Chapter 7 Reflections on Martian Mesoscale Meteorology from a Global Climate Modeler

7.1 Introduction

At the First International Workshop on Mars atmosphere modeling and observations (Granada, Spain, 13—15 January 2003), Scot Rafkin of the Southwest Research Institute presented what he called, "an editorial designed to foster discussion," which was entitled, "Reflections on Mars Global Climate Modeling from a Mesoscale Meteorologist" (hereafter RMGCM3). RMGCM3 describes Rafkin as a "mesoscale meteorologist and modeler who is decidedly outside the general circulation modeling box (literally and figuratively)…a terrestrial mesoscale modeler, and…a classically trained Earth meteorologist." In effect, RMGCM3 claims a unique perspective within the martian meteorological community and asks whether mesoscale processes important for the forcing of the general circulation of the Earth are important on Mars and therefore should be included in Mars global climate models.

In some sense, this thesis has replied indirectly to RMGCM3 by breaking the most uncertain (and often mesoscale process-driven) forcings of the martian general circulation into their component parts. So I will conclude the thesis with a more direct reply to RMGCM3. The title of this Chapter is an inversion of RMGCM3 on the grounds that my primary training is as a climate scientist, a planetary historian, and a martian meteorologist. My first paper as a senior author [*Heavens et al.*, 2008] described possible improvements to a martian global climate model and experiments with the model that determined the effects of these improvements. Thus, my training and experience points me toward Mars, the large-scale, and the long-term, just as Rafkin's experience (c. 2003) pointed him toward Earth, the mesoscale, and short-term.

The significant questions raised by RMGCM3 are not only relevant to the study of the martian atmosphere for purposes of weather prediction and comparative planetology. The mesoscale processes we see today also may have some effect on the formation of climate archives in the rock record and in the ice record, though this issue is not considered in RMGCM3. Chapter 7.3 will very briefly discuss the significance of mesoscale processes for interpreting the geological record of Mars.

7.2 A Review of Modern Mesoscale Phenomena

7.2.1 Hot Towers of Dust

RMGCM3 reviews current understanding of how the water vapor distribution in Earth's tropics arises, emphasizing the significance of the tropical minimum in the moist static energy (E_{moist}) in the middle troposphere:

$$E_{moist} = c_p T + gz + L_v q \tag{7.1}$$

where c_p is the isobaric heat capacity, T is the temperature, g is the acceleration due to gravity, z is the altitude above the surface, and L_v is the latent heat of vaporization/sublimation, and q is the water vapor mass mixing ratio. The significance of the moist static energy lies in its conservation under moist processes. If water is lost through condensation, the energy “loss” is compensated through latent heat release. The parcel either warms or gains gravitational potential energy. A minimum in moist static energy above the surface thus implies that the vertical distribution of water vapor (in an energetic rather than a physical sense) is not controlled by vertical eddy diffusion due to the overturning of Earth’s Hadley cells, which would produce a moist static energy distribution that decays with height. In other words, the abundance of water vapor should decrease with distance from its source. Instead, numerically rare and areally insignificant deep convective cells preferentially transport water vapor into the upper troposphere. RMGCM3 then asks if such hot towers occur on Mars in the form of dust clouds and if they are significant for the transport of dust and volatiles.

These two questions can be answered hesitantly in the affirmative. The dust distribution of the martian atmosphere during much of northern spring and summer has a local maximum in mass mixing ratio high above the surface (at least on the nightside) (Chapters 4 and 5). Assuming conservation of dust, the tropical dust distribution of Mars around northern summer solstice is analogous to the moist static energy distribution of Earth’s tropics and raises the same theoretical problem. The pseudo-moist dust convection described in Chapter 5 is a solution very similar to the idea of “hot towers,” but Chapter 5 admits that this distribution also can be explained by invoking processes, such as scavenging by water ice particles, that violate the assumption of conservation of dust and act on timescales faster than the large-scale vertical eddy diffusion timescale of the martian tropics.

In another instance described in Chapter 5, evidence was presented of a highly enriched layer of dust that likely originated from a regional dust storm near the southern tropic and then was advected across the equator against the likely direction of the cross-equatorial transport due to the PMOC at that season. This layer of dust likely carried water vapor concentrations typical of the surface during its ascent and thereby supported an unusually dense (five times the zonal average density-scaled opacity, see Figure 6.3c) water ice cloud at high altitude. Both the cause and effects of this top-heavy dust distribution have broad implications for radiative balance, dynamics, and atmospheric chemistry.

