TROPICAL DUST CYCLONES ON MARS. Scot C. R. Rafkin[1] [1]Southwest Research Institute, Department of Space Studies, Suite 300, Boulder, CO USA, 80302, Rafkin@boulder.swri.edu.

Introduction: Atmospheric dust plays an important role in regulating the climate of Mars and strongly influences the deposition of incoming solar energy and outgoing infrared radiation, thereby affecting atmospheric dynamics through heating. The lifting of dust from the surface is fundamentally a result of atmospheric circulations, and this provides an opportuntity for feedback between atmospheric dynamics, dust lifting processes, and the radiative forcing perturbations that ensue.

Dynamical atmospheric instabilities resulting from radiatively active atmospheric dust have been previously recognized [1,2,3]. None of these studies included the process of dust lifting, and there was no direct investigation of whether the disturbances were capable of maintaining or enhancing the dynamically unstable atmospheric dust distribution through the replenishment of dust from the surface. Furthermore, none of these studies investigated the instabilities or feedbacks that might result from horizontally finite dust disturbances from which any effectively horizontally infinite or global dust distribution must originate. More recent general circulation modeling studies have included dust-lifting parameterizations tied directly to the atmospheric wind stress and atmospheric lapse rate [4,5,6]. However, these studies did not investigate the possible interplay between atmospheric dust, ***local*** atmospheric dynamics, and dust lifting. Does the lifted dust lead to amplification of the local circulation producing the initial dust lifting (as opposed to an amplification of the large-scale mean circulation)? Or, is the lifted atmospheric dust primarily passive, revealing only the presence of an atmospheric circulation while contributing little to its dynamical forcing?

The proposed positive feedback mechanism explored in this study mechanism works as follows: 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. This mechanism is not unlike the Wind-Induced Sensible Heat Exchange (WISHE) mechanism proposed for the development and maintencance of tropical cyclones on Earth [7].

Numerical Experiment Design: The Mars Regional Atmospheric Modeling System (MRAMS) is employed for these studies [8]. However, we also couple the dynamical MRAMS model to the Cloud Aerosol and Radiation Model for Atmospheres (CARMA) to achieve a more physically realistic representation of dust and dust processes [9] that are at the core of the proposed feedback cycle.

MRAMS/CARMA distributes atmospheric dust into 8 discrete mass bins. Each dust bin is carried in the model as an individual scalar quantity that is both advected, and diffused, and each dust bin undergoes mass-dependent sedimentation. All atmospheric dust is radiatively active, and heating rates are calculated based on a two-stream correlated-k model [10].

Dust lifting, when activated, is parameterized using a typical representation whereby dust flux is coupled to the surface wind stress:

$$F_{dust}=\alpha\tau^2(\tau-\tau_\chi)/\tau_\chi\ , \qquad (1)$$

where τ_c is the critical surface stress (lifting threshold) above which dust lifting is allowed, and α determines the total flux of dust lifted. The lifted dust is assumed to follow a log-normal distribution with a mode of approximately 1 μm.

The model is started with the atmosphere at rest, but the background dust is perturbed in the center of the model domain to initiate a disturbance. The perturbation is of variable horizontal size, but is ~200 m deep with an optical depth of 1.0. The model is integrated in time for approximately three sols.

