Chapter 1 Introduction

The modern martian atmosphere interests the scientific community and human society in general for three fundamental reasons.

First, the environmental conditions of Mars's past are thought to have been more conducive to biological life. The current martian atmosphere is thus one outcome of the evolution of the planet from being potentially habitable, with widespread liquid water on the surface, to the cold global desert it is today. Following aktualism, the principle that the processes that occur in the present environment occurred in the past, investigations of processes in the current atmosphere can be used to develop models of the weather and climate of the Martian past that can be further constrained by evidence from the geological archives of rock and ice currently extant on the planet.

For example, Mars experiences weather systems on scales from the meter to the planetary that lift, transport, and deposit dust. Investigations of the planet's surface geology have found cyclical deposits of dust, potentially formed by variations in dust deposition on Milankovitch timescales [*Lewis et al.*, 2008]. It is impossible to observe the millions of individual events that formed these deposits. Yet if the dynamics of dust transport on the planet today are sufficiently well understood to model under different orbital parameters/atmospheric pressure etc., it may be possible to infer the formation conditions of these deposits.

In some cases, phenomena in the modern atmosphere may be relevant to the ancient atmosphere but have only indirect geological evidence to constrain them. For instance, carbon dioxide clouds sometimes form at altitudes of 50—90 km above the tropics [e.g., *Clancy et al.*, 2007]. These clouds strongly reflect infrared radiation and so produce a modest greenhouse effect [*Forget and Pierrehumbert*, 1997]. If the carbon dioxide partial pressure (pCO_2) of Mars was higher in the past, these clouds may have formed lower in the atmosphere and been thicker, which may have enhanced their greenhouse effect and contributed to the warming of surface temperatures above the freezing point of water. Yet if the processes by which these clouds form in the modern system are insufficiently understood (such as the extent and efficiency with which they are nucleated by surface dust from below or meteoritic dust from above), simulations of their role in the climate of the past may be erroneous, especially since these clouds likely leave no trace in the geological record.

Second, the modern Martian atmosphere can be compared with the atmospheres of the Earth and other planetary bodies. Comparisons between the Earth and Mars generally focus on phenomena more extreme on Mars than on the Earth (such as dust storms and the thermal tides) and generally apply data, models, and assumptions developed for the Earth to Mars. Occasionally, insight gained from study of the Martian atmosphere directly informs studies of the Earth's atmosphere. While developing the LMD Mars general circulation model (GCM), *Forget et al.* [1999] determined that longwave scattering by dust aerosols could not be neglected in the radiative transfer for Mars, though most radiative transfer schemes in Earth GCMs did neglect this term. *Forget et al.* [1999] consulted Yves Fouquart about this issue. Soon *Dufresne et al.* [2002] (including Fouquart) found that longwave scattering by dust was significant in dry, dusty areas of the Earth in the "atmospheric window region" between 9 and 13 μm.

Third, the modern Martian atmosphere needs to be monitored and studied to support current robotic exploration and as a prerequisite for weather forecasting and climate modeling to support future exploration and habitation. Current methods of delivering spacecraft to the surface of Mars are affected by the density, wind, and particulate density profiles along the path of entry [*Braun and Manning*, 2007]. Once on the surface, the planet's weather creates hazards for surface operations, such as low visibility and impairment of the solar power supply. Investigations of the atmosphere from orbit also can be affected by variations in visibility and atmospheric density. And for future proposed missions that may be time sensitive and dependent on multiple spacecraft safely landing, such as the return of samples from the planet or human expeditions, the hazards of the weather for Martian exploration only will increase [*Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars, National Research Council*, 2002].

In the more distant future, Mars weather forecasting and climate modeling will be a necessary component of any efforts to use Mars as a base to process materials mined from the asteroids or supply asteroid mines with food and other necessities. A recent documentary on the National Geographic Channel [*Davis*, 2009] speculated that terraforming Mars through re-engineering of its volatile reservoirs and atmosphere may be a viable plan that human society will have to consider by the end of this century. This process would be analogous to the anthropogenic modification of the climate system currently taking place on the Earth (if more extreme) and would require monitoring and modeling of the martian climate system on the same scale as the Earth's climate system is modeled at present.

And while these last possible directions for martian atmospheric science seem to belong to science fiction and the unknowable future, they do seem to stimulate the imagination of wider society. The author recalls taking a cab to Richmond Airport and mentioning to the cab driver that the author just had attended a conference on the martian atmosphere. The cab driver replied, "Oh, you're planning for when we move there." Mars may be one of the next planets human beings call home, so it is worth remembering that future martian atmospheric science may be relevant to society on the basis of the contention of *Bates* [1949] that, "[Weather is] a factor that is surpassed only among sex and hunger among the stimuli to the human race."