Enriched layers of dust above the surface are not restricted to northern spring and summer. They can occur during global dust storm activity as well. *Clancy et al.* [2009] report detection of such a layer at ~40 km above the surface in limb retrievals from the Thermal Emission Spectrometer (TES) on Mars Global Surveyor (MGS) during the 2001 dust storm. *Clancy et al.* [2009] also detect an enriched layer of scattering particles at 70-80 km, which they interpret as water ice. The enriched dust layer at 40 km is a clear contradiction to standard dynamical understanding. The heating of the atmosphere by the absorption of solar radiation by dust is thought to enhance the PMOC overturning, so dust storms would be expected to have uniformly mixed dust distributions. In addition, sedimentation is faster at lower densities than higher densities (Chapter 5), so a uniform dust distribution or a bottom-heavy dust distribution would be expected. *Newman et al.*

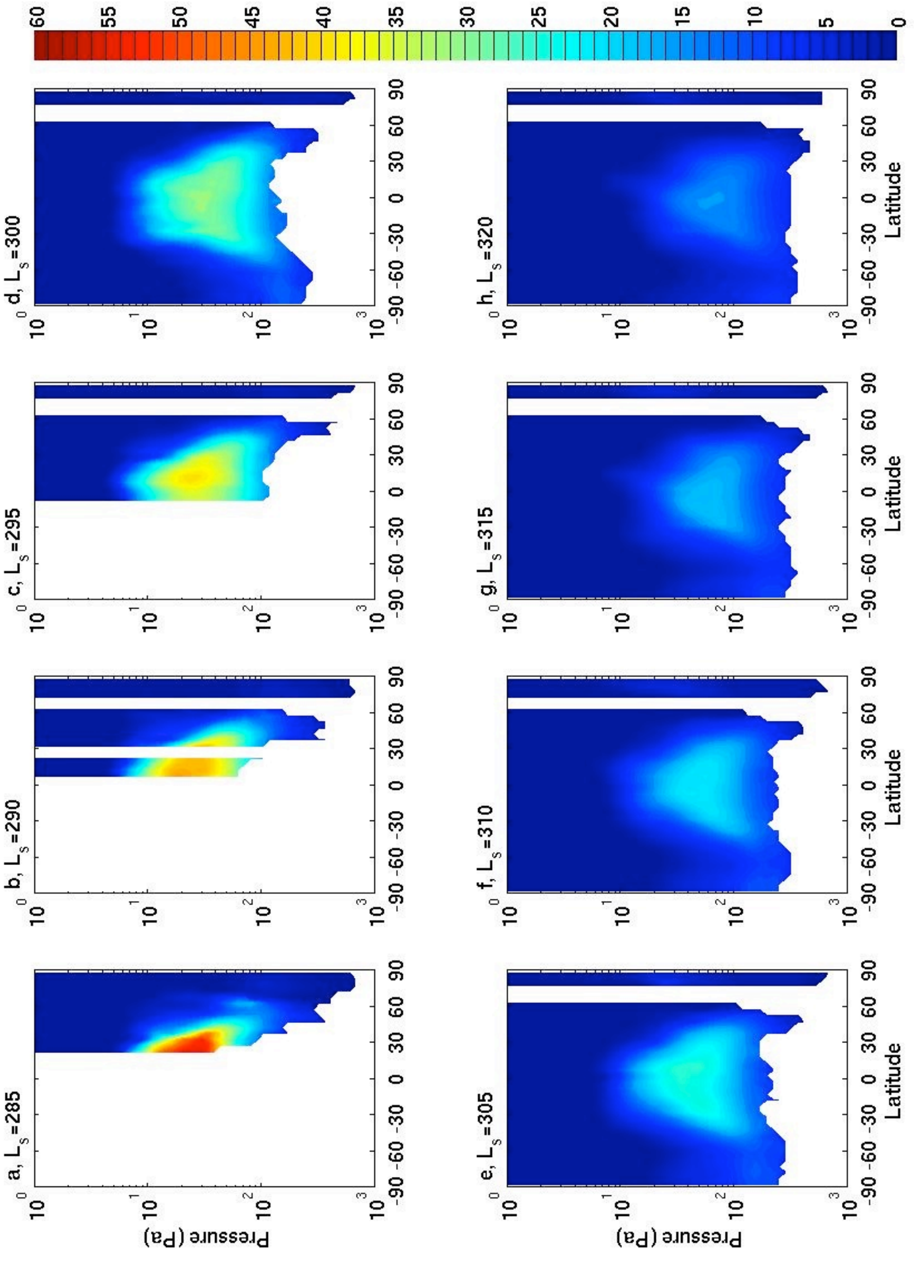

Figure 7.1: Estimated zonal average dust mass mixing ratio, nightside, MY 28, as labeled on the top of each panel.

[2002] and *Kahre et al.* [2008] have simulated enriched layers during large-scale dust storm activity, but *Clancy et al.* [2009] determined that the behavior they observed was "more extreme" than the simulations of *Kahre et al.* [2008].

Figures 7.1a-h show the zonal average dust mass mixing ratio (calculated as in Chapter 4) from MCS retrievals during the waning phases of the 2007 global dust storm (The nightside averages are shown, but the dayside averages are similar.) As retrieval coverage improves, a broad and enriched layer emerges and gradually decays over the course of 35° of L_s. While the observational biases described in Chapters 2 and 4 may have some quantitative effects on the zonal averages, the detection of an enriched layer by *Clancy et al.* [2009] similar to that implied by Figure 7.1b provides further confidence in this result. Thus, during the 2007 global dust storm, we infer that a zonal average layer of dust mass mixing ratio of >50 ppm was present over the martian tropics at a pressure level of ~30 Pa (or less).

While the observed dust distribution in the wake of the 2007 global dust storm looks extreme from the perspective of more modern models such as *Kahre et al.* [2008], it is consistent with the older three-dimensional model of the 1977b global dust storm by *Haberle et al.* [1982] and a simulation by *Newman et al.* [2002] of a synthetic dust storm near Hellas. *Haberle et al.* [1982] ran three experiments that evolved the dust distribution from a storm center in the southern mid-latitudes under three different sets of conditions: (1) dust was treated as a radiatively inert tracer; (2) dust was treated as radiatively active but a simple convective adjustment scheme was not applied; (3) dust was treated as radiatively active but a simple convective adjustment scheme was applied. In the case of

(1), the simulated dust distribution was confined very near to the surface in the southern hemisphere. In the cases of (2) and (3), the simulated dust distribution was relatively uniformly mixed over the southern tropics and mid-latitudes, while a highly enriched layer was present at ~25 km above the surface over the northern tropics. In the simulation of *Newman et al.* [2002], enriched layers of dust occur at 40 km above the surface.

Since water ice clouds near the surface of the tropics are likely as rare during global dust storms as they are during northern winter generally (Chapter 2), the enriched layers of dust at high altitude observed during global dust storms most likely arise from pseudo-moist dust convection on a horizontal scale that may be somewhat greater than during northern summer. Such convective plumes may be partly resolved by the simulations of *Haberle et al.* [1982] and *Newman et al.* [2002]. If the observed enriched layer were supplied by pseudo-moist dust convection, the implied fractional area occupied by the plumes would be around two to three orders of magnitude greater than the high altitude tropical dust maximum (HATDM) (see Chapter 5), that is, between 0.1 and 1%, which is a reasonable estimate for the fractional area of active saltation in a terrestrial dust storm [*Park and In*, 2003]. In addition (as noted in RMGCM3), dust plumes with morphologies that resemble terrestrial cumuli have been observed in visible imagery at the beginning of the 2001 dust storm [*Strausberg et al.*, 2005]. Thus, both the morphologies of dust clouds and the vertical dust distribution during global dust storms suggest that pseudo-moist dust convection occurs during seasons other than northern spring and summer. Thus, the “hot towers” of dust proposed by RMGCM3 seem to be a genuine atmospheric feature.

7.2.2 Mind the Water Ice!

The discussion of the vertical transport of dust in RMGCM3 begins by drawing an analogy between the role of water in Earth’s atmosphere and the role of dust in Mars’s atmosphere, which was discussed in far greater detail in Chapter 5. The importance of dust in Mars’s atmosphere and the very limited latent heating effect of water should not encourage neglect of the significant infrared heating due to water ice clouds (discussed in Chapter 6) and potential coupling between the dust and water cycles (discussed in Chapter 5). The martian atmosphere is a thin atmosphere. Radiative heating terms due to aerosol of any kind are comparable to latent heating in Earth’s atmosphere.

7.2.3 Cold Towers of Carbon Dioxide Ice?

Carbon dioxide ice mostly has been mentioned in this thesis as a hindrance, either because of its association with high hazes (equatorial mesospheric clouds) in Chapter 3 or because of its tendency to be retrieved as dust in MCS retrievals (Chapter 4). Carbon dioxide moist convection at the winter pole also was identified as potential source of gravity waves in Chapter 3. The possible importance of carbon dioxide clouds at the winter pole for polar energy balance and the large-scale circulation is definite excuse for investigation of the mesoscale dynamics of these clouds. Promising work on this subject is ongoing at UCLA (P. Hayne and D.A. Paige, Snow Clouds and the Carbon Dioxide Cycle on Mars, paper presented at the American Geophysical Union Fall Meeting, San Francisco, CA, 14—18 December 2009).

Also of interest is the importance of carbon dioxide moist convection at high altitudes above the tropics (or possibly elsewhere), especially during global dust storms. *Leovy et al.* [1973] reports that there was a carbon dioxide cloud at about 70 km above the surface during the 1971 global dust storm, which *Leovy et al.* [1973] attributes to condensation of adiabatically cooled air over the strongly heated dust clouds of the storm. *Clancy et al.* [2009] observed some sort of scattering haze at 70 km during the 2001 dust storm, which *Clancy et al.* [2009] identifies as water ice. If such high hazes are widespread enough during global dust storms, they may be important for the thermodynamic control of dust storms (outlined in Chapter 3), since they broadly re-emit in the infrared at very cold temperatures and lower the effective emission temperature of the planet.

7.2.4 Gravity Waves

Gravity waves are almost an aside in RMGCM3, but they are a common occurrence in mesoscale simulations [*Rafkin et al.*, 2002; *Rafkin*, 2009; *Spiga and Forget*, 2009]. In all of these cases, the gravity wave source is non-orographic. While the analysis in Chapter 3 cannot make any definite attributions of the source of the middle atmospheric local convective instabilities, a role for convective processes and higher wavenumber baroclinic disturbances remains likely, since: gravity wave energy above the tropics does not correlate with current simulations of wind stress [*Creasey et al.*, 2006], the strongest evidence for gravity wave drag in the extratropics is in Mars's flatter hemisphere (Chapter 3); and local convective instabilities in the middle atmosphere were detected in the tropics just before the 2007 dust storm (see Figure 3.10a). Yet specifically non-orographic gravity waves are not parameterized in present Mars GCMs.

7.2.5 Summary

The portrait that RMGCM3 painted of the martian atmosphere in 2003 was indeed prescient. Their temperature and pressure ranges of Earth's and Mars's atmospheres may differ. Solids and fluids may be present in them in differing proportions. But both of these atmospheres experience a variety of mesoscale and turbulent phenomena that are difficult to simulate in large-scale models of the general circulation but whose accurate representation may be critical to the predictive success of those models. Mars in fact seems to have at least five significant and genetically distinct forms of atmospheric convection: (1) dry convection in the planetary boundary layer; (2) dry convection in the middle atmosphere (Chapter 3); (3) pseudo-moist dust convection (Chapter 5); (4) carbon dioxide moist convection in polar night; and (5) high altitude carbon dioxide moist convection. Only the first type of convection is generally simulated in GCMs, though the effects of the second type are sometimes included by means of a gravity wave drag parameterization.

Like RMGCM3, I look forward to the continued progress of martian mesoscale models as a means to develop routines for upscaling mesoscale phenomena into the GCMs. It will be important, however, for these models be carefully validated against the important observational record provided by Mars Climate Sounder and by other means described throughout this thesis, adapting techniques and approaches used in studies of Earth's atmosphere whenever possible and appropriate (as in Chapter 3 and Chapter 5.4.3).

7.3 Historical and Geological Significance

From the perspective of a planetary historian, the minutiae of processes that occur on timescales of minutes to days and on smaller than global scales seem intuitively irrelevant; at least in comparison with the grand orbital variations of Mars on timescales of thousands to millions of years that are hypothesized to drive cyclical deposition of ice and dust during the Amazonian era [e.g., *Milkovich and Head*, 2005; *Lewis et al.*, 2008]. This intuition is fundamentally wrong.

Mesoscale processes likely affect the most classic case of dust deposition on a polar cap. During some dust storms, the north polar vortex, which partially isolates the polar cap from the rest of the atmosphere, breaks apart. The disruption of the polar vortex is signified by considerable warming in temperatures at a pressure of 10-100 Pa above the pole (see discussion in Chapters 2 and 3). There is evidence for north polar vortex disruption during the 2007 global dust storm (D.M. Kass et al., MCS Views of the 2007 Global Dust Storm, paper presented at the 39th Meeting of the Division for Planetary Sciences of the American Astronomical Society, Orlando, FL, 7—12 October 2007), though Figures 7.1a-h show that the north pole still remained much clearer throughout much of the storm than lower latitudes, consistent with past simulations [*Haberle et al.*, 1982; *Barnes*, 1990]. It has been proposed that polar vortex breakdown allows greater mixing with dusty air at lower latitudes and high rates of dust deposition on the polar cap through water ice scavenging during a time in which CO_2 ice and water ice are being deposited [*Barnes*, 1990 and references therein]. Since dust and water vapor transport from the southern hemisphere may be controlled in part by the intensity of pseudo-moist dust convection and polar vortex breakdown may require significant tidal and/or gravity wave drag [*Wilson*, 1997; *Kuroda et al.*, 2009] but may not necessarily require a global dust storm [*Wang*, 2007], even this relatively simple case of polar dust deposition will be significantly affected by the poorly understood processes discussed in Chapter 7.2 or discussed in greater detail in the previous Chapters. Therefore, it will be important for future models to represent these processes with as generalized physics as possible in order to understand changes in the frequency of polar vortex breakdown or the intensity of pseudo-moist dust convection in different climate regimes.

Analogy with the dust cycle of the Earth confirms that the details of the meteorological dynamics of dust transport in different climate regimes are important for understanding the extant records of dust deposition. Dust concentrations in high-latitude ice cores on the Earth are 2-200 times greater during glacial periods than in interglacial periods such as the Holocene [*Mahowald et al.*, 1999 and references therein]. The best global modeling now can reproduce dust deposition rates consistent with these ice cores [*Mahowald et al.*, 2006], but the simulations suggest that the global increase in dust loading in the atmosphere only increases by a factor of 2.5 during glacials relative to interglacials, which is consistent with rates of dust deposition in tropical dust deposits [*Winckler et al.*, 2008]. The variability in ice core dust concentrations that exceeds this factor is mainly the combined effect of lower rates of snowfall at the high latitudes during glacials; enhanced transport of dust toward the poles due to a more vigorous atmospheric circulation during glacials; and the activation of additional dust source regions during glacials [*Mahowald et al.*, 2006; *Winckler et al.*, 2008]. In addition, there is sub-millennial variability in dust grain size among different ice cores in East Antarctica, which can be interpreted as resulting from sub-millennial variability in subsidence over ice core sites during times of high dust loading [*Delmonte et al.*, 2004]. Thus, the dust concentrations in high-latitude ice cores are controlled by climate variability on both the global and the local scales.

On Mars, the extreme cost of “coring” deposits at the north and south poles likely will limit the number of ice core records from Mars in the next couple of generations to one or two (hopefully one from each pole). This sampling density will preclude the perspective that multiple ice cores can provide about the role of local variability in dust deposition. So atmospheric modeling will be as necessary to provide perspective on the sampling site as it will be to provide perspective on changes in polar dust deposition under variations in incident solar radiation and/or atmospheric density.

7.4 Conclusion

The most appropriate summary of this thesis would be a series of global climate model experiments that demonstrate that a proper representation of the forcings of the general circulation at least reproduced the observed thermal structure. While I hope to perform such experiments in the future, there is still considerable uncertainty about important elements of such experiments (e.g., the dayside aerosol distribution in the tropics during much of northern spring and summer), even if they were to use prescribed distributions of aerosol and gravity wave drag rather than more generalized physics. Instead, I have taken a new look at the broad significance of mesoscale processes for martian weather and climate.

The way forward in martian atmospheric science does not lie in better dynamical cores or new physics packages cribbed from Earth. It lies in realizing that the atmospheric dynamics of Mars is no less complex than the atmospheric dynamics of Earth, it is just different. It lies in being cognizant of those differences when determining the means of injecting dust into the boundary layer and beyond, the sources of gravity waves, and the dynamics of volatile clouds from the surface to the middle atmosphere. It lies in focusing on the little, the brief, and the shallow to understand the big, the long, and the deep.

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