

Key Points:

- MAVEN dayside temperatures are shown to vary by 80 K (~180–260 K) over solar cycle 24, reduced from the Mars Global Surveyor (MGS) value of 120 K
- Mars temperature versus EUV sensitivity is similar for MAVEN and MGS exospheric measurements at 38 and 45 K m² mW⁻¹
- Mars thermal conduction balances EUV heating (160–180 km) for solar maximum conditions, while CO₂ cooling is secondary

Supporting Information:

Supporting Information may be found in the online version of this article.

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MAVEN/NGIMS Dayside Exospheric Temperatures Over Solar Cycle and Seasons: Role of Dayside Thermal Balances in Regulating Temperatures

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Abstract Several important processes of the Mars upper atmosphere are regulated by exospheric temperature (Texo) variations, including atmospheric escape rates. From the MAVEN mission, significant and largely periodic variability of Mars dayside Texo is now revealed by Neutral Gas and Ion Mass Spectrometer (NGIMS) data sets collected throughout solar cycle 24. Two complementary methods are utilized to extract temperatures from NGIMS data sets. These NGIMS dayside mean exospheric temperatures are shown to vary by ~80 K (~180–260 K) over solar cycle 24. This corresponds to a $\Delta\text{Texo}/\Delta\text{EUV}$ sensitivity of ~38 K m² mW⁻¹, where Lyman- α is the solar index. Previous Mars Global Surveyor derived Texo values for solar cycle 23 yielded a sensitivity of ~45 in the same units. This close correspondence suggests that the underlying dayside energy balances are similar yet slightly different over these two solar cycles. Corresponding Mars Global Ionosphere-Thermosphere Model simulations show that molecular thermal conduction largely balances EUV heating for the Mars dayside thermosphere, while CO₂ 15- μm cooling is secondary in importance, along with global winds. It is valuable to compare this Mars sensitivity to that computed for the dayside thermosphere of Venus. Pioneer Venus dayside data sets imply a sensitivity of ~17.5 K m² mW⁻¹ units for solar cycle 21, a factor of ~2.2 smaller than computed for Mars. This is because Venus CO₂ cooling strongly balances EUV heating near its peak, thereby serving as a more efficient thermostat regulating dayside temperatures. CO₂ cooling is much weaker for Mars.

Plain Language Summary Modern Earth global warming of its lower atmosphere is complemented by enhanced CO₂ 15- μm cooling in its upper atmosphere. This CO₂ cooling process also has a role in the CO₂ dominated upper atmospheres of Venus and Mars. From the MAVEN mission, significant and largely periodic variability of Mars dayside exospheric temperatures is revealed by Neutral Gas and Ion Mass Spectrometer (NGIMS) data sets collected during the declining phase of the solar cycle (2014–2019). These NGIMS dayside mean exospheric temperatures vary by ~80 K (180–260 K) over this weak (low sunspot number) solar cycle 24. Corresponding Global Climate Model (GCM) simulations of the Mars upper atmosphere reproduce this 80 K variability, revealing Extreme Ultraviolet heating is largely conducted downward to lower thermosphere altitudes providing net cooling, while CO₂ 15- μm cooling is secondary in importance. By contrast, Pioneer Venus Orbiter dayside data sets (1978–1992) also imply a similar ~80 K variability at Venus, now for the very strong (~3-times larger sunspot number) solar cycle 21. GCM simulations for Venus determine that CO₂ cooling strongly balances EUV heating near its peak, thereby serving as an efficient thermostat regulating dayside temperatures. CO₂ cooling is much weaker for Mars, yielding larger solar cycle variations in exospheric temperatures.

1. Introduction and Background

The Mars dayside thermal structure of its upper atmosphere can change dramatically over time since its energy balance is typically controlled by two highly variable components of the Sun's energy output: solar radiation (~0.1–200 nm) and solar wind particle precipitation (e.g., S. W. Bougher et al., 2002, 2009; S. W. Bougher, Brain, et al., 2017; Fang et al., 2013). Usually, soft X-ray (0.1–5) and EUV (5–110 nm) solar radiation are responsible for heating the Mars thermosphere and forming its ionosphere. These contributions vary significantly over time. Specifically, both solar rotation (~27-day periodic) and solar cycle (~11-year periodic) variations of these solar fluxes are significant, producing dramatic variations in global thermospheric temperatures, composition, and

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resulting winds (e.g., S. W. Bougher et al., 2000, 2002, 2009; Forbes et al., 2008), as well as ionospheric densities (e.g., Fox, 2004). Furthermore, this solar radiation received at Mars varies by $\pm 22\%$ throughout the Martian year, solely the result of the periodic change of the heliocentric distance. Conversely, solar wind particle fluxes and resulting energy deposition into the Mars thermosphere are largely episodic in nature (e.g., Fang et al., 2013).

