $L_s < 273$  (Fig.5).



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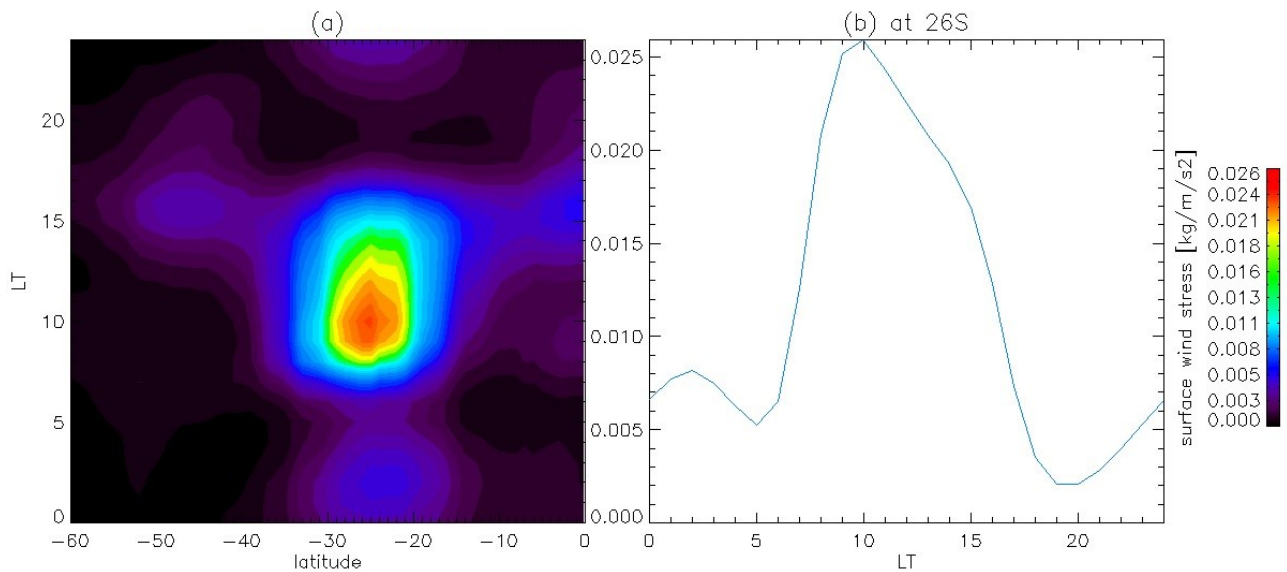
254 Fig.7. Dust opacities as a function of LT for different  $L_s$  bins shown in the legend in MY 34 for the  
255 southern hemisphere ( $0 - 40.5^\circ\text{S}$ ). The “error bars” represent the standard deviation of each averaged  
256 value and provide an indication of the observed zonal and meridional variations. As expected, such  
257 variations are particularly large during a global dust storm.

258

259 **Fig. 7** shows a similar behavior of dust opacities as a function of LT for the core and the decay phase  
260 of storm in MY 34. However, some differences are observed with respect to MY 28. In MY 34, the  
261 maximum is observed at 10 - 11 LT. Observations at 11 - 12 LT show small decreases of dust opacities  
262 with respect to values at 10 LT. Contemporaneously these observations at 11 - 12 LT show a variation  
263 with season from  $L_s = 195^\circ$  to  $200^\circ$ . There is then a gap at larger  $L_s$  for this LT. At  $L_s = 203^\circ - 209^\circ$   
264 we also observe the dust increasing from 9 to 10 LT. Also, the dust activity at 9 LT grows with season  
265 in the core of the dust storm and decreases, for example, at  $L_s = 233^\circ$  (lightest green points). As in  
266 the case of MY 28, we observe again a large difference in dust opacities between 9 - 10 LT and in the  
267 evening during the  $L_s$  interval from  $212^\circ$  to  $222^\circ$ . However, the diurnal differences are also present  
268 in the decay stage of the storm, at a time when active dust lifting is almost certainly less pronounced.  
269 Dust opacities are within 1.3 – 1.4 in the morning (9 – 10 LT), whereas in the evening 21 – 22 LT we  
270 find still large values but less than 0.7 ( $L_s = 212^\circ - 231^\circ$ ). Finally, at the end of the storm (decay  
271 phase) at  $L_s = 231^\circ$  we still observe differences between morning and evening hours, but these  
272 differences decrease gradually to achieve a very similar level during the whole day.

273 Here we note a strong correlation between surface wind stress and the observed daily variation of  
274 dust opacity during the global dust storm of MY28. In **Fig. 8a** we show the zonally averaged surface  
275 wind stress as a function of local time for the southern hemisphere ( $0-60^\circ\text{S}$  latitude) as inferred from  
276 the MCD v5.3 (Millour et al., 2015; Forget et al, 1999a,b). We use the MY 28 scenario, which  
277 corresponds to the best representation by the model of this specific year, both in terms of daily  
278 atmospheric dust loading and daily solar EUV (Extreme Ultraviolet scenario) input. Solar longitude  
279 is  $L_s = 270^\circ$  (southern summer solstice), which is during the onset of the MY 28 global dust storm  
280 (**Fig. 3 and 4**). The surface wind stress shows a strong temporal (LT) and latitudinal dependence.  
281 Similar to dust, it rapidly increases after 6 LT and the largest values are observed between 8 LT and  
282 12 LT, with a peak around 10 LT (Fig.8b). Then, it rapidly decreases until 15 LT and stays low  
283 afterwards. The surface wind stress is maximum around the sub-solar latitudes, between  $20^\circ$  and  $30^\circ$   
284 S (**Fig. 8a**). Newman et al. (2002) find a threshold-dependence for wind stress lifting to reproduce  
285 Martian dust storms. With this feature applied, sharp increases in opacity could be produced upon  
286 dust storm initiation, as observed. Moreover, these authors also note an important feedback effect for

287 wind stress lifting. Dust raised from the surface heats the near-surface atmosphere forming the  
288 temperature gradient which strengthens low-level winds, and thus encourages further lifting.

