# THE CORNELL/CALTECH MARS MM5 MESOSCALE MODEL.

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## Introduction

The study of dynamical processes operating within the Martian atmosphere has benefited greatly from the modification and application to Mars of atmospheric models developed for Earth. These models have provided insight into the dynamics of the Martian general circulation, including the response of the Hadley circulation to changes in aerosol heating [*Haberle et al.*, 1982; *Wilson*, 1997], and the behavior of the aerosol and volatile cycles [e.g., *Pollack et al.*, 1993; *Murphy et al.*, 1995; *Richardson*, 1999]. However, these models have been global and of sufficient resolution to resolve only synoptic scale processes (greater than a few hundred kilometers). Results from global models increasingly suggest the importance of smaller scale processes, for example, the lifting of dust from the surface and injection into the atmosphere, and the exchange of water with and transport of vapor to or from the northern polar cap. At the same time, high resolution thermal and imaging data are now available that require atmospheric models capable of resolving motions on scales of a few hundreds of meters to a few hundreds of kilometers. These data include observations of the polar regions, dust devils, dust storms, water ice cloud systems, and aeolian features.

We have developed a Martian mesoscale model that is designed to address motions on scales smaller than resolvable by current numerical models of the atmosphere. The model is based on the Pennsylvania State University (PSU)/National Center for Atmosphere Research (NCAR) Mesoscale Model Version 5 (MM5) [*Dudhia*, 1993] and is fully converted to Martian conditions. The model is designed to work in tandem with a global model which provides initial and boundary conditions. The mesoscale model (Mars MM5) simulates a limited domain within this global context, at resolutions ranging from 10 m to 100 km. The model has been developed to address a number of outstanding problems in Martian atmospheric studies. These include:

- How is dust lifted from the surface and injected into the atmosphere?
- What is the nature of the polar regional circulation and how does the circulation moderate transport of aerosols and volatiles into and out of the polar caps?
- What processes are important in cloud formation?
- What controls the evolution and structure of Martian dust storm systems?
- How does the atmosphere interact with the surface in terms of mechanically eroding, transporting, and depositing sediment, and sculpting the surface?
- What processes control the dynamics of the boundary layer? How important are tides vs. slopes in generating the diurnal cycle of wind at the surface?

## Mars MM5

The basis of the model used is the fifth-generation (version 3) PSU/NCAR Mesoscale Model (MM5) which we have adapted for Mars. The original version of the model is described by *Anthes and Warner* [1978] and the current version is described by *Dudhia* [1993]. The model is nonhydrostatic and uses time split-explicit integration. The model uses an Arakawa “B” grid, where temperature and pressure are calculated at grid points at the center of a box, and the winds are calculated at the corners of the box. The MM5 uses three different types of map projections: Mercator, Lambert conformal, and polar stereographic. In each case, placement of grid points is constrained to form squares in the particular map projection chosen for the given simulation. The model also uses terrain-following sigma-coordinates, with an upper boundary set by the user. The model allows for arbitrary domain specification (using 3 different map projections) and for multiple domain nesting, which creates higher-resolution areas within the coarser grid. These higher-resolution domains can be nested one within each other up to a maximum of 10 times. The initial and boundary conditions are provided by the Geophysical Fluid Dynamics Laboratory (GFDL) Mars General Circulation Model (GCM).

Conversion of the model to Mars involved three different types of modification. First, we made structural changes within the model related to the time integration of the various forcing functions. These included the planetary rotation and orbital revolution periods and modification of the model’s definition of a “day” and a “year.” We also replaced the model’s orbital code which generates the daily and seasonal cycles of solar insolation. Second, various constants within the model such as the planetary radius, the Coriolis parameter, the gravitational constant, the gas constant of the atmosphere, and the solar constant. Third, the wholesale replacement of parameterizations for physical processes which are significantly different on Mars, such as radiation, the surface and subsurface heat balance model, the $CO_2$ cycle, the water cycle, and the dust cycle. In all cases the Mars-specific and scale-independent parameterizations are taken directly from the version of the Geophysical Fluid Dynamics Laboratory (GFDL) Mars General Circulation Model (GCM) described by *Wilson and Hamilton* [1996].

The model includes the radiation scheme used in the *Wilson and Hamilton* [1996] version of the Geophysical Fluid Dynamics Laboratory (GFDL) Mars General Circulation Model (GCM). This radiation scheme treats solar absorption by $CO_2$ gas using a parameterized band model [*Burk*, 1976] and by atmospheric dust using a two-stream model [*Briegleb*, 1992]. The optical depth used in the radiation code is derived from dust tracers of two particle sizes that are advected and diffused by the model dynamics. In the infrared, radiative heating due to $CO_2$ is treated using the band model of *Hourdin* [1992]. For dust the infrared scheme developed by *Haberle et al.* [1982] is used, and again the optical depths derived from the model dust tracers are used. The optical properties for dust are the same as used in *Wilson and Hamilton* [1996]. Radiative effects due to water ice and $CO_2$ ice are not treated. In the case of $CO_2$, this is justified as $CO_2$ ice will only form in the depths of polar night. Water ice may play a role under certain circumstances, such as in frontal cloud systems and in the tropical cloud belt in northern summer.

