Introduction: Dynamics of the Martian Middle Atmosphere

The middle atmosphere of Mars moderates the vertical transport of species lost to space, and is the region of the atmosphere used by spacecraft to aerobrake into mapping orbit. As a result, study of the middle atmosphere (defined in this proposal to be the region between ~80 and 180km) is central both to the theoretical problem of how Martian volatile inventories and climate have evolved, and to the very practical problem of "charting" how the density of the atmosphere changes spatially and temporally for use by future spacecraft missions. While we do not intent to pursue modeling of the full atmospheric loss problem within the scope of this proposal (this would require addition of detailed, in-line photochemistry and loss processes), the effort proposed here is an essential foundation for using full 3D models to attack this problem in the future.

Spacecraft have been using the middle atmosphere to aerobrake since the Mars Global Surveyor (MGS) mission – indeed, surprising variations in density combined with a damaged solar panel joint led to a pause of aerobraking for that mission [Albee, 2000]. In 2002, the Mars Odyssey (MO) orbiter entered mapping orbit with the assistance of aerobraking, and the same is planned for the Mars Reconnaissance Orbiter (MRO), launched in the summer of 2005 (Figure 1). Ironically, although information on the middle atmosphere is needed to make aerobraking safer, it is spacecraft aerobraking activities that provide the best available observations of the middle atmospheric density structure: as they pass through the atmosphere to altitudes as low as 95 km (Figure 1), the measurement of spacecraft acceleration [Keating *et al.*, 1998, 2001a,b; Withers *et al.,* 2003; Withers, 2005] and orbit decay [Tracadas *et al.*, 2001] allows the atmospheric density to be determined for altitudes from 90 to 180 km. Yet while the data provide a unique picture of the atmosphere, the dataset is limited both in terms of spatial and temporal coverage, thus we must use models to extract maximum information and understanding from these *in situ* measurements.

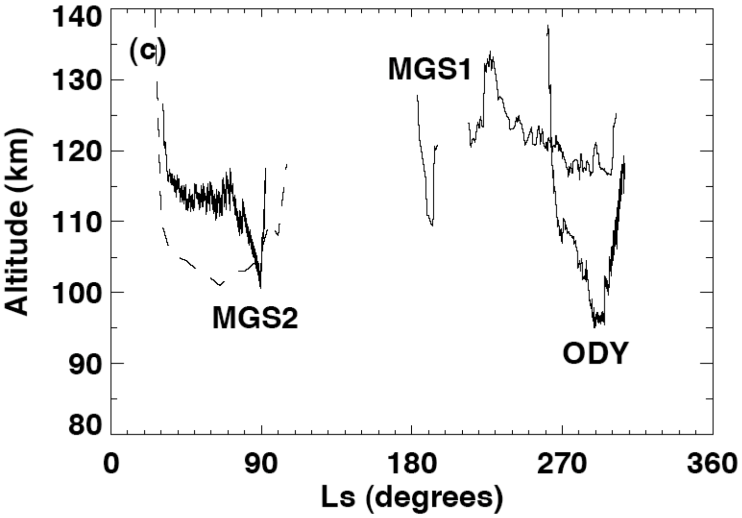


Figure 1. The distribution of spacecraft accelerometer measurements with season (Ls) and mission (MGS1 and MGS2 refer to two separate phases of aerobraking, while ODY stands for Mars Odyssey. Dashed line is predicted distribution for MRO). [Withers, 2005]. (Season is indicated by the planetocentric solar longitude or Ls, with Ls=0° at northern spring equinox, summer solstice at Ls=90°, etc.)

Until recently, the Martian middle atmosphere has been modeled separately from the troposphere. This has been due to the differences in physical process parameterizations needed for the lower and middle atmosphere, the computational expense of full-atmosphere models (due to the number of model vertical layers needed), and the existence of good, but separate models of the terrestrial lower and the upper atmosphere that could readily be applied to other planets. Although these separate models have been used in coupled simulations in the past [*e.g.* Bougher *et al.*, 1999], only recently have several groups from France, Japan, Canada, and Germany reported the development of "monolithic" General Circulation Models (GCM) extending from the ground to altitudes above 100 km with adequate treatment of radiative and conductive heating [Angelats i Coll *et al.*, 2005, Takahashi *et al.*, 2003, Moudden and McConnell, 2005, Meister *et al.*, 2003]. The drive to develop such models has been provided by the existence of the aerobraking data sets and the apparently strong signature of waves in these data, thought to have originated in the lower atmosphere. Extended GCMs have been used to study these thermal tides and Kelvin waves [Wilson, 2002, Angelats i Coll *et al.*, 2004]; to empirically characterize the longitudinally dependant diurnal cycle of density variations [Forbes and Hagan, 2000]; and to begin characterization of the atmospheric structure [Keating *et al.*, 1998, Bougher *et al.*, 1999]. Although work has now been done on modeling the MGS accelerometer data, assessment of the full seasonal variation exhibited by the data is far from complete, and in particular, there have been few publications addressing the Odyssey accelerometer data [Tolson *et al.*, 2005, Bougher *et al.*, 2005]. More generally, a detailed mechanistic study of how the middle atmosphere varies with season and solar cycle has not been published, and studies exploring the region's sensitivity to dust storms of various sizes in the lower atmosphere have only just begun [*e.g.* Bougher *et al.*, 2005]. It is the goal of this project to provide a systematic study of the middle atmosphere under differing forcing scenarios, and to use this modeling to extract information from the full range of available accelerometer data.

It is important to note that additional data sets on the Martian middle atmosphere are being acquired that place further constraints on dynamical models. These include UV airglow data and occultation profiles from the Mars Express UV and IR atmospheric spectrometer [SPICAM, Bertaux *et al.*, 2005] instrument, and measurements of the electron and ion distributions from radio science observations (from all orbiters) [*e.g.* Bougher et al., 2004] and the Mars Express energetic neutral atoms analyser (ASPERA) instrument. As SPICAM observations become more generally available, they can (will) be used directly to constrain the model, while the charged-particle data can be used in conjunction with a simple offline (diagnostic) photochemical and loss model [*e.g.* Martinis *et al.* 2003]. In any case, the extended version of the Mars WRF GCM proposed here will provide a jumping off point for analysis of these additional data sets, and hence ultimately the atmospheric loss process.

