SUB-GRID SCALE PROCESSES: TOWARDS A NEXT-GENERATION DUST LIFTING SCHEME FOR MARTIAN GCMS

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Introduction:

A realistic spatio-temporal variability in atmospheric dust loading is essential to accurately simulate the Martian climate, yet dust lifting in Mars Global Climate Models (MGCMs) is still in relative infancy. We detail several improvements can be made to lifting schemes, following recent developments in observational data and MGCM physics, and taking inspiration from terrestrial dust emission work. The impacts of these additions are found to be significant, though they act in somewhat opposite directions – which perhaps allowed earlier dust-lifting MGCMs to perform as well as they have.

Macroscale lifting rate calculation:

MGCMs are typically run at a horizontal resolution of 5°, and where dust lifting schemes are utilised, lifting rates are calculated at the same resolution. Besides the neglect of sub-grid scale variability (which is dealt with in the next section), several other factors have been absent from previous dust-lifting MGCMs [1,2,3].

Heterogeneous surface roughness. In the absence of more detailed information, previous MGCMs have assumed a uniform surface aerodynamic roughness length (z_0), usually 1cm, following measurements made by the Viking landers [4]. Recently a global z_0 map has been derived from TES rock abundances [5], and is suitable for use by MGCMs. The map, shown in Figure 1, features z_0 variation of around two orders of magnitude, and reveals that the northern hemisphere is, broadly speaking, considerably smoother than the southern hemisphere. Despite this, dust storms are frequently observed in the southern hemisphere [6].

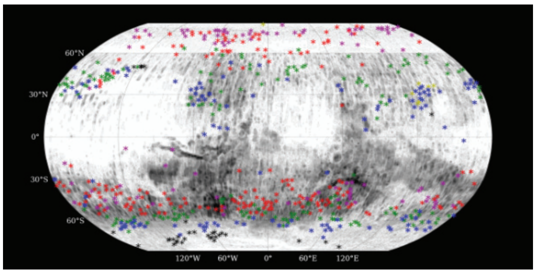

Figure 1: The surface roughness length (z_0) map from [5] (shading; dark areas feature large z_0 values), with observed dust storm locations from [6] overlaid.

Surface roughness length impacts the calculation of both the drag velocity, , and the threshold drag velocity for wind stress lifting, ; thus, it should strongly control dust lifting rates [7]. Roughness length affects the distribution of momentum between the underlying surface (from which dust is lifted) and roughness elements (rocks and boulders, and vegetation on Earth) that impede the near-surface flow. This is encapsulated by the drag partition function, f_{eff}, defined as the ratio of the threshold drag velocity over a smooth surface ( ) to the threshold drag velocity for the rough surface in question. The required threshold is therefore

Several functional forms for f_{eff} have been proposed [8,9], all of which show a decrease in f_{eff} with increasing z_0, leading to increased thresholds for rough areas. At z_0 = 1cm, threshold is predicted to be 2-4 times the 'smooth' threshold, : the latter has typically been used as the guideline level for calculated or prescribed thresholds in dust-lifting MGCMs to date.

Increases to the threshold drag velocity over rough surfaces are offset by increases to , such that the spatial distribution of the impact on dust lifting 'difficulty' depends on the precise form of f_{eff} used.

Figure 2 shows that if the form of Raupach et al. [8] – which appears to be supported by recent work [10,11] – is used, dust lifting becomes relatively more difficult in rough areas, such as the southern midlatitudes, than it does in aerodynamically smooth areas.

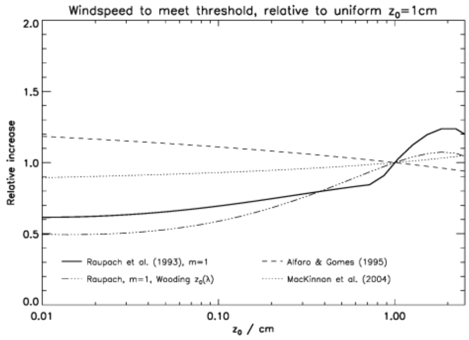

Figure 2: Increase in the 5m windspeed required to meet the lifting threshold for lifting, relative to the windspeed needed when using a uniform z_0 = 1cm, for various f_{eff} functions.

