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Quantifying the atmospheric impact of local dust storms using a martian Global Circulation Model

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Abstract

We investigate the modelled impact on the global atmosphere of local dust storm simulations on the martian atmosphere. The investigation utilises existing observations from Mars Global Surveyor's Mars Orbiter Camera and the Thermal Emission Spectrometer instruments, and the UK version of the LMD Mars Global Circulation Model. A typical example investigated here is a local dust storm in the Terra Sirenum region centered at (40°S, 146.5°W), with lateral coverage of $\sim 2.1\text{E}+5 \text{ km}^2$ and peak optical depth of 0.7. We find atmospheric cooling, initially mainly restricted to the planetary boundary layer, by up to 8 % (-14K) during the night of the first sol with a consequential abrupt rise (+15K) on the following sol, compared to the pre-storm diurnal range of 175–210K at this location. Divergent wind currents, with a high-pressure centre, develop on the first day of the storm resulting in changes in both wind components up to three times their base values ($\pm 10\text{m/s}$). Atmospheric densities above 15 km altitude exhibit a peak increase of +9 % from pre-storm values, while surface pressures show less change ± 3 %. Dynamical changes triggered by a local dust storm are quantified and their importance are thus considered in the context of potential future Mars spacecraft missions.

Keywords: Mars, climate, Dust storm, Atmospheres, dynamics, Infrared observations, Satellites, atmospheres

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1. Introduction

Dust is as influential as it is ubiquitous on Mars. The thin, CO₂-rich martian atmosphere is heavily influenced by the dust cycle, in particular its quantity and distribution. Absorption and emission of solar and infrared radiation by airborne dust is one of the primary drivers of changes in martian weather through heating and cooling the atmosphere, (Haberle et al. (2017), Chapter 10). Dust absorbs, scatters and reflects both solar energy and infrared emissions from Mars. Changes in radiative flux exchange, temperature gradients and thus vertical wind shears occur as a result, which in turn affects dust transport and facilitates further dust lifting (Read and Lewis (2004), Chapter 7).

Remote sensing techniques have been used for decades to observe and subsequently create and continuously refine Global Circulation Models (GCM) mimicking martian weather and climate (e.g. Smith et al., 2000; Cantor et al., 2001; Strausberg et al., 2005). Continued inter-comparisons utilising observations and GCMs is necessary to further understanding of the underlying mechanisms, impacts and key prognostic variables for understanding martian weather (Pollack et al., 1979; Haberle et al., 1982; Forget et al., 1999; Guzewich et al., 2013; Toigo et al., 2018). Effective modelling endeavours seek to further understanding of the more basic aspects of dynamical structures and mechanisms, while also highlighting potential weaknesses in our current understanding, creating avenues for further research attention (e.g. Spiga et al., 2013; Mulholland et al., 2013).

An ongoing aspiration of martian weather research is to be able to reliably and accurately predict significantly influential martian weather events (Levine and Winterhalter, 2017; Rogberg et al., 2010). The challenge is the absence of coherent and detailed understanding of the primary causes of well-defined dust storm, the precise atmospheric impact of a dust storm and its role in encouraging other dust events and the causes for escalation or de-escalation of dust storms, for example from a local to a regional dust storm (Haberle et al., 2017) likely through superposition of different circulation components (Leovy et al., 1973; Rafkin, 2009).

A positive feedback between understanding martian weather and subsequently being able to instigate and reap the benefits of successful science missions on Mars is thus vital (Chen et al., 2010). The aim of this work is to provide modelling insights into otherwise directly unobservable simpler phenomena arising from a spontaneous local dust storm, and contextualising

37 our results with regards to future missions which aim to land and operate
38 safely on the surface of Mars.

39 2. Motivation

40 The primary goal of this paper is to understand the potential impact of
41 a local dust storm from a global modelling perspective, while also validating
42 results against the current observational dataset. We seek to highlight any
43 potential risks a local, or small regional, storm may pose to future mars
44 missions. This study makes use of a GCM to assess the global impact of
45 several rather generic storms initiated at different latitudes, in contrast to a
46 smaller scale atmospheric model targeted for specific landing site applications
47 (Mars-GRAM) (Golombek et al., 2003; Rafkin and Michaels, 2003). A
48 particular local dust storm can emerge quickly , inducing atmospheric
49 and dynamical changes impacting spacecraft operations, and its detailed
50 evolution might depend on the small-scale, local topography, which a GCM is
51 unable to capture. It follows that the ensuing study is intended to summarise
52 and estimate the magnitude of dust storm impact on a Mars mission entering
53 the planetary boundary layer over a wide range of options, but is only
54 a starting point for a more detailed and highly-tailored study applied a
55 particular landing site, time of year and set of conditions, if the potential
56 risks appear significant.

57 Spacecraft Entry Descent and Landing (EDL) performance is sensitive
58 to changes in atmospheric conditions (mainly through thermal effects on
59 density and winds) on Mars since it dictates; the engineering tolerances of
60 the spacecraft for example, and to a lesser degree, the planning endeavours
61 regarding the ‘when’ and ‘where’ of a potential mission. Table 2 in Vasavada
62 et al. (2012) states EDL uncertainty tolerance thresholds in atmospheric
63 state variables; density: 10-15% between 8-30 km altitude and horizontal
64 winds: 20-25% between 4-20 km altitude. The Mars Science Laboratory
65 (MSL) (Chen et al., 2010), was fitted with modules that react to changes in
66 drag as they enter the final 30 km of atmosphere, allowing it to change its
67 flight altitude based on the drag sensed. A change in 10% of atmospheric
68 density amounts to a decrease of 1 km in landing capability below 30 km
69 altitude, which is especially true at 10-15 km altitude above the surface.
70 Our work is intended to quantify the potential atmospheric repercussions
71 that a spontaneously occurring dust storm could have on an EDL mission.

The principal scientific question we address in this paper is: what is the short-term impact of a spontaneous local dust storm on martian atmospheric variables? We address this by examining the extent of the immediate impact of a local dust storm on Mars at different latitudes. In the process, we consider: a) what measurable effects are caused by the local dust storm on both observed and unobserved atmospheric variables?; and b) does the modelled local dust storm impact agree with observations?

To be able to quantify and understand our answers to these questions, we guide our investigation through the use of observations of previously occurring dust storms, discussed in section 3, and compose relevant experiments using an MGCM, discussed in section 4. Local dust storm impact is shown through the analysis of model output against observations discussed in section 5; firstly in terms of its spatial evolution, section 5.1, radiative and heating processes in section 5.2, pressures and densities in section 5.3 and zonal and meridional winds in 5.4. To contextualise our original question, we consider the impacts found in our work in light of the following final question: are the dust storm impacts of significance to warrant further considerations for future spacecraft missions? This is touched upon, where appropriate, throughout the paper and answered in the conclusions section 6.

3. Observations

The observations we use in this investigation are from Mars Global Surveyor's (MGS) two instruments: the Wide Angle Mars Orbiter Camera (MOC) (Cantor et al., 2001) and Thermal Emission Spectrometer (TES) (Smith et al., 2000; Conrath et al., 2000). Observation coverage of these instruments commence just under a third of the way through MY24: $L_S = 107^\circ$ for MOC and $L_S = 104^\circ$ for TES (Mar-1999 and May-2000) respectively. We use the observations in two ways; to determine the spatial and temporal properties of simulated dust storm runs (dust storm area, height, time of year and day, duration and optical depths) via the pictures taken by MOC, and as a reality marker for MGCM simulation output, enabling us to understand which observed phenomena are reproduced as verification, and which unobserved phenomena warrant further investigation and interpretation.