This study is motivated by the significant and largely periodic variability of Mars dayside exospheric temperatures (Texo) revealed by new MAVEN Neutral Gas and Ion Mass Spectrometer (NGIMS) data sets (e.g., Benna et al., 2015; S. W. Bougher, Roeten, et al., 2017; Stone et al., 2018). Several important features of the Mars upper atmosphere are driven by Texo variations. For instance, exobase temperatures are a key state variable that impacts atmospheric escape (e.g., directly via Jeans escape, indirectly via hot O/H escape). For example, extremes of the solar cycle and seasonal variability indeed impact hot oxygen escape rates (e.g., Lee et al., 2015). Furthermore, it is important to constrain the relative role of O enhanced CO₂ 15- μ m cooling at Mars in the context of its unique role at Venus, Earth, and Mars (e.g., S. Bougher et al., 1999; S. W. Bougher et al., 1999). The same O-CO₂ deactivation rate coefficient should apply to all three terrestrial planets. This three planet comparison is made possible by leveraging new detailed O abundances now constraining Mars CO₂ cooling and its role in regulating dayside temperatures (S. W. Bougher, Jakosky, et al., 2015; Mahaffy et al., 2015). Finally, characterization of modern Mars dayside thermosphere temperatures (and associated heat budgets) is a crucial step for properly benchmarking subsequent ancient Mars calculations of thermosphere-ionosphere structure and volatile escape.

1.1. Pre-MAVEN Data Sets of Dayside Exospheric Temperatures

The combined solar cycle and seasonal variations in Martian dayside thermosphere (and exosphere) temperatures have been the focus of considerable investigation and analysis since the early Mariner Ultraviolet Spectrometer (UVS) measurements (1969–1972) and proceeding to recent Mars Atmospheric and Volatile Evolution Mission (MAVEN) measurements (2014–present) (see also Section 2.1) (e.g., S. Bougher et al., 1999; S. W. Bougher et al., 1999, 2000, 2009; S. W. Bougher, Brain, et al., 2017; Forbes et al., 2008; González-Galindo et al., 2009; Huestis et al., 2010; Keating et al., 2003, 2008; Krasnopolsky, 2010; Leblanc et al., 2006; A. I. F. Stewart, 1987; Withers, 2006). Even before MAVEN, it was clear that the significant Mars eccentricity demands that both the solar cycle and seasonal variations in near exobase temperatures be considered together in the characterization of their solar driven (periodic) values (e.g., S. W. Bougher et al., 2000; S. W. Bougher, Pawlowski, et al., 2015; S. W. Bougher, Brain, et al., 2017). For example, 3-D model simulations previously compared Equinox simulations with both Aphelion and Perihelion seasonal Texo values (for the same intrinsic solar minimum and maximum EUV fluxes, respectively) and found dayside Texo differences of $\Delta T \sim 25\text{--}40$ K (S. W. Bougher, Pawlowski, et al., 2015). By contrast, predicted solar cycle variations (for constant Equinox season) are much larger ($\Delta T \sim 120\text{--}130$ K).

Near solar minimum, dayside low solar zenith angle (SZA) Texo values have previously been extracted from the Viking 1 entry science data sets (~ 186 K) (e.g., Nier & McElroy, 1977; Seiff & Kirk, 1977), MGS accelerometer density scale heights ($\sim 190\text{--}200$ K) (Keating et al., 2008; Withers, 2006), and from Mars Express SPICAM UVS airglow scale heights ($\sim 201 \pm 10$ K) (Leblanc et al., 2006). These limited spacecraft measurements were used before MAVEN to characterize Mars Texo for near solar minimum, aphelion conditions. Conversely, solar moderate-to-maximum, near perihelion Texo values were estimated from Mariner 6–7 CO Cameron emissions (~ 315 K) (e.g., A. I. Stewart, 1972) and Mariner 9 CO Cameron emissions (~ 325 K) (Stewart et al., 1972). Perhaps the most comprehensive pre-MAVEN study of Texo utilized MGS drag measurements (from the Precise Orbit Determination [POD] method) near ~ 390 km (S. W. Bougher et al., 2009; Forbes et al., 2008) to reveal dayside Texo spanning $\sim 170\text{--}180$ to ~ 300 K, appropriate for solar cycle #23 (SC23) conditions. Overall, a composite estimate of the “extreme” solar cycle plus seasonal variation of Mars dayside exospheric temperatures of about $\sim 100\text{--}140$ K was estimated before MAVEN (S. W. Bougher, Brain, et al., 2017). These estimates are all based on measurements obtained during solar cycles #19–23.

