AN ABSTRACT OF THE DISSERTATION OF

Daniel Tyler, Jr, for the degree of Doctor of Philosophy in Atmospheric Sciences presented on October, 1, 2004.
Title: A Mesoscale Model Study of Atmospheric Circulations for the Northern Hemisphere Summer on Mars.

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Jeffrey R. Barnes

The Penn-State/NCAR MM5 mesoscale model was adapted for mesoscale simulations of the Martian atmosphere (the OSU MMM5). The NASA Ames Mars GCM provides initial and boundary conditions. High-resolution maps for albedo, thermal inertia and topography were developed from Mars Global Surveyor (MGS) data; these baseline maps are processed to appropriate resolutions for use in the GCM and the mesoscale model. The OSU MMM5 is validated in Chapter 2 by comparing with surface meteorology observed at the Viking Lander 1 (VL1) and Mars Pathfinder (MPF) landing sites. How the diurnal cycle of surface pressure (the surface pressure tide) is affected by boundaries, domain/nest choices and the resolution of surface properties (topography, albedo and thermal inertia) is examined. Chapter 2 additionally shows the influence of regional slope flows in the diurnal surface pressure cycle for certain locations on Mars. Building on the methods of Chapter 2, Chapter 3 describes the northern midsummer polar circulation and the circulations (both large and small scale) that influence it. Improvements to the model for these studies include: the topographical gradient is now considered when computing surface insolation, and the thermal inertia maps and model initialization
are improved for high latitudes; this yields a realistic simulation of surface
temperatures for the North Pole Residual Cap (NPRC) and the surrounding region.
The midsummer polar circulation is vigorous, with abundant and dynamically
important transient eddies. The preferred locations of transients varies significantly
during this study, between \( L_s = 120 \) and \( L_s = 150 \). At \( L_s = 120 \) transient circulations are
seen primarily along the NPRC margin, consistently producing strong flow over the
residual cap (~15 m/s). By \( L_s = 135 \), transient eddies form a "storm track" between the
northern slopes of Tharsis and the NPRC. By \( L_s = 150 \), the circulation is becoming
strong and winter-like. These transient eddies may be important in the Martian
annual water cycle; many of the observed circulations are poorly (or not) simulated in
present day Mars GCMs. Increased resolution and polar stereographic domains
provide improvement over GCMs for high latitude studies of atmospheric
circulations. These results are in agreement with recent observations. Future work
includes model refinements and water vapor transport studies.
A Mesoscale Model Study of Atmospheric Circulations for the Northern Hemisphere Summer on Mars

by

Daniel Tyler, Jr.

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Daniel Tyler, Jr., Author
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A Mesoscale Model Study of Atmospheric Circulations for the Northern Hemisphere Summer on Mars

1. General Introduction and Overview

The "Red Planet" has always fascinated Mankind. Its color in the dark night sky and its erratic movement across the background of stars are central reasons for why so much interest and wonder have been directed towards Mars throughout human history. As Astronomy became a true science, emerging from the dominion of religious doctrine/dogma, Mars influenced our models of the Universe. Kepler would not have been able to reach his conclusions about planetary orbits if it were not for the highly eccentric orbit of Mars. Mars, however, does not give up its secrets easily; it is a small planet, with a radius about half that of Earth (3393 km), which makes telescopic observations from the surface of Earth very difficult indeed. Although, with rare seeing conditions (a very clear and stable atmosphere), and if observed during a perihelic opposition (occurring with a period of ~16 yr), we can indeed see enough of Mars through surface based telescopes to wonder, and even wonder rather imaginatively...

Examining the work of Giovanni Schiaparelli and Percival Lowell (the most important telescopic observers of Mars in history) causes us to realize that surprising connections between the limitations of the human eye, the failings of language and the power of the human imagination can easily lead honest science awry. Lowell was a brilliant and imaginative man who “saw” a great deal more in his telescope than was actually there. He believed that the canali of Schiaparelli (Italian for channels) were canals constructed by a dying Martian civilization to bring water from the polar ice caps on Mars (assumed to be water at the time) to the lower latitudes for survival. These linear features (canali/canals), fleeting structures seen through the telescope by
Schiaparelli, Lowell and others, are fundamentally optical illusions. However, the power of how Lowell had interpreted what he saw captivated the world; and, despite some early remote-sensing spectroscopy performed in the 1950s that demonstrated otherwise, Lowell’s story remained highly accepted until dramatic photographs taken during the Mariner 4 fly-by (July 4, 1965) revealed Mars to be very much like the Moon, a dead cratered world...

Throughout the study of Mars there have been many interesting flip-flops in scientific views of the planet. The images sent back to Earth by Mariner 9 (late in December, 1971) showed Mars to be a much more interesting place than had been revealed by Mariner 4, with huge shield volcanoes and enormous channels that had presumably directed massive floods, enlivening the ideas of a dramatically altered climate and the possibility of life. Readers that are interested in greater details are referred to Sheehan (1996) for an accessible, comprehensive and entertaining discussion of how our thoughts about Mars have changed with our “science” during known history. Sheehan (1996) ends by describing some of the important scientific questions facing present day Mars scientists and the planning of missions that are, at the time of this writing, providing extremely rich datasets to help describe the surface, atmosphere and climate(s) of the Red Planet.

1.1. The Changing Climate(s) of Mars

The NASA Viking missions of the late 1970s provided a wealth of data that sustained Mars science for more than twenty years, a dramatic leap forward from that of Mariner 9. A huge treatise was compiled to gather this information in one single volume (Kiefer et al., 1992); it is a comprehensive description of the state of Mars science that includes detailed reports from all disciplines. The discussion in this section, which can be considered based on numerous chapters from Kiefer et al. (1992), will briefly describe our understanding of the Martian climate system as we enter a new era of discovery, with new missions and the arrival of new Mars data.
The atmosphere of Mars is 95% carbon dioxide with a mean global and annual surface pressure of ~6 mbar. Every year a dramatic cycle in the mass of the atmosphere occurs (~25% variation), as carbon dioxide condenses on the surface (or falls condensed to the surface) during winter at high latitudes in both hemispheres; it sublimes back into the atmosphere each spring. The resulting cross equatorial mass flow is dramatic and this annual cycle is by no means symmetric in strength and season with respect to the two hemispheres; the seasonal carbon dioxide ice cap that forms in the southern hemisphere is much larger than its counterpart in the north. One of the most important factors causing this asymmetry is the eccentricity of the present day orbit; the southern winter/summer is long/short whereas the northern winter/summer is short/long. Additionally, the topography in the south is different from that of the north in two important ways; the southern hemisphere is much higher on average than the northern hemisphere, although the zonal variation of topography in the north is generally more dramatic than in the south. This is seen in Fig. 1.1, and
may be very important in terms of how weather systems differ between the two hemispheres.

A further distinction between hemispheres is that the southern hemisphere surface is ancient compared with that of the north. The southern hemisphere is primarily heavily cratered terrain dating back to the formation of the solar system at the end of heavy bombardment (~3.8 Gyr ago). The northern hemisphere surface exhibits far fewer craters in comparison and is thus generally much younger. It is only in the heavily cratered terrains where we see the channel features called Valley Networks. The Valley Networks are much smaller than the huge Outflow Channels such as Valles Marineris (the largest canyon system in the solar system, seen to the east of the highest plateau on Mars in Fig. 1.1, Tharsis); they are believed to be evidence of sustained flow over time. The morphology of the Valley Networks is not fully understood, although they must all be very old since they are only seen within the heavily cratered ancient terrains. Somewhat surprisingly these Valley Networks exhibit a high degree of variability in their state of erosion, with some only barely remaining visible and others quite pristine. The prevailing hypothesis is that long ago when the Valley Networks were still forming there was a dramatic change in the climate of Mars, specifically the rate at which surface erosion occurred, which left the Valley Networks that formed at the end of this period of changing climate far less eroded. This idea is closely related to the controversy over a warm and wet early Mars with a thick greenhouse atmosphere, an idea that has risen and fallen with the changing paradigms of Mars science.

Additionally, there is strong evidence for much more recent climate change on Mars. At both poles of the planet there are residual ice caps that remain throughout the year. The geologies of these two regions differ significantly and are rather complex; however, both regions exhibit layering in the vertical over large spatial scales (~2000 km) near the poles. This layering is not uniform in the thickness of the layers, geological unconformities can be seen and much of the vertical structure may still be hidden beyond the resolution of the most sophisticated imaging taken of the
polar regions to date. It is widely believed that these Polar Layered Deposits (PLDs) develop over time due to "Milankovich cycles" in the orbital parameters of Mars: the obliquity (tilt of the spin axis), the eccentricity (non-circularity of the orbit) and the precession of the spin axis. These parameters evolve chaotically, changing in response to gravitationally induced forces/torques from other bodies in the solar system. Since the distribution of the mass of the planet Mars is highly asymmetric in comparison to that of the Earth, the gravitational torques on Mars are much larger and the chaotic variation of obliquity is far more dramatic.

The obliquity of Mars (which is presently 25.2°) varies between 15° and 35° with a period of 120 kyr, although in more ancient epochs (~2 Gyr ago) it has probably reached 60°. The obliquity of the Earth (which is presently 23.5°) varies between 21° and 24.5° with a period of 42 kyr. The eccentricity of Mars (which is presently 0.093) varies between zero and 0.13 with a period of 2 Myr. The eccentricity of the Earth (which is presently 0.017) varies between zero and 0.05 with a period of 95 kyr. At low obliquities huge perennial carbon dioxide ice caps will form at both poles and the atmospheric mass will be very low; at high obliquities thin seasonal caps will form as described above and large dust storms will occur each spring, excited by the strong winds that form in response to the dramatic surface temperature gradients (~100 K) along the edge of the receding seasonal carbon dioxide caps in the much more massive atmosphere (even ~10^6 times more massive).

The hypothesis is that the result of these two different extremes leaves alternating layers of ice and dust (maybe just cleaner ice and dirtier ice) at the poles. Accepting that the formation of the PLDs is governed by chaotic cycles upon chaotic cycles, the complexity of polar geology can be accepted easily. With Mars, a sophisticated understanding of the climate of the polar regions is paramount to understanding the climate of the entire planet.

As with studies of the terrestrial atmosphere, General Circulation Models (GCMs) have become very important tools for describing the large-scale atmospheric circulations, the natural variability of the atmosphere and the climate of Mars. These
models have shown how the Hadley Circulation on Mars is a cross-equatorial cell, quite distinct from the two-cell structure seen with the Earth. Mars GCMs simulate the annual cycle of atmospheric mass (the formation of the seasonal polar caps) quite well, although this success is achieved through a high degree of parameterization of the seasonal frost radiative properties (Robert M. Haberle, personal communication, 2004). Output from Mars GCMs has also been very important in describing the structure and variability of the upper atmosphere, aiding in the development of aerobraking techniques for spacecraft establishing Martian orbit, such as with the Mars Global Surveyor mission. Most Mars GCMs, however, are grid point models that are limited by lower model resolutions; and, their results at high latitudes are hindered by a "pole problem." This "pole problem" stems from the fact that grid point GCMs are traditionally integrated on domains in spherical coordinates with constant latitude and longitude spacing. Thus, due to the convergence of meridians near the pole the true model resolution becomes poor in the N/S direction compared to the E/W direction. This "pole problem" leads to a poor simulation of atmospheric dynamics near the poles due to the very elongated rectangles that Mars GCM gridboxes have become. New datasets will require more accurate simulations of polar circulations as we strive to develop a better understanding of polar weather and climate. Thus, other viable approaches must be considered, which is one of the primary reasons that atmospheric mesoscale models are being adapted to study Mars.

1.2. New Data and the Need for Mars Mesoscale Models

The NASA Mars Global Surveyor (MGS) mission has been returning data that is bringing studies of the Martian atmosphere into a new era (MGS entered Mars orbit on 9/12/1997 and completed its prime mapping mission on 1/31/2001; the extended mission continues at the time of this writing). For studying the atmosphere of Mars, three instruments on MGS have gathered extremely useful data. The Mars Orbital Laser Altimeter (MGS/MOLA) provided very accurate high-resolution maps of the
topography of Mars (Zuber et al., 1998). Additionally, MGS/MOLA provides observations of polar winter cloud heights (Pettengill et al., 2000); and, analysis of MGS/MOLA data is even allowing for estimates of the thickness of the seasonal carbon dioxide polar frost deposits (Smith and Zuber, 2003). Data from the Thermal Emission Spectrometer (MGS/TES) provides global maps of surface thermal properties and global observations of atmospheric and surface temperatures at ~0200 and ~1400 Local Mean Solar Time (LMST) (Christensen et al., 1998; Christensen et al., 2001; Mellon et al., 2002; Banfield et al., 2004; Smith, 2004). Also aboard MGS is the Mars Orbital Camera (MGS/MOC); the imagery returned from this instrument is extremely useful due to its wide range of resolutions (from ~5 m/pixel to full hemispheric scenes). Imagery of clouds over the northern polar region has provided scaling of polar circulations and estimates of winds (Wang and Ingersoll, 2003). MOC imagery has provided observations of weather phenomena that may repeat annually (Cantor et al., 2002) and has revealed that there are surprising seasonal peaks in cloud abundances over Alba Patera, the northernmost volcano of the Tharsis massif (Benson, et al., 2003). MOC is also providing insight into the structure of developing dust storms (Cantor, 2003).

Along with MGS, there is the Mars Odyssey mission (Odyssey entered Mars orbit on 10/24/2001 and completed its prime mapping mission on 8/24/2004; an extended mission continues at the time of this writing). The Thermal Emission Imaging System (THEMIS) aboard Odyssey is returning spectacular high-resolution visible and infrared imagery of the surface that is helping to answer questions about the importance of water in the geological history of Mars (Christensen, 2003). Also aboard Odyssey are the Gamma Ray Spectrometer (GRS) and Martian Radiation Environment Experiment (MARIE) instruments; data from these instruments are being used to create global maps of water ice in the near subsurface (Boynton et al., 2004; Prettyman et al., 2004).

The Mars Pathfinder (MPF) mission (landed July 4, 1997; final transmission September 27, 1997) provided valuable new in-situ data, late northern summer
records of surface air temperature (three heights), surface pressure and wind direction (Schofield et al., 1997), occasionally at high temporal resolution. However, the MPF wind speed sensor was not correctly calibrated before flight; this problem was never fully resolved and wind speed data from this mission was never widely released. The only other in-situ atmospheric observations that have been made since Viking are from the Mini-TES instrument aboard the Mars Exploration Rovers (MER). This spectrometer has been pointed upwards to provide the very first high-resolution atmospheric temperature profiles of the Martian Planetary Boundary Layer (PBL) (Wolff, 2004; Squires, 2004). Real data has "holes," and can be difficult to work with; however, modeling is extremely useful for filling in such "holes." In this tried and true fashion, numerous investigators used GCMs to better understand the Viking era data (Pollock et al., 1990; Wilson and Hamilton, 1996; Haberle et al., 1999). Our present day understanding of the Martian atmosphere is surely a testament to such brilliant synthesis of modeling and data. These new data beg present day Mars scientists to do the same.

In terms of improving our understanding of the climate of Mars and the dynamics of the atmosphere through modeling, MGS has provided high-resolution maps of topography, surface albedo and thermal inertia via MOLA and TES. These data are the most important surface properties for producing realistic simulations of atmospheric circulations on Mars; and, they should absolutely be used to improve Mars GCMs. However, as mentioned above, current Mars GCMs are hindered by their relatively coarse spatial resolution and the "pole problem." Current Mars GCMs are additionally limited by the hydrostatic assumption, which means that spatial scales must remain reasonably large since atmospheric pressure is entirely determined by the column of atmospheric mass above:

$$\frac{dp}{dz} = -\rho g. \quad (1.1)$$

There are numerous circulations that would remain poorly or completely unresolved given these limitations, especially within and "near" regions of Mars with complex topography, which may be a large fraction of the planet. Moreover, these
new datasets (as briefly described above) draw our attention towards smaller/shorter length/time scales, into the true realm of mesoscale circulations and the scales and complexities that must be considered to simulate such circulations. The future of modeling cannot be limited by the hydrostatic assumption. The transition to the mesoscale can be described in terms of the Rossby Number:

\[
Ro = \frac{U^2/L}{Uf_0} = \frac{U}{Lf_0}.
\]  

(1.2)

\(U, L\) and \(f_0\) are characteristic scales for speed, length and the Coriolis parameter; thus, the Rossby Number, \(Ro\), is a measure of the acceleration force to the Coriolis force. Small Rossby Numbers describe circulations that are quasi-geostrophic or global in nature with large values of \(L\) and/or smaller values of \(U\). Smaller length scales will increase \(Ro\). Time scales can be defined by \(L/U\), implying that shorter time scales generally imply increased speed scales. As \(Ro\) approaches unity we reach the mesoscale, with circulations that are importantly influenced by both large-scale and small-scale forcings. Terrestrially speaking, severe weather is mesoscale in nature; and, as we begin to describe the smaller, stronger and shorter duration circulations on Mars, we will become familiar with the Martian mesoscale.

Some prominent examples of mesoscale circulations on Mars that warrant detailed study are: local and regional dust storms, frontal structures associated with transient baroclinic eddies, the regional structure of the diurnal and semidiurnal thermal tides, the local and regional nature of “western boundary currents” and the full 3-D evolution and interaction of slope flows (including complex katabatic flows off the permanent polar ice caps, which are climatologically important in the annual water cycle). New tools are required to study such circulations and the new datasets will help to resolve these circulations. The appropriate tools are mesoscale models for the Martian atmosphere. The final section of this chapter introduces the model that was developed at Oregon State University as part of this doctoral research and serves as an introduction for the two manuscripts contained in Chapters 2 and 3 of this dissertation which describe research using this model. These two research efforts
have contributed importantly in defining the direction this research has taken, and is to be going in the future.

1.3. A New Model of the Martian Atmosphere: the OSU Mars MM5

The Oregon State University Mars MM5 (OSU MMM5) is an adaptation of the MM5 mesoscale model (Fifth-Generation Penn-State/NCAR Mesoscale Model, Grell et al., 1994). The OSU MMM5 was developed as part of this doctoral research. Initial and boundary conditions for the OSU MMM5 are provided by a version of the NASA Ames Mars GCM that is maintained at OSU. Haberle et al. (1999) describe this version of the NASA Ames Mars GCM. Using output from the Ames GCM within the OSU MMM5 involved a great deal of code modification; these methods are described in Chapter 2. Atmospheric radiation on Mars is entirely different from that on the Earth simply because the atmosphere of Mars is 95% carbon dioxide. To address this issue and maintain a high degree of consistency with the Ames GCM boundary conditions the OSU MMM5 uses the same radiation routines that are used in and were developed for the Ames GCM. The PBL scheme utilized in the OSU MMM5 is the MRF (Medium Range Forecast). This scheme has benefited from the work of Troen and Mahrt (1986), who developed the concept of non-local mixing (countergradient flux theory) to represent large eddy mixing in the PBL. The MRF code implemented in the MM5 includes this modification (Hong and Pan, 1996). This scheme should perform fairly well in simulating very strong thermal convection, highly desirable for Mars studies. Atmospheric dust is treated as having a globally uniform vertically decreasing profile, which is part of the NASA Ames Mars GCM radiation package that is used in the OSU MMM5 (see Chapter 2). The atmosphere is assumed dry for all of the simulations described in this dissertation.

The MM5, and thus the OSU MMM5, can be run using either hydrostatic or nonhydrostatic dynamics. For all the simulations described in this dissertation the model was run using the hydrostatic dynamical core. This approach has been taken
for essentially three reasons: 1) during midsummer the hydrostatic approximation is valid beyond even the highest resolutions being used in these studies (18 km); 2) the lesser computational burden of hydrostatic dynamics allows for larger domains and longer simulations (both are important aspects of this work); 3) there are unresolved issues when using nonhydrostatic dynamical cores that were developed for terrestrial modeling in a Martian atmosphere. This third point requires discussion.

Dudhia (1993) developed the nonhydrostatic version of the MM5. He relied on the work of Klemp and Wilhelmson (1978), who realized that certain terms in the pressure tendency equation, terms which represent the contribution of diabatic heating and the convergence of subgrid-scale heat flux, can be neglected to save several computations (the amplitude of these terms is small in comparison to the other terms in the equation for Earth). However, in a nonhydrostatic mesoscale model for Mars these terms should not be neglected since diabatic heating in the Martian atmosphere is important and responsible for significant atmospheric thermal tides (Wilson and Hamilton, 1996; Zurek and Haberle, 1988). As part of an international workshop to compare Mars mesoscale models it was noticed that nonhydrostatic Mars models would overestimate the diurnal amplitude of the surface pressure cycle (Tyler et al., 2003). After the workshop it was discovered (S. C. R. Rafkin and J. R. Barnes, personal communication) that the problem is likely a consequence of neglecting these diabatic heating terms in the nonhydrostatic dynamics. The nonhydrostatic dynamics of the OSU MMM5 will be modified at a future date to include these neglected terms so that either dynamical core can be used reliably, broadening the range of scales over which the OSU MMM5 can be used.

Chapter 2 has been published (Tyler et al., 2002); it contains the following important elements: 1) a thorough description of the model development phase for the OSU MMM5; 2) a model validation comparison with surface meteorology gathered at the VL1 and MPF sites; 3) a suite of idealized experiments that shows how finite domain simulations are inherently more problematic for Mars because of thermal tides and reflections from zonal model boundaries; 4) a study that reveals how
topography, albedo, thermal inertia and model resolution all play very important roles in the longitudinal structure of the diurnal and semidiurnal amplitudes of the surface pressure cycle; and, 5) a study that shows slope flows on Mars can significantly affect the diurnal cycle of surface pressure at some locations on the planet.

