REFLECTIONS ON MARS GLOBAL CLIMATE MODELING FROM A MESOSCALE METEOROLOGIST.

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Introduction: Thinking "outside the box" occasionally produces alternative solutions to problems, or elucidates problems that would have not otherwise been identified. This paper highlights two areas in Mars Global Climate Modeling that may benefit from such a viewpoint, at least as viewed by this mesoscale meteorologist and modeler who is decidedly outside the general circulation modeling box (literally and figuratively). The opinion may be regarded as an editorial designed to foster discussion. The two areas of focus are: vertical transport of dust and volatiles, and the representation of dust lifting by the atmosphere. The ideas presented herein are in many cases developed from experiences as a terrestrial mesoscale modeler and as a classically trained Earth meteorologist.

Many of the GCM and mesoscale models of Mars' atmosphere have terrestrial dynamical cores. Furthermore, in some aspects, the Martian atmosphere responds to forcing in a manner similar—although with different amplitude—to that of Earth. With this in mind, it seems reasonable to revisit what we know to be important and unimportant for properly modeling the climate of Earth, and then ask whether or not such processes are properly included in Mars General Circulation Models (MGCMs).

Vertical Transport of Dust and Volatiles: Dust plays a critical role in the radiative forcing of Mars just as clouds (liquid water and water ice) and water vapor play an important role in the climate of Earth. Proper distributions of dust (Mars) and water (Earth) are absolutely necessary to obtain realistic climate simulations.

Deep convective transport. The distribution of water vapor on Earth is strongly controlled by the transport mechanisms that move air from the boundary layer tropics where specific humidity is large. Examination of the mean tropical circulation would lead to the incorrect assumption that the Hadley Cell circulation is the dominant process by which vapor is vertically transported and then advected poleward.

There exists a mid-troposphere minimum of moist static energy in the tropics (Ooyama 1969) that cannot be explained by advection of entropy and water vapor by the Hadley Cell. Indeed, it is in direct conflict with this notion, as such transport would produce monotonically decreasing moist static energy as a function of height. Additionally, a majority of the tropical troposphere is found to be subsiding rather than rising as might be suspected from the mean circulation.

The resolution to the paradox of the transport implied by the general circulation and the observed moist static energy profile is the existence of deep convective clouds. Although these clouds, or so-called hot towers (Palmén and Newton 1969, Riehl and Malkus 1958) occupy a small fraction of the total area within the tropics, they are primarily responsible for the vertical transport of water vapor. At GCM-like scales, these clouds are not resolvable, but provide an important non-local transport mechanism for water vapor. Furthermore, conservation of mass produces the broad subsidence that dries the mid-troposphere and generates the trade wind inversion. The upward mass flux within the clouds in combination with the compensating subsidence in the environment results in the net, slow ascent of the Hadley Cell. However, it is important to realize that the Hadley Cell is the average, large-scale view of the circulation and not necessarily representative of the circulations that result in the mean water vapor distribution. Stated yet another way, the mean water vapor field need not result completely or directly from the mean atmospheric circulation.

Terrestrial modelers recognized early on the importance of hot towers, and the development of parameterizations that represent these phenomena in increasingly realistic ways continues to the present. Of course, the recognition of the importance of deep convection was probably aided by the easily viewed tropical thunderstorms that leave little of their transport processes to the imagination.

Except in rare instances, the Mars meteorologist lacks the visual clues and certainly the observational data that permit the terrestrial meteorologist to easily recognize transport mechanisms. Occasionally, enough dust is entrained into Mars' atmosphere so as to make circulations visible. MOC images of the last global dust storm indicated deep convective circulations along the leading edge of the initial lifting near Hellas Basin. It is not clear whether these circulations triggered the event or whether they were passive and simply became visible due to the entrainment of dust. Clearly, they did transport dust vertically, probably in a manner similar to the way hot towers transport water vapor on Earth.

Based on our understanding of transport processes on Earth and on the limited observational data for Mars the following questions arise:

1) Does there exist a Mars equivalent to Earth's hot towers?
2) If hot towers do exist on Mars what is their relative contribution to the mean circulation and to the vertical transport of dust and volatiles?
3) How might the existence or absence of Martian hot towers be confirmed?
4) Should non-local vertical transport be parameterized in MGCMs and in what manner?

If in fact hot towers do exist and they are important, than they should be parameterized in MGCMs and perhaps mesoscale models. We can turn to the literature in the terrestrial community for guidance on these issues (*e.g.*, Rafkin 1996).

MGCM convective adjustment. One type of vertical transport is implicit in global and some mesoscale models: convective adjustment. The rationale for this purely artificial mixing of the boundary layer appears to be two-fold. First, the Earth's atmosphere is rarely observed to be statically unstable. Second, the numerics of the models have difficulty properly handling an atmosphere that is significantly unstable.

The stability regimes of the Earth's atmosphere are a consequence of the ability of convective motions (thermals) to remain in quasi-equilibrium with the sensible heat flux that is trying to destabilize the environment. This idea of quasi-equilibrium does not appear to be valid for Mars. The convective circulations on Mars are much too inefficient to remove the instabilities generated through low-level radiative heating (Michaels and Rafkin, 2002). Consequently, there is no physical basis for artificially imposing on the simulated Martian atmosphere the neutral lapse rates that result from convective adjustment.

The consequences of convective adjustment are numerous and not necessarily inconsequential. First, radiative forcing depends strongly on the temperature structure. Errors in the temperature profile will produce errors in radiative forcing, which can result in a nunwanted feedback process. Second, horizontal pressure gradients are generated from temperature gradients. Inaccurate temperature fields will indirectly induce errors in the wind field. These errors are amplified in regions of high topographic relief. Third, the predicted boundary layer will be too deep in models with convective adjustment, as the heat must be distributed over an unrealistically thick layer in order to produce a neutral lapse rate. Fourth, nonhydrostatic mesoscale models (Rafkin *et al.* 2001, Toigo and Richardson 2002) utilize MGCM fields as initial and boundary conditions. The mesoscale models must necessarily begin with inaccurate boundary layer profiles and are forced at the boundaries by unrealistic afternoon conditions.

If the numerical cores of the MGCMs are unable to handle statically unstable profiles than extreme care must be taken in interpreting the results, particularly in the boundary layer. For example, the reliability of surface winds and near surface afternoon temperatures should be considered at least somewhat suspect. If the numerical cores can handle superadiabatic lapse rates, than at the very least a soft convective adjustment should be imposed.

Any convective adjustment (soft or hard) should in principle also uniformly mix momentum and scalars. What than is the purpose of an explicit boundary layer turbulent parameterization? The use of both seems redundant at best and certainly it is physically inconsistent. We can use Large Eddy Simulations—those that explicitly resolve thermal convection—to better represent boundary layer mixing or improve soft convective adjustment parameterizations (Michaels and Rafkin, 2002).

Transport by thermal circulations. The existence of deep thermal circulations forced by topography is almost certain on Mars. Fig. 1 is a vertical crossection from a mesoscale model simulation of the circulation associated with the Tharsis volcano Arsia Mons (Rafkin *et al.* 2002). The simulation reveals locally intense updrafts capable of rapid and deep vertical transport similar to those that might be expected by Earth's hot towers. The mid-atmosphere minimum of dust predicted in the simulation is not unlike the mid-atmosphere water vapor minimum in Earth's tropical regions. Similar circulations have also been simulated at potential Mars Exploration Rover landing sites in Valles Marineris and Gusev Crater (not shown).

Given that Mars is dotted with numerous topographic features it seems reasonable to conclude that many if not most of these features are venting boundary layer in a manner similar to that of Arsia Mons. Some MGCMs do partially resolve the larger features such as the Tharsis volcanoes. However, partially resolving these features means that the amplitude of the topography and the resulting circulation will be reduced. While the model may reproduce elevated dust layers, they will be at the wrong altitude, and the circulation intensity will be underestimated.

The notion that topographic circulations help to maintain the global atmosphere dust budget or contribute in some significant way to the transport of water vapor and other volatiles should be explored in greater detail. Simple scaling of the Arsia Mons circulation shows that it is capable of producing a mass and dust flux thousands of (or perhaps tens of thousands) times greater than a dust devil of radius 1 km. The height of the transport is also a factor of five or more higher.

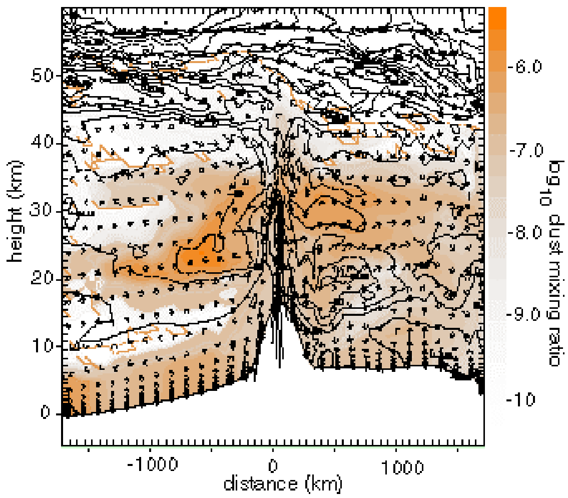

Figure 1: Vertical, east-west crossection through Arsia Mons as simulated by the Mars Regional Atmospheric Modeling System. The arrows show the wind vector in the plane of the crossection. Contours are isotachs of wind perpendicular to the plane of the crossection. Solid lines are into the page, dashed are out of the page. Shading indicates dust concentration as given by the scale to the right of the figure. The thermal circulation forced by the volcano extends to a height in excess of 35 km. Dust is transported from the boundary layer and detrained aloft to produce an elevated dust layer and a mid-atmosphere dust minimum. The entire circulation is an intense warm core vortex with tight cyclonic rotation near the core and weaker anticyclonic outflow aloft. Peak wind speeds within the circulation are in excess of 40 m/s, and updrafts near the core are ~10 m/s.

The representation of dust lifting. If numerical models could accurately transport dust, the issue of a representing the source of dust would remain as an important problem. Presently, dust lifting parameterizations are based on the predicted near surface wind speed or stress, and/or on the ability of dust to be injected by inferred dust devil simulations. The latter of these two methods is documented poorly if at all in the literature. The focus of this section will be on the former method.

A central issue surrounding dust lifting by the wind is whether or not the dust is lifted by the mean wind, and in particular the mean wind as defined by a model box, or by perturbations on that mean wind. For example, imagine a simple case of a perfectly symmetric mountain peak surrounded by perfectly flat plains. Furthermore, suppose that the large-scale pressure gradient was zero. A very large model grid box such as in an MGCM would not properly represent the atmospheric circulation in and around the peak. The mean wind would be zero (as it should be) in response to the zero pressure gradient field. No dust would be lifted in such a case. However, along the slopes of the mountain, the winds may very well be non-zero. In fact, the winds (and surface stress) can easily exceed dust lifting thresholds.

Given the topographic relief of Mars and the strong thermal circulations that accompany topographic features, neglect of dust lifting by the sub-grid or unresolved thermal circulations may be a grievous error. This is not to say that the large-scale wind may not also contribute to the lifting, but there are few if any observations or terrestrial analogues to support the idea that dust is lifted uniformly over regions hundreds of kilometers on side. Regional dust storms and the last global dust storm show that dust lifting is often associated with mesoscale boundaries or circulations. Thunderstorm downbursts and circulations near frontal boundaries usually generate dust storms on Earth.

As the grid spacing of a model decreases, a dust lifting parameterization based upon the model predicted wind speed or stress should be increasingly realistic. The scale at which this happens is open for debate. In the meantime, the necessity of a sub-grid scale dust lifting parameterization based upon sub-grid scale topographic relief or sub-grid scale turbulent kinetic energy should be considered.

Summary: The Martian climate is strongly dependent on the atmospheric dust distribution. The response of the climate to a uniformly dusty atmosphere or in an atmosphere with monotonically decreasing dust concentration is relatively well understood (at least to the extent that GCMs capture the essence of the circulations) as is the response of the atmosphere to increases in overall dust loading. It is unlikely, however, that the actual Martian atmosphere is uniformly dusty, or that dust concentration decreases monotonically with height. Unless a realistic distribution of dust is known or can be predicated, it is unlikely that GCMs will accurately capture the details of the general circulation. As an analogy, how accurate would Earth GCM models be without a reasonable prediction of water vapor and clouds?

Given the paucity of observations of the global dust distribution, prediction of the dust distribution is the only reasonable method to incorporate dust information into models. Doing so requires knowledge of the dust sources and transport methods. Furthermore, the sources and transport must either be explicitly resolved or parameterized.

Mesoscale simulations suggest that mass, dust, water and other volatiles can be transported from the boundary layer to heights in excess of 30 km in an hour or less by the thermal circulations associated with the largest topographic features on Mars. Smaller orography produces similar but smaller transport. The net large-scale vertical transport need not (and in fact, may not) be accomplished principally by the Hadley cell circulation. This is analogous to Earth where a large fraction of the mass flux in rising branch of the Hadley cell is actually found in tropical thunderstorms. An area of 100 km by 100 km (*e.g.*, Arsia Mons) rising at an average rate of 5 m/s produces a mass flux equivalent to an area 1000 km by 1000 km rising at 5 cm/s. It is easy to see from these back of the envelope calculations how the thermal circulations can account for a significant portion of the Hadley cell mass flux. Likewise, the vertical flux of dust and volatiles by such a circulation could easily exceed fluxes from dust devils, which have been forwarded as a possible mechanism for the maintenance for the global dust budget.

Unlike the Hadley cell or turbulent mixing (diffusion), the vertical transport of mass does not require significant mixing or dilution over the depth of the transport. Consequently, these circulations can produce local maxima of transported quantities at high altitude. Once aloft, large-scale horizontal transport can effectively distribute the mass, dust, or water. Again, this is similar to the transport of water vapor in the Hadley cell of Earth. This type of process cannot be properly modeled by gradient transport theory (turbulent diffusion), and generally cannot be properly modeled by General Circulation Models (GCMs) as they lack the spatial resolution, and typically produce a concentration that monotonically decreases with increasing distance from the source.

Changes in the refractive index for atmospheric waves associated with thermal and kinematic changes induced by smaller scale circulations may alter the general circulation. For example, the easterly winds in the outflow branch (Fig. 1) effectively enhance the depth of the upper level large-scale easterly winds. Westerly winds in the outflow located below the large-scale upper level easterly winds increase the wind shear. The outflow circulations are approximately a zonal wave number three or four disturbance. The circulations also induce a gravity-wave drag, and rapidly redistribute atmospheric momentum over large vertical scales.

Elevated layers of dust and clouds originating from the circulations will alter the radiative budget. This in turn will feedback to the dynamics. The dust would also serve as condensation nuclei for water-ice cloud particles, which provide an additional radiative feedback mechanism.

References:

Michaels, T. I., and S. C. R. Rafkin, 2002: Large Eddy Simulation of Atmospheric Convection on Mars. Submitted to *Quart. J. Royal. Met. Soc.*

Ooyama, K., 1969: Numerical Simulation of the Life Cycle of Tropical Cyclones. *J. Atmos. Sci.* **26,** 3-40.

Palmén E., and C. W. Newton, 1969: Atmospheric Circulation Systems: Their Structure and Physical Interpretation. *International Geophysical Series*, **13**, pp. 439-441, Academic Press.

Rafkin, S. C. R., M. R. Sta. Maria, and T. I. Michaels, 2002: The Atmospheric Thermal Circulation of a Martian Volcano as Simulated by a Mesoscale Model. To appear in *Nature.*

______, R. M. Haberle, and T. I. Michaels, 2001: The Mars Regional Atmospheric Modeling System: Model Description and Selected Simulations. *Icarus,* **151**, 228-256.

______, 1996: Development of a Cumulus Parameterization Suitable for Use in Mesoscale Through GCM-Scale Models. Ph.D. Dissertation. **No. 611**, *Department of Atmospheric Science, Colorado State University*, 126pp.

Riehl, H. and J. S. Malkus, 1958: On the heat balance in the equatorial trough zone. *Geophysica*, **6**, 503-537.

Toigo, A. and M. J. Richardson, 2002: A Mesoscale Model for the Martian Atmsophere. *J. Geophys. Res.,* **107(E7)**, 10.1029/2000JE001489, 2002.