All three of these purposes motivate understanding of the martian atmosphere and related aspects of the climate system. All three purposes require qualitative and preferably quantitative models of the atmosphere and climate that will be a summation of that understanding and in some cases directly economically useful for human society. And for all three purposes, a variety of analytical and numerical models exist and likely will be developed in the future. The most sophisticated of these are the general circulation/global climate models (GCMs), which simulate the three-dimensional structure of planetary atmospheric circulation using appropriate simplifications of the equations of fluid dynamics [e.g., *Haberle et al.*, 1993; *Wilson and Hamilton*, 1996; *Forget et al.*, 1999; *Takahashi et al.*, 2003; *Moudden and McConnell*, 2005; *Hartogh et al.*, 2005; *Kuroda et al.*, 2005; *Richardson et al.*, 2007].

While the results of these simulations have some sensitivity to the dynamical core used (the dynamical core transports heat, momentum, and tracer species such as dust within the computational space of the model), the largest uncertainties in simulations arise from the routines broadly called, “the physics.” These routines represent processes that may not involve fluid dynamics, such as radiative transfer, or processes that occur on scales much finer than the computational grid, such as boundary layer convection.

The latter type of process falls into the broad category of the mesoscale and so is often simulated in more finely gridded mesoscale models. More rigorously, *Glickman* [2000] defines “mesoscale” as

> Pertaining to atmospheric phenomena having horizontal scales ranging from a few to several hundred kilometers, including thunderstorms, squall lines, fronts, precipitation bands in tropical and extratropical cyclones, and topographically generated weather systems such as mountain waves and sea and land breezes.
>
> From a dynamical perspective, this term pertains to processes with timescales ranging from the inverse of the Brunt–Väisälä frequency to a pendulum day, encompassing deep moist convection and the full spectrum of inertio-gravity waves but stopping short of synoptic-scale phenomena, which have Rossby numbers less than 1.

The physics routines of a model can be highly parameterized, that is, they can be empirically tuned and gross approximations to the very complex physics of the process. In the case of Mars models, some of these parameterizations may be inherited from Earth models, so their empirical tuning may be inappropriate for Mars. Moreover, martian atmospheric models usually do not have the computational resources or staff support of their Earth cousins, which are used for the societally important functions of weather and climate prediction. Thus, in many cases, some physical processes are not represented by the model physics for the sake of efficiency or because the modeler deems them unimportant.

Therefore, the current range of Mars models uses a broad diversity of physics routines. For instance, dust suspended in the atmosphere is an important contributor to the radiative budget of the atmosphere. Some models represent it as a radiatively active but spatially prescribed absorber [e.g., *Forget et al.*, 1999], while other models explicitly represent its lifting, transport, and interactions with radiation [e.g., *Newman et al.*, 2002; *Kahre et al.*, 2006]. These differences usually arise from the particular interests of the investigation. *Montmessin et al.* [2004] studies water ice clouds and therefore uses a spatial prescription for dust but actively simulates water ice clouds, while *Kahre et al.* [2006] focuses on dust transport and so neglects water ice clouds altogether.

Yet terrestrial atmospheric models have an even greater diversity of dynamical cores and physics. The approach to this diversity is typically pragmatic: weather forecasters use the models that have worked well in a similar weather situation in the past or make an ensemble forecast based on the entire suite of available models. Climate forecasters/policymakers tend to follow similar procedures. Fundamentally, models are evaluated based on how well they match observations.

Observations of Mars over the last decade, however, show that the climatology of the planet's thermal structure is not simulated well by the full ensemble of Mars GCMs. For example, observations by *McCleese et al.* [2008] suggested that Mars GCMs mainly underestimate the temperature and proximity to the south pole of a temperature inversion at ~50 km above the surface during southern winter. The typical response of modelers to these kinds of discrepancies between observations and models is to tune some aspect of the model currently unconstrained by observations to match the observed thermal structure.

At present, at least three research groups are developing the capability to adjust their models to match observations in a more rigorous way, that is, by data assimilation [*Lewis et al.*, 2007] (Lawson et al., Assimilating TES radiances with the DART/Planet-WRF ensemble data assimilation system, paper presented at 1st Symposium on Planetary Atmospheres, American Meteorological Society, Atlanta, GA, 17—21 January 2010; Kalnay et al., Assimilation of TES data into a Mars general circulation model using LETKF, paper presented at 1st Symposium on Planetary Atmospheres, American Meteorological Society, Atlanta, GA, 17—21 January 2010). In data assimilation (called re-analysis in some contexts), different realizations of a model can be used to generate a model state that is consistent with observations within some uncertainties that are often explicitly provided by the data assimilation scheme. Data assimilation is an exciting and promising new avenue to understand complex and difficult to observe meteorological systems on Mars, such as the global dust storms that occasionally envelop most of the planet in a thick dust haze. It also is a way of initializing a Mars atmospheric model for purposes of numerical weather prediction. Data assimilation, however, faces some important challenges.