The surface models used were topography derived from the Mars Orbiter Laser Altimeter (MOLA); albedo maps of the equatorial regions are from *Pleskot and Miner* [1981] and of the polar regions from *Paige et al.* [1994] and *Paige and Keegan* [1994]; and ground thermal inertia maps of the equatorial region from *Palluconi and Kieffer* [1981] (as modified by *Haberle and Jakosky* [1991]) and of the polar regions from *Vasavada et al.* [2000]. The ground temperature calculation scheme uses a 12 layer subsurface heat diffusion model that captures the annual and seasonal temperature waves by simulating the uppermost 2 m of the subsurface. The subsurface layer temperatures are initialized from the GCM input, and are implicitly integrated (as implemented in the GCM [*Wilson and Hamilton*, 1996]).

The model has been modified to handle the presence of interactive tracers, such as dust particles, which are used in the radiation scheme. Two dust particle sizes are currently used as described in *Wilson and Hamilton* [1996], although this will be expanded to a greater number in the future. The water cycle is also simulated in the model, including water vapor transport, atmospheric ice formation, transport, and precipitation, and the formation of surface ice deposits. These process are taken from *Richardson* [1999] and used in place of the various hydrological cycle parameterizations included in the terrestrial version of the MM5. In the case of transport of dust, water vapor, and water ice, the tracer transport dynamics built into the MM5 were used unmodified. $CO_2$ ice is not treated as an aerosol in the current version of the model.

The MM5 boundary layer option we employ in our simulations is the Medium Range Forecast (MRF) scheme, based on the one used in the National Center for Environmental Prediction (NCEP) Medium Range Forecast (MRF) model. It is described by *Hong and Pan* [1996] and is based on the formulation by *Troen and Mahrt* [1986]. This parameterization of the boundary layer is only modified by the coupling to the calculation of surface temperatures and heat fluxes determined by the Mars sub-surface model. Even in the very highest vertical resolution simulations, we do not fully resolve the spectrum of turbulent motions. As the resolution increases, an increasing fraction of the spectrum is captured explicitly by the model. However, there is still the need to represent the effects of the remaining unresolved turbulence for which the boundary layer parameterization is used.

Since the model does not start from rest (e.g., no winds and an isothermal temperature structure) there is no traditional “spin-up” time. However, experience shows that the first day of integration is affected by adjustment from the initial conditions to a balanced higher-resolution simulation. This time scale is roughly consistent with the radiative time scale of the Martian atmosphere.

## Initial Results

In comparing to the GFDL Mars GCM, the Mars MM5 is found to accurately capture most of the structures generated in the GCM when the Mars MM5 domain is essentially global. This fidelity extends even to the reasonable simulation of the three-dimensional distribution of dust, which involves detailed radiative and dynamical feedback systems.

Near-surface air temperatures measured by the two Viking Landers and Mars Pathfinder are relatively well-simulated for all seasons examined. This suggests that both the subsurface heat diffusion code and the surface layer parameterization are good.

The Mars MM5 faithfully reproduces the variations in surface pressure generated by the GCM. As most of these pressure variations result from large to global scale dynamical systems (e.g., the global tide or baroclinic storm systems), it is not surprising that the Mars MM5 does not significantly alter them. Indeed, the fact that they are reproduced so faithfully suggests that the coupling of the Mars MM5 to the GCM through the time-evolving boundary conditions is well-implemented.

Wind directions for all the landing sites and for all seasons are relatively well-reproduced. In most cases, the Mars MM5 variation in wind directions is not greatly different from that generated by the GCM. This suggests that control of wind directions is provided by the global tide as modified by topography on a scale greater than a few hundred kilometers. However, we have observed that locations in the Mars MM5 model domain that are more proximate to large local topography exhibit significant deviations from the large scale (GCM-predicted) flow (not shown). We also note that the wind directions provided by the GCM are reported for a height of roughly 200 m above the surface, and that consequently there appears to be little rotation in the lower boundary layer. In general, the prediction of wind directions appears to be quite good, although we typically underpredict peak wind speeds.

A significant result in relation to previous studies of the diurnal cycle of winds relates to their driving mechanism. In one-dimensional boundary layer models it has been common to apply uniform upper level winds and allow the diurnal cycle of wind to be generated by slope forcing [*Haberle et al.*, 1993; *Savijärvi and Siili*, 1993]. Our results suggest that the global tide is at least as important as local slope in generating the variability of winds. Indeed, at Mars Pathfinder and Viking Lander 2, slopes on a scale smaller than that of the GCM grid spacing (a few hundred kilometers) are not particularly important.

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