A combination of radiative and dynamical processes determines the structure of the Martian middle atmosphere. The interpretation of accelerometer data to date suggests that waves propagating from the lower atmosphere produce a strong signature in the density structure in the middle atmosphere [Forbes *et al.*, 2002; Forbes and Hagan, 2000; Wilson, 2002; Angelats i Coll *et al.*, 2005]. Locally-forced tides, as a results of near-infrared heating of CO_2 and also due to UV/EUV absorption also appear to have a noticeable presence [Angelats i Coll *et al.*, 2005]. The propagation (or not) of waves into and through the middle atmosphere depends in a non-linear way on the atmospheric thermal and dynamical structure, since the waves modify the background state. By calculating the eddy fluxes of heat and momentum from the model, we can assess the total impact of all wave modes on the background state. By applying linear wave theory to the simulated background states, we can assess the ability of differing wave modes to grow and propagate and hence their likely relative role in producing the observed eddy fluxes. In combination, these approaches allow a great deal of insight into the types of waves important for the atmosphere.

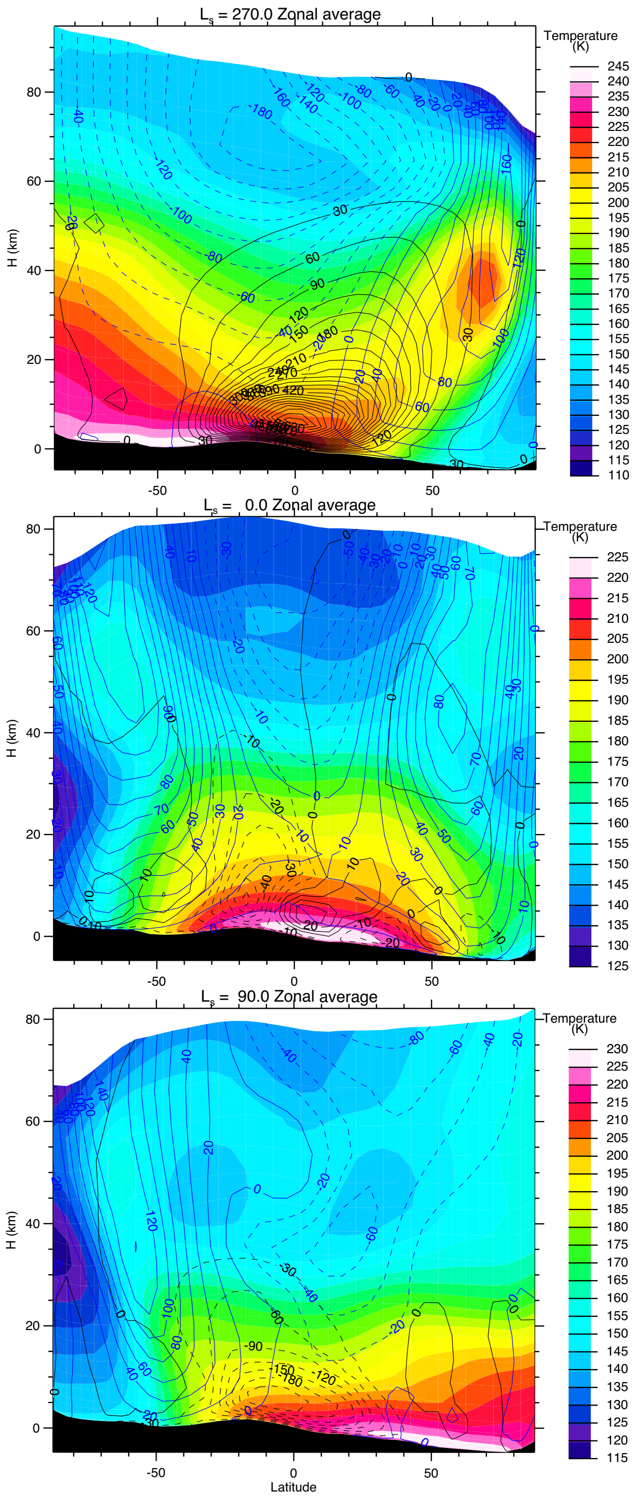
The structure of the middle atmosphere is expected and observed to be dependent upon changes in forcing: due to the changing seasons, due to changes in EUV insolation with the solar cycle, and due to changes in the lower atmosphere dust distribution. Mars has on obliquity of roughly 25°, yielding a change in the seasonal distribution of insolation that is similar to the Earth. In addition, the eccentricity of the Martian orbit (0.093) yields a strong asymmetry between southern summer (solstice is just after perihelion) and northern summer. Not only will this changing pattern of insolation affect EUV/UV and near-IR heating of the middle atmosphere *in situ*, but also the structure and dynamics of the lower atmosphere, profoundly influencing wave conduction from the surface and lower troposphere. The EUV/UV insolation at Mars will also depend on the solar output at these wavelengths as the solar cycle proceeds. The total UV/EUV insolation will impact the thermal forcing of the middle atmosphere above roughly 110km. The influence of dust is less directly obvious: dust suspended in the atmosphere, primarily below about 30-60 km, strongly modifies the amount of direct solar (visible) heating of the atmosphere. The effect is so large that the circulation strength in the lower atmosphere can be dramatically increased [Haberle *et al.*, 1982; Wilson, 1997], as can the amplitude of the thermal tides [Zurek, and Leovy, 1981]. The significant modification of the lower atmosphere circulation is expected to have major consequences for the middle atmosphere.

This project will conduct a systematic study of the effects of season, solar cycle, and lower atmosphere dust content on the dynamics and thermal structure of the middle atmosphere. The modeling will be used in conjunction with available accelerometer (and other) data sets to help us understand what combination of processes yields the observed and simulated atmospheric states. Such a study is expected to have significance both: 1. for future use of the middle atmosphere by increasingly complex spacecraft missions but also (and perhaps more importantly) 2. to provide some understanding of the region of the atmosphere important for atmospheric loss (both in terms of photochemistry and as a lower boundary condition for calculating atmospheric loss rates).

