WIND ENHANCED INTERACTION OF RADIATION AND DUST (WEIRD): APPLICATION UNDER A REALISTIC SCENARIO.

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Introduction:

In previous studies, a positive radiative-dynamic feedback process has been shown to operate under specific conditions within idealized local dust disturbances on Mars [Rafkin 2010]. Here, we extend these studies to more realistic conditions by analyzing the local response of the atmosphere to regional and local dust storms using a radiatively active dust cycle within a mesoscale model [Rafkin et al 2001].

The question as to whether this feedback mechanism can operate under realistic conditions, as opposed to the idealized conditions imposed in the earlier study, remains open. The following questions are also unanswered: How does dust modulate the local and regional scale circulations? What are the conditions inside a dust storm near regions of active lifting? Does a radiative-dynamic feedback process operate under more realistic conditions? What influence do topography, background thermal state, and winds have on any feedback? Can the evidence of these circulations be found in orbital imagery?

The Radiative-Dynamic Feedback Mechanism:

Briefly, the positive feedback mechanism works as follows (Fig. 1):

1) Wind lifts dust from the surface into the atmosphere;
2) The increased atmospheric dust load results in increased radiative heating of the atmosphere during the day, or less radiative cooling during the night, thereby producing a relatively warm region on the scale of the lifted dust;
3) Surface pressure is hydrostatically lowered in the warm region, which leads to an amplification of the low-level pressure gradient force;
4) The increased pressure gradient results in stronger winds, which lift more dust, and thus completes the positive feedback loop.

In Rafkin [2010] the feedback process was shown to operate in a manner similar to the Wind Induced Sensible Heat Exchange (WISHE) process—essentially a Carnot Engine—that explains the intensification of tropical cyclones on Earth. For the case of Mars dust disturbances, it is a Wind Enhanced Interaction of Radiation and Dust (WEIRD), as it is the radiative heating of lifted dust rather than sensible heat that drives the feedback on Mars. Like tropical cyclones, the storm environment and surface thermodynamic properties strongly influence the intensification process. Barotropic environments and steep lapse rates are favorable while strongly sheared environments and environments with cold air near the surface or warm air aloft are not. The availability and amount of dust available for lifting is important for dust disturbances just as the availability of warm water is important for hurricanes. Beyond environmental factors, latitude plays an important role