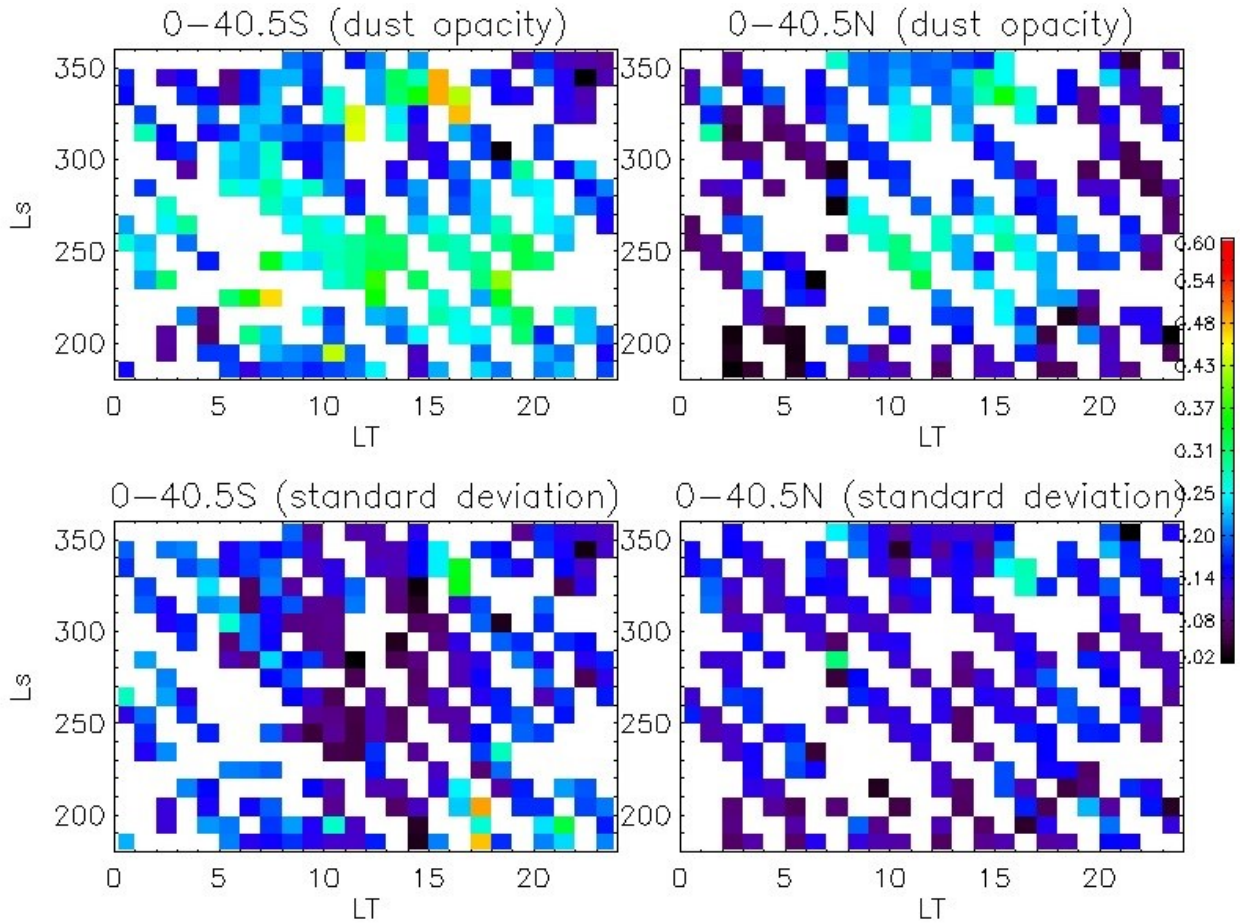


289  
290 **Fig. 8.** Zonally averaged surface wind stress at the southern summer solstice as a function of local  
291 time, as inferred from the MCD v5.3 using the Mars Year 28 scenario (a) for the latitudinal range 0-  
292 60°S latitude, and (b) at 26°S latitude.

293  
294 As a consequence, lifting via near-surface wind stress is an explosive process, making it a suitable  
295 candidate for the rapid injection of dust that is observed by PFS.

296  
297  
298 **2.2. Dust in typical Martian year (dusty season). Storms A, B and C in PFS results as a function**  
299 **of latitude and LT.**

300  
301 Contrary to the dust increase observed during strong dust activity in MY 28, MY 29 and MY 34, we  
302 find no special trend in variation of dust opacity with LT in the dusty season for a typical Martian  
303 year. We will call the typical Martian year the year of all MYs combined together, observed by PFS,  
304 except for MY 28, MY 29 and MY 34. The peculiar behavior with the large increase of dust opacity  
305 before midday is not observed in other MYs during the dusty season.



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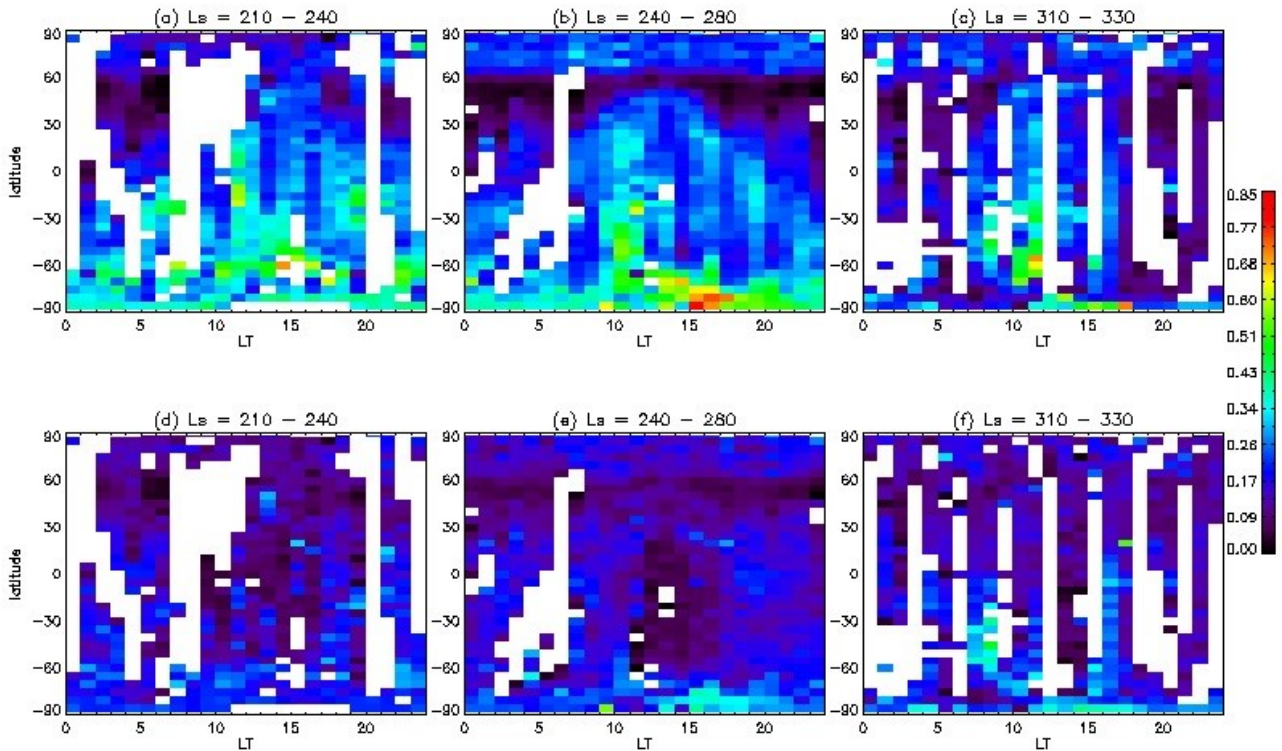
307 Fig. 9. Dust distribution as a function of solar longitude ( $L_s$ ) from  $180^\circ$  to  $360^\circ$  and LT for southern  
 308 hemisphere ( $0 - 40.5^\circ\text{S}$ ) left and for northern hemisphere ( $0 - 40.5^\circ\text{N}$ ) right in typical MY.

309

310 **Fig. 9** presents the distribution of measurements as a function of  $L_s$  and LT for dust opacity with  
 311 standard deviations within each bin. Bins of  $10^\circ$  of  $L_s$  and 1 hour were used in the plot. The difference  
 312 in dust opacity between daytime and nighttime is more visible in the northern than in the southern  
 313 hemisphere (**Fig.9**), especially in the  $L_s$  range from  $220^\circ - 270^\circ$ . We observe a clear growth in dust  
 314 opacities with sunrise and decrease with sunset. The next seasonal increase of dust opacities is  
 315 observed in the  $L_s$  range  $310^\circ - 350^\circ$ , in the southern as well in the northern hemisphere. At the  
 316 beginning of this  $L_s$  interval moderate dust opacities around 0.45 occur between 11 – 12 LT in the  
 317 southern hemisphere, and in the northern hemisphere relatively less. With season the dust activity is  
 318 shifted toward later hours (15 – 17 LT) in both hemispheres. The seasonal variations of dust were  
 319 studied in terms of atmospheric temperatures at 0.5 mbar from the MCS MRO observations (Kass et  
 320 al., 2016). Using this dataset, they defined three types of dust storms (A, B and C), which are  
 321 recognized in seasonal variations of PFS dust opacities (Wolkenberg et al., 2018). We find similarities

322 to seasonal types of storms defined by Kass et al. (2016). Our purpose in this section is to present  
323 some characteristic features of these storm types with LT illustrated also in **Fig. 9** for the typical  
324 Martian year. In our results (**Fig.9**) A and B storms are overlapped or combined in one storm starting  
325 from around  $L_s$  220° to 270°. The duration of C storms is longer in our results than in MCS  
326 observations. The end of C storms is observed at  $L_s = 350^\circ$  (**Fig.9**). To compare better our results  
327 with MCS observations we plotted the dust variations with LT for  $L_s$  intervals when these three types  
328 of storms took place (**Fig. 10a, b, c**). **Fig. 10a** presents the dust opacities during the  $L_s$  interval  
329 corresponding with the duration of A storms (210° – 240°). Dust in A storms occurs at all LTs and is  
330 mostly confined to the southern hemisphere. There are no special regions and time of day when dust  
331 is pronounced. We found less dust in the northern hemisphere up to 50°N than in the southern  
332 hemisphere. This amount in the northern hemisphere decreases from midday to around 16 LT.

