DUST CYCLE MODELING WITH THE GFDL MARS GENERAL CIRCULATION MODEL.

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Introduction: An outstanding problem for simulating the present Mars climate is representing the spatial and temporal variability of aerosols and the feedbacks that connect dust raising and transport with the evolving atmospheric circulation. Various modeling groups have simulated aspects of the dust cycle with Mars global climate models (MGCMs) with limited success [*Newman et al*. 2002b, *Basu et al.* 2004, 2006; *Kahre et al*. 2005, 2006]. These efforts have all employed parameterizations based on convective activity (so-called "dust devil lifting") and explicitly resolved surface stress. It is generally accepted that surface stresses account for much of the dust lifting associated with storm events. Stress-related dust lifting parameterizations are characterized by two tunable parameters: the threshold surface stress, σ_t (equivalently U_t, the threshold drag velocity) and α, the so-called "efficiency factor" [*Newman et al*. 2002; *Basu et al*. 2004; *Kahre et al.* 2006]. A stable, seasonally-varying dust cycle can be achieved for a range of choices of the tuning parameters, with a global mean opacity that is more or less strongly peaked around L_s=270°, reflecting the relative weighting of dust injection due to dust devil and resolved surface stresses. Wind stress lifting accounts for the peak in dust lifting during the SH spring/summer season, while dust devil lifting is required to provide the background dust opacity present in other seasons when stress levels are generally weak. Such simulations are only in rough agreement with the observations, which generally show pre- and post-solstice peaks in opacity [*Wang et al*. 2005; *Wilson et al*. 2006]. Moreover, significant interannual variability (major dust storms some years, and quiescent storm seasons in others) has been elusive.

Until recently, MGCM studies have employed a globally uniform stress threshold (σ_t) as one of the tuning parameters. This assumption can be problematic for simulating large dust storms because there are very strong spatial and seasonal variations in resolved surface stress that are associated with specific topographic features. As a result, a few regions tend to unrealistically dominate the simulated dust storm climatology. *Pankine and Ingersoll* [2004] proposed that the effective local lifting threshold should increase as surfaces become depleted and the remaining dust becomes increasingly sheltered by nonerodible surface features. They considered the issue of interannual variability of global dust storms in the context of a highly simplified model that represented the Hadley cell. The circulation intensity was set to depend on dustiness, which was coupled to the implied surface wind. Two variables, ΔU_t and $\mathring{U}_t$ were introduced to represent the rapid increase in threshold friction velocity associated with dust injection following a global dust storm and the resupply of dust on a much longer timescale by small-scale processes (dust devils were proposed). The resulting model system yielded interannually variable dust storm behavior when the time scale defined by $\Delta U_t / \mathring{U}_t$ was longer than an annual cycle.

Wilson and Kahre [2009] carried out an initial study of this formulation in a more realistic context by implementing a finite surface dust reservoir in the GFDL MGCM and allowing σ_t to vary as a function of the evolving surface dust depth. These simulations yielded interannual variability in major dust storm occurrence. The model surface dust field evolved towards a statistically stable distribution (apart from the polar regions) that reflects the seasonally-integrated effects of stress dust lifting (Figure 1). In this fashion, the finite surface dust reservoir serves as a source of long term memory, which would seem to be likely basis for interannual variability. While the details of the depletion pattern depend on the model resolution, the basic pattern is quite robust. Dust is relatively depleted in the vicinity of Hellas, Alba Patera, and Solis Planum, and σ_t is significantly greater than the assumed nominal value. Thus the

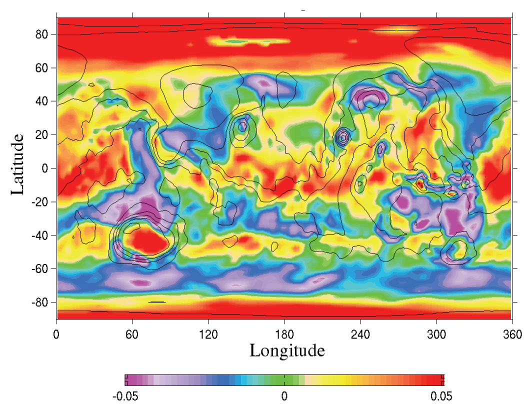

Figure 1. Spatial distribution of the change in surface dust mass (kg/m^2) from an initially uniform field. The model resolution is 2°x2° and the integration has run 36 years. The mean surface pressure field is contoured. Surfaces with depleted dust have an increased stress lifting threshold, reflecting the assumed increased difficulty in lifting the remaining dust.

impact of these high stress regions is reduced, allowing greater spatial variability in the source regions than in previous simulations with an infinite dust reservoir. Other depleted regions correspond to the latitudes dominated by the SH summer tropical jet and the high stress region that develops along the retreating south polar cap that peaks at $L_s \sim 240°$

Significant dust lifting is typically initiated in the SH following a sequence of flushing storm events originating in the northern hemisphere in the pre-solstice season. This activity leads to a triggering of dust lifting along the high-stress region that migrates southward with the retreating south polar CO_2 ice cap. The Chryse and Isidis channels make significant contribution to flushing storm activity. There is now greater variability in localized lifting along the edge of the retreating south polar cap. These simulations still had the unrealistic aspect of persistent dust lifting through the SH summer solstice season in years when major dust activity is triggered.

The dominating positive feedback in the SH subtropical jet is prominent in all published dust cycle simulations, and results in a persistent simulated dust opacity peak around solstice (L_s =270). However, it is evident that traveling waves in the northern hemisphere and associated flushing storms comprise a significant component of the dust cycle, with major activity in the pre- and post-solstice seasons [*Wilson et al.*, 2006]. These regional storm events have evidently not been well represented in model simulations. This is particularly the case for the post-solstice window (L_s= 310-340°), which are notably absent in all published dust cycle studies.

Water ice clouds: There is increasing evidence that radiatively active water ice clouds contribute to the thermal structure of the atmosphere [*Wilson et al.* 2008; *Wilson*, 2011, *Haberle et al.* 2011], particularly in the tropics. However, *Wilson et al*. [2008] noted that including the radiative influence of water ice clouds can have a significant impact on atmospheric temperatures in the vicinity of the polar hoods as well. Our simulations suggest that radiative cooling by polar hood clouds can influence the structure of the polar vortex during the spring and fall seasons. In this case, enhanced IR cooling appears to compensate for warm, low level polar temperature biases that appear to be evident in many climate models in these seasons. The resulting changes to the westerly jet embedded in the polar vortex can significantly influence traveling wave characteristics and thus dust lifting activity . Figure 2 shows the significant strengthening of low-level eddy meridional winds (dominated by eastward propagating waves with periods of 1.5-10 sols) when cloud radiative effects are included. The two simulations employ the same relatively weak dust [*Hollingworth et al*. 2011]. We are currently continuing the dust cycle simulations described in *Wilson and Kahre* [2009] with radiatively active clouds and will represent one aspect of the new simulations that we intend to present.

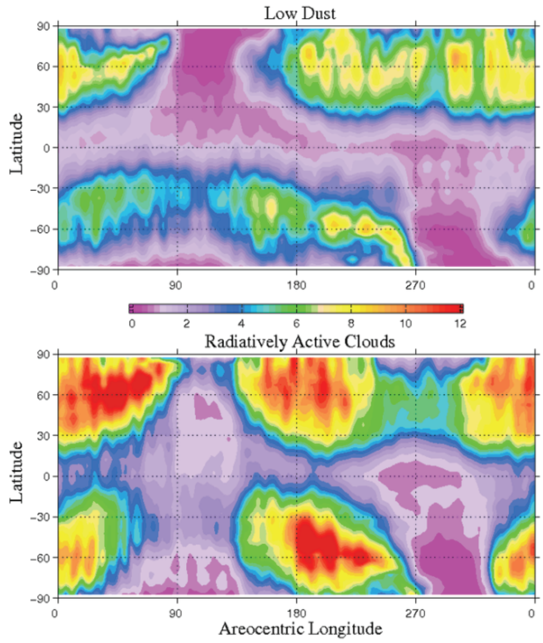

Figure 2. Standard deviation of zonally-averaged transient eddy meridional wind amplitude (ms^{-1}) at ~ 2km above ground level as a function of latitude and season. (a) Simulation employing a specified weak dust loading (b) Simulation with radiatively active water ice clouds. The dust loading is the same in the two cases.

GFDL Mars general circulation model: The current GFDL Mars GCM is based on a finite volume atmospheric dynamical core that has been implemented on a cubed-sphere grid. The modeling described here uses resolutions of 4° x 4°, 2° x 2° and 1° x 1°. The MGCM includes surface and subsurface physics, which allow the calculation of realistic surface temperatures; a budget for gaseous and condensed CO_2 which yields a realistic annual cycle of global atmospheric mass; and a turbulent boundary layer parameterization. Spatially-variable input fields include topography, surface albedo, thermal inertia, emissivity and surface roughness. The advection scheme can transport an arbitrary number of tracer constituents that are used to represent the particle size distributions of dust aerosol, water vapor, and cloud ice. The model maintains mass-conserving inventories of dust mass (surface dust and aerosol, by particle size), which are used for accounting where dust has been lifted and deposited on the surface. The NASA/Ames radiation code is used to account for solar and infrared radiative heating by gaseous CO_2 and atmospheric aerosols. Aerosol heating rates are calculated using the optical properties of the evolving aerosol size distribution and composition.

The MGCM is run with fairly typical representations of convective and wind stress lifting [*Basu et al. 2004*]. We have specified σ_t as a function of the surface dust depth, varying about a nominal value of 0.028 N/m^2. We have also included a provision for dust replenishment in regions where the accumulated surface dust has fallen below the initial, globally-uniform value. This replenishment is in addition to dust accumulation associated with transport and sedimentation and is intended to compensate for the gradual export of dust to the polar regions. Since lifting is not allowed from surfaces that are covered by CO_2 ice, these growing high latitude deposits tend to be effectively isolated from the simulated dust cycle. The weak replenishment tendency enables a "stable" dust cycle over long runs of multiple decades.

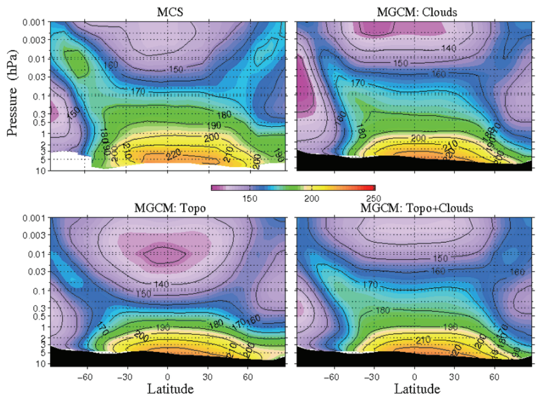

Figure 3. Comparison of observed and simulated zonally-averaged temperatures for L_s= 160° as a function of latitude and pressure (hPa). (a) MCS temperature, based on 3am and 3pm observations. (b) Simulated temperatures with radiatively active water ice clouds, but without parameterized topographic drag. (c) Simulation with parameterized topographic drag, but without radiatively active clouds. (d). Simulation with both topographic wave drag and radiatively active clouds.

The recent availability of MCS temperature retrievals has allowed us to begin the comparison of observed and simulated temperatures through a much deeper region of the atmosphere than was permitted by TES. Preliminary comparisons suggest that the GFDL MGCM (as well as LMD, WRF, and Ames) tend to underestimate midlevel (30-50) km temperatures in the tropics and, most notably, in the polar regions [*McCleese et al*. 2009] during the relatively non-dusty seasons. We are finding that this cold pole bias may be alleviated somewhat by the inclusion of parameterized gravity wave drag and radiatively active water ice clouds. *Wilson et al.* [2008] proposed that the influence of radiatively active water ice clouds could account for a cold temperature tropical bias in model simulations. Interestingly, the tropical warming associated with the absorption of upwelling IR radiation by tropical ice clouds leads to stronger forcing of the Hadley circulation and results in enhanced polar temperatures due to adiabatic descent. We have implemented a parameterization that represents the effects of subgrid-scale gravity waves forced by topography. This parameterization includes an input file representing the variance of topography based on the 1/16 degree MOLA data set. A summary of some of our preliminary results is shown in Figure 3.

TES dust assimilation: We have also been carrying out annual cycle simulations to compare with the TES temperature record and identify model biases. These simulations are carried out with multiple radiatively active dust tracers whose summed column optical depth is constrained by the evolving observed TES column opacity. We have focused on a representative annual cycle based on MY24/25 (L_s=150-360-150°) in one class of simulations [*Kahre et al*. 2009] while another set of simulations have focused on the 2001 planet-encircling dust storm [*Wilson et al*. 2008]. The observed opacity constraint is applied only when and where valid observations are available. Differences between predicted and observed dust column opacity are reconciled by adding or removing dust from the model boundary layer. Thus we have allowed the model to assimilate the evolving dust distribution subject to the constraint of matching the observed dust column. This is distinct from other modeling studies, including the UK data assimilation [*Montabone et. al.,* 2006], which specify the vertical distribution of dust. Current simulations are using 5 dust tracers, and we adjust the input size distribution to best satisfy the comparison between simulated and observed temperatures. The vertical distribution of dust has a particularly notable effect on polar temperatures. A spectrum of particle sizes, with different sedimentation rates, is necessary to simultaneously provide good agreement with observed polar and tropical temperatures. It is interesting to note that some of these assimilation experiments predict the presence of a maximum in density-scaled dust mixing ratio above the surface in the tropics in the late NH summer season that appears to be consistent with vertical structure revealed in recent MCS limb retrievals [*Heavens et al.,* 2010].

An equilibrated surface dust field is being used to investigate the development of the 2001 global dust storm. In this case, we are evaluating the dust lifting response in the Tharsis region following the observed increase in optical depth in the Hellas hemisphere. Initial results suggest that rapidly amplifying thermal tides can account for the burst of dust lifting in Daedalia/Thaumasia/Solis Planum. A critical issue is accounting for storm decay by L_s=210, when simulated stress levels are continuing to increase.

Continuing Work: The lack of regional scale dust storms, with moderate opacity levels, has been a major shortcoming in our dust cycle modeling to date. We speculate that a more realistic range of storm activity should yield greater variability in surface dust deposition and reduce dependence on the arbitrary, weak replenishment employed in the simulations.

A consequence of the spatially-variable σ_t is that a relatively greater fraction of the planetary surface is primed for explosive dust lifting compared with the case with fixed, uniform σ_t, since lifting in the highest stress regions has been de-emphasized. Thus there is a decreased tendency for strong dust lifting events in the SH to remain localized as regional storms. There may be other mechanisms which may inhibit this potential for global instability, which results in the all-or-nothing behavior seen in the current simulations. Some possibilities will be described.

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