Proposed Research: Global Modeling of the Martian Middle Atmosphere

We propose to examine the behavior of the Martian middle atmosphere with a General Circulation Model with the goal of developing a basic picture of how the circulation and thermal structure of the middle atmosphere are controlled.

The project will be broken into three parts:


L_s = 270.0 Zonal average

L_s = 0.0 Zonal average

L_s = 90.0 Zonal average

Figure 2. The zonal-mean structure of the lower atmosphere as simulated by the WRF Mars GCM. The model compares well with other Mars GCM's and available data. Mass stream function is shown in black contour, zonal winds in blue.

1. Incorporation and “validation” of middle atmosphere radiative, thermal conduction, and gravity wave parameterizations;
2. Simulation of the middle atmosphere over the diurnal, seasonal, and solar cycles for non-dust storm conditions; and,
3. Simulation of the response of the middle atmosphere to dust storms of various sizes.

Full use of available spacecraft data will be made at all stages.

A new Martian General Circulation Model, based on the National Center for Atmospheric Research (NCAR) Weather Research and Forecast (WRF) model will be used in this project. This model is novel in many respects resulting from the generality of the implementation of the dynamical core. While the model is based on a standard c-grid finite difference mesh, the map projection and boundary conditions are sufficiently general that the model can be run-time configured to run as a limited-area, global, or nested model using arbitrary map projection. The code is also capable of running on numerous different platforms, including distributed memory parallel processor systems. The code includes hydrostatic and non-hydrostatic options and the full 3D treatment of Coriolis effects. Differencing can be run-time configured from 2nd to 6th order accuracy spatially, with time stepping using leap-frog or 3rd order Runga Kutta approaches and a split explicit scheme in order to treat fast gravity and acoustic wave modes. A terrain-following vertical coordinate based on the hydrostatic pressure is used (see www.wrf-model.org and documentation linked thereto). The model has very little implicit dissipation – indeed idealized test cases with no initial or boundary perturbations will run indefinitely in the unstable equilibrium state corresponding to zonally symmetric flow. Sub-grid scale horizontal diffusion is treated in the model with a flow-deformation-dependent diffusivity, and in the vertically, with a Richardson number-dependent diffusivity (there is no convective adjustment – convective effects are captured by the vertical diffusivity). An important capability of the Mars WRF GCM for this project is the ability to rotate the numerical pole from the geographical pole. Since some fraction of the aerobraking observations takes place at high latitude (above 60° where grid point GCMs apply fourier filtering), we will experiment with simulations using a numerical pole at the equator.

The model has been fully converted to Mars, with some results shown in Figure 2. In addition to changes in constants and timing convention, the model "physics" have been augmented by options to simulate radiative heating of the atmosphere in the thermal and near IR by dust and CO_2 gas (several options exist in the model, including Newtonian cooling, schemes similar to those described for the GFDL Mars GCM [Richardson and Wilson, 2002] and the LMD Mars GCM [Forget et al., 1999], and a based on a modification of the Hadley Center Unified Model radiative transfer model), to treat the condensation and sublimation of CO_2, and to model the evolution of surface and subsurface temperatures using measured albedo and thermal inertia maps. A full model description paper is under preparation [Richardson *et al.*, 2005].

Task 1. Vertical Extension of the WRF Mars GCM and "Validation"

A number of processes and effects not needed for the lower atmosphere will be / have been added to the WRF Mars GCM for middle atmosphere simulation. The heating/cooling processes that define the structure of the Martian middle atmosphere are [Bougher *et al.*, 1990, Angelats i Coll *et al.*, 2005]:

a) Direct absorption of solar radiation in the near infrared (NIR) CO_2 band (1-5 μm) at altitudes (mostly between 60 and 140 km – see Figure 3); (***added***)
b) CO_2 15-μm band thermal infrared radiative transfer (mostly below 140 km); (***added***)
c) Absorption of extreme ultraviolet and ultraviolet solar radiation (EUV/UV, 0.1 - 337.7 nm) by atmospheric constituents and trace gases (CO_2, O_2, O, H_2, H_2O and H_2O_2) - (most important for altitudes above 120 km – Figure 3); (***to be added***)
d) Thermal conduction of the heat (again, mostly of importance above 120 km); (***to be added***)
e) Upward propagating tides and gravity waves (mechanical heating/cooling of the thermosphere). (***inherently included / parameterization to be added – see text, below***)

The radiative processes and molecular thermal conduction dominate the heat budget of the middle atmosphere (Figure 3), with gravity wave and tidal heating of importance below about 100 km [Angelats i Coll et al., 2005]. Importantly, above about 85 km, radiative transfer takes place under conditions of non local thermodynamic equilibrium (NLTE), such that the lower atmosphere radiative transfer schemes for CO_2 solar and thermal radiative heating are no longer