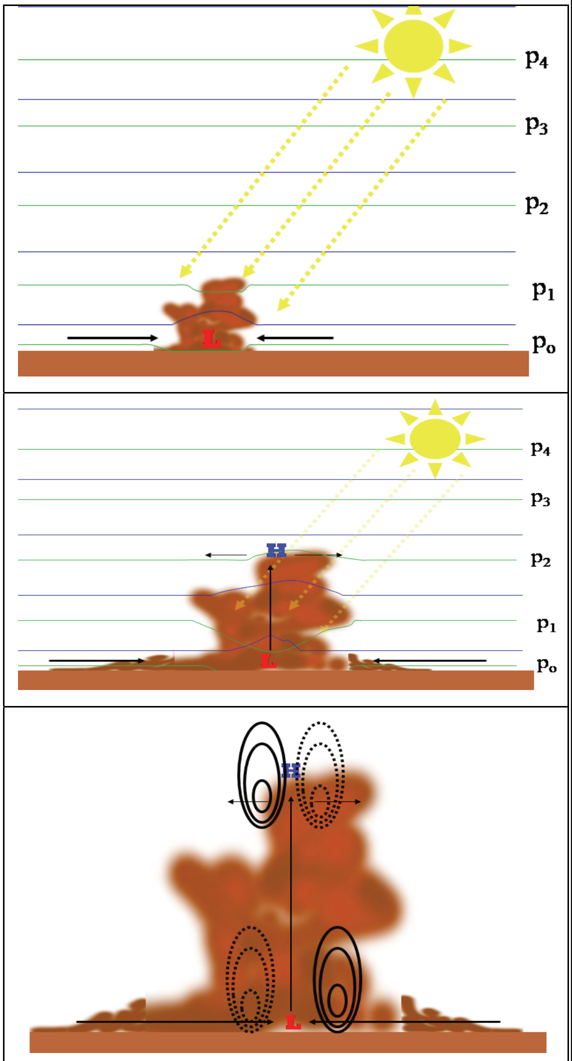

Figure 1. Schematic illustration of the wind-enhanced interaction of radiation and dust (WEIRD) radiative-dynamic positive feedback mechanism. The heating of an initial dust disturbance (top) induces a hydrostatic lowering of pressure and an inward acceleration of winds. The increased winds lift more dust and upper level divergence develops from mass continuity (middle). Over time, a balanced dynamical response, consistent with a classic warm core low pressure system is established (bottom). A strong cyclonic circulation is produced near the surface and an anticyclone is present aloft.

in the feedback process. Latitude exerts dynamic control via the coriolis torque and parameterically determines the available solar input as a function of aerocentric longitude. Low latitudes have the greatest solar input, but lack the planetary vorticity to develop and sustain intense, balanced circulations. High latitudes are dynamically favorable, but lack the solar forcing. The subtropics provide the most favorable combination of solar forcing and coriolis forcing.

Model Description

The model used to explore WEIRD in a more realistic setting is the Mars Regional Atmospheric Modeling System (MRAMS), the core of which is described by Rafkin et al [2001]. Two important improvements since Rafkin [2010] are applied for this study. First, the dust lifting parameterization of Michaels [2006] is used. Second, dust is treated via a dual tracer field that permits both a background distribution and a perturbation distribution.

Dust Lifting Parameterization

Most dust lifting parameterizations used in models use the model predicted wind or surface wind stress to determine whether dust lifting is active and further use the wind stress value to compute the dust flux. A subgrid lifting, usually associated with dust devils is often invoked as well. Michaels [2006] recognized that the model predicted wind is, in the Reynolds averaging sense, the mean wind within the model grid cell, and that dust devils are a member of a continuum of circulation sizes. Based on these two axioms, a new dust lifting model was developed.

On Earth, wind speed distributions are often well described by a Weibull probability distribution function. There is some evidence that the same distribution holds generally for Mars. This distribution has a tail at higher wind speeds, and the width of the distribution is related to the turbulence of the atmosphere. A purely laminar flow would have a distribution of zero width, and the all winds would have a unit probability of being exactly the mean wind. Highly turbulent flows, such as those that are expected during a convective afternoon on Mars, would have a broad distribution with strong gusts and dust devils occupying the tail end of the distribution. Although the mean wind may not be of sufficient strength to lift dust, there is still a finite probability of winds exceeding a given lifting threshold.

If the model predicted wind speed/surface stress, u_*, is assumed to be the mean of a Weibull distribution, the fraction of winds exceeding a given threshold can be calculated if the width of the distribution is known. For simplicity, three possible wind regimes are identified based upon the value of the bulk Richardson Number (R_i) in the lowest model layer. The first is a highly turbulent and gusty regime corresponding to $R_i<0$, the second is a moderately turbulent regime $0\le R_i\le 0.03$, and the final is a laminar regime for $R_i>0.03$. The width, γ, of the distributions for each regime is then set, with the largest width corresponding to the most turbulent case. Future versions of this scheme will utilize a continuous specification of widths functionally related to R_i.

Once the full Weibull distribution, W, is determined, the flux of dust, F_d, for a wind threshold above a critical lifting threshold, u_t, is normalized by the Weibull probability distribution function to generate the actual dust flux, F_d^*:

$$F_d^*(u_*) = W(u_*,\gamma)F_d(u_*) \qquad (1)$$

where

$$F_d = C_N(\rho_a\rho_d)^{0.5}u_*^3(1-\frac{u_t}{u_*})(1+\frac{u_t^2}{u_*^2}) \qquad (2)$$

C_N is an empirical constant, and subscripts a and d refer to atmosphere and dust, respectively.

