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Tutorial Lecture

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Comparative Terrestrial Planet Thermospheres:
Venus, Earth, and Mars
CEDAR WORKSHOP 2000
COMPARATIVE TERRESTRIAL PLANET THERMOSPHERES:
VENUS, EARTH, AND MARS

I. Introduction

- Basic fundamental planetary parameters and implications
- Hierarchy of model development at NCAR (1975-present)

II. Basic Features of Structure and Dynamics of Thermospheres

- Vertical temperature structure and global mean composition (over solar cycle)
- Common thermospheric processes and possible thermostatic controls
- EUV/UV energy deposition and heating efficiencies
- Auroral and joule heating
- 1-D global mean heat balances and implications
- Global scale wind patterns

III. Recent (V-M) Thermospheric Data Illustrating Key Features

- Venus and Mars upper atmosphere sampling over past 25 years
- Solar cycle (rotational) responses of thermospheric temperatures
- Compositional variations (horizontal) from data and empirical models
- Storm responses : Mars (dust forcing)
- Mars planetary waves : MGS discovery of longitude fixed waves (diurnal Kelvin wave explanation)

IV. TGCM Modeling Tools (Venus, Earth, and Mars)

- Descriptions of the VTGCM, TIEGCM, and MTGCM
- Common inputs for equinox and solstice, solar cycle simulations
V. TGCM (V-E-M) Simulations for Equinox Conditions

- Global temperature, composition, and wind distributions (homopause and exobase)
- Solar cycle variations of same
- Dayside heat balances (radiative and dynamical)
- Time dependent variation of dayside composition and temperatures
- Role of CO$_2$-O cooling as a thermostat controlling temperatures
- Role of global dynamics as a thermostat controlling temperatures

VI. TGCM (E-M) Simulations for Solstice Conditions

- Global temperature, composition, and wind distributions (homopause and exobase)
- Seasonal plus solar cycle variations of same
- Role of orbital eccentricity impacting temperatures
- Mars lower atmosphere dust impacts on its thermosphere (coupling of atmospheric regions)

VII. Summary and Conclusions

- Key comparative planetary thermosphere problems
- UA website archive of TGCM results
### Table 1a. Terrestrial Planet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity, cm/s²</td>
<td>982</td>
<td>888</td>
<td>373</td>
</tr>
<tr>
<td>Heliocentric distance AU</td>
<td>1.0</td>
<td>0.72</td>
<td>1.38-1.67</td>
</tr>
<tr>
<td>Radius, km</td>
<td>6371</td>
<td>6050</td>
<td>3396</td>
</tr>
<tr>
<td>Ω, rad/s</td>
<td>7.3(-5)</td>
<td>3.0(-7)</td>
<td>7.1(-5)</td>
</tr>
<tr>
<td>Magnetic dipole moment (wrt Earth)</td>
<td>1.0</td>
<td>≤4.0(-5)</td>
<td>≤2.5(-5)</td>
</tr>
<tr>
<td>Obliquity, deg</td>
<td>23.5</td>
<td>1-3</td>
<td>25.0</td>
</tr>
</tbody>
</table>

### Table 1b. Implications of Parameters

<table>
<thead>
<tr>
<th>Effect</th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale heights, km</td>
<td>10-50</td>
<td>4-12</td>
<td>8-22</td>
</tr>
<tr>
<td>Major EUV heating, km</td>
<td>~200-300</td>
<td>~140-160</td>
<td>120-160</td>
</tr>
<tr>
<td>O Abundance (ion peak)</td>
<td>~40%</td>
<td>~7-20%</td>
<td>~1-4%</td>
</tr>
<tr>
<td>CO₂ 15-μm cooling</td>
<td>≤130 km</td>
<td>≤160 km</td>
<td>≤125-130 km</td>
</tr>
<tr>
<td>Dayside thermostat</td>
<td>conduction</td>
<td>CO₂ cooling</td>
<td>winds/conduction</td>
</tr>
<tr>
<td>Dayside solar cycle T</td>
<td>900-1500 K</td>
<td>230-310 K</td>
<td>220-325 K</td>
</tr>
<tr>
<td>Rotational forces</td>
<td>important</td>
<td>negligible</td>
<td>important</td>
</tr>
<tr>
<td>Cryosphere</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Auroral/Joule heating</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Seasons</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>
ONE DIMENSIONAL GM MODELS (1D)