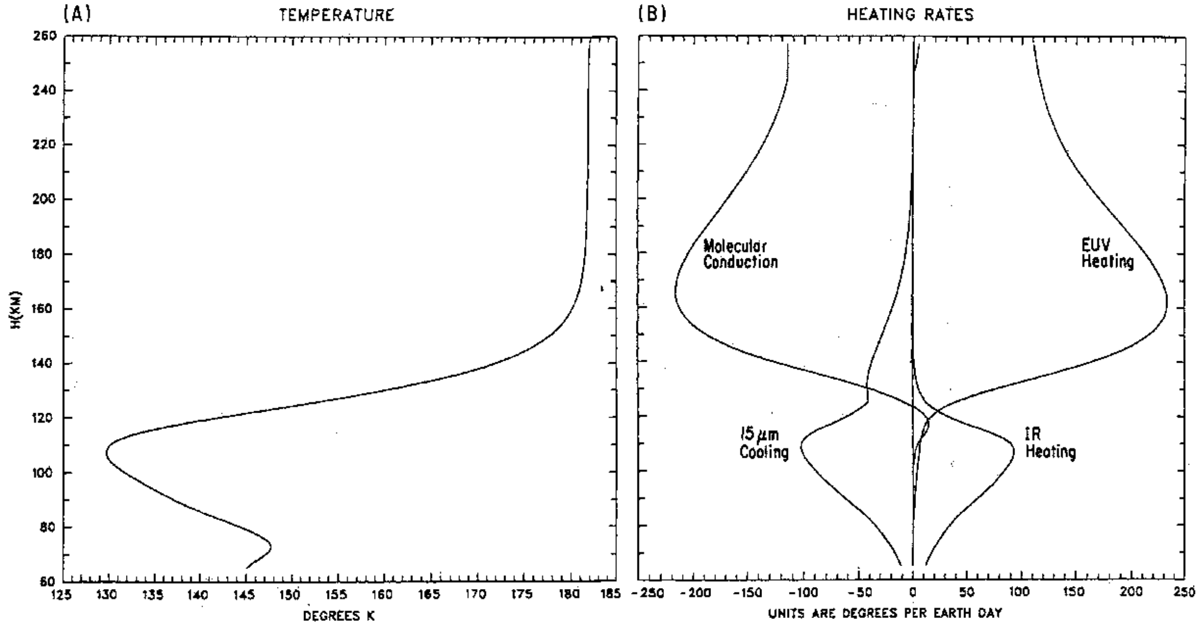


Figure 3. The relative importance of radiative and conductive heating as a function of altitude (B) is indicated along with the corresponding temperature distribution (A) as predicted by a one-dimensional global mean model [Bougher *et al.,* 1990]. All four major effects will be treated in the extended Mars WRF GCM.

valid. The Mars WRF GCM CO$_2$ radiative transfer scheme has been recently modified to account for NLTE effects. We propose to incorporate thermal conduction and UV/EUV heating processes into the Mars WRF GCM. While heating effects associated with the thermal tides will explicitly be resolved by the model dynamics, the fraction of the gravity wave spectrum at wavelengths shorter than (two times) the grid spacing will not be resolved. A model resolution sensitivity study will be undertaken to assess the importance of gravity waves, and a sub-grid scale parameterization of gravity wave effects added and tested.

a) and b) CO$_2$ NIR absorption and IR cooling. Above approximately 85 km the NIR absorption and IR cooling take place under NLTE conditions [Lopez-Valverde and Lopez-Puertas, 1994, Lopez-Valverde *et al.*, 1998]. Here, the frequency of molecular collisions is low and the population of vibrational states participating in thermal exchange in CO$_2$ molecules cease to obey the Boltzman distribution. This complicates solving the radiative transfer equation, since the collisional and radiative exchange processes between many excited states need to be modeled simultaneously.

Due to their computational complexity, “full” models of the NIR absorption and IR cooling in the Martian atmosphere [Ogibalov and Shved, 2003; Lopez-Valverde and Lopez-Puertas, 1994] are not suitable for GCMs. Instead, simplified or “parameterized” models have been developed and have been included in the Mars WRF GCM. This approach has been taken by the other GCM groups [Angelats i Coll *et al.*, 2005, Moudden and McConnell, 2005] and simulations with these parameterizations compare well to the available observations [Angelats i Coll *et al.*, 2004].

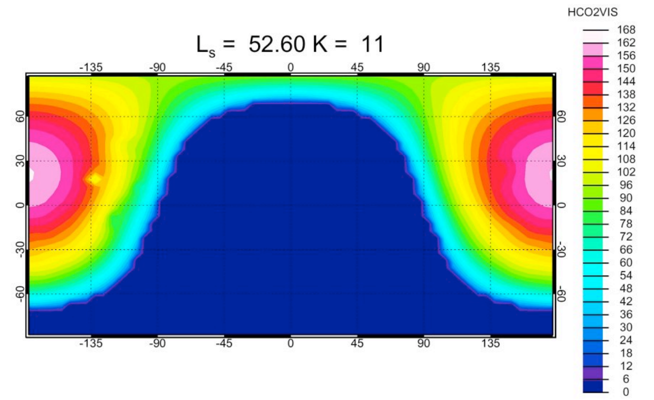


Figure 4. Map of the NIR CO_2 heating rates (in K/day) for L_s=52.6° and an altitude of about 110 km. The heating rate spatial pattern reflects the distribution of the incoming solar flux for this season (Northern hemisphere late spring). The heating rate is the largest for the local solar elevation angle of 90° (sun is directly overhead, longitude of 180°) and decreases with decreasing local solar elevation angle.

Specifically, the near infrared (solar) CO_2 NLTE absorption scheme has been taken from Lopez-Valverde and Lopez-Puertas [1995]. The NLTE CO_2 thermal infrared cooling (15-μm band) parameterization is taken from Lopez-Valverde and Lopez-Puertas [2001], and simplifies the NLTE model by reducing the number of excited vibrational states of the CO_2 molecule under consideration to just two. The corresponding collisional and exchange rates, collisional production and loses rates, and escape functions are parameterized as functions of local temperature, pressure and volume mass ratios of atmospheric constituents CO_2, O, N_2, CO. Since the GCM in its current state does not calculate concentrations of the trace gases (O, N_2, CO), constant model altitude profiles of concentrations of these species from Lopez-Valverde and Lopez-Puertas [2001] were incorporated into the model for calculations of the cooling rates. This approximation should not significantly affect the simulations, since the concentrations of the trace gases do not vary enormously for different atmospheric conditions, and in any case, the error associated with the approximation is larger than that associated with the assumption of constant composition. The behaviors of the NLTE solar and thermal schemes are illustrated in Figures 4 and 5.