1.2. Early-MAVEN Data Sets of Dayside Exospheric Temperatures

Early-MAVEN mission characterization of dayside solar cycle exospheric temperature variations for Mars was addressed by initial NGIMS, IUVS, and Extreme Ultraviolet Monitor (EUVM) instrument studies for which only a portion of solar cycle #24 measurements were available (S. W. Bougher, Roeten, et al., 2017; Jain et al., 2015;

E. M. Thiemann et al., 2018). In these studies, extracted Texo values for near overlapping sampling periods yielded reasonable comparisons of IUVS and NGIMS temperatures. EUVM solar occultation studies revealed CO₂ densities and exospheric temperatures at dawn and dusk locations for perihelion and aphelion seasons. Overall, solar cycle trends were found to be consistent with pre-MAVEN measurements (see Section 1.1). Later, Stone et al. (2018) carried out a careful analysis of NGIMS extracted temperatures (vertical profiles) from eight-Deep Dip campaigns. Both solar cycle and diurnal variations of thermospheric temperatures (including Texo) were derived. In addition, initial heat balance terms for reproducing Deep Dip #2 temperatures were derived from a 1-D model, necessarily focused on radiative terms and neglecting global dynamics. The need for a full 3-D model treatment (including large scale winds) is important to address the dynamical processes contributing to the maintenance of NGIMS temperature profiles.

Most recently, a comprehensive investigation making use of nearly 4-Martian years of IUVS dayside airglow derived thermosphere and mesopause temperatures was conducted (Jain et al., 2021). This study covers solar cycle #24 (SC24) measurements from MAVEN. A few important findings are as follows: (a) thermospheric temperatures show strong long-term variability, for which temperatures are largely driven by solar EUV variations and Mars seasons; (b) the thermosphere tends to be colder in the morning hours compared to the evenings where the temperatures are higher; (c) temperatures from both the Martian thermosphere and mesosphere show strong short-term variability indicating coupling from the lower atmosphere; and (d) this seasonal and solar cycle dependence of dayside thermospheric temperatures was largely predicted by global models (e.g., S. W. Bougher, Pawlowski, et al., 2015; González-Galindo et al., 2015) prior to MAVEN.

1.3. New Approach Using 6-Year of NGIMS Exospheric Temperatures

In this paper, we examine the solar cycle variation of the dayside Texo over the MAVEN mission throughout solar cycle #24—(SC24). The data set of MAVEN NGIMS scale height temperatures spans dayside local times at all latitudes and seasons (for SZA $\leq 60^\circ$). This enables a statistical picture of dayside Texo solar cycle variations to be made first, followed by key seasonal and SZA dependencies next. This NGIMS study is complementary to that conducted from the IUVS instrument described in Section 1.2 (Jain et al., 2021).

For consistency, we validate the Texo derivation from the scale height technique using eight-specific NGIMS sampling periods (SZA $\leq 60^\circ$) now applying a hydrostatic integration technique. This validation is meant to confirm the robustness of the scale height derived exospheric temperatures for our studies.

These newly derived MAVEN Texo variations are placed into context by comparing to pre-MAVEN Texo variations from MGS. Comparison between MGS and MAVEN Texo data sets is achieved using a common sensitivity calculation for which Lyman- α is selected as a proxy of solar EUV fluxes providing heating to the upper atmosphere.

A brief outline of the sections of this paper is as follows. Section 2 provides descriptions of the MAVEN data sets used in this study. Section 3 provides an overview of the Mars Global Ionosphere-Thermosphere Model (M-GITM) modeling framework and its usage to compute Texo variations over solar cycle #24 and the corresponding thermal balances that drive these variations. Section 4 presents NGIMS data analysis Texo trends as well as M-GITM modeling outputs that serve to interpret these NGIMS observations. Section 5 provides a comparative planetology view by comparing Mars and Venus Texo variations and underlying thermal balances. Finally, Section 6 finishes with a summary and conclusions.