333 **Fig. 10b** illustrates the behavior of B storms with LT for the  $L_s$  range from 240° to 280°. The elevated  
334 dust opacity is evident over southern polar regions during daytime and nighttime. The maximum of  
335 the dust opacities (around 0.7) is found at 15 – 17 LT, close to the South Pole which is consistent  
336 with **Fig. 1** in Kass et al. (2016). In **Fig.1** in Kass et al. (2016) B storms start at the end of A storms.  
337 The decay phase of the A storms is observed in the B storms between 9 and 12 LT. The storm's  
338 moderate dust activity (0.4) is found over southern and mid-northern latitudes. This dust opacity  
339 maximum in B storms is similar to the increase at 10 – 12 LT for the strong dust activity in MY 28  
340 and MY 34 in **Fig. 5, 6, 7**. A relatively clear atmosphere is observed over latitudes from 30°N to  
341 60°N. This non-dusty condition continues from the late afternoon until night.



342

343 Fig.10. Dust opacity as a function of latitude and LT for specific  $L_s$  intervals corresponding to the  
 344 duration of A (a), B (b) and C (c) storms. Standard deviations of dust opacity for each bin  
 345 corresponding to the duration of A (d), B (e) and C (f) storms. We collected all MYs except for MY  
 346 28 and MY 34.

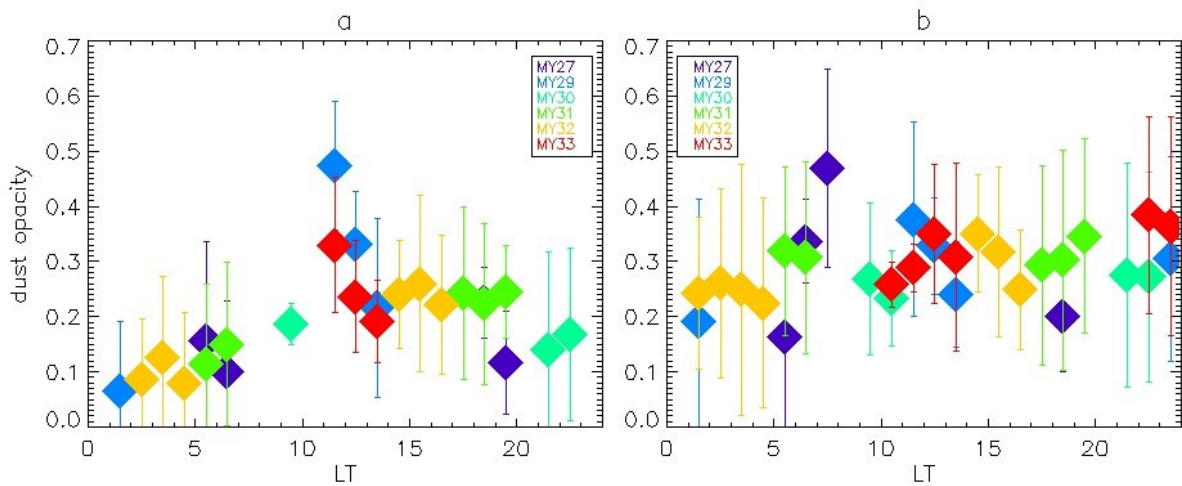
347

348 C storms are mainly constrained to southern latitudes in the  $L_s$  range from  $310^\circ$  to  $330^\circ$ . It occurs  
 349 from the late morning to midday (**Fig. 10c**). However, again, dust is still active with opacity around  
 350 0.3 over northern mid-latitudes at 11 - 12 LT. In **Fig.1** in Kass et al. (2016) C storms are extended  
 351 from the southern polar region to the equator. **Fig.10c** clearly shows the dusty atmosphere at 16 – 17  
 352 LT over the South Pole.

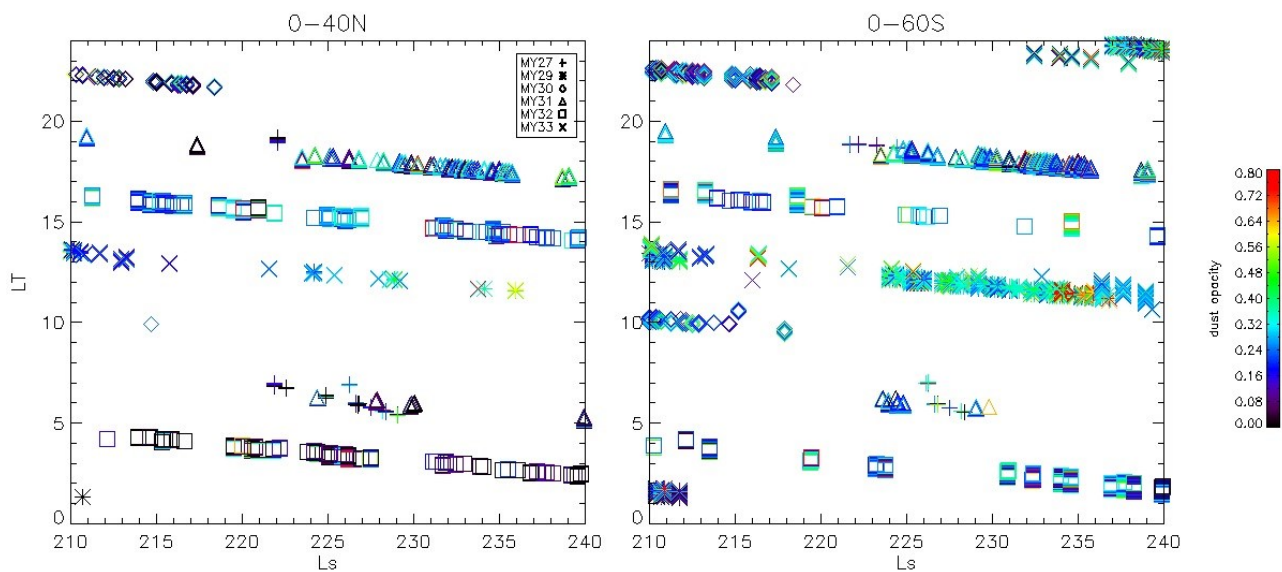
353 A clear atmosphere is recognized over northern high-latitudes around  $60^\circ\text{N}$  during the night in all  
 354 panels of **Fig.10**. Kass et al. (2016) point out that atmospheric temperature increases in the high  
 355 northern latitudes are the northern response to the atmospheric circulation. They exclude high dust  
 356 loads which could induce the increase of atmospheric temperatures at 0.5 mbar.

357 We also investigated interannual variations of dust for A, B and C storms by plotting dust opacities  
 358 as a function of LT for different years. A storms show some dust LT variations only for the northern  
 359 hemisphere (**Fig.11a**), where the maximum of the dust opacity occurs at 11 LT in MY 29 as well as

360 in MY 33. The dust opacity is elevated in MY 29 because of the regional dust storm and this is the  
 361 year following the global dust storm. However, considering Fig.11a along with Fig.12a the peak at  
 362 11 LT in MY 29 in the northern hemisphere is due to the advancing season. A similar behavior is  
 363 found in MY 33. Only two LTs (14 LT and 1 LT) are measured in the same day in MY 29 and they  
 364 show a contrast in opacity. From 13 to 20 LT dust opacity is at around 0.2 - 0.25, and it is relatively  
 365 large with respect to the other LTs during the night (0.1). After this detailed analysis, the A storms  
 366 show only around twice the elevated dust opacities with respect to nighttime observations in the  
 367 northern hemisphere. For the southern hemisphere there is no clear LT variation of dust opacity  
 368 (**Fig.11b, 12b**). We observe the elevated dust opacity between 0.3 – 0.4. The similar dust behaviors  
 369 over northern and southern hemispheres are shown in **Fig.10a**.



370  
 371 Fig. 11. Dust opacities as a function of LT for different MYs for A storms (a) 0 - 40°N, (b) 0 - 60°S.