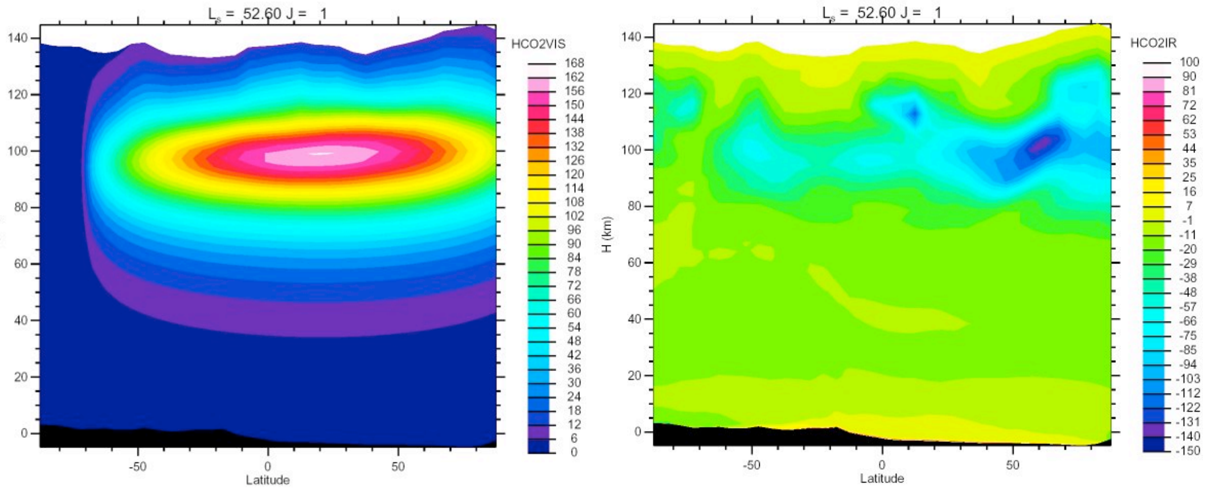


Figure 5. (left) Latitudinal cross-section of NIR CO_2 heating (in K/day) from the surface to 140 km along 180° longitude in the WRF Mars GCM. The peak heating rate occurs at an altitude of about 100 km and at a latitude of about 20°N, corresponding to a solar elevation angle of 90° for this location. (right) Same as left panel but for CO_2 IR cooling/heating rates (in K/day). The NLTE IR cooling also peaks at an altitude of about 100 km. The altitudes of maximum heating/cooling compare well with 1D models – see with Figure 3.

c) EUV/UV scheme. We propose to implement a simple EUV/UV scheme in the GCM that will calculate atmospheric heating in the EUV/UV due to absorption by CO_2 only and at a single wavelength assuming Beer-Lambert absorption law:

$$Q(z) = EUV_{eff} n \sigma(\lambda) F(\lambda) e^{-\tau(\lambda, z)} \Delta\lambda$$

where EUV_{eff} is the EUV/UV heating efficiency, n is concentration of the absorber, σ is the wavelength dependant absorption cross-section, F is the incident solar flux, τ is optical depth and $\Delta\lambda$ is the equivalent width of the CO_2 EUV/UV absorption band. A similar approach has been used by Moudden and McConnell [2005], yielding realistic temperatures in the thermosphere. Reducing the number of absorbing species to just one and using a single wavelength to calculate absorption enables us to avoid computational complexities and speed up GCM runs. Importantly, even this simple model retains enough realism to respond to variability of the solar cycle forcing (through the incident solar flux F) and to variability of the atmospheric structure (through the temperature dependant absorption cross-section σ). Hence the model is appropriate for the proposed effort.

The needed model parameters – CO_2 absorption cross-section, solar flux - are available in the literature [SOLAR2000, Yoshino *et al.*, 1996, Anbar *et al.,* 1993]. We will investigate the impact of including more than one wavelength in the EUV/UV scheme on the computational speed of the Mars WRF GCM and on the simulated thermospheric temperatures. We will implement a model with more than one wavelength if the accuracy and speed considerations warrant it.

d) Thermal conduction. Parameterization of thermal conduction needs to be included in the model as it provides the main heat loss mechanism in the region of the EUV/UV absorption (120 to 260 km, see Figure 3). Implementation of this parameterization is straightforward – it involves including a thermal conduction term in the temperature tendency equation:

$$\partial T / \partial t = \ldots + \partial / \partial z \left(k \, \partial T / \partial z \right) / \rho C_p$$

where k is the temperature dependent thermal conduction coefficient. The dependency of k (for CO_2) on temperature will be parameterized using a fit to the National Institute of Standards and Technology data [NIST].

e) Tides and gravity waves. Planetary scale thermal tides [Forbes *et al.*, 2002] and other large-scale waves are explicitly resolved by the Mars WRF GCM, whose default resolution is 5°of latitude (and similar in longitude). Further, as the model resolution is increased, a correspondingly more complete fraction of the gravity wave spectrum is also explicitly treated. Terrestrial experience suggests that capturing the full spectrum of gravity waves, and specifically the heat and momentum they transport, can be important for determining the structure of the middle atmosphere [*e.g*. Andrews *et al.*, 1987]. For example, it is possible to show that high spatial resolution is critical to proper simulation of the stratospheric and mesospheric polar circulation [*e.g*. Hamilton *et al*., 1995].

To date, the effects of gravity waves in Martian GCM's has been addressed using gravity wave drag parameterizations [Collins *et al*., 1997; Forget *et al*., 1999; Angelats i Coll *et al*., 2004]. The assumption is that the waves are forced primarily by topography, which is on scales of a few tens of kilometers (maps of slope angle and direction calculated from 1° topographic maps are used to force the gravity wave model used by Forget *et al.* [1999] and Angelats i Coll *et al.* [2004], for example). The impact of topography on this scale on mesoscale flow has been demonstrated by several mesoscale models for Mars [Rafkin and Micheals, 2003; Toigo and Richardson, 2003], supporting the idea that these scales may provide strong forcing for gravity waves – this is also evident in preliminary very high resolution (0.5° - "global mesoscale") simulations with the Mars WRF GCM.

