RADIATIVE-DYNAMIC FEEDBACK BETWEEN THE ATMOSPHERE AND THE SURFACE OF MARS.

S. C. R. Rafkin, Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder CO 80302, rafkin[at]boulder[dot]swri[dot]edu.

Introduction: The possibility of a positive feedback mechanism involving atmospheric circulations and radiatively active dust in the atmosphere of Mars has been recognized for some time. Ghan [1] showed that the radiative effects of atmospheric dust could result in a kinetic energy growth rate of atmospheric disturbances that is comparable to that of baroclinic instability. Haberle et al. [2] demonstrated that atmospheric dust loading similar to that expected in planet-encircling dust storms could accelerate the mean zonal flow. None of these earlier studies included the process of dust lifting from the surface into the atmosphere; there was no direct investigation of whether the disturbances are capable of maintaining the dynamically unstable atmospheric dust distribution through replenishment of airborn dust from the surface.

More recent general circulation modeling studies [3,4] have included dust lifting parameterizations tied directly to the atmospheric wind stress and atmospheric lapse rate. The results of these investigations show that the atmospheric dust loading is sensitive to the choice of free parameters within the lifting parameterization; the models can generate regional dust storms and even global dust storms with suitably tuned parameter values. However, these studies do not investigate the possible interplay between atmospheric dust, atmospheric dynamics, and dust lifting. Does the lifted dust lead to a more energetic atmospheric circulation resulting in additional dust lifting and further strengthening of the winds?

The feedback mechanism investigated in this study involves the atmospheric circulation, the lifting of dust by the circulation, and the radiative forcing of the lifted dust. It is conceptually described 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 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 lifts more dust, which closes the positive feedback loop. If this feedback takes place over timescales of a sol or greater at latitudes with appreciable coriolis force, and if the system is of sufficient scale compared to the Rossby Radius of Deformation, the system could also begin to exhibit a quasi-balanced (e.g., rotational) structure.

Hurricane feedback analogy. The radiative-dynamic feedback mechanism is highly analogous to the Wind-Induced Sensible Heat Exchange (WISHE) hypothesis proposed by Emanuel [5] as a hurricane feedback process. In this hypothesis, near-surface air flowing towards the center of the hurricane gains entropy at nearly constant temperature via water vapor flux at the ocean surface. 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. 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 output temperature aloft. The work done is balanced by a frictional loss of energy primarily lost at the surface. As the input temperature increases, greater frictional loss is required to maintain balance. This is accomplished by increasing surface winds (which are proportional to the pressure gradient), as may be computed by integrating the Bernoulli equation along an isothermal surface streamline. 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, concomitant increase in frictional loss, decrease in pressure, and an increase in entropy input from increased water vapor flux.

Deviations from WISHE. Unlike hurricanes, the inflow into a dust disturbance is not isothermal; as dust is lifted, the atmosphere radiatively warms. In contrast to the dust flux on Mars, water vapor flux into the atmosphere is a latent heating that is not realized until the adiabatic ascent within the eye wall. In dust storms, an injection of dust into the atmosphere provides an almost instantaneous heating term. Even so, once near the core of the dust storm, the air does rise nearly adiabatically and is expelled at a level of near neutral environmental thermal buoyancy. This air then radiatively and nearly isothermally looses entropy as it ultimately descends to complete the cycle. Thus, with the exception of the anisothermal surface leg of a dust storm, there is similarity to the WISHE hypothesis for hurricanes.

Although the dust heating in dust storms is not latent, there is still a net increase in entropy for an air parcel as it moves from the periphery of the disturbance towards the center. Work is being done, and for a balanced circulation, it must be balanced by frictional loss, primarily at the surface. As with hurricanes, the frictional loss is realized by increased surface wind speeds (resulting from a decrease of central pressure), which further increases the flux of dust into the atmosphere.

The lack of an isothermal surface leg along a streamline makes the integration of work *(=Tds*, where *T* is temperature and *ds* is the change of entropy) along the streamline analytically more difficult than for a hurricane, and therefore it is more difficult to relate the thermodynamics to the kinematic field as was done by Emanuel [5]. The line integral can, however, be accomplished numerically, and it is shown that a Carnot-like cycle does exist for dust storms, and the strength of the system can be measured by an efficiency factor relating the input temperature to the output temperature of the storm exhaust.

The WISHE hypothesis and the WISHE-like hypothesis for Martian dust storms do not explain how rotational disturbances might develop. An initial, incipient quasi-dynamically balanced vortex is required *a priori* so that the surface wind speed is related to a radial pressure gradient. However, the evolution of a vortex from a localized heat source in a flow with only planetary vorticity is reasonably well understood. Thus, WISHE can be thought to operate once an incipient vortex is present.

Numerical experiments: Summary results from a number of two- and three-dimensional numerical simulations designed to investigate the radiative-dynamic dust feedback mechanism of Mars and to answer a multitude of questions are presented. Does this feedback exist? If so, under what circumstances? At what scales does it operate? Are critical thresholds of atmospheric dust opacity or dust lifting required? Can this mechanism explain at least some observed dust disturbances? How similar is the feedback to WISHE? The simulations are idealized so as to get at the essence of the feedback mechanism in the absence of other effects that would otherwise obfuscate the underlying physics.

The basic approach in identifying the presence and strength of a potential feedback mechanism is to conduct simplified numerical simulations in which the lifting of dust is switched on and off. Under otherwise identical conditions and forcing, the "on" and "off" simulations can be compared to see whether the ability of the atmosphere to lift dust produces a more energetic, robust, or dynamically stronger system than in the case where no dust lifting is permitted.

We use the Mars Regional Atmospheric Modeling System (MRAMS), with the core of the model as described in Rafkin et al. [6]. However, in this study, we couple the dynamical MRAMS model to the Cloud Aerosol and Radiation Model for Atmospheres (CARMA) to achieve a higher degree of fidelity in the representation of dust physics, as described in Michaels et al. [7].

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 advected, and diffused, and each dust bin undergoes mass dependent sedimentation. All atmospheric dust is radiatively active, and heating rates are calculated based on the two-stream correlated-k model of Toon et al. [8].

Dust lifting is parameterized such that a critical surface stress, τ^*, must be exceeded before activation, and then once activated, the flux of dust is roughly a function of the cube of the stress multiplied by a dust flux efficiency factor, α [3]. We assume that the distribution of lifted dust is log-normal.

In these highly simplified simulations, 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 model domain is sufficiently large such that the circulation of interest in the center of the domain is insensitive to the boundaries or choice of boundary conditions.

Because of the speed at which simulations can be conducted in two-dimensions, two-dimensional simulations with one kilometer horizontal grid spacing are employed to cover a large range of dust lifting parameters and initial dust disturbance distributions. However, there are necessarily fundamental dynamics (e.g., the development of a dynamically balanced system) that are best represented in three-dimensions, and we employ three-dimensional simulations to further investigate these situations.

In the 2-D simulations, the coriolis parameter is zero, and the radiative forcing is set to local noon at equinox (Ls=0). Thus, in the 2-D simulations, the sun is always directly overhead. Under this radiative forcing, circulations develop rapidly, which makes for easier identification of a feedback signal.

A similar design is employed for 3-D simulations, except for the assumption of an f-plane, and a change of the solar flux as function of the chosen f-plane latitude. Also, these simulations are run with a realistic diurnal cycle so that the sun rises and sets.

2-D Simulation Results. An initial dust perturbation of unit optical depth is superimposed on a clear, isothermal (170K) atmosphere. The atmospheric dust is ~200 *m* deep and is 1 *km* in horizontal extent. The dusty region quickly becomes hotter than the surroundings and a direct thermal circulation ensues. After several hours, the circulation is very well defined, with inflow in the lowest few kilometers towards the center of the dust disturbance and outflow aloft (Fig. 1), although individual thermal plumes disrupt an otherwise laminar flow.

The strength of the thermal circulation is strongly dependent on the dust lifting parameters (Fig. 2). In the case of no dust lifting, a mean inflow/outflow of just a few meters per second develops. However, when dust lifting is allowed and when the lifted dust is radiatively active, a positive feedback occurs. The lifted dust strengthens the circulation, which leads to enhanced dust lifting.

Keeping in mind that kinetic energy goes as the square of velocity, it becomes evident that variations in dust lifting can have dramatic impacts on the atmospheric energetics. By computing the ratio of dust lifting inflow speeds to no-dust-lifting inflow speeds, a quantitative measure of feedback is obtained (Fig. 3). There are optimal dust lifting parameters that produce an axis of maximum feedback. For very high dust lifting thresholds, little dust is lifted, and the feedback effect is limited. Still, even a minor amount of dust can enhance the circulation speed by a factor of three or four. In cases where the dust lifting efficiency is high, and especially where the lifting threshold is low, the atmosphere becomes almost uniformly dusty, and the horizontal temperature gradient that drives the circulation is reduced. Maximum feedback requires a modest lifting threshold and modest efficiency. Peak circulation enhancement factors are in excess of 30. However, even in the minimal case, lifted dust greatly affects the circulation.

3-D Simulation Results. The 2-D simulations are unable to investigate the ability of the circulation to develop into a dynamically balanced system. However, the 2-D studies are used to guide the 3-D simulations, since the latter are much more computationally expensive.

In 3-D, there are a number of factors that determine the strength and level of balance of a disturbance. First, solar flux, which provides the energy input, varies as a function of latitude. At high latitudes, there is less energy available, and this generally tends to decrease the strength of the thermal circulation, all other things being equal. Acting in favor of increasing latitude is the increasing coriolis force (and shrinking

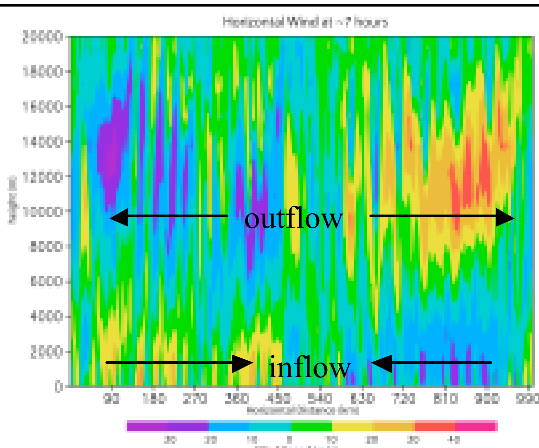

Figure 1. Direct thermal circulation resulting from initial dust perturbation with active dust lifting and radiatively active dust. Horizontal wind speed is shaded.

Rossby Radius of Deformation). A disturbance at the equator, no matter how strong, cannot develop into a balanced circulation. Once the heating is lost, the circulation will dissipate rapidly as convergent motions rush to fill the low pressure center. This situation is once again analogous to hurricanes: Energy input for hurricanes is at a maximum where sea surface temperatures are greatest (near the equator), but the systems are unable to develop due to the small coriolis force. High latitudes provide a favorable planetary vorticity background, but the sea surface temperatures are too low. Thus, hurricanes generally develop between 15-30 degrees latitude.

Fig. 4 shows the low level wind field from 3-D simulations after a full diurnal cycle at two different latitudes. Not shown is the equatorial simulation, which has no circulation. The 60° N case has a weak vortex; solar heating is not able to provide sufficient energy to drive a strong circulation. In comparison, the 30° N case has a very strong (>40 *m/s*) circulation and an equally impressive low pressure center (not shown).

The scale of the initial disturbance also determines whether a balanced circulation develops. Initial dis-

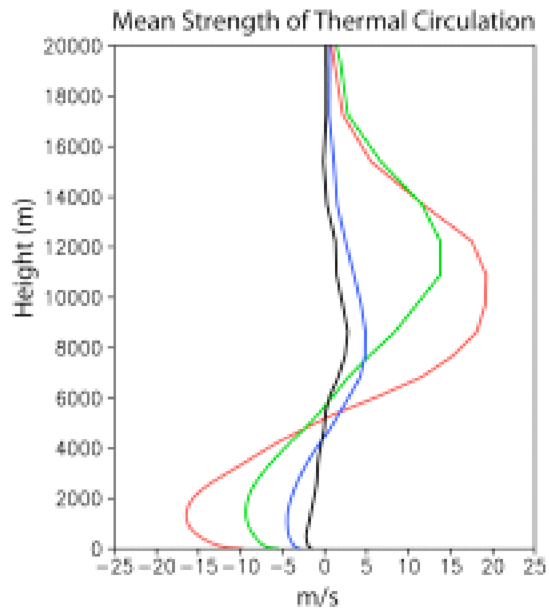

Figure 2. The impact of dust lifting parameters on the thermal circulation. The average horizontal wind over the right half of the modeling domain provides a measure of circulation strength. Negative wind speeds are inflow, positive values are outflow. The case with no dust lifting (black) has the weakest thermal circulation. The strongest circulation is for a low lifting threshold and modest efficiency factor (red). The canonical parameter values (blue) produce a circulation stronger than without dust lifting, while allowing dust to be very easily and efficiently lifted (green) produces a strong, but not the strongest, circulation.

turbances with a horizontal scale near or in excess of the Rossby Radius of Deformation more easily achieve balance. Thus, all other things being equal, initial disturbances at high latitudes are more likely to develop into persistent vortices. However, the reduction of solar flux at high latitudes will once again limit the source of energy for these disturbances. Likewise, although solar heating is a maximum at low latitudes, the Rossby Radius of Deformation becomes quite large, making it increasingly unlikely that an initial disturbance would be large enough to develop into a balanced circulation. Thus, there is an optimal latitude range for the radiative-dynamic dust feedback process—the subtropics.

A balanced and strong circulation is important, because it allows for the WISHE-like feedback process to take place. Further numerical experiments (not shown), demonstrate that the simulated vortices behave like a Carnot engine. When background temperature profiles are varied to control exhaust temperatures in the outflow of the circulation, the strength of the circulations as measured by kinetic energy and central pressure depression responds as expected with increasingly intense circulations as a function of input and output temperature difference. Also, there is a stong correlation between atmospheric dust loading and system strength.

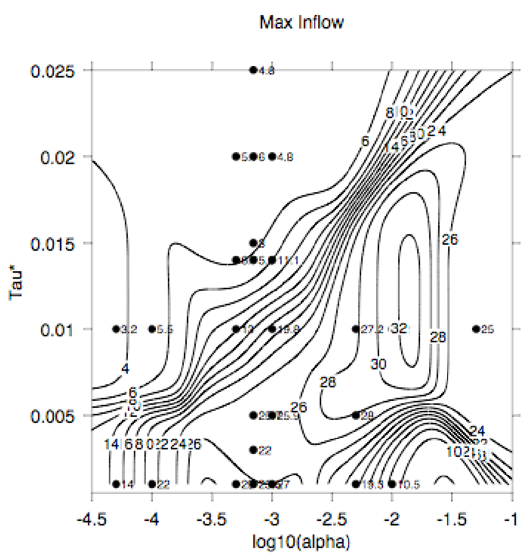

Figure 3. Feedback factor for 2-D simulations as a function of dust lifting parameter space. Maximum feedback occurs for modest lifting thresholds (Tau*) and modest to high efficiency factors (alpha). Very low lifting thresholds or very large efficiencies make the entire domain dusty and reduce the horizontal temperature gradient that drives the circulation. Inflows in excess of 30 times the nominal value are possible, although the dust lifting parameters required to achieve this level of feedback are not entirely realistic.

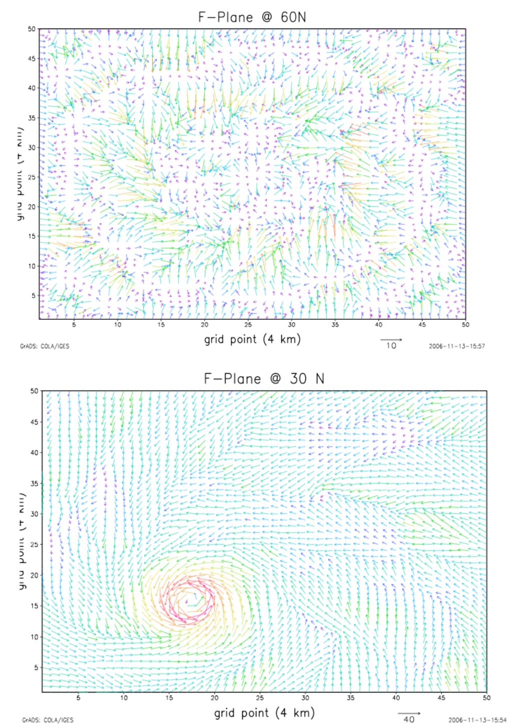

Figure 4. Circulations at different latitudes with latitudinal varying solar flux and otherwise equal conditions. The heating at 60N is reduced, and there is insufficient energy to maintain the circulation and lift dust after one sol. In contrast, the 30N circulation intensifies, producing winds in excess of 40 m/s and lifting and transporting large quantities of dust toward the center of the circulation.

On Mars, the true nature of dust disturbances and radiative-dynamic dust feedback is complicated by background atmospheric structure and non-zero initial wind fields. In particular, the background state almost certainly affects the feedback rate, just as the background wind shear is known to disrupt hurricanes. Further work is needed to investigate these more complicated effects. Regardless, the radiative effect of lifted dust appears to have a significant impact on the dynamics and energetics of the parent disturbance.

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