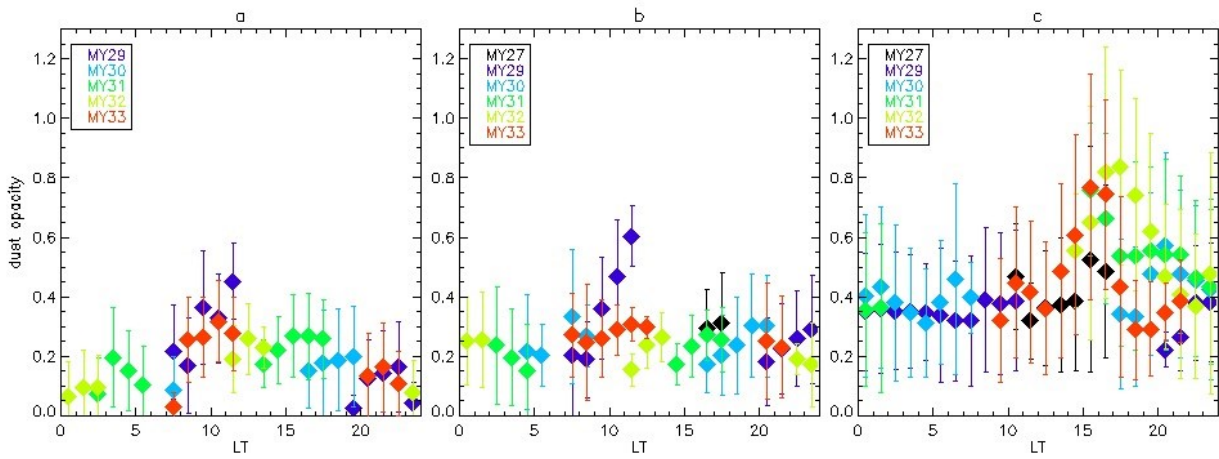
372

373 Fig.12. Dust opacities as a function of Ls and LT in different MYs during A storms for a) 0 - 40°N  
374 and b) 0 – 60°S. Different symbols correspond to different MYs and they are presented in the legend.

375

376 B storms “” have a particular behavior because a large dust activity occurs close to the South Pole  
377 and, thus we considered three regions separately: 1) from the equator to 40°N (northern hemisphere)  
378 (**Fig.13a**), 2) from the equator to 60°S (southern mid-latitudes) (**Fig.13b**) and 3) from 75°S to 90°S  
379 (South Pole) (**Fig.13c**). The maximum dust opacity is observed at 11 LT in MY 29 for the northern  
380 and southern hemispheres in “B” storms (**Fig.13a and 13b**). The spike in MY 29 B-storm activity at  
381 11 LT shown in Figures 13a and 13b appears to be a hold-over from the relatively late A-season storm  
382 in that year. The decrease in opacity as local time moves to 8 LT is due to the advancing season.  
383 However, the difference in opacity between 11 LT and 21 – 22 LT is observed in the northern  
384 hemisphere as well as in the southern hemisphere for the same day in MY 29 (Fig.13a,b). A similar  
385 behavior for dust is also found in A storms in MY 29 and 33 (**Fig.11**). However, in B storms we found  
386 more inter-annual LT variation of dust than in A storms. **Fig.13b** shows the LT dust variation for the  
387 region from the equator to 60°S. The dust activity is different only in MY 29 in B storms with respect  
388 to other MYs. The LT variation of dust is within 0.15 to 0.35 except for MY 29. Again the dust  
389 opacity increase with LT in the morning in MY 29 is due to the advancing season. However, the  
390 regional storms in MY 29 show a large contrast between 11 LT and 23 LT observations. This  
391 difference in opacity resembles the activity of dust during global dust storms.

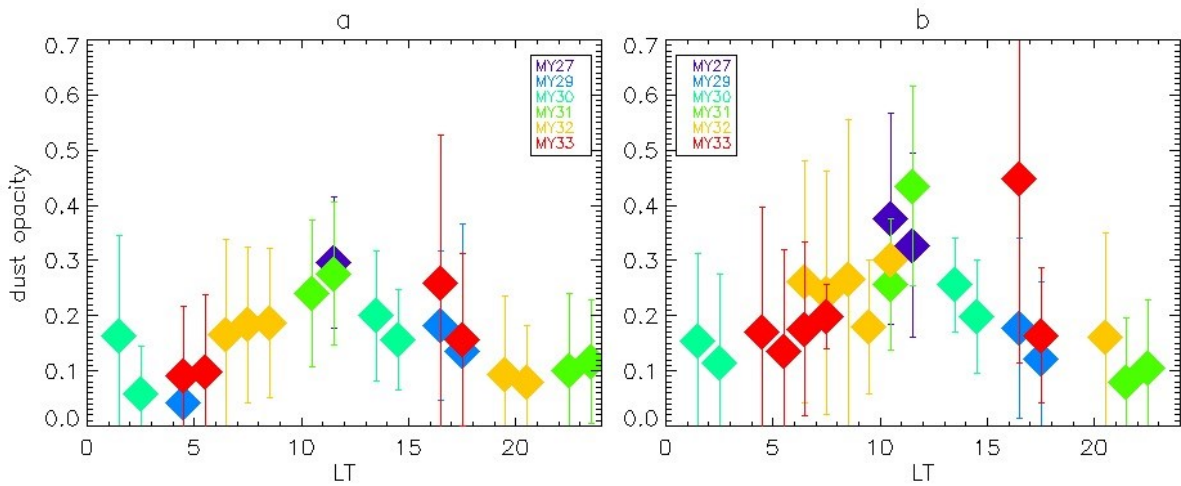
392 B storms over the South Pole are characterized by a peculiar behavior (**Fig.13c**). We observe the  
393 maximum of dust opacity in the afternoon from 15 LT in MY 33 to 20 LT in MY 30. This peak is  
394 present each Martian year except for MY 29 due to lack of data. The maximum is most pronounced  
395 at 15 LT in MY 32 and at 17 LT in MY 33. Less intense dust activity is found at 20 LT in MY 30 and  
396 elevated dust opacities (0.55) are observed from 17 LT to 21 LT in MY 31. A small peak during late  
397 afternoon (15 – 16 LT) is observed in MY 27. During the night there is no large year-to-year LT  
398 variation. The dust opacity oscillates around 0.4 (Fig.13c).



399

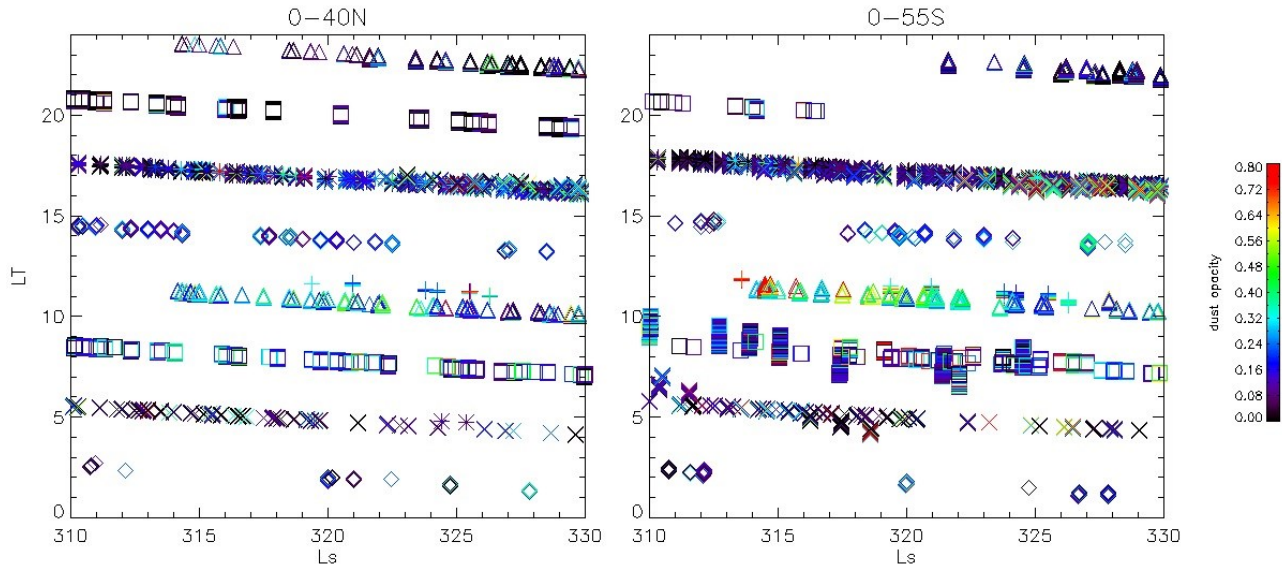
400 Fig.13. Dust opacities as a function of LT for different MYs for B storms (a) 0 - 40°N, (b) 0 - 60°S,  
 401 (c) 75°S - 90°S.

402



403

404 Fig.14. Dust opacities as a function of LT for different MYs for C storms (a) 0 - 40°N, (b) 0 - 55°S.



405  
 406 Fig.15. Dust opacity as a function of Ls and LT in different MYs for C storms a) 0 – 40°N and b) 0 -  
 407 55°S. Different symbols correspond with different MYs as in the legend of Fig. 12.

