# DEVELOPMENT AND VALIDATION OF THE GROUND-TO-EXOSPHERE MARS GITM CODE: SOLAR CYCLE AND SEASONAL VARIATIONS OF THE UPPER ATMOSPHERE

**S. W. Bougher and A. Ridley**, AOSS Department, University of Michigan, Ann Arbor, MI, USA (bougher@umich.edu); **D. Pawlowski**, Physics Department, Eastern Michigan University, Ypsilanti, MI, USA; **J. M. Bell,** SouthWest Research Institute, San Antonio, TX, USA; **S. Nelli**, Las Cruces, NM, USA.

**Introduction:**

The existing Mars Global Ionosphere-Thermosphere Model (M-GITM) is currently undergoing final stages of development at the U. of Michigan. This effort essentially combines the terrestrial GITM framework [e.g. Ridley et al., 2006] with Mars fundamental physical parameters, ion-neutral chemistry, and key radiative processes in order to capture the basic observed features of the thermal, compositional, and dynamical structure of the Mars atmosphere from the ground to ~250 km**.** This comprehensive 5-year model development, testing and validation effort has been ongoing since 2006. The objectives for this new M-GITM code are three-fold: (a) to investigate the thermal and dynamical coupling of the Mars lower and upper atmospheres, and (b) to provide an accurate representation of the observed thermosphere-ionosphere structure and its variations over the Mars seasons and solar cycle, and (c) to link M-GITM (thermosphere-ionosphere structure) with other exosphere and plasma models in order to address Mars atmospheric escape processes and determine modern escape rates. These objectives are designed to support MAVEN mission planning and data analysis activities.

The GITM code is a 3-D spherical model that was developed originally to simulate the terrestrial thermosphere - ionosphere system (~100-500 km) using an altitude based vertical coordinate [e.g. 1, 2]. 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 (latitude and longitude) domain decomposition that allows the model to have a flexible horizontal resolution. For parallel computation, GITM uses the message passing interface (MPI) standard to allow for platform independence when passing information between 2-D blocks. The earth GITM code is typically used to address neutral and ion temperatures, composition and wind fields from ~100 to 500 km for numerous space weather modeling applications [e.g. 1, 2, 3, 4, 5].

Unlike at Earth, M-GITM simulates the conditions of the Martian atmosphere all the way to the surface. The formulations and subroutines required for incorporation into the new M-GITM code have largely been taken from existing Mars GCM codes. For the Mars lower atmosphere (0-80 km), a state-of-the-art correlated-k radiation code was adapted from the NASA Ames MGCM [6] 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 ~80 km). In addition, dust opacity distributions (horizontal) are typically prescribed based upon empirical dust opacity maps obtained from several Martian years of MGS/TES, and Odyssey/THEMIS measurements [e.g. 7, 8]. Finally, a simple (fast) formulation for Mars surface temperatures was implemented and tested within the M-GITM code. This scheme is based upon Mars empirical temperatures and is shown to match seasonal, latitude, and local time variations in temperatures reasonably well. These surface temperatures are needed for proper computations by the correlated-k radiative transfer code.

For the Mars upper atmosphere (~80 to 300 km), a fast formulation for NLTE $CO_2$ 15-micron cooling was implemented into the M-GITM code [see 9 and 10], along with a correction for NLTE near-IR heating rates (~80-120 km) using an extension of the same correlated-k radiation code. In addition, the earth GITM thermospheric EUV-UV heating routines have been modified for a $CO_2$ atmosphere, by incorporating an expanded set of cross sections and yields. These additions specify the in-situ heating (EUV-UV), dissociation, and ionization rates spanning ~80 to 250 km. Finally, a comprehensive set of 30+ key ion-neutral chemistry reactions and rates has been incorporated into the M-GITM code [11], based upon those used in the modern Mars Thermospheric General Circulation Model (MTGCM) [e.g. 10 and 12]. 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. At this point, M-GITM assumes photochemical equilibrium when solving for the ionosphere (above ~80 km).

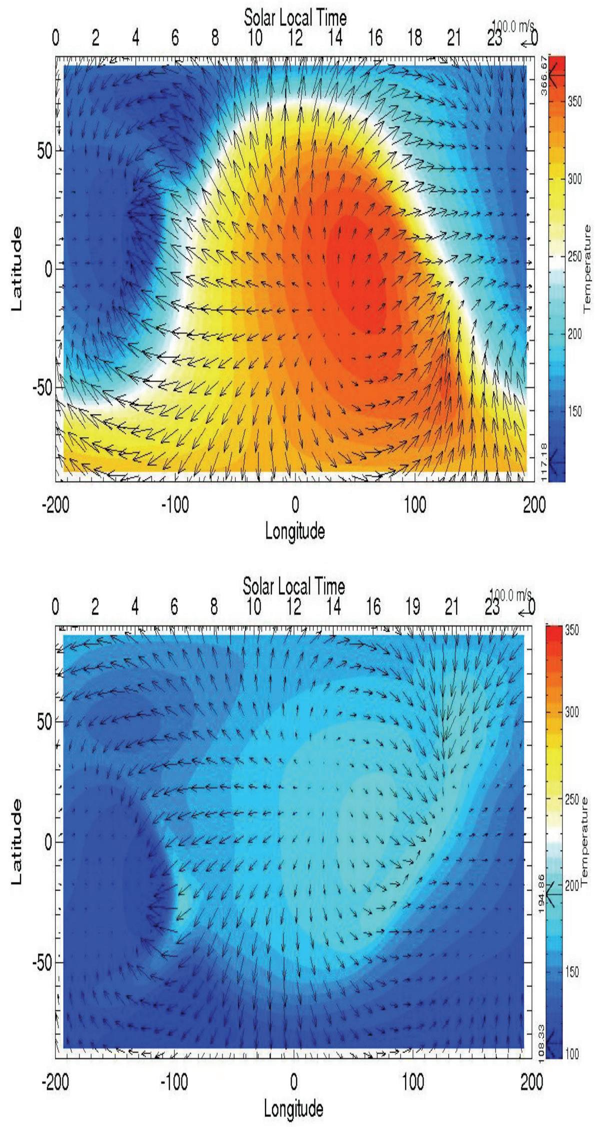


**Figure 1**. Mars GITM simulations, illustrating the exobase for: (top) solar maximum, perihelion conditions, and (bottom) solar minimum, aphelion conditions [16]. These extreme conditions reveal dayside (low SZA) exospheric temperatures that range from ~175 to 340 K. Superimposed wind vectors show divergent flow away from the dayside subsolar latitude (in mid-afternoon), and convergence in the winter hemisphere (at low latitudes) just after mid-night (around 0200 to 0400 LT).

For the entire atmosphere, the M-GITM dynamical core solver was modified to accommodate a vertical coordinate system that does not require altitude to be constant with horizontal position. The Martian terrain is being incorporated into the M-GITM code making use of MGS Mars Orbiter Laser Altimeter (MOLA) topographic data files [13]. In addition, a simplified gravity wave momentum deposition formulation was recently included, similar to the scheme used by [14]. This scheme is currently being tested within the M-GITM code in order to examine the role gravity waves play in regulating zonal and meridional winds (and the corresponding winter polar warming temperatures) in the lower and middle atmospheres, and their impact (if any) on the upper atmosphere (above ~ 80 km).

Further improvements to the M-GITM code are in process. For instance, the existing NASA Ames MGCM $CO_2$ condensation/sublimation and planetary boundary layer routines will be added. At the surface, global empirical maps of albedo and thermal inertia will also be supplied to the correlated-k radiation calculations to provide accurate global variations.

The M-GITM code presently simulates the following neutral and plasma fields around the planet. Neutral temperatures are solved for self-consistently, but ion and electron temperatures are presently prescribed based upon Viking measurements. Key neutral species (11) include: $CO_2$, CO, O, $N_2$, $O_2$, $N(^4S)$, $N(^2D)$, NO, Ar, He and H. Key ion species (5) 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, the M-GITM code can be run for various horizontal and vertical resolutions. Typically, production runs are conducted for a 5x5 degree regular horizontal grid, with a constant 2.5 km vertical resolution (~0.25 scale height) above the lowest ~50 km. A "stretched" vertical grid is used at lower altitudes to accommodate the variable terrain.

**Results and Model Validation Thusfar:**

The M-GITM code can be run for various seasonal, solar cycle, and dust conditions. Initial M-GITM simulations indicate this extended model is stable, convergent, and captures the basic observed ground-to-exobase temperatures, major upper atmosphere neutral and ion composition, and expected wind structures throughout the Mars atmosphere [15, 16]. Model validation thusfar has focused upon simulations for Ls = 0, 90, 180 and 270 for both solar minimum (F10.7 = 70) and solar maximum (F10.7 = 200) conditions.

For instance, Figure 1 shows extreme solar cycle plus seasonal conditions for the Mars upper atmosphere; i.e. for Periehlion/solar maximum plus Aphelion/solar minimum inputs. Neutral exosphere temperatures are illustrated near ~200 km (latitude versus local time) [16]. The noontime dayside exospheric temperature variation calculated is ~160 K. This is similar to that observed and recently calculated by the MTGCM [12]. Simulated mesopause temperatures (~90-110K), not shown, are also similar to those observed for these same seasons [8].

Corresponding Aphelion/solar minimum horizontal winds near 200 km (not shown) diverge from the mid-afternoon near the sub-solar latitude, are quite strong over the terminators (~200-300 m/s) and converge on the nightside in the mid-to-high latitudes of the Southern (winter) hemisphere. Winter polar warming at low thermospheric altitudes is minimal in this simulation, in agreement with limited MGS aerobraking observations [e.g. 10].

The simulated photochemical ionosphere for Aphelion/solar minimum conditions (Figure 2) provides realistic dayside ion densities below ~200 km, similar to Viking observations [17]. Five major ions are calculated, and the corresponding electron densities are given. The incorporation of elevated dust levels (similar to Viking) would have raised the altitude of the simulated ionospheric peak closer to that observed (~130 km). Further improvements in ionosphere calculations will later include ion-transport and electron precipitation sources.

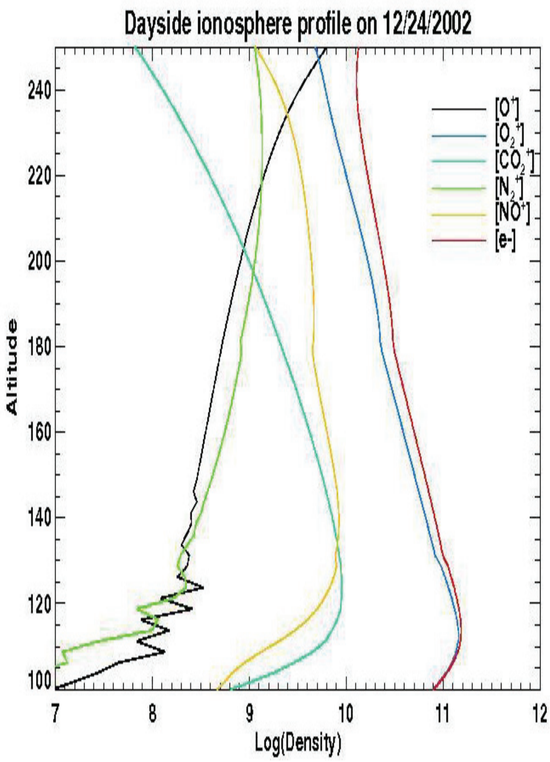


Figure 2: M-GITM simulated photochemical dayside ionosphere profiles for major species (#/m$^3$). The primary ionospheric peak occurs at ~115 km, and is dominated by [O2+]; [O+] becomes comparable with [O2+] near ~240 km. See [16].

**Future Plans:**

The Mars GITM code is scheduled for numerical integration with the Michigan MHD (magnetohydrodynamic) and the DSMC (Monte Carlo, kinetic model, exosphere) codes for the self-consistent simulation of the Mars thermosphere-ionosphere-exosphere regions and the solar wind interaction with the planet. This model integration activity will make use of the existing Michigan Space Weather Modeling Framework (SWMF). The SWMF is a fully functional and high performance computational framework developed to enable the integration of a number of numerical models of the entire Sun-heliosphere-Earth system for space weather modeling [18]. Application to Mars will enable these three independent models to exchange fields with one another (2 and 3-way coupling). The ultimate goal is to address volatile escape processes and the corresponding loss rates from modern Mars for comparison with anticipated MAVEN datasets.

**References:**

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