INTERANNUAL VARIABILITY OF THE MARS THERMOSPHERE: NEW SIMULATIONS AND COMPARISONS WITH RECENT MARS DATASETS.

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Introduction

Detailed studies exist that explore the global, seasonal, and interannual variations of the Martian lower atmosphere (below 90 km) [e.g. Liu et al., 2003]. Key findings indicate that observed temperatures are quite repeatable from one Mars aphelion season to the next. Conversely, perihelion temperatures can change radically on an interannual basis, depending on the timing and intensity of dust events and the accompanying atmospheric heating that results. A growing climatology of Martian lower atmosphere temperatures, derived thermal winds, and dust opacity distributions is now available for investigating interannual variability [e.g. Smith, 2004].

However, no detailed climatology or analogous studies exist for the Martian thermosphere, despite the fact that thorough characterization of this region is critical to future aerobraking and aerocapture activities [e.g. Bougher et al., 2004]. Our ongoing research is focused upon the detailed characterization of the interannual variations of the Martian upper atmosphere (∼100-240 km) making use of available spacecraft data (Mars Global Surveyor-MGS and Mars 2001 Odyssey-ODY) and new simulations from the coupled Mars General Circulation Model-Mars Thermosphere General Circulation Model (MGCM-MTGCM). Thermospheric densities and inferred temperatures (∼100-160 km) are available from MGS and ODY accelerometer datasets obtained during aerobraking [e.g. Keating et al., 1998; Withers et al., 2003; Keating et al., 2003; Bougher et al., 2005]. An assortment of solar local times (SLT), latitudes, and seasons is covered by this limited sampling [Withers et al., 2005]. Also, MGS Radio Science profiles of electron densities are used to track the height of the primary electron density peak, from which interannual variations of the underlying neutral atmosphere near aphelion have been derived [Bougher et al., 2004]. Finally, higher altitude (160-240 km) nightside neutral densities have recently been extracted from MGS Electron Reflectometer (ER) measurements in the vicinity of crustal magnetic fields [Lillis et al. 2005], providing upper atmosphere constraints above the region where accelerometers typically sense the atmosphere. These datasets provide a limited (spatial and temporal) climatological database against which global thermospheric model simulations must be judged.

A proper understanding of interannual variations of the Martian upper atmosphere will be the product of careful interpretation of these limited datasets using several global thermospheric model simulations. Our strategy is to focus on changing lower atmosphere conditions from one Martian year to the next, while holding topside forcing (e.g. solar fluxes) constant. For this presentation, we have selected Martian solstice simulations, which are driven by solar and aerosol heating corresponding to aphelion (Ls = 90) and perihelion (Ls = 270) conditions appropriate to existing MGS and ODY observing periods. New MGCM-MTGCM simulations are conducted using three available mapping years of infrared (IR) optical depth data acquired by the Thermal Emission Spectrometer (TES) instrument on board MGS. Interannual variations in these dust opacity distributions of the Mars lower atmosphere are utilized to investigate the dust's subsequent impacts (both dynamical and thermal) upon the Mars upper atmosphere structure and dynamics. Solar cycle effects are minimized in this investigation by focusing the model-data comparisons on thermospheric features at and below ∼120 km. Our goal is to isolate the the impact of changing lower atmosphere conditions (e.g. dust distributions) upon the interannual variations of key features in the Martian thermosphere. Consequences for aerobraking planning exercises will be discussed.

MGCM-MTGCM Model Formulation

The Mars Thermospheric General Circulation Model (MTGCM) itself is a finite difference primitive equation model that self-consistently solves for time-dependent neutral temperatures, neutral-ion densities, and three component neutral winds over the globe [see formulation details in Bougher et al., 1999; 2004]. MTGCM prognostic and diagnostic thermospheric fields are simulated on 33-pressure levels (at altitudes above 1.32 μbar corresponding to ∼60-300 km), with a 5x5 ° latitude and longitude resolution. Recently, a fast non-Local Thermodynamic Equilibrium (NLTE) 15-micron cooling scheme was implemented in the MTGCM, along with corresponding near-IR heating rates. These improvements are based upon recent detailed one dimensional (1-D) NLTE model calculations for the Mars upper atmosphere [see Lopez-Valverde et al; 1998].

The MTGCM is currently driven from below by the NASA Ames Mars General Circulation Model (MGCM) code [e.g. Haberle et al., 1999] at the 1.32 μbar level (near 60-80 km), permitting a detailed coupling across this boundary. This coupling scheme captures both migrating and non-migrating upward propagating tides plus the thermal expansion and contraction of the Mars lower atmosphere with the passage of the seasons and dust storm events [see details in Bougher et al., 2004]. Key prognostic (temperatures, zonal and meridional winds) and diagnostic (geopotential height) fields are passed upward from the MGCM to the MTGCM at the 1.32-μbar pressure surface at every MTGCM gridpoint on 2-minute timestep intervals. No downward coupling from the MTGCM to the MGCM is presently activated. The inclusion of the Ames MGCM in providing a realistic lower atmosphere is critical for achieving a realistic simulation of the Mars upper atmosphere within the MTGCM domain [Bougher et al., 2005].