2. MAVEN Data Sets Used in This Study

NGIMS is a quadrupole mass spectrometer on the MAVEN spacecraft designed to measure the densities of major neutral and ion species in the upper atmosphere with a vertical resolution of <5 km and an accuracy of $<25\%$ for most species. Measurements are made at altitudes between 150 and 500 km along the inbound and outbound segments of the elliptical science orbit. Excursions to altitudes as low as ~ 125 km were completed during 9 week-long “Deep Dip” (DD) campaigns. NGIMS leverages its dual ionization sources to measure both key nonreactive neutral species (e.g., CO₂, Ar, N₂, and He) and surface reactive neutral species (e.g., O and CO) and as well as ambient ions (e.g., Benna & Elrod, 2020; Benna et al., 2015; Mahaffy et al., 2015).

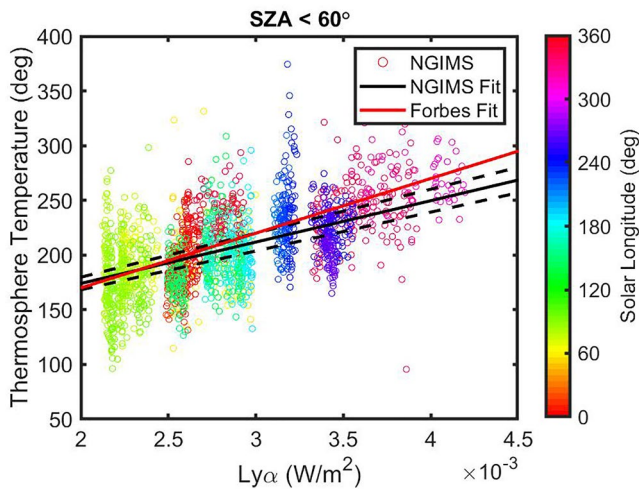


Figure 1. Neutral Gas and Ion Mass Spectrometer (NGIMS) scale height exospheric temperatures versus Lyman- α index (measured at Mars by Extreme Ultraviolet Monitor) over the entire MAVEN mission (solar zenith angle = 0° – 60° , LT = 06:00–18:00). Both Mars Global Surveyor (Forbes Fit, solid red curve) and NGIMS (NGIMS Fit, solid black curve) trends are provided for comparison of solar cycle trends for # 23 and 24, respectively. The open circles denote the individual NGIMS orbit exospheric temperature values, color coded by season (Ls). The dashed curves represent the uncertainty of the NGIMS linear fit due to the errors in the scale height temperatures themselves. These errors are larger for solar high conditions.

Our studies utilize NGIMS Level 2, Version 8, Revision 1 (V08_R01) neutral and ion densities and Level 3 Version 6, Revision 1 (V06_R01) scale height extracted temperature products spanning MAVEN periapsis to exobase altitudes. This most recent density data include corrections for CO densities following extensive recalibration studies (Benna & Elrod, 2020). See details in Sections 2.2.1 and 2.2.2 below.

Finally, solar fluxes measured at Mars are provided from the EUVM instrument. See Section 2.1 below.

2.1. EUVM Solar Fluxes Used for Data Analysis and M-GTIM Simulations

MAVEN EUVM daily fluxes from the FISM-M empirical model (an L3 product, V14_R3) (E. M. B. Thiemann et al., 2017) are used to supply inputs to the M-GTIM numerical model for calculating solar EUV-UV heating, photo-dissociation, and photo-ionization rates (see Section 3.1). These FISM-M fluxes correspond to the NGIMS orbits following a daily cadence with subdaily values interpolated for the specific orbit. The FISM-M spectral intervals (~ 0.1 – 210 nm) are rebinned for the 59-wavelength intervals (and associated cross sections) captured by the M-GTIM model (0.1 – 175.0 -nm) (S. W. Bougher, Pawlowski, et al., 2015). In addition, the Lyman- α index used in this paper (i.e., proxy for EUV fluxes as a whole) is taken from this same empirical model. In this regard, these Lyman- α fluxes will be used to derive a correlation with NGIMS derived exospheric temperatures for the generation of a least squares empirical trend (see Figure 1). The slope of this linear trend is designated the $\Delta\text{Texo}/\Delta\text{EUV}$ sensitivity, a key parameter for discussion in this paper. See Section 4.1 for a detailed discussion.