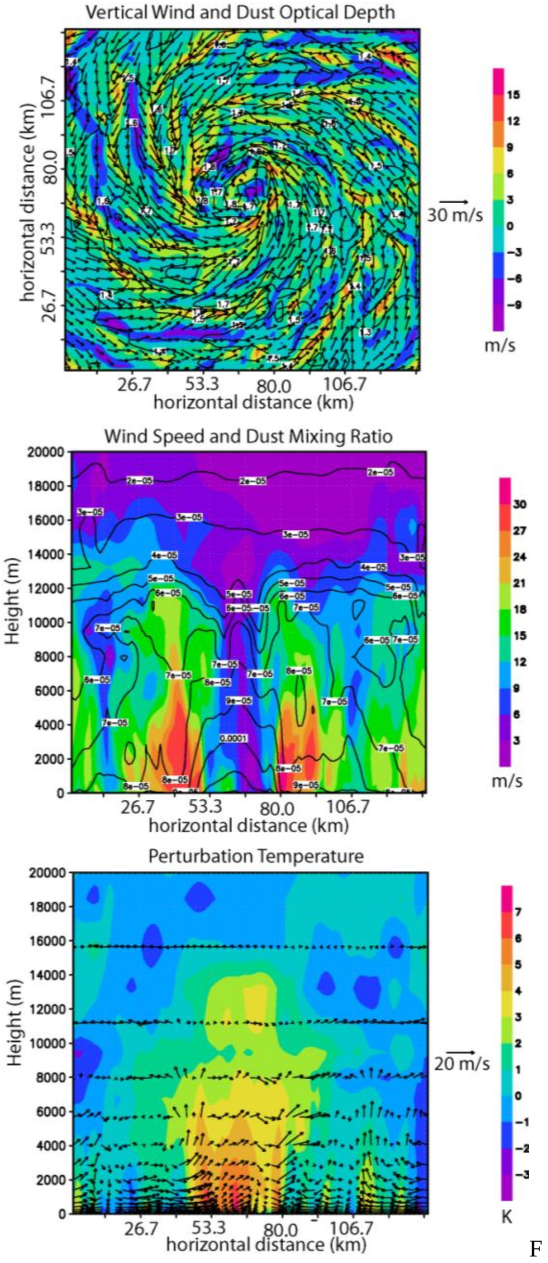
The model domain is sufficiently large (>10^3 km across) such that the circulations of interest in the center of the domain are insensitive to the boundaries or choice of boundary conditions. Test simulations and previous studies indicate that organized convective structures at scales of (O)10 km are present in the convective boundary layer. Dust lifting variability is expected to follow the scale of wind variability associated with these structures, but it is not computationally possible to have a grid with 10^3 points on a side. Instead, nested grids with the following dimensions and grid-spacing are used: 40x40 at 64 km (grid 1); 62x62 at 16 km (grid 2); 50x50 at 4 km (grid 3); 101x101 at 1.33 km (grid 4). There are 40 sigma-z vertical points that are geometrically stretched by a factor of 1.18 from an initial spacing of 15 m to a maximum of 3000 m, resulting in a model top at 50 km.

In all of the studies, a full solar cycle was imposed with the simulation starting at sunrise at $L_s=180^o$. The incident solar flux depends on latitude, and the simulations use an *f*-plane (constant coriolis parameter) approximation with a value corresponding to the solar flux latitude. The coriolis force was switched off (*f=0*) in some cases with non-zero latitudes.

Results: Under a variety of conditions, substantial positive feedback is observed, and in the strongest cases, results in disturbances structurally and dynamically resembling hurricanes (Fig. 1). When dust lifting is disabled or reduced, dust disturbances do not develop, and the initial dust perturbation dissipates. Radiative-dynamic interaction between the dust and the circulatoin are essential for development. In the case of positive feedback, the initial dust perturbation is able to generate local winds that reinforce the dust perturbation through the development of an organized, quasi-dynamically balanced vortex.

Both tropical cyclones and the simulated disturbances are warm-core low pressure systems with maximum pressure perturbations at the surface. Both are characterized by quasi-balanced circulations (except for the equatorial cases) with low level radial inflow toward the center, strong upward vertical velocity in an eye wall just outside the center of the circulation, and descending air in the eye of the storm. In the case of hurricanes, the descending air creates a visible eye due to adiabatic warming and drying. This is not the case for these dust storms, as dust mixing ratio is not sensitive to temperature. However, dust does gravitationally settle out, and the downward motion at the eye tends to create a minimum in dust optical depth. During the afternoon, when the atmosphere is convecting, the dust storm may develop spiral arm bands, which are organized updrafts aligned with the mean wind. Horizontal wind speed is at its absolute maximum at the eye wall and local speed maxima are collocated with the spiral arms. Updrafts in the dust storm are also collocated with the arm bands and are strongest at the eye wall. Aloft, both circulations are characterized by anticyclonic outflow and positive pressure perturbations (not shown).

Wind-Induced Sensible Heat Exchange: The structural and dynamical similarity between the simulated disturbances and hurricanes suggests it is perhaps reasonable that the dust storms may be regulated by a WISHE-like mechanism. In the WISHE hypothesis, near-surface air flowing towards the center of the hurricane gains entropy via water vapor flux at the ocean surface while undergoing isothermal expansion at a temperature near the sea surface temperature. Within the hurricane eye wall the moist air then ascends adiabatically (in the moist sense) and is exported horizontally in the upper level anticyclone, also adiabatically. The excess entropy is lost gradually and nearly isothermally through radiation during slow descent in the upper troposphere. Finally, the air descends (nearly adiabatically) back to the surface far from the vortex center to complete the circuit. These paths closely represent the isothermal and adiabatic legs of a Carnot Cycle, with the efficiency of the hurricane engine being proportional to the input surface temperature and out-


Vertical Wind and Dust Optical Depth

Wind Speed and Dust Mixing Ratio

Perturbation Temperature

Figure 1. The structure of the strongest dust storms resemble that of a hurricane. Spiral arm bands (top) are collocated with the strongest vertical velocity at 2 km AGL (shaded) and with an increase in dust opacity (contoured). In the vertical cross-section (middle) winds are maximum in the eye wall (shaded) and the dust field (contoured) shows an eye structure. Perturbation temperatures in the cross-section (bottom, shaded) indicate a warm core structure. There is low-level storm inflow, upper-level outflow, upwelling in the eye wall and spiral arm bands, and downwelling in the eye.

put temperature aloft: $\varepsilon=(T_s-T_o)/T_s$, where T_s is the sea surface temperature and T_o is the exhaust temperature (or output temperature) at the top of the storm. The work done is balanced by a frictional loss of energy that takes place primarily at the surface. As the input temperature increases, greater frictional loss is required for steady-state conditions. This is accomplished by increasing surface winds (which are proportional to the pressure gradient). However, increasing the surface winds (by decreasing the central pressure) also increases the water vapor flux, which further increases the entropy of the system. The increase in entropy results in more work done by the hurricane that must be balanced by a further increase in wind speed, a concomitant increase in frictional loss, a decrease in pressure, and an increase in entropy input from increased water vapor flux.

As an analog, we may consider the dust storm efficiency to be the fraction of energy and pressure work that is converted to mechanical energy of the system, but rather than the acquired energy being latent, it is realized nearly immediately through solar heating of lifted dust. And, just as the latent energy in a hurricane is proportional to the amount of water evaporated into the air, the amount of heating in the dust storm is proportional to the amount of dust lifted into the atmosphere.

Exhaust Temperature. The background lapse rate strongly controls the exhaust temperature of the dust storms. Simulations were conducted to investigate the effect of different thermal structures. An isothermal state at 170K, 215K and a sunrise temperature profile extracted from a realistic mesoscale simulation were used to initialize the model. The results from the 215K isothermal case and the realistic temperature case are nearly indistinguishable in terms of circulation strength, and the 215 K and realistic profiles produce weaker circulations than the 170K isothermal cases (Fig. 2). In all cases, the near-surface air is rapidly heated, but to roughly the same temperature regardless of the initial condition. However, the higher levels of the atmosphere are less susceptible to the heating, resulting in a very steep lapse rate for the 170K isothermal case. The lapse rate is less steep in the 215K isothermal case, and, as it turns out, is nearly the same as in the realistic temperature profile.

The difference in intensity between the circulations with different background thermal states now makes sense in the context of a Carnot engine. The greatest difference between the two temperatures ($\Delta T \sim 50K$) occurs in the 170K case during the warmest part of the afternoon and corresponds to an efficiency of about 22%. At night, the input temperature is still warmer than the output temperature by about 15K. In contrast, the other simulations have a maximum ΔT of $\sim 30\ K$ corresponding to an efficiency of about 14%. At night, the input temperature in the other cases is colder than the output temperature. When this happens, the Carnot engine runs in reverse, and extracts mechanical energy from the system; the system spins down.

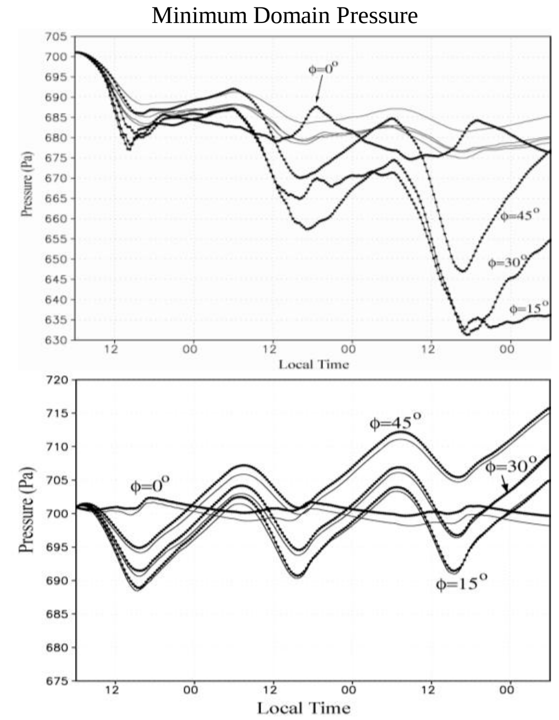


Figure 2. Minimum domain pressure (mdp) is a proxy for circulation strength. The solid line in the top panel shows the timeseries of mdp as a function of latitude for a simulation where dust lifting is disabled. The top panel with circles shows a strong feedback case with an 170K isothermal background. The bottom panel is identical to the 170 K case in the top , but for a 215 K isothermal background (solid) and realistic temperature background (circles).

Geostrophic Adjustment. The input temperature is strongly controlled by solar insolation. All other things being equal, an equatorial simulation should show the strongest feedback. When the coriolis parameter is set to be invariant with latitude, there is a monotonic decrease in feedback and circulation intensity with increasing latitude (Fig. 3). However, when the coriolis force is allowed to vary with latitude, geostrophic adjustment considerations become important.

Despite the largest solar forcing at the equator, the equatorial simulation is not the lowest pressure case, because the mass field is constantly adjusting to fill in the pressure deficit (via gravity waves). At 15^o, the solar forcing is slightly less than at the equator, but the conversion of some of the solar energy to kinetic energy as part of a geostrophically balanced circulation permits some of the mass to remain in a pressure deficit configuration. The dynamics at this latitude slightly counteract the decrease in solar forcing and result in a slightly more intense system than at the equator. At 15^{o}, the Rossby Radius of Deformation is still quite large (although not infinite as in the equatorial case), so the dynamic contribution to the pressure deficit is relatively small, but still large enough to exceed the equatorial case. The model solution at 30^{o} nearly matches the equatorial case even though there has been a further reduction in solar heating. Here, the dynamic response is stronger than at 15^{o}, but the solar forcing is less. At 45^{o} the loss of solar insolation begins to overwhelm the increasing tendency to develop a more geostrophically balanced system. Correspondingly, the pressure deficit is less than at the lower latitudes.

WISHE development of hurricanes is latitudinally confined to subtropics. The requirement of a balanced circulation component precludes substantial amplification at very low latitudes. At high latitudes, WISHE is not efficient for hurricanes, because the sea surface temperature is too low. WISHE intensification of the simulated dust storms is similarly latitudinally confined, with the coriolis force limiting the low latitude extension and solar heating limiting the high latitudes.

Conclusion. Numerous idealized simulations were presented to investigate the potential for a positive radiative-dynamic feedback mechanism for the maintenance and growth of dust disturbances on Mars. Under some conditions, a strong positive feedback was found. The thermodynamics and dynamics of the simulated dust storms were similar in many respects to hurricanes. However, many of the structures may be difficult to observe from orbit. Like hurricanes, the conditions that favor a positive feedback are best explained by a combination of the geostrophic adjustment process and a WISHE-like Carnot engine cycle.

The geostrophic adjustment process favors locations with strong solar forcing, and a non-negligible coriolis force. These conditions are maximized in the subtropics, and might be further enhanced by seasonal shifts toward the summer pole driven by solar insolation. Increasing coriolis force (or equivalently, increasing latitude) makes for a dynamically more efficient circulation that can retain more of the solar energy input as a balanced circulation. However, the increasing dynamic efficiency as a function of latitude is tempered by a decrease in solar insolation.

The positive radiative-dynamic feedback described in this paper may be able to explain the growth of disturbances not clearly linked with known causal mechanisms, such as baroclinic systems and polar cap circulations. This might include some disturbances that lead to regional or larger dust storms. It might also explain how such disturbances can be maintained over many sols. In order for a positive feedback to occur, conditions have to be just right, and this may explain why most dust storms do not grow explosively and instead dissipate within one sol.

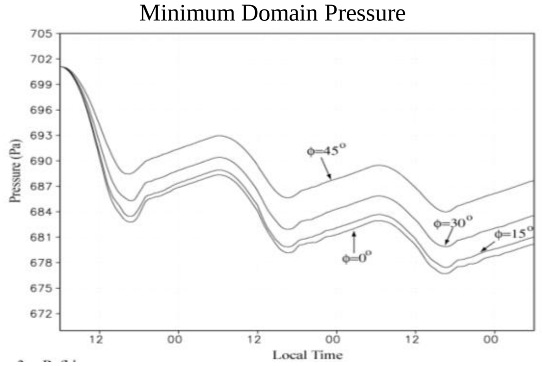


Figure 3. Minimum domain pressure as a function of time and latitude for a case where the variation of coriolis with latitude is disabled. In this case, only solar insolation varies with latitude, and the strength of the circulation decreases monotonically with increasing latitude. Compare with the cases in Fig. 2.

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