We propose to undertake resolution sensitivity studies to examine the impact of increasing spatial resolution on the circulation of the middle atmosphere (*i.e.* as the fraction of the explicitly resolved gravity wave spectrum is increased) and to test existing gravity wave drag parameterizations. We propose to undertake a handful of simulations at equinox and the two solstices with model resolution roughly doubling from 5°, to 2°, 1°, and 0.5° - the highest resolution case corresponding to about 30 km grid spacing (at the equator). The vertical resolution will also be varied, from a case close to the resolution used by Angelats i Coll *et al.* [2004] (32 layers between the surface and 120 km - about half a scale height average sampling) to that used by Moudden and McConnell [2005] (100 layers between the surface and ~170 km – or roughly 1-2 km resolution, on average).

We will run the simulations using initial conditions extrapolated from fully spun-up versions of the model at lower resolution. Simulations will be run for 60 Martian days to allow for steady state to be achieved. At 0.5° resolution, the model runs on 32 processors at roughly double real-time (model elapsed time equals twice wall elapsed time). We will almost certainly launch several of the highest resolutions simultaneously such that we will consume a couple of hundred processors for a couple of months of wall time (every doubling of resolution yields a factor of 8 increase in required CPU time, since the number of grid points increases as the square of the linear sampling, while the timestep must halve to maintain stability – thus the very highest resolution simulations will completely dominate the required computational time). For details of the estimated CPU usage on the dedicated Caltech Division of Geological and Planetary Sciences 2048 processor Xeon parallel computer (see facilities section), see Table 1.

The impact of the differing fractions of gravity wave spectrum resolved (i.e. of the different spatial resolution simulations) will be assessed by intercomparison of the circulations and thermal states generated in the different simulations (*i.e.* addressing "does resolution matter?") and by comparison with observations. In the latter case, the model will be sampled using a similar pattern (lat, lon, altitude, local time) as the real atmosphere. The accelerometer data also indicate the presence of high frequency vertical variations in density that may be the direct signature of gravity waves, which may be replicable with the model. The spectral content of the model gravity waves as a function of resolution will be documented with traditional harmonic analysis and will be compared with the spectral content of the surface topography (which is presumably forcing the waves), and with the static stability distribution in the atmosphere. The forcing of the gravity waves can be further assessed by running the model at higher resolution but with topography smoothed to that of the standard GCM (5°).

Lower resolution models often use gravity wave drag parameterizations to capture momentum and heat transports. These schemes have never been tested against explicit representation of gravity waves (largely because of the computational loads). We propose to use our collection of high resolution simulations to do this. For comparison, we will implement a standard gravity wave drag parameterization (common in terrestrial GCMs – for Mars see Collins *et al.* [1997] or Forget *et al.* [1999]) and test the efficacy of such a scheme forced by slope angles and directions derived from the 1° and 0.5° topography data sets.

Simulation	Number / Length of Simulation	Total Computational Time (days)
"Standard" resolution (5°)	~20 sims / 60 Mars days each	2.5 days (16 processors)
2° simulation	6 sims / 60 Mars days each	3 days (32 processors)
1° simulation	6 sims / 60 Mars days each	25 days (32 processors)
0.5° simulation	6 sims / 60 Mars days each	200 days (32 processors)

Table 1. Simulation series, number of runs per series, and computational requirement for the "gravity wave spectrum" part of the project. Note that many simulations will run concurrently (*i.e.* using 192 processors – or less than 10% of the GPS parallel computer, all of the 0.5° simulations will be completed in one month).

How high to place the model top and what determines this altitude?

The incorporation of the EUV/UV heating and thermal conduction will allow the Mars WRF GCM to be used to simulate atmosphere dynamics from the surface to altitudes of roughly 260 km [Bougher *et al.*, 1990]. Since the major data set to be simulated in this study extend to only 160 km (in the case of accelerometer data) or at most 200 km (spacecraft orbit evolution data [Tracadas *et al.*, 2001]), we will generally limit ourselves to simulations with model tops at 200 km.

Task 2. Idealized Study of Diurnal, Seasonal, and Solar Cycle Influence on Middle Atmosphere Structure

The major goals of this section/task are to:

- Undertake an explorative study of the impact of the seasonal cycle and the solar cycle on the structure and dynamics of the middle atmosphere,
- To use the resulting model output to assess the quality of fit to spacecraft observations, and hence to use the model to better understand the global processes contributing to the observed patterns.

Using the "best fit" form of the gravity wave drag parameterization (see Section 1), we propose to generate a suite of annual and solar cycle simulations. The limited number of published, whole-