Lifting threshold. It is the threshold over smooth surfaces, , then, that should be calculated according to theoretical formulae, and later modified according to local roughness length. If the conventional view of dust emission – that it occurs whenever sand-sized particles are mobilized in saltation – is retained, the threshold can be calculated with relatively high confidence using a formula such as that of [12]. An alternative theory for Martian wind stress lifting [13] invokes direct detachment of low-density dust particle aggregates rather than saltation as the relevant process. This results in a that is perhaps 20% lower; however, this does not significantly alter the results shown below.

Boundary layer instability. Lifting rates are also dependent, for a particular near-surface wind velocity, on atmospheric stability in the planetary boundary layer (PBL). MGCMs have, until now, assumed a logarithmic wind profile in order to derive the drag velocity from near-surface windspeed, but such an assumption is valid only in conditions of neutral stability. The new version of the Laboratoire de Météorologie Dynamique (LMD) MGCM includes a boundary layer scheme that accounts for variations in stability [14]. The strong diurnal cycle in PBL stability results in more pronounced diurnal variation in than has previously been simulated by MGCMs.

The result of these combined effects is that MGCM surface winds, taken from the Mars Climate Database [15], apparently never reach the magnitudes required to initiate dust lifting almost anywhere on the planet (Figure 3).

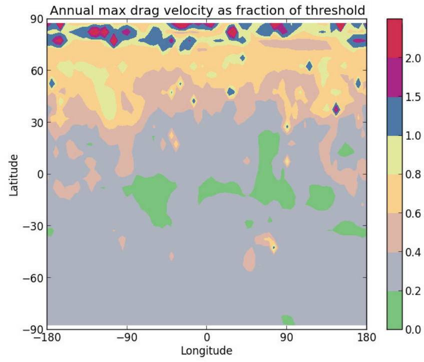

Figure 3: Mars Climate Database output for a typical no-dust-storm year, showing the maximum drag velocity as a fraction of the local lifting threshold.

Sub-grid scale variability:

In order to explain the discrepancy between MGCM predictions and the observational record for southern hemisphere dust storms, we investigate the potential for sub-grid scale variability in both z_0 and to increase MGCM dust lifting rates. In both cases, net emission from a surface gridbox increases due to the resolution of areas within the gridbox with conditions (the combination of and) that are more favourable for dust lifting than are the gridbox-mean conditions.

Roughness length. Lifted fluxes were calculated using the full, $^1/_8°$ z_0 map, and compared to those from a map smoothed to 5° resolution. Due to the presence of lower minimum roughness lengths at full resolution, lifting begins at lower values of , which implies that it is appropriate to reduce thresholds in an MGCM, in order to capture these earlier 'switch-on' points. The reductions required are particularly large in high-z_0 areas, as a consequence of the $(f_{eff})^{-1}$ dependence of the threshold. With the Raupach et al. drag partition function, reductions of as much as 50% are required to reproduce $^1/_8°$ lifting rates at MGCM resolution.

Surface windspeed gustiness. Windspeed variability over the spatial (~100 km) and temporal (~30 minutes) resolution of an MGCM must be parameterised in order to account for the formation of hotspots in [16], where the lifting threshold may be met, even whilst the gridbox-mean is below the threshold value. Results from the LMD Large Eddy Simulation model [17] show that, at a ~km scale, gusts of 2-3 times the mean value are common (Figure 4), and therefore that the hotspot theory is indeed relevant to Martian dust lifting, with respect to windspeed variability. Using convective updraft velocity as a proxy for horizontal gustiness, Mars Climate Database data show that gustiness peaks in the subtropics in local spring and summer, and that gustiness is, on average, stronger in the southern hemisphere than in the northern hemisphere.