Dust Aerosol Representation

In Rafkin [2010], only lifted dust was considered in the radiative transfer calculations. In reality, there exists a background dust concentration that is perturbed by local lifting, transport and sedimentation of dust. MRAMS now carries two distinct dust fields. The first is a background dust concentration and the second is a perturbation dust field. The background dust concentration is static (i.e., no transport, sedimentation or surface sources) and may be initialized in any user-specified manner (including a zero background field). The background dust is always radiatively active. The perturbation dust field utilizes the microphysical bin model to track a user specified number of dust mass bins subject to lifting, sedimentation and transport; the perturbation dust distribution is allowed to freely evolve. The perturbation field can also be initialized with any user-specified distribution.

The surface dust reservoir is explicitly tracked and tied directly to both the lifting and sedimentation of perturbation dust as a function of size. Dust lifted off the surface is assumed to follow a log-normal distribution with a user-specified mode (r≈1.5 μm). In most cases, the larger dust particles lifted from the surface fall rapidly to the surface leaving only dust of several microns and smaller in the atmosphere.

Often, the first few hours of model spin-up produce strong winds or transient circulations associated with the adjustment of the initial GCM conditions. These spurious circulations can lead to nonphysical lifting and perturbations of the dust field. Prevention of spurious lifting is achieved by disabling lifting within a user-specified period of time from initialization.

Both the background and perturbation dust fields can be independently radiatively active. The background dust size distribution follows a long-normal distribution (mode of r≈1.5 μm) with appropriate constants computed based on compositional properties and the assumed size distribution. The perturbation dust distribution optical properties are based on the instantaneous size distribution. The radiative activity of perturbation dust can be switched on or off within simulations as desired.

Model Simulation Design

Ongoing MRAMS simulations conducted to assess the atmospheric environment at potential MSL landing sites are leveraged for this study. Here, results from Mawrth Valles landing site (~22.3N, 16.5W) simulations. All simulations are configured identically with four grids, beginning with a nearly hemispheric grid at

240 km horizontal grid spacing and decreasing by a factor of three on each successive grid down to 8.9 km on the fourth grid. Vertical grid spacing is ~10 m at the lowest level and is gradually stretched to a spacing not to exceed ~2 km. The top of the model is ~60 km.

A simulation with radiatively active lifted dust is compared to a baseline simulation in which lifted dust is not radiatively active. The impact of dust on local and regional circulations and the role of WEIRD is then assessed. The value of the lifting efficiency factor (C_N) is varied as a function of the model grid. The efficiency on all but the finest grid is set to a value that produces typical dust optical depth perturbations (~0.1). On the fourth grid, however, the efficiency is set to a large value. This has the result of producing a highly dusty grid that mimics the development of a local dust storm.

A major advantage to tuning C_N to produce the different scenarios is that the dynamical field evolves in a completely self-consistent manner with the dust field. Dust is only lifted where the winds are of sufficient strength, and the circulation feels through radiative forcing the impact of the lifted dust. A disadvantage of this method is the location and evolution of dust disturbances cannot be easily controlled; the disturbances form where the winds dictate and evolve according to overall evolution of the circulation. Alternatives to specifying C_N include initialization of the model with an incipient dust disturbance (as was done in Rafkin [2010]) or turning off lifting altogether and specifying the perturbation dust distribution as a function of time. The latter allows for the precise control of when and where the dust disturbance appears and how it grows and decays. The disadvantage to this latter method is that the dust field is generally not consistent with the wind field; the winds respond to the specified dust, but the dust field is independent of the winds.

Numerical Simulation Results

If dust were a primarily passive tracer, all the simulations would evolve in a similar manner; lifted dust would have little to no impact on the circulation. Dust lifting is initiated in the simulations near sunset on the first day, and during the night, dust behaves very much like a passive tracer (Fig. 2).