Lyman- α fluxes are chosen as the proxy for EUV fluxes in this paper for three reasons: (a) this index has been well measured from Earth for many years, and is tabulated in the LISIRD electronic database at LASP (Machol et al., 2019), (b) this Earth based index can easily be shifted to the Mars-Sun line orientation for interpolation to Mars, and (c) the available Pioneer Venus (PV) proxy for EUV solar fluxes is best tied to measured Langmuir Probe current, which is dominated by Lyman- α fluxes (see Section 5). The ultimate goal in choosing this common index is to compare the $\Delta\text{Texo}/\Delta\text{EUV}$ sensitivities for Venus and Mars, both CO_2 dominated planets.

2.2. MAVEN NGIMS Data Sets of Densities and Derived Temperatures

2.2.1. Details of L3 Data Sets: Overview Texo Sampling Method

The L3 scale height and temperatures are high level products derived from the L2 abundances. The L3 data typically span the altitude range of the CO_2 exobase to the periapsis. This valuable data set provides topside (near traditional exobase) scale heights for key species as measured by the NGIMS instrument. These scale heights are determined by linear fits of altitude versus log (density) between the periapsis and the exobase altitude (Benna & Elrod, 2020). The exobase altitude is defined by computing the altitude where the overhead integrated density accounts for one mean free path for CO_2 molecules. This method works for each orbit for which periapsis altitudes ≤ 185 km (prior to MAVEN periapsis raise in mid-June-2020). This condition is relevant to all SC24 NGIMS orbits used in this paper. Retrieval of scale height temperatures for periapsis altitudes above 185 km will be outlined in a future publication and is beyond the scope of this paper.

For this study, we utilize Argon densities and derived scale heights and temperatures. Being a nonreactive species with a low-sticking coefficient, Argon does not interact with the sensor's internal surfaces. Therefore, its measured altitude profile is immune to background variations observed for reactive species due to gas/surface buffering (Mahaffy et al., 2015). This scale height derivation method can be applied rapidly across $\sim 12,000$ NGIMS orbits for computing exospheric temperatures (Texo) and their variations over solar cycle, season, and SZA (see Figures 1 and 2).

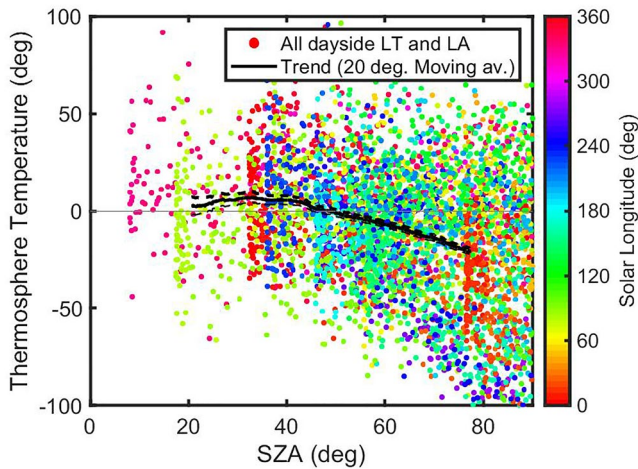


Figure 2. Both morning (LT = 06:00–12:00) and afternoon (LT = 12:00–18:00) sector (solar zenith angle [SZA] = 0°–90°) temperatures are combined and colored coded to illustrate Ls (seasonal) behavior. The solar cycle MAVEN trend line from Figure 1 is removed, yielding this detrended exospheric temperature behavior as a function of SZA. The dashed curves represent the errors to this trend owing to the errors in the scale height temperatures themselves. LT refers to Local Solar Time and LA refers to Latitude.

The uncertainties for NGIMS scale height derived exospheric temperatures were computed for each orbit. The error method is stated in the NGIMS PDS Software Interface Specification (Benna & Elrod, 2020). Basically, using a linear regression method produces a correlation and error. The temperature errors (Temp-error) reported in the L3 data set are the residuals from the least squares fit for each orbit sampled. Specifically, we performed a chi-square fit of the trend with uncertainty determination. Typical temperature errors are about ± 50 K (see Table 1 caption). In summary, all temperature uncertainties (Temp-error) from the linear fit of each orbit are included within the L3 files. These Temp-error values are now incorporated into the solar cycle linear fits presented (or used) in Figures 1–3.