Chapter 3 is in review at the time of this writing; it represents the first comprehensive study of northern midsummer polar atmospheric circulations using a Mars mesoscale model. The OSU MMM5 was modified in three important ways for this study of northern midsummer polar circulations: 1) the gradient of topography is now considered when determining the solar energy incident on the surface; 2) the thermal inertia data used in the model has been significantly improved at high latitudes to provide a realistic simulation of polar surface temperatures; and 3) the initialization of soil model temperatures has been improved so that the NPRC energy balance is well represented. Three long simulations (29 sols each, a solar day on Mars is ~40 min longer than on Earth) are performed at \(L_o=120\), \(L_o=135\) and \(L_o=150\) (\(L_o\), which is Solar Longitude, is the location of Mars in its orbit around the Sun, \(L_o=0\) is Spring Equinox in the northern hemisphere, \(L_o=90\) is northern Summer Solstice, etc...). Statistics from each of these simulations are determined, presented and compared. The northern midsummer polar circulation is vigorous and filled with dynamically significant transient eddies; there is a great deal of change seen in the period between \(L_o=120\) and \(L_o=150\). The changes observed in the polar circulation agree very well with observations from TES and MOC. As a consequence, the changing nature of the polar circulation and the appearance of strong transient eddies have important implications for the annual water cycle on Mars.

This research is unique in that it examines Mars at spatial and temporal scales that are respectively larger and longer than how others have generally approached Mars mesoscale modeling (Michaels and Raftin, 2004; Toigo et al., 2002, Raftin et al., 2001, Toigo et al., 2003). The methodology used in these simulations (especially those described in Chapter 3) allows for a statistical characterization of circulations that is more akin with that produced in GCM studies. Examination of Martian
circulations at intermediate spatial and temporal scales should prove extremely valuable as we reconsider the importance of model resolution, domain choices and the "pole problem" in modeling efforts with new models for the Martian atmosphere. Mars GCMs and Mars mesoscale models are now both important research tools; studies at intermediate scales will surely aid our understanding of numerical modeling issues and how the different scales of circulations on Mars interact. Future studies with the OSU MMM5 will certainly require smaller scales and nonhydrostatic dynamics for certain studies. Having a tested hydrostatic mesoscale model to compare with at intermediate resolutions will be valuable. However, the hydrostatic model may prove most important to have for initializing a nonhydrostatic model (the construction of boundary and initial conditions) from an atmosphere that is already spun-up at scales similar with those being studied.
Simulation of Surface Meteorology at the Pathfinder and VL1 Sites Using a Mars Mesoscale Model

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Abstract

The MM5 (Fifth-Generation Penn-State/NCAR Mesoscale Model) has been adapted to study circulations in the Martian atmosphere. The NASA Ames Mars GCM provides initial and boundary conditions. The meteorology of this Mars MM5 (the OSU MMM5) is compared with Pathfinder and VL1 data for late northern summer. The MMM5 uses an equator-crossing semi-global polar stereographic mother domain, significantly reducing the boundary reflections inherent in Martian mesoscale simulations. Using two-way nests, simultaneous simulations of two regions are performed: 1) Chryse Planitia (MPF/VL1) and 2) the central chasmas of Valles Marineris. Simulations are hydrostatic and dry. The MMM5 uses the same atmospheric radiation package as the GCM, but a much-enhanced near-surface vertical resolution and a different PBL scheme. Model topography, thermal inertia and surface albedo maps have all been developed using the most recent data from the MGS MOLA and TES experiments. The diurnal cycles of surface air temperature, surface pressure and surface wind all show improvement in comparison with the GCM. For certain regions the local surface pressure tidal amplitudes are strongly dependent on the resolution of the model and/or the topography; VL1 and MPF are in such a region. The diurnal cycles of wind are complex, and for many locations the near-surface winds are dominated by slope flows of multiple scales. Comparison with data indicates that resolving these slope flows is very important for simulating the diurnal wind cycle. At specific locations these slope flows dramatically influence the diurnal surface pressure cycle.
2. Simulation of Surface Meteorology at the Pathfinder and VL1 Sites Using a Mars Mesoscale Model

2.1. Introduction

The Pathfinder and MGS missions have returned exciting new data from Mars. With data continuing to accumulate, our understanding of Mars is maturing, making it clear that the present climate is the latest chapter in an interesting and complex history. A full investigation of climate change requires knowledge of the present-day energy balances and of atmospheric circulations at all scales, a daunting task. The mesoscale is the conduit through which the general circulation and micrometeorology interact; climatologically it is extremely important. It is also the most difficult meteorological scale to study dynamically, since both large-scale and small-scale forcings can play very important roles. Computer models must be significantly more complex to account for all of the important factors. As for Earth, mesoscale modeling will be critical for improving our understanding of Martian weather and climate. This paper presents the key initial results from a study with one of the first mesoscale models of the Martian atmosphere.

The present-day understanding of Martian weather and climate has grown from the Mariner 9 and Viking missions of the 1970s, as well as through numerous Earth-based observations. Computer modeling has played a major role in efforts to better understand the Martian atmosphere and climate, but until very recently these studies have only been conducted on large scales or with idealized 1-D or 2-D models. GCMs have contributed significantly in efforts to describe and understand the general circulation and climate of Mars (e.g., Haberle et al. 2001, Wilson and Hamilton 1996, Zurek et al. 1991, Zurek and Haberle 1988, Pollack et al. 1990). 1-D modeling has increased our understanding of meteorology within the Martian Planetary Boundary Layer (PBL) (Savijarvi 1999, Haberle et al. 1993). Other 1-D models have yielded understanding of primordial Martian atmospheres that is
important for climate evolution; the work of Kasting (1991) placed important physical constraints on the greenhouse effect that could be provided by an H₂O/CO₂ atmosphere. Other studies have used 2-D models to investigate the strong slope flows and low-level nocturnal jets which are expected to exist given the huge Martian topography and the near-surface environment that is so strongly dominated by radiative forcing (Savijarvi and Siili 1993, Siili et al., 1999).

Current GCMs are hindered by relatively coarse spatial resolution and the hydrostatic assumption; 1-D and 2-D models can only provide idealized solutions. Thus, there are numerous mesoscale circulations that will remain poorly or completely unresolved in such models, especially within and over complex topography. Some prominent examples of mesoscale circulations that warrant detailed study on Mars are: local and regional dust storms, frontal structures associated with transient baroclinic eddies, the regional structure of the diurnal and semidiurnal thermal tides, the local and regional nature of “western boundary currents” and the full 3-D evolution and interaction of slope flows (complex katabatic flows off the polar ice caps are climatologically important in the water cycle).

Using data gathered during the Pathfinder and Mars Global Surveyor missions (surface meteorology from Pathfinder, topography from MOLA, and albedo, thermal inertia and temperatures from TES), higher resolution atmospheric modeling has become more appropriate. In this paper we introduce a new model to study mesoscale circulations on Mars. Our results are carefully compared against data gathered by the ASI/MET instrument flown on Pathfinder, as well as with data gathered by Viking Lander 1 (VL1) for the same season. Model results are also compared with the NASA Ames Mars GCM, showing that the use of 3-D mesoscale models can be very revealing, providing information not otherwise available.

Rafkin et al. (2001) have recently developed a fully nonhydrostatic 3-D mesoscale model for Mars and have used this model to perform simulations of Pathfinder meteorology, mountain waves, crater circulations, and very small-scale boundary layer circulations. Their model is based upon the terrestrial RAMS
mesoscale model; they make use of the same Mars radiation schemes that we have adopted (from the Ames GCM). The RAMS model is based upon a basic system of dynamical equations that is different from those used here, and it uses different numerical methods and grids. Additionally, the PBL scheme and the soil temperature model differ from those employed within our model. Thus, these Mars mesoscale models are quite independent, despite sharing the same radiation algorithms and using Ames GCM output for boundary and initial conditions. The model domains employed in this study are dramatically different than those utilized by Rafkin et al. (2001), which is of central importance for many of the results presented in this paper.

Very recently, Toigo and Richardson (2002) have developed a Mars mesoscale model that is also based upon the MM5 modeling system (Fifth-Generation Penn-State/NCAR Mesoscale Model, Grell et al., 1994). They have performed various simulations of Pathfinder, VL1 and VL2 meteorology. They use the GFDL Mars GCM for boundary and initial conditions, and use the radiative schemes from that model in their Mars MM5. Beyond these differences, the greatest difference from the studies presented here is that Toigo and Richardson (2002) make use of very small mesoscale model domains, domains that are only 125 km on a side, smaller than a single GCM gridbox. The approach that we have adopted for this study is quite different; we use very large and nested domains, in which the coarsest grid resolution (mother domain) is not much smaller than that used with the Ames GCM in which our model is itself nested. This approach is typical for terrestrial mesoscale studies.

As is very much the case with GCMs, multiple independent models are essential for studying mesoscale circulations and near-surface meteorology. Comparison of independent simulations can provide much greater confidence in results, leading to basic improvements for all models. The results obtained in this study are thus highly complementary to those of Rafkin et al. (2001) and Toigo and Richardson (2002); they are also highly unique given the model differences and the methods employed.
2.2. Model Development

2.2.1. Dynamics, Initialization and Boundary Conditions

We have adapted the MM5 for simulating mesoscale circulations on Mars, creating the OSU MMM5. The MM5 evolved from the work of Anthes and Warner (1978). Nonhydrostatic dynamics were added by Dudhia (1993), who lists many of the important contributions in the development of the MM5. The source code is public domain, and the model is certainly prominent on a short list of state-of-the-art research and regional forecast tools currently available.

The hydrostatic dynamical core of the MM5 is being used for these simulations, not the nonhydrostatic. For the studies performed here, given the "moderate" resolutions and particular scientific objectives, the hydrostatic version of the model was deemed to be entirely adequate. This version of the model runs faster computationally than the nonhydrostatic version, allowing longer simulations in the very large model domains required for these studies. On the basis of scaling analyses, nonhydrostatic dynamics will not be of considerable importance until the horizontal length scales of the circulations become comparable to the vertical length scales (e.g., Dutton, 1976). The maximum horizontal resolution used in the simulations here is 20 km; thus, the circulations in the model should be hydrostatic to a good approximation unless they are both very deep (10 km or more) and of the smallest horizontal scales.

Circulations like this do not appear to be present in the mesoscale simulations we have performed, except possibly in Valles Marineris where terrain can be quite steep. For higher resolution studies of such regions (Valles Marineris, Hellas, etc...) nonhydrostatic dynamics will be required. A careful comparison of hydrostatic and nonhydrostatic simulations should be very instructive.

2.2.1.1. Model Initialization. The preprocessing of meteorological data for the MM5 permits analyses from numerous horizontal and vertical grids, but this data
is generally expected on standard atmospheric pressure levels. Use of the Ames GCM to provide boundary and initial conditions required significant modification of the MM5 preprocessing codes.

The version of the Ames GCM we are using is very similar to the one described by Haberle et al. (1999). We are running the model on the standard 25x40 grid (7.5° in latitude and 9.0° in longitude). The GCM uses a sigma ($\sigma$) vertical coordinate, defined as:

$$\sigma = \frac{p_\sigma - p_{top}}{p_{top} - p_{top}} = \frac{p_\sigma - p_{top}}{p^*}.$$  \hspace{1cm} (2.1)

A value of $\sigma = 0$ signifies the model top, and $\sigma = 1$ at the ground; sigma is a terrain following vertical coordinate. We run the Ames GCM with 30 vertical layers with the model top at 50 nbar (0.00005 mbar). The hydrostatic OSU MMM5 uses the same sigma vertical coordinate, although we use a much lower model top ($p_{top} = 0.03$ mbar) and a much greater near-surface vertical resolution than in the GCM. The top of the MMM5 was chosen to coincide with the pressure level where the mean temperature structure becomes isothermal in the GCM, the Martian "tropopause."

Using the Ames GCM with the OSU MMM5 requires the conversion of GCM data (on sigma levels) to appropriate pressure levels at each MMM5 mother domain gridpoint. Since there are dramatic differences between the highly smoothed GCM topography and that of the MMM5, a realistic representation of the relatively smooth meteorological fields of the GCM over the much more complex terrain in the MMM5 is important. The construction of a complex terrain surface pressure field, consistent with the GCM and accounting for the MMM5 mother domain topography, solves the problem.

This complex terrain surface pressure is a hydrostatic refinement of the GCM surface pressure interpolated to each mother domain gridpoint. It is dependent upon the difference in topography and a pressure scale height. Using a mean near-surface temperature ($\bar{T}$) that is appropriate for that time and location, the pressure scale height is:
The complex terrain surface pressure is then:

\[ H = \frac{RT}{g} \]  

(2.2)

The complex terrain surface pressure is then:

\[ P_{\text{MMM5}} = P_{\text{GCM}} \exp(-dz/H). \]  

(2.3)

The difference in topography \((dz)\) is equal to the topography of the mother domain minus the GCM topography interpolated to that location.

At each MMM5 location the complex terrain surface pressure is used in the definition of sigma to determine the modified pressure for each GCM sigma level (now over complex terrain). All meteorological fields are then interpolated to the pressure levels we have adopted for use in our modified MM5 preprocessing codes. In the final preprocessing step these fields are used to generate initial conditions and hourly boundary condition updates on the MMM5 sigma surfaces.

To first order, atmospheric variables in the Martian PBL are most strongly influenced by the local height above ground. Using the complex terrain surface pressure field when converting GCM data to a pressure vertical coordinate assures that we are generating pressure dependent profiles that are consistent with this fact. We use 32 sigma levels in the MMM5 simulations discussed in this paper. At Pathfinder in the 20 km Chryse Planitia nest, the average height for the middle of the lowest layer is 1.7 m above ground; the middle of the second layer is at 7.4 m, and the middle of the third layer is at 34 m.

We have insured that meteorological variables near the mother domain boundary initialize to simple interpolations of the GCM profiles by setting the MMM5 topography in the boundary region (five outermost points) to interpolations from the GCM topography (no complex terrain surface pressure modification). Thus, the large-scale parts of the forcing terms used within the boundary region during simulations are exactly as in the GCM (MM5 relaxation boundary condition, Grell et al., 1994). The topography of the next five points inward is a linear blending from the GCM topography to the higher resolution topography of the MMM5, although the dynamics are entirely determined by the MMM5.
Figure 2.1: Location of domains on MOLA topography. Part of the semi-global polar stereographic mother domain boundary is shown (heaviest line). This is where the MMM5 meteorology is held to NASA Ames Mars GCM boundary conditions. The first two-way nest (64x85 at 60 km) surrounds the 20 km nests. Pathfinder (19.2° N, 33.4° W) and VL1 (22.5° N, 48° W) are marked with (*). MOLA topography (at a resolution of 1") is contoured to show geographical location of the MMM5 domains.

We have experimented with numerous mother domain sizes, gridpoint separations, domain locations, and map projections. Our experiments have shown that results can be rather sensitive to such changes. A semi-global polar stereographic mother domain has been adopted, mainly to eliminate problems observed with the diurnal pressure cycles when using other domains. Sizeable boundary reflections, mostly associated with the large amplitude Martian thermal tides, cannot generally be avoided when using Lambert Conformal or Mercator mother domains (zonally limited domains). These reflections are essentially eliminated when using this semi-global mother domain (covering all of Mars to about 45° S latitude). A discussion of why we have adopted this approach is presented in the next subsection. All of the domains used in our simulations (mother domain and the higher resolution nests) are shown in Fig. 2.1.
2.2.1.2. Reflections: A Mars Mesoscale Modeling Issue. Reflections cannot be eliminated from limited-area computer simulations; they will arise simply from differences in the numerical grids across boundaries, as well as from any other differences in the two models being used. In general, the very large diurnal cycles and thermal tides on Mars will always lead to significant problems at the boundaries of limited-area models, where models (or models and data analyses) with differing physics and resolution must interface. The Martian atmospheric thermal tides simply have no terrestrial analogue; they are as large in surface pressure amplitude as hurricanes, and they will pass through any zonal boundaries each day.

For terrestrial studies, mesoscale model domains can be designed so that the circulations being studied will not pass through boundaries during simulations. For Earth, these circulations are generally midlatitude cyclones and the speed at which they travel is quite slow; large domains can generally contain them for periods appropriate for their study or for real-time forecasts (a few days). Nests are utilized to examine regions of interest at higher resolutions, where the physics, dynamics and vertical grid structures are generally duplicated on either side of the nest boundary. In the MM5, much attention is directed at smoothing out any reflections that would occur at nest boundaries because of discontinuities in horizontal resolution. Grell et al. (1994) describe the numerical methods used at nest boundaries in the MM5, and Haltiner and Williams (1980) explain some of the reasons these methods are required.

Our decision to adopt a semi-global polar stereographic mother domain resulted from the success it provided in eliminating the large boundary reflections that were observed when using zonally limited mother domains. For Mars, containing the very large diurnal cycles within zonally limited domains is simply not possible. This is because of the very high speeds at which they travel and the time periods required for simulating mesoscale circulations. The passage of strong tidal signals through zonal boundaries cannot be avoided in simulations of a sol or longer; thus, there will be reflections at these boundaries whenever any mismatches in dynamics, physics,
and resolution (vertical or horizontal) exist. Unrealistic horizontal gradients in meteorological variables will appear at boundaries when none in reality exist.

Applying state-of-the-art mesoscale models to Martian studies is a new field, and the unique modeling challenges in simulating Martian circulations are just starting to be addressed. Using a semi-global polar stereographic mother domain to eliminate zonal boundaries is one approach to addressing these fundamental problems that arise from the dramatic diurnal cycles on Mars. For the simulation of Martian dust devils (a LES study), as in Rafkin et al. (2001), the model can be initialized from a single vertical profile and the boundary conditions can be treated as cyclic, thus eliminating all reflections.

Toigo and Richardson (2002) employ a very small domain in their simulations, one that is actually smaller than a single GCM gridbox. This effectively forces the mesoscale model to closely follow the GCM it is nested in, minimizing boundary reflection problems. However, to capture the evolution of all but the smallest scale mesoscale circulations requires much larger model domains. The simulation of complex and multiple-scale slope flows requires relatively large domains, since these circulations can span large distances over diurnal time scales.

2.2.1.3. Simulations on a “cue ball” Mars. We have performed a suite of experiments to demonstrate the benefits of removing zonal boundaries from the mother domain. These simulations use the semi-global polar stereographic mother domain, or one of two Mercator mother domains. Each simulation uses boundary and initial conditions generated from a GCM run that was performed with a completely homogeneous surface (flat topography and constant/mean albedo and thermal inertia, our “cue ball” Mars). The MMM5 was run using this same homogeneous surface. After allowing for spin-up the MMM5 surface pressure output is used to generate average diurnal surface pressure cycles at each gridpoint. These cycles are decomposed into diurnal and semidiurnal amplitudes and the resulting fields are interpolated to the latitude of Pathfinder (19.2°), yielding longitudinal tidal amplitude profiles for each case. These data are compared with the corresponding GCM
profiles in Fig. 2.2. With a homogenous surface and spatially uniform dust the
diurnal and semidiurnal tidal amplitudes will be constant in longitude (except for
normal mode noise), since the excitation of Kelvin modes is essentially eliminated.
This provides a very stiff test for the simulated tidal amplitudes in the mesoscale
model, and allows an examination of the behavior near any zonal boundaries.

**Figure 2.2:** Comparison of diurnal and semidiurnal tidal amplitudes for “cue-ball”
experiments with the MMM5 and the GCM. Amplitudes are interpolated to
Pathfinder (19.2° N). The curves marked with circles are the GCM diurnal (~0.0095)
and semidiurnal (~0.0065) amplitudes. The polar stereographic amplitudes were
constructed from the diurnal and semidiurnal fields at 5° longitude intervals. The
dashed lines in the lower panel are for the large Mercator domain; the solid lines are
for the small Mercator domain.
The tidal amplitudes in the upper panel of Fig. 2.2 are eight sol averages, while those in the lower panel are six sol averages. The GCM profiles are smoother with the longer averaging period, consistent with the existence of atmospheric normal modes. Both Mercator domains have the same latitude range (approximately 40° S to 70° N), but one has a much greater longitudinal extent.

In the lower panel of Fig. 2.2 we see that very large reflections are generated at the western boundaries of the Mercator domains. The shape of the western end of the profiles for each Mercator case is nearly identical for the diurnal (upper) and the semidiurnal (lower) amplitudes in each subplot. This shows that the magnitude of the reflections is independent of the zonal extent of the mother domain. Thus, the reflections are not a consequence of the MMM5 dynamics or physics amplifying the tides as they pass through the mother domain; they are generated at the western boundaries. The MMM5 amplitudes agree exactly with the GCM at the boundary points simply as a consequence of the time-varying boundary condition used in the MMM5.

Since the semi-global polar stereographic mother domain extends well into the southern hemisphere, the strongest tidal amplitudes do not pass through any domain boundaries; thus, the strongest signals cannot produce reflections. The diurnal amplitude in the MMM5 is very well behaved, although it is somewhat larger than that of the GCM. We suspect that this difference is most likely a consequence of using different PBL schemes, since the diurnal tide is very sensitive to surface heating and the transfer of thermal energy into the atmosphere. Since the two models are using the same radiation package and the diurnal amplitude in the MMM5 is 12% larger than that of the GCM, the influence of the PBL scheme on the diurnal amplitude appears to be quite substantial.

