THE NCAR MARS THERMOSPHERIC GENERAL CIRCULATION MODEL: A REVIEW.

S. W. Bougher, *Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48189-2143 USA***,**
S. Engel, P. Withers, *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721-0092 USA***.**

Introduction

Recent Mars Global Surveyor (MGS) (1997-1999) and 2001 Mars Odyssey (ODY) (2001-2002) aerobraking exercises confirmed that the Martian upper atmosphere is largely controlled by in-situ driven EUV fluxes that vary considerably over the solar cycle and Mars seasons. The extremes of this variability, and the impact on thermospheric temperatures, densities, and global scale winds, have not yet been fully explored by spacecraft measurements (Figure 1) [Bougher et al. 2000].

In addition, the Mars lower thermosphere (roughly 100-160 km) was shown to be a highly variable region on time scales of a day or less. Orbit-to-orbit 2-sigma variability of MGS densities at a constant height was observed to be at least 70% [Keating et al., 1998], in accord with Mariner and Viking values [Stewart, 1987]. Roughly half of this variability is related to small scale processes (e.g. gravity waves) that persist from sol-to-sol about the planet. The remainder consists of longitude fixed thermospheric variations which were observed throughout MGS aerobraking at low to mid-latitudes; these features appear to be related to the large scale features of the topography at similar latitudes [e.g. Keating et al. 1998; Forbes et al., 2001; Bougher et al., 2001; Wilson, 2002; Forbes et al., 2002]. Diurnal Kelvin waves have been identified as likely responsible for these oscillations. ODY accelerometer data at high Northern latitudes failed to identify longitude fixed features, but rather observed what may be traveling (baroclinic) waves during local Northern winter. These aerobraking experiences (near Mars perihelion and aphelion seasons) suggest that the strong coupling of the Mars lower and upper atmospheres is composed of : (1) inflation/contraction of the entire atmosphere due to infrared and aerosol heating, and (2) upward propagating waves (tides, planetary waves, gravity waves) which reach the thermosphere, and are modulated by the largely unexplored middle atmosphere (50-100 km) [Forbes et al., 2002].

Mars three-dimensional general circulation models of the lower (NASA Ames GCM) and upper (NCAR MTGCM) atmospheres were recently coupled in an effort to capture both upward propagating tidal/planetary waves (below 100 km) and in-situ forced waves (above 100 km) resulting from local solar EUV/UV heating. Coupled simulations are presented that illustrate longitude fixed oscillations for aphelion and perihelion seasons. Comparisons will be made with corresponding MGS and ODY thermospheric and ionospheric (MGS)

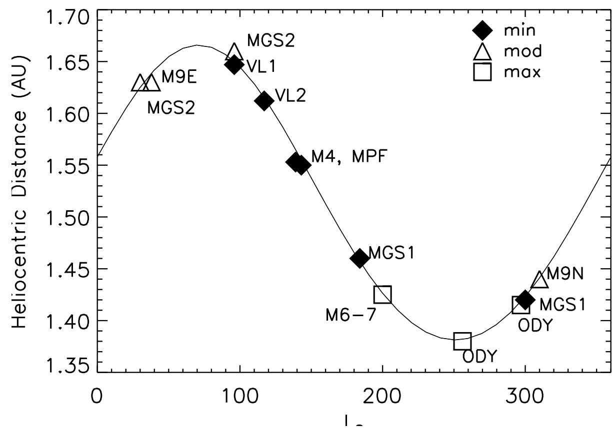

Figure 1: Mars Ls versus heliocentric distance. Spacecraft seasonal and solar cycle sampling of the Mars upper atmosphere to date. Solar cycle minimum (min, filled diamonds), moderate (mod, triangles), and maximum (max, squares) observations are indicated. Revised from Bougher et al., [2000].

datasets. Both thermal and tidal diagnostics will be presented to confirm the tidal modes and heat balances responsible for the simulated features. The capabilities and shortcomings of this coupled model approach will be summarized.

