A FINAL REPORT TO
THE NASA MARS DATA ANALYSIS PROGRAM

IMPROVED MARS UPPER ATMOSPHERE CLIMATOLOGY
(NAG5-12567)
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I. INTRODUCTION

A. Brief Research Overview

The detailed characterization of the Mars upper atmosphere is important for future Mars aerobraking activities. Solar cycle, seasonal, and dust trends (climate) as well as planetary wave activity (weather) are crucial to quantify in order to improve our ability to reasonably depict the state of the Mars upper atmosphere over time. To date, our best information is found in the Mars Global Surveyor (MGS) Accelerometer (ACC) database collected during Phase 1 (Ls = 184-300; F10.7 = 70-90) and Phase 2 (Ls = 30-90; F10.7 = 90-150) of aerobraking. This database (100-170 km) consists of thermospheric densities, temperatures, and scale heights, providing our best constraints for exercising the coupled Mars General Circulation Model (MGCM) and the Mars Thermospheric General Circulation Model (MTGCM). The Planetary Data System (PDS) contains level 0 and 2 MGS Accelerometer data, corresponding to atmospheric densities along the orbit track. Level 3 products (densities, temperatures, and scale heights at constant altitudes) are also available in the PDS. These datasets provide the primary model constraints for the new MGCM-MTGCM simulations summarized in this report.

Our strategy for improving the characterization of the Mars upper atmospheres using these models has been three-fold : (a) to conduct data-model comparisons using the latest MGS data covering limited climatic and weather conditions at Mars, (b) to upgrade the 15-micron cooling and near-IR heating rates in the MGCM and MTGCM codes for addressing climatic variations (solar cycle and seasonal) important in linking the lower and upper atmospheres (including migrating tides), and (c) to exercise the detailed coupled MGCM and MTGCM codes to capture and diagnose the planetary wave (migrating plus non-migrating tidal) features throughout the Mars year. Products from this new suite of MGCM-MTGCM coupled simulations are being used to improve our predictions of the structure of the Mars upper atmosphere for the upcoming MRO aerobraking exercises in 2006. A Michigan website, containing MTGCM output fields from previous climate simulations, is being expanded to include new MGCM-MTGCM simulations addressing planetary wave influences upon thermospheric aerobraking fields (densities and temperatures). In addition, similar MTGCM output fields have been supplied to the MSFC MARSGRAM-200X empirical model, which will be used in mission operations for conducting aerobraking maneuvers.

In conclusion, this completed research addresses a high priority area of study that supports planning for future spacecraft missions to Mars. Specifically, we have upgraded 3-D atmospheric models that improve our understanding (and forecasting capability) of Mars upper atmospheric structure for the benefit of future spacecraft aerobraking exercises. Presently observed solar cycle, seasonal, and mean dust trends (climate) as well as planetary wave driven variability (weather) of the upper atmosphere are better understood owing to the upgraded suite of MGCM-MTGCM simulations that have been used to interpret available MGS datasets.

B. Institutional Transfer (FY02 and FY03 Funding)

The research contained in this grant was originally proposed to NASA's MDAP Program in 2001. FY01 MDAP funding of the awarded grant (NAG5-10660) was sent to the PI (S. W. Bougher) at the University of Arizona. Subsequently, the PI permanently moved from the University of Arizona to the University of Michigan (late Spring 2002). Both FY02 and FY03 funding resulting from this MDAP grant were de-obligated from Arizona (effective March 31, 2002) and newly obligated to the University of Michigan (April 1, 2002) in concert with the grant anniversary date (April 1, 2002). Research conducted in FY02-03 took place at the University of Michigan under NASA Grant #NAG5-12567.