By midday, the situation is dramatically different (Fig. 3). In the radiatively active case, the dusty region is strongly heated to produce a negative pressure perturbation and a tendency for cyclonic rotation. Wind speeds nearly double in the radiatively active case. These characteristics are exactly those predicted based on the idealized experiments [1].

The location of Mawrth Valles is also at an acceptable latitude for positive feedback, because solar heating is still rather strong in the subtropics and the coriolis force is strong enough to produce rotation. However, the simulation season of Ls=150 means that the solar forcing is reduced over what it could be in the northern subtropics.

A vertical cross-section through the disturbance in the top panel of Fig. 3 is displayed in Fig. 4, but with data taken from the fourth grid. Dust mixing ratio is maximized in the center of the storm and is lofted primarily in the deep updrafts. Note that the storm produces an elevated dust layer in the outflow region; dust mixing ratio has a maximum value at ~15 km with the top of the dust extending to ~20 km. Stong gravity wave activity is also present above the storm. In contrast, the radiatively passive storm does not produce vertically-enhanced updrafts (not shown); heating of dust must be producing the additional buoynacy in the radiatively active case. Also, because the passive case does not have penetrative convection, no elevated dust layers above the boundary layer are produced.

The dynamical storm structures that develop during the day rapidly dissipate at night and are not seen to regenerate the next sol. The reason for the dissipation is, as described in the idealized situation, due to the loss of solar heating, which ultimately provides the energy for the system. Topographic influences and wind shear then destroy the incipient vortex. Finally, dust lifting was so intense during the day that much of surface dust reservoir is depleted, and this makes it difficult for a new system to develop the next day.

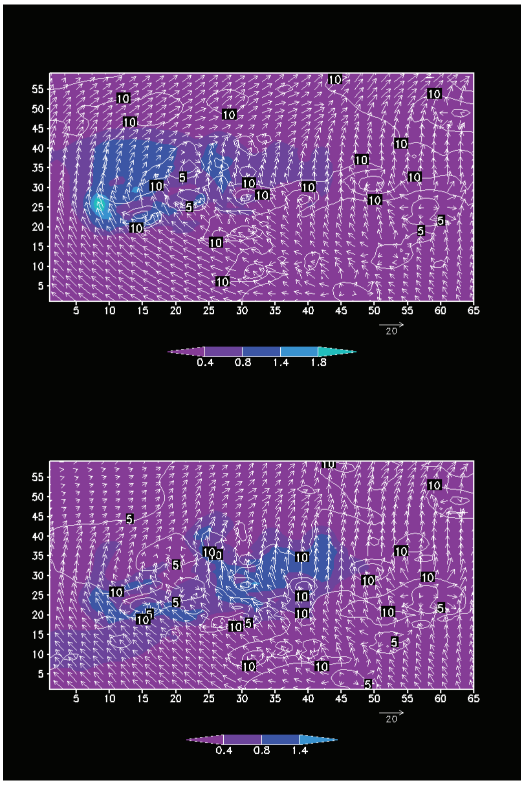

Figure 2. During the night after dust lifting is initiated, dust behaves much like passive tracer. The dust field and the winds in the radiatively active (top) and radiatively passive (bottom) cases are very similar indicating that dust has had little impact on dynamics. Data from the third grid (~27 km grid spacing are shown). Dust optical depth is shaded, wind speed is contoured.

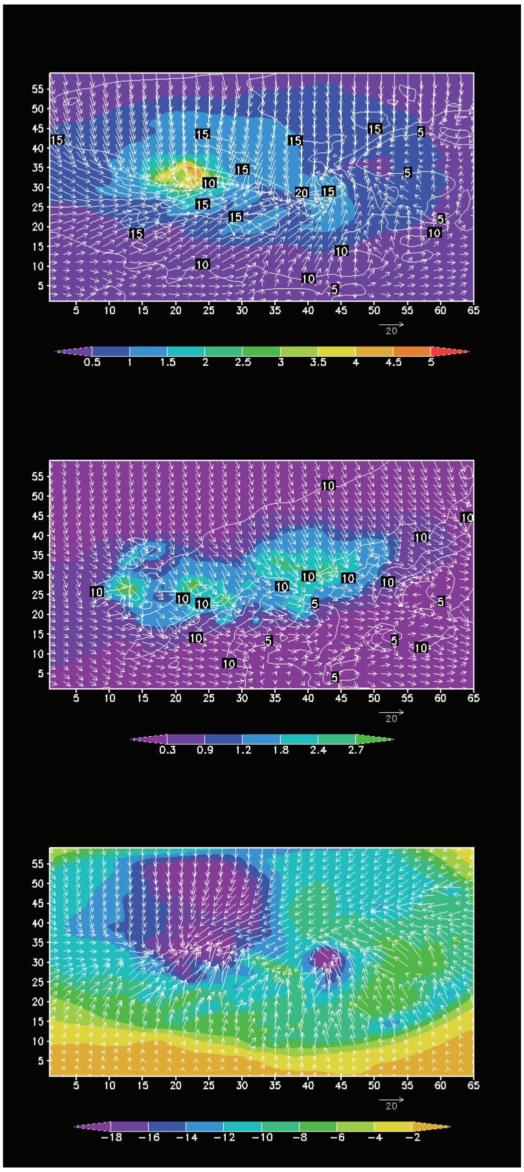

Figure 3. Radiatively active dust has a dramatic influence on the evolution of the atmosphere. Dust intensifies the circulation and causes additional dust to be lifted, thereby producing a positive feedback as described by WEIRD. Top and middle as in Fig. 2. Bottom panel shows the pressure difference in Pa between top and middle (shaded) and wind vector differences with 20 m/s scale vector as indicated.

Summary:

Experiments under more realistic conditions indicate that the WEIRD positive feedback mechanism is operating and provides substantial forcing that dramatically modifies the kinematic and thermodynamic state of the atmosphere. Pressure deficits accompanied by cyclonic motion and intensified winds are found to be consistent with the WEIRD. Locally lifted dust has a large, quantifiable impact on the local circulation. In the vertical, dust plays an important role in invigorating updrafts that penetrate into the stable air above the boundary layer; dust plays a role in producing the deep updrafts that produce elevated dust layers.

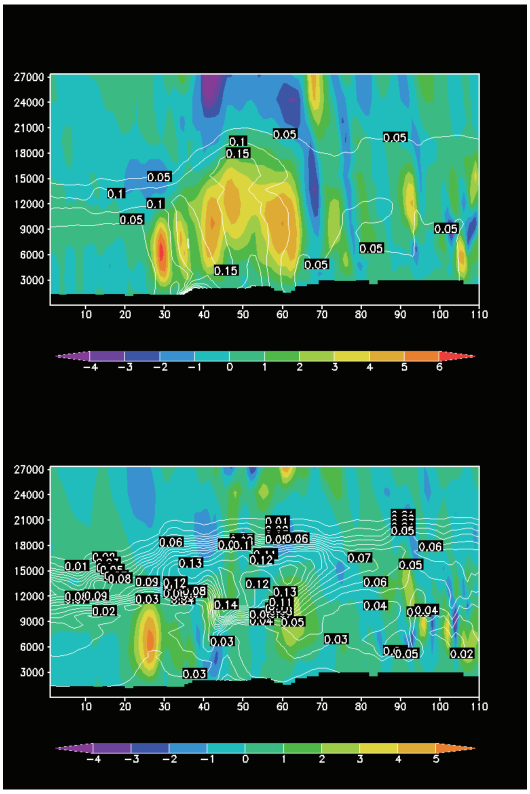

Figure 4. Vertical cross-section of the disturbance seen in the top panel of Fig. 3 (y=30). The data above are taken from the fourth grid during the peak of the storm and after it begins to dissipate near sunset Vertical velocity is shaded and dust mixing ratio (g/kg) is contoured. Note the development an elevated dust layer.

References

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