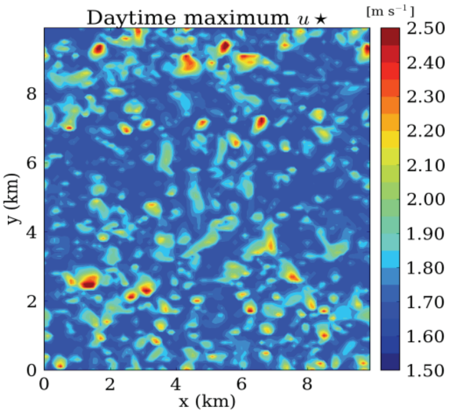

Figure 4: Daytime maximum , from an LMD LES model simulation using a background wind equivalent to 1 ms^{-1}.

Using a Weibull distribution to represent variability in , activation points for dust lifting are lowered, resulting in equivalent reductions to MGCM-resolution thresholds of 20-60%, depending on the shape parameter used in the Weibull distribution, and the minimum probability for lifting activation imposed on .

Taken together, sub-grid scale variability in and in z_0 appears to be sufficient to allow MGCM dust lifting in the rough southern midlatitudes, where it was previously out of reach of model winds. Results will be presented, showing how parameterisation of these effects both increases mean model lifting rates and modifies the spatial and temporal distribution of dust emission.

Conclusions:

We have found that several dust lifting scheme components, thus far neglected from MGCM schemes, exert a strong influence on lifting rates, altering both magnitude and spatial distribution. To maintain realistic dust storm frequency when including heterogeneous surface roughness lengths in lifting threshold calculations, parameterisation of sub-grid scale variability, in both and z_0, appears to be essential. Both of these considerations boost lifting preferentially in the high-z_0 regions of the southern subtropics and midlatitudes, and it is therefore expected that both will have an impact on the representation by MGCMs of major dust storms, many of which originate in these regions. It remains for the additions described here to be evaluated fully, through incorporation into a dust-lifting MGCM.

References: [1] Newman, C. E. et al. (2002), *J. Geophys. Res. (Planets)*, 107:5123-+. [2] Basu, S. et al. (2004), *J. Geophys. Res. (Planets)*, 109(E18):11006-+. [3] Kahre, M. A. et al. (2008), *Icarus*, 195:576-597. [4] Sutton, J. L. et al. (1978), *J. Atmos. Sci.*, 35 :2346-2355. [5] Hébrard, E. et al. (2012), *J. Geophys. Res. (Planets),* 117 :E04008. [6] Cantor, B. A. et al. (2001), *J. Geophys. Res.,106:23653-23688.* [7] Gillette, D. A. (1999), *Contr. Atmos. Phys.*, 72(1):67-77. [8] Raupach, M. R. et al. (1993), *J. Geophys. Res.,* 98:3023-3029. [9] MacKinnon, D. J. et al. (2004), *Geomorphology*, 63:103-113. [10] Okin, G. S. (2008), *J. Geophys. Res.,* 113(F12):F02S10. [11] Gillies, J. et al. (2007), *Boundary-Layer Meteorology*, 122:367-396. [12] Shao, Y. and Lu, H. (2000), *J. Geophys. Res.*, 105:22437-22444. [13] Sullivan, R. et al. (2008), *J. Geophys. Res. (Planets),* 113:E06S07. [14] Colaitis, A. et al. (2013), *J. Geophys. Res.,* 118(7):1468-1487. [15] Millour, E. et al. (2012), *EPSC 2012*, p302. [16] Spiga, A. and Lewis, S. R. (2010), *International Journal of Mars Science and Exploration,* 5:146-158. [17] Spiga, A. and Forget, F. (2009), *J. Geophys. Res.*, 114, E02009.