DETAILED THERMAL BALANCE

NEUTRAL COMPOSITION + DETAILED THERMAL BALANCE

COUPLED NEUTRALS-IONS + DETAILED THERMAL BALANCE

SIMPLIFIED DYNAMICAL MODELS (2D)

ZONALLY AVERAGED

SPECIAL GEOMETRY

GLOBAL MODELS (3D)

SEMI-EMPIRICAL

• EMPIRICAL COMPOSITION
• ENERGETICS, WINDS

COUPLED

• NEUTRALS
• ENERGETICS ($T_n$)
• WINDS

COUPLED

• NEUTRALS
• IONS
• ENERGETICS ($T_e, T_i, T_n$)
• WINDS

TIEGCM

COUPLED

• NEUTRALS / IONS
• ENERGETICS ($T_e, T_i, T_n$)
• ELECTRODYNAMICS
• WINDS

TIME-GCM

COUPLED

• THERMOSPHERE
• IONOSPHERE
• MESOSPHERE
• (ELECTRODYNAMICS)
COMMON (UNIQUE) THERMOSPHERIC PROCESSES

- HEATING
  - Solar EUV/UV heating (1.0-225.0 nm)
  - Solar near-IR heating (1.0-4.3 microns) (Venus and Mars)
  - Auroral/Joule heating (Earth)
  - Tidal heating and/or GW dissipation
  - Dynamical (advection/compression) heating

- COOLING
  - Molecular thermal conduction
  - Eddy thermal conduction (Venus and Mars)
  - CO₂ IR cooling at 15-microns
    (Main IR radiator at mesopause heights)
    (Enhanced by atomic-O collisions)
  - NO(5.3-microns) (Earth)
    (Importance presently under debate)
  - Dynamical (advection/expansion) cooling

- CONSTITUENTS
  - O₂ and N₂ dominated atmosphere (Earth)
  - CO₂ dominated atmosphere (Venus and Mars)
  - Chemical sources and sinks
  - Molecular vs. eddy diffusion
  - Hydrostatics and redistribution by global winds
  - Exospheric escape
  - Downward fluxes into lower atmosphere (Earth, others?)

- WINDS
  - Neutral pressure gradient driven
  - Molecular and eddy viscosity
  - Hydrodynamic advection; non-linear terms
  - Coriolis torques (Earth and Mars)
  - Gravity wave drag (Venus)
  - Ion drag (Earth)
  - Tidal forcing of MLT region (Earth and Mars)
Paxton and Anderson (92)

\[ \uparrow = 1 \]
VENUS GLOBAL MEAN HEATING RATES

Bougher et al., (94)
Figure 14. (Left) Heating rates due to various sources as a function of altitude for the dayside atmosphere (Fox 1988). (Right) Heating efficiencies estimated for a standard model (curve A) using a “best guess” value for the fraction of energy that appears as vibrational excitation in the quenching of metastable atomic oxygen and for a lower limit (“not unreasonable” value) model (curve B) (Fox 1988). Curve C is from Hollenbach et al. (1985). Preferred values are 16 to 25% (curves A, B) in the range of 115 to 200 km (Fox 1988).
Figure 9. Global mean and dayside mean exospheric temperatures as a function of the $F_{10.7}$-cm index scaled to each planet: (a) Venus, (b) Earth, and (c) Mars. Available data are plotted for comparison with 1-D model calculations. Dayside mean conditions are simulated with double the heating allocated to the global mean. MSIS83 refers to Hedin [1983], VIRA refers to Keating et al. [1985], VTS3 refers to Hedin et al. [1983], and J77 refers to Jacchia [1977]. Notice that the Venus solar cycle variation of global mean exospheric temperatures is far less than that observed for the Earth. The Mars variation of 150 K lies midway between that for Venus and Earth. The key lies in their respective heat budgets, specifically the relative importance of CO$_2$ cooling. Taken from Bougher and Rable [1991].
Figure 1. Cartoon of the SS-AS flow versus RSZ flow and its effects on the local time distribution of helium (figure adapted from Mayr et al. 1985).
Schematic diagram of the zonal mean meridional circulation in the earth's thermosphere during equinox for various levels of auroral activity: (a) extremely quiet geomagnetic activity, (b) average activity, and (c) geomagnetic substorm. [Source: NCAR]