Semidiurnal tidal amplitudes are contaminated by boundary reflections in all experiments, but the disagreement with the GCM is significantly reduced when using the semi-global polar stereographic mother domain. Errors are generally much less than 20%, when they can be nearly 50% with the Mercator domains. The mean
semidiurnal amplitude is very close to that of the GCM, consistent with the fact that radiative processes in the atmosphere (the same in both models) are quite important for forcing this tidal mode.

Boundaries and their complicating effects cannot be removed from mesoscale modeling, and a careful consideration of boundary locations is especially important for Mars. The use of a semi-global polar stereographic mother domain completely removes the largest reflections that result from interfacing the OSU MMM5 with the Ames GCM. Anthes and Warner (1978) argue that the location of mesoscale model boundaries is a question of scale that is quite dependent upon the object of study. For Mars the scale is inherently global when considering surface pressure variations, and zonal boundaries cannot be pushed far enough away. An obvious approach for examining the fine structure of atmospheric tides is to use a very high resolution GCM. However, the importance of accurately simulating the spatial variations of the surface pressure tides in a mesoscale model, when modeling regional and local circulations on Mars, is not known at the present time. For phenomena that may involve the local amplification of tides, as has been suggested to play a key role in the genesis of local and regional dust storms (Zurek et al., 1991), it is obviously very important that tides be well-simulated.

The specific lateral boundary condition being used in the MMM5 deserves comment. Presently we use a relaxation boundary condition, the details of which are discussed by Grell et al. (1994). The condition utilizes two forcing terms, a Newtonian linear relaxation term and a diffusion term. These terms are added together to nudge predicted quantities within the mother domain boundary region (five outermost points). The condition allows for a gradual blending and smoothing of model tendencies, from GCM values at the boundary to MMM5 values five points within. The predicted variables for the boundary points are held at GCM conditions and the strength of nudging decreases linearly inward from the lateral boundary. We have experimented with the relative strengths of the diffusion and Newtonian terms by doubling and halving the respective coefficients, but these tests did not yield any
significant reduction in the reflections at western boundaries. We have also experimented extensively with the sponge boundary condition in the MM5, but this condition appears to produce larger boundary reflections than does the relaxation condition.

2.2.2. Radiation Scheme

The terrestrial MM5 schemes for the absorption and emission of atmospheric radiation are not appropriate for Mars. We have adopted the algorithms of the Ames GCM for the parameterization of radiative influences on atmospheric temperatures. These four algorithms (Pollack et al., 1990), determine the solar heating and IR cooling for both CO2 and dust. The mixing ratio for dust in the GCM and MMM5 is assumed to follow a globally uniform vertical profile in pressure, and a dust optical depth of $\tau = 0.35$ is chosen to be consistent with the seasonal period being simulated, as measured by the Pathfinder IMP (Haberle et al., 1999). The four individual forcings are combined into a single radiative tendency, which is then used in the MMM5 as if it was computed with one of the standard MM5 radiative packages.

Verifying our implementation of the GCM radiation package in the MMM5 was done via a suite of test simulations. The first used boundary and initial conditions from a GCM run where solar input was held at the diurnal average value appropriate for each latitude circle (no diurnal cycle). The MMM5 was run using this same constraint, and the ground temperatures used in the MMM5 were set to horizontal interpolations from the GCM temperatures. Atmospheric temperature profiles predicted by the MMM5 remained constant in time and agreed closely with those from the GCM. Small temperature differences were found in comparison between the models, but the wind fields seemed to indicate that these differences were due to adiabatic warming and cooling from circulations over the complex terrains not resolved within the GCM. This first test verified radiative consistency
with the GCM, despite the major differences between the vertical grids used with the two models.

2.2.3. Ground Temperature and Soil Model

Keeping solar forcing at the diurnal average values as described above, prediction of ground temperature in the MMM5 was allowed. The MM5 has a five-layer soil model with a vertical structure much different than used in the GCM, so layers were added and we increased the total depth of the soil model to match the GCM. Consistency with the GCM required that soil conductivity be calculated from thermal inertia (within the soil model). Modifying the soil model structure was important since the diurnal temperature wave will be dramatic in Martian soil (compared to Earth); a greater soil depth and vertical resolution are both required for its simulation. Initial tests revealed that MMM5 surface air temperatures were not agreeing very well with the GCM. A comparison of terms in the surface energy budgets revealed that the surface heat flux predicted by the GCM was significantly smaller than that predicted by the MMM5. A subtle timestep coding error was repaired in the GCM PBL routines, eliminating this discrepancy between surface heat flux predictions. The GCM group at NASA Ames has also modified their PBL routines (R.M. Haberle, personal communication, 2002).

The final step in validating the radiation code was to activate diurnally varying solar forcing. Using the default method of the MM5 to initialize soil model temperatures (all layers set to the local diurnal average surface temperature), it takes four sols for the soil model to fully spin-up. After spin-up, the diurnal cycles of surface energy budget terms in the MMM5 agree very well with those of the GCM. Moreover, considering the differences in solar longitude ($L_s$) and location, the heat flux values and air-ground temperature differences predicted by the MMM5 are consistent with those determined by Sutton et al. (1979) for VL1.
The PBL model being used in the MMM5 is the MRF (Medium Range Forecast). This scheme has benefited from the work of Troen and Mahrt (1986), who introduced non-local mixing (countergradient flux theory) for large eddies in the PBL. The MRF code in the MM5 was modified to include this (Hong and Pan, 1996); it should perform fairly well in simulating very strong thermal convection, desirable for Mars studies. In the MMM5 the MRF scheme is essentially unmodified, although the values of some basic constants were changed. We have experimented with two other PBL schemes available in the MM5 modeling system, and our model results are quite sensitive. Comparisons against data have so far been most successful when using the MRF scheme, but more study with various PBL schemes is needed. The PBL is a critically important aspect of mesoscale modeling, and we suspect that important progress will be made in this realm as studies of this type mature and new data accumulate. However, for the present we accept, as do Sutton et al. (1979), that similarity theories and PBL schemes developed for Earth are also appropriate for simulating the Martian PBL.

In order to run the MMM5 for arbitrary values of \( L_s \) without reconfiguring the basic seasonal scheme, we developed a 12 “month” Martian calendar. Three of these “months” have 55 sols and 9 have 56 sols. Variation of the subsolar latitude in the MMM5 is determined exactly as in the MGCM, and this calendar works seamlessly with the eight-digit date code of the MM5 modeling system.

### 2.2.4. Surface Albedo and Thermal Inertia Maps

Running the MMM5 with an active diurnal cycle requires surface albedo and thermal inertia maps consistent with those in the GCM. Since the MM5 determines surface properties based upon a look-up table for a variety of surface types, further modification of the MMM5 code was required. Our first experiments simply interpolated the smooth GCM maps onto the MMM5 grids. Satisfied that our modifications were functioning correctly we developed maps based on the most
recent MGS data. The OSU MMM5 uses albedo and thermal inertia maps developed from data returned by the TES (Thermal Emission Spectrometer) instrument. Several members of the MGS TES team facilitated the development of these maps (P. Christensen, personal communication, 2000; M. Mellon, personal communication, 2000).

Figure 2.3: Maps of thermal inertia and albedo used with the 60 km nest (color). Thermal inertia is given in (cal cm$^{-2}$ sec$^{-1/2}$ K$^{-1}$) $\times 10^3$. Pathfinder and VL1 are marked by ($\ast$). The topography of the 60 km nest is shown at 1 km intervals.

The thermal inertia and albedo maps used in the 60 km nest are shown in Fig. 2.3. The same data sets used to interpolate these maps are smoothed to generate maps for the MMM5 mother domain. The Pathfinder lander is at 19.2° N, 33.4° W, on a small region of relatively high thermal inertia and a sharp meridional gradient in surface albedo. Since thermal inertia and albedo strongly control the diurnal cycle of temperature at and near the surface, accurate values for both quantities are critical for simulating lander meteorology. The use of this newest MGS data significantly improved the skill of the MMM5 in matching surface air temperatures; we also realized some improvement in our simulation of wind and pressure cycles.

For the 20 km nests in our simulations, the maps of albedo and thermal inertia are not just interpolations of the coarser 60 km nest data, they are generated appropriately from higher resolution data. For the mother domain (180 km) and the
first nest (60 km), thermal inertia and albedo values are generated from a 2° resolution map. For our 20 km nests the values are interpolated from a 1° map. Our surface property maps will be improved as better global datasets become available. Analysis of TES and THEMIS data should allow the development of even better maps of thermal inertia and albedo; however, the MGS TES datasets are already a vast improvement over what has previously been available.

Figure 2.4: Maps of thermal inertia and albedo used with the 20 km Pathfinder/VL1 nest (as in Fig. 2.3). The locations of Pathfinder and VL1 are marked by (*). The topography of the 20 km Chryse Planitia nest is shown at 500 m intervals. The terminus of Ares Valles is just southeast of Pathfinder.

To compare map resolution, the surface albedo and thermal inertia maps used for the 20 km Chryse Planitia nest are shown in Fig. 2.4. The single thermal inertia maximum in Fig. 2.3 (at MPF) becomes two local maxima in Fig. 2.4; the lander is actually on a gradient of thermal inertia, as well as albedo. It is not surprising that previous modeling efforts (e.g., Haberle et al., 1999) have required ad-hoc values of these surface parameters in order to produce results that agree with MPF temperature data. In our comparisons with Pathfinder and VL1 data we use the TES thermal inertia and albedo values at the MMM5 gridpoint that is closest to the lander; interpolations or ad-hoc values are not used. GCM results are interpolated to the lander sites, but the MMM5 results presented for MPF and VL1 in this paper are those of the closest point in the 20 km Chryse Planitia nest.
The MMM5 temperatures shown below agree quite well with the Pathfinder data, indicating that the TES maps are accurate datasets of Martian surface thermal properties. The MMM5 surface air temperatures for VL1 do not match as well as those for Pathfinder. We suspect that the nominal location of VL1 (22.5° N, 48° W) may be somewhat inaccurate, as is suspected to be the case (R. Kirk, personal communication, 2001).

2.3. Simulation Results

The Ames GCM being used to provide initial and boundary conditions is nearly identical to that of Haberle et al. (1999) for their simulations of the Pathfinder ASI/MET data. Our version of the model uses MOLA topography and surface maps of albedo and thermal inertia that were constructed to maintain consistency with the maps generated for the MMM5. The GCM is run for 45 sols so the final output file (sols 30-45) begins at $L_s = 145$, early in the landed phase of the mission (Pathfinder landed at $L_s = 142$). The GCM required ~20 sols to completely spin-up in the configuration we are using (the latitudinal extent of the seasonal polar caps is specified).

The MMM5 is run a total of 14 sols (beginning at $L_s = 145$) using hourly boundary condition updates generated from hourly GCM output. After running the MMM5 for two sols with just a mother domain, we initialize the nests. The model is run another four sols to allow for complete spin-up; we use only the final eight sols of output for our analyses. The MMM5 air temperatures spin-up quickly since they are initialized to GCM values and the same radiation package is used in the MMM5. The soil model requires four sols to spin-up fully since all layers are initialized to the local diurnal mean surface temperature. Thus, the surface pressure and wind cycles also require four sols to spin-up. The soil temperature initialization will be modified for future efforts to shorten spin-up time.
These eight sols of data represent the pseudo-cyclic behavior of the model for the middle of the Pathfinder primary landed mission at the Sagan Memorial Station. With these data we examine the behavior of near-surface air temperature, surface pressure and near-surface winds. The behavior of each of these variables is essentially periodic, as we find with the Pathfinder data, although interdiurnal variability is seen in both the data and the model results. The MPF MET data provides an excellent benchmark for comparing the OSU MMM5 against the much coarser resolution Ames GCM.

2.3.1. Comparison of Near-Surface Air Temperature Cycles

![Near Surface Air Temperatures](image)

**Figure 2.5:** Surface air temperatures at Pathfinder. The lowest MMM5 sigma level (~1.7 m on average) air temperature is shown with red (o) markers. The red (*) markers are MMM5 air temperatures interpolated to a height of 1.27 m (top thermocouple on the MET mast). The yellow points are the continuous MET temperature data for sol 25; the green points are the binned (51 bins/sol) temperatures for the entire 30-sol primary mission. The blue square markers are temperatures from the lowest GCM sigma level (~5 m on average) interpolated to Pathfinder.
In Fig. 2.5 we compare air temperatures from the Pathfinder gridpoint in the 20 km Chryse Planitia nest with measurements taken from the top thermocouple on the Pathfinder MET mast (1.27 m above ground). The open circles are the actual model temperatures at the lowest sigma level (center of lowest layer). The height of this sigma level is nominally 1.7 m, but it ranges from 1.5 m to 2 m. We use the surface air temperature predicted by the MMM5 and the temperature of this lowest sigma level to linearly interpolate a model temperature at 1.27 m; the interpolation accounts for the diurnal variation in height of the lowest sigma level. Linear interpolation provides a reasonable estimate in this case since the lowest model level is so near the actual height of the top thermocouple. Both Haberle et al. (1999) and Lewis et al. (1999) perform interpolations when comparing their model air temperatures with the Pathfinder data; it is an essential step given the very large near-surface lapse rates observed in the Pathfinder data and the variability in the height of sigma surfaces.

Nighttime model temperatures match the data very well, an apparent consequence of using TES albedo and thermal inertia. After sunrise and through the afternoon the agreement is not as good; the MMM5 temperature rises too fast and peaks about 1.5 hrs earlier than was observed. However, the MMM5 does simulate the diurnal amplitude, as the maximum temperature predicted by the MMM5 agrees quite well with observations. The differences between the simulated and the actual daytime temperatures suggest the consideration of two factors.

The first is that there may be physical processes affecting the MMM5 near-surface temperature structure that are not effectively represented in the PBL scheme. The strongly convective regime is an aspect of PBL modeling that many schemes (if not all) appear to simulate only marginally well in terrestrial studies (L. Mahrt, personal communication, 2000). A critical study of the relationships that parameterize strong convection, which appears to dominate the Martian daytime PBL, may be required. It is also quite possible that hydrostatic dynamics are not fully sufficient for modeling temperatures in the surface layer during strong convection.
Future studies with the MMM5 will use the nonhydrostatic dynamical core. The PBL will become a more constrained aspect of Mars modeling as new data are obtained, and as the emerging mesoscale models are applied to its study.

The second factor is that the Pathfinder lander itself has possibly caused some biasing of the MET temperature record, and the observed temperatures are not truly representative of the near-surface environment. Given that the mean flow tends to come across the lander before reaching the MET mast during a large fraction of the period in question (when solar heating and near-surface radiative cooling are most intense), this possibility deserves some consideration. It is believed that actual errors in the measurement of air temperature (from radiation and conduction effects) are small, but biasing due to effects of the lander itself on the local thermal environment is still possible. This happened with the Viking Landers, and was primarily due to the effects of the very warm lander body on the air flowing over it (lander interference). Similar effects could certainly be present in the Pathfinder temperature record; they may also be variable since the thermal properties of the spacecraft are quite different from the surrounding ground. We have examined the point-by-point MPF temperatures and have indeed found at least some evidence for biasing, beginning in the morning and continuing into the middle afternoon just after the daily temperature maximum. The strongest effects appear to occur in the early afternoon, where temperatures appear to be biased towards warmer values than exist in the ambient environment at the same vertical level (when the wind does not pass over the spacecraft the temperatures at all three sensor levels become significantly cooler during this time of day). Without quantifying these effects and then removing them from the data record (as was done with Viking data), it is not clear just how the measured temperature cycle is biased in comparison to the true ambient cycle, but it is certainly possible that both the value of the temperature maximum and its timing are biased in the data.
Figure 2.6: Meteorology at the VL1 gridpoint in the 20 km Chryse Planitia nest is compared with GCM and VL1 data. The black line is the average of the binned VL1 data (green points). The red (★) markers are interpolations of MMM5 data to a height of 1.6 m (height of VL1 sensors); the blue square markers are GCM data from the lowest sigma level (~5 m on average) interpolated to VL1. The red circles in the temperature plot are from the lowest sigma level of the MMM5.

A comparison with VL1 data lends some support to the possibility that the diurnal temperature maximum in the Pathfinder data is indeed biased to later in the day than actually occurs in the ambient atmosphere. Comparing against average diurnal cycles constructed from archived VL1 data (spanning the seasonal range of the MPF mission) we examine the meteorology of the point closest to VL1 in the 20 km Chryse Planitia nest; the comparisons of surface air temperature, pressure and winds are all shown in Fig. 2.6. The MMM5 air temperature is too warm at night and during the warmest times of the day, indicating that higher resolution (or an improved
location for VL1) may be required for an accurate albedo value. However, the MMM5 does agree quite closely with the diurnal amplitude and the timing of the observed daily temperature maximum (MMM5 temperatures are interpolated to the 1.6 m height of the VL1 sensor). We also note that the shapes of the observed and modeled temperature cycles are more similar for VL1 than for Pathfinder.

There may be some biasing of the MET temperatures due to lander interference effects. However, we have not studied the importance of possible small-scale variations in soil thermal properties on the diurnal cycle of air temperature. As Rafkin et al. (2001) point out, assuming that the thermal conductivity of the soil can be completely described using thermal inertia and constant (planet-wide) values for soil density and soil heat capacity is questionable at best.

2.3.2. Comparison of Surface Pressure Cycles

The average surface pressure of all simulations was "calibrated" to the Pathfinder MET data by initializing the GCM runs using a global surface pressure of 5.2 mbar. Differences in model topography will systematically offset the surface pressure cycles of the two models, so to compare surface pressure cycles all data are normalized using the local average. In Fig. 2.7 we compare the MMM5 output from the 20 km Chryse Planitia nest against the MPF data and the GCM. As specific examples at the end of the Pathfinder mission, the complete (continuous) surface pressure records for sols 25 and 32 are also shown.

2.3.2.1. Comparison at Pathfinder. The MMM5 simulates the daily surface pressure cycle better than the GCM, but the diurnal amplitude is still smaller than was observed. A complete explanation of this is potentially very complex; however, it is important to note that (in the same run and nest) the MMM5 simulates the surface pressure cycle quite well at VL1 (see Fig. 2.6). There may be some error in the diurnal amplitude of the Pathfinder data related to the temperature correction for the pressure sensor (J. T. Schofield, personal communication, 2001), but it is
believed that this error is not large enough to explain the model-data differences seen in Fig. 2.7.

![Surface Air Pressure graph](image)

**Figure 2.7:** Comparison of normalized diurnal surface pressure cycles at Pathfinder. The green dots are binned (51 bins/sol) MPF data from the 30-sol primary mission. The red (*) markers are for the MMM5 (Pathfinder location in the 20 km Chryse Planitia nest) and the blue square markers show Ames GCM output interpolated to the location of Pathfinder. The yellow points show the continuous surface pressure records for sols 25 and 32.

Throughout the day there is a significant range in the actual surface pressure data. The curves for sols 25 and 32 show that much of this range comes from interdiurnal variations, and that the duration of such excursions is \( \sim 3 \) hrs. The random passing of mesoscale convective eddies could cause this, and model resolution alone may explain why the MMM5 appears to simulate the hourly range in pressure better than the GCM. These features could also be the result of small-scale perturbations in the eastward propagating Kelvin modes, which may be excited by regional variations in the spatial distribution of atmospheric dust, something that may vary significantly on a daily basis.
It has been suspected that the Ames GCM is systematically underestimating the tidal forcing for a given atmospheric dust loading (Haberle et al., 2001). Recent comparisons of GCM data with MGS TES data for the 2001 dust storm event indicate this is probably the case (Haberle, personal communication, 2001). This may also be why the MMM5 underestimates the diurnal amplitude of the surface pressure at Pathfinder. However, since the MMM5 simulates the diurnal amplitude of surface pressure so well for VL1, we suspect that eliminating the systematic heating biases in the GCM radiation code is not entirely at the heart of simulating the surface pressure cycle for specific locations. Spatial variation in the global dust loading can certainly affect the surface pressure cycles, although we have yet to include this effect in the MMM5. It may be important for accurately simulating the pressure cycles at both lander sites.

2.3.2.2. Surface Properties and Tidal Amplitude Variations. To develop an understanding of the relative importance of the factors that produce the spatial variations in the surface pressure tidal amplitudes is very much of interest. Variations in surface properties (topography, thermal inertia and albedo) drive circulations (Siili, 1996), and these circulations can dramatically modify the diurnal and semidiurnal amplitudes of the pressure cycle (Wilson and Hamilton, 1996). This occurs through the forcing of eastward propagating Kelvin modes, which modulate the tidal pattern. Since the GCM and the MMM5 use the same radiation package, the differences in the simulated pressure cycles are due to one or more of the following factors: 1) the resolution of surface properties (topography, thermal inertia and albedo), 2) differences between PBL schemes, 3) boundary reflections, or 4) differences between the dynamical cores of the two models. Examining the effects of using different dynamical cores at different spatial resolutions is entirely beyond the scope of this study, but differences may be significant. Held and Suarez (1994) compared the dynamical cores of two different GCMs and found that the models performed quite similarly, but they noted that differences were dependent upon model resolution. As discussed above, we believe we have largely eliminated the effects of boundary
reflections in the OSU MMM5. Running the MMM5 and the Ames GCM with the same PBL scheme would allow a direct examination of the role of these schemes in producing tidal differences in the two models; this has not yet been done.