In some cases, a data assimilation scheme may only use temperature profiles [e.g., *Lewis et al.*, 2007]. The thermal structure, however, is a somewhat degenerate function of various atmospheric processes. For instance, at night, similar amounts of dust and water ice at the same level of the atmosphere will generate similar infrared heating to warm the atmosphere. Depending on the assimilation scheme and the physics routines of the model, this kind of degeneracy may result in a dust haze being simulated in cases in which a water ice cloud is present in the real system.

In other cases, a data assimilation scheme may assimilate observations such as the measured limb radiances that are less degenerate, but the model used may lack physics routines that simulate an important process, such as the drag of breaking gravity waves on the westerly jets (e.g., Lawson et al., 2010, *sup.*). In such cases, the model states produced by the data assimilation scheme may have such large uncertainties that they are useless for atmospheric studies or weather prediction, though the location of these uncertainties in the atmosphere may be in part diagnostic of missing processes.

Thus, the risk data assimilation poses for martian atmospheric science is very similar to the risk that the desire for originality presents for poetry (see epigraph on p. iii). In an attempt to complement an incomplete observational record, modelers may simulate the meteorological equivalent of “A dolphin burrowing in the woods/Or a playful boar in the rolling waves.”

The logical remedy to this problem is to observe the forcing of the atmospheric circulation concurrently with variables indicative of the circulation such as the thermal structure, winds, or surface pressure. The analysis of the forcing in particular can be used both as a validation of the results of data assimilation schemes that use degenerate input and also as a basis for improving the physics routines of atmospheric models.

The chief forcings of interest in the martian atmosphere are some of the most uncertain forcings in the Earth’s climate system, particularly because the processes involved usually are not explicitly resolved on the scale of a GCM and must be parameterized. In the lower atmosphere, suspended dust and water ice clouds are strongly seasonally and spatially variable. Due to the tenuousness of the atmosphere, these aerosols can produce significant radiative heating in relatively small amounts. In the middle atmosphere, vertically propagating gravity waves and tides can grow to unstable amplitudes, depositing significant energy and momentum as they dissipate. While aerosol and gravity/wave tidal forcings are important at different latitudes and levels of the atmosphere, they are often controlled by similar kinds of mesoscale processes, such as the interaction of the wind with topography or convection that penetrates into highly stable atmospheric layers.

Moreover, these forcings are not just significant for atmospheric dynamics *qua* atmospheric dynamics but may be important for processes of interest to the two upcoming missions to Mars, Mars Atmosphere and Volatile Evolution (MAVEN) and the 2016 ExoMars Trace Gas Orbiter (TGO), that focus on the chemistry of the upper and lower atmospheres. Gravity waves and tides not only affect the circulation through the momentum they transport from the lower atmosphere to the middle and upper atmospheres, but their saturation also enhances the vertical diffusivity and thus the vertical exchange between the lower and upper atmospheres. Dust may affect the chemistry of the lower atmosphere through heterogeneous processes, in which adsorption of chemical species on a dust particle catalyzes a variety of reactions that may be slower or even non-existent in the gas phase [e.g., *Anbar et al.*, 1993; *Usher et al.*, 2003].

This thesis develops many of the necessary observational constraints for future modeling of the circulation of the martian lower and middle atmospheres and its forcings, using simultaneous retrievals of temperature, pressure, and dust and water ice opacity from measurements of limb radiance by the Mars Climate Sounder (MCS) on Mars Reconnaissance Orbiter (MRO): a dataset with unprecedented capability for middle atmospheric sounding and vertical aerosol profiling in the martian atmosphere. In

Chapter 2, I provide a broad overview of the annual cycle of the thermal structure and aerosol distribution of the lower and middle atmospheres and infer some aspects of the mean meridional circulation. In Chapter 3, I detect and map local convective instabilities in the middle atmosphere to infer the drag in the middle atmosphere due to the saturation of gravity waves and the thermal tides. In Chapter 4, I use MCS profiles of temperature, pressure, and dust opacity to reconstruct the zonal average vertical distribution of dust and its seasonal evolution during northern spring and summer. One particular feature of the vertical dust distribution is quite unexpected from previous theory and modeling work, so the purpose of Chapter 5 is to consider what processes may be responsible for this unexpected feature and to isolate potential observational signatures of these processes. In Chapter 6, I show that the distribution of water ice clouds in the tropics during northern summer is inconsistent with published models. In Chapter 7, I summarize the results of this thesis by describing the variety of mesoscale processes identified in these studies and briefly consider the general importance of mesoscale processes for studying climate variability on Mars.

Chapters 2-6 either are published papers or papers currently in preparation for publication as part of my work for the MCS Science Team. Therefore, they often contain repetitive methodological material tailored to the particular study. In addition, the material in these Chapters will refer to more advanced versions of or more detailed information about the retrieval algorithm than currently described in the peer-reviewed literature. This material represents contributions by members of the MCS Science Team, particularly Armin Kleinböhl and Wedad Abdou. In all cases, the vast majority of the analysis beyond the retrieval product, the interpretation, and the writing are my own.

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