Schematic diagram of the zonal meridional circulation of the earth's thermosphere during solstice for various levels of auroral activity: (a) extremely quiet geomagnetic activity, (b) average activity, and (c) geomagnetic substorm. [Source: NCAR]
Kasprzak et al., (97)

Figure 2. Solar activity as a function of year with date ranges for the various neutral density data sets obtained above 100 km. The 3-solar rotation 10.7-cm radio flux index, $F_{10.7}$, is measured at Earth and adjusted for the difference in phase of Earth and Venus. The solar EUV index, $I_{pe}$ (Brace et al. 1988) is measured at Venus and has more than half of its contribution from Lyman-α.
Figure 12. Dayside and near midnight exospheric temperatures measured over the solar cycle and predicted by several models for Venus.
Figure 7. Scale-height temperatures, Tex, derived from PV ONMS dayside atomic oxygen measurements (Niemann et al. 1980b), the Langmuir Probe VEUV index (Brace et al. 1988), the daily $F_{10.7}$ index (corrected for the Earth-Venus phase difference) (Mahajan et al. 1990) and PV OAD exosphere temperature change derived from mass density measurements (Keating and Bougher 1992a,b) plotted as a function of local solar time.
Hedin et al., (83) VTS3

Exospheric temperature (K) vs. hour angle (hrs)

- EQUATOR
- 150 Km
- 100 Km

Number density (cm$^{-3}$) vs. hour angle (hrs)

- CO$_2$
- O
- CO
- N$_2$
- N
- He
VIRA 98 Temperature vs Latitude

Alt = 165; \( F_{10.7} = F_{10.7\text{bar}} = 80 \)
Figure 2. (a) The OUVS NO(0,1) δ-band vertical intensity distribution. The latitude and local time grid is filled with 198 nm data as obtained and revised in absolute intensity according to Bougher et al. (1990). This statistical map of the airglow is obtained over 35 orbits early in the PVO mission, and exhibits a dark-disk average intensity (120–180° SZA) of 460±120 R. (b) Spatial variability of the observed OUVS 198 nm individual bright airglow patches included in the statistical map of (a). The half maximum intensity spatial extent of each individual NO patch is plotted as a function of local time and latitude. The aspect ratio, defined as the local time to latitude ratio, of each equatorial to mid-latitude patch is on the order of 2:1. This value is largely independent of latitude, and it implies strong zonal winds (figure from Bougher et al. 1990).
Bougher et al., (00)

$L_s$ vs. Heliocentric Distance

![Graph showing $L_s$ vs. Heliocentric Distance with markers for minimum (min), moderate (mod), and maximum (max) values.

- M9E
- MGS2
- M4, MPF
- M6-7
- MGS1
- M9N

Heliocentric Distance (AU) vs. $L_s$
Table 1. Mars Spacecraft Observations of the Upper Atmosphere

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Dates(s)</th>
<th>F10.7</th>
<th>Ls</th>
<th>Dsm</th>
<th>SZA</th>
<th>Texo</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>650715</td>
<td>77.0</td>
<td>139.0</td>
<td>1.553</td>
<td>67.0</td>
<td>212.0</td>
</tr>
<tr>
<td>M67</td>
<td>690731</td>
<td>167.0</td>
<td>200.0</td>
<td>1.425</td>
<td>57.0</td>
<td>315-350.0</td>
</tr>
<tr>
<td></td>
<td>690805</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M9N</td>
<td>71FALL</td>
<td>103.0</td>
<td>306.0</td>
<td>1.440</td>
<td>50-60.0</td>
<td>325.0</td>
</tr>
<tr>
<td>M9E</td>
<td>72SPRG</td>
<td>100.0</td>
<td>38.0</td>
<td>1.630</td>
<td>70-90.0</td>
<td>268.0</td>
</tr>
<tr>
<td>VL1</td>
<td>760720</td>
<td>69.0</td>
<td>96.0</td>
<td>1.647</td>
<td>44.0</td>
<td>186.0</td>
</tr>
<tr>
<td>VL2</td>
<td>760903</td>
<td>76.0</td>
<td>117.0</td>
<td>1.612</td>
<td>44.0</td>
<td>145.0</td>
</tr>
<tr>
<td>MPF</td>
<td>970704</td>
<td>70.0</td>
<td>143.0</td>
<td>1.557</td>
<td>135.0</td>
<td>153.0</td>
</tr>
<tr>
<td>MGS1</td>
<td>980116</td>
<td>93.0</td>
<td>256.0</td>
<td>1.382</td>
<td>73.5</td>
<td>220.0</td>
</tr>
<tr>
<td>MGS2</td>
<td>981027</td>
<td>127.0</td>
<td>48.5</td>
<td>1.653</td>
<td>57.0</td>
<td>230.0</td>
</tr>
</tbody>
</table>

F10.7 refers to the 10.7-cm index used to select reference EUV/UV flux datasets; Ls refers to the angular measure of the Mars seasons (Ls = 90 is Northern Summer Solstice, Ls = 270 is Southern Summer Solstice, etc.); Dsm refers to the Mars heliocentric distance (AU); SZA refers to solar zenith angle; T-exo refers to exospheric temperature. Dates are listed as follows: YYMMDD. Spacecraft are indicated as follows: M4 (Mariner 4), M67 (Mariner 6 and 7), M9E (Mariner 9 Extended), M9N (Mariner 9 Nominal), VL1 (Viking Lander 1), VL2 (Viking Lander 2), MPF (Mars Pathfinder), MGS1 (Mars Global Surveyor Phase 1 Aerobraking sample), MGS2 (Mars Global Surveyor Phase 2 Aerobraking sample).
Seiff and Kirk (77)

Hanson et al., (77)
Bougher and Keating (99)

MARS THERMOSPHERIC TEMPERATURE STRUCTURE
45N FALL/WINTER
LOW SOLAR ACTIVITY

MGS ACCELEROMETER

BOUGHER GCM

PHASE I
AB

MARS THERMOSPHERIC TEMPERATURE STRUCTURE
45N SPRING/SUMMER
MEDIUM SOLAR ACTIVITY

MGS ACCELEROMETER

PHASE II
AB
Fig. 2 MGS Accelerometer versus MTGCM simulated mass densities at 130 km for P050-P200. A combination of latitude, local time, longitude and dust variations encountered at the spacecraft periapses is contained in the MGS Accelerometer densities. MTGCM simulations account for latitude, local time, and dust variations. MGS data (asterisks), MTGCM simulations for static tau = 0.3 dust case (solid line), and MTGCM simulations for static tau = 1.0 dust case (dotted line).

Fig. 3 MGS Accelerometer 1.26-nanobar pressure heights measured during Phase I aerobraking (P005-P120). Taken from Keating et al. (1998).
Fitted density ratioed to mean fitted density
Phase 2, outbound, daytime, 130km

Longitude ('E) 40 second data

Latitude ('N)
Wave-5 fit to outbound densities
Phase 2, 0 to 10 'N, 40 second data, daytime

+ = MGS data, solid line = least squares wave-5 fit,
dotted lines = 1 sigma uncertainty in fit,
levels = 120 130 140 150 km
VTGCM AND MTGCM THERMOSPHERE MODELS:
BASIC DESCRIPTIONS

- VTGCM: NCAR Venus Thermospheric GCM (94-200 km)
  - Resolution: 5 x 5° horizontal; 32-layers
  - Neutral Fields: T, U, V, W, O, CO, CO₂, N₂, O₂, He
  - Odd Nitrogen Fields: NO, N(4S), N(2D)
  - Airglow Fields: NO(198.0 nm), O₂(1.27-micron and 400-800 nm)
  - Ion Fields: PCE Only (O²⁺, CO₂⁺, O⁺, NO⁺)
  - Ion-neutral reactions and rates from Massie et al., [1983]
  - Prescribed EUV (20%) and UV (22%) heating efficiencies.
  - Eddy diffusion coefficient: \( \leq 1.0 \times 10^7 \text{ cm}^2/\text{sec} \)
  - Gravity wave drag: slowing day-to-night wind speeds by factor of 2

- MTGCM: NCAR Mars Thermospheric GCM (70-300 km)
  - Resolution: 5 x 5° horizontal; 32-layers
  - Neutral Fields: T, U, V, W, O, CO, CO₂, N₂, O₂, AR
  - Ions: PCE (O²⁺, CO₂⁺, O⁺, NO⁺, CO⁺, N₂⁺ ≤200 km)
  - Ions: DYN (O²⁺, O⁺ ≥200 km)
  - Ion-neutral reactions and rates from Fox et al., [1995]
  - Empirical electron and ion temperatures from Fox [1993]
  - Prescribed EUV/UV (22%) heating efficiencies.
  - Eddy diffusion coefficient: \( \leq 1.0-3.0 \times 10^7 \text{ cm}^2/\text{sec} \)
  - Non-Solar Forcing: semi-diurnal tides

Coupling of Mars Lower and Upper Atmospheres
- Mars fundamental parameters for season from AMES MGCM (0-90 km)
- Zonally and time averaged Ts and heights exchanged at p=1.32-ubar
- Semi-diurnal tidal amplitudes and phases exchanged at p=1.32-ubar

Dusty Lower Atmosphere Cases
- Static dust, globally horz. uniform with specified vertical distribution
- \( \tau \) (visible) = 0.3 to 1.0, spanning MGS aerobraking data outside storm
- Inflation accommodated by MGCM zonally averaged heights
- Waves accommodated by MGCM semi-diurnal tidal fields
TIEGCM MODEL
(THERMOSPHERE-IONOSPHERE-ELECTRODYNAMICS)
BASIC DESCRIPTION

A. Calculation Scheme/Solution System

- Independent Variables: z, λ (long.), φ (lat.), t (time)
- Many Prognostic Equations: T, U, V, 9-SPECIES
- Major Neutral Species = O, O₂, N₂
- Minor Neutral Species = N(^2D), N(^4S), NO, He, Ar
- Plasma Species = O⁺, O₂⁺, NO⁺, N₂⁺, N⁺, electrons
- Plasma Temperatures = Tion, Telec
- Two Diagnostic Equations: W, Φ
- Dynamo electric field and currents

B. Geometry/Model Resolution

- Vertical: \( z = \log(p₀/p) \); \( p₀ = 0.5\)-nbar; \( Δz=0.5 \)
  Levels (29); Thermos-Ionos.: -7 to 7 or 95-800 km
- Horizontal: 5 x 5° Grid; 0-24 LT; Pole to pole

C. Specific TIEGCM Processes Included:

- Roble et al., [1987] and Roble [1995] aeronomic scheme
- Self-consistent EUV/UV neutral heating calculated (non-local)
- Empirical models of high-latitude ion convection
- Empirical models of auroral particle precipitation
- Richmond et al., [1992] dynamo model (electrodynamics)
- Coupling of semi-diurnal and diurnal tidal components
- Eccentricity variation as a function of season (recent)
COMMON TGCM INPUTS FOR
SEASONAL - SOLAR CYCLE CASES

- F10.7-cm indices used to specify standard EUV-UV fluxes
  - F10.7 = 70, 130, 200 for SMIN, SMED, SMAX cases
  - Hinteregger contrast ratio method (Solomon subroutine)
  - Fluxes from 2.0 to 200.0 nm
  - Eccentricity variations (±3% Earth; ±20% Mars)

- Heating efficiencies specified based upon off-line calculations
  - VTGCM : EUV (20%), UV(22%)
  - MTGCM : EUV (22%), UV(22%)
  - TIEGCM : EUV (30-40% over 200-300 km; up to 60% below 200 km)
  - TIEGCM : UV(30-40%)