Cantor et al. (2001) provides a comprehensive catalogue of the spatial properties of 783 dust events, 343 northern hemisphere and 440 in the

108 southern hemisphere, observed by MOC during MY24. Improved definitions
 109 of dust storm classifications defined by the greatly increased general
 110 observational coverage in MY 24 resulted in local dust storms being classified
 111 as dust events with surface areas ranging from $0.5\text{-}20 \times 10^3 \text{ km}^2$ up to about
 112 $1.6 \times 10^3 \text{ km}^2$, and regional dust storms are anything above that which do not
 113 encircle the entire planet. Altitudes reached by local dust storms can vary
 114 greatly Strausberg et al. (2005) documented the initial local dust storms
 115 (around Hellas Basin at $L_S = 177^\circ$) leading to the MY25 global dust storm,
 116 reaching heights of 5-7.5 km. More extreme cases record local dust storms
 117 observed by MOC during the loading phase of the global dust storm in MY25,
 118 derived from cloud shadow length measurements of MOC images, reaching
 119 altitudes of 21.5-29 km over Isidis and 11.4-24.2 km over the southern cap
 120 (Cantor et al., 2001; Cantor, 2007), while the concentrated part of smaller
 121 local dust storms tended to operate within Mars' Planetary Boundary Layer
 122 (PBL) (Cantor et al., 2001; Petrosyan et al., 2011). The spatial and temporal
 123 distribution of dust storms can be seen in Figure 1. The average observed
 124 duration of a local dust storm lasts anywhere between 1-3 sols, whereas a
 125 regional dust storm can last from 2-10 sols.

Figure 1: Distribution of dust storms occurring in the Mars Year 24 period during the MOC observation cycle (data from Cantor et al. (2001)) binned into two seasons: dust storm ‘quiet season’, where 341 dust events occurred, $L_S = 109^\circ - 180^\circ$ (top plot) and the ‘dust storm season’, where 467 dust events occurred, $L_S = 181^\circ - 275^\circ$ (bottom plot). The dust storms are arranged by size and colour coded to represent the area of the storm at maturity. Local storms are of size $0 - 1599 \times 10^3 \text{ km}^2$ and regional storms are $\geq 1600 \times 10^3 \text{ km}^2$. The storms simulated for this study are shown in the yellow-filled black bordered boxes by the size of the area of dust insertion. Topography taken from MOLA shown as a gray-scale with appropriate colour bar showing height (km) above Mars’ areoid.

126 The MOC observations from Cantor et al. (2001) were used from a
 127 perspective of dust storm sizes and their spatial temporal distributions, as
 128 shown in Figure 1. The numerically simulated dust storms were strategically
 129 placed by using MOC data to mimic the sizes and points in time where the
 130 local storms occurred, shown in Table 1. This enables us to viably compare
 131 our results to the observations more directly as appropriate.

132 The dust optical depths observed by MOC for MY24 range from $\tau_{red} =$

133 0.54 – 2.17 (red wavelength band = 575-625 nm), with local dust storms
 134 ranging between $\tau_{red} \sim 0.5 - 1.6$. The uncertainty associated with these
 135 readings however is quite high, $\pm 30\%$, originating from uncertainty in
 136 albedos due to an identified bias (Cantor et al. (2001), Table 5). TES
 137 observations of MY24 shown in (Smith (2004), Figure 5 and Smith et al.
 138 (2001), Plate 1, middle plot) put day-time (14:00 local time) zonally averaged
 139 dust optical depth range between $\tau = 0-0.5$, with an uncertainty of ± 0.05 for
 140 $\tau \leq 0.5$ for any one retrieval, for observed wavelength 1075 cm^{-1} (equivalent
 141 to $\tau \sim 9 \mu\text{m}$), at 6.1 mbar (surface). An equivalent comparison using the
 142 same data with the addition of newer data and an elaborate interpolation
 143 scheme, (Montabone et al. (2015), Figure 16), shows a zonally averaged dust
 144 optical depth range for $9.3 \mu\text{m}$, of $\tau \sim 0.1-0.8$, normalised to 610 Pa (surface),
 145 and (Montabone et al. (2015), Figure 6) shows an isolated instance of local
 146 dust storm (12:00 local time) in time series reaching an optical depth of
 147 $\tau = 0.8$ at the heart of the storm. Moreover, direct observations of storms
 148 around Noachis Terra, which eventually led to the formation of the Noachis
 149 Terra regional dust storm occurring in MY24 $L_S = 223^\circ$ in the region
 150 ($0^\circ - 20^\circ\text{S}, 10^\circ\text{W} - 40^\circ\text{W}$), shows optical depths peaking at $\tau = 0.75$ and
 151 between $\tau = 0.3-0.5$ in the surrounding vicinity, (Smith et al. (2001), Plate
 152 2), with an observed lingering dust haze with optical depth ~ 0.35 in the
 153 southern hemisphere after its occurrence.

154 Smith et al. (2000) documented temperature increases of 10-15K at
 155 the 0.3 mbar ($\sim 30 \text{ km}$) pressure level due to the Noachis Terra regional
 156 dust storm observed at $L_S = 225^\circ$, citing the relationship between optical
 157 depth and temperature. Regional dust storms were documented to raise
 158 temperatures by 15K Smith et al. (2001) (TES limb and nadir observations).
 159 TES observations in Conrath et al. (2000), specifically around the time of the
 160 Noachis Terra regional dust storm, showed abrupt temperature increases of
 161 10-15K at 0.3 mbar ($\sim 30 \text{ km}$), with asymmetrical structures spanning both
 162 hemispheres, in the 30°S and 30°N latitudes.

163 Wind speed estimates used from TES limb and nadir observations are the
 164 zonally averaged latitudinally binned temperature and gradient wind data
 165 from (Smith et al. (2001), Plates 5, 6 and 7) respectively (between $10^\circ\text{S}-70^\circ\text{S}$
 166 and 3-4 mbar ($\sim 5-8 \text{ km}$)); $L_S = 135^\circ$, 0 - 20 ms^{-1} , $L_S = 180^\circ$, 0 - 20 ms^{-1} and
 167 $L_S = 270^\circ$, -20 - 0 ms^{-1} (westward wind). These temperature and gradient
 168 wind structures are also shown in (Conrath et al. (2000), Figure 7 (a),(b))
 169 for all pressure levels from the surface up to approximately $\sim 65 \text{ km}$.

170 4. Experimental Design

171 The modelling period used as a basis for our MGCM dust storm
172 simulations is MY24. MY24 is a reasonably representative year where
173 the dust cycle is typical in comparison to other Mars years containing
174 sufficient dust events of all sizes (not global) with good temporal and spatial
175 distributions. MY24 was nearly two decades ago, so the dataset is thus
176 more mature and its quality, integrity and availability is sufficient for our
177 purposes. It is important to note that the MGCM utilises MY24 interpolated
178 dust optical depth maps whereby the first 224 sols of MY24 is an averaged
179 interpolation of the first 224 sols of MY25 and MY26 (see Montabone et al.
180 (2015), Appendix B).

181 We conduct twin experiments: a reference unperturbed simulation and
182 a dust storm run (denoted ‘rr’, ‘ds’ respectively). The dust storm run is
183 equivalent in its background with the addition of a prescribed injection of
184 dust covering a range of geographies guided by the dust storm ‘hot-spots’
185 observed in the past, Figure 1.

186 The UK version of the LMD MGCM (MGCM hereafter) (Lewis, 2003),
187 is based on Laboratoire de Météorologie Dynamique’s (LMD) MGCM
188 (Forget et al., 1999), but uses a spectral dynamical core derived from a
189 pseudo-spectral technique (Hoskins and Simmons, 1975), with an energy
190 and angular momentum conserving vertical finite-difference scheme and a
191 semi-Lagrangian tracer advection scheme Newman et al. (2002). The spectral
192 method alleviates the problem encountered at the poles by finite-difference
193 schemes and space derivatives are calculated precisely. Temperature,
194 vorticity, divergence and the surface pressure logarithm are manipulated in
195 the form of spherical harmonics in the horizontal, with non-linear terms and
196 physical tendencies calculated on model grids. The horizontal resolution of
197 the grid is dictated by the triangular wave-number truncation, which is set
198 to a total wave-number of 31 (T31) for these numerical simulations.

199 The model is run at a spectral resolution of T31 and with 35 vertical model
200 levels (~ 100 km). The horizontal resolution, intended to be equal in both
201 latitudinal and longitudinal directions, is a triangular spectral truncation at
202 a total wavenumber of 31, with nonlinear products calculated on a 3.75° grid
203 and physical parameterizations run on a regular 5° grid.

The transportation of dust in the MGCM is based on a semi-Lagrangian
scheme Newman et al. (2002). The values of winds are used from the current
and previous time-step to compute the departure points for each model grid

point. The mass mixing ratios of each tracer are then computed at the departure points and passed to the arrival model grid points. Dust in the MGCM is represented by two tracers; total number of dust particles per kilogram of air (N) and the dust mass mixing ratio (q). We alter dust levels in the MGCM through these tracers gradually over time:

$$\begin{aligned} q^{i+1} &= q^i + s_q q^i, \\ N^{i+1} &= N^i + s_N N^i, \end{aligned} \tag{1}$$

where i superscript denotes the MGCM physical parameterization time-step and s is the time-dependent growth factor for the relevant quantity denoted in the subscript. All experiments use dust-growth factors such that $s_q = s_N = 0.1$, ensuring a gradual compounding increase in dust at the desired location, keeping optical depths within the bounds of dust optical depths observed by TES, (Cantor et al., 2001; Cantor, 2007).

Dust in the model was transported using a two-moment scheme with a log-normal distribution, (Madeleine et al., 2011). The mean effective radius (1.3 - 1.8 microns) and the radiative properties (extinction efficiency factor, single scattering albedo and asymmetry factor) used for the model dust were derived from observational work, (Wolff et al., 2006, 2009).

Dust Storm and Region Name		Solar Longitude	Local Time	Dust Insertion Boundary		Pressure (mbar)
				Lat	Lon	
1	Vastitas Borealis	134.50°	18:00	72°N - 80°N	80°W - 90°W	6.1-2.8
2	Vastitas Borealis	158.82°	19:40	74°N - 80°N	60°W - 50°W	6.1-2.8
3	Terra Sirenum	161.47°	14:00	45°S - 35°S	150°W - 143°W	6.1-2.8
4	Hellas Planitia	165.21°	05:00	50°S - 40°S	68°E - 74°E	6.1-2.8
5	Noachis Terra	193.64°	23:00	56°S - 63°S	12°W - 20°W	6.1-2.8
6	Alba Patera	206.74°	15:00	42°N - 50°N	127°W - 132°W	6.1-2.8
7	Arcadia Planitia	219.90°	12:00	35°N - 45°N	173°E - 180°E	6.1-2.8
8	Tempe Terra	224.25°	20:15	30°N - 40°N	60°W - 67°W	6.1-2.8

Table 1: Dust storm simulations. All storms are administered between pressures: 6.1-2.8 mbar, which are equivalent to 5 m-8.5 km in the MGCM. All the simulated storms have a dust loading phase of 24 hours.

Table 1 details the whereabouts, temporally and spatially, of the dust storms we have composed for our investigation, reiterating what is shown pictorially in Figure 1. All dust insertion areas differ horizontally, as shown

218 by the dust insertion boundaries in Table 1 and Figure 1, with the dust
 219 insertion altitude remaining fixed (6.1-2.8 mbar or 5 m-8.5 km).

220 5. Results and analysis

221 In this section we analyse and discuss the impacts of the dust storm
 222 as exhibited by the MGCM and their meaning in a wider context. In the
 223 interests of literary economy we selectively utilise the most illustrative results
 224 from a wider dataset which sufficiently and effectively answer our initial line
 225 of inquiry.

Throughout the paper we quantify the impact by utilising the following measure:

$$\frac{\mathbf{x}_{\text{ds}}^i - \mathbf{x}_{\text{rr}}^i}{\mathbf{x}_{\text{rr}}^i}, \quad (2)$$

226 where $\mathbf{x} \in \mathbb{R}^3$ refers to MGCM variable at time i . The subscripts ‘ds’ and
 227 ‘rr’ denote ‘dust storm’ and ‘reference run’ respectively. This is referred to
 228 as the ‘relative error’ herein.

229 We use the Terra Sirenum dust storm as a typical example in the analysis
 230 that follows. Here the dust optical depth increases in the DS3 simulation area
 231 (Fig. 1) from ~ 0.23 at sol 338, 12:00 local time (L_s 161°), to ~ 0.67 near
 232 the end of sol 340 (Fig. 3).

Figure 2: Terra Sirenum dust storm. Time series of difference in dust mass mixing ratios ($q = q_{ds} - q_{rr}$) with latitude and longitude at ~ 20 m altitude. Red indicates difference surplus and blue indicates deficit. Each plot is at 2 hour intervals from time of dust storm insertion. Topography from MOLA is shown as contour lines above Mars' reference areoid (solid black) and below Mars areoid (dotted).

234 Evidence of sedimentation surrounding the dust loading region can be
 235 seen as early as sol 338 at 16:00 (Figure 2(b)), increasing in size and quantity
 236 after dust insertion cessation (sol 339 14:00, Figure 2(m)), suggesting a
 237 circulatory motion may have already begun. One sol after dust storm
 238 instigation, Figure 2(m), longitudinal coverage has increased to more than ~ 8
 239 times and latitudinal coverage has increased by ~ 3 times. The longitudinal
 240 coverage increase is more than double the latitudinal. Although not shown
 241 here, the dust storm altitude takes nearly 1 sol to at least double, where by
 242 sol 339 at 14:00 the dust reaches ~ 18 km, up from the originally prescribed
 243 ~ 8.5 km dust insertion (data available upon request).

Figure 3: Terra Sirenum dust storm. Zonally averaged dust optical depth with latitude and martian sol. Reference simulation (a), dust storm simulation (b) and (c) interpolated and ‘gridded’ TES data, (Montabone et al. (2015), Figure 21). ‘X’ marks the dust storm.

244 While noting the lack of latitudinal banding smoothness between Figure
 245 1(c) and the model runs, note the strong similarities of optical depth peaks
 246 between the model (~ 0.6 , midday sol 339, Figure 3(b)) and the data (~ 0.5 ,
 247 sols 338-341, Figure 3(c)). These characteristic optical depth rises in the
 248 presence of a dust storm are also reflected in the same period of time as
 249 shown in $L_S \approx 161^\circ$ at 45°S , (Smith et al. (2001), Plate 1, middle plot),
 250 where an optical depth peak of ‘0.5+’ is evident. The exact timings of these
 251 peaks differ due to the exact properties of our dust storm in comparison to
 252 the multiple dust storms occurring in this location, (Figure 1(b)), where the
 253 dust content has temporally compounded. This shows that our dust storm
 254 simulation is a good representation of a real dust storm by closely mimicking

255 the optical depth banding structure observed from multiple sources.

256 In summary, we have shown the optical depth structures; latitudinal
257 banding and peaking characteristics of newly instigated dust storms are
258 largely in agreement with observations, ((Smith et al. (2001), Plate 1, middle
259 plot); (Montabone et al. (2015), Figure 21)). We have also shown that after
260 just 1 sol, the modelled dust mmr increases by 3 longitudinally, 8 latitudinally
261 and 2 times vertically.

262 5.2. Radiative impact

263 In this section we discuss the impact of the local dust storm on radiative
264 fluxes and temperatures. These impacts are discussed in the context of the
265 observations to validate and explore potential reasons for any new innovations
266 from the observations.

267 5.2.1. Radiative fluxes

268 Figure 4(a) shows initial increase of 6% in incident IR rising to 21%
269 by 12:00, sol 339, a lead time of 1 sol. The initial relative increase in
270 IR incidence coupled with the low solar absorption at night (sols 338-339,
271 Figures 4(a) and (c)), indicates local radiative equilibrium independent of
272 solar absorption since it continues throughout the night of sol 338 into sol
273 339. The surface incident IR rise shortly after this phase suggests the dust
274 particles have attained equilibrium, via their heat exchange with surrounding
275 dust throughout the night, and are now beginning to absorb solar radiation
276 during the day. This is perhaps easier to determine from model data than
277 direct observation, since observing this phenomena would require in-situ
278 measurements of temperature, from dust storm inception to dissipation with
279 reasonable temporal accuracy.

280 There are faint blue columns of surface incident IR reductions seen in
281 Figure 4(a), spread latitudinally between sols 340-342 reaching as far as the
282 poles. This feature suggests atmospheric planetary wave disturbance. It is
283 likely that these planetary waves can contribute to the initiation of other
284 dust events much further away, by conditioning the atmosphere such that
285 it is more prepared to incubate further dust storms, as discussed in Toigo
286 et al. (2018). In order to observe this phenomena occurring as a result
287 of a dust storm in such detail, we would require enhanced spatially and
288 temporally distributed observations which is not yet available Hollingsworth
289 and Barnes (1996). While planetary waves are generally observable (Conrath,

1981; Hinson et al., 2003), their contribution towards dust storms and their
 impacts has not been observed directly as of yet.

Figure 4: Terra Sirenum dust storm marked with an ‘X’. Zonally averaged relative difference change against latitude and martian sol, as a percentage of: (a) surface incident IR flux, (b) model atmosphere top (~ 80 km) IR flux, (c) surface incident solar flux and (d) model atmosphere top (~ 80 km). Red indicates difference surplus and blue indicates deficit. Solar flux integrated over averaged bi-broadband regions of $0.1\text{-}0.5\text{ }\mu\text{m}$ and $0.5\text{-}5\text{ }\mu\text{m}$ and thermal infra-red (IR) similarly integrated over $5\text{-}11.5\text{ }\mu\text{m}$ and $20\text{-}200\text{ }\mu\text{m}$.

Figure 4(a) also shows continuously increasing IR incidence for 4 sols with some evidence of diurnally synchronised peaks and troughs, although this diurnal variation is not as pronounced as the other radiative fluxes. These peaks in incident surface IR are synchronised with solar flux troughs in Figure 4(c), indicating that day-time IR surface incidence is slightly more than night-time IR incidence. The ensuing surface heating as a result will trigger new vertical circulations. This is known and confirms past observations.

To summarise, the impacts of the dust storm on radiative fluxes is

300 as follows. Surface incident IR increases immediately by $\sim 6\%$, Figure
 301 4(a), rising to 21% after 1 sol. The initial response is due to radiative
 302 equilibrium taking place and the ensuing IR increase largely characterises
 303 solar contribution, since the dust storm begun at 16:00 not long before sunset.
 304 The temperature response to the dust storm shows that dust build up without
 305 solar contribution is sufficient to emit more IR. The increase in IR emission
 306 (Figure 4(a)) is ~ 3 fold when solar heating begins, in comparison to before
 307 solar heating takes place.

308 5.2.2. Temperatures

Figure 5: Terra Sirenum dust storm marked with an ‘X’. Zonally averaged atmospheric temperature differences between dust storm and reference simulations ($T_{\text{diff}} = T_{\text{ds}} - T_{\text{rr}}$) against latitude and solar longitude. Red indicates difference surplus and blue indicates deficit. Plots shown at three different altitudes; plot (a) ~ 0.5 mbar (~ 27 km), (b) ~ 1.3 mbar (~ 18 km), (c) ~ 3.7 mbar (~ 6 km).

309 The temperature response to the simulated Terra Sirenum dust storm
 310 shows asymmetry across the hemispheres at all model levels in Figure

311 5(a-c), for example in Figure 5(a) $L_S = 163^\circ - 170^\circ$, between 30°N - 60°N
 312 and 30°S - 60°S . The response at ~ 27 km is more widespread, whereas the
 313 planetary-wave response at ~ 6 km is more evident, particularly at the south
 314 pole, Figure 5(c) between $L_S = 166^\circ - 174^\circ$. This complements findings
 315 and conclusions in the observations: (Smith (2004), Fig6, top panel; Smith
 316 et al. (2001), Plate 6, top plot; Conrath et al. (2000)), where they cite that
 317 dust storms cause assymetric rises in the temperatures in the atmosphere
 318 due to adiabatic heating in the descending branch of an enhanced Hadley
 319 circulation.

320 Figure 5(a) at the ~ 0.5 mbar level shows a pronounced and consistent
 321 temporal trend of atmosphere cooling (-1.5 K) at 40°S , with a ‘halo’ of
 322 atmosphere heating around it ($+2$ K). This suggests that the vertical motion
 323 of both; warmer air and perhaps dust particles from the lower atmosphere
 324 are ascending through the regions of evident temperature increase around
 325 the dust storm centre at the surface, and falling in the latitudes where
 326 cooling is shown at 50°S in Figure 5(a). This effect lasts for over 22 sols,
 327 from $\sim L_S = 162^\circ - 173^\circ$, and shows that the impact of a local dust storm
 328 on the vertical circulations reach up to ~ 27 km, in agreement with observed
 329 dust storm lifting phases in terms of vertical reach, (Section 3).

Figure 6: Terra Sirenum dust storm. Temperature profile differences at (47.5°S , 145°W); day-time profiles (orange) and night-time profiles (blue). Each plot represents 1 sol (12 profiles at hr intervals) of profiles beginning at dawn of dust storm insertion day till dawn of the following day. So the coverage of each plot is as follows: (a) sol 338 06:00 to sol 339 06:00, (b) sol 339 06:00 to sol 340 06:00, (c) sol 340 06:00 to sol 341 06:00 and (d) sol 341 06:00 to sol 342 06:00.

Initially, night-time boundary layer temperature profiles (up to ~ 4 km) peak at 14K, while day-time profiles start at 6K and increase to 10K by the following sol, Figure 6(a)-(b).

This abrupt cooling phenomena can be explained by the similarly abrupt onset of dust inhibiting short-wave radiation, illustrated by the solar surface flux drop seen in Figure 4(c), and sunlight reflectance at the top of the atmosphere in Figure 4(d). Subsequently the dust particles warm and reach their threshold temperatures, similar to their immediate vicinity, and begin emitting IR. This effect is visible after just 1 sol, (Figure 6(a) to (b)). This initial cooling reaction of the MGCM simulation to the dust storm provides a new insight, which is not easily verifiable by observations, since this would require apriori radiances and in-situ temperature measurements with good temporal resolution.

343 The strong PBL day-time heating shown in Figure 6(b) is due to solar
 344 absorption by dust. However, it is important to bear in mind that both
 345 effects, of initial cooling and strong PBL day-time heating seen in Figure 6
 346 is likely to be quite sensitive to the dust loading rate and method used to
 347 add dust to the model.

348 The MGCM dynamics react to the impact caused by the dust storm,
 349 initially at the surface, then subsequently further up in the atmospheric
 350 column upon examining the plots Figure 6(a)-(c), with a temperature heating
 351 peak of 16K and a subsequent cooling peak of 12K. The MGCM's dynamic
 352 response is its natural attempt to re-establish a dynamical steady-state. The
 353 heating continues to cause day and night-time temperature profile changes,
 354 further suggesting vertical motions throughout the atmospheric column. The
 355 upper-atmosphere shows cooling in line with this, which decreases over time
 356 and is later followed by a balancing-dynamic of heating.

357 Day-time temperature troughs reach 5K near the surface while equivalent
 358 night-time temperature decreases are comparatively more pronounced with
 359 troughs of 9K. Night-time cooling seems to be more pronounced than
 360 day-time cooling or even heating (with the exception of 1 sol after the
 361 storm, where 3 profiles, equating to 6 hours in total, show peaks of +16K),
 362 throughout the 4 sols exhibited in Figure 6. Figures 6(c) and (d), show that
 363 the night-time temperature troughs endure more than any heating.

364 In summary:

- 365 1. Planetary wave disturbance can be seen through all latitudes, with
 366 reasonably defined structures, enough to identify the regions of
 367 circulations, such as the Hadley cell. These structures also conform
 368 to observations.
- 369 2. The immediate initial response to the dust storm in the PBL is cooling.
 370 The temperature drop is approximately 8 % at night, dropping by as
 371 much as -14K, (Figure 6(b)). This response is not something that
 372 has been previously observed, and complements the low increase in
 373 solar-independent IR incidence seen in Figure 4(a) in the previous
 374 section.
- 375 3. The PBL, especially the first 10km of altitude, shows the most
 376 pronounced dust storm impact within 1 sol. Further up between
 377 15-40 km a milder inversion response shows a consistent day-time
 378 temperature decrease of 5K, Figure 6(b).
- 379 4. The following impacts are in agreement with observations:

380 (a) As the dust storm develops a subsequent temperature increase
381 up to +16K is exhibited near the surface. The magnitude of this
382 temperature increase is in agreement with discussed observations
383 (Conrath et al., 2000; Smith et al., 2001; Smith, 2004).

384 (b) The latitudinal asymmetrical radiative response pattern shown
385 in Figure 5 agrees with observations (Smith et al., 2001).

386 (c) The vertical structure of temperature changes shown in Figure
387 5, where it is warmer lower down in the atmosphere (3.7 and 1.3 mbar)
388 and cooler at 0.5 mbar, suggest convection-induced currents due to
389 the cascading intensification of Hadley circulations in the region. The
390 vertical reach of this impact is implicitly inferred by observations
391 Cantor et al. (2001); Cantor (2007) as mentioned in Section 3, where the
392 author states that this phenomena is observed to altitudes of 21-27 km,
393 equivalent to MGCM 0.5 mbar temperatures seen in Figure 5(a).

- 394 5. Night-time cooling temperature profiles in the PBL seem to be more
395 pronounced in comparison to day-time temperature decreases or even
396 increases, up to 3 sols after the dust storm Figure 6.

397 *5.3. Impact on pressures and densities*

398 In this section we briefly discuss the short-term impact of the dust storm
399 on atmospheric pressures and densities.

Figure 7: Terra Sirenum dust storm marked with an ‘X’. Relative difference percentages in (a) surface pressure fields and (b) atmospheric density fields up to $\sim 20\text{m}$ at longitude: 145°W . Red indicates relative difference surplus and blue indicates deficit.

Figure 7 shows relative pressure changes are much smaller in comparison to the changes in atmospheric density near the surface, where the relative changes in density exhibit troughs of $\sim 9\%$ and peaks of $\sim 6\%$ from an average base value of 1.5×10^{-2} , compared to troughs of $\sim 3\%$ and peaks of $\sim 1\%$ from an average base value of 420 Pa in this location. Changes in density and pressures are realised after half a sol near the surface synchronous to increases in temperature, (Figure 6).

Figure 8: Terra Sirenum dust storm. Atmospheric density relative difference profiles calculated in a similar manner to equation (2) and represented as a percentage. The profiles represent densities at longitude: 145°W averaged between latitudes $42.5^{\circ}\text{S} - 52.5^{\circ}\text{S}$ up to 100 km. Initial plot (a) starts at sol 338 14:00, and every subsequent plot are in intervals of 4 hours, starting from sol 338 14:00 (a) and ending at sol 341 02:00 (p).

407 From dust insertion, we can see it takes 4-8 hours for the density to
 408 visibly increase at the surface, Figure 8(b)-(c), continuing to increase for
 409 the first 16 hours, Figure 8(a)-(e), coinciding with the temperature cooling
 410 seen earlier. At the end of the first sol of the storm, Figure 8(g), we
 411 see vertical inversions already taking place. Figures 8(h) to (m) which
 412 represent the following sol, show much more visible wave-like peak/trough
 413 characteristics indicating rising hotter air and perhaps dust particles from
 414 the lower-atmosphere (Figures 5, 2 respectively) with the troughs in density.
 415 Once the air and dust particles have cooled they descend back down through
 416 the atmosphere, following the pathways triggered by the vertical motions
 417 caused by the dust storm. The initial density decrease (heating) exhibited
 418 at 80 km coupled with density increase (cooling) near the surface (0-3 km),
 419 in Figure 8(e) shows it takes only 16 hours from dust insertion for the upper
 420 atmosphere as far up as 80 km to be impacted by the local dust storm.

Figure 9: Terra Sirenum dust storm at 12:00 of sol 339, 22 hours after initial insertion (4 hours before end of dust insertion). Annotated coloured contour lines show the surface pressure *difference* ($ps_{diff} = ps_{ds} - ps_{ref}$) with values as in the legend. The solid black and dotted black contour lines are the topography lines above and below the Mars areoid respectively. The arrows show the vectors of surface wind difference. The colour bar shows the surface temperature difference ($T_{diff} = T_{ds} - T_{ref}$) where red indicates difference surplus and blue indicates deficit.

421 Surface temperature increase (5K peak, Figures 6, 9) at the centre of
 422 the storm causes pressures to increase (Figure 7(a)), densities to decrease
 423 (Figures 8(f)-(g)), which then results in the emerging divergent anti-cyclonic
 424 wind current, both horizontally and vertically, as illustrated by Figure 9.
 425 This new current can super-impose itself on nearby horizontal currents,
 426 such as the Hadley circulation discussed in the previous section, or hinder
 427 opposing currents. This impact also illustrates a possible root cause of the
 428 atmospheric ‘preconditioning’ effect discussed in Toigo et al. (2018), where
 429 the author showed that dust storms instigate the necessary changes required
 430 for subsequent dust storms to develop. The observations also show that ‘lone’

431 storms are quite rare and that they occur in clustered groups Cantor et al.
 432 (2001), Figure 1. These outward currents can cause dust transportation from
 433 this location, or in adjacent locations and cause triggering effects elsewhere,
 434 especially if the local orography permits it.

435 In summary, the overall impact of the dust storm on pressures and
 436 densities are:

- 437 1. The peak atmospheric air density changes exhibited in the first two and
 438 a half sols, mainly after the second sol amidst the third sol of the local
 439 dust storm are $\nabla \sim 9\%$ occurring between 70-100 km. Peak changes
 440 in the PBL are $\nabla \sim 4\%$, mainly in the first sol after dust insertion, as
 441 the simulated dust loading is still occurring in the MGCM.
- 442 2. The dynamical response takes 4-8 hours for densities to change from
 443 the moment dust is inserted in the PBL, whereas it takes 16 hours for
 444 the upper atmosphere to react.
- 445 3. Surface pressure peak increase is small: $\nabla \sim 1\%$ and decrease: $\nabla \sim 3\%$.
 446 A trend in increasing pressure at the centre of the storm due to heating
 447 marries with the divergent instigation of newly formed wind differences
 448 at the surface.
- 449 4. The dust storm causes a high pressure centre anti-cyclonic divergent
 450 wind current propagating horizontally and vertically due to surface
 451 heating.

452 In the context of a lander mission, since the lower 30 km of atmosphere is
 453 shown not to exhibit density impacts beyond 3 %, the decrease in landing
 454 capability due to the lower part of the atmosphere should not exceed 300 m
 455 based on the EDL threshold criterion discussed earlier in section 1. However,
 456 beyond the PBL at 70-100 km, there is potential for an extra 1km decrease
 457 of spacecraft landing capability, although this impact comes 2-3 sols after
 458 dust storm initiation. This 1km reduction in landing capability is estimated
 459 while assuming that the 10% atmospheric density change is in the lower
 460 30 km of atmosphere, where we have used this as a rough guide for the
 461 whole atmosphere. Moreover, it is clear that these impacts do not exceed
 462 the uncertainty tolerance thresholds in density (10-15 % at 8-30 km and
 463 20-25% at 4-20 km) and are therefore not significant.

464 5.4. *Impact on winds*

465 The temperature gradients exhibited by the GCM as discussed in section
 466 5.2 are the primary cause of the wind gradients, which we analyse in this

467 section as a direct consequence or impact of the dust storm.

Figure 10: Terra Sirenum dust storm marked with an ‘X’. Zonally averaged atmospheric wind differences between dust storm and reference simulations against latitude and solar longitude. Red indicates difference surplus and blue indicates deficit. Altitude: near surface up to ~ 20 m.

468 While most of the impact is predictably in the latitudes where the dust
 469 storm occurred (30°S - 60°S), there is an evident movement of differences
 470 towards the south pole. Temperature gradients move towards the south
 471 since it is cooler than the equator, thus being a more natural path of flow
 472 for the newly generated motions generated by the dust storm.

473 Figure 10(a),(b) shows a latitudinal split of wind differences, for both
 474 meridional and zonal winds, which not only indicates a change of direction,
 475 but also shows a clear wind current division along the latitudes likely
 476 due to a Hadley cell circulation. The scattered smaller wind differences
 477 scattered further outside the area of the dust storm indicate a planetary
 478 wave disturbance in the model.

479 Zonal winds show their largest changes in the first sol of dust storm
 480 insertion. Increases in the upper-half ($32.5\text{--}40^\circ\text{S}$) peaking at $\nabla \sim 12$ m/s and
 481 mirrored decreases up to $\nabla \sim 10$ m/s in the lower-half ($42.5\text{--}45^\circ\text{S}$), Figure
 482 10(a).

483 The changes in meridional winds show the same wind current split,
 484 albeit with a more pronounced, widespread latitudinal response with reversed
 485 differences. Figure 10(b) shows an upper-latitudinal decrease $\nabla \sim 13$ m/s and
 486 lower-latitudinal $\nabla \sim 17$ m/s. The main impacts on meridional and zonal
 487 winds occur during the day time (08:00 - 20:00), where the meridional winds
 488 are earlier to respond.

Figure 11: Terra Sirenum dust storm. Zonal wind velocity profile differences ($u_{\text{diff}} = u_{\text{ds}} - u_{\text{tr}}$) at (47.5°S , 145°W). Day-time profiles (orange) and night-time profiles (blue). Positive values indicate increase in dust storm simulation winds in the eastward direction. MGCM temporal resolution dictates 12 profiles at 2 hour intervals. Temporal coverage of each plot: (a) sol 338 06:00 to sol 339 06:00, (b) sol 339 06:00 to sol 340 06:00, (c) sol 340 06:00 to sol 341 06:00 and (d) sol 341 06:00 to sol 342 06:00.

Figure 12: Terra Sirenum dust storm. Meridional wind velocity profiles at (47.5°S , 145°W); day-time profiles (orange) and night-time profiles (blue). Meridional wind velocity profiles; (a): reference simulation, (b): dust storm simulation. The profiles constitute 3 sols (36 profiles) starting from midnight of sol 338 to midnight of sol 341. Positive meridional wind velocities are northwards.

489 The lower-latitudinal response seen in Figure 10(a) is also seen in Figure
 490 11, as an increase of westward wind speeds. Initial dust storm impact on
 491 zonal wind velocities is evident mainly at night, which begin to increase
 492 eastward peaking at 7 m/s in the PBL, coinciding with initial cooling seen in
 493 temperatures in Figure 6(a). Sharp subsequent westward winds as a result
 494 of the subsequent heating in the next sol (Figure 11(b), Figure 6(b)), is
 495 evident in the first 5 km of the PBL, reaching peak changes of $\nabla \sim 30$ m/s.
 496 Upper-atmosphere changes seem to be synchronous with day-time eastward
 497 winds and night-time westward winds with peak changes of 16 m/s (E) and
 498 30 m/s (W).

499 Meridional winds are not as dominant as zonal winds, however there is a
 500 clear day-time northward and night-time southward trend prior to the dust

storm in the PBL, which is inverted further up in the atmosphere (Figure 12(a)). This effect is amplified by the local dust storm, where peak northward winds increase from 9 m/s to 28 m/s and southward winds increase from 9 m/s to 21 m/s in the PBL (Figure 12(b)). Upper-atmosphere impact on meridional winds in comparison to zonal winds are minimal. Peak changes in the meridional winds are northward $\nabla \sim 19$ m/s and southward $\nabla \sim 12$ m/s in the first few kilometres of atmosphere at (47.5°S, 145°W) in the first 3 sols. A plot of meridional wind speed changes have not been included in the interests of literary economy.

The dust storm impact on atmospheric winds are:

1. Initial eastward zonal wind increases coinciding with initial cooling seen in section 5.2.
2. Increasing zonal wind speeds dominantly towards the west in the first sol, by up to ~ 3 times their original westward value, with peak *changes* of $\nabla \sim 30$ m/s, eastward zonal wind peak change is $\nabla \sim 7$ m/s. All impacts are within the PBL mostly in the first 2 km of altitude.
3. Increasing meridional wind speeds in both directions to more than double their original value within the PBL. Northward winds peak changes of $\nabla \sim 25$ m/s in the first 2 km in the PBL. Southward winds are less affected with peak changes of $\nabla \sim 16$ m/s in the first 1 km of altitude in the PBL. There is negligible change in upper-atmosphere meridional winds.

6. Conclusions

This paper is concerned with the impacts of representative local dust storms upon the large-scale circulation as represented in a Mars GCM, at resolutions comparable with scales used in global climate databases (Lewis et al., 1999; Millour et al., 2015). Detailed study of the evolution of an individual dust storm clearly depends on the resolution of mesoscale winds and topography that is not possible with the Mars GCM, but is the subject of ongoing work. A selection of mesoscale simulations have been used to verify the average thermal and wind impact calculated here by the GCM.

The atmospheric impact of a spontaneous local dust storm in our simulations indicates separate phenomena triggered by the initial insertion of dust. Initial dust insertion causes an abrupt change in the radiative fluxes, which then causes subsequent temperature fluctuations, mainly in

536 daytime heating in the atmosphere. The significant changes in flux are seen
537 approximately 1 sol after dust insertion at the surface, with IR incident fluxes
538 rising by as much as 20% and solar fluxes decreasing concurrently by as much
539 as 12% for moderate additions of dust with broadband visible optical depth
540 increases of ~ 0.5 , typical of small dust storms that are observed on Mars.

541 The MGCM exhibits distinct yet short-lived local temperature cooling,
542 mainly at the surface in the initial sol, prior to these radiative flux changes.
543 This initial cooling is a direct consequence of increased dust immediately
544 blocking sunlight, thus reducing the surface heating in the model. Subsequent
545 night-time atmospheric temperature dropped by as much as 12 K. Day-time
546 atmospheric temperature rises sharply dominated the next sol, reaching
547 peaks of +16 K, constituting a 9% increase from local base temperature
548 in-line with equivalent observations. The temperature gradient resulting from
549 the radiative flux perturbation, consequently triggering vertical convective
550 currents in the MGCM, and balancing latitudinal asymmetric heating
551 responses, show that the MGCM largely agrees with the observations in this
552 regard. The impact of vertical motions triggered by temperature gradients
553 and wind shears were seen in the analysis of zonal and meridional wind
554 velocities. Zonal winds were seen to change by up to three times their original
555 value and meridional winds by up to double their original values.

556 Atmospheric air densities in the MGCM local dust storm simulations can
557 change by up to 4% in the PBL during the dust loading phase, which could
558 translate into 400m in loss of landing capability to a potential lander for
559 example, (Chen et al., 2010; Vasavada et al., 2012). Larger changes in air
560 densities in the MGCM seem to occur in the upper parts of the atmosphere,
561 reaching a peak change of 9% 2 sols after the dust storm was initiated.
562 Changes seen in surface pressures were relatively small (maximum of 3 Pa)
563 but showed flows of wind divergent ‘cyclonic’ patterns initiated one sol after
564 dust insertion. These patterns comprised higher surface pressure centres
565 differences between reference and control, emanating outward from the centre
566 of the storm.

567 Whilst this paper has focused on the changes to the physical variables that
568 might most affect entry, descent and landing a spacecraft, it is important also
569 to consider that dust storms are known to obscure vision, cover solar panels,
570 block vents and affect communications, which may all pose an equal or greater
571 threat to the safe operation of a spacecraft mission on the martian surface,
572 (Levine and Winterhalter, 2017). Dust deposition rates can be calculated
573 from the model, but are highly spatially non-uniform, and require detailed

574 modelling on a case-by-case basis for such important considerations that
575 may affect the viability of a precious spacecraft and eventually, perhaps, the
576 survivability of human astronauts.

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585 References

- 586 B. A. Cantor. MOC observations of the 2001 Mars planet-encircling dust
587 storm. *Icarus*, 186(1):60–96, 2007.
- 588 B. A. Cantor, P. B. James, M. Caplinger, and M. J. Wolff. Martian dust
589 storms: 1999 Mars orbiter camera observations. *Journal of Geophysical*
590 *Research: Planets*, 106(E10):23653–23687, 2001.
- 591 A. Chen, A. Vasavada, A. Cianciolo, J. Barnes, D. Tyler, S. Rafkin,
592 D. Hinson, and S. Lewis. Atmospheric risk assessment for the Mars Science
593 Laboratory entry, descent, and landing system. In *Aerospace Conference,*
594 *2010 IEEE*, pages 1–12. IEEE, 2010.
- 595 B. J. Conrath. Planetary-scale wave structure in the Martian atmosphere.
596 *Icarus*, 48(2):246–255, 1981.
- 597 B. J. Conrath, J. C. Pearl, M. D. Smith, W. C. Maguire, P. R. Christensen,
598 S. Dason, and M. S. Kaelberer. Mars Global Surveyor Thermal Emission
599 Spectrometer (TES) observations: Atmospheric temperatures during
600 aerobraking and science phasing. *Journal of Geophysical Research:*
601 *Planets*, 105(E4):9509–9519, 2000.
- 602 F. Forget, F. Hourdin, R. Fournier, C. Hourdin, O. Talagrand, M. Collins,
603 S. R. Lewis, P. L. Read, and J.-P. Huot. Improved general circulation
604 models of the Martian atmosphere from the surface to above 80 km.
605 *Journal of Geophysical Research: Planets*, 104(E10):24155–24175, 1999.

- 606 M. Golombek, J. A. Grant, T. Parker, D. Kass, J. Crisp, S. W. Squyres,
607 A. Haldemann, M. Adler, W. Lee, N. Bridges, et al. Selection of the mars
608 exploration rover landing sites. *Journal of Geophysical Research: Planets*,
609 108(E12), 2003.
- 610 S. D. Guzewich, A. D. Toigo, M. I. Richardson, C. E. Newman, E. R. Talaat,
611 D. W. Waugh, and T. H. McConnochie. The impact of a realistic vertical
612 dust distribution on the simulation of the Martian general circulation.
613 *Journal of Geophysical Research: Planets*, 118(5):980–993, 2013.
- 614 R. M. Haberle, C. B. Leovy, and J. B. Pollack. Some effects of global dust
615 storms on the atmospheric circulation of Mars. *Icarus*, 50(2-3):322–367,
616 1982.
- 617 R. M. Haberle, R. T. Clancy, F. Forget, M. D. Smith, and R. W. Zurek. *The*
618 *atmosphere and climate of Mars*. Cambridge University Press, 2017.
- 619 D. Hinson, R. Wilson, M. Smith, and B. Conrath. Stationary planetary waves
620 in the atmosphere of Mars during southern winter. *Journal of Geophysical*
621 *Research: Planets*, 108(E1), 2003.
- 622 J. L. Hollingsworth and J. R. Barnes. Forced stationary planetary waves
623 in Mars’ winter atmosphere. *Journal of the atmospheric sciences*, 53(3):
624 428–448, 1996.
- 625 B. Hoskins and A. Simmons. A multi-layer spectral model and the
626 semi-implicit method. *Quarterly Journal of the Royal Meteorological*
627 *Society*, 101(429):637–655, 1975.
- 628 C. Leovy, R. Zurek, and J. Pollack. Mechanisms for Mars dust storms.
629 *Journal of the Atmospheric Sciences*, 30(5):749–762, 1973.
- 630 J. S. Levine and D. Winterhalter. Dust in the atmosphere of Mars and its
631 impact on human exploration: Houston texas, june 13-15, 2017, 2017.
- 632 S. R. Lewis. Modelling the martian atmosphere. *Astronomy & Geophysics*,
633 44(4):4–6, 2003.
- 634 S. R. Lewis, M. Collins, P. L. Read, F. Forget, F. Hourdin, R. Fournier,
635 C. Hourdin, O. Talagrand, and J.-P. Huot. A climate database for mars.
636 *Journal of Geophysical Research: Planets*, 104(E10):24177–24194, 1999.

- 637 J.-B. Madeleine, F. Forget, E. Millour, L. Montabone, and M. Wolff.
638 Revisiting the radiative impact of dust on Mars using the LMD Global
639 Climate Model. *Journal of Geophysical Research: Planets*, 116(E11), 2011.
- 640 E. Millour, F. Forget, A. Spiga, T. Navarro, J.-B. Madeleine, L. Montabone,
641 A. Pottier, F. Lefèvre, F. Montmessin, J.-Y. Chaufray, et al. The
642 mars climate database (mcd version 5.2). In *European Planetary Science*
643 *Congress*, volume 10, 2015.
- 644 L. Montabone, F. Forget, E. Millour, R. Wilson, S. Lewis, B. Cantor, D. Kass,
645 A. Kleinböhl, M. Lemmon, M. Smith, et al. Eight-year climatology of dust
646 optical depth on Mars. *Icarus*, 251:65–95, 2015.
- 647 D. P. Mulholland, P. L. Read, and S. R. Lewis. Simulating the interannual
648 variability of major dust storms on Mars using variable lifting thresholds.
649 *Icarus*, 223(1):344–358, 2013.
- 650 C. E. Newman, S. R. Lewis, P. L. Read, and F. Forget. Modeling the Martian
651 dust cycle, 1. Representations of dust transport processes. *Journal of*
652 *Geophysical Research: Planets*, 107(E12), 2002.
- 653 A. Petrosyan, B. Galperin, S. E. Larsen, S. Lewis, A. Määttänen, P. Read,
654 N. Renno, L. Rogberg, H. Savijärvi, T. Siili, et al. The Martian
655 atmospheric boundary layer. *Reviews of Geophysics*, 49(3), 2011.
- 656 J. B. Pollack, D. S. Colburn, F. M. Flasar, R. Kahn, C. Carlston, and
657 D. Pidek. Properties and effects of dust particles suspended in the
658 Martian atmosphere. *Journal of Geophysical Research: Solid Earth*, 84
659 (B6):2929–2945, 1979.
- 660 S. C. Rafkin. A positive radiative-dynamic feedback mechanism for the
661 maintenance and growth of Martian dust storms. *Journal of Geophysical*
662 *Research: Planets*, 114(E1), 2009.
- 663 S. C. Rafkin and T. Michaels. Meteorological predictions for 2003 mars
664 exploration rover high-priority landing sites. *Journal of Geophysical*
665 *Research: Planets*, 108(E12), 2003.
- 666 P. L. Read and S. R. Lewis. *The Martian climate revisited: atmosphere and*
667 *environment of a desert planet*. Springer Science & Business Media, 2004.

- 668 P. Rogberg, P. Read, S. Lewis, and L. Montabone. Assessing atmospheric
669 predictability on mars using numerical weather prediction and data
670 assimilation. *Quarterly Journal of the Royal Meteorological Society*, 136
671 (651):1614–1635, 2010.
- 672 M. D. Smith. Interannual variability in TES atmospheric observations of
673 Mars during 1999–2003. *Icarus*, 167(1):148–165, 2004.
- 674 M. D. Smith, J. C. Pearl, B. J. Conrath, and P. R. Christensen. Mars Global
675 Surveyor Thermal Emission Spectrometer (TES) observations of dust
676 opacity during aerobraking and science phasing. *Journal of Geophysical
677 Research: Planets*, 105(E4):9539–9552, 2000.
- 678 M. D. Smith, J. C. Pearl, B. J. Conrath, and P. R. Christensen. Thermal
679 Emission Spectrometer results: Mars atmospheric thermal structure and
680 aerosol distribution. *Journal of Geophysical Research: Planets*, 106(E10):
681 23929–23945, 2001.
- 682 A. Spiga, J. Faure, J.-B. Madeleine, A. Määttänen, and F. Forget. Rocket
683 dust storms and detached dust layers in the Martian atmosphere. *Journal
684 of Geophysical Research: Planets*, 118(4):746–767, 2013.
- 685 M. J. Strausberg, H. Wang, M. I. Richardson, S. P. Ewald, and A. D. Toigo.
686 Observations of the initiation and evolution of the 2001 Mars global dust
687 storm. *Journal of Geophysical Research: Planets*, 110(E2), 2005.
- 688 A. D. Toigo, M. I. Richardson, H. Wang, S. D. Guzewich, and C. E.
689 Newman. The cascade from local to global dust storms on Mars: Temporal
690 and spatial thresholds on thermal and dynamical feedback. *Icarus*, 302:
691 514–536, 2018.
- 692 A. R. Vasavada, A. Chen, J. R. Barnes, P. D. Burkhart, B. A. Cantor, A. M.
693 Dwyer-Cianciolo, R. L. Fergason, D. P. Hinson, H. L. Justh, D. M. Kass,
694 et al. Assessment of environments for Mars Science Laboratory entry,
695 descent, and surface operations. *Space Science Reviews*, 170(1-4):793–835,
696 2012.
- 697 M. Wolff, M. Smith, R. Clancy, R. Arvidson, M. Kahre, F. Seelos, S. Murchie,
698 and H. Savijärvi. Wavelength dependence of dust aerosol single scattering
699 albedo as observed by the compact reconnaissance imaging spectrometer.
700 *Journal of Geophysical Research: Planets*, 114(E2), 2009.

701 M. J. Wolff, M. D. Smith, R. Clancy, N. Spanovich, B. Whitney, M. T.
702 Lemmon, J. Bandfield, D. Banfield, A. Ghosh, G. Landis, et al. Constraints
703 on dust aerosols from the mars exploration rovers using mgs overflights and
704 mini-tes. *Journal of Geophysical Research: Planets*, 111(E12), 2006.