2.2.2. Details of L2 Data Sets: Overview Texo Sampling Method and Specific Intervals

Temperatures can also be extracted from the NGIMS L2 data sets by vertically integrating CO₂ or Argon densities from the top down to obtain pressures (S. W. Bougher, Roeten, et al., 2017). The L2 data along the in situ aeropass can have a ~ 0.9 – 1.0 km vertical resolution near 200 km, and very small vertical resolution near the periapsis (where the spacecraft horizontal motion is significant). For the present work, the vertical density profile is assumed to be in hydrostatic equilibrium, and the hydrostatic equation is integrated for Ar densities to obtain the local partial pressure. From additional application of the ideal gas law, temperatures can be computed. This same basic method of deriving temperature profiles from densities was recently used in S. W. Bougher, Roeten, et al. (2017) and Snowden et al. (2013). For

the hydrostatic integration, a range of pressures for the upper boundary condition have been tested (i.e., S. W. Bougher, Roeten, et al., 2017) to determine their impacts on the resulting topside temperature profile. It was found that the temperature profile was negligibly altered by the choice of upper boundary condition below a certain altitude range, which was typically ~ 220 km for near perihelion conditions and ~ 200 km for near aphelion conditions. Additionally, for the lower altitudes of the profile, it should be noted that near periapsis, in particular, there is a more significant horizontal component to the spacecraft trajectory, and thus variations along the measured density profile (Stone et al., 2018). In order to better ensure the hydrostatic integration is appropriate, the temperature profiles examined here are limited to altitudes approximately a scale height above the orbit periapsis. Correspondingly, the altitude region of near isothermal temperatures used for this analysis was ~ 200 – 220 km for

Table 1

Specific MAVEN Eight-Periods (Campaigns) for Extracting 1-D Neutral Gas and Ion Mass Spectrometer Temperature Profiles and Associated Exospheric Temperatures From the Hydrostatic Integration Method (L2-Exo)

Period	Dates	Ls and orbit (range)	SZA (range)	# Days (MY)	L2-Exo(K) (1-sigma)	L3-Exo(K) (1-sigma)
1 (DD2E)	15 April 2015–13 May 2015	328–341 (1059–1200)	6–42	28 (32)	252 ± 43.3	246.7 ± 31.3
2	15 October 2016–27 October 2016	250–270 (3982–4045)	49–59	13 (33)	224.5 ± 22.0	226.9 ± 15.4
3	9 April 2017–23 April 2017	340–360 (4900–4971)	40–54	15 (33)	233.8 ± 36.8	239.9 ± 20.1
4	4 May 2017–16 May 2017	0.0 (5029–5095)	32–34	13 (33)	209.2 ± 50.3	202.8 ± 21.2
5	20 September 2017 to 2 October 2017	60–80 (5769–5836)	45–59	13 (34)	190.1 ± 27.7	196.2 ± 18.4
6 (DD8)	16 October 2017–22 October 2017	75–77 (5909–5946)	20	7 (34)	187.3 ± 40.6	188.6 ± 27.9
7 (DD9)	23 April 2018–28 April 2018	160–180 (6931–6961)	54–60	6 (34)	211.1 ± 39.8	205.9 ± 15.5
8 (PC19)	16 September 2019–30 September 2019	84–86 (9929–10017)	38–40	15 (35)	185.8 ± 40.9	185.7 ± 40.0

Note. Only SZA = 0°–60° is sampled, from which $\Delta\text{Texo}/\Delta\text{EUV}$ sensitivity is extracted and compared to pre-MAVEN and MAVEN values (see Table 3). L3-Exo corresponds to scale height derived Texo. The 1- σ tabulated values correspond to the standard deviation of the orbital dispersion about the period mean Texo. DD2E corresponds to an extended Deep Dip 2 campaign interval. DD8 and DD9 correspond to MAVEN Deep Dip 8 and 9 campaigns, respectively. PC19 corresponds to the postconjunction period in 2019. The number of days for data processing in each period is tabulated. Typical temperature uncertainties gleaned from the L3-Exo method are about ± 50 K. L2-Exo derived temperature errors are related to Argon density uncertainties themselves and atmospheric wave structure (e.g., Stone et al., 2018) and are on the same order as L3 errors (± 30 – 50 K). Text describes comparison of the two methods.