- Common O-CO₂ relaxation rate
  - 3.0 x 10⁻¹² cm³/sec at 300K
  - Weak temperature dependence (square root of T)

- Eddy diffusion/conduction from standard formulations. Kmax :
  - VTGCM : 1.0 x 10⁷ cm²/sec at 135 km
  - MTGCM : 1.0-1.5 x 10⁷ cm²/sec at 125 km
  - TIEGCM : 1.6 x 10⁶ cm²/sec near 100 km

- Low auroral activity parameters for Earth TIEGCM
  - Cross tail potential of 45KV
  - Integrated global power input of 16.0 GW

- Tidal parameters specified at the lower boundaries
  - MTGCM : semi-diurnal amplitudes and phases
    from NASA AMES MGCM
  - TIEGCM : diurnal & semi-diurnal amplitudes and phases
    from Forbes seasonal climatology
Bougher et al. (1999)

Venus - Equinox

![Graph showing temperature vs. height for Venus equinox conditions with different LT values and mixing ratios.](image)

Venus Equinox

![Graph showing height vs. O/CO₂ mixing ratio for Venus equinox conditions with different LT values.](image)
VTGCM

NEUTRAL TEMPERATURE (DEG K)
UT=12.00 ZP= 7.00 AVE HT= 176.9

LOCAL TIME (HRS)
MIN, MAX = 1.0427E+02 3.0843E+02 INTERVAL = 1.0000E+01
VTGCM /BOUGHER/SWBV97/EQUMAX (DAY, HR, MIN = 10, 0, 0)

0.263E+03
UN+VN
VTGCM

NEUTRAL TEMPERATURE (DEG K)
UT=12.00 ZP= 0.00 AVE HT= 129.5

LATITUDE (DEG)
-90 -60 -30 0 30 60 90

LONGITUDE (DEG)
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180

MIN, MAX = 1.0579E+02 1.9356E+02 INTERVAL = 5.0000E+00
VTGCM /BOUGHER/SWBV97/EQUMAX (DAY, HR, MIN = 10, 0, 0)

0.163E+03
→
UN + VN
VTGCM

NEUTRAL TEMPERATURE (DEG K)
UT=12.00 LAT= 2.50 (DEG)

MIN, MAX = 1.0425E+02  3.0829E+02
INTERVAL = 1.0000E+01
VTGCM /BOUGHER/SWBV97/EQUMAX (DAY, HR, MIN = 10, 0, 0)
Figure 6. The VTGCM SMAX model. A set of night airglow distributions corresponding to the wind field is given for: (top) the NO(0,1) δ-band emission at 198 nm (NO NTGL); (middle) the O₂ Herzberg II visible nightglow over 400 to 800 nm (O₂ VIGL); and (bottom) the O₂ 1.27-μm infrared nightglow (O₂ IRGL). The peak volume emission (PVE) rate altitude is indicated for each nightglow distribution.
Bougher et al. (1999)

Mars Equinox

Temperature (K)

Height (km)

LT=4

LT=15

min

mod

max

Mars Equinox

Height (km)

0.001

0.010

0.100

1.000

10.000

O/CO₂ Mixing Ratio
Bougher et al. (1999)

SLT = 15

[Diagram of atmospheric profiles with labels for COND, ADIA, AOVECT, QTOT, CO2 15μm, and pressure contours.]
MTGCM

NEUTRAL TEMPERATURE (DEG K)
UT=12.00 ZP= 6.00 AVE HT= 216.0

MIN, MAX = 1.4060E+02 3.2752E+02 INTERVAL = 1.0000E+01
MTGCM /BOUGHER/SWBM97/EQUMAX (DAY, HR, MIN= 10, 0, 0)

0.305E+03
UN+VN
MTGCM

NEUTRAL TEMPERATURE (DEG K)
UT=12.00 ZP= 0.00 AVE HT= 123.4

LATITUDE (DEG)

LONGITUDE (DEG)

LOCAL TIME (HRS)
MIN,MAX = 1.1309E+02 1.8911E+02 INTERVAL = 1.0000E+01
MTGCM /BOUGHER/SWBM97/EQUMAX (DAY,HR,MIN= 10, 0, 0)

0.160E+03
UN+VN
MTGCM

NEUTRAL TEMPERATURE (DEG K)
UT=12.00 LAT= 2.50 (DEG)

MIN, MAX = 1.1360E+02 3.2596E+02 INTERVAL = 1.0000E+01
MTGCM /BOUGHER/SWBM97/EQUMAX (DAY, HR, MIN = 10, 0, 0)
Bougher et al., (99b)

Earth Equinox

Height (km)

Temperature (K)

0 500 1000 1500 2000

LT=4

min

mod

max

LT=16

Earth Equinox

Height (km)

0.1 1.0 10.0 100.0

\( \frac{O}{O_2+N_2} \) Mixing Ratio

max

LT=16

min

LT=4
TIEGCM

NEUTRAL TEMPERATURE (DEG K)
UT = 0.00 ZP = 7.00 AVE HT = 732.5

UT = 0.00 ZP = 7.00 AVE HT = 732.5
TieGCM

Neutral Temperature (Deg K)

UT = 0.00 ZP = -6.00 AVE HT = 101.7

Minimum, Maximum = 1.4354E+02 1.7940E+02 Interval = 2.5000E+00

TieGCM / ROBLE / TieGCM / PEQSS01 (DAY, HR, MIN = 4, 0, 0)

0.468E+02

UN + VN
TieGCM

NEUTRAL TEMPERATURE (DEG K)
UT = 0.00 LAT = 2.50 (DEG)

MIN, MAX = 1.5156E+02 1.4591E+03 INTERVAL = 1.0000E+02
TGCM13/ROBLE/TGCM13/PEQSX01 (DAY, HR, MIN = 4, 0, 0)
Solar Cycle 1.26 nbar Heights for SZA=0, 60

Bougher et al., (00)
Ls = 270/Max

Neutral Temperature (Deg K)

UT=12.00 ZP= 6.00 AVE HT= 229.7

MIN,MAX = 1.236E+02 3.8879E+02 INTERVAL = 1.0000E+01
MTGCM /BOUGHER/SWBM97/SSLMAX (DAY, HR, MIN = 5, 0, 0)

0.403E+03
UN + VN
MTGCM

NEUTRAL TEMPERATURE (DEG K)
UT=12.00 ZP= 6.00 AVE HT= 171.2

0.216E+03
\rightarrow
UN+VN

MIN, MAX = 1.0143E+02 2.0452E+02 INTERVAL = 1.0000E+01
MTGCM /BOUGHER/SWBM97/NSLMIN (DAY, HR, MIN = 5, 0, 0)
Bougher et al., (00)

NEUTRAL TEMPERATURE (DEG K)
UT= 0.00 ZP= 7.00 AVE HT= 756.5

NEUTRAL TEMPERATURE (DEG K)
UT= 0.00 ZP= 7.00 AVE HT= 501.5
Bougher et al., (00)
Table 1a. Terrestrial Planet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity, cm/s²</td>
<td>982</td>
<td>888</td>
<td>373</td>
</tr>
<tr>
<td>Heliocentric distance AU</td>
<td>1.0</td>
<td>0.72</td>
<td>1.38-1.67</td>
</tr>
<tr>
<td>Radius, km</td>
<td>6371</td>
<td>6050</td>
<td>3396</td>
</tr>
<tr>
<td>Ω, rad/s</td>
<td>7.3(-5)</td>
<td>3.0(-7)</td>
<td>7.1(-5)</td>
</tr>
<tr>
<td>Magnetic dipole moment (wrt Earth)</td>
<td>1.0</td>
<td>≤4.0(-5)</td>
<td>≤2.5(-5)</td>
</tr>
<tr>
<td>Obliquity, deg</td>
<td>23.5</td>
<td>1-3</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Table 1b. Implications of Parameters

