SIMULATING THE MARTIAN ATMOSPHERE WITH THE MARS GLOBAL IONOSPHERE-THERMOSPHERE MODEL.

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Introduction

Over the past several years, a model of the Martian atmosphere has been under development. The goal of the Mars Thermosphere-Ionosphere Model (M-GITM) is to be able simulate the state of Mars' upper atmosphere in a realistic manner under a wide range of solar and Mars geophysical conditions. In particular, the model has been developed with the goal of better understanding the response of the martian upper atmosphere to dynamic external forcing, or space weather.

M-GITM has recently been benchmarked against existing upper atmospheric datasets as well as other Mars upper atmosphere models. The results indicate that M-GITM captures expected trends in the global neutral temperatures and densities as well as in the ion composition. Additionally, M-GITM is in the process of being integrated into the University of Michigan's Space Weather Modeling Framework (SWMF). In particular, M-GITM is currently being coupled to existing and MHD model and an existing monte carlo model of the Mars space environment. Ultimately, the goal of these coupled models is to make it possible to accurately follow the flow of energy and momentum from the solar wind into the upper atmosphere, thereby enabling a better understanding of the effects of space weather on the Mars space environment.

Model Background

M-GITM has been adapted from the existing Earth GITM framework (Ridley et al., 2006). It combines the Mars fundamental physical parameters, ion-neutral chemistry, and key radiative processes with the core numerics developed for use at Earth in order to capture the basic observed features of the thermal, compositional, and dynamical structure of the Mars atmosphere from the ground to the exosphere (Bougher et al., 2008, 2011; Pawlowski et al., 2010, 2012). The M-GITM code utilizes a 3-D spherical grid with an altitude based vertical coordinate. This allows for the relaxation of the assumption of hydrostatic equilibrium and enables the model to resolve sound and gravity waves in both the vertical and horizontal directions. GITM solves for the bulk horizontal neutral winds, while in the vertical direction, the momentum equation is solved for each of the major species and the bulk vertical wind is specified as a mass density weighted average of the individual vertical velocities. The model is fully parallel and utilizes a block-based 2-D domain decomposition that allows for an extremely flexible horizontal resolution that can be specified at run time.

Neutral temperatures are solved for self-consistently, but ion and electron temperatures are presently prescribed based upon Viking measurements (Fox et al., 1993). M-GITM currently solves for 6 major neutral species: CO_2, CO, O, N_2, O_2, and Ar as well as 5 minor species N(4S), N(2D), NO, He and H. Key ion species (6) currently include: O+, O_2+, CO_2+, N_2+ and NO+. Plasma velocities (zonal and meridional ion velocities) are not calculated, but await the coupling with a solar wind interaction (plasma) code. As mentioned previously, the M-GITM code can be run for various horizontal and vertical resolutions. Typically, production runs are conducted for a 5°x5° regular horizontal grid, with a constant 2.5 km vertical resolution ($\sim$0.25 scale height) above the lowest $\sim$80 km. A "stretched" vertical grid is used at lower altitudes to accommodate the variable terrain.

The solar fluxes and cross sections (0.1 to 175.0 nm) that are included span 59-wavelength intervals. Cross sections (and yields) for EUV bins are adopted from (Schunk and Nagy, 2009). The solar irradiance can be specified using a variety of solar flux models, including those based on the $F_{10.7}$ proxy (Hinteregger et al., 1981; Tobiska and Barth, 1990; Richards et al., 1994). Additionally, M-GITM is capable of using Earth-based data from the Solar Extreme Ultraviolet (SEE) (Woods et al., 2005) or EUV Variability Explorer (EVE) (Woods et al., 2010) instruments as well as model results from the Flare Irradiance Spectral Model (FISM) (Chamberlin et al., 2008). Once the solar flux is calculated, the values are adjusted by the inverse of the Mars–Sun distance squared for the Mars' precise orbital position. A heating efficiency of 18% is used to specify the EUV heating.

A comprehensive set of 30+ key ion-neutral chemical reactions and rates has been incorporated into the M-GITM code (Fox and Sung, 2001), based upon those used previously in the modern Mars Thermospheric General Circulation Model (MTGCM) (Bougher et al., 2004, 2006, 2009). In order to calculate chemical sources and losses, M-GITM utilizes a sub-cycling technique whereby several chemical time steps may be taken during a single advective time step.

For the Mars upper atmosphere ($\sim$80 to 250 km), an existing fast formulation for NLTE CO_2 15-micron cooling was implemented into the M-GITM code (López-Valverde et al., 1998) and includes a correction for NLTE near-IR heating rates. Additionally, the effect of the O(3P) emission from the fine structure of atomic oxygen is also included using an optically thin LTE formulation (Banks and Kockarts, 1973) with an NLTE correction (Roble et al., 1987). For the Mars lower atmosphere (0-80 km), a state-of-the-art radiation (RT) code was adapted from the NASA Ames MGCM (Haberle et al., 2003) for incorporation into M-GITM. This provides solar heating (long and short wavelength), seasonally variable aerosol heating, and CO_2 15-micron cooling in the LTE region of the Mars atmosphere (below $\sim$80 km). The radiation code presently being used for Mars is based on a two-stream solution to the radiative transfer scheme with CO_2 and water vapor opacities calculated using a correlated-k approach.

The coordinate system within M-GITM has been modified to include the use of topography measurements provided by the Mars Orbiter Laser Altimeter (MOLA) instrument onboard MGS. The data are provided at 1/4° by 1/4° resolution, and upon being read in to the model, are interpolated to the M-GITM grid. The core M-GITM solver and lower boundary condition has been adapted to handle the terrain following coordinate system following the work done by Kasahara (1974).

Sample simulation results during aphelion

M-GITM simulations have been performed for a wide range of solar and seasonal conditions (see Table 1). Figure 1 shows results from a 1D simulation during equinox at the equator, $F_{10.7} = 70$. The model gives realistic composition profiles and indicates a transition from a CO_2 dominated atmosphere to an atomic oxygen dominated one occurs just below $\approx$ 200 km altitude. In this simulation, the exospheric temperature is just above 200 K.

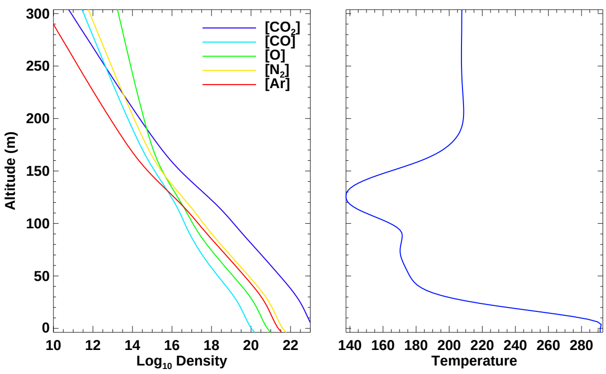

Figure 1: M-GITM results from 1D simulation of equator during equinox for $F_{10.7}$ =70. The neutral composition (left panel) and neutral temperature (right panel) are shown as a function of altitude.

Figure 2 shows the exospheric temperature (200 km) and neutral wind vectors during aphelion (Ls = 90, $F_{10.7}$ = 70) for a full 3D simulation. The simulated global wind patterns are as expected with divergence from mid-afternoon local times near the sub-solar latitude and convergence just after midnight just south of the equatorial region. Dayside temperatures of 180 - 200 K are inline with observations under these conditions. Winter polar warming is minimal in this simulation in agreement with MGS aerobraking observations (Bougher et al., 2006).

Additionally, the ionospheric composition (not shown) is simulated realistically and the dayside ion densities below 200 km are similar to Viking observations (Hanson et al., 1977). The peak dayside electron density occurs just below the observed height of $\approx$ 130 km. This simulation did not include the effects of the elevated dust levels that were observed by Viking which would have caused the simulated ionospheric peak to be slightly higher.

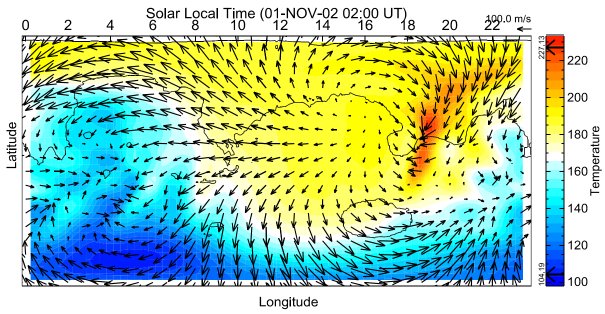

Figure 2: M-GITM neutral densities and neutral wind vectors at 200 km for L_s=90 and $F_{10.7}$ = 70.

Current efforts

M-GITM is currently being used to investigate the state of the thermosphere and ionosphere under a range of solar and Mars geophysical conditions. Additionally, the model is currently being used to investigate the effects of solar flares and dust storms on the Martian thermosphere. M-GITM is also starting to be integrated with the existing Michigan Space Weather Modeling Framework. Currently, M-GITM is coupled directly to the Michigan Mars MHD model (Najib et al., 2011; Dong et al., 2013). At this state, the coupling is one-way, such that the MHD code uses fields that are calculated by M-GITM, but M-GITM does not use any information from the MHD model to update it's own calculations. In the coming years, a full two-way coupling will be performed. Additionally, M-GITM is in the process of being coupled to a Direct Simulation Monte Carlo (DSMC) model (Valeille et al., 2010) of the Martian exosphere. As with the MHD model, a one-way coupling already exists between M-GITM and the DSMC code, from M-GITM to DSMC. The integration of these three models will allow for detailed studies of the processes that lead to volatile escape from the Martian atmosphere. Figure 3 provides a graphical overview of the current state and future goals of this coupled framework. Results

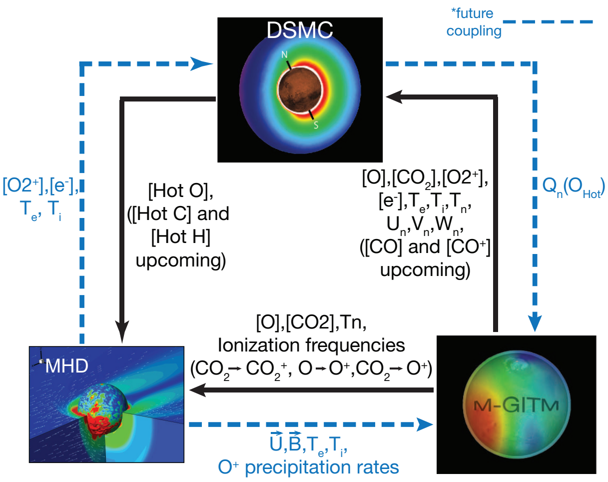

Figure 3: Current and future state of the coupling between M-GITM, the Mars MHD and Mars DSMC codes.

from M-GITM and the coupled models will be used to complement observations from the upcoming MAVEN mission (2013 - 2016) and help to achieve science closure. In preparation for the MAVEN mission, a set of 12 baseline simulations have been performed using both M-GITM and DSMC model. Table 1 shows the parameters used in these simulations.

Parameters	**M-GITM**	**DSMC**
Ls (season)	0, 90, 180, 270	0, 90, 180, 270
$F_{10.7}$ (solar cycle)	70, 130, 200	70, 130, 200
τ (CR) (Dust)	0.5 (0.003)	0.5 (0.003)

Table 1: Parameters used in 12 simulations by M-GITM and the DSMC model in preparation for the MAVEN mission

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