MTGCM Description

The NCAR Mars Thermosphere General Circulation Model (MTGCM) is a finite difference, time-dependent, primitive equation model that self-consistently solves for thermospheric neutral temperatures, neutral-ion densities, and three component neutral winds over the globe [e.g. Bougher et al. 1990; 1999; 2000]. Prognostic equations for the major neutral species (CO_2, CO, N_2, and O), selected minor neutral species (Ar, He, and O_2), and four photochemical ions (O_2+, CO_2+, O+ and NO+ below 200 km) are included. Zonal, meridional, and vertical velocities, total temperatures, and geopotential heights are also obtained on 33 pressure levels (above 1.32 μbar), corresponding to ∼70-300 km (solar maximum conditions), with a 5° latitude and longitude resolution. The vertical coordinate is log-pressure, with a vertical spacing of two grid points per scale height. Adjustable parameters which can be varied for individual MTGCM cases include the F10.7 index (solar EUV/UV fluxes), heliocentric distance (orbit), solar declination (seasons), and the maximum eddy coefficient (K_t) for eddy diffusion and viscosity.

The MTGCM was recently modified to accommodate inflation/contraction of the Mars lower atmosphere plus upward propagating migrating and non-migrating tidal mode amplitudes and phases consistent with clear or dusty conditions throughout the Martian year [Bougher et al., 2002]. The latter capability presently utilizes a detailed coupling with the NASA Ames MGCM at 1.32-microbars. MGCM fields (T, U, V, geopotential) are passed upward on each 5x5 ° grid point at 2-minute time steps throughout the Martian day. Output histories are generated at 2-3 hour intervals in order to capture the diurnal evolution of the tidal oscillations. Accelerometer data from the MGS and ODY nearly sun-synchronous orbits can be examined using these coupled MGCM-MTGCM output fields at a fixed solar local time (SLT) spanning all longitudes sampled during the course of a Martian day.

MTGCM Recent Results

The MTGCM has been validated using a variety of spacecraft observations taken throughout the solar cycle at different seasons (see Figure 1). Solar cycle and seasonal variations of the Mars thermosphere have previously been compared with Mariner, Viking, Mars Pathfinder and MGS observations [Bougher et al. 1999, 2000]. The combined effects of solar cycle and seasonal variations on dayside and nightside exospheric temperatures are illustrated in Figure 2.

Most recently, MGS Accelerometer (ACC) and corresponding MGS Radio Science (RS) datasets have been used to examine longitude variations of sampled mass densities and related electron densities using the coupled MGCM-MTGCM codes [Bougher et al., 2001; 2002; Withers et al., 2002]. Figure 3 illustrates a latitude-longitude slice of densities at 130 km for SLT = 3 sampling. This constant altitude slice is appropriate to Ls = 90 (aphelion) and F10.7 = 130 (solar moderate EUV flux) conditions at Mars. Notice that wave-3 features are prominent at 60-80N during this season at this altitude. The phasing of these peaks and troughs corresponds closely to the F1-peak height variations (1-sigma = ±3.5 km) noted in the MGS/RS data reported by Bougher et al; [2001]. This correspondence is consistent with the photochemical control of electron densities and their peak altitudes in the Martian dayside ionosphere. Clearly, Martian weather (near the ground) is having a profound influence upon thermosphere- ionosphere structure aloft. The coupled MGCM-MTGCM codes are able to capture some features of this variability.

Sample outputs from various aphelion and perihelion MGCM-MTGCM simulations will be presented and compared to MGS and ODY observations to illustrate the capabilities and present limitations of our 3-D modeling effort. A summary of solar-only forced MTGCM simulations and a collection of outputs can be found on our

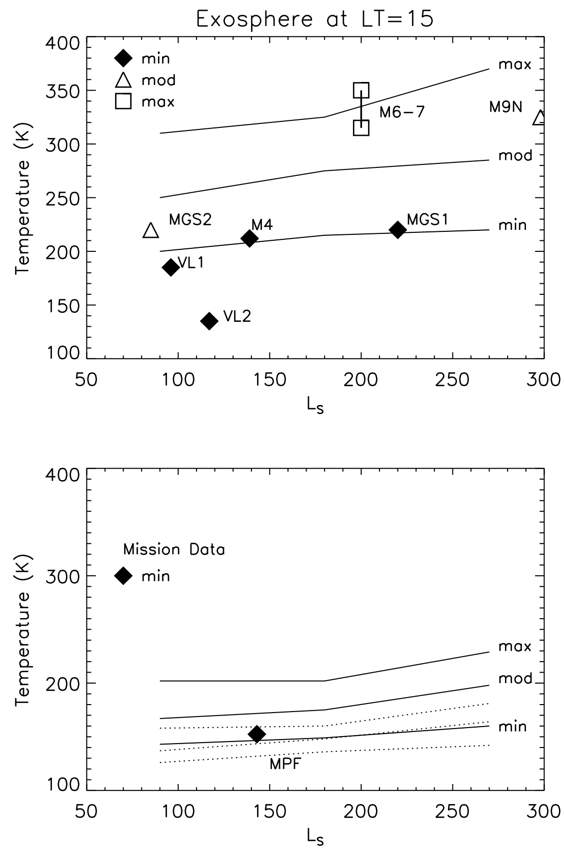

Figure 2: Mars exosphere temperatures at (a) LT = 1500, and (b) LT = 3 near the equator. Exospheric temperatures from various spacecraft measurements (solar cycle symbols from Figure 1) are compared to MTGCM simulations (solid lines). The strong solar cycle plus seasonal dependence of dayside and nightside exospheric temperatures is clearly illustrated. Adapted from Bougher et al., [2000].

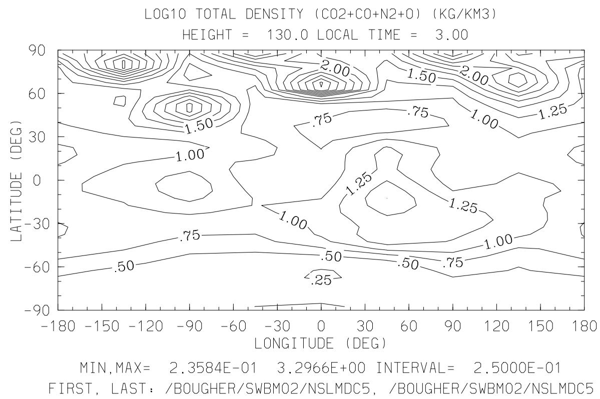

Figure 3: A latitude-longitude slice of mass densities (kg/km3) at 130 km from a coupled MGCM-MTGCM simulation appropriate to Ls = 90 (aphelion), F10.7 = 130 (solar moderate EUV flux), and low dust conditions. Sampling at a constant SLT = 3 is plotted for comparison to MGS Radio Science data from high Northern latitudes (60-70N) near aphelion. From Bougher et al., [2002].

website: www.lpl.arizona.edu/∼sengel/thermo.html.

References

Bougher, S. W., R. G. Roble, E. C. Ridley, and R. E. Dickinson, The Mars thermosphere II. General circulation with coupled dynamics and composition, **J. Geophys. Res., 95**, 14811-14827, 1990.

Bougher, S. W., S. Engel, R. G. Roble, and B. Foster, Comparative Terrestrial Planet Thermospheres : 2. Solar Cycle Variation of Global Structure and Winds at Equinox, **J. Geophys. Res., 104**, 16591-16611, 1999.

Bougher, S. W., S. Engel, R. G. Roble, and B. Foster, Comparative Terrestrial Planet Thermospheres : 3. Solar Cycle Variation of Global Structure and Winds at Solstices, **J. Geophys. Res., 105**, 17669-17689, 2000.

Bougher, S. W., D. P. Hinson, J. M. Forbes, and S. Engel, MGS Radio Science Electron Density Profiles and Implications for the Neutral Atmosphere, **Geophysical Res. Lett., 28**, 3091-3094, 2001.

Bougher, S. W., J. R. Murphy, and S. Engel, Coupling Processes and Model Simulations Linking the Mars Lower and Upper Atmospheres, **34th COSPAR Scientific Assembly**, 10-19 October, Houston, TX, 2002.

Forbes, J. M., M. E. Hagan, S. W. Bougher, and J. L. Hollingsworth, Kelvin Wave Propagation in the Upper Atmospheres of Mars and Earth, **Adv. in Space Research, 27, #11**, 1791-1800, 2001.

Forbes, J. M., A. F. C. Bridger, M. E. Hagan, S. W. Bougher, J. L. Hollingsworth, G. M. Keating, and J. R. Murphy, Nonmigrating Tides in the Thermosphere of Mars, **J. Geophysical Res.**, in press, 2002.

Keating, G. M. et al. The Structure of the Upper Atmosphere of Mars : In-situ Accelerometer Measurements from Mars Global Surveyor, **Science, 279**, 1672-1676, 1998.

Wilson, R. J., Evidence for Non-migrating Thermal Tides in the Mars Upper Atymosphere from the Mars Global Surveyor Accelerometer Experiment, **Geophysical Res. Lett., 29 (7)**, 10.1029/2001GL013975, 2002.

Withers, P. G., S. W. Bougher, and G. M. Keating, The effects of topographically-controlled thermal tides in the Martian upper atmosphere as seen by the MGS Accelerometer, **Icarus**, submitted, 2002.