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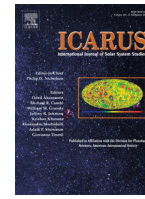

The meteorology of Gale crater as determined from rover environmental monitoring station observations and numerical modeling. Part I: Comparison of model simulations with observations

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Air temperature, ground temperature, pressure, and wind speed and direction data obtained from the Rover Environmental Monitoring Station onboard the Mars Science Laboratory rover Curiosity are compared to data from the Mars Regional Atmospheric Modeling System. A full diurnal cycle at four different seasons (Ls 0, 90, 180 and 270) is investigated at the rover location within Gale crater, Mars. Model results are shown to be in good agreement with observations when considering the uncertainties in the observational data set. The good agreement provides justification for utilizing the model results to investigate the broader meteorological environment of the Gale crater region, which is described in the second, companion paper.

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1. Introduction

This is the first part of a two-part paper on the meteorology of Gale crater, Mars. Gale crater, in which the Mars Science Laboratory (MSL) landed in August 2012, is the most topographically complex area visited to date by a Mars spacecraft. Based on earlier modeling and studies of Gale crater and similar features elsewhere (Tyler and Barnes, 2013; Rafkin and Michaels, 2003), the meteorology within the crater was expected to be one of the most dynamically complex meteorological environments on the planet. Gale crater did not disappoint. The Rover Environmental Monitoring Station (REMS) has returned data on the nature of this complex meteorology. As with all single station measurements, the meteorological interpretation is hindered by a lack of spatial context in which to place the observations. Ideally, numerical models properly validated against observations can be used to provide this context. In the case of REMS, complete model validation has been challenging. Operational constraints, REMS sensors accommodation, measurement uncertainties, and inadvertent destruction of one of the REMS wind sensors by flying debris at landing has made comprehensive model validation a difficult enterprise. Nevertheless, there is enough data of sufficient quality to conduct some model validation, and where the data are absent or of poor quality, models can play a role in providing a more complete picture of the meteorological environment; the data and models are synergistic.

Part I of this paper is concerned with comparing the model results to observations, with the goal of establishing some measure of confidence in the model results. Where there is disagreement between the observations and models, every attempt is made to determine the root cause of the discrepancy, considering the possibility of errors in both the model and observations. Part II of this paper is concerned with the interpretation of the observations based on the context provided by the modeling (Rafkin et al., this issue).

2. Numerical experiment design and configuration

2.1. The Mars Regional Atmospheric Modeling System (MRAMS)

The Mars Regional Atmospheric Modeling System (MRAMS) is a versatile numerical mesoscale model that simulates the circulations of the Martian atmosphere at regional and local scales (Rafkin et al. 2001, 2002, 2009). MRAMS is derived from

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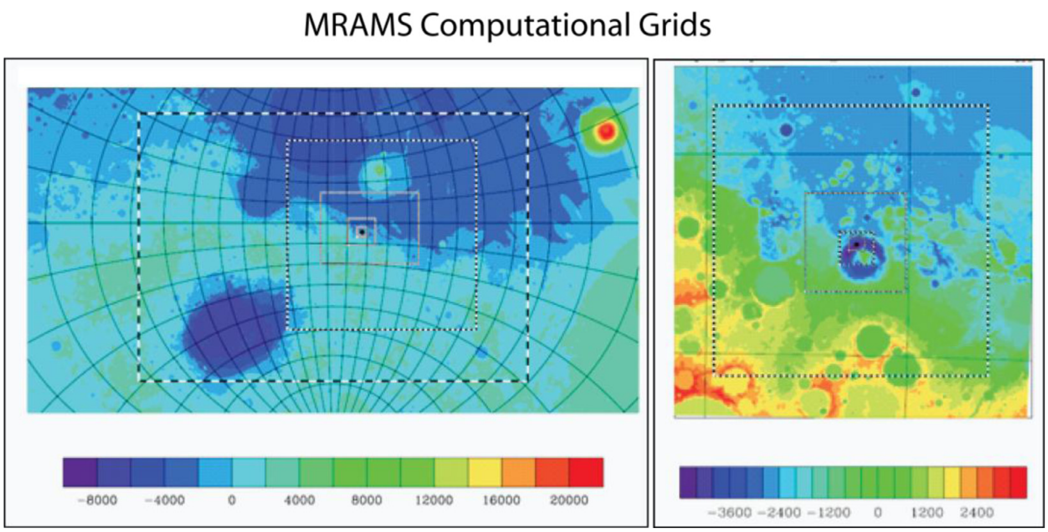

Fig. 1. Horizontal grid spacing for grids 1 to 7 (left) and 4 to 7 (right). The grid spacing on each grid is shown by the alternating black and white bars around the border. Topography is shown as color-coded elevation (m) from the Mars Orbiter Laser Altimeter (MOLA).

the regional atmospheric modeling system (RAMS) which is a widely used nonhydrostatic Earth mesoscale and cloud-scale model (Pielke et al., 1992) designed to simulate synoptic-scale, mesoscale, and microscale atmospheric flows over complex terrain. MRAMS is explicitly designed to simulate Mars atmospheric circulations at the mesoscale and smaller scales with realistic, high-resolution surface properties.

Key features of MRAMS include non-hydrostatic fully compressible dynamics, the capability for explicit tracking of dust, water and CO_2 aerosol via a bin microphysical model, a level 2.5 Mellor-Yamada subgrid scale turbulent closure scheme (Mellor and Yamada, 1974), a surface layer based on Monin–Obukhov similarity theory coupled to a dust lifting parameterization, and a fully prognostic conductive regolith model that includes carbon dioxide deposition and sublimation. Neither the microphysical models nor the dust lifting scheme are activated in the simulations described herein; a static dust scenario is specified. Radiative heating is based on a two-stream correlated-k parameterization (Toon et al., 1989), with dust optical properties given by Wolff et al. (2006).

2.2. Description of numerical grids

MRAMS uses a nested grid configuration whereby progressively higher resolution grids are embedded into a parent grid. The boundary conditions for each nested grid come from its parent, and the solution on the nested grid is averaged back to and replaces the solution on the parent grid. This is a so-called two-way nesting configuration. The code allows for an infinite number of nested grids, but there is a practical limit. Since the Courant–Friedrichs–Lewy stability condition is a function of grid spacing, the model time step on each nested grid is generally reduced from the parent grid value, and the reduction must be an integral factor. For each parent grid model time step, the physics must be solved two or three times on the nested grid. In practice, computational power limits the number of nested grids to 6 or 7, which can involve 20 or more innermost nest time steps for the outermost nest time step. The integration time also depends on the size of the grid domains and contributes to determining the practical limit. The simulations presented here are run in parallel using up to 24 computational nodes. Additional nodes can be used, but communication between nodes typically starts to impact computation efficiency at numbers much above 24.

To simulate the MSL meteorological environment, MRAMS is configured with seven grids centered over the Gale crater landing site (Fig. 1). The grids are configured, as much as practicable, to cover topographic regions that might influence the solution on a particular grid. The outermost grid (the mother domain), extends well into the northern and southern hemisphere, covering the Hellas impact basin and the hemispheric topographic dichotomy. This configuration can capture the strong topographic flows that sometimes occur near the hemispheric dichotomy, and it can capture the seasonal mean meridional flows (i.e., the Hadley Cell) that are nearly global in extent. The east–west domain is large so as to capture as much of the thermal tide wave as possible and to limit any potential boundary effects as the tide enters or leaves the mother domain. As pointed out by Tyler et al. (2002), the mother domain can produce spurious waves due to interactions with the boundary, however there is little to no evidence of this in the simulated pressure signal at Gale crater. Grids are also specified so as to minimize, as much as possible, the crossing of large topographic features at the boundaries. The horizontal grid spacing at the center of the seven grids is 240, 80, 26.7, 8.9, 2.96, 0.98 and 0.33 km, respectively, with domains shown in Fig. 1.

All the grids have the same vertical grid configuration with the vertical winds staggered between thermodynamic levels. The lowest thermodynamic level (where temperature and pressure are prognosed) is ~14 m above the ground. This vertical spacing is gradually stretched with height until reaching a maximum spacing of 2500 m, and the levels gradually transition from terrain-following near the surface to horizontal at the top of the model. Ideally, the first vertical level would be located at the height of the REMS sensors, but this is not computationally practical; the integration time step for nonhydrostatic models is closely coupled to the thickness of that layer. Using a lowest model thickness of one to two meters would have required a mother domain time step of fractions of a second compared to a value closer to 10 s. Thus, the model would have run approximately two orders of magnitude slower. The spacing does not exceed 100 m in the lowest 1 km, and does not exceed 400 m in the lowest 4 km. The model top is 51 km with 50 vertical grid points.

2.3. Initialization and boundary conditions

Output from the NASA Ames General Circulation Model (GCM) (Kahre et al., 2006) is used to initialize the atmospheric state in

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