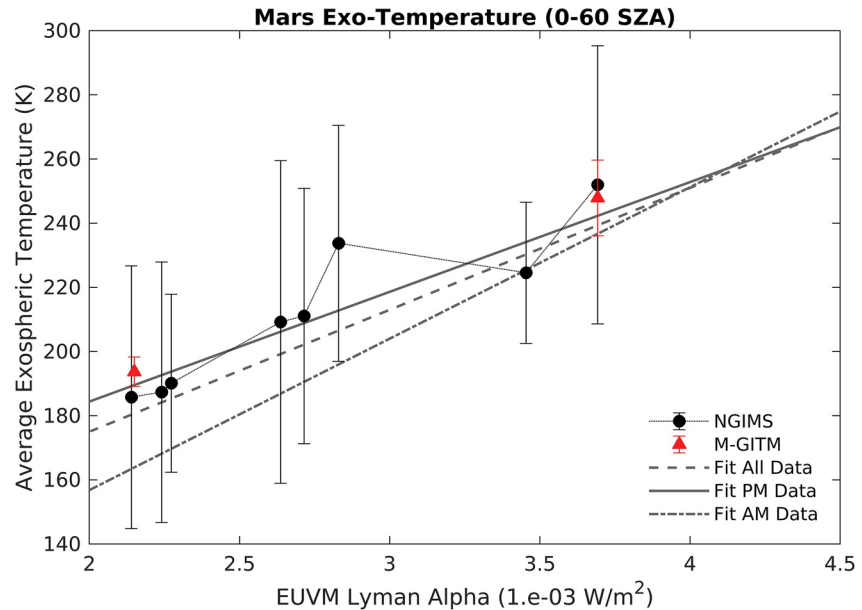


Figure 3. Neutral Gas and Ion Mass Spectrometer (NGIMS) dayside exospheric temperatures versus Extreme Ultraviolet Monitor Lyman- α index are illustrated for eight-specified periods over the MAVEN mission for solar zenith angle = 0° – 60° (see Table 1). Black dots correspond to hydrostatic integration estimates of period averaged Texo values, with uncertainty bars added to denote $1\text{-}\sigma$ orbital variations about the mean. An NGIMS full dayside scale height trend is plotted (dashed curve) from Figure 1 (LT = 06:00–18:00) and contrasted (solid curve) with a second trend (LT = 12:00–18:00) for afternoon conditions only. Finally, a third trend (LT = 06:00–12:00) for morning conditions is displayed. Notice that full dayside and afternoon trends are similar, while that for morning conditions is cooler, especially for Lyman- α fluxes less than 3.5 mW/m^2 . Mars Global Ionosphere-Thermosphere Model simulated mean Texo values (red triangles, plus $1\text{-}\sigma$ orbital variations about the mean) are also plotted for DD2E and PC19 intervals.

perihelion/solar high conditions and ~ 180 – 200 km for aphelion/solar low conditions. These two altitude ranges for these different periods approximately correspond to the CO_2 density interval of $\sim 10^8$ to 10^7 cm^{-3} . Therefore, we elect to extract Texo values making use of this CO_2 density interval criteria.

Table 1 outlines 8-intervals (key selected campaigns) for extraction of NGIMS 1-D temperature profiles and associated exospheric temperatures. Only $\text{SZA} = 0^{\circ}$ – 60° conditions are sampled, spanning solar minimum/aphelion to solar maximum/perihelion conditions encountered during the MAVEN mission (during SC24). The altitude range for the derivation of Texo values is 180 – 200 km for solar low conditions, while 200 – 220 km is used for solar high conditions. For this paper, solar high and low values are defined as periods above and below the Lyman-alpha flux of $\sim 3.5\text{ mW/m}^2$, respectively. Period #1 (DD2 extended) covers ~ 140 orbits (nearly 28 days), in order to smooth out variations of exospheric temperatures due to solar rotation (S. W. Bougher, Roeten, et al., 2017; Jain et al., 2015). Most subsequent periods contain ~ 60 – 70 orbits (nearly 5-full longitude sampling cycles over 13–15 days); solar rotation variations are expected to be small after mid-October 2016 during the declining phase of solar cycle #24. Periods #6 and 7 span the full duration of DD8 and DD9 campaigns only, about 6–7 days each. Finally, these computed 8-period mean exospheric temperature values are compared to the computed $\Delta\text{Texo}/\Delta\text{EUV}$ sensitivity and linear trends extracted from scale height temperatures derived from MAVEN NGIMS dayside observations (see Figure 3, Table 1). The detailