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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 $(40^\circ S, 146.5^\circ W)$, with lateral coverage of $\sim2.1\times10^5$ 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 ($\pm10$ m/s). Atmospheric densities above 15 km altitude exhibit a peak increase of +9\% from pre-storm values, while surface pressures show less change $\pm3$\%. 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, CO$_2$-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
our results with regards to future missions which aim to land and operate safely on the surface of Mars.

2. Motivation

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

Spacecraft Entry Descent and Landing (EDL) performance is sensitive to changes in atmospheric conditions (mainly through thermal effects on density and winds) on Mars since it dictates; the engineering tolerances of the spacecraft for example, and to a lesser degree, the planning endeavours regarding the ‘when’ and ‘where’ of a potential mission. Table 2 in Vasavada et al. (2012) states EDL uncertainty tolerance thresholds in atmospheric state variables; density: 10-15% between 8-30 km altitude and horizontal winds: 20-25% between 4-20 km altitude. The Mars Science Laboratory (MSL) (Chen et al., 2010), was fitted with modules that react to changes in drag as they enter the final 30 km of atmosphere, allowing it to change its flight altitude based on the drag sensed. A change in 10% of atmospheric density amounts to a decrease of 1 km in landing capability below 30 km altitude, which is especially true at 10-15 km altitude above the surface. Our work is intended to quantify the potential atmospheric repercussions 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
southern hemisphere, observed by MOC during MY24. Improved definitions of dust storm classifications defined by the greatly increased general observational coverage in MY 24 resulted in local dust storms being classified as dust events with surface areas ranging from $0.5-20 \times 10^3 \text{ km}^2$ up to about $1.6 \times 10^3 \text{ km}^2$, and regional dust storms are anything above that which do not encircle the entire planet. Altitudes reached by local dust storms can vary greatly Strausberg et al. (2005) documented the initial local dust storms (around Hellas Basin at $L_s = 177^\circ$) leading to the MY25 global dust storm, reaching heights of 5-7.5 km. More extreme cases record local dust storms observed by MOC during the loading phase of the global dust storm in MY25, derived from cloud shadow length measurements of MOC images, reaching altitudes of 21.5-29 km over Isidis and 11.4-24.2 km over the southern cap (Cantor et al., 2001; Cantor, 2007), while the concentrated part of smaller local dust storms tended to operate within Mars’ Planetary Boundary Layer (PBL) (Cantor et al., 2001; Petrosyan et al., 2011). The spatial and temporal distribution of dust storms can be seen in Figure 1. The average observed duration of a local dust storm lasts anywhere between 1-3 sols, whereas a 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, $L_S = 109° - 180°$ (top plot) and the ‘dust storm season’, where 467 dust events occurred, $L_S = 181° - 275°$ (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.

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

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

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

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

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

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

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

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

\[
q^{i+1} = q^i + s_q q^i, \\
N^{i+1} = N^i + s_N N^i, \tag{1}
\]

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).

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

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

5. Results and analysis

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

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

\[ \frac{x_{ds}^i - x_{rr}^i}{x_{rr}^i}, \]  

(2)

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

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

Evidence of sedimentation surrounding the dust loading region can be seen as early as sol 338 at 16:00 (Figure 2(b)), increasing in size and quantity after dust insertion cessation (sol 339 14:00, Figure 2(m)), suggesting a circulatory motion may have already begun. One sol after dust storm instigation, Figure 2(m), longitudinal coverage has increased to more than ∼8 times and latitudinal coverage has increased by ∼3 times. The longitudinal coverage increase is more than double the latitudinal. Although not shown here, the dust storm altitude takes nearly 1 sol to at least double, where by sol 339 at 14:00 the dust reaches ∼18 km, up from the originally prescribed ∼8.5 km dust insertion (data available upon request).
While noting the lack of latitudinal banding smoothness between Figure 1(c) and the model runs, note the strong similarities of optical depth peaks between the model (∼0.6, midday sol 339, Figure 3(b)) and the data (∼0.5, sols 338-341, Figure 3(c)). These characteristic optical depth rises in the presence of a dust storm are also reflected in the same period of time as shown in $L_S \approx 161^\circ$ at 45°S, (Smith et al. (2001), Plate 1, middle plot), where an optical depth peak of '0.5+' is evident. The exact timings of these peaks differ due to the exact properties of our dust storm in comparison to the multiple dust storms occurring in this location, (Figure 1(b)), where the dust content has temporally compounded. This shows that our dust storm simulation is a good representation of a real dust storm by closely mimicking...
the optical depth banding structure observed from multiple sources.

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

5.2. Radiative impact

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

5.2.1. Radiative fluxes

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

There are faint blue columns of surface incident IR reductions seen in Figure 4(a), spread latitudinally between sols 340-342 reaching as far as the poles. This feature suggests atmospheric planetary wave disturbance. It is likely that these planetary waves can contribute to the initiation of other dust events much further away, by conditioning the atmosphere such that it is more prepared to incubate further dust storms, as discussed in Toigo et al. (2018). In order to observe this phenomena occurring as a result of a dust storm in such detail, we would require enhanced spatially and temporally distributed observations which is not yet available Hollingsworth 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 (\(\sim 80\) km) IR flux, (c) surface incident solar flux and (d) model atmosphere top (\(\sim 80\) km). Red indicates difference surplus and blue indicates deficit. Solar flux integrated over averaged bi-broadband regions of 0.1-0.5 \(\mu\)m and 0.5-5 \(\mu\)m and thermal infra-red (IR) similarly integrated over 5-11.5 \(\mu\)m and 20-200 \(\mu\)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
as follows. Surface incident IR increases immediately by ∼6%, Figure 4(a), rising to 21% after 1 sol. The initial response is due to radiative equilibrium taking place and the ensuing IR increase largely characterises solar contribution, since the dust storm begun at 16:00 not long before sunset. The temperature response to the dust storm shows that dust build up without solar contribution is sufficient to emit more IR. The increase in IR emission (Figure 4(a)) is ∼3 fold when solar heating begins, in comparison to before solar heating takes place.

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).

The temperature response to the simulated Terra Sirenum dust storm shows asymmetry across the hemispheres at all model levels in Figure
5(a-c), for example in Figure 5(a) $L_S = 163^\circ - 170^\circ$, between 30$^\circ$N-60$^\circ$N and 30$^\circ$S-60$^\circ$S. The response at $\sim 27$ km is more widespread, whereas the planetary-wave response at $\sim 6$ km is more evident, particularly at the south pole, Figure 5(c) between $L_S = 166^\circ - 174^\circ$. This complements findings and conclusions in the observations: (Smith (2004), Fig6, top panel; Smith et al. (2001), Plate 6, top plot; Conrath et al. (2000)), where they cite that dust storms cause asymmetric rises in the temperatures in the atmosphere due to adiabatic heating in the descending branch of an enhanced Hadley circulation.

Figure 5(a) at the $\sim 0.5$ mbar level shows a pronounced and consistent temporal trend of atmosphere cooling (-1.5 K) at 40$^\circ$S, with a ‘halo’ of atmosphere heating around it (+2 K). This suggests that the vertical motion of both; warmer air and perhaps dust particles from the lower atmosphere are ascending through the regions of evident temperature increase around the dust storm centre at the surface, and falling in the latitudes where cooling is shown at 50S in Figure 5(a). This effect lasts for over 22 sols, from $\sim L_S = 162^\circ - 173^\circ$, and shows that the impact of a local dust storm on the vertical circulations reach up to $\sim 27$ km, in agreement with observed 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.
The strong PBL day-time heating shown in Figure 6(b) is due to solar absorption by dust. However, it is important to bear in mind that both effects, of initial cooling and strong PBL day-time heating seen in Figure 6, is likely to be quite sensitive to the dust loading rate and method used to add dust to the model.

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

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

1. Planetary wave disturbance can be seen through all latitudes, with reasonably defined structures, enough to identify the regions of circulations, such as the Hadley cell. These structures also conform to observations.
2. The immediate initial response to the dust storm in the PBL is cooling. The temperature drop is approximately 8 % at night, dropping by as much as -14K, (Figure 6(b)). This response is not something that has been previously observed, and complements the low increase in solar-independent IR incidence seen in Figure 4(a) in the previous section.
3. The PBL, especially the first 10km of altitude, shows the most pronounced dust storm impact within 1 sol. Further up between 15-40 km a milder inversion response shows a consistent day-time temperature decrease of 5K, Figure 6(b).
4. The following impacts are in agreement with observations:
(a) As the dust storm develops a subsequent temperature increase up to +16K is exhibited near the surface. The magnitude of this temperature increase is in agreement with discussed observations (Conrath et al., 2000; Smith et al., 2001; Smith, 2004).

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

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

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

5.3. Impact on pressures and densities

In this section we briefly discuss the short-term impact of the dust storm on atmospheric pressures and densities.
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 \( 1.5 \times 10^{-2} \), 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°S - 52.5°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).

From dust insertion, we can see it takes 4-8 hours for the density to visibly increase at the surface, Figure 8(b)-(c), continuing to increase for the first 16 hours, Figure 8(a)-(e), coinciding with the temperature cooling seen earlier. At the end of the first sol of the storm, Figure 8(g), we see vertical inversions already taking place. Figures 8(h) to (m) which represent the following sol, show much more visible wave-like peak/trough characteristics indicating rising hotter air and perhaps dust particles from the lower-atmosphere (Figures 5, 2 respectively) with the troughs in density. Once the air and dust particles have cooled they descend back down through the atmosphere, following the pathways triggered by the vertical motions caused by the dust storm. The initial density decrease (heating) exhibited at 80 km coupled with density increase (cooling) near the surface (0-3 km), in Figure 8(e) shows it takes only 16 hours from dust insertion for the upper 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 ($p_{\text{diff}} = p_{\text{ds}} - p_{\text{ref}}$) with values as in the legend. The solid black and dotted black contour lines are the topography lines above and below the Mars aeroid respectively. The arrows show the vectors of surface wind difference. The colour bar shows the surface temperature difference ($T_{\text{diff}} = T_{\text{ds}} - T_{\text{ref}}$) where red indicates difference surplus and blue indicates deficit.

Surface temperature increase (5K peak, Figures 6, 9) at the centre of the storm causes pressures to increase (Figure 7(a)), densities to decrease (Figures 8(f)-(g)), which then results in the emerging divergent anti-cyclonic wind current, both horizontally and vertically, as illustrated by Figure 9. This new current can super-impose itself on nearby horizontal currents, such as the Hadley circulation discussed in the previous section, or hinder opposing currents. This impact also illustrates a possible root cause of the atmospheric ‘preconditioning’ effect discussed in Toigo et al. (2018), where the author showed that dust storms instigate the necessary changes required for subsequent dust storms to develop. The observations also show that ‘lone’
storms are quite rare and that they occur in clustered groups Cantor et al. (2001), Figure 1. These outward currents can cause dust transportation from this location, or in adjacent locations and cause triggering effects elsewhere, especially if the local orography permits it.

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

1. The peak atmospheric air density changes exhibited in the first two and a half sols, mainly after the second sol amidst the third sol of the local dust storm are $\nabla \sim 9\%$ occurring between 70-100 km. Peak changes in the PBL are $\nabla \sim 4\%$, mainly in the first sol after dust insertion, as the simulated dust loading is still occurring in the MGCM.

2. The dynamical response takes 4-8 hours for densities to change from the moment dust is inserted in the PBL, whereas it takes 16 hours for the upper atmosphere to react.

3. Surface pressure peak increase is small: $\nabla \sim 1\%$ and decrease: $\nabla \sim 3\%$. A trend in increasing pressure at the centre of the storm due to heating marries with the divergent instigation of newly formed wind differences at the surface.

4. The dust storm causes a high pressure centre anti-cyclonic divergent wind current propagating horizontally and vertically due to surface heating.

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

5.4. Impact on winds

The temperature gradients exhibited by the GCM as discussed in section 5.2 are the primary cause of the wind gradients, which we analyse in this
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 ∼20m.

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

Figure 10(a),(b) shows a latitudinal split of wind differences, for both meridional and zonal winds, which not only indicates a change of direction, but also shows a clear wind current division along the latitudes likely due to a Hadley cell circulation. The scattered smaller wind differences scattered further outside the area of the dust storm indicate a planetary wave disturbance in the model.
Zonal winds show their largest changes in the first sol of dust storm insertion. Increases in the upper-half (32.5-40°S) peaking at $\nabla \sim 12$ m/s and mirrored decreases up to $\nabla \sim 10$ m/s in the lower-half (42.5-45°S), Figure 10(a).

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

Figure 11: Terra Sirenum dust storm. Zonal wind velocity profile differences ($u_{\text{diff}} = u_{\text{ds}} - u_{\text{rr}}$) 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.
The lower-latitudinal response seen in Figure 10(a) is also seen in Figure 11, as an increase of westward wind speeds. Initial dust storm impact on zonal wind velocities is evident mainly at night, which begin to increase eastward peaking at 7 m/s in the PBL, coinciding with initial cooling seen in temperatures in Figure 6(a). Sharp subsequent westward winds as a result of the subsequent heating in the next sol (Figure 11(b), Figure 6(b)), is evident in the first 5 km of the PBL, reaching peak changes of $\nabla \sim 30$ m/s. Upper-atmosphere changes seem to be synchronous with day-time eastward winds and night-time westward winds with peak changes of 16 m/s (E) and 30 m/s (W).

Meridional winds are not as dominant as zonal winds, however there is a 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 $(47.5^\circ S, 145^\circ W)$ 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 $\sim 3$ 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
daytime heating in the atmosphere. The significant changes in flux are seen
approximately 1 sol after dust insertion at the surface, with IR incident fluxes
rising by as much as 20% and solar fluxes decreasing concurrently by as much
as 12% for moderate additions of dust with broadband visible optical depth
increases of ~0.5, typical of small dust storms that are observed on Mars.

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

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

Whilst this paper has focused on the changes to the physical variables that
might most affect entry, descent and landing a spacecraft, it is important also
to consider that dust storms are known to obscure vision, cover solar panels,
block vents and affect communications, which may all pose an equal or greater
threat to the safe operation of a spacecraft mission on the martian surface,
(Levine and Winterhalter, 2017). Dust deposition rates can be calculated
from the model, but are highly spatially non-uniform, and require detailed
modelling on a case-by-case basis for such important considerations that
may affect the viability of a precious spacecraft and eventually, perhaps, the
survivability of human astronauts.

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