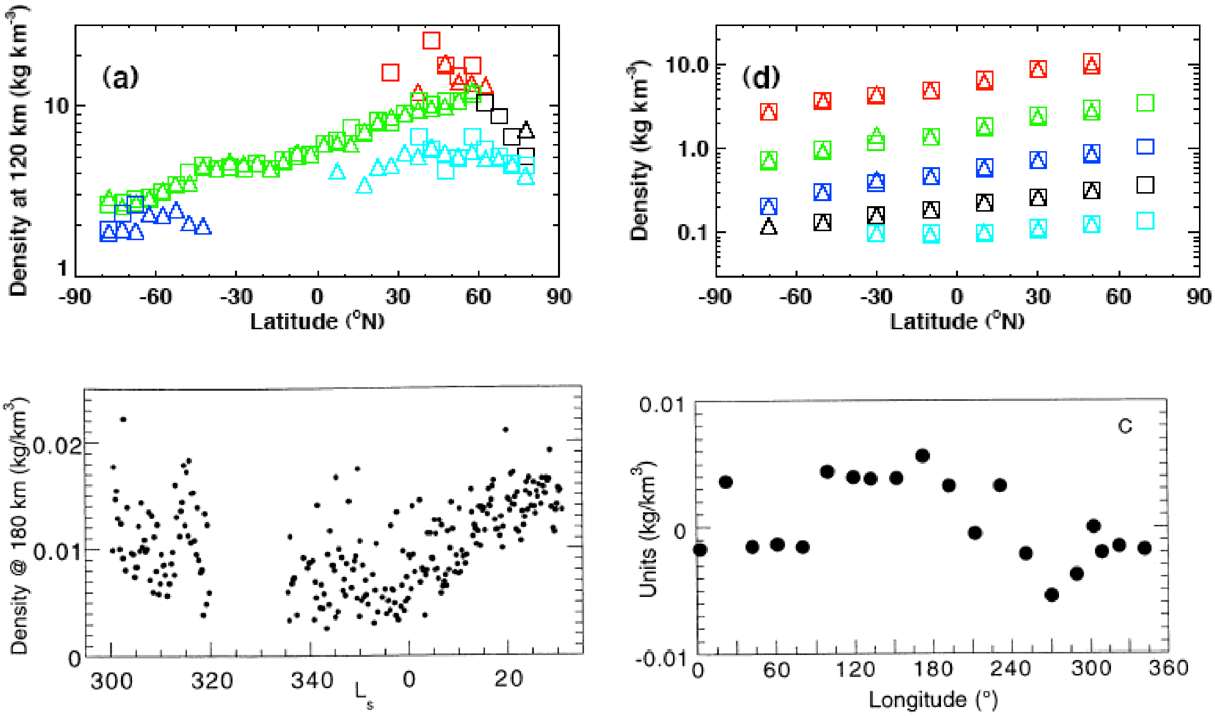


Figure 6. Data from accelerometer and orbital decay analysis provide important constraints on the model (in other words, a model that can "fit" the available data can provide a more complete idea of how atmospheric processes are working). Top left and right – data from MGS and MO accelerometer from Withers [2005] (green=MGS phase 2, red=MGS phase 1, black and light blue=MO). Lower left and right – data from MGS orbit decay [Tracadas *et al.*, 2001] as a function of season (left) and for the Ls=315°-320° period as a function on longitude.

atmosphere GCM studies have tended to focus on validation and simulation of limited sets of spacecraft observations. This is partly due to the very recent emergence of such models, and to the computational demands of undertaking long-term simulations. In this project, the efficiency of the parallel WRF code and the computing resources enable such a study.

The suite of multiannual simulations we propose to generate will explore the effect of: 1. the changing distribution of solar insolation with season; 2. the changing solar insolation with distance from the Sun; 3. prescribed changes to the lower atmosphere dust distribution and opacity; and, 4. the changing solar UV/EUV flux with solar cycle. We will examine several "storm-free" dust scenarios. These will test the importance of variations in total opacity, and the three-dimensional spatial distribution of dust. These scenarios will be within the plausible ranges of observed dust opacities.

The simulation output will be examined in terms of the zonal-mean circulation (jets and meridional circulation), the thermal structure, the wave types active and their spectral content (relative strength of different frequency components), and the changes in radiative and conductive heating. This part of the study is explorative – to assess the impact of changes in season and solar UV/EUV flux on the atmosphere. We expect that (for example) as the seasons change, the jet structure and hence the wave propagation channels will change in a non-linear manner. *We* *propose to undertake a first-cut assessment of changes in circulation and to relate them to the changes in seasonal and solar cycle forcing.* Nothing in the analysis techniques employed is radically new – we will simply be applying tried-and-true means of examining model dynamical behavior to a new suite of simulations (no such assessment has yet appeared in the literature, and will provide an important prognostic for assessment of future aerobraking data sets.)

To compare model output with data, it is best to sample the model using a pattern consistent with the aerobraking observations. These observations generally take the form of density as a function of location, local time, and season at a reference height, as illustrated in Figure 6. With the suite of simulations in hand, we will then pick the simulation that best matches the observations. The analysis of the circulation corresponding to "fit" periods is the same as that to be employed for assessing the complete annual/solar cycle simulations (see above).

We anticipate conducting ten five-Martian-year simulations at UV/EUV fluxes appropriate from solar minimum to solar maximum, and for five different dust scenarios. We will likely also conduct a "real time" simulation with our best-case dust scenario (TBD pending the results of the fixed solar flux simulations) using a solar cycle in phase with the seasonal cycle so as to simulate the period of 1997 (start of MGS) through to 2020 (roughly 10 Martian years covering the period of aerobraking and other upper atmosphere observations). Additional sensitivity studies using diurnal mean solar forcing, varied atmospheric trace gas composition, and other factors that may arise during the study will be undertaken.

Simulation	Number of Simulations	Total Computational Time (days)
Five year sims	50	300 (16 processors)
Real-time 1997-2020 sim	1	12 (16 processors)
Sensitivity studies	~20 (1 year each)	24 (16 processors

Table 2. Simulation series, number of runs per series, and computational requirement for this part of the project (seasonal / solar cycle). Note that many simulations will run concurrently – for example, consuming just 40% of the GPS parallel computer, all of the "five-year" simulations would be completed in 6 days.

Task 3. Influence of Dust Storms on Middle Atmosphere Structure

Dust storms greatly affect the lower atmosphere of Mars – dramatically increasing mean air temperatures and intensifying the circulation. The impact of this heating merely on the hydrostatic structure of the atmosphere has a great influence on the middle atmosphere by shifting it upwards by several to several tens of kilometers. However, the impact on the circulation, wave generation, and thermal structure of the lower atmosphere profoundly modifies the dynamical forcing of the middle atmosphere as well. Some indication of the impact of dust storms on the middle atmosphere is made clear by accelerometer observations from the first phase aerobraking by MGS during which time the 1997 Noachis storm of mid southern spring occurred (note the rise in periapse location for the MGS1 phase near Ls=220°-230° in Figure 1.) Some initial work on modeling the impact of dust storms on the middle atmosphere is now underway [Bougher *et al.*, 2005], however no systematic study of mechanisms and connections has yet been published. In this section, we propose to investigate the means by which the middle atmosphere is modified by storms of various size and occurring at various times and locations, and to constrain this modeling in particular with the observations of the 1997 Noachis storm.

In a separately funded NSF project (see bottom of this document), we have been conducting extensive studies of the seasonal dust cycle and dust storm generation within a Mars GCM. We intend to leverage this experience in this project by forcing the upper atmosphere with simulated dust storms. Our first aim will be to somewhat artificially manufacture dust storms within the model that mimic the 1997 Noachis event, the 2001 global storm, and the 2003 cross-equatorial Chryse storm. From our experience, specifying surface dust injection and allowing the model winds to advect and mix the dust can accomplish this. This forcing has the advantage that it allows better comparison with the aerobraking observations.