Specific MGCM-MTGCM model inputs are prescribed for six cases which include the MGS (aphelion) and ODY (perihelion) sampling periods described above. For all six cases, solar moderate fluxes (F10.7-cm index = 130 at Earth) are specified. Over the lifetime of the MGS TES observations, a dust climatological database has emerged, that provides comprehensive spatial and temporal coverage for three consecutive Martian years. Hence, detailed horizontal maps of integrated dust opacity distributions are obtained from MGS TES observations for mapping Years #1, 2, and 3 [as defined in Liu et al., 2003]. A factor of 2 is used to scale IR to visible integrated dust opacity values. For Ls = 90 conditions, a $\tau \sim 0.3$ globally averaged vertically integrated visible dust opacity is acheived. For perihelion, corresponding detailed horizontal dust opacity distributions are likewise obtained from the same MGS TES datasets. Now for perihelion, visible opacity values achieve a global average of $\sim$1.0.

The vertical dust distributions for the two simulations are prescribed making use of the Conrath parameter (CR) [Conrath et al, 1975], which defines a pressure to which dust is essentially well mixed, with a decreasing mixing ratio above this level. For both aphelion and perihelion, the depth of vertical mixing is permitted to vary locally with the TES horizontal dust distribution, so that the deepest mixing regions (e.g. up to $\sim$50 km) correspond to the largest integrated dust opacities (τ = 1.3-1.5) [see Bougher et al., 2005]. These chosen dust distributions (both horizonal and vertical) are crucial to providing improved MGCM-MTGCM simulations of the thermospheric winter polar regions over previous simulations using the MTGCM alone [see Keating et al., 2003; Bougher et al., 2005].

Model Results Illustrating Variability

Results from coupled MGCM-MTGCM simulations comparing TES year #1 and 2 dust forcing for aphelion (Ls = 90) conditions suggest that interannual variations in thermospheric temperatures, densities, and winds are small.

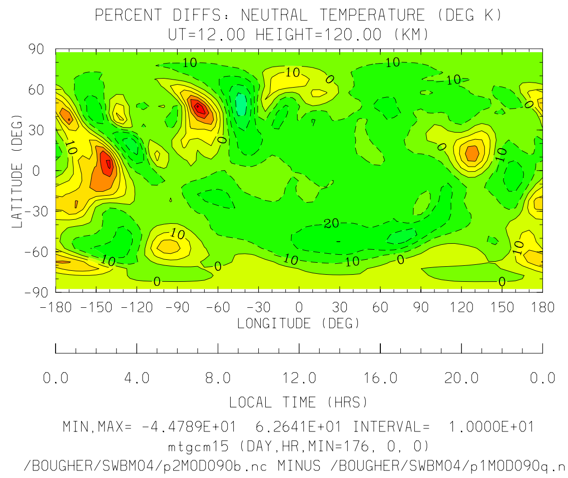

Figure 1: MGCM-MTGCM simulation for Ls = 90 conditions appropriate to the end of MGS aerobraking. A comparison is illustrated of percent temperature changes at 120 km resulting from two MGCM-MTGCM simulations driven by dust distributions obtained from MGS TES mapping years #1 and 2.

Figure 1 illustrates percent changes in 120 km temperatures for these two Martian seasons during which MGS TES dust opacities where measured and mapped. Global temperature varations are typically less than 20% (10-20 K), particularly in the winter polar night region poleward of 60° S latitude. Previous MGS Radio Science studies also indicate repeatability of the neutral atmosphere near aphelion conditions [Bougher et al., 2004]. This implies that mean thermospheric densities encountered at aerobraking altitudes during this season (even in polar night regions) are likely to be similar from one Martian year to the next.

Conversely, results from coupled MGCM-MTGCM simulations comparing TES year #1 and 2 dust forcing for perihelion (Ls = 270) conditions suggest that interannual variations in thermospheric temperatures, densities, and winds can be significant. Figure 2 illustrates percent changes in 120 km temperatures for these two Martian seasons. Global temperature varations can be as much as 40-60% (up to 60 K), particularly in the winter polar night region poleward of 60° N latitude. Corresponding density changes (not shown) can be as large as 50-75%. Changes in the near-perihelion dust distributions from one Martian year to the next are often due to interannual variations in the onset and decay of dust storm events [e.g. Smith, 2004]. These variations are shown here and elsewhere to drive changes in the inter-hemispheric (summer to winter) global circulation, and the resulting winter polar warming at thermospheric altitudes. This implies that mean thermospheric densities encountered