II. FINAL REPORT ON RESEARCH (MICHIGAN/FY02-03)

A. TEXTUAL SUMMARY (FY02-03)

Our strategy for improving the Mars upper atmosphere climatology calls for the isolation of various forcing processes (solar and wave driven) for systematically building up a suite of detailed coupled MGCM-MTGCM simulations of the Mars lower and upper atmospheres. Year #1 (Arizona) was devoted to "zonally averaged" simulations and their improvement to investigate climatic (solar cycle/seasonal/dust) variations of the Mars upper atmosphere. Both diurnal and semi-diurnal tidal amplitudes and phases were specified at the MTGCM lower boundary, based upon new NASA Ames MGCM simulations. Longitude variability was specifically neglected in these simulations in order to isolate the latitude/local-time/altitude variations for various solar cycle and seasonal conditions at Mars. Years #2 and 3 (Michigan) were focused upon : (a) upgrading the NLTE 15-micron cooling and near-IR heating routines in the NASA Ames MGCM code (0-90 km) and the Michigan/NCAR MTGCM code (70-300 km), (b) conducting a new suite of coupled simulations (MGCM-MTGCM) for 36-solar cycle/ seasonal/dust conditions at Mars, and (c) analyzing the thermal balance terms from a selected subset of these 36-simulations. MGS Thermal Emission Spectrometer (TES) maps of dust opacities were used to drive the lower atmosphere MGCM code throughout the Mars year; the impacts of these changing dust conditions were propagated into the Mars thermosphere. In addition, coupled MGCM-MTGCM output products were generated for each of the 36-cases for the benefit of upgrading the MSFC MARSGRAM 200X empirical model.

The MTGCM and MGCM codes are currently being coupled at the 1.32 μbar level, which falls in the altitude range of 60-80 km. This coupling allows both migrating and non-migrating upward propagating tides to cross the MTGCM lower boundary and the effects of the thermal expansion and contraction of the Mars lower atmosphere to extend to the thermosphere. Key prognostic and diagnostic fields are passed upward from the MGCM to the MTGCM at the 1.32-microbar pressure surface at every MTGCM gridpoint: temperatures (T), zonal (U) and meridional (V) winds, and geopotential heights (Z). Two dimensional interpolation is applied to construct MGCM fields at 1.32-microbars that match the specific 5x5° MTGCM grid structure. No downward coupling from the MTGCM to the MGCM is presently activated. These two climate models are each run with a 2-minute timestep, with the MGCM exchanging fields with the MTGCM at this frequency. Ten Martian day simulations are typically conducted for various Mars seasonal and solar cycle conditions. Model histories are archived at 1 or 3-hour intervals throughout the Martian day, in order to capture the impact of longitude forcing upon time-dependent (specific local time) features throughout the integration. This coupled MGCM-MTGCM system has been validated using an assortment of spacecraft observations, including MGS Phase 1 and 2 aerobraking data [e.g. *Bougher et al.*, 1999b, 2003b]. Assuming constant solar EUV fluxes, the coupled MGCM-MTGCM system can now be used to simulate interannual variability in the Mars lower and upper atmospheres by utilizing these MGS TES dust opacity datasets obtained over 2-3 Martian years.

Coupled MGCM-MTGCM cases were conducted throughout the Martian year at 30° Ls intervals (i.e. Ls = 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330) each for

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three levels of solar activity (F10.7 = 70, 130, and 200). Horizontal dust opacity distributions were prescribed within the MGCM code based upon MGS TES datasets for mapping year #1 [Smith, 2004]. Vertical dust distibutions were specified based upon the Conrath formulation for moderate vertical mixing [Conrath, 1975; Bell et al., 2004]. Interannual repeatability is expected for these dust opacity distributions throughout most of the Martian seasons. However, dust opacities near perihelion (270±60) can vary greatly from one Mars year to the next owing to regional or global dust storm events. MGCM-MTGCM predictions for various "types" of dust storm events will be addressed in future research.

The capabilities of these coupled MGCM-MTGCM models have been demonstrated using recent MGS Phase 2 Accelerometer density data as well as MGS Radio Science (RS) electron density profiles [c.f. Bougher et al. 2004]. For example, ionospheric peak heights gleaned from observed RS electron profiles were sorted as a function of longitude at high Northern latitudes during aphelion conditions [Bougher et al., 2004]. It was found that wave #2-3 longitude waves appeared in these ionospheric peak heights, with phasing and amplitudes that were similar one Martian year apart (i.e. suggesting interannual repeatibility near aphelion). MGCM-MTGCM simulations reproduced this self-consistent oscillation of the neutral densities and the photochemically driven ionospheric peak height. Tidal decomposition subsequently identified the semi-diurnal (σ=2), eastward propagating wave#1 (s = -1) non-migrating tidal mode as the most likely cause of the wave#3 oscillations observed [Bougher et al., 2004]. This is consistent with Mars tidal decompositions recently conducted by Forbes et al; [2002], and previous modeling work by Wilson [2002] and analysis by Withers et al., [2003]. Clearly, the coupled MGCM-MTGCM system is able to capture in-situ driven tides and upward propagating migrating and non-migrating tides that determine the structure of the Martian lower thermosphere and ionosphere (100-160 km) during the aphelion season. See attached re-print [Bougher et al., 2004].