The other approach is to use the model parameterizations of dust lifting (rather than prescribing surface dust injection), enabling the generation of spontaneous and interannually-variable global dust storms [Basu *et al.*, 2004]. The advantage of this approach is that while unlikely to produce storms exactly like those observed by recent spacecraft, a range of storm types and timings will emerge, and the model additionally is self-consistent. In this case, the focus will not be on specific observations, but on exploring the range of possible atmospheric behavior.

The analysis approach for these simulations will be the same as for the annual / solar cycle simulations. We are primarily interested in how much the hydrostatic inflation of the atmosphere, increased circulation, and modified wave forcing impact the thermal structure and dynamics of the middle atmosphere.

Simulation	Number of Simulations	Total Computational Time (days)
Specified source (one year)	20	35 days (16 processors)
Fully interactive (10 year)	20	230 days (16 processors)

Table 3. Simulation series, number of runs per series, and computational requirement for the last part of the project. Note that multiple runs can be conducted simultaneously. For example, the fully interactive runs could be run in 12 days using only 16% of the GPS parallel computer.

Dissemination of Results and Impact

The primary avenue for dissemination of results from this work will be through the peer-reviewed literature. Our budget includes a request to support publication of at least one paper per year. We also request funds for travel to conferences in order to discuss results with the community.

It is hoped that the work proposed in this document will move us towards greater understanding of the Martian middle atmosphere. This region is a critical part of the Martian atmosphere, whose influences range from the very practical (aerobraking and atmospheric entry) to those at the heart of major scientific questions for Mars (atmospheric loss). The model development will also provide a venue for simultaneous interpretation of numerous data sets, and as a basis for detailed, 3D modeling of the ionosphere and loss processes.

Training, Teaching, and Facilities

This proposal includes funds for the training of early-stage graduate students. While the majority of salary is requested for professional research staff, the proposal includes funds for three years of 30% time for a graduate student. At Caltech, first year graduate students are required to undertake two research projects in preparation for oral exams at the start of their second years. Typically, support of the level requested is needed to allow a first year graduate student to work on a research project as one of these two "propositions." The proposed research is highly conducive to the development of "bite size" research projects for such graduate students, as the whole can be broken into smaller parts associated with the role of particular forcing mechanisms, particular wave systems, and particular data set comparisons. The advantage of having a large time commitment by a professional research scientist guarantees a solid support base for optimal training of these new graduate students and the successful completion of the devolved tasks. We anticipate three different students will participate in such training as a part of their first year activities over the course of this research project.

The proposed work will take advantage of a massively-parallel computing system at Caltech that was developed in large part with over $1m of NSF funds (an NSF MRI, PI Prof. Jeroen Tromp). This 2048 processor Xeon computing system makes it possible for us to conduct very computationally expensive simulations, of the kind needed to explore solar cycle simulations and high-resolution gravity wave studies, as described in the proposal. The original NSF MRI that facilitated the computing system was targeted at geophysics, terrestrial climate science, and planetary climate / atmospheric science. This proposal will add to the program of planetary science envisioned in this latter part of the proposed system usage (due to the relatively small number of PI groups associated with the computing system, we are assured of substantial ongoing access to the system). In addition to computational capacity, the system includes over 35Tb of disk space, sufficient for storage of the model output generated as

Figure 7. The 2048-processor Dell Xeon supercomputer ("Pangu"), partially supported by NSF MRI funds, being installed in the GPS Division at Caltech, August 2005. This machine will be used for the simulations in this project.

a part of this study. Since this computing and storage system will fulfill all computing requirements, no new computing systems are requested. Instead, funds for support of the system (system administrator time, *etc.*) is requested. Analysis of output will utilize the network of ten PC workstations, and a 32-processor analysis Beowulf PC system, within the PI's research group.

Summary of Anticipated Work

During the three years of this project, the major tasks associated with Sections 1-3, above, will be undertaken. All work will involve the PI and Co-I, Pankine, while Collaborator Withers will be consulted on issues of observational comparisons and numerical experiment design. Dr. Pankine will undertake most of the day-to-day work of running the model, processing output, modifying the model where necessary, *etc*. The PI and Co-I are both in Pasadena, such that regular communication will be easy. Funds are requested to allow a dedicated in-person meeting on project issues between all team members in Pasadena, in addition to meetings at conferences. Papers will be jointly written. Certain tasks will be delegated to first year students under close guidance by the PI and Co-I – these include (for example) assessment of wave modes propagating to the middle atmosphere in task 2. These sub-projects will form essential introductory training on use and analysis of atmospheric numerical models by first year graduate students.

The work breakdown closely follows the task/section breakdown:

Year 1 – Task 1

- Complete the implementation of EUV/UV heating scheme
- Complete the implementation of conductive heating
- Complete the study of gravity wave impacts on the middle atmosphere
- Write-up an initial model description paper with focus on role of gravity waves and simulation of the Ls=65° period simulated with the LMD Mars GCM.

Year 2 – Task 2

- Undertake the study of the impact of season and solar cycle on the middle atmosphere structure and circulation – write-up the study

Year 3 – Task 3

- Undertake the study of the impact of dust storms on the middle atmosphere structure and circulation – write-up the study

Results of Prior NSF Funding

This proposal is not a renewal, however, the PI has received NSF Planetary Astronomy funding within the last five years. The project associated with that funding (AST-0406653, for a total of 3-years support, at $273,948 total for all three years, with a period of performance of 6/01/04 - 5/31/07) is entitled "Dust and the Martian Climate" and is directed at understanding controls on the seasonal cycle of dust in the Martian atmosphere and on the development of dust storms. The project has been very successful, yielding one published paper [Basu *et al*., 2004], and two more to be submitted by end 2005. In addition, the funding supported graduate student Shabari Basu throughout the remainder of her time at Caltech, concluding with her graduation with a PhD in mid 2005. She is now research faculty at Texas A&M University.