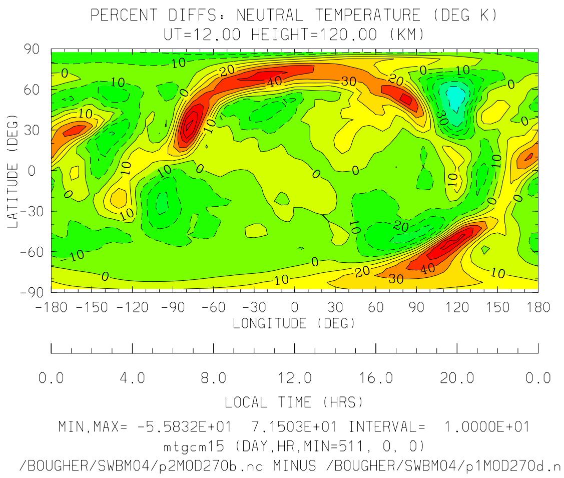

Figure 2: MGCM-MTGCM simulation for Ls = 270 conditions appropriate to mid-to-late Odyssey aerobraking. A comparison is illustrated of percent temperature changes at 120 km resulting from two MGCM-MTGCM simulations driven by dust distributions obtained from MGS TES mapping years #1 and 2.

at aerobraking altitudes during this season (especially in the polar night regions) are likely to be highly variable from one Martian year to the next.

Future Work Planned

It is demonstrated from this current research and previous studies that the entire Mars atmosphere is an integrated system that is highly coupled dynamically, thermally, and chemically. Therefore, systematic progress in the investigation of Mars atmospheric coupling processes will require ground-to-exobase (0-250 km) models to be developed, tested, validated, and exercised [e.g. Gonzalez Galindo et al., 2006]. Our group is now embarking on the development and testing of such a Mars Whole Atmosphere Climate Model (MWACM) [Ridley et al., 2004] making use of many of the physical processes already incorporated within the NASA Ames MGCM and Michigan MTGCM codes described above.

References

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, D. P. Hinson, and J. R. Murphy, MGS Radio Science Electron Density Profiles : Interannual variability and implications for the neutral atmosphere, **J. Geophys. Res., 109,** E3, E03010, 10.1029/2003JE002154, 2004.

Bougher, S. W., J. R. Murphy, and J. M. Bell, Polar warming in the Mars lower thermosphere : Seasonal variations owing to changing insolation and dust distributions, **Geophys. Res. Lett.,** in press, 2005.

Conrath, B. J., Thermal structure of the Martian atmosphere during the dissipation of the dust storms of 1971, **Icarus, 24**, 36-46, (1975).

Gonzalez-Galindo, F., S. W. Bougher, J. M. Bell, M. A. Lopez-Valverde, and F. Forget, Thermal structure of the Martian thermosphere: LMD-GCM and MTGCM Intercomparisons, *Mars Atmosphere Modeling and Observations Workshop*, Granada, Spain, February 27 - March 3, 2006.

Haberle, R. M., et al., General Circulation Model Simulations of the Mars Pathfinder Atmospheric Structure Investigation/Meteorology Data, **J. Geophys. Res., 104**, 8957-8974, 1999.

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.

Keating, G. M. et al., Brief review on the results obtained with the MGS and Mars Odyssey 2001 Accelerometer Experiments, Proceedings, *International workshop: Mars atmosphere modeling and observations*, Granada, Spain, January 13-15, 2003.

Lillis, R. J., J. H. Engel, D. L. Mitchell, D. A. Brain, R. P. Lin, S. W. Bougher, and W. H. Acuna, Probing upper thermosphere neutral densities at Mars using electron reflectometry, **J. Geophys. Res.**, in press, 2005.

Liu, J., M. I. Richardson, and R. J. Wilson, An assessment of the global, seasonal, and interannual spacecraft record of Martian climate in the thermal infrared, **JGR, 108, E8**, 5089, doi 10.1029/2002JE001921, 2003.

Lopez-Valverde, M. A., et al., Non-local thermodynamic equilibrium in general circulation models of the Martian atmosphere. I. Effects of the local thermodynamic equilibrium approximation on thermal cooling and solar heating, **J. Geophys. Res., 103**, 16799-16812, 1998.

Ridley, A. J., G. Toth, and S. W. Bougher, The Global Ionosphere Thermosphere Model and it's applications to planetary atmospheres, **EOS Trans. AGU, 85(17), Jt. Assem. Suppl.**, Abstract SA41A-06, 2004.

Smith, M. D., Interannual variability in TES atmospheric observations of Mars during 1999-2003, **Icarus, 167,** 148-165, 200

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, 164**, 14-32, 2003.
Withers, P. G., Mars Global Surveyor and Mars Odyssey Accelerometer observations of the martian upper atmosphere during aerobraking, **Geophys. Res. Lett.,** in press, 2005.