To gain further insight into the importance of surface properties we have performed two separate experiments to compare with our baseline results. These experiments are single domain runs that use the semi-global polar stereographic mother domain. The first experiment allows for spatial variation of surface thermal inertia and albedo fields but there is no topography (“flat”). The second experiment includes topography, but surface thermal inertia and albedo are set to constant/mean values (“smooth”). In Fig. 2.8, longitudinal profiles of the MMM5 diurnal and semidiurnal amplitudes are compared with profiles constructed from the GCM run used to generate the boundary and initial conditions of that experiment. As in Fig. 2.2, all curves are interpolations to the latitude of Pathfinder.

In the “flat” case we observe very strong wave 2 and wave 4 patterns in the respective diurnal and semidiurnal amplitudes. The diurnal pattern is the result of interference between the wavenumber one sun-synchronous mode and an eastward propagating wavenumber one Kelvin mode (Wilson and Hamilton, 1996). The semidiurnal pattern is caused by a similar wavenumber two interference. The principal difference between the GCM and the MMM5 tidal amplitude patterns for the “flat” case is a zonal shift and amplification of the MMM5 diurnal amplitude. The increased resolution of albedo and thermal inertia in the MMM5 does not introduce higher order structure into the longitudinal profiles of the tidal amplitudes. Using higher resolution in these fields certainly produces fine structure in the near-surface meteorology of the MMM5, but this fine structure is probably lost to convective mixing and diffusion higher in the atmosphere.
Figure 2.8: Diurnal and semidiurnal amplitudes from all three cases, “flat,” “smooth” and baseline. The “flat” case has thermal inertia and albedo variations but uses flat topography; the “smooth” case has topography variations but uses planet-wide constant/mean thermal inertia and albedo. Curves for the MMM5 and the GCM (with circles) are shown in each subplot. The bottom two subplots compare the baseline cases, with full variation of all surface properties.

We believe, as suggested in section 2.1.3, that the PBL scheme in the MMM5 is the primary reason for this difference in the diurnal amplitudes. Comparing the vertical temperature profiles throughout the day (not shown) reveals that the depth of
the PBL and the hourly evolution of the two profiles are different enough so that
induced circulations would also develop somewhat differently in the two models.
The stability criterion that is used in the PBL schemes of both models is dependent
upon a Bulk Richardson Number \((R_i)\). The formulation of \((R_i)\), the thickness of
atmospheric levels and the values of \((R_i)\) chosen for determining transitions in stability
are all different in the two PBL schemes. These factors, along with the different
vertical grid structures, will change the timing of transitions between stable (night)
and unstable (day) periods enough to cause significant differences in atmospheric
heating rates, thus affecting the temperature profiles.

For the forcing due to topography (the "smooth" experiment) there are
dramatic differences between the MMM5 and GCM in both the diurnal and
semdiurnal amplitude profiles. Much of the longitudinal structure in the MMM5
diurnal amplitude appears to be amplification of smaller features in the GCM profile.
Olympus Mons is the cause of the largest spike in the MMM5 diurnal amplitude; the
profile passes directly over the volcano. This massive topographical feature
influences the tidal amplitudes over the entire latitude circle through the excitation of
eastward propagating Kelvin modes. *Wilson and Hamilton (1996)* showed that
topography is a primary forcing for the eastward propagating modes, along with
thermal inertia and albedo contrasts. These MMM5 sensitivity experiments show a
very important aspect of this; relatively small increases in the resolution of
topography can produce dramatic changes in the spatial structure of the tidal
amplitudes, significantly affecting local surface pressure cycles.

The bottom panels of Fig. 2.8 show the baseline case, where thermal inertia,
albedo and topography all vary according to model resolution. The baseline profiles
are certainly not simple sums of the profiles for the two forcings, although they retain
features present in both the "flat" and "smooth" cases. Dramatic differences between
the diurnal tidal amplitudes in the MMM5 and the GCM are very apparent in a region
stretching from Olympus Mons to just east of the prime meridian. The differences are
large at both the Pathfinder and VL1 sites.
Figure 2.9: The effects of topography and model resolution on diurnal amplitude in the MMM5 mother domain at 19.2° N (Pathfinder). The baseline GCM and MMM5 runs are shown as in Fig. 2.8 (black). The red line is the diurnal amplitude of the MMM5 when using interpolated GCM topography. The blue line and dots show the results from a higher resolution (135 km) MMM5 run.

When the MMM5 is run using topography interpolated from the highly smoothed GCM map, we see dramatic reduction in the diurnal amplitude near Olympus Mons and significant changes over Tharsis and in Chryse Planitia. The diurnal amplitude profile from this GCM topography case is compared with those from the baseline simulation, the GCM and a higher resolution simulation (135 km mother domain grid spacing) in Fig. 2.9. When using interpolated GCM topography, the MMM5 diurnal amplitude profile is shaped much more like that of the GCM. Examining the baseline profile, the relative maximum at 45° W is the reason the MMM5 simulates the diurnal amplitude so well at VL1; it is not present when using interpolated GCM topography. The local enhancement of the diurnal amplitude near VL1 is a consequence of the higher resolution topography map used in the baseline MMM5 simulation.
The diurnal amplitude profile from the higher resolution experiment demonstrates that results do not necessarily improve in comparison with data when the resolution of the model is increased. Small changes in model topography may change the phasing of the Kelvin modes, causing significant changes in the diurnal amplitudes for particular locations. Moreover, the numerical phase speeds of Kelvin modes are also affected by model resolution; this would affect the phasing of modes excited from distant locations even when the topography had not changed. Interestingly, all the MMM5 simulations agree quite well between 30°W and 45°E, suggesting that these changes to the model do not influence this region in late northern summer. However, in all experiments there is a large region in which the diurnal tidal amplitudes in the MMM5 systematically differ from those in the GCM; something other than the radiation scheme, the degree to which topography is smoothed, or the model resolution is causing this. Differences between the PBL schemes used in the MMM5 and the GCM may certainly be responsible.

In view of the results obtained in this study it seems clear that running Mars GCMs at increased spatial resolution, with higher resolution topography, will yield smaller-scale structure in the surface pressure tidal amplitudes. This can significantly affect the tidal results for specific locations. This tidal “fine structure” has not yet been observed, except in so far as the VL1 and MPF observations can be directly compared for the late northern summer season. Diurnal amplitudes for the higher resolution single domain experiment are presented in Fig. 2.10, showing this “fine structure.” Importantly, some regions on Mars exhibit a very high degree of spatial variability in the diurnal amplitude, while other regions do not. Thus, it may be a significant challenge to determine whether Mars atmospheric models are simulating the tides satisfactorily at specific locations when: 1) surface pressure data are extremely limited, and 2) the dust distributions, topography, surface property maps, and spatial resolution being used in the models may all be quite different. The Mars GCM of Lewis et al. (1999) was run at a fairly high spatial resolution (3.75°), and simulated the Pathfinder surface pressure cycle extremely well. However, it did so
with pre-MOLA topography. More recent simulations performed with the French GCM [same physics routines as the Lewis et al. (1999) GCM] show that the diurnal amplitude at the MPF site is underestimated (Wanherdrick et al., 2001), much as with our MMM5 results shown in Fig. 2.7. Studies with the GFDL Mars GCM indicate that longitudinally variable dust loading is probably required to accurately simulate the late summer diurnal tidal amplitudes at the MPF site (J. Wilson, personal communication, 2000). The results from this study show that relatively high-resolution topography is required to simulate the spatial variations in tidal amplitudes.

**Figure 2.10:** Diurnal amplitude of the higher resolution (135 km) single domain experiment (color) shown on the topography of the domain (contour intervals not uniform). The locations of VL1 and Pathfinder are marked by (*). The maximum diurnal amplitude is 0.0361. The line through the MPF lander site is the transect along which the longitudinal profiles of tidal amplitudes in Figs. 2.2, 2.8 and 2.9 are shown.

Clearly, a combination of factors is important for accurately simulating surface pressure cycles. The parameterizations used for atmospheric and surface
radiative heating are obviously very important, as are the PBL schemes which transfer heat from the ground and mix it within the atmosphere. This study indicates that thermal inertia and albedo contrasts cause longitudinal variations in the diurnal tidal amplitudes that could be even larger than those caused by topography, further supporting the importance of PBL schemes for the simulation of tides. Current Mars GCMs do not appear to agree very well in predicting local surface pressure cycles, but it is not clear what factors are most responsible for the differences in model results (Haberle et al., 1999). “Cue ball” simulations from various Mars GCMs would be very helpful in identifying these factors. Model resolution and the degree to which the topography is smoothed are very important in the simulation of local tidal amplitudes; any model comparisons should consider these factors.

2.3.3. Comparison of Surface wind Cycles

Comparing the surface winds predicted by the two models at both the MPF and VL1 sites reveals important differences. In the top left panel of Fig. 2.11 we show wind direction data gathered during the Pathfinder mission and that simulated by the two models. The MMM5 agrees relatively well with the MET data, certainly much better than the GCM. The reason for this is that the zonal component of the MMM5 surface wind reverses direction (allowing for full clockwise rotation of the wind vector), whereas the zonal wind component in the GCM never becomes easterly at the MPF site. Easterlies in the MMM5 occur at night and in the early morning hours, and are associated with downslope flows off the elevated terrain to the east and south of MPF. The zonal wind in the MMM5 differs significantly from that in the GCM, but the meridional wind components agree quite well. The primary mechanisms affecting the surface wind cycles are: 1) diurnal variation in the near-surface pressure gradient (pressure tide), 2) turbulent vertical mixing of momentum and 3) slope flows on multiple scales. The basic importance of slope flows at the MPF site is clear since classical tidal theory predicts a westerly wind maximum at
about 0300-0400 LST (Zurek, 1976); the winds in the MMM5 are easterly at this time.

Figure 2.11: Comparison of the MMM5 Pathfinder wind data (taken from the 20 km Chryse Planitia nest) with GCM data and the MPF ASI/MET wind directions. In the upper left panel the yellow dots show all wind direction data for sol 25, while the green dots are the binned data (51 bins/sol) from the 30-sol primary mission. The black diamond markers are hourly averages of all binned wind direction data. In all four panels, the blue square markers are for the GCM and the red (*) markers are for the MMM5.

The thermal forcing that drives downslope flow is destroyed at sunrise, leading to a rapid reversal of the zonal surface wind at about 0900 LST at the MPF site. It appears that even modest increases in model resolution allow slope flows to develop more fully. Comparing the evolution of surface winds in all of the MMM5 domains near Pathfinder is revealing. As a function of increasing resolution, slope flows strengthen and the complexity of surface circulations increases significantly as
we examine winds in the mother domain (180 km), the 60 km nest and finally in the 20 km nest. Clearly, if a nest is to develop interior circulations appropriate for its scale it must be large enough so that the winds at its boundaries cannot entirely dictate the development of winds in the interior. Our domains are very large and slope flows generally develop quite freely. Higher resolution studies will require using the output from simulations such as these to generate boundary and initial conditions for smaller mother domains, where nonhydrostatic dynamics will certainly be required. Such an approach was used by Dudhia (1993) to simulate a cold front on Earth. We suspect that the use of zonally limited mother domains will then become a viable option, since the physics and vertical grid structure of the model will match that across the mother domain boundary.

In Fig. 2.12 we show an 8-sol average of the surface winds in the 20 km Chryse Planitia nest for just before sunrise and for mid-afternoon. The wind fields contain very well defined slope flows at both times of day. In the early morning the flow is down the eastern slopes of Tharsis and down Tiu Valles and Ares Valles. Clear frontal boundaries appear at the edges of these features, most prominent in the southern portion of Chryse Planitia. There is potentially a significant amount of mass being deposited in this basin at night by downslope flows, which is then removed during the day by upslope flows. This mechanism may contribute significantly to the amplification of the diurnal tidal amplitude over certain regions.

The zonal wind cycle for Pathfinder in the GCM is actually rather similar to that of the MMM5 (Fig. 2.11), although it is shifted westerly (positive) by about 3 m/s. This may indicate that a stronger mean westerly flow in the GCM at Pathfinder causes most of the difference. There could also be a stronger coupling with winds aloft in the GCM, especially at night. Since the nighttime surface layer is so stable on Mars, even small differences in PBL schemes and the near-surface vertical resolution of the models will significantly affect the structure of slope flows and low-level nocturnal jets. The near-surface vertical resolution of the model and an accurate representation of PBL processes are both very important for simulating slope flows.
Figure 2.12: 8-sol average winds in the 20 km Chryse Planitia nest at 0513 hrs and at 1413 hrs (LST for MPF longitude). Maximum wind speeds are ~10 m/s. Color and contour lines show topography at 500 m intervals.
The MMM5 winds at the VL1 site (Fig. 2.6) agree fairly well with the data for this late summer season, both in direction and speed. Slope flows are very important in producing the diurnal variation of wind direction. The MMM5 and the GCM both predict stronger westerlies (downslope flows) during the night and early morning than were observed; the use of a globally constant aerodynamic roughness height (0.01 m) may be the reason. The MMM5 simulates the observed winds from 0900 to 1600 very accurately, and it does very well in simulating northerlies in the late afternoon.

The MMM5 may also be simulating a feature in the VL1 meridional wind data that occurs between 0600 and 0900, but the timing is poor and the magnitude in the MMM5 is overestimated. There is a perturbation in the MMM5 surface pressure cycles of both the VL1 and Pathfinder results that occurs at the same time (Fig. 2.6 and Fig. 2.7). The MMM5 does better than the GCM in capturing the VL1 and MPF surface pressure cycles, but neither model does very well in matching the observed early morning pressure tendency or the timing of the daily maximum. This anomalous behavior may be associated with the onset of instability in the PBL schemes, since sunrise signals the start of the perturbations seen in both models as well as an immediate shift in wind direction and an increase in wind speed. The latter could be associated with the destruction (via downward mixing) of a low-level nocturnal jet.

Examining changes in the MMM5 surface winds with increasing model resolution reveals increasing local wind speeds and improvements in comparison with the observed MPF MET wind directions. In all of the MMM5 domains the winds rotate fully each day, but agreement with the Pathfinder data (particularly between 0000 and 0600) is best in the 20 km nest, an apparent consequence of better resolved slope flows. The strong afternoon upslope flow to the ridgeline that separates Tiu and Ares Valles is a good example of the complexity and increased speeds that develop with higher resolutions (see Fig. 2.12); it is a region of strong surface convergence, producing mesoscale vertical motions that are not resolved in the coarser domains.
The MMM5 wind speeds, shown in the upper right panel of Fig. 2.11, exhibit a relative minimum (as do those of the GCM) near midday. It appears (J. Murphy, personal communication, 2001) that analysis of the MET wind sensor data yields average wind speeds that are greatest during midday, in contrast to the MMM5 results. Large midday wind speeds may be a consequence of strong convection. As on Earth, convection cells drive a near-surface mass redistribution that requires surface wind speeds greater than those predicted by a model not resolving such scales. The discovery of dust devils on Mars (Schofield et al., 1997; Metzger et al., 1999) certainly shows that surface wind speeds become large randomly during periods of strong surface heating. At a resolution of 20 km the MMM5 is still simulating background winds, which may be small in comparison to the random local gusts resulting from strong unresolved convection. The use of nonhydrostatic dynamics and high spatial resolution will be critical for determining the scale of convective features on Mars.

Mars is topographically very different from Earth in that there are huge regions with very significant slopes. At smaller scales there are many regions with very steep slopes, ranging up to the angle of repose and greater. Since radiative processes on Mars play a much larger role than they do on Earth, the local topographic slope and its geographical orientation need to be considered when computing the local insolation; Rafkin et al. (2001) have recently included these effects in their mesoscale model. The timing of slope flows would be altered and daily wind cycles will be influenced, quite dramatically in regions of complex and steep topography. This model modification would not affect radiative heating/cooling in the atmosphere directly, but it might be important over the convective depth of the PBL, influencing the mass distribution sufficiently to be important in the diurnal cycle of surface pressure.
Figure 2.13: 8-sol average winds in the 20 km Valles Marineris nest for 0039 hrs and 1239 hrs. Maximum wind speeds are ~20 m/s. Color and contour lines show topography at 1 km intervals.
As an example of a region where slope-dependent insolation effects must be quite important, winds from the 20 km Valles Marineris nest are shown for two times in Fig. 2.13 (for just after midnight and just after noon for the center of the domain). The winds near canyon walls are characterized by strong upslope and downslope flow. Actual slope flows would not develop simultaneously throughout the canyon system; some walls would be in shade well after sunrise and some well before sunset, with a strong seasonal dependence in the daily phase relationships. Slope flows dominate Valles Marineris in this high-resolution simulation, and simulated wind speeds become twice as strong as those predicted within the Chryse Planitia nest. The diurnal amplitude of the surface pressure cycle in the Valles Marineris nest (computed using the eight sols of nest surface pressure data) is shown in Fig. 2.14.
The high correlation between topography and the diurnal amplitude strongly suggests that slope flows are the dominant factor driving the large diurnal tidal amplitudes found within the canyon system in this simulation. There is a dramatic enhancement (25% or more) of the diurnal tidal amplitude maxima over that predicted in the simulation with only a mother domain (see Fig. 2.10), where slope flows in the canyon system are much weaker and much less resolved.

The daily phase relationships between the strong slope flows in this canyon system are probably crucial for channeling flows along the canyon floor, a phenomenon that may also have a strong seasonal dependence. Higher resolution and realistic studies of the Valles Marineris canyon system will require using a modified surface insolation as well as nonhydrostatic dynamics, two elements that should be readily incorporated into the OSU MMM5 at this stage in its development.

2.4. Summary

A numerical model has been developed to simulate mesoscale circulations in the atmosphere of Mars. The model is an adaptation of the public domain MM5, a Mars MM5 (the OSU MMM5). The NASA Ames Mars GCM is used to provide initial and boundary conditions for the MMM5. The MMM5 uses a semi-global polar stereographic mother domain with a nominal grid spacing of 180 km, essentially covering all locations north of 45° S. The use of this very large mother domain minimizes the boundary reflections that are inherently present when a mesoscale model is interfaced with a GCM or with data analyses. For Mars these problems can be dramatic because of the very large amplitude thermal tides. We utilize two-way nesting to increase spatial resolution by a factor of three for each nest level and examine two regions at a resolution of 20 km: 1) Chryse Planitia (Pathfinder and VL1) and 2) the central region of the Valles Marineris canyon system. All simulations are hydrostatic and dry and performed for late northern-hemisphere summer (the Pathfinder mission period). The MMM5 results for Pathfinder and VL1
are compared with the Ames GCM and with the meteorology observed at the two lander sites. The MMM5 uses the Ames GCM radiation package, but utilizes a much different dynamical core, a different PBL scheme, and a much-enhanced near-surface vertical resolution. Using the MMM5 to "zoom in" on the GCM has uncovered differences in model behavior that warrant further study, although we have begun to understand these differences while developing confidence in this new model.

A considerable effort has been made in this study to determine the factors causing the differences between the diurnal surface pressure cycles in each of the models in comparison with the actual observations. Thermal tides in the Martian atmosphere drive very large diurnal and semidiurnal variations in surface pressure and in winds throughout the atmosphere. As a consequence of all the differences between the Ames GCM and the MMM5, the existence of these large tidal variations causes problems at the boundaries of the MMM5 mother domain. Differences in model resolution (both vertical and horizontal) and in model physics lead to sharp gradients in meteorological variables across boundaries; these gradients cause reflections. Our initial simulations used Lambert Conformal and Mercator mother domains, but reflections from the zonal boundaries of these domains contaminated the diurnal cycle of surface pressure so that model results at specific locations became significantly dependent upon the location of the mother domain boundary. A semi-global polar stereographic mother domain essentially eliminates zonal boundaries, thus eliminating the largest reflections and the dependence of our results on the location of the mother domain boundary. Moreover, this approach facilitated a study that has been quite instructive for understanding how the model resolution and the resolution of surface properties influence the surface pressure cycle. Some regions appear to be much more sensitive to these factors than others, and these MMM5 simulations indicate that Pathfinder and VL1 landed in one such region.

A set of experiments with or without topography, or thermal inertia and albedo variations, was performed to examine the pronounced structure in the diurnal and semidiurnal tidal amplitudes that is caused by the variations in these surface
properties. This study revealed that the longitudinal variations in the diurnal and semidiurnal amplitudes, when forced by topography or by thermal inertia and albedo variations, are of comparable magnitude. The increased resolution of topography in the MMM5 causes dramatic spatial variation in the tidal amplitudes for some regions, whereas increases in the resolution of thermal inertia and albedo have a rather small effect on the spatial variation of tidal amplitudes. The diurnal surface pressure amplitude shows a high degree of sensitivity to model topography in the equatorial region from Olympus Mons to Chryse Planitia (150° W to 30° W, ~30° S to ~30° N); there are large variations over relatively small horizontal scales. This "fine structure" in the tidal amplitudes is sensitive to the model resolution as well as the degree to which the topography in the model is smoothed. Other regions on the planet are essentially unaffected by such changes.

The existence of relatively small-scale variations in surface pressure tidal amplitudes considerably complicates the comparison of MPF and VL1 data with simulated surface pressure cycles. The MMM5 simulates the diurnal amplitude of the surface pressure cycle at VL1 quite well (in the baseline 180 km resolution mother domain experiment), but it underestimates the diurnal amplitude at Pathfinder, only about 800 km away. Changes in the dust radiative heating in the GCM and MMM5 (so as to increase the solar heating relative to the IR cooling) could certainly improve the agreement at the MPF site, but this would then seemingly lead to sizeable disagreements with the observed pressure cycle at the VL1 site. Spatial variations in dust loading are almost certainly crucial to simulate the pressure cycle at both sites in late summer (Wilson and Hamilton, 1996). A thorough study of this problem really requires surface data from numerous locations (ideally from a network of surface pressure sensors), as well as global temperature data obtained from orbit.

We have used the most recent TES thermal inertia and albedo maps, and these data yield much better simulations of MPF MET surface air temperatures than do the older datasets. The temperature cycle predicted for VL1 is too warm in comparison to the data, although the observed diurnal amplitude is very well simulated by the
The simplest explanation for this is that the albedo value used for VL1 in the MMM5 is too low, either because of errors in the assumed aerocentric location of VL1, or as a result of sub-grid scale albedo variations. A westward “relocation” of VL1 would increase the surface albedo and improve agreement with the VL1 temperatures, but the possible change in albedo would not appear to be sufficient. A smaller thermal inertia would yield better agreement with the nighttime minimum temperatures, but this would also tend to increase the daytime maximum. The use of linear interpolation to obtain VL1 and MPF constant-height temperatures overestimates the daily maximum, since the actual temperature profile should be close to logarithmic near the surface. More problematically, simulating near-surface air temperatures for intensely convective conditions is certainly subject to the likely existence of deficiencies in the PBL scheme. There is much work that needs to be done in this realm.

The MMM5 surface winds exhibit a great deal of steering and channeling that is a result of topographical slopes and thermally induced flows. The daily cycles of surface wind in the vicinity of the Pathfinder and VL1 landers are complex, and a good prediction requires sufficient model resolution to adequately simulate the contributing slope flows in the region. Frontal boundaries are seen to form and strengthen in the MMM5 during nighttime, as strong drainage winds interact with the background flow. On slopes, dramatic reversals of wind direction appear shortly after sunrise. These slope flows appear to filling and then emptying topographical basins, a mechanism that appears to be significantly influencing the distribution of atmospheric mass on local and possibly regional scales, thus modifying surface pressure cycles. At high resolution, this mechanism produces a dramatic enhancement of the diurnal amplitude of the surface pressure cycle within the Valles Marineris canyon system. In view of the substantial differences between the GCM and the MMM5 diurnal tidal amplitudes in the vicinity of Pathfinder and VL1 (see Fig. 2.9), we suspect that a similar amplification may be important in the Chryse Planitia basin on a regional scale. On a smaller regional scale, the Isidis Planitia
basin (90 E and 15 N) is another location where slope flows affect the diurnal amplitude of the surface pressure cycle (see Fig. 2.10 and the 135 km resolution profile of Fig. 2.9).

The differences between the GCM and MMM5 results, in comparison with the Pathfinder and VL1 data, certainly point to the great importance of PBL schemes in mesoscale simulations of the Martian atmosphere. The development of slope flows and the transfer of heat and momentum are crucially dependent upon the various parameterizations used in PBL schemes. There is a very strong need for additional meteorological boundary layer data from Mars to help further the development and validation of PBL schemes. The MER mini-TES radiometer should obtain very valuable temperature profiles in the boundary layer, and future landed missions (e.g., Netlander) will hopefully provide better quality meteorological data from multiple heights above the surface. Terrestrial field data might also be quite useful; a high altitude terrestrial desert may provide a sufficient analogue to better understand the turbulent exchanges of heat and momentum and the development of slope flows in environments that are characterized by very large diurnal variations.
2.5. Acknowledgments

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A Mesoscale Model Study of Midsummer Atmospheric Dynamics for the North Polar Region of Mars

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The OSU Mars MM5 mesoscale model has been used in a comprehensive study of midsummer atmospheric circulations over the north polar region of Mars. We focus on three simulations (L_s=120, L_s=135 and L_s=150); the duration of each is 29 sols. The model atmosphere is dry and the dynamics we are using for this study are hydrostatic. Seasonally correct boundary conditions for each simulation are provided by the NASA Ames Mars GCM. For this work we have developed a thermal inertia map that is complete to the North Pole, providing a very good representation of the surface thermal behavior as observed by the MGS/TES. Modeled atmospheric temperatures also agree very well with MGS Radio Science temperature data. The highest resolution nest of this modeling study (18 km) resolves flows over the residual cap, producing zonal-mean easterlies of ~10 m/s and zonal-mean off cap katabatic winds of ~5 m/s. The katabatic flow is shallow (~300 m) while the easterlies are deeper (~1.5 km); these zonal mean flows are relatively steady during this midsummer period. Transient circulations observed over and near the pole can be quite vigorous within the first atmospheric scale height; they are excited in ways and locations that vary greatly over this midsummer period. At L_s=120, transient eddies form along the edge of the residual cap with a dominant zonal wavenumber one structure, producing strong winds (10-15 m/s) that blow regularly and directly across the residual cap. By L_s=135 changes in the large-scale circulations have created a favorable environment for transient eddies to form on the slopes of Alba Patera and Tharsis. These eddies reach the residual cap, apparently contributing in the breakdown of the pattern of transient eddies forming primarily along the residual cap edge at L_s=120. By L_s=150 the winter polar jet has formed and stronger/deeper winter-like circulations form along the jet, although strong transient circulations continue to form in response to near surface flows. The equatorward transport of water vapor could be very strongly affected by the changing dynamics found in this study, and these model results are at least qualitatively consistent with observations of atmospheric water vapor and water ice clouds.
3. A Mesoscale Model Study of Midsummer Atmospheric Dynamics for the North Polar Region of Mars

3.1. Introduction

Mesoscale models have recently become very important tools for the study of the Martian climate system, and are increasingly being used to study climatologically important regional and smaller-scale circulations (e.g., Rafkin et al., 2002; Toigo et al., 2002; Tyler et al., 2002; Michaels et al., 2004). Atmospheric dynamics are important for the climate of the polar regions, potentially affecting the formation and recession of the seasonal carbon dioxide frosts and playing a key role in the annual water cycle of the North Pole Residual Cap (NPRC). Mesoscale circulations must be important for the annual water cycle because of the sharp changes in topography, albedo and thermal inertia along the edge of the NPRC, which exist on relatively small spatial scales. In this study we use a mesoscale model to characterize the midsummer atmospheric circulations in the northern polar region, providing a context within which specific questions about the role of the atmosphere in the annual water cycle can be asked.

General Circulation Models (GCMs) are valuable tools for investigating the complex relationships between the numerous physical processes at work in the polar regions of Mars. Pollack et al. (1990) used an early version of the NASA Ames Mars GCM to study feedbacks and hemispheric asymmetries involved in the formation and recession of the seasonal carbon dioxide frosts, complex mechanisms that are related to the poleward atmospheric transport of heat. The water cycle has been studied with 2-D models (Jakosky, 1983; Haberle and Jakosky, 1990) and with 3-D models (Houben et al., 1997; Richardson and Wilson, 2002). Collectively these studies raise two important questions in trying to simulate the annual water cycle as measured by the Mars Atmospheric Water Detector (MAWD) on Viking and the Thermal Emission Spectrometer (TES) flown on Mars Global Surveyor (MGS). Haberle and
Jakosky (1990) suggested that the equatorward transport of water is severely limited by the weakness of the summertime circulations, implying that either 2-D dynamics cannot sufficiently represent the transport of water vapor equatorward, or that sources of water besides the NPRC are important in the annual cycle. The regolith certainly may be involved (Jakosky, 1983; Houben et al., 1997; Bottger, 2004). Houben et al. (1997) attempted to determine the capacity of the regolith by adjusting this value as a parameter in a 3-D climate model to achieve the best fit to the observed water cycle. Richardson and Wilson (2002) simulated the annual water cycle in a GCM without the need for an active regolith, although their columnar water mass abundances are too large by a factor of two. However, with the relatively coarse grids used in current GCMs these models cannot be expected to provide a realistic representation of the smaller-scale circulations near the NPRC. GCMs typically use eddy diffusion to include the effects of sub-grid scale circulations on scales that must be important in the vicinity of the NPRC. Summertime eddies in the polar region most certainly have spatial and temporal scales that are not appropriate for representation by eddy diffusion. Due to the convergence of meridians, the deformation of the actual GCM resolution at high latitudes becomes dramatic even though the latitude and longitude spacing remains uniform; this is the “pole problem” of grid point GCMs. It cannot be the case that atmospheric variables should be assumed constant over much larger meridional than zonal spatial scales; in fact there will be strong meridional gradients in polar circulations where this problem is most pronounced in grid point GCMs. Richardson and Wilson (2002) suggest that mesoscale models are required to really understand the role of atmospheric dynamics in the polar regions. If midsummer dynamics can be better understood through mesoscale simulations then it should become more possible to determine the importance of the regolith in the annual water cycle.

The dynamics of the polar atmosphere is a large uncertainty in modeling the annual water cycle; this is the first high-resolution comprehensive study of these circulations. With mesoscale models, the grids that are used do not have a “pole
problem” and they allow for much higher spatial resolutions. Increased resolution is required to characterize polar circulations, for which a broad size spectrum might be expected, as indicated by imagery of polar summertime clouds. Conversely, due to the increases in spatial resolution when using these models, the simulations are generally shorter in duration because of computational requirements, a problem that is only exacerbated with nonhydrostatic dynamics. This is a major reason why we have used a hydrostatic mesoscale model for this study. At scales not much smaller than those examined here (~5 km), nonhydrostatic dynamics should become important.

In this work we examine a relatively short period of the year, midsummer in the northern hemisphere. This period is crucial in the water cycle of the NPRC; it is when the majority of water sublimes from the residual cap into the atmosphere, which produces the largest increase in atmospheric water vapor over the course of the Martian year. This season is also the easiest part of the year to simulate since water ice clouds are relatively infrequent (Smith, 2004), and can thus be neglected in a study focusing on dynamics. Moreover, this period has the most complete observational record of surface temperatures and thermal properties (surface albedo and thermal inertia) with which to constrain model results. The NPRC is a physical record that ultimately will yield a vast amount of information about the climate history of Mars. Atmospheric processes are fundamental for the formation and evolution of the NPRC and the polar layered deposits (Herkenhoff and Plautt, 2000). This study is a first step in the investigation of the north polar atmosphere at high spatial resolution.

3.2. OSU MMM5 Specifications and Modifications

3.2.1. Model Description

The computer model used in these studies is the Oregon State University Mars MM5 (the OSU MMM5). Development and validation of the OSU MMM5 against lander observations is described by Tyler et al. (2002). The Penn-State/NCAR MM5
(Grell et al., 1994) was modified to study mesoscale circulations on Mars. The NASA Ames Mars GCM (Haberle et al., 1999) provides boundary and initial conditions for the mesoscale simulations. The radiation code used in the OSU MMM5 was adapted from the Ames GCM. The OSU MMM5 is configured with 32 sigma levels; the model top is at 0.03 mbar and the lowest level is ~1.7 m above the surface. Approximately 2/3 of the model levels are in the lowest pressure scale height. The hydrostatic version of the OSU MMM5 (used in this study) uses the same sigma vertical coordinate formulation as in the NASA Ames Mars GCM:

$$
\sigma = \frac{p - p_{\text{top}}}{p_{\text{sfc}} - p_{\text{top}}}.
$$

(3.1)

Surface maps for topography (MGS/MOLA), albedo (Christensen et al., 2001) and thermal inertia (Mellon et al., 2002) were produced from high-resolution global maps for our modeling efforts. We use minimally smoothed versions of our final maps, at appropriate resolutions, in both the Ames GCM and the OSU MMM5, maintaining consistency in surface properties between the two models.

Figure 3.1: Topography of the two nests used in these simulations. Both nests are dynamically two-way. Contour intervals are 750 m in the 54 km nest and 250 m in the 18 km nest. The zero meridian is shown with a black dashed line.

Because of the differences between the computational grids and the physical parameterizations used in the GCM and the mesoscale model, boundary reflections become unavoidable in mesoscale model simulations. These reflections can be quite
problematic depending upon the choice of mesoscale domains and the objectives of
the modeling study. Using the same approach as Tyler et al. (2002) to minimize these
problems, the mother domain used in this study is a semi-global polar stereographic
one. The mother domain of the mesoscale model interacts with the GCM boundary
conditions; in these studies it has a nominal spatial resolution of 162 km, covering the
entire northern hemisphere and reaching to ~30° S. For these simulations we activate
two higher resolution nests 2 sols into the integration. The first nest has a nominal
resolution of 54 km and the second is 18 km. These nests provide good resolution for
circulations in the polar region; both nests are dynamically “two-way” (affecting and
being affected by the next lower resolution domain). The geographical location and
topography of these two nests are shown in Fig. 3.1.

Three simulations were performed for this study, at solar longitudes of
L_s=120, L_s=135 and L_s=150, each for a duration of 29 sols. The final 20 sols of each
simulation are centered on the specific solar longitude of the run (L_s advances during
the run). The OSU MMM5 simulations were performed using hydrostatic dynamics
and a dry atmosphere. At these resolutions the assumption of hydrostatic dynamics is
a reasonable one. By reducing the computational burden in relation to nonhydrostatic
dynamics, this allows for multiple and extended simulations, along with a careful
“tuning” of the model to observed temperatures. Nonhydrostatic simulations
performed by mesoscale modeling groups participating in a Mars mesoscale model
intercomparison (Tyler et al., 2003) have led to some concerns about nonhydrostatic
dynamical cores that were developed for terrestrial studies. These concerns have not
been fully resolved at present.

TES temperatures for the surface of the NPRC, at dates somewhat before or
after this study, are significantly lower than those between L_s=120 and L_s=150,
indicating that there is some carbon dioxide frost on the surface in early summer and
well before fall equinox. Thus, simulations before or after the dates of this study are
at least somewhat inconsistent with the albedo and thermal inertia maps being used in
the model (described below). However, a parameterization of a retreating seasonal
carbon dioxide cap in the albedo and thermal inertia maps of the OSU MMM5 has allowed studies to be performed at earlier dates that are relevant to the landing of the future Mars Scout Phoenix mission. Simulations of the fall and winter seasons will require additional physics to represent the condensation of carbon dioxide on the surface and in the atmosphere. Collaboration with the NASA Ames Mars GCM group will provide cloud routines that will be incorporated into our model so fall and winter simulations can be performed in the future.

Finally, since the sun remains at elevations low above the horizon all day near the pole, and since topography can be quite steep at the margin of the residual cap, it is important to include the effect that topographic slopes have on incident surface insolation. The OSU MMM5 was recently modified to account for this important effect, although we do not consider shadowing (unimportant at these resolutions). For the 18 km nest, at the margin of the residual ice cap and on the walls of Chasma Boreale, we find that the effect on the local noon and midnight surface insolation is ~10% over fairly extensive regions.

3.2.2. Thermal Inertia Map Construction

![Albedo and Thermal Inertia Maps](image)

**Figure 3.2:** Albedo and thermal inertia from the 18 km nest are shown. The SI units of thermal inertia, as given in the colorbar, are J m$^{-2}$ K$^{-1}$ s$^{-1/2}$. 
Mesoscale circulations on Mars, as on Earth, are strongly affected by near-surface diurnal temperature cycles. Realistic high-resolution simulations near the NPRC require that surface thermal properties be represented as accurately as possible in the model. Data collected by the MGS TES have provided a high quality global map of surface albedo (Christensen et al., 2001). Thermal inertia (derived from thermal conductivity, density and heat capacity: \( I = (k \rho C)^{1/2} \)) is not observable; it is determined via modeling and the quality of the result depends upon the quality and coverage of the nighttime surface temperature data, which is sparse to non-existent at the highest latitudes. The best thermal inertia data to date were provided to the modeling community by Mellon et al. (2002). Their map is complete between 80° S and 80° N, actually providing coverage onto the NPRC at some longitudes. This has allowed for the use of reasonable extrapolations to construct a thermal inertia map that is complete to the pole.

We have made some simplifying assumptions to allow for this extrapolation of the thermal inertia data: 1) the thermal inertia of high albedo ice surfaces is represented with a single value (800 J m\(^{-2}\) K\(^{-1}\) s\(^{1/2}\)), the present maximum value in the Mellon et al. (2002) map); 2) the nature of the thermal inertia gradient observed at the margin of the residual ice cap at certain longitudes is representative for the margin of the entire cap, providing a direct correlation with surface albedo; 3) a mean high-latitude value is used for lower albedo locations that are missing data (500 J m\(^{-2}\) K\(^{-1}\) s\(^{1/2}\)) above 80° N. Using these assumptions thermal inertia was extrapolated to latitudes above 80° N, extending our high-resolution map to the pole. From this map, all maps used in our simulations were constructed at appropriate scales. For example, the albedo and thermal inertia maps used in the 18 km nest are shown in Fig. 3.2. The correlation between thermal inertia and the brightest albedo values is very apparent, including the outlier ice deposits. Specific areas like the inner reaches of Chasma Boreale and Olympia Planitia have questionable thermal inertia values, although TES surface temperatures suggest this is a reasonable representation.

Tuning the OSU MMM5 to match temperature observations involved adjusting the
specifics of the assumptions above. This process provides some insight into the nature of changes in subsurface properties near the margin of the residual ice cap, as discussed below.

3.2.3. Comparison of Model Temperatures with Observations

![Image of temperature comparison between OSU MMM5 and TES surface temperatures.

Figure 3.3: A temperature comparison between the OSU MMM5 and TES surface temperatures. TES (0200 and 1400 LST) and OSU MMM5 20-sol maximum and minimum temperatures from the 18 km nest of the Ls=135 simulation are shown. Solid black lines show uneven intervals of topography.

In addition to constructing thermal inertia maps we have modified the method used to initialize the temperature at the bottom of the soil model in the OSU MMM5. At locations assumed to be predominantly non-ice to depths greater than that of the soil model (0.5 m), the deep soil temperature (a constant) is determined through
spatial interpolation of the diurnal mean GCM surface temperature. However, since the residual ice cap is very poorly resolved in the Ames GCM (7.5° latitude by 9° longitude), this method does not provide a reasonable temperature field for the higher resolution nests that are initialized during the mesoscale simulations. The physical makeup of the subsurface is unknown, although it is reasonable to assume that the fractional amount of ice in this layer correlates well with albedo for higher albedo values. We initialize the deep soil temperature of high albedo locations ("ice" locations) at 175 K, averaging the ~200 K summer and ~150 K winter surface temperatures. *Paige and Ingersoll* (1985) showed that substantial heat flux into the subsurface is required to balance the summertime energy budget of the residual ice cap, providing the fundamental rationale for modifying our model initialization in this way. With this modification, and using our best-guess thermal inertia and albedo maps, the simulated surface temperatures and the magnitude of the diurnal temperature cycle agree quite well with TES observations of the NPRC surface temperatures. TES polar surface temperatures (0200 and 1400 LST) are compared with maximum and minimum temperatures from the 18 km nest in Fig. 3.3. The model maximum temperatures occur very close to 1400 LST; the minimum temperatures occur closer to 0300 LST. The daytime/maximum temperatures agree extremely well; however, there are some differences in the nighttime temperatures, related to outlier ice deposits and Olympia Planitia, which suggest that our chosen thermal inertia values could still be tuned a bit more precisely. Specifically, 800 J m$^{-2}$ K$^{-1}$ s$^{1/2}$ seems a bit low (the modeled diurnal temperature cycle of ice regions is a bit large) and the mean high latitude value we used to fill in missing thermal inertia data above 80° N (500 J m$^{-2}$ K$^{-1}$ s$^{1/2}$) is a bit high (Olympia Planitia does not cool sufficiently at night).

Both the Ames GCM and the OSU MMM5 use a globally uniform dust optical depth of 0.075, in good agreement with the MGS/TES observations for this midsummer period (*Smith et al.*, 2004). This dust loading provided the best model agreement with Radio Science (RS) temperature profiles (*Hinson et al.*, 2001). To
tune the model to data we used 99 RS profiles, distributed evenly over longitude, to construct a zonal-mean RS temperature profile that was compared with one constructed similarly from model output. The RS temperature profiles are evenly and tightly grouped around $L_s=135$, a local time of 0630 and 85° N latitude. The RS zonal-mean temperature profile is compared with a 0630 zonal-mean from the 18 km nest of the $L_s=135$ simulation in Fig. 3.4.

**Figure 3.4:** Comparison of the zonal-mean OSU MMM5 temperature profile with one constructed from Radio Science (RS) data. The RS mean profile (black line from cyan) is given for a seasonal date of $L_s=135$, 0630 local time and a latitude of 85° N. The zonal-mean profile from the OSU MMM5 for 85° N and 0630 local time is also shown for $L_s=135$ (red line from yellow).

This comparison of zonal-mean temperature profiles also helped to refine our construction of thermal inertia maps. The latitude circle where the zonal-means are constructed (85° N) is often perpendicular to the sharpest gradients in surface albedo,
thus parallel to transitions in our assumptions about the subsurface (the amount of ice in the "soil" being directly related to albedo), as seen in Fig. 3.2. At altitude, the modeled zonal-mean temperature profile agrees very well with that of RS data, primarily a consequence of tuning the dust opacity value. However, the lowest ~5 km of the modeled temperature profile can be significantly affected by the specific range of albedo we assume represents the transition zone from mostly ice in the "soil" to mostly not ice (and also if the temperature at the bottom of the soil model is set to 175 K in this zone or not). Our best fit to both the RS and TES data was found by adopting the following basic premise: as albedo drops rapidly from the brightest locations, the subsurface remains primarily ice and subsurface heat flux remains an important component of the surface energy budget. The extent to which the soil is predominantly ice near the margin of the NPRC may be important for local circulations near the cap edge. Recent observations of water ice in the Martian polar subsurface (Boynton, et al., 2004; Prettyman, et al., 2004) are very helpful in our efforts to better understand the thermal properties of the polar region and further refine our maps of thermal inertia for future studies.

Given that the model agrees fairly well with the TES observed amplitude of the high latitude diurnal surface temperature cycle, one can question why the inversion in the simulated zonal-mean temperature profile is so much stronger than that in the RS data. The cause may be one or more of the following: 1) the PBL scheme (using terrestrial scaling and parameter values) causes the near-surface temperature behavior to become somewhat unrealistic for Mars; 2) the RS temperature profiles and the modeled profiles differ too much in footprint, causing the near-surface comparison to be less valid than it is for higher levels in the atmosphere; 3) the RS temperature profiles underestimate the strength of the inversions. The RS temperature profiles may indeed underestimate the near-surface inversions (D.P. Hinson, personal communication, 2003; Hinson et al., 2004, currently in review); however, we believe that all of these factors play a role. The parameterized NPRC in the OSU MMM5 is somewhat small, as can be seen in the
temperature comparisons of Fig. 3.3, which causes the near-surface temperature (which is nearer the cap edge than in reality) to be higher. However, an additional simulation (not shown), with a modified thermal inertia parameterization to account for this (enlarging the parameterized NPRC) yielded little change in the modeled zonal-mean temperature profile, although some improvement in comparison with the RS profile resulted. For a better understanding of the PBL, there is a great need to obtain high vertical resolution meteorological data from the lowest ~1 km of the Martian atmosphere; this can only be done with surface stations, as in the case of MER and the mini-TES instrument, or with balloons.

3.3. Results

The nesting capability available in mesoscale models allows examination of model output at multiple scales in a single simulation. Mother domain results should demonstrate large-scale consistency with GCM simulations and can also be used to compare with spacecraft observations, such as MGS TES atmospheric temperatures. Results from higher resolution nests show how smaller scale circulations affect large scale circulations and the climate of specific regions.

GCM grids, traditionally in spherical coordinates with fixed spacing in latitude and longitude, are not well designed to study polar atmospheric dynamics. This is not an issue with the domains we have configured for these simulations. A basic trade off exists: to more accurately simulate polar dynamics, and still capture the large-scale circulation, we have to accept some consequences. These include the computational burden of a large mother domain (100x100). With this mother domain the true model resolution is less than nominal near the pole (where greater resolution is most desired), but greater than nominal at the mother domain boundaries (where it is not needed). The nests add significant computational overhead, although they provide the resolution required for this study.
The central focus of this work is the characterization of the mean state and transient eddy activity in the 54 km and 18 km nests during northern hemisphere midsummer. Transient eddies form in response to many factors that contribute at different spatial scales. Large-scale circulations and their zonal asymmetries, along with smaller scale circulations that are well resolved, drive a surprisingly vigorous midsummer polar circulation. To begin our characterization of the midsummer polar circulations we will examine the zonal-mean fields of the mother domain.

3.3.1. Zonal-mean Fields

3.3.1.1. Large-Scale Zonal-means and Zonal Asymmetry. The OSU MMM5 has a much lower model top in comparison with current Mars GCMs, $3 \times 10^{-2}$ mbar versus $5 \times 10^{-5}$ mbar for the Ames GCM used in this study. Since the mother domain boundaries are in the southern hemisphere, it is important to show that the circulations in the mother domain exhibit the characteristic features of the northern hemisphere midsummer general circulation. A basic comparison to make is between the zonal-mean atmospheric fields of zonal velocity, meridional velocity and atmospheric temperature ($U$, $V$ and $T$) from the OSU MMM5 and those from the Ames GCM.

There are two approaches for constructing zonal-mean fields using output from a sigma vertical coordinate model: 1) construct zonal-means on sigma levels and then transform to a pressure vertical coordinate, or 2) first interpolate output to pressure levels and then construct zonal-means. The first approach produces accurate near-surface zonal-mean fields even with large topography, while the second is more appropriate for theoretical analyses. We use the first method since we are very interested in the circulations in the lower atmosphere; the resulting zonal-mean fields are shown in Fig. 3.5. The zonal-means were constructed using twenty sols of hourly data, discarding the first nine sols of output to allow spin-up of atmospheric circulations and for soil temperatures to reach equilibrium.
Figure 3.5: Zonal-mean fields are shown for the mother domain for each simulation (there is complete longitudinal coverage to 20° S in the mother domain). The zonal-mean averages were generated on sigma surfaces and then a coordinate transformation was performed onto zonal-mean pressure levels. Each of these plots shows a 20-sol average that is centered in time on the indicated solar longitude.

As the subsolar latitude moves southward from ~22° N to ~12° N, between $L_s=120$ and $L_s=150$, the zonal-mean temperature field changes significantly in the polar region. Poleward of 80° N the lower atmospheric temperature decreases sharply (~20 K) over this period. These temperature changes are similar to changes in the Ames GCM zonal-mean temperature field, although the gradients and changes in the polar regions are sharper in the OSU MMM5. The zonal-mean zonal wind fields of Fig. 3.5 show the lower reaches of the lower latitude easterly jet, much as shown in the NASA Ames Mars GCM Climate Catalogue (available on the internet at NASA Ames Research Center). Both the Ames GCM and the OSU MMM5 show this jet weakening over the seasonal period of this study. The OSU MMM5 also predicts weak near-surface equatorial easterlies as in the GCM. By $L_s=150$, partly in response
to a cooling polar environment and a growing meridional temperature gradient, a polar jet is seen to form in the mesoscale model. This jet marks the onset of circulations that are much more winter-like, although it does not form in the GCM, presumably due to the relatively coarse meridional resolution of the Ames GCM. In the OSU MMM5 the appearance of this jet is related to asymmetries in large-scale circulations associated with distant topography. The zonal-mean meridional winds are much weaker (note colorbar range), and change less during the period of this study than do the zonal winds. The most interesting change is in the strong near-surface meridional flow, as discussed below. Southward flow in the upper left of each meridional wind subplot is part of the upper branch of the Hadley Cell; and, as in the Ames GCM, this flow weakens with time in the OSU MMM5. Collectively, these basic agreements between the zonal-mean fields of the two models indicate that the OSU MMM5 mother domain satisfactorily reproduces the large-scale circulations of the Ames GCM. However, the additional spatial resolution and the use of polar stereographic domains appear to aid the formation of additional (arguably realistic) flow features, specifically an early fall polar jet at Lₐ=150.

In the construction of the zonal-means shown in Fig. 3.5, all near-surface flow is explicitly included. Near-surface flows in the OSU MMM5 are well simulated due to the excellent vertical resolution; large-scale near-surface flows are very important on Mars. The largest changes in the zonal-mean meridional winds in this study occur in the strongest flow feature of this zonal-mean field near the surface, making it instructive to discuss the mechanisms that form this feature and cause it to change. At Lₐ=120 these strong mean meridional winds extend significantly poleward of where they would be expected to terminate if this feature were simply the return branch of the Hadley Cell. This flow is thus a consequence of multiple circulations and more than one mechanism is required to explain it. It weakens between Lₐ=120 and Lₐ=135, but much more so near the equator (south of ~20° N) than at higher latitudes. The northern part of this poleward flow persists even after the southern part has all but disappeared by Lₐ=150. Thus, the northern section of this flow cannot be
part of the Hadley Cell, as the southern portion is, reversing with the approach of fall equinox. We believe that two different mechanisms are responsible for the northern portion of this near-surface meridional flow; they are thermal low-pressure circulations and western boundary currents. Joshi et al., (1995) describe western boundary currents in their GCM simulations, which are a consequence of the huge topographical basins on Mars. Large thermal low-pressure circulations also form because of the Martian topography; and together, given horizontal and vertical overlap, these two very different circulations can produce strong meridional flows at specific longitudes. The strongest winds from thermal low-pressure circulations form at altitudes greater than those of boundary currents, but these two circulations can cause acceleration of the same air near the surface. Slope flows may also be quite important in the resulting circulation; however, individual slope flows are difficult to isolate, since they exist over very large regions (Tyler et al., 2002), making it difficult to separate their effects from other circulations (or from other slope flows) within the complex large-scale topography near Tharsis.

To better visualize these complex circulations we examine Fig. 3.6, which shows the 20-sol diurnal mean wind field at sigma level 22 (~1 km), direction vectors scaled by speed on the left and a color plot of speed on the right. Thermally driven circulations influence the diurnal mean winds over Elysium Mons, Olympus Mons, Alba Patera and each of the Tharsis Montes. The strongest winds in Fig. 3.6 are generally related to the thermal circulations resulting from these topographical features. Over Elysium Mons and Alba Patera the winds show a clear thermal low-pressure circulation, counterclockwise flow around the volcanoes. Over Elysium Mons the strengthening of the northward wind on the east flank of the volcano may be evidence of a strengthening western boundary current influencing the circulation, as is additionally evidenced by the developing gyre in the region between Arcadia and Amazonis Planitias. Elysium Mons is isolated from the other volcanoes, which
Figure 3.6: The diurnal mean wind field (a 20-sol average) is shown for a subset of the mother domain at \( \sigma = 22 \) (\(-1\) km). Arrows for wind direction (left) are proportional to speed (right) in color. The blue/black dashed line in the left/right subplot is the Equator. Latitude is contoured at 15° intervals and topography is contoured with black solid lines.
explains why the thermal low-pressure circulation over this volcano is much more clearly defined. Considering the complex flows around the volcanoes on Tharsis, we gain a good sense of the large scales over which slope flows and thermal circulations can interact when driven by the Martian topography. The circulations over Tharsis and Alba Patera are far more complex than those over Elysium Mons for exactly this reason. Within this complexity we suggest that the strong northward meridional flows on the northeast slopes of Tharsis, the western boundary of Isidis Planitia and possibly the eastern flanks of Elysium Mons are affected, or are being significantly enhanced, by atmospheric western boundary current effects. A very large thermal low-pressure circulation forms over the huge topographical massif of Alba Patera and Tharsis. Accelerations resulting from the thermal low and the western boundary current are additive and will produce a net northward flow, producing the zonal-mean surface flow feature seen at $L_a=120$. On the east and west flanks of Alba Patera the respective northward and southward meridional flows do not change equally in time as if they were the meridional components of a single thermal circulation, although at altitude they do (not shown). This suggests that the northward component, which remains more constant with solar longitude, is maintained by a western boundary current. The result of these changing circulations, and a weakening Hadley Cell, drives the changes we see in the near-surface flow of the zonal-mean meridional winds.

3.3.1.2. High-Resolution Polar Zonal-mean Fields. In addition to comparing the zonal-mean fields from the mother domain with those of the Ames GCM, it is extremely interesting to examine the zonal-mean fields at high-resolution over the most polar latitudes. In Fig. 3.7, we show the zonal-means of $U$, $V$ and $T$ from the 18 km nest for latitudes poleward of $70^\circ$ N. As seen in the mother domain zonal-mean temperature field, polar atmospheric temperatures decrease sharply (~20 K) between $L_a=120$ and $L_a=150$. However, due to the much higher resolution of this domain (and that of the surface properties) the model resolves the forcings for circumpolar and off-cap katabatic winds, which are related respectively to a
stationary high-pressure system over the cap and the topography of the cold NPRC. Except for being somewhat weaker at $L_s=120$ due to transient circulations that dominate weather over the NPRC at that time (discussed below), these circumpolar and katabatic winds are very prominent features of the midsummer polar circulation.

Figure 3.7: As constructed for Fig. 3.5, zonal-mean fields are shown for the 18 km nest.

The circumpolar zonal winds have a depth-scale of ~1.5 km, whereas the off cap katabatic meridional winds are only ~1/5 as deep. In the zonal-mean, winds over the NPRC above ~250 m are from the east. Near the surface, winds blow about 20° down-slope of the local topographical contour at speeds between ~5 m/s and ~10 m/s. At $L_s=120$ these winds can be significantly modified by transient circulations that form along the cap edge (discussed below), which is why these winds appear weaker in the zonal mean at $L_s=120$. However, by $L_s=135$ and until $L_s=150$, these zonal
mean winds are very representative of the mean wind state over the NPRC. The spiral troughs in the NPRC are certainly suggestive of aeolian processes, and may have formed in response to midsummer winds such as described here (Howard, 1999). However, if the residual cap ice undergoes glacial flow then the morphology of the spiral troughs may be much different (Hvidberg, 2003).

### 3.3.2. Transient Eddy Circulations

Transient eddy circulations are very important for the transport of heat and momentum into the polar regions during winter. Northern winter storms are generally much stronger than those of southern winter, as has being shown through analyses of TES atmospheric temperature data (Banfield et al., 2004; Barnes, 2003a; Barnes, 2003b). Moreover, GCM studies have shown that northern hemisphere topography plays an important role in the generation of stronger northern winter storms than those found during southern winter (Barnes et al., 1993). This work also points to the importance of topography for the excitation of midsummer transient eddy circulations. These transient eddies can traverse large meridional distances and significantly influence midsummer weather over the NPRC. Fluxes of heat and momentum into the polar region associated with these transients can be significant and the nature of these eddies is surprisingly sensitive to the specific midsummer seasonal date.

For this study we extract transient circulations from our model output in a simple fashion. We first construct 20-sol mean hourly diurnal cycles at all locations for U, V and T. With another pass through the model data, subtracting the appropriate local hourly mean values, we have 20-sol records of excursions from the mean diurnal cycle of each variable, as defined for zonal velocity by:

\[
u'(\lambda, \phi, z, t) = u(\lambda, \phi, z, t) - \bar{u}(\lambda, \phi, z, hr).
\] (3.2)

To generate the best record of transient excursions for this study, the model must be fully spun-up before the 20-sol period begins. We neglect the first nine sols
of model output (seven for the nests, which initialize two sols into the simulations), which may seem to be an excessive amount of spin-up time. However, considering the highly parameterized initial state of the north residual ice cap and the larger scale circulations that form in the OSU MMM5 (which are not represented in the GCM initial conditions), it is not. Experience with our model has shown that significant spin-up times are generally required. The 54 km and 18 km nests are the most affected, requiring the full seven sols for soil model temperatures to equilibrate and for circulations to mature and adjust to the high-resolution topography. We assume that a 20-sol period is short enough so changes due to seasonal trends are small, but long enough to capture sufficient statistics for an effective characterization of the behavior of transient circulations at the specific seasonal dates of this study. An examination of hourly level-mean values of wind speeds and temperatures, at all levels in both nests over the entire course of these simulations (not shown), shows that multiple cycles of natural variability in these simulations are captured over a 20-sol period.

In each simulation of this study specific regions are much more influenced by transients than other regions. These locations can be seen in Fig. 3.8, which shows a 20-sol mean of the RMS excursion values in the 54 km nest at sigma level 20 (~1.5 km altitude) for U, V and T, as defined for zonal velocity by:

$$\overline{u'}(\lambda, \phi, z) = \text{SQRT} \sum_{t=1}^{t=N} \left[ \frac{1}{N} \left( u'(\lambda, \phi, z, t) \right)^2 \right]. \tag{3.3}$$

This field provides a measure of how regularly or strongly transient circulations affect local weather at all locations in the domain. The existence of transient circulations at preferential locations shows that there are favored locations for their formation and development.

At Lₜ=120 transient circulations appear in the polar region, although generally only along the edge of the NPRC. By Lₜ=135, circulations related to the topography of Alba Patera and Tharsis excite transient circulations, and these transient eddies link the midlatitude atmosphere dynamically to the polar region. Also by this time, the
strong activity over the NPRC has mostly subsided. Some of the largest mean excursions at $L_s=135$ occur in the region of transient activity between Alba Patera and Tharsis and the NPRC. By $L_s=150$ the circulation has evolved again, partly in response to the onset of the polar jet in the zonal-mean zonal wind field of Fig. 3.5. The maximum seen in the mean temperature excursion in Arcadia Planitia at $L_s=150$ is related to a jet maximum in this polar jet.

![figure](image)

**Figure 3.8:** RMS values of meteorological excursions from the diurnal mean cycle for sigma level 20 in the 54 km nest for $L_s=120$, $L_s=135$ and $L_s=150$.

Describing the changes in the zonal-mean and diurnal mean circulations in the context of a rapidly changing insolation environment, we can construct a reasonable
explanation of what is happening to alter the polar circulations so dramatically during the relatively short seasonal period of this study. At \( L_s = 120 \) the sun is still well above the polar horizon, maintaining warm surface temperatures just off the NPRC. A careful examination of the temperature data in Fig. 3.7 shows that the near-surface meridional decrease in temperature (cap edge to the pole) is \(-5 \) K greater at \( L_s = 120 \) than at \( L_s = 135 \); the cap temperatures decrease less over this period than those in the region surrounding the cap margin. This stronger near-surface temperature gradient may be related to the weak high latitude jet at \( L_s = 120 \) that can be seen in the zonal-mean zonal velocity of Fig. 3.5 and Fig. 3.7. Strong coriolis torques at these latitudes will steer off cap near-surface katabatic flows into anticyclonic circumpolar easterlies. Because of vertical wind shears and the asymmetric topography of the NPRC, perturbations along these sharp horizontal gradients develop easily, producing excursions from the mean diurnal cycles. The location and relative strength of these eddies is depicted in Fig. 3.8. Flow associated with Chasma Boreale is an important factor, leading to the region of greatest activity at the outlet (\( \bar{u}' \)) and southeast of Chasma Boreale (\( \bar{v}', \bar{T}' \)).

By \( L_s = 135 \), the steepest northward facing slopes on the poleward side of the Tharsis and Alba Patera massif are receiving significantly less insolation. The diurnal surface temperature cycle of this region is large since the thermal inertia is low. Both of these factors enhance nocturnal drainage flows, which in this region are already expected to be strong. Thus, stronger drainage flows are influencing the daily weather cycles further poleward by \( L_s = 135 \). Additionally, the thermal low circulation over Olympus Mons and Alba Patera has weakened significantly, as evidenced in Fig. 3.6 by the decreasing strength of the counterclockwise circulation around this region between \( L_s = 120 \) and \( L_s = 135 \). We note, however, that the poleward flow on the eastern slopes of Alba Patera and Tharsis has not diminished in strength significantly (the result of a western boundary current effect). These factors all apparently work together to form a pathway for transient circulations to efficiently reach the highest latitudes. The result is clearly seen in the changes between \( L_s = 120 \) and \( L_s = 135 \) in
Fig. 3.8. Due to these changes, the northern slopes of Tharsis have become a region where transient eddies form. These transients form at the shoulders of Alba Patera and Tharsis and move poleward, dynamically connecting the middle latitude atmosphere to that over the NPRC.

Figure 3.9: The 20-sol diurnal mean zonal wind field is shown at 9 sigma levels for $L_s=150$. Level 6 is at $\sim18$ km and level 22 is at $\sim1$ km.

By $L_s=150$, changes in the large-scale circulations have dramatically modified the polar circulation, which is quickly becoming winter-like. The diurnal mean winds near Elysium Mons appear to be involved, helping to provide a favorable environment for the increase in transient eddy activity that develops poleward of Elysium Mons. Examining Fig. 3.6 we see that the diurnal mean winds near Elysium
Mons strengthen between \( L_s = 135 \) and \( L_s = 150 \). Reaching poleward from Elysium Mons, the mean excursion amplitudes also increase significantly in Fig. 3.8. The mean meridional excursion winds now connect the atmosphere near Elysium Mons to polar latitudes, a transition similar to what occurred with Alba Patera and Tharsis at \( L_s = 135 \) (described above). The maximum in the mean temperature excursion field of Fig. 3.8 is related to a maximum of the jet seen in the zonal-mean zonal wind at \( L_s = 150 \) in Fig. 3.5. The collocation of these features suggests that baroclinic processes have become very important in the polar region by \( L_s = 150 \). This early fall jet has two maximums, one north of Elysium Mons and one north of Tharsis (the strongest). The spatial structure of this jet is depicted at nine levels in the atmosphere from \(~18\) km above the surface down to \(~1\) km in Fig. 3.9. Although the details of the dynamics that excite this jet are not entirely clear at this time in our analyses, it seems fairly clear that circulations excited by the topography of Elysium Mons, Alba Patera and Tharsis are involved. With Alba Patera and Tharsis, strong transient circulations continue to form and move northward, although eddies now follow trajectories that are directed more easterly.

A primary motivation for this work is to develop a modeling system to help better understand the water cycle of the NPRC. Even with a dry atmosphere in the model, some useful information about the potential for meridional transport and mixing of water vapor can be extracted in terms of the dynamics of the atmosphere and the transient circulations that produce fluxes of momentum and heat. Time histories of momentum and heat fluxes can be constructed from the \( U, V \) and \( T \) excursion records. For the purpose of qualifying the changing midsummer polar climate we examine \( 20\)-sol mean fluxes. For each simulation the momentum and heat fluxes are shown in Fig. 3.10 and defined as follows:

\[
\overline{u'v'}(\lambda, \phi, z) = \sum_{i=1}^{N} \left( \frac{1}{i} \right) (u' \lambda, \phi, \phi, z, t) \left( v' \lambda, \phi, \phi, z, t) \right);
\]

\[
\overline{v'T'}(\lambda, \phi, z) = \sum_{i=1}^{N} \left( \frac{1}{i} \right) (v' \lambda, \phi, \phi, z, t) \left( T' \lambda, \phi, \phi, z, t \right).
\]

(3.4)

(3.5)
Figure 3.10: 20-sol mean values for momentum flux ($\overline{u'v'}$) and heat flux ($\overline{v'T'}$). Values are shown for solar longitudes of 120, 135 and 150, respectively from top to bottom.
At $L_s=120$, circulations in the polar region are clearly isolated from middle latitudes. The fluxes of momentum and heat provide additional evidence for how transient eddies form along the margin of the NPRC. These fluxes are strongest near Chasma Boreale, as also noted above. Atmospheric water vapor is at a maximum over the NPRC at this season (Smith, 2004), with a strong meridional gradient and column abundances decreasing towards the equator. The eddies that produce the regions of elevated momentum and heat flux form within this strong meridional gradient of water vapor; thus, they will drive a down-gradient (equatorward) mixing (transport) of atmospheric water. This process will move water vapor off the cap, although there no mechanism is seen in the model at $L_s=120$ to continue strong transport into middle latitudes.

At $L_s=135$ in Fig. 3.10, the transient fluxes provide additional evidence for how atmospheric dynamics connect the atmosphere over the northern slopes of Alba Patera and Tharsis to that of the polar region. These fluxes would still be occurring within a strong meridional gradient of atmospheric water vapor, again implying that equatorward (down-gradient) transport of water vapor may be strong within this region of enhanced momentum and heat fluxes. Moreover, this mechanism provides a consistent explanation for the surprising two-peak behavior of water ice clouds observed by Benson et al. (2003) over Alba Patera.

In Fig. 3.6 of Benson et al. (2003), the first and strongest peak forms at $L_s=60$. Presumably this is in response to the release of water into the atmosphere as the seasonal cap retreats. Because the subsolar latitudes at $L_s=120$ and $L_s=60$ are nearly identical, the polar circulations at these times are similarly isolated from mixing with the atmosphere at lower latitudes; a separate simulation we have performed at $L_s=78$ (middle of the Mars Scout Phoenix mission landing window), which includes a parameterized seasonal cap, supports this assertion. In our Phoenix simulation there is strong transient activity at the edge and over the receding cap, although strong meridional mixing equatorward of these latitudes, as suggested by the fluxes in our simulation at $L_s=135$, does not exist. Thus, as the edge of the retreating
seasonal cap reaches the NPRC by $L_s=90$, the supply of water to lower latitudes is significantly reduced. As summer progresses, the polar circulation injects a great deal of water into the polar atmosphere due to strong mixing over the NPRC, as produced by the polar circulations at $L_s=120$. By $L_s=135$, water vapor is transported into lower latitudes due to the dynamical connection that forms along the corridor between the northern slopes of Alba Patera and Tharsis and the NPRC, and the second peak of water ice clouds found by Benson et al. (2003) appears. The column integrated TES water abundances of Smith (2004) are consistent with this, since there is a build up of water in the polar region until $L_s=135$ when equatorward transport appears to increase at the same time abundances over the pole sharply decrease. By $L_s=150$ the NPRC is receiving much less insolation, is getting much cooler, and the supply of water vapor to the atmosphere essentially ends. In the context of the results of Smith (2004), the period between $L_s=120$ and $L_s=150$ is very important in the annual water cycle. We believe we are resolving some of the mesoscale atmospheric dynamics that are involved in the water cycle during this midsummer period. Explicit examination of the midsummer transport of water vapor with the OSU MMM5 will be important to confirm this and is the subject of future studies.

By $L_s=150$ the atmospheric circulation at high latitudes is beginning to look winter-like. A strong dynamical connection remains between the polar region and the northern slopes of Tharsis and Alba Patera. By this date Elysium Mons has also formed a dynamical link to the polar region. Significant meridional transport of heat is taking place along the rapidly intensifying polar vortex.

3.3.2.1. Surface Pressure Excursions. Before examining the instantaneous circulations that cause certain regions to have greater RMS excursions and mean fluxes of momentum and heat, as discussed above, it is instructive to examine RMS excursions from the local mean diurnal cycle of surface pressure, $P_{s0}$. Topographical variation on Mars strongly affects surface pressure, thus the amplitude of surface pressure excursions as transient circulations move along topographical gradients. However, this bias can be removed from our analysis by normalizing the surface
pressure excursions with the local 20-sol diurnal mean surface pressure of each simulation. We have constructed 20-sol records of normalized surface pressure excursions. To construct the most correct excursion amplitudes over 20-sol periods, the hourly mean diurnal surface pressure cycle is trended with a function that has a mean value of unity, $\alpha(t)$. This function is a cubic fit to the normalized hourly mean domain surface pressure, which accounts for the systematic seasonal drift in the surface pressure field so that a systematic trend is not generated in the records of surface pressure excursions. The 20-sol records of normalized surface pressure excursions are constructed as follows:

$$P'_{\lambda \phi} = 100 \times \left( P_{\lambda \phi} - \alpha(t) \bar{P}_{\lambda \phi} \right) \left( \bar{P}_{\lambda \phi} \right)^{-1}. \quad (3.6)$$

Using these records of normalized excursions, the 20-sol RMS normalized surface pressure excursion fields are constructed using the same approach as applied above to generate other RMS excursions, as defined by:

$$\bar{P}'_{\lambda \phi} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( P'_{\lambda \phi} \right)^2}. \quad (3.7)$$

The resulting fields are shown in Fig. 3.11. The upper two subplots show results for the $L_s=120$ case (both the 54 km and 18 km nests); the lower subplots show results from the $L_s=135$ and $L_s=150$ 54 km nests. At $L_s=120$, transient eddies are strongest along the edge and onto the NPRC, with a region of strong activity that reaches southward from the mouth of Chasma Boreale to $\sim 70^\circ$ N. A 20-sol mean amplitude of $\sim 0.75\%$ is rather considerable, since excursions of $\sim 1\%$ are dynamically similar with average terrestrial synoptic disturbances. As expected for $L_s=120$, there is very little transient eddy activity on the northern slopes of Alba Patera and Tharsis, although Alba Patera is seen to be active in the 54 km nest. Immature eddies will track westward north of Alba Patera, although they quickly decay in conditions apparently unfavorable for growth with the stronger thermal low-pressure circulation at this time. By $L_s=135$ the large-scale circulation has changed and we see the result that has been discussed above. This region of stronger transient eddy activity is a “storm track,” which connects the atmosphere over Alba Patera and Tharsis with that
of the most polar latitudes. Transient eddies that form on the shoulder of Alba Patera and Tharsis grow and move poleward before they decay at the edge of the NPRC. By $L_s=150$ eddies that form on Alba Patera and Tharsis do so more east of the summit. It appears that a unique balance of circulations exists at $L_s \approx 135$ and allows the formation of this "storm track" feature; however, we do not yet fully understand the dynamics. The appearance of the circumpolar jet by $L_s=150$ (Fig. 3.9) is clearly involved in the dramatic increase in the strength of the mean transient eddies.

**Figure 3.11:** 20-sol RMS normalized excursions (in percentage) from the mean diurnal surface pressure cycle are shown. The upper two subplots show the $L_s=120$ case for both nests (54 km and 18 km); the lower subplots show $L_s=135$ and $L_s=150$. Topography is contoured with solid black lines. Color shows percentage amplitude of the mean normalized $P_{sfc}$ excursion (white solid lines contour it).
Figure 3.12: Six snapshots from the $L_\alpha=120$ simulation are shown. UTC time is 0 Z and each subplot is two sols later than the previous. Color is the instantaneous percentage deviation from the local surface pressure cycle. The arrows are instantaneous wind excursions (every other point) from the mean diurnal wind cycle.
3.3.2.2. Synoptic Eddy Structure. After examining the results above, we find that transient eddies are prominent in northern midsummer and have favored locations that vary with season. These eddies are excited by multiple mechanisms in a complex fashion that changes significantly within this seasonal study period. Thus, a more careful examination of the synoptic structure and evolution of these eddies is needed to better understand the dynamics. In this section we examine the actual near-surface wind excursions and surface pressure excursions to provide a clear picture of the strength, structure and lifetime of these circulations. See Appendix A for additional depiction of the transient eddy structure.

The L_s=120 case is examined in Fig. 3.12, which shows the excursion wind field for every other gridpoint at σ = 20 (~1.5 km) and the normalized surface pressure excursion field for six times; these data are from the 18 km nest. Each subplot is two sols after the previous one, showing the evolution of individual eddies over a full 10-sol period. The surface pressure excursion field exhibits a pronounced zonal wavenumber one structure between ~75 N and ~85 N. The high and low centers of pressure have amplitudes of ~1% and are generally centered along the edge of the NPRC, separated in longitude by ~180°. The excursion pressure centers exhibit a retrograde motion (east to west) along a weak low-level westerly jet with easterly zonal mean surface winds (see Fig. 3.5). The transient eddies that give the flow a zonal wavenumber one character are the largest, with spatial scales between ~500 km and ~1000 km, although the model does resolve smaller eddies in the flow with spatial scales to ~100 km. An examination of all 20 sols of model output shows the circulation can vary significantly from this general wavenumber one structure at times. The retrograde motion can be seen in Fig. 3.12 by tracking the largest individual eddies to the west. The strongest excursion winds are found at the sharpest excursion pressure gradients (between the high and low pressure regions), strong winds (~15 m/s) that blow directly across the residual cap on a very regular basis. The structure of this circulation constantly changes and it seems that Chasma Boreale may play an important role, enhancing pressure centers when they are oriented such
Figure 3.13: Six snapshots from the $L_x=135$ simulation are shown. UTC time is 0 Z and each subplot is two sols later than the previous. Color is the instantaneous percentage deviation from the local surface pressure cycle. The arrows are instantaneous wind excursions from the mean diurnal wind cycle.
that thermally driven diurnal surface circulations enhance those of the transient eddies. This idea would be better studied with a nonhydrostatic version of the OSU MMM5, after first picking an appropriate period from this simulation and using it to provide initial and boundary conditions (including soil temperatures) for a much shorter duration nonhydrostatic simulation. For the $L_s=120$ case, the retrograde circumpolar transit time for the zonal wavenumber one structure of excursion surface pressure is $\sim 5.5$ sols (see Appendix A).

In Fig. 3.13 we examine eddies in the $L_s=135$ case for a subset of the 54 km nest, showing the excursion wind field at $\sigma = 20$ ($\sim 1.5$ km) and the normalized surface pressure excursion field; these data are from the 54 km nest. Subplots show six times, each is two sols after the previous. In the bottom left corner of the first subplot a cyclonic eddy has formed on the flanks of Alba Patera and Tharsis. This eddy grows much deeper and travels northward along the “storm track” mentioned above, lasting for $\sim 10$ sols until it reaches the NPRC where its energy dissipates after another sol or so. This transient eddy is surprisingly long-lived, strong (fractional surface pressure depressions of $\sim 1.5\%$ with excursion wind speeds of $\sim 15$ m/s) and travels a large meridional distance. At the end of this sequence we note that another such eddy is apparently forming in the same location, suggesting there is a recurring “cycle” of formation, growth, poleward migration and dissipation over the NPRC during some portion of the midsummer season. The eddy in Fig. 3.13 travels northward $\sim 35^\circ$ of latitude in 10 sols, averaging $\sim 2$ m/s. At step 240 in Fig. 3.13 this eddy is in a strong developmental stage with a clear frontal boundary in the wind field. A significant amount of meridional mixing should occur in response to the excursion winds of these large eddies (spatial scales of $\sim 1000$ km. This “storm track” corridor may be very important for transporting water into lower latitudes at $L_s=135$; however, this hypothesis must be explicitly addressed once water vapor transport is activated in the model. Other large and long-lived eddies form at $\sim 70^\circ$ N between $\sim 90^\circ$ E and $\sim 180^\circ$ E, and these circulations would enhance meridional mixing of the
Figure 3.14: Six instants from the $L_s=150$ simulation are shown. UTC time is 0 Z and each subplot is two sols later than the previous. Color is the instantaneous percentage deviation from the local surface pressure cycle (note the greater range than for $L_s=120$ and $L_s=135$). The arrows are instantaneous wind excursions from the mean diurnal wind cycle.
atmosphere. Weaker eddies with retrograde motion continue to form along the edge of the NPRC. Using a nonhydrostatic version of the OSU MMM5, as described above for closer examination of the \( L_s = 120 \) case, would be very useful to better understand the dynamics of the “storm track” region observed in the \( L_s = 135 \) case.

We examine the \( L_s = 150 \) case in Fig. 3.14, which shows the excursion wind field for every other gridpoint at \( \sigma = 20 \) (~1.5 km) and the normalized surface pressure excursion field; these data are from the 54 km nest. The \( L_s = 150 \) circulation is more complex than the earlier two cases since, besides being excited by near-surface circulations related to topography, transient eddies are also forming along an early fall winter-like polar jet (see Fig. 3.9). We can see that the \( L_s = 150 \) case is different by examining Fig. 3.15, which shows the level mean and level maximum temperature and speed excursions versus model sigma level for each simulation; these data were extracted from the 18 km nest 20-sol mean temperature and speed excursion fields. Generally the \( L_s = 120 \) and \( L_s = 135 \) cases are quite similar in all four subplots, although the level max speed excursion at \( L_s = 120 \) is stronger at altitude than at \( L_s = 135 \) because of the stronger eddies along the residual cap edge at that time. In this same subplot, the two peaks in the \( L_s = 150 \) case show that strong eddies can occur near the surface or higher in the atmosphere, although the level mean speed excursion suggests that the near surface formation mechanisms are still more prevalent, at least in this domain. The largest amplitude in the level max temperature excursion occurs significantly higher in the model at \( L_s = 150 \), although all three cases drop to background levels by \( \sigma = 10 \) (essentially one pressure scale height), the top of most transient eddy activity. Transient eddies at \( L_s = 150 \) are much stronger (a wider colorbar range in Fig. 3.14 that in Fig. 3.12 and Fig. 3.13), reaching surface pressure amplitudes of ~2%. In the bottom left of each subplot we can see that the atmosphere near Alba Patera is best described as large-scale turbulence. Eddies that form on Alba Patera and Tharsis now track NE, crossing the NE shoulder of Tharsis as they move into northern Acidalia Planita. The consequence of this can be seen clearly in the mean heat and momentum fluxes for \( L_s = 150 \) in Fig. 3.10. The \( L_s = 150 \) case in
Fig. 3.11 also helps to put an important constraint on the location of the strongest eddies seen in Fig. 3.14; the path they follow is an elongated ellipse in this domain (which is best seen in animations). As can be seen at steps 288 and 384 in Fig. 3.14, the pole can be under the influence of a strong low pressure or high pressure center. Step 336 provides a good example of the size of these eddies (~1500 km) that produces the maximum amplitude in the mean heat flux of Fig. 3.10. Appendix A provides a more complete depiction of the eddy structure as shown in Figs. 3.12, 3.13 and 3.14.

**Figure 3.15:** Level mean and maximum temperature and speed excursions from the diurnal mean cycles. The profiles are constructed from 20-sol averages for each model level in the three simulations of this midsummer study. The altitude at $\sigma = 20$ is ~1.5 km and at $\sigma = 10$ is approximately one pressure scale height. The red, green and blue lines respectively represent the $L_s=120$, $L_s=135$ and $L_s=150$ simulations.
3.4. Summary, Discussion and Conclusions

The hydrostatic OSU Mars MM5 has been used to characterize midsummer atmospheric dynamics in the northern polar region. To produce a realistic thermal environment in the highest latitudes, we have extrapolated thermal inertia data to the pole. Our method essentially correlates thermal inertia to surface albedo at latitudes above 80° N, which results in simulated temperatures that agree quite well with MGS TES and RS observations. The OSU MMM5 was run with a dry atmosphere using hydrostatic dynamics. This approach has allowed for reasonable model tuning and a suite of long simulations (29 sols) that span the midsummer season: Lₕ=120, Lₕ=135 and Lₕ=150. The final 20 sols of output from each simulation are centered on these seasonal dates and were used to generate numerous model statistics. This seemingly long spin-up period is required due to the modified polar surface thermal properties used in these simulations. Modeling time is required for soil temperatures to reach equilibrium; however, time is also needed for larger-scale circulations that are not in the GCM initial conditions to fully develop and adjust to the higher resolution topography being used in the OSU MMM5.

Midsummer polar circulations vary significantly between Lₕ=120 and Lₕ=150. At Lₕ=120 there is continual transient eddy activity along the margin of the NPRC. These eddies produce strong winds (~15 m/s) that blow directly across the residual ice cap. These winds may be quite important in the transport of water vapor away from the cap and for aiding the sublimation of residual cap ice by providing unsaturated air and driving turbulent mechanical mixing near the surface. At Lₕ=120, a companion circulation that would effectively mix water vapor equatorward (water vapor freed by the suggested mechanisms) is not observed in our results. And, as observed (Smith, 2004), water vapor builds up in the atmosphere over the most northern latitudes (the annual maximum). By Lₕ=135, in response to changes in the large-scale circulations over Alba Patera and on the northern slopes of Tharsis, the dynamics of the atmosphere are connecting the atmosphere of this middle latitude region to that of the polar atmosphere via transient eddies. The isolated nature of the
circulation over the NPRC at $L_s=120$ breaks down by $L_s=135$, due in part to strong eddies moving along this "storm track" from Alba Patera and Tharsis into the NPRC region. Moreover, by providing a pathway for elevated meridional mixing within a strong meridional water vapor gradient, the appearance of this "storm track" in the $L_s=135$ simulation is consistent with the two-peak distribution of water ice clouds observed over Alba Patera by Benson et al. (2003). By this time the maximum amount of water vapor over the pole has begun to decline (Smith, 2004); thus, an important pathway for the equatorward transport of water vapor via strong meridional mixing is likely to exist along this "storm track" between the NPRC and Alba Patera at $L_s=135$. The transient eddies in the $L_s=120$ and $L_s=135$ cases are primarily excited by the interaction of strong near surface flows. The maximum excursion surface pressure amplitudes for transient eddies at $L_s=120$ and $L_s=135$ are respectively $\sim1\%$ and $\sim1.5\%$. More figures that depict the eddy structures for each of the three simulations are provided in Appendix A, along with a single point eddy correlation analysis that clearly demonstrates the zonal wavenumber one structure at $L_s=120$ and its $\sim5.5$ sol period.

By $L_s=150$ the polar region has cooled dramatically and the polar circulation is beginning to look very winter-like. An early fall polar jet has formed; its formation appears to involve circulations that are excited by Elysium Mons and the Alba Patera and Tharsis massif. This jet has a zonal mean maximum of $\sim20$ m/s and produces transient circulations with large surface pressure excursions ($\sim2\%$). The transient eddies at this time exhibit greater vertical extent than the two previous cases. The interaction of near surface flows still seems to be the dominant mechanism for forming transient eddies, but those excited along the polar jet (the deeper eddies) are becoming quite prevalent by $L_s=150$. As a result, the poleward eddy fluxes of heat and momentum have become quite significant by this time in certain regions.

This midsummer period ($L_s=120$ to $L_s=150$) is extremely important for the annual water cycle of the NPRC, since this is when the columnar mass of water vapor drops sharply from a maximum, and when the greatest equatorward transport of water
vapor most likely occurs. Enabling the sublimation of surface water ice and the transport of atmospheric water vapor in the OSU MMM5 will allow for studies leading to a better understanding of the NPRC water cycle, and the importance of atmospheric dynamics during this season. The upcoming Phoenix Mars Scout mission, landing in 2007, will provide in-situ meteorology from a high northern latitude location in late spring and summer. The Mars Reconnaissance Orbiter (MRO), landing in 2005, will provide improved measurements of atmospheric and surface temperatures, water vapor and ice abundances. MRO will provide data during northern summer as well as for other seasons. We look forward to working with the exciting data that will be returned from these missions. Using the nonhydrostatic version of our model to provide more careful examination of the structure and formation of the transient eddies described in this study may be an important part of moving forward towards a better understanding of the climatology of the northern polar region once issues with nonhydrostatic dynamics have been resolved.

This chapter (Chapter 3) was submitted for publication and has just completed the peer review stage. Small changes to the submitted manuscript have been incorporated for clarity, although university deadlines preclude a full inclusion of responses to reviewer comments. Thus, Appendix B has been provided for purposes of describing the reviewer comments and our planned response to assure publication of the final manuscript upon resubmission.
3.5. Acknowledgements

We thank Nathaniel Putzig for his generous assistance in providing thermal inertia maps and answering dumb questions. We thank Leslie Tamppari for inviting our efforts to help with the Mars Scout Phoenix mission; our work for Phoenix so far has resulted in model improvements that would otherwise not have been developed.
4. General Summary, Conclusion and Direction

4.1. General Summary

This dissertation has described the development, testing and initial research performed with a new computer model to study the atmosphere of Mars, The OSU MMM5. The OSU MMM5 was developed by converting the MM5, a state-of-the-art terrestrial mesoscale model (Fifth-Generation Penn-State/NCAR Mesoscale Model, Grell et al., 1994), into a mesoscale model for Mars. This process was outlined in Chapter 1 and is described in detail in Chapter 2. Successful development of the OSU MMM5 was demonstrated by comparing model results with surface meteorology gathered by MPF and VL1, presented in Chapter 2.

Using state-of-the-art mesoscale models to study Mars is a new endeavor (Rafkin et al., 2001; Toigo and Richardson, 2002; Tyler et al., 2002), the following three reasons are central in why these models are presently being developed: 1) the computing power required to run mesoscale models is now affordable within any science budget (desktop computers); 2) there is new data describing the surface of Mars that allows mesoscale models to have very accurate and high resolution representations of the Martian surface; and, 3) modeling is one of the most effective ways to understand the large and extremely rich new datasets that have become available in this exciting new era of planetary exploration.

Until recently, GCMs were the only tools providing 4-D descriptions of circulations in the atmosphere of Mars. GCMs are integrated on coarse resolution global domains, typically with uniform grid spacing in latitude and longitude (the NASA Ames Mars GCM grid spacing is 7.5° in latitude by 9° in longitude). The simulations discussed in this dissertation were all performed using the hydrostatic OSU MMM5 (unresolved issues exist with nonhydrostatic dynamics, see Chapter 1). This approach has allowed for long simulations on large semi-global domains due to the reduced computational overhead of hydrostatic dynamics. The OSU MMM5 has
been used much like a GCM, although at significantly higher resolution in the model and in the baseline maps of surface properties (topography, albedo and thermal inertia) that are used at initialization to generate the surface maps actually used during simulations. Modeling at this intermediate spatial scale, between that of GCMs and the true realm of present day mesoscale models (nonhydrostatic with resolutions of ~1 km) has been quite instructive. Chapter 2 describes some idealized modeling investigations that provide insight into how model resolution, the domain/nest choices and the model boundaries can affect results in a Mars mesoscale model. Comparing with terrestrial mesoscale modeling, these issues are more important because of the thermal tides in the Martian atmosphere (Wilson and Hamilton, 1996; Zurek and Haberle, 1988). Additionally, large slope flows, which are regional mesoscale circulations on Mars, can influence the diurnal cycle of surface pressure. Thus, for some locations on Mars, the diurnal cycle of surface pressure is not simply driven by large-scale circulations that result from thermal tides in the atmosphere. Modeling domains must be chosen wisely in consideration of such regional scale flows and possible problems with boundaries.

Chapter 3 builds on the methods developed and used in Chapter 2, particularly the use of a large semi-global polar stereographic mother domain. Three simulations (each lasting for 29 sols) are used to characterize midsummer northern hemisphere polar circulations (L_s=120, L_s=135 and L_s=150). Chapter 3 is the culmination of this dissertation; the results presented there have provided focus for future research. The conclusions, questions and future research directions are discussed generally in the final section.

4.2. Conclusion and Direction

The climate of Mars is determined by the energy balances of the polar regions. The truth of this bold statement results from the basic fact that the atmosphere of Mars is primarily carbon dioxide (95%). Annual temperature variations at the poles
cause the primary constituent of the atmosphere to precipitate out and/or condense on the surface every winter in both hemispheres (winter temperatures drop to \(\sim 150 \text{ K}\)). In response to present day values of the orbital parameters (obliquity, eccentricity and precession of the spin axis), the annual polar energy balances determine the annual cycle of atmospheric mass, and importantly the degree to which this behavior is asymmetric between the two hemispheres.

**Figure 4.1:** The annual cycle of Viking surface pressure. The topographical height at VL2 is lower than that at VL1 (included here with the permission of J. E. Tillman).

The Viking Landers of the late 1970s have provided the best record of this annual cycle by tracking the surface pressure at two locations over multiple years on Mars; the VL1 record is the longest. The annual cycle of surface pressure is highly repeatable, although it is seen to vary somewhat during global dust storms; these data are shown above in Fig 4.1. Surface pressures are lowest during southern winter.
when the greatest amount of carbon dioxide is on the ground. Based on the amplitude of the surface pressure oscillation the mass of the atmosphere varies by ~25% each year. This annual cycle is by no means symmetric, as there is much more carbon dioxide in the southern winter seasonal CO₂ cap. Polar atmospheric dynamics would seemingly be very important in producing the asymmetry in the annual cycle of atmospheric mass, since the atmospheric transport of heat into the polar regions is an important part of the annual polar energy balance. However, this is a hypothesis that has not been fully explored; it may be that sophisticated mesoscale models become important in more thorough investigations of these ideas.

Figure 4.2: Columnar water vapor mass abundances versus Lₙ. Zonally integrated mass abundances (in precipitable microns) are shown for a little more than two Mars years. The image is a subplot from a figure in the work of Smith (2004) (included here with the permission of M. Smith).

Concerning the importance of atmospheric dynamics in the polar regions, the residual water ice cap at the North Pole is believed to be the primary source of water in the annual cycle of atmospheric water vapor (Richardson and Wilson, 2002). The “pole problem,” shared by all present day grid point Mars GCMs, is a real hindrance to realistic simulations of atmospheric circulations and weather over the residual water ice cap, northward of ~70° N; mesoscale models are much more appropriate tools for studying atmospheric circulations in the polar regions. Chapter 3 provides the first comprehensive mesoscale modeling study of midsummer polar circulations for the northern hemisphere. Three OSU MMM5 simulations (Lₙ=120, Lₙ=135 and Lₙ=150) show that between Lₙ=120 and Lₙ=150 there are dramatic changes in the
polar circulation that might be important in how water vapor is mixed equatorward. Importantly, during this short seasonal period, the water vapor columnar mass abundances drop quickly from the annual maximum towards an annual low at high latitudes, arrived at shortly after $L_s=150$. This transition can be seen clearly in Fig. 4.2 for three separate midsummer periods.

By $L_s=60$, Fig 4.2 shows that a strong meridional gradient in the zonally averaged abundance of atmospheric water vapor has formed (increasing poleward). The maximum amount of atmospheric water vapor over the northern polar region is seen at $L_s=120$, with a strong meridional gradient fully established. By $L_s=150$ this gradient has disappeared and water vapor is well mixed throughout the northern hemisphere. The changes between $L_s=120$ and $L_s=150$ are dramatic; it is an extremely important time in the annual water cycle. A detailed description of the physical processes that cause these changes is needed; this research seems to have provided some of this by simulating the dynamics.

Significant transient eddy activity develops on the northern slopes of Alba Patera and Tharsis in the $L_s=135$ simulation. These eddies form in an environment with a strong meridional gradient of atmospheric water vapor (Fig. 4.2); thus, the meridional mixing (the implied equatorward transport of water vapor) in that region should be significant due to the prominence and strength of the eddies (Fig. 3.13). Benson et al. (2003) examined MOC wide-angle imagery of the Tharsis region and noted that there are two distinct maximums in observed cloud frequency over Alba Patera, with the second maximum appearing at $L_s=135$. Considering how the polar circulation simulated by the OSU MMM5 changes between $L_s=120$ and $L_s=135$, the observations of Benson et al. (2003) provide compelling evidence in support of strong equatorward transport of water vapor along a transient eddy “storm track” that is located between the northern slopes of Alba Patera and Tharsis and the polar region. This “storm track” can be seen clearly in Fig. 3.11, along with where the dramatic increases in transient eddy activity occur between $L_s=120$ and $L_s=150$ in the OSU MMM5. At $L_s=120$ there is little capacity for significant meridional mixing south of
Although, by $L_s=150$ the 54 km domain is essentially dominated by strong eddies, which would seemingly cause the atmosphere of the northern hemisphere to rapidly become very well mixed, highly consistent with the results of Smith (2004). Also, by $L_s=150$ the polar region has cooled dramatically, especially near the surface of the residual cap as seen in Fig. 3.7. This suggests that the residual cap is now too cold to sublimate water vapor into the atmosphere; thus, the supply of water vapor would end, the remaining water vapor would be mixed southward and the abundance of vapor in the northern hemisphere would drop quickly as winter threatens (the circulation at $L_s=150$ look very winter-like with the formation of a strengthening polar jet, Fig. 3.9).

This research has provided new and valuable information about the nature of the midsummer polar circulation in the northern hemisphere. It has also provided some insight into the importance of atmospheric dynamics in the annual water cycle, although only in relation to observations, not directly. The period between $L_s=120$ and $L_s=150$ is crucial for the climatological stability of the north residual ice cap; a characterization of the full annual water cycle is required to effectively address this issue. Such modeling efforts would need to include water vapor sublimation and transport processes (fairly obvious next step), along with a parameterization for clouds (simulating the return of water to the NPRC is much more difficult to do realistically). Very recently (at the request of the team leader of the Phoenix Mars Scout mission) we have extended our modeling studies into earlier seasons ($L_s=78$), a date associated with the landing of the Phoenix mission at high latitudes in the northern hemisphere, when a significant seasonal carbon dioxide cap is still on the ground. This simulation has provided some additional evidence for how the polar circulation is dramatically dependent upon seasonal date. We look forward to working further with the Phoenix team, the success of the mission and the gathering of in-situ meteorological data from a high latitude location.

Development of the OSU MMM5 has identified the importance of improving two aspects of Mars mesoscale models: the PBL schemes and the nonhydrostatic
dynamical cores. This work has also shown that mesoscale modeling of the Martian atmosphere requires that more care be taken with model boundaries and domain choices. At OSU we will be developing a Large Eddy Simulation (LES) model to better understand the lowest ~1 km of the Martian PBL. We hope to improve the PBL scheme in the OSU MMM5 based on the results from this effort (the importance of radiation in the Martian PBL is much greater than it is for Earth). As part of these efforts we will include the neglected diabatic heating terms (Dudhia, 1993) in the nonhydrostatic dynamics of the OSU MMM5; the best comparison with an LES model would be with a nonhydrostatic OSU MMM5. Finally, collaboration with members of the NASA Ames Mars GCM team will provide an improved radiation scheme and various solutions to simulating clouds in our mesoscale model.

There is a career of work waiting. The time between now and the landing of Phoenix should provide for a great deal of progress in model development, clearly in anticipation of in-situ meteorology from the northern polar region. This “young” scientist has become fascinated with the climatological history recorded in the PLDs of the NPRC; and, hopes, someday, to contribute towards a better understanding of their evolution and climatological stability.
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Appendices

Chapter 3 of this dissertation is a manuscript that was submitted to JGR Planets for publication, as declared in its title page. A few small changes have been made to Chapter 3 for purposes of clarity; however, it remains essentially unaltered from the submitted manuscript besides formatting as required by OSU. At the request of my committee, Appendix A was added to provide a more complete depiction of the transient eddies and their spatial structure (more than provided in Chapter 3 figures). Comments from peer review were forwarded by the editor of JGR Planets recently (10/19/04), and since this dissertation was recently defended (10/1/04), the OSU deadlines do not provide sufficient time to both modify the manuscript in response to these comments and incorporate the revised version into this document. Thus, Appendix B has been added for a short explanation of the changes that will be made to Chapter 3, in response to review, before the manuscript is resubmitted.

Appendix A: Eddy Structure in Chapter 3

Three figures were included in Chapter 3, one for each of the cases in the northern midsummer polar study (Figures 3.12, 3.13 and 3.14 for cases $L_r=120$, $L_r=135$ and $L_r=150$ respectively). These figures show the structure and location of transient eddies in the flow at six times, each time two sols later than the previous. In this appendix additional figures are provided for a more complete depiction of the behavior of these eddies throughout each of these simulations. Additionally, the eddies at $L_r=120$ in the 18 km nest are examined statistically to show the zonal wavenumber one structure existing around the northern residual polar ice cap and the phase speed of their propagation. These features of the circulation were alluded to in Chapter 3 but not shown directly. The statistical method used to show this (single point correlation) does not yield valuable results for the $L_r=135$ or $L_r=150$ cases, indicating there is no similar eddy correlation structure that occurs at those times.
Figure A.1: The domain-mean normalized surface pressure for the $L_0=135$ case is shown versus time. The thin blue line shows the actual data and the thick black line is a third degree polynomial fit to this data, $\alpha(t)$, as used in the formulation of surface pressure excursions described below in text. There is a $\sim 1\%$ decrease in atmospheric mass over this time.

Because amplitudes of surface pressure excursions are strongly correlated with Martian topography, and since the mass of the atmosphere varies continuously throughout the Martian year (see Fig. 4.1), constructing a record of surface pressure excursions cannot be done by simply subtracting the 20-sol local hourly mean value from the instantaneous local value at that hour (a method which works quite well for perturbations in the velocity components). Constructing realistic and representative surface pressure excursions requires greater care. However, the amplitude bias of surface pressure excursions with topography can be easily removed by normalizing all surface pressure excursions with the local diurnal mean surface pressure. In terrestrial analyses, sea level pressure is utilized for this very reason, an unrealistic approach to use for Mars. Seasonal trends in atmospheric mass are removed by
trending the 20-sol mean hourly cycle of surface pressure at each location according to the trend in the mean surface pressure of the entire domain. With these simple modifications, realistic records of surface pressure excursions are produced for each simulation using the formulation of equation 3.6, which is shown again here for convenience:

\[
P'_{\varphi}(\lambda, \phi, t) = 100 \times \left( P_{\varphi}(\lambda, \phi, t) - \alpha(t) \overline{P}_{\varphi}(\lambda, \phi, hr) \right)^{-1}.
\]  

(A.1)

The factor, \( \alpha(t) \), which trends the mean hourly surface pressure, is constructed for each simulation/domain being considered by fitting the normalized domain-mean surface pressure as described above. Specifically, a fit for the 54 km nest at \( \text{L}=135 \) is shown in Fig. A.1. This factor clearly accounts for the changing mass of the atmosphere without being affected by transient circulations in the domain. Finally, dividing by \( \overline{P}_{\varphi}(\lambda, \phi) \) removes the bias of amplitude with topography, normalizing surface pressure excursions and allowing for discussion of relative dynamical strength in terms of terrestrial analogy.

The figures presented in the next six pages depict eddy structure (the surface pressure excursion fields) at 0.5 sol intervals (12 hr) for the entire 20 sols of data for each of the three midsummer simulations, \( \text{L}=120, \text{L}=135 \) and \( \text{L}=150 \). There are two figures for each case; the two figures for the \( \text{L}=120 \) case show results from the 18 km nest, whereas the others are from the 54 km nest. The use of color (including the respective colorbars) is identical to that of the three figures shown in Chapter 3, although the vectors showing instantaneous excursion winds have been removed in favor of clearly depicting the non-dimensional strength of the surface pressure excursions, the transient eddies. There is a diurnal cycle in the strength of these circulations that is most easily seen in single frame animations, although the 0.5 sol interval used in these figures does allow this to become somewhat apparent upon careful inspection. The six pages of figures follow.
Figure A.2: Percentage surface pressure excursions from the $L_o=120$ simulation in the 18 km nest. The color axis is the same as in Fig. 3.12 (-1.5% to 1.5%). This plot shows sols 1-10 at 12 hr intervals (20 subplots). Time is given with respect to the zero meridian (time:12 is noon on the zero meridian).
Figure A.3: As in Fig. A.2, except for sols 11-20 of the L₄=120 simulation.
Figure A.4: Percentage surface pressure excursions from the Lₜ=135 simulation in the 54 km nest. The color axis is the same as in Fig. 3.13 (-1.5% to 1.5%). This plot shows sols 1-10 at 12 hr intervals (20 subplots). Time is given with respect to the zero meridian (time:12 is noon on the zero meridian).
Figure A.5: As in Fig. A.4, except for sols 11-20 of the $L_s=135$ simulation.
Figure A.6: Percentage surface pressure excursions from the $L_n=150$ simulation in the 54 km nest. The color axis is the same as in Fig. 3.14 (-2% to 2%). This plot shows sols 1-10 at 12 hr intervals (20 subplots). Time is given with respect to the zero meridian (time:12 is noon on the zero meridian).
Figure A.7: As in Fig. A.5, except for sols 11-20 of the Lₜ=150 simulation.
Concerning the Ls=120 simulation, a single point correlation analysis has proven very useful for depicting the zonal wavenumber one structure of the transient eddies that form predominantly around the edge of the residual polar ice cap. This structure was mentioned in Chapter 3 but is shown more clearly with this method. With a lagged single point correlation analysis the mean phase speed of this zonal wavenumber one structure can also be determined. Specific results from single point correlation analyses are sensitive to the point being used to correlate with the other points. Different points were tested; the qualitative nature of the result remained the same. This analysis was performed using a point from a region of elevated eddy activity (but not the strongest). The point chosen is (70,70), and can be located in the upper right subplot of Fig. 3.11, showing the 20-sol RMS surface pressure excursion.

**Figure A.8:** Excursion surface pressure records for two points are shown. The points are equidistant from the pole, but separated in longitude by 180°. The correlation is clearly negative since these curves generally vary in opposite directions throughout the entire period.
If two records vary in phase a correlation between them will approach unity, whereas if two records vary out of phase by $\sim 180^\circ$ the correlation approaches minus one. For example, in Fig A.8 above the final 10 sols of surface pressure excursion data are shown for the location (70,70) and a point equidistant from the pole but separated by $180^\circ$ of longitude, (32,32). The correlation coefficient between these records is $-0.668$, suggesting a zonal wavenumber one structure.

**Figure A.9:** Maps showing results of single point correlations of surface pressure excursion records. The point used for correlation is indicated with a white asterisk and the value of the correlation coefficient is shown with color. Topography is contoured in black at 500 m intervals.

If all points in the 18 km $L_s=120$ simulation are correlated against location (70,70) in the same way, a map can be constructed that shows all the correlation coefficients. This map is shown in Fig. A.9, along with a single point correlation map that utilizes a 2.75 sol lag. For the lagged single point correlation the 10 sol record at (70,70) was correlated with records 2.75 sols earlier (a lag of 66 hr). Since the lagged correlation has essentially changed algebraic sign, the eddy structure 2.75 sols earlier is thus $\sim 180^\circ$ out of phase, indicating that the "phase speed" of the wavenumber one structure is $360^\circ$ per twice 2.75 sols, or $\sim 5.5$ sols.
Figure A.10: Maps showing single point correlations for the $L_s=135$ and $L_s=150$ cases. The black asterisks mark the location of the excursion surface pressure record that was used to correlate against all other locations. For convenience the mean surface pressure excursion maps (from Fig. 3.11) are shown to the left of the respective correlation map. Topography is contoured at 1000 m intervals.

This same analysis can be applied to the other cases ($L_s=135$ and $L_s=150$). The zero lag single point correlation maps are shown to the right of the mean surface pressure excursion maps in Fig. A.10. The eddy structure for these two dates is more complex than at $L_s=120$, rendering this method a bit less revealing at these times. However, it does appear that the $L_s=150$ correlation coefficients show a rather elongated zonal wavenumber two structure. If a different point is chosen for the $L_s=150$ correlation, the resulting map continues to suggest this same qualitative
structure (not shown, trust me), suggesting it does actually form along the developing polar jet. $L_4=135$ however, as was suggested in Chapter 3, seems to be a time during the year when the polar circulation is undergoing significant transition, with a very complex circulation. The transient eddies at this time have no prevailing direction of travel around the polar region and the polar circulation is being strongly influenced by circulations that are excited by topography at much lower latitudes (specifically Alba Patera and Tharsis at this time). Because this is a transition period there is no established pattern in correlation coefficients, a hypothesis that is supported when using different points to create the correlation coefficient map. The qualitative nature of the result itself is quite dependent upon the point being used, which is different from the $L_4=120$ and $L_4=150$ cases.

This single point correlation method was used to support statements that were made in Chapter 3 about the structure and movement of eddies around the residual cap at $L_4=120$. As part of this exercise some additional structure became more apparent, which may deserve additional attention at a future time. Animations of the meteorological excursions show clearly that the transient eddies retain a fairly strong diurnal signal, even though the mean diurnal cycle was carefully removed in the construction of the meteorological excursions. This suggests that diurnal cycles behave differently and/or are more dramatic within the influence of a large transient circulation. This raises questions about the importance of the diurnal cycle in the growth and lifetime of transient eddies. As has clearly been suggested (Zurek et al., 1991), the importance of atmospheric tides (diurnal thermal cycles) in the lifetime of transient circulations on Mars may be extremely important. This topic will, however, remain one to be addressed in future work.
Appendix B: Refinement of Chapter 3 (Peer Review)

Chapter 3 of this dissertation was adapted from a manuscript that was recently submitted to JGR Planets for publication (see Chapter 3 title page). The editor of JGR Planets just sent the comments of the two peer reviews; the reviewers split on recommending the manuscript for publication. Reviewer comments show that minor changes are needed for purposes of clarity. Both reviewers suggest that additional figures would be useful to more completely develop the primary results of the manuscript. In response to reviewer comments, changes will be made to the manuscript before it is resubmitted to JGR Planets and this appendix is being used to describe how it will be strengthened.

In terms of manuscript clarity, Chapter 3 has already been reworked to some extent. The essential focus is to edit the manuscript so readers with an appropriate background understand the points being made (and why they are being made) within the context and limitations of our method. This, in general, is not a trivial exercise, although some may be quite gifted at doing so; experience increases ones ability. Both reviewers’ comments suggest they did not entirely understand some arguments being made in the manuscript, which will focus the efforts to clarify the manuscript on the needed sections.

One reviewer has correctly indicated that there is a weakness in our method due to the fact that the vertical profile of visible dust opacity is treated as globally uniform. The reviewer suggests that additional comparison with observed TES atmospheric temperatures would be appropriate, beyond simply tuning the model to the polar RS atmospheric temperatures at L_e=135. This reviewer would also like to see discussion comparing the circulations observed in the GCM with those of the OSU MMM5. Given the importance of lower latitude atmospheric circulations related to features of topography, we agree that additional figures and discussion (as suggested by this reviewer) would strengthen the paper. Changes along these lines will be made to the manuscript.
The other reviewer has suggested that the high-resolution wind field results could be utilized to constrain parameterizations of water vapor supply from the residual polar ice cap. This reviewer suggests that the two most commonly utilized supply prescriptions could be compared (the saturation of the lowest layer as over an ocean, or a wind stress related evaporative flux prescription). Such a result might help to guide GCM modelers in future simulations of the water cycle. We believe that this could be a useful addition to the manuscript and the manuscript will be modified to include a brief examination of these two approaches. This reviewer additionally suggests that the figures showing mass streamfunctions comparing the two models would be very useful for understanding the differences between the modeled circulations; this suggestion is related to the first reviewer’s concerns and will be performed to examine if it would add to the manuscript.