Likewise, coupled MGCM-MTGCM simulations have been targeted to address Odyssey aerobraking data (near perihelion) to determine the physical processes giving rise to the Northern hemisphere winter polar warming observed in the lower thermosphere [Keating et al., 2003; Bougher et al., 2003b]. Figure 1 illustrates a constant local time (SLT = 3) slice of MGCM-MTGCM temperatures appropriate to Mars conditions toward the end of Odyssey aerobraking operations. A strong polar warming (130 to 185 K) is obtained near 100-130 km covering 60-90N latitude, similar to Odyssey accelerometer observations. Thermal diagnostics (Figure 2) indicate that a strong inter-hemispheric (south to north) circulation gives rise to strong downwelling and adiabatic heating in the Northern winter polar region. Again, the coupled MGCM-MTGCM code shows great promise for reproducing observed features in the Mars upper atmosphere.

From the MGS Accelerometer data, it is also clear that the hydrostatic connection of the Mars lower and upper atmospheres requires that the temperature structure be calculated throughout the middle atmosphere (60-120 km) with accuracy. The fidelity of our new MGCM-MTGCM temperature predictions (and the associated height scale) was tested by comparing MTGCM simulations with corresponding MGS Accelerometer measurements. The improvement of NLTE CO_2 cooling and heating rates using state-of-the-art radiative transfer model (fast) parameterizations does indeed help explain most of the "disconnection or height offset effect" that we have experienced thusfar while comparing

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MGS density data with MTGCM predictions. However, a small height offset (≤ 3.0 km) is still required over most of the Martian year. We attribute this remaining "error" to several minor effects: (a) constant gravity utilized within the NASA Ames MGCM code, (b) the need for fine tuning of the vertical dust distribution as a function of season, and (c) other discontinuities between the MGCM and MTGCM code fields at the 1.32 μbar interface..

The experience gained with these numerous MGCM-MTGCM simulations suggests there are various advantages and limitations of this 2-model approach. The coupling of separate codes permits the unique physical processes (and timescales) of the lower and upper atmospheres to be addressed separately within codes which can be optimized for this purpose. Molecular diffusion is one example for the upper atmosphere, for which an implicit (vertical) formulation permits a longer MTGCM time-step to be used. However, linking two separate models across an interface is not "seamless". By this we refer to the lack of an exact match of thermal and dynamical processes (e.g. solar heating, CO_2 15-micron cooling, eddy diffusion, numerical filtering) across this interface. Both upward and downward coupling (fluxes and global dynamics) is not easily activated across separate models. In addition, the ideal interface would be located at a level where horizontal winds are weak (this is not the case for the 1.32-microbar level available for the MGCM-MTGCM coupling). Finally, post-processing of coupled MGCM-MTGCM model simulations is complicated by the need to exercise separate visualization tools and "stitch" the plots together numerically. For the future, we plan to develop, test, and validate a ground-to-exobase Mars GCM model that will "seamlessly" connect the Martian lower and upper atmospheres to address lower thermosphere density variations.

B. Publications and Presentations (FY02 and FY03)

Publications from MDAP research. Several publications have directly benefitted from the coupled MGCM-MTGCM simulations conducted for this MDAP research. One final publication is being drafted in the summer of 2004.

1. Justus, C. G., B. F. James, S. W. Bougher, A. F. C. Bridger, R. M. Haberle, J. R. Murphy, and S. Engel, MARS-GRAM 2000 : A Mars atmospheric model for engineering purposes, **Adv. in Space Research, 29**, 2002.
2. Bougher, S. W., R. G. Roble, and T. J. Fuller-Rowell, "Simulations of the Upper Atmospheres of the Terrestrial Planets", in *AGU Monograph : Comparative Aeronomy in the Solar System*, Eds. M. Mendillo, A. F. Nagy, and J. H. Waite, 2002.
3. Witasse, O., et al; Prediction of a CO2++ Layer in the Atmosphere of Mars, **Geophysical Res. Lett., 29, 8,**, 10.1029/2002GL014781, 2002.
4. 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., 107**, 10.1029/2001JE001582, 2002.
5. 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.
6. Bougher, S. W., S. Engel, and P. G. Withers, The NCAR Mars Thermospheric General Circulation Model : A Review, *Published Conference Abstract, International Workshop:*

Mars Atmosphere Modelling and Observations, Granada, Spain, January 13-15, 2003.

7. 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, JGR, 109, E3, E03010, 10.1029/2003JE002154, 2004.

8. Witasse, O., P.-L. Blelly, J. Lilenstein, and S. W. Bougher, Self-consistent modeling of the dayside ionosphere of Mars : III. Outputs of the fluid module in the Viking 1 lander and Mariner 6 cases, **JGR**, in press, 2004.

9. Bougher, S. W., J. R. Murphy, and J. M. Bell, Polar warming in the Mars lower thermosphere : Seasonal variations owing to changing tides and the global circulation, **GRL**, in preparation, summer 2004.

Presentations from MDAP Research. In addition, several invited and contributed presentations were given by Bougher illustrating the results from our data analysis research using the "detailed coupled" MGCM and MTGCM simulations described above.
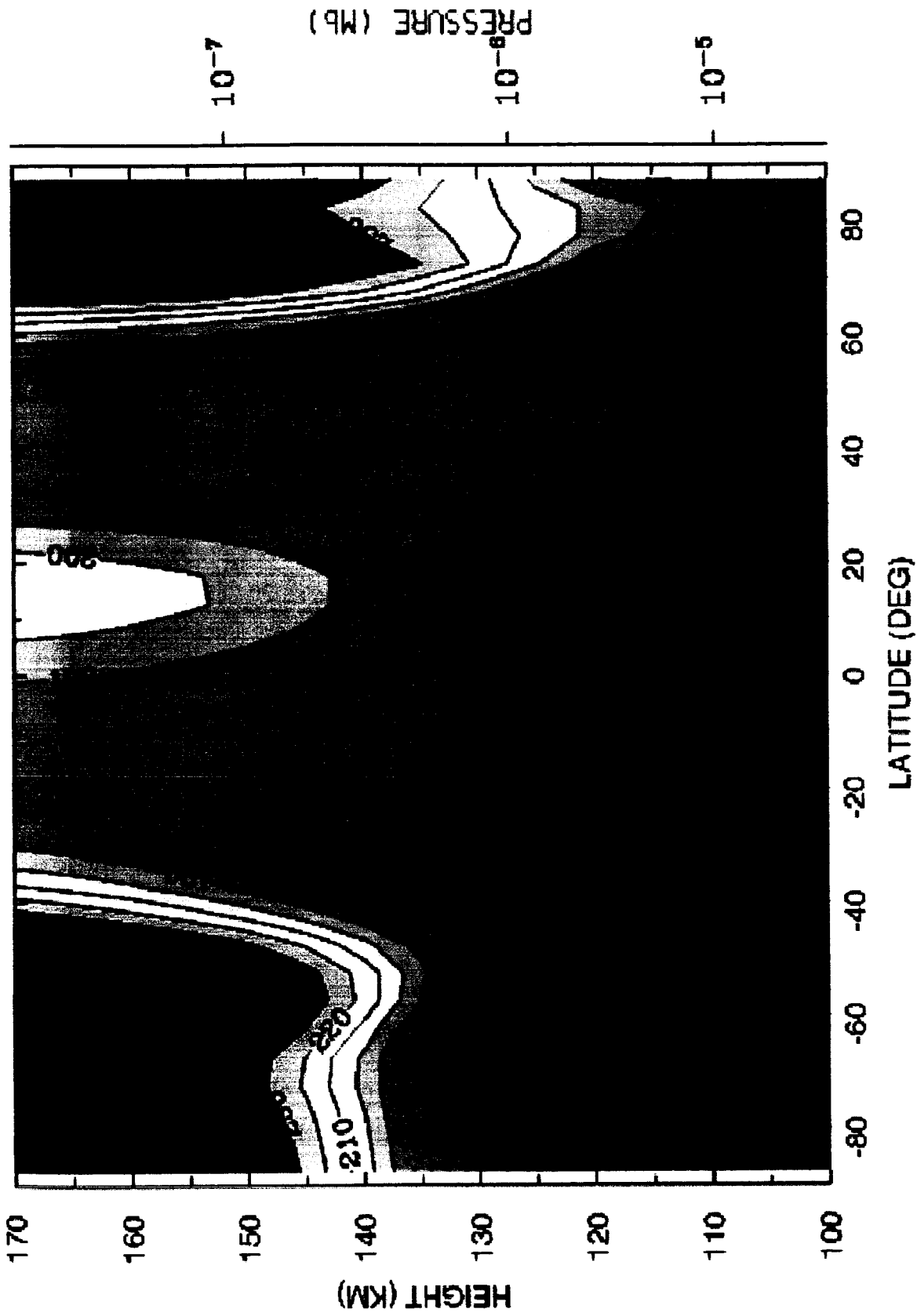
1. Bougher, S. W., J. R. Murphy, and S. Engel, Coupling Processes and Model Simulations Linking the Mars Lower and Upper Atmospheres, **34th COSPAR Scientific Assembly**, 10-19 October, Houston, TX, 2002.

2. Bougher, S. W., S. Engel, and P. G. Withers The NCAR Mars Thermospheric General Circulation Model : A Review, **Mars Atmospheric Workshop**, Granada, Spain, 13-15 January, 2003.

3. Bougher, S. W., and R. G. Roble, Helium as a Tracer of Terrestrial Planet Upper Atmosphere Dynamics : Predictions for Mars, **EOS Transactions, Am. Geophys. Union, Supplement**, XXX, 2003.

4. 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, **6th International Conference on Mars**, Pasadena, July 20-25, 2003.

5. Bougher, S. W., and J. R. Murphy, Polar warming in the Mars lower thermosphere : Odyssey Accelerometer data interpretation using coupled general circulation models, **EOS Transactions, Am. Geophys. Union, Supplement, 84(46)**, P21C-05, 2003.

6. Bougher, S. W., J. H. Waite, T. Majeed, and J. R. Murphy, Response by the Mars and Jupiter upper atmospheres to external forcings: Contrasts from TGCM simulations, **EOS Transactions, Am. Geophys. Union, Supplement, 85(17)**, SA51B-05, 2004.

C. Figure Legends and Figures

Figure 1 MTGCM constant local time (SLT = 3) plot of temperatures for Odyssey aerobraking conditions near Ls = 270. A strong winter polar warming is simulated over 100-130 km approaching the Northern polar region (70-90N latitude), similar to Odyssey accelerometer observations.

Figure 2 MTGCM constant local time (SLT = 3) plot of adiabatic heating for Odyssey aerobraking conditions near Ls = 270. A strong winter polar warming is simulated over 100-130 km approaching the Northern polar region (70-90N latitude), similar to Odyssey accelerometer observations. Dynamical heating (in excess of 1500 K/day) due to subsiding winds is clearly responsible. The south-to-north interhemispheric circulation is quite strong during the Mars perihelion season, giving rise to this warming.
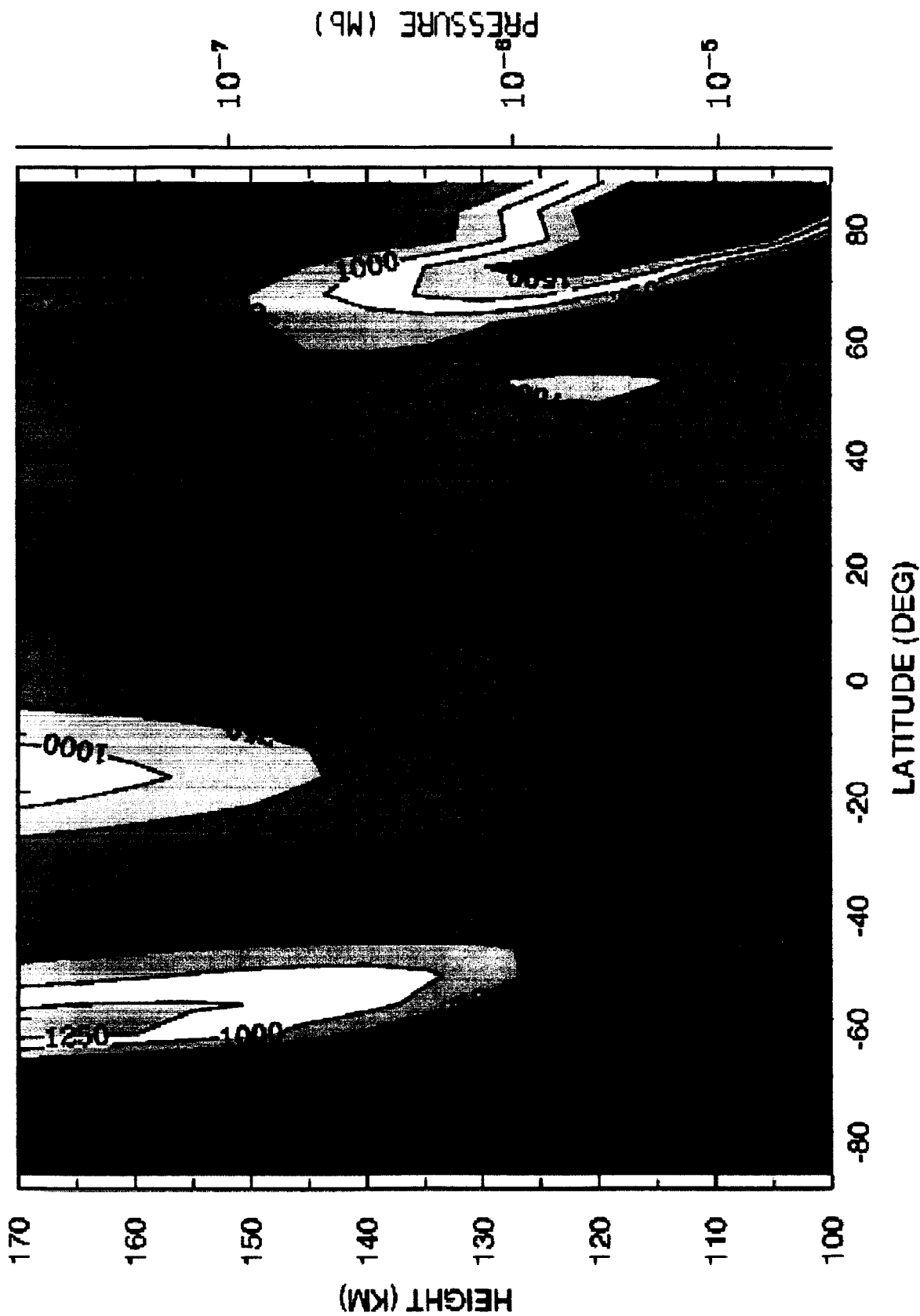
NEUTRAL TEMPERATURE (DEG K)
YEAR 1999 UT=12.00 LON= -135.00 (DEG) SLT= 3.00 (HRS)

PRESSURE (MB)

10^{-7}

10^{-6}

10^{-5}

80

60

40

20

0

-20

-40

-60

-80

LATITUDE (DEG)

170

160

150

140

130

120

110

100

HEIGHT (KM)

MIN,MAX= 1.0771E+02 2.9231E+02 INTERVAL= 1.0000E+01
mtgcm15 /BOUGHER/SWBM04/p10DY270d.nc (DAY,HR,MIN=511, 0, 0)

F/G. 1

YEAR 1999 UT=12.00 LON= -135.00 (DEG) SLT= 3.00 (HRS)

adia ()

PRESSURE (Mb)

10^{-7}

10^{-8}

10^{-5}

LATITUDE (DEG)

HEIGHT (KM)

MIN,MAX= -5.9436E+02 2.5220E+02 INTERVAL= 2.5000E+02
mtgcm15 /BOUGHER/SWBM04/s10DY270c-d.nc (DAY,HR,MIN=511, 0, 0)

FIG. 2

D. Michigan Website

A Michigan website is being maintained and upgraded to include 2-D plots of aerobraking fields (mass densities and temperatures) from selected MGCM-MTGCM simulations conducted for the research under this MDAP grant. The goal is to provide interested Mars community scientists with MTGCM outputs that can be used for engineering or scientific studies. The url for this site is as follows:

http://data.engin.umich.edu/tgcm_planets_archive/thermo.html

A subset of these same 2-D plots of aerobraking fields (mass densities and temperatures) is being forwarded to the Mars Exploration Program (MEP) at JPL for use in MRO mission planning.

E. Coefficients from MTGCM for MARGRAM

The 36-cases described above were also utilized to generate coefficients that are required to update the MSFC MARSGRAM empirical model, which is largely based upon well constrained NASA Ames MGCM (0-80 km) and Michigan/NCAR MTGCM (80-200 km) fields (i.e. temperatures, densities, winds) for various solar, seasonal and dust conditions at Mars. The required MGCM and MTGCM coefficients (and their formats) have been used previously and are described in detail in Justus and Johnson [2001]. Briefly, for each atmospheric parameter (temperature, pressure, density, and zonal plus meridional wind components), both MGCM and MTGCM data tables provide a diurnal (daily) mean value, and amplitudes and phases of the diurnal and semi-diurnal tidal components. A Fourier decomposition of the MGCM and MTGCM output fields is conducted yielding a separate data file for each of the 36-cases (described above). MGCM and MTGCM tidal coefficients were provided at 5-km intervals spanning 0-80 km (MGCM) and 80-200 km (MTGCM). MGCM coefficient data were provided at a 7.5° latitude spacing, while the MTGCM data have a 5° spacing. Both the MGCM and MTGCM data tables were generated for every 30° Ls interval around the Martian year.