<table>
<thead>
<tr>
<th>Effect</th>
<th>Earth</th>
<th>Venus</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale heights, km</td>
<td>10-50</td>
<td>4-12</td>
<td>8-22</td>
</tr>
<tr>
<td>Major EUV heating, km</td>
<td>~200-300</td>
<td>~140-160</td>
<td>120-160</td>
</tr>
<tr>
<td>O Abundance (ion peak)</td>
<td>~40%</td>
<td>~7-20%</td>
<td>~1-4%</td>
</tr>
<tr>
<td>CO₂ 15-μm cooling</td>
<td>≤130 km</td>
<td>≤160 km</td>
<td>≤125-130 km</td>
</tr>
<tr>
<td>Dayside thermostat</td>
<td>conduction</td>
<td>CO₂ cooling</td>
<td>winds/conduction</td>
</tr>
<tr>
<td>Dayside solar cycle T</td>
<td>900-1500 K</td>
<td>230-310 K</td>
<td>220-325 K</td>
</tr>
<tr>
<td>Rotational forces</td>
<td>important</td>
<td>negligible</td>
<td>important</td>
</tr>
<tr>
<td>Cryosphere</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Auroral/Joule heating</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Seasons</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>
Key Comparative Planetary Thermospheres Problems

I. The role of CO2 cooling in the upper atmospheres of Venus, Earth, and Mars
   -- Confirm a fast de-activation rate (O-CO2 collisions) for all 3-planets
   -- Quantify the CO2 cooling rates in thermal budgets of these upper atmospheres
   -- Confirm the mechanism underlying the Earth ‘‘falling sky’’ effects

II. The coupling of the lower and upper atmospheres of Earth and Mars
    -- Quantify the combined/individual impact of tides, other planetary-scale waves, and gravity waves upon the Mesosphere-Thermosphere-Ionosphere (MTI) regions of both these planets as a function of season, solar cycle, latitude, etc.
    -- Improve predictions of the Mars upper atmosphere for aerobraking exercises

III. Large scale circulation patterns in the Venus, Earth and Mars upper atmospheres
     -- Role of fundamental planetary parameters in driving wind patterns
     -- Quantify how the changing solar EUV/UV fluxes alter the thermospheric circulation patterns of these 3-planets over the solar cycle?

IV. Super-rotation in planetary atmosphere (Venus, Earth, Titan, etc).
    -- Ascertain what planetary conditions favor the generation of such SR winds and why the SR wind magnitudes differ on various planets

V. Atmospheric escape processes for Venus, Earth, and Mars
    -- Quantify of the present rates of escape for the various mechanisms proposed as spacecraft data become available
    -- Extrapolate these mechanisms into the past (using proposed young sun EUV/UV/IR fluxes) to estimate the amount of water lost from Venus, Earth, and Mars since the cessation of early heavy bombardment.
    -- Answer key questions of atmosphere and climate evolution such as:
        (1) Was Mars’ early climate warm and wet? How warm and how wet? What conditions might have supported such a climate?
        (2) Where has all the water gone that is thought to have formed the Mars fluvial features?
        (3) Where has all the Venus water gone that its D/H ratio suggests must have once been present on the planet?

VI. Solar wind interaction with non-magnetic (Venus, Mars) versus magnetic (Earth, Jupiter, Saturn, etc.) planets
    -- Compare magnetospheric processes on Earth and Jupiter (magnetospheric convection driving ion drifts; particle precipitation; auroral processes giving rise to airglow features and driving neutral winds)
    -- Quantify the specific processes that enable the non-magnetic planets to partially or totally stand off the solar wind
At this website, we present recent model results that illustrate the thermal, compositional and dynamical responses of the upper atmospheres of Venus, Earth, and Mars to solar EUV-UV flux variability making use of the Venus VTGCM, the Earth TIEGCM, and the Mars MTGCM three-dimensional models. Each of these models has been developed and exercised at the National Center for Atmospheric Research (NCAR) using its CRAY computers.

... read more

http://www.lpl.arizona.edu/insengel/thermo.html

Archives of Thermospheric Model Runs
Comparative terrestrial planet thermospheres 2. Solar cycle variation of global structure and winds at equinox

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R. G. Roble and B. Foster
National Center for Atmospheric Research, High Altitude Observatory, Boulder, Colorado

Comparative terrestrial planet thermospheres
3. Solar cycle variation of global structure and winds at solstices

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