TOWARD SIMULATING REALISTIC, SELF-CONSISTENT, AND POTENTIALLY PREDICTABLE DUST CYCLES AND STORMS IN MARS GLOBAL ATMOSPHERIC MODELS

C. E. Newman, M. I. Richardson, *Aeolis Research, Pasadena, CA, USA (claire@aeolisresearch.com)*, **M. A. Mischna, J. H Shirley**, *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*.

Introduction:

While it can be valuable to prescribe atmospheric dust distributions or dust lifting based on observations in order to produce a realistic global climate and circulation, the ultimate goal is to be able to *predict* the realistic variation of dustiness. Such predictive skill - which signifies understanding of the underlying processes - is vital for such applications as weather forecasting and the simulation of past climate epochs.

Aspects of dust cycle simulation currently being explored include the effects of model resolution, the interaction between the dust, CO_2 and water cycles, the impact of allowing surface regions to become depleted (‘finite dust’ simulations), and the potential impact of additional accelerations (‘coupling term accelerations,’ CTA) on wind stress patterns and hence the amount and timing of dust lifting.

We will present results demonstrating the impact of finite surface dust and the CTA - both separately and in combination - on the dust cycles produced in a global atmospheric model, and the potential impact on predictability of major dust storms.

Finite surface dust:

Dust cycle modeling in global atmospheric models typically assumes that dust devil dust lifting provides primarily the ‘background’ dust loading while wind stress dust lifting is largely responsible for dust storms. The former is parameterized based on thermodynamics of convective vortices and involves one tunable parameter (a lifting rate factor, α_D), whereas the latter is parameterized by assuming that dust is only lifted above some threshold wind stress, τ_t, with the second tunable parameter for wind stress lifting being another lifting rate factor (α_N).

Using three different global models, Newman et al. [2002], Basu et al. [2006], and Newman and Richardson [2015] (henceforth NR15) were all able to simulate dust cycles with some interannual variability in the occurrence and size of major (global and large regional) dust storms for sufficiently high threshold wind stresses. However, aside from occurring in some years but not others, the major storms produced were rather repeatable, as demonstrated by the ‘global T15’ temperatures simulated in NR15’s infinite dust simulation (shown in Fig. 1a).

In addition, NR15 found that 3 (out of 2304 total) grid points contributed over a third of the dust supplied to the atmosphere in their infinite dust simulation. Fig. 2a shows the top-100 source grid points for that simulation, colorized by the relative abundance of dust contributed. Such a concentration of dust lifting at very few grid points is inconsistent with observations of widespread dust sources. Also, these grid points regained far less dust than they lost over time, resulting in a net loss of dust equivalent to a mm every 3 years. This implied that such regions would likely lose their entire dust cover in a few thousand years (or a far shorter time period). In addition, observations of albedo changes on Mars support the idea that many source regions lose much of their dust cover every few years due to storm lifting, which again makes the assumption of infinite dust supply unrealistic [Szwast et al., 2006].

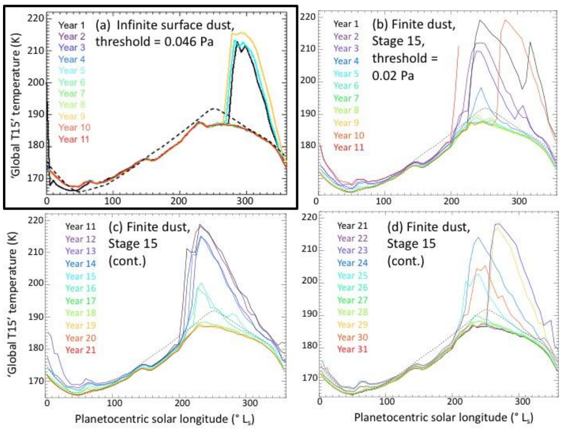

Figure 1: T15 temperatures for (a) 10 years of an infinite surface dust, high threshold simulation, and (b),(c),(d) the first 30 years of Stage 15 of an interactive dust simulation with finite surface dust and a low threshold. T15 values are vertically-integrated temperatures, averaged from 40°S to 40°N, designed to mimic observations by the Viking IRTM instrument’s 15μm band, and strongly linked to the amount of atmospheric dust present in the middle atmosphere. From Newman and Richardson [2015].

We therefore used an iterative approach to seek a steady state, *finite* surface dust distribution in the MarsWRF General Circulation Model (GCM). The steady state surface dust distribution should:

(a) Show no long-term net changes over periods of order ten Mars years, and

(b) Continue to produce realistic major dust storms with realistic interannual variability.

The iterative approach involved (i) tuning the dust lifting parameters to produce the most realistic major storms and interannual variability for a given (low) threshold wind stress, (ii) running the model until sufficient grid points were permanently exhausted of dust and dropped out as primary source regions to shut down major storms, then (iii) increasing α_N until storms resumed. Steps (ii) and (iii) were then repeated, with each repetition referred to as a 'Stage' of the simulation. (Note that this was not intended to represent a physical adjustment process, but was done so that the model-predicted patterns of dust lifting and atmospheric transport would dictate the steady state arrangement of surface dust.)

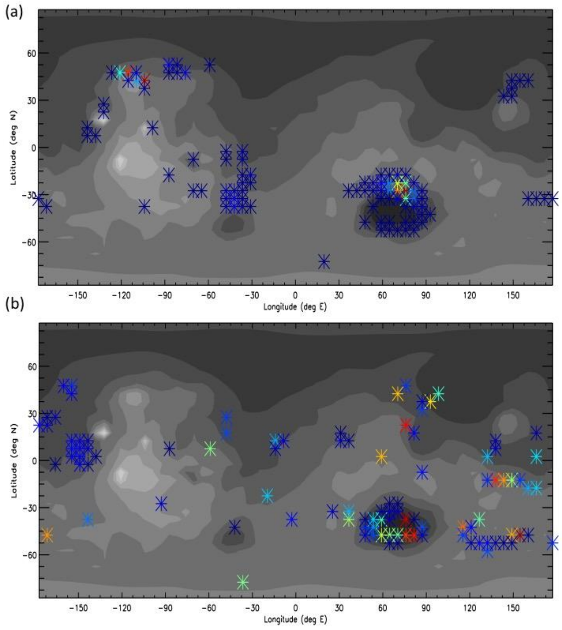

Figure 2: Top 100 dust source grid points, colorized according to relative fraction of dust mass contributed over 10 years of a simulation. Deep red shows the top ranked grid points, dark blue shows the lowest contributions within the top 100. (a) shows results for the infinite surface dust simulation shown in Fig. 1a. (b) shows results for Stage 15, Years 21-30 of the finite dust simulation shown in Figs. 1(b),(c),(d) and 3. Note the range of contributions is much smaller in (b) than (a). E.g. the deep red points in (a) indicate a contribution of ~11%, whereas those in (b) indicate a contribution of only ~2%. From Newman and Richardson [2015].

In the early Stages of the simulation, major storms rapidly disappeared as the original primary source regions were rapidly exhausted. As the simulation continued, however, the new primary source regions switched to those locations at which dust was replenished at a rate comparable to the rate at which dust was depleted, and the rate at which major storms ceased in each Stage began to slow.

After running the model for 276 years (and 14 Stages), in the 15^{th} Stage we found a 40-year period throughout which realistic major storms continued to occur, with only a few more source regions dropping out permanently during this period. Although sufficient points ultimately dropped out and major storms ceased, we used the 15^{th} Stage of the simulation as a proxy for true steady state behavior, in order to investigate the impact on dust storms and interannual variability of surface dust depletion and replenishment on timescales of seasons to several years.

Fig. 1(b),(c),(d) shows global T15 values in the first 30 years of Stage 15 and demonstrates increased interannual variability in storm types and timings compared to infinite dust simulations (Fig. 1a). Fig. 2b shows the far broader spread and more equal contribution of top-100 source regions in Years 21-30, compared to that found in an infinite surface dust run (Fig. 2a). And finally, Fig. 3 shows maps of dust opacity during a simulated global dust storm that occurred in Year 24 of this Stage (see Fig. 1d).

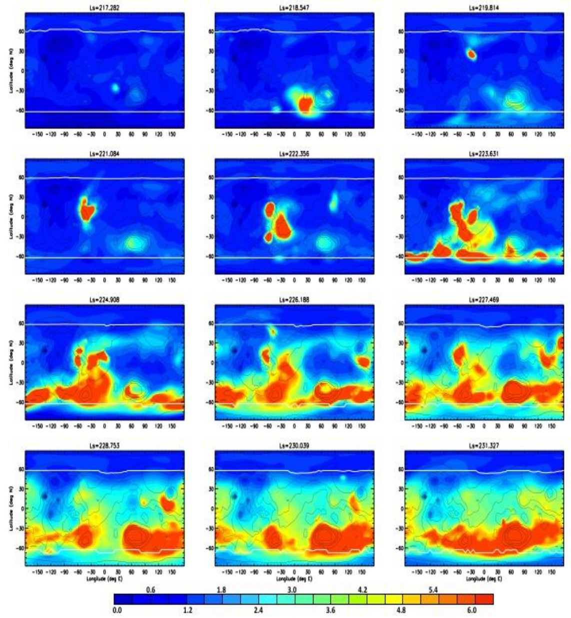

Figure 3: Maps of visible dust opacity every two sol from Ls~217° to 231° in Year 24 of the 15^{th} Stage of the finite dust simulation. A Noachis/Hellas regional storm combines with an Acidalia–Chryse regional storm and leads to onset of an early global storm. From Newman and Richardson [2015].

NR15 demonstrated that simulated storms of a particular type often had similar patterns of primary source grid points for their onset and/or growth phase. This suggested that adequate surface dust availability over a particular set of points might be a necessary (but not sufficient) condition for a particular storm type to occur. The ability to identify such sets of points would have great predictive power. Unfortunately, no two storms in the model (or in reality) have identical lifting patterns during their onset, let alone growth, phase. This makes it difficult to attribute the absence (or weakness) of a particular storm type in a given year to the lack of dust over a particular set of points at the start of the storm season. However, the idea of being able to predict that e.g. no storm will occur before a certain time of year - or occur at all - based on only the albedo map prior to the dust storm season, is very appealing, and the concept deserves further attention.

Achieving steady state with threshold feedbacks: Pankine and Ingersoll [2002, 2004] proposed a threshold feedback, in which the threshold wind stress would increase as dust was depleted from the surface, due to the remaining dust being more sheltered by non-erodible elements and lower in the wind profile. Having been unable to achieve a true steady state with continuing major storms by using a constant threshold (as described above), NR15 tested several formulations of such a threshold feedback. We were able to produce a steady state, finite surface dust distribution with continuing major storms using a feedback in which the threshold variation has a cubic dependence on the variation in surface dust and never drops below 1/8th of the original value.

Fig. 4 shows the variation in surface dust cover, wind stress dust lifting, and dust deposition, at the top three source grid points over 46 years of the threshold feedback simulation after it has reached steady state. The surface dust is strongly depleted in years with major storms (shown as strong peaks in dust lifting), but recovers gradually over years between major storms, with no long-term net loss over decades, enabling the storms to continue long term.

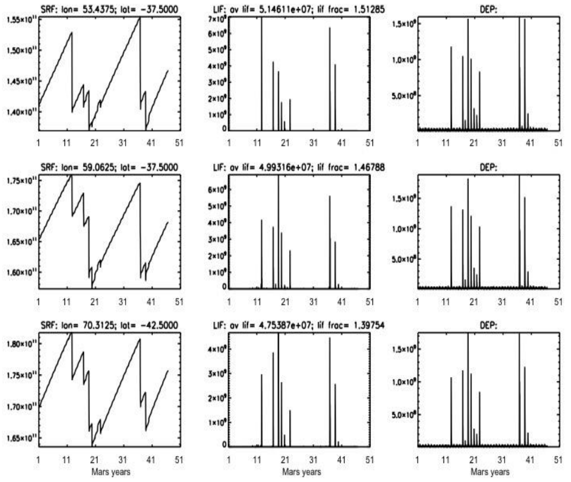

Figure 4: Area-weighted surface dust cover in kg (left), and total wind stress dust lifting (middle) and dust deposition (right) over the previous 10 sols in kg/10 sols, for the top 3 contributor grid points over 46 steady state years of a simulation with the threshold feedback. From Newman and Richardson [2015].

Coupling term accelerations (CTA):

Shirley [2015] proposed that an additional 'orbit-spin coupling' term arises from the derivation of the momentum equation in a barycentric, or inertial, reference frame. This couples the time rate of change of planetary orbital angular momentum to the angular velocity of Mars's rotation about its spin axis. The magnitude of the coupling 'efficiency' factor between the orbital and rotational reservoirs - which determines the impact on atmospheric processes - is constrained by observations to be very small. But the key point is that the variation of the CTA in magnitude and sign at a given point in Mars's atmosphere is *not* in phase with the annual cycle in solar forcing.

In other words, the CTA provide a driver of atmospheric behavior (such as surface wind stress patterns that affect dust lifting) that is both predictable and does not simply repeat each year. If the coupling efficiency is large enough, the CTA could potentially drive the observed interannual variability in the size and timing of major dust storms that is presently thought to be largely unpredictable.

CTA results assuming unlimited surface dust:

Shirley and Mischna [2015] and Mischna and Shirley [2015] discuss the impact on wind stresses in simulations with no dust effects in the model. Mischna et al. (2017, this meeting) presents further work using radiatively active dust, including simulations with parameterized dust lifting, which allows more realistic feedbacks between dust lifting and the circulation.

The impact of including the CTA in such fully interactive dust storm simulations is demonstrated by Fig. 5, which shows (a) six years of a control run and (b) six years of a run in which the CTA are included as per the Mars Year (MY) shown. The key result is that including the CTA greatly increases the interannual variability, yet does so in a rather predictable way. To demonstrate this, Fig. 5 (c) and (d) show the same six years in two additional simulations with slightly different lifting efficiencies used. While the details differ, the timing and *relative* sizes of the major storms are very similar between all three simulations with CTA included, supporting the idea that - if they are truly large enough to affect the atmospheric circulation in this manner - the CTA may exert a significant control on what has previously been considered a somewhat chaotic process.

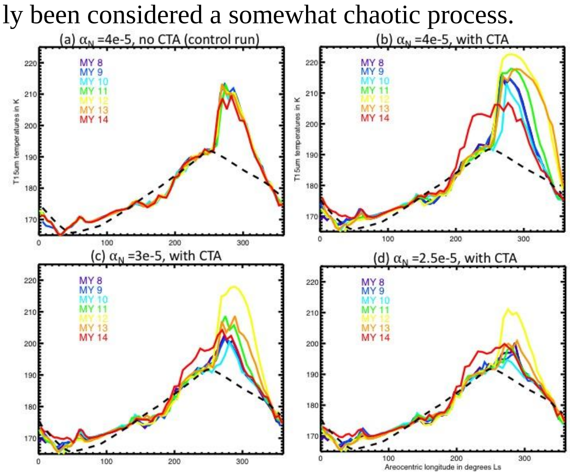

Figure 5: T15 temperatures for four interactive dust simulations. (a) has no CTA, while (b), (c), (d) include CTA specific to MY 9 through 14, with increasing values of the lifting rate factor, α_N.

How well do our interactive dust simulations with CTA predict the observed pattern of global dust storms (GDS)? One simulation lasting from MY 9 to MY 32 (for which we are missing observations of the storm season in some years) correctly predicts ten out of eleven years in which we're certain that no GDS occurred. However, the simulation also incorrectly predicts a GDS in one year where we know that no GDS occurred, and only predicts GDS in four out of the seven years in which they were observed. This work is in its early stages, however, and we are still exploring the impact of other dust lifting parameters and assumptions. In particular, we are investigating the impact of allowing surface dust to be fully depleted, as discussed below.

CTA results assuming finite surface dust:

The results shown in Fig. 5 use a high wind stress threshold and assume unlimited surface dust. However, as discussed above for non-CTA simulations, the latter assumption results in too few primary source regions, most of which would in reality be depleted of dust, since they gain far less dust than they lose over time. This concentration of dust lifting in relatively few - and potentially unrealistic - source regions means that the impact of the CTA is restricted to those regions too. The impact of the CTA in infinite dust simulations is therefore strongly confined to its influence on wind stresses in those few peak wind stress locations, which in turn limits the impact of the CTA on year-to-year storm variability. In particular, interannual variability is tied to the relative magnitude and peak timing of CTA accelerations *at a very few grid points*, rather than over a wider portion of the planet.

This may explain some of the discrepancies between the predicted (with CTA included) and observed storm seasons in certain Mars Years. For example, Fig. 6a shows the pattern of surface dust after 29 years of an infinite dust simulation with CTA included, whereas Fig. 6b shows the same but after 21 years of a *finite* dust simulation initialized with a surface dust cover of 2 kg/m^2. The primary source regions shown in Fig. 6a are exhausted in Fig. 6b, meaning that the *new* primary source regions have shifted elsewhere and are far more widespread. Note that to generate the same intensity of dust storms with the new surface dust map would require an increase in α_N and potentially α_D also, as described in the finite dust section above and in NR15.

We will present preliminary results from CTA simulations with finite surface dust cover, and discuss whether this improves the match to the observed pattern of dust storms.

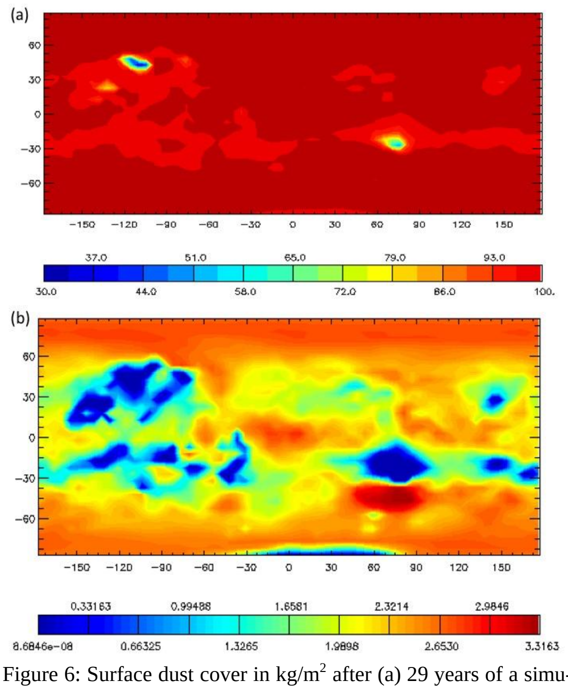

Figure 6: Surface dust cover in kg/m^2 after (a) 29 years of a simulation with CTA and effectively *infinite* surface dust (the actual initial dust cover is 100 kg/m^2 but no grid point is ever exhausted during the simulation), and (b) 21 years of a simulation with CTA and *finite* surface dust (the initial dust cover is 2 kg/m^2).

Summary: We will present two mechanisms that may be vital to improving the realism and predictability of dust storms in the atmosphere of Mars.

We will show that a more realistic range of dust cycles, dust source regions, and interannual variability are produced if we do not assume the supply of surface dust is infinite, and instead allow regions to be depleted of dust over time. We will also show that a steady state finite surface dust distribution with continuing major storms can be achieved by including a threshold feedback in which the threshold increases as surface dust is removed. And we will discuss the implications for predicting storm activity based on the arrangement of surface dust prior to a given dust storm season.

We will also present results from interactive dust simulations including 'orbit-spin coupling term' accelerations (CTA) and demonstrate that - if the coupling efficiency is large enough - the CTA may strongly control the timing, size, and occurrence of major dust storms on Mars, potentially making such storms far more predictable than previously believed.

We will finish by showing preliminary results combining both processes, and discuss whether the assumption of a limited dust supply improves the match between storm seasons simulated using the CTA forcing and those observed in a given MY.

References:

Basu, S., R. J. Wilson, M. I. Richardson and A. P. Ingersoll, Simulation of spontaneous and variable global dust storms with the GFDL Mars GCM, *J. Geophys. Res.*, 111, E09004, 2006.

Newman, C.E., S.R. Lewis, P.L. Read and F. Forget, Modeling the Martian dust cycle. 2: Multi-annual radiatively active dust transport simulations, *J. Geophys. Res.*, 107 (E12), Art. No. 5124, 2002.

Newman, C.E. and M.I. Richardson, The impact of surface dust source exhaustion on the Martian dust cycle, dust storms and interannual variability, as simulated by the MarsWRF General Circulation Model, *Icarus*, 257, 47-87, 2015.

Pankine, A.A. and A.P. Ingersoll, Interannual variability of martian global dust storms simulations with a low-order model of the general circulation, *Icarus*, 155, 299–323, 2002.

Pankine, A.A. and A.P. Ingersoll, Interannual variability of Mars global dust storms: An example of self-organized criticality? *Icarus*, 170, 514–518.

Shirley, J.H., Solar system dynamics and global-scale dust storms on Mars, *Icarus*, 252, 128-144, 2015.

Shirley, J.H., Orbit-spin coupling and the circulation of the Mars atmosphere, http://arxiv.org/abs/1605.02707.

Mischna, M.A. and J.H. Shirley, Numerical Modeling of Orbit-Spin Coupling Accelerations in a Mars General Circulation Model: Implications for Global Dust Storm Activity, http://arxiv.org/abs/1602.09137.

Szwast, M.A., M.I. Richardson and A.R. Vasavada, Surface dust redistribution on Mars as observed by the Mars Global Surveyor and Viking orbiters, *J. Geophys. Res*., 111, E11008, 2006.