408  
 409 “C” storms have a similar behavior with LT for the northern and southern hemispheres (**Fig.14a and**  
 410 **14b**). The dust opacity peaks at 11 - 12 LT in MY 27 and MY 31 (Fig.15a,b). However, the dust  
 411 opacity maximum at 11 - 12 LT is a true relative maximum only in MY 31 because the decrease of  
 412 dust opacity is observed at 22 LT in the same day. In MY27, gaps occurred in the data. In MY 33,  
 413 dust maximum is observed only at 16 LT for the northern as well as for the southern hemispheres.  
 414 The decrease of dust opacity from 16 LT to 17 LT in MY 33 is due to the seasonal effect (Fig.15a,b).  
 415 However, in both hemispheres a difference in afternoon (16 LT) and night dust opacities is observed  
 416 for the same day in MY 33. This maximum at 16 LT is also observed in Fig.9a. In Fig.10c this  
 417 maximum is not visible because all MYs except for MY 28 and 34 were used in the calculation of  
 418 averages for each bin. Two measurements in MY 29 and MY 33 averaged at 16 LT give a mean value  
 419 consistent with the value in Fig.10c. A similar peak was also observed in B storms at the southern  
 420 polar region. At night, dust opacities have lower values down to 0.1 and less than 0.1 for the northern  
 421 region.

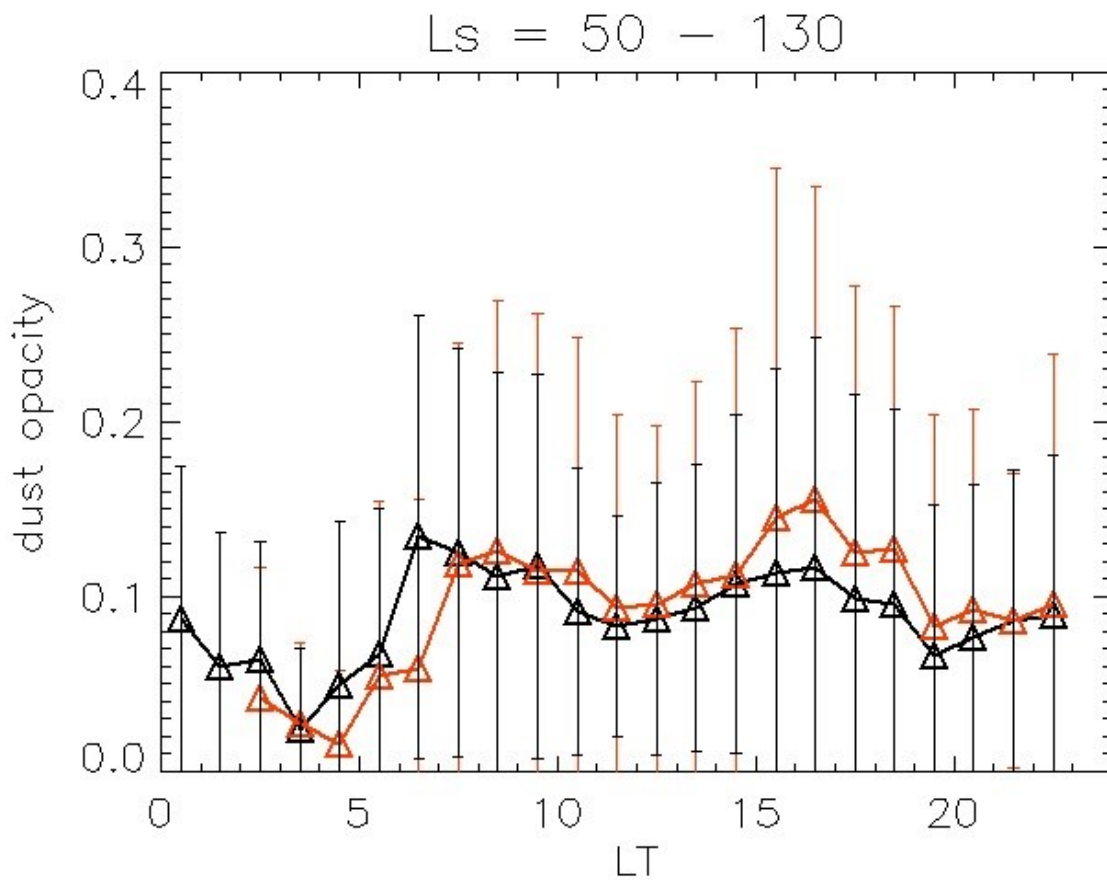
422 With this analysis we found clear differences between dust opacities during day and night, especially  
 423 for the northern hemisphere for all types of storms. Dust over the southern mid-latitudes shows a  
 424 moderate and constant variation with LT with some inter-annual discrepancies. The most unusual  
 425 behavior is found in B storms at the South Pole with maximum dust opacity observed in the afternoon  
 426 (14 – 20 LT).

427

428 **2.3. Dust activity in non-dusty season for all MYs**

429

430 Northern springs and summers are characterized by small dust activity. Even in the year with the  
431 global dust storm (MY28) there is no special dust increase in these two seasons. In order to illustrate  
432 better a behavior of dust over the course of a 24-hour day, we selected the  $L_s$  range from  $50^\circ$  to  $130^\circ$ ,  
433 on either side of the northern summer solstice. **Fig.16** presents the dust variation with LT for both  
434 hemispheres. We clearly observe that dust activity follows the sun respectively in both hemispheres.



435

436 Fig.16. The dust variation with LT for  $L_s$  interval from  $50^\circ$  to  $130^\circ$  on either side of the northern  
437 summer solstice. Data binned with 1-hour bin and collected for the southern ( $0 - 25^\circ S$ ) and northern  
438 hemispheres ( $0 - 25^\circ N$ ) are plotted by red and black triangles, respectively. The “error bars” represent  
439 the standard deviation of each averaged value and provide an indication of the observed zonal,  
440 meridional, and inter-annual variations.

441

442 Sunrise, and with it dust increases, occur approximately one hour earlier in the northern than in the  
443 southern hemisphere. This is consistent with the northern summer solstice period when the sun

444 insolation is greatest over northern mid-latitudes. There is a clear trend of dust opacity during the  
445 daytime, with two local maxima observed in the morning and in the late afternoon around 17 LT. The  
446 similar bimodal distribution of dust devil activity during daytime in the northern spring and summer  
447 can be reproduced by a model (Chapman et al., 2017). Maxima of dust devil activities are found at  
448 around 8 – 9 LT and in the afternoon at 15 – 17 LT, consistent with our results. The next specific  
449 behavior is characterized by a minimum atmospheric dust content, and is found during night/early  
450 morning. The minimum with respect to the daytime variation lasts longer during the night in the  
451 southern than in the northern hemisphere at this time at the year. The sun rises later for the southern  
452 hemisphere, leading to the longer night there. The variation of standard deviations is larger for the  
453 southern hemisphere than for the northern hemisphere. The nighttime behavior of dust with a  
454 minimum at 4 - 5 LT is strictly associated with the occurrence of water-ice clouds. Fig.12 in Hinson  
455 and Wilson (2004) shows the model LT variations of water-ice clouds and temperatures in the  
456 equatorial region during the aphelion season. Maximum activity of water-ice clouds was found from  
457 23 – 8 LT, depending on altitudes, and this behavior illustrates the extent of control on clouds by tides  
458 (Hinson and Wilson, 2004).

459 In conclusion, during the non-dusty season we observe a different daily cycle of dust compared to the  
460 daily variation in the dusty season during global dust storms. The minimum of dust opacity is found  
461 during the early morning, then suddenly at around 6 – 7 LT dust content starts increasing threefold.  
462 Dust opacity increases faster in the northern hemisphere than in the southern hemisphere. During the  
463 daytime, the dust amount varies around the mean value (0.15) for this season with two small local  
464 maxima. After sunset it decreases gradually. These results are consistent with those obtained from  
465 the MCS MRO instrument describing the high altitude dust maximum (HATDM) over the tropics  
466 during the northern summer solstice (Heavens et al., 2011). They also found that the dust opacity  
467 increases threefold during the daytime compared to nighttime.

468

### 469 **3. Discussion**

470

471 During global dust storms we find a large daily variation of dust opacities (**Fig.5, 6, 7**). We analyzed  
472 the results in terms of capabilities in a retrieval of dust opacities in the vicinity 5 – 9 LT and 16 – 19  
473 LT, when only a small contrast between atmospheric and surface temperatures should occur. This  
474 contrast undergoes a change in sign in the morning as surface temperatures climb above air  
475 temperatures (in the lower atmosphere) and again in the evening as the surface begins to cool down.

476 The impact of dust storm events is likely to make this issue more problematic, as nighttime surface  
477 temperatures are increased by increased downward IR flux from the warmed atmosphere, while  
478 daytime surface temperatures are decreased due to attenuated solar radiation. However, we found that  
479 for the considered latitude range from 40.5N to 40.5S, the contrast was not small. An isothermal  
480 atmosphere was absent in this region. We demonstrated this through a calculation of synthetic spectra  
481 for different dust opacities at three LTs (6.18, 18.81, 18.32). Dust had a large impact on spectra,  
482 which was clear in the dust absorption band (Appendix B, Fig.B1 and B2), especially when an  
483 atmospheric thermal inversion occurred. Thereby, we are confident in these retrievals of dust  
484 opacities even in the morning and in the evening, although they can have a large uncertainty as is  
485 shown in Fig.1b.

486 The difference in dust opacities found before midday and in the evening is large and can be associated  
487 with the presence of winds. Significant daily variation of a wind system (Goody and Belton, 1967;  
488 Gierasch and Goody, 1968) can lift the dust from the surface, possibly inducing the daily dust  
489 variations. Whether or not the surface wind stress plays a key role in the rapid increase of dust  
490 observed by PFS in the morning, the decrease of opacity consistently observed in the evening (early  
491 night) is even more puzzling. Once suspended, dust particles will slowly fall to the ground under the  
492 influence of gravity, as their density is greater than the atmospheric density. Settling velocity  
493 increases with particle size, with sedimentation timescales varying from hours for large particles to  
494 days and months for small particles, depending also on their altitude. Sedimentation is likely the main  
495 mechanism of dust deposition on the surface because scavenging by water ice is not very likely in the  
496 core of a global dust storm during daytime due to great atmospheric temperatures. Cantor et al. (2001)  
497 suggest that local dust storms that are observed to disappear within one diurnal cycle are probably  
498 composed of large particles, because coarse-grained particles will settle out of the Martian  
499 atmosphere very rapidly. The observed rapid variation of opacity with LT requires large dust particles  
500 to be lifted and deposited back to the surface each day in about ten hours.

501 The dust particles, depending on their size, are raised from the surface by saltation process, dust devils  
502 and surface winds (Cantor et al., 2001). The wind tunnel experiments conducted in the simulated  
503 Martian conditions allow the sufficient wind velocity to be estimated (Greeley et al., 1980). The  
504 required surface wind speed in order to lift particles with sizes around 100  $\mu\text{m}$ , is around 50 m/s over  
505 a flat surface of erodible grains (Greeley et al., 1980). However, the meteorological data obtained  
506 from the sites of the Viking landers show that 25 – 30 m/s winds are able to raise grains with sizes  
507 from 10 – 100  $\mu\text{m}$  (Greeley et al., 1980). Moreover, the wind tunnel experiment demonstrates that  
508 the threshold wind shear (friction wind speed) is minimal for particles with diameters of 80 – 100  $\mu\text{m}$

509 in Martian conditions (Balme and Greeley, 2006). Thus these particles are most easily introduced into  
510 the atmosphere (Balme and Greeley, 2006). It also means that grains with smaller or larger sizes  
511 require stronger winds. Recently, wind tunnel experiments conducted under 0.38g (g - terrestrial  
512 acceleration) (Musiolik et al., 2018) show that the derived threshold wind shear velocity is lower than  
513 obtained in prior experiments (Greeley et al., 1980). As a result, the saltation of dust particles and  
514 their suspension are possible under Martian conditions at a lower threshold shear velocity ( $0.82 \pm$   
515  $0.04$  m/s) (Musiolik et al., 2018) than originally estimated (1.5 – 2 m/s) by Greeley et al. (1980).

516 Cantor et al. (2001) suggest that large particles are involved in the diurnal variation of local dust  
517 storms because they have a tendency to be suspended in the atmosphere for a very short time.  
518 However, according to Cantor et al. (2001) the coarse-grained particles cannot be responsible for  
519 large local dust storms over the landing sites of the Viking rovers. Large particles undergo saltation  
520 but their trajectories are ballistic near the surface. Thus they are not able to soar to high altitudes.  
521 However, the impact of large particles on the ground induces the lifting of small particles. When the  
522 saltation process is repeated many times, finer dust particles are raised from the surface and are  
523 suspended in the atmosphere longer than coarse ones.

524 On the other hand, all grain sizes are involved in dust devils. The vortex threshold speed for such an  
525 injection appears to be relatively independent of particle size (Neubauer, 1966; Greeley et al., 1981;  
526 Cantor et al., 2001). Dust devils can extend as high as the convective boundary layer, that is on the  
527 order of 10 km (Mulholland et al., 2015; Chapman et al., 2017). Particles are lifted from the ground  
528 and enter in a vertical, upward-spiraling column of air (Chapman et al., 2017). Numerical simulations  
529 of the vertical transport in dust devils were performed by Gu et al. 2006; Spiga et al. 2016. They  
530 considered three sizes of grains (100, 200 and 300  $\mu\text{m}$ ). They point out that the small sized particles  
531 (100  $\mu\text{m}$ ) are lifted up and form a dust devil core. The others rotate around the core. After some time,  
532 the heaviest and the finest particles are found close to the surface and in the top of the core,  
533 respectively, leading to stratification (Gu et al., 2006; Spiga et al., 2016).

534 The dust devils shown by Viking orbiter images are roughly 100 – 1000 m wide and extend a few  
535 kilometers above surface (Ellehoj et al., 2010). Many dust devil tracks are found during southern  
536 summer seasons over Argyre and Hellas basins from MOC images (Balme et al., 2003). Thus, we  
537 anticipate that the dust particles with large grains might be lifted up to relatively high altitudes in  
538 many dust devils. However, at the moment, we know little about the processes that actually dominate  
539 in the extreme conditions of an on-going global dust storm. Other mechanisms could be established,  
540 such as enhanced tides, vertical transport and velocities, and possibly other unidentified mechanisms.

541 As a matter of fact, the current climate models are unable to reproduce the observed diurnal (and  
542 daily) variation in the dust content, even during the non-dusty season.

543

#### 544 **4. Summary and conclusions**

545

546 We analyzed dust opacities obtained from PFS measurements from  $L_s = 331^\circ$  of MY 26 until  $L_s =$   
547  $300^\circ$  of MY 34. We found three typical behaviors of dust opacities varying with LT depending on  
548 the season in the Martian year. We separated the data from MY 28 and MY 34 with the global dust  
549 storms, and from MY 29 with the regional storm from other MYs. We observed a striking behavior  
550 of dust opacities during these three years in the dusty seasons. Namely, we find large values of dust  
551 opacities at around 10 - 11 LT compared to the evening observations. The study of models of dust  
552 devil activity using MGCM (Mars Global Circulation Model) also predicts a peak before midday at  
553 many locations on Mars (Chapman et al., 2017). Large areas on Mars are involved in dust devil  
554 activity in the morning according to the MGCM (Chapman et al., 2017).

555 When surface stresses as a result of winds are strong enough, dust enters the Martian atmosphere  
556 (Haberle, 1986) by saltation and other means (Greeley et al., 1980). Some local dust storms can last  
557 about a day and can be of limited scale (around  $10^4 \text{ km}^2$ ) (Haberle, 1986). During the global dust  
558 storms, large size particles can be lifted from the surface by increasing upward motions in the morning  
559 as an effect of growing insolation (Goody and Belton, 1967; Gierasch and Goody, 1968). Then after  
560 midday large particles of dust can deposit onto the surface very quickly, causing the dust opacity  
561 depletion in the atmosphere (Cantor et al., 2001). Significant dust opacities which are small with  
562 respect to the increase during the morning hours are then observed by PFS during the early evening  
563 (20 LT). Other processes such as a nucleation of water ice crystals can be involved in the sudden drop  
564 of dust content. Dust can be the nuclei for water-ice clouds and then it becomes transparent in attempts  
565 at its detection.

566 We also analyzed the behavior of dust opacities with LT in the dusty seasons of other MYs (typical  
567 Martian year). Elevated dust opacities are observed, but there is no significant variation with LT. In  
568 our results, with plots of zonally averaged dust opacities as a function of latitude and LT, we recognize  
569 three types of storms presented by Kass et al. (2016) and fully describe their variations with LT for  
570 the typical Martian year. We find that A storms are uniformly distributed with LT over the southern  
571 hemisphere during the whole nighttime and daytime. Elevated dust opacities are observed during  
572 afternoon hours compared to low values during the night in A storms in the northern hemisphere. B

573 storms are clearly seen during late afternoon close to the South Pole. C storms show a more intense  
574 activity in the southern latitudes with respect to the northern hemisphere. Large dust opacities are  
575 found before midday (10 – 11 LT) compared to the evening/early night observations. C storms also  
576 have an exceptional second peak of activity at 16 LT in MY 33.

577 In the non-dusty seasons of other MYs, dust shows significant minima during late night and early  
578 morning compared to the variation during daytime. We observed at the northern summer solstice that  
579 the variation of dust opacities strictly follows the sun in the morning. Two small local maxima  
580 prominent in the morning and afternoon are similar to the daily dust devil activity described by  
581 Chapman et al. (2017). The low dust content is observed longer in the atmosphere over the southern  
582 than the northern hemisphere. Dust varies threefold between daytime and nighttime, consistent with  
583 results by MCS (Heavens et al., 2011) for this season.

584

## 585 **Acknowledgments**

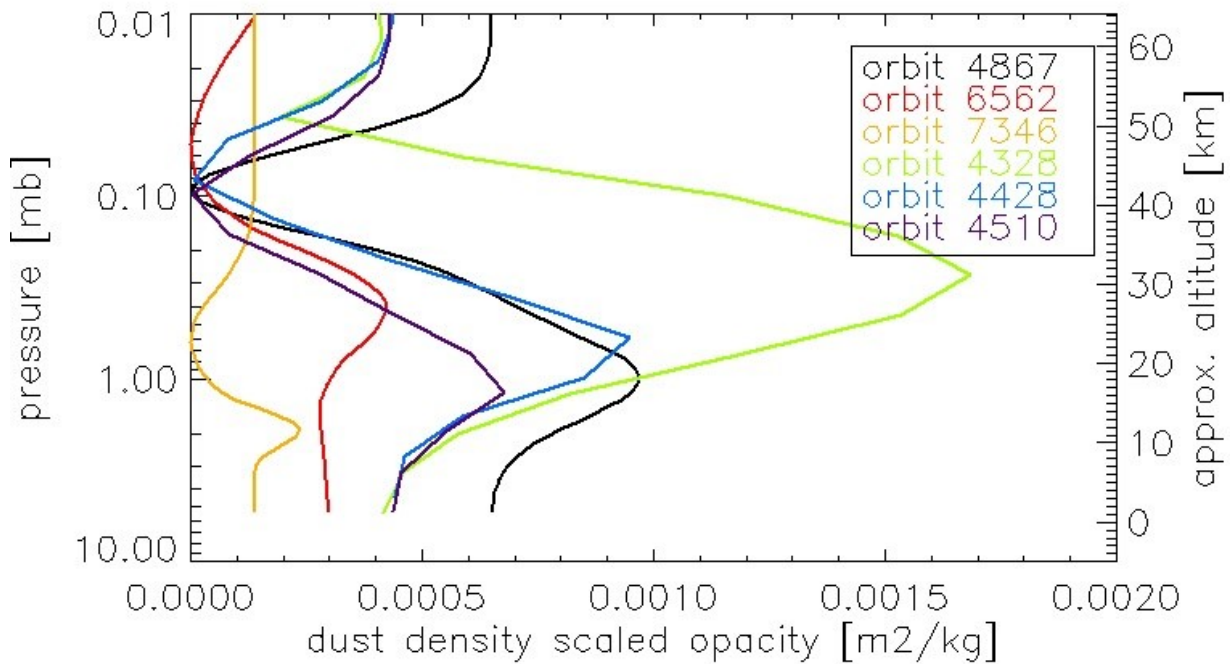
586 This work has been performed under the UPWARDS project. This project has received funding from  
587 the European Union’s Horizon 2020 research and innovation programme under grant agreement  
588 No633127. We also thank Michael Wolff and John Wilson for their insightful comments.

589

## 590 **Appendix A**

591

592 We analyzed an effect of different vertical dust profiles (‘a priori’) on a retrieval of column-integrated  
593 dust opacities. The different vertical dust profiles were derived from a dataset of coefficients provided  
594 by Nicholas Heavens based on the paper (Heavens et al., 2011). This dataset was built using the MCS  
595 data, namely, an analytical formula introduced by Heavens et al. 2011 was used to fit to the measured  
596 vertical dust extinction profile by the MCS. The vertical dust profiles were extended to the surface  
597 using the formula (eq.15) in Heavens et al. 2011. The vertical dust profiles built from the coefficients  
598 provided by N. Heavens were density scaled dust opacities. To simulate the effect of the different  
599 vertical dust profiles, we selected 7 PFS measurements from 7 different orbits. The analysis was  
600 performed for 6 different dust vertical profiles taken during day (corresponding with PFS orbits: 4328,  
601 4428 and 4510) and night (corresponding with PFS orbits: 4867, 6562, 6568, 7346 (Fig.A1)). The  
602 same vertical dust profile was selected for two orbits: 6568 and 6562. All of these vertical dust  
603 distributions are the best guesses in latitudes and seasons for corresponding PFS orbits. These profiles  
604 were inserted as initial vertical dust profiles to our retrieval code.



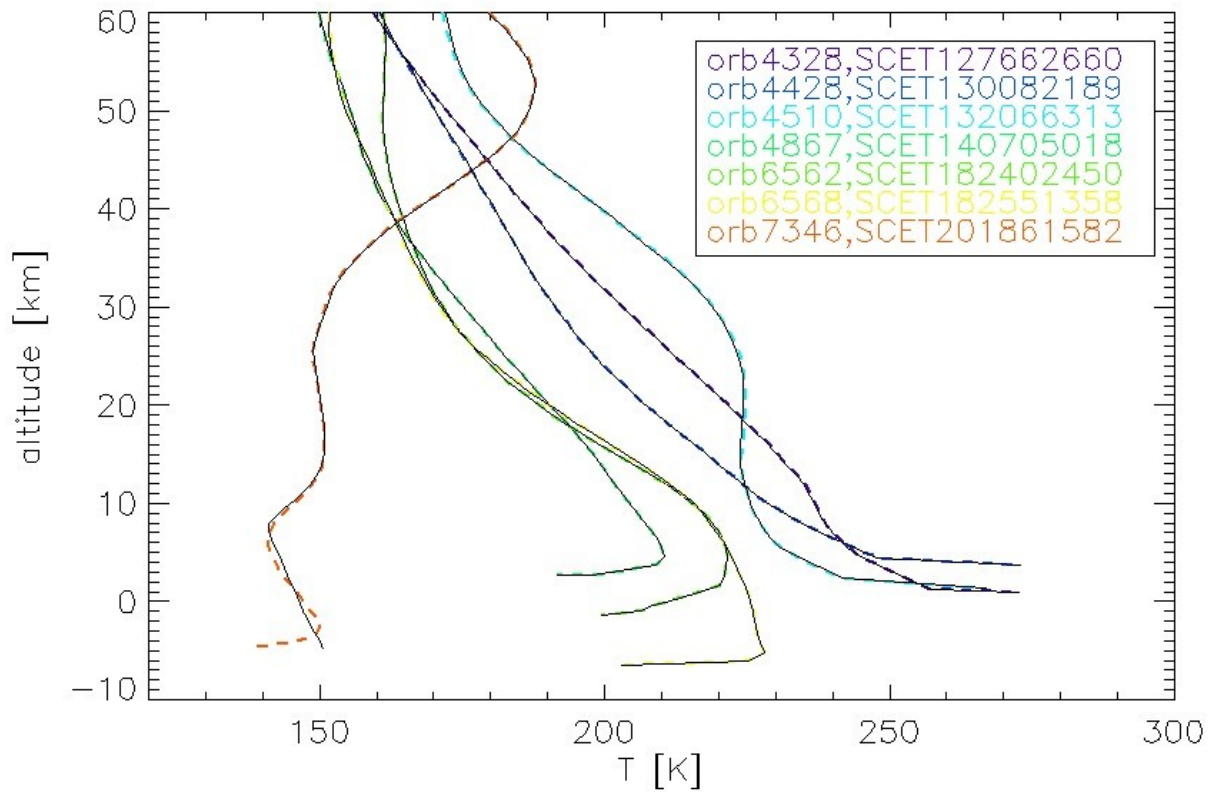
605

606 Fig.A1. Vertical dust distributions derived from fits to MCS data for a location and season of each  
 607 PFS measurement.

608

609 For these vertical dust profiles (Fig.A1) we determined temperature profiles and column integrated  
 610 dust optical depths. We compared then them with original temperature profiles and total dust optical  
 611 depths based on initial vertical dust distributions taken from EMCD v.4.2 database, which were a  
 612 function of exponential decrease.

613 Fig.A2 shows temperature profiles retrieved for ‘MCS’ dust profiles (dashed lines) and for dust  
 614 profiles taken from EMCD v.4.2 (solid lines). We observe differences between temperature profiles  
 615 for two orbits: 7346 and 4510. The temperature profile obtained from the measurement of orbit 7346  
 616 for the initial MCS vertical dust distribution shows the thermal inversion close to the surface (first 3  
 617 km) (dashed red line in Fig.A2). In the case of orbit 4510 we observe only ~ 1 K difference at ~20  
 618 km of altitude. In conclusion, we see no impact on temperature profiles. For the other measurements  
 619 temperature profiles are consistent. The characteristic features of measurements are given in Tab. A1.



620

621 Fig.A2. Atmospheric temperatures for selected PFS measurements using initial vertical dust profiles  
 622 from Fig.A1 (dashed lines) and original from EMCD 4.2 (solid line).

623

624 Table. A1. Characteristic features of measurements and calculated values of dust opacities for initial  
 625 MCS vertical dust distributions and EMCD.

| Number of orbit | Ls  | LT    | Latitude | Longitude (-180E;180E) | Dust opacity (MCS) | Dust opacity (EMCD) | Surface temperature (MCS) | Surface temperature (EMCD) |
|-----------------|-----|-------|----------|------------------------|--------------------|---------------------|---------------------------|----------------------------|
| 4328            | 241 | 14.22 | 40.13S   | -3.04 E                | 0.414              | 0.412               | 296.8                     | 296.632                    |
| 4428            | 259 | 12.82 | 34.08S   | -111.18 E              | 0.163              | 0.162               | 301.385                   | 301.339                    |
| 4510            | 273 | 12.13 | 27.46S   | 116.91 E               | 1.527              | 1.727               | 248.855                   | 249.94                     |
| 4867            | 332 | 5.76  | 23.25S   | -79.84 E               | 0.186              | 0.184               | 189.522                   | 189.474                    |
| 6562            | 208 | 1.82  | 47.31S   | -53.24 E               | 0.212              | 0.212               | 198.848                   | 198.822                    |
| 6568            | 209 | 1.74  | 45.96S   | 61.72 E                | 0.775              | 0.767               | 198.55                    | 198.573                    |
| 7346            | 343 | 3.76  | 66.93N   | -71.7 E                | 0.191              | 0.188               | 147.948                   | 147.955                    |

626

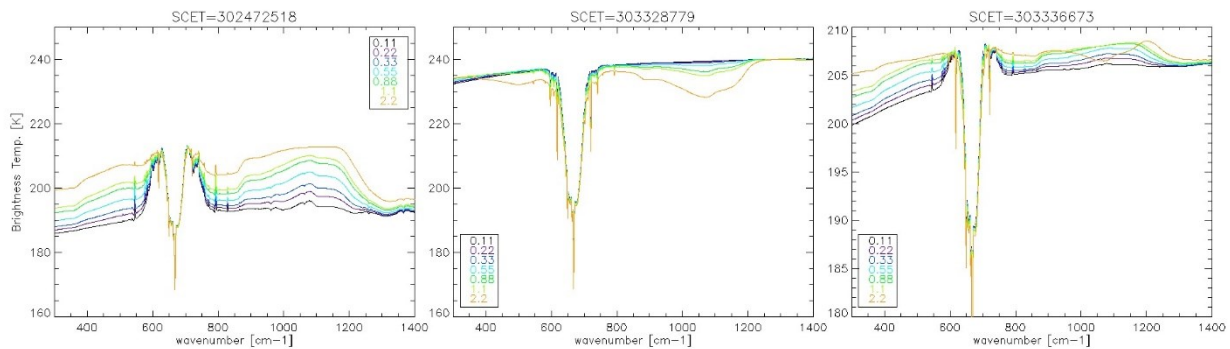
627 A small variation of total dust opacity is found for orbit 4510 when high dust loading occurs. The  
628 difference is ~12% with respect to the original version (Tab. A1). Most of the dust opacity variations  
629 due to location and season are larger than this difference for high dust loadings (during global dust  
630 storms), for example Fig.4. For the other orbits, the difference between results is ~1% even for a  
631 medium dust opacity (orbit 6568). On this basis, the dust opacity uncertainty due to unknown vertical  
632 dust distribution can be estimated for ~10%.

633

## 634 Appendix B

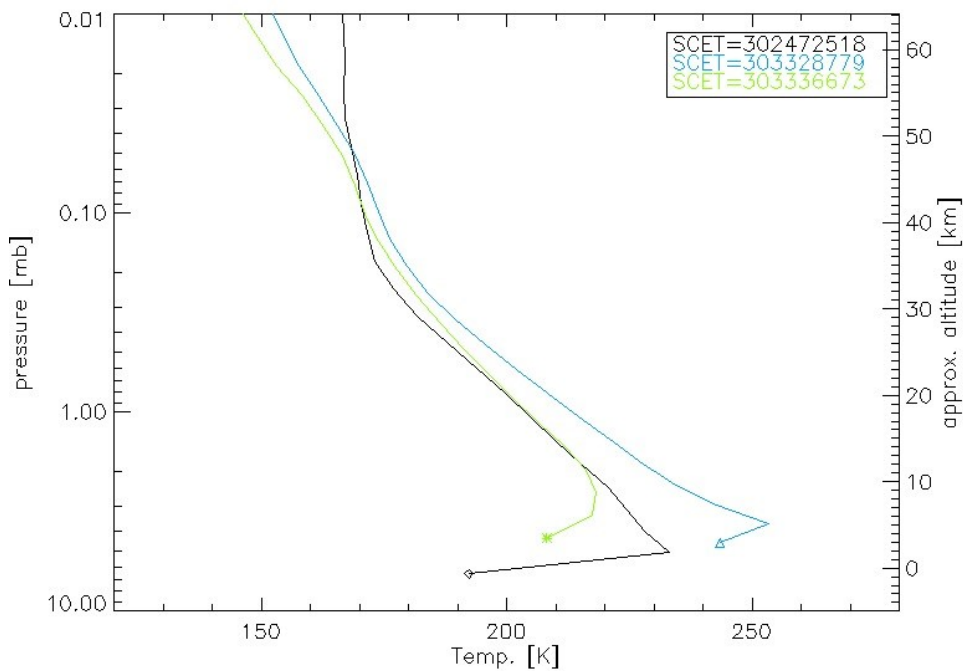
635

636 An impact of different dust opacities on spectra at three LTs (in the morning and in the evening) is  
637 presented in Fig.B1. The smallest differences between spectra calculated for the different dust  
638 opacities are observed for the measurement taken at 6.18 LT (SCET number 303336673).



639

640 Fig.B1. Model spectra calculated for three different temperature profiles (at three LTs: 6.18, 18.81,  
641 18.32) presented in Fig.B2 and for different dust opacities shown in the legend.



642

643 Fig.B2. Temperature profiles extracted from EMCD v5.3 for atmospheric conditions similar to three  
 644 PFS measurements in MY31. Black line corresponds to the PFS measurement (SCET 302472518)  
 645 taken at 18.81 LT,  $L_s = 217.38$ , latitude 16.77N and longitude 15.52E. Blue line corresponds to the  
 646 PFS measurement (SCET 303328779) taken at 18.32 LT,  $L_s = 223.52$ , latitude 28.18S and longitude  
 647 136.69E. Green line corresponds to the PFS measurement (SCET 303336673) taken at 6.18 LT,  $L_s =$   
 648  $223.58$ , latitude 28.6S and longitude -73.14E. Symbols mean surface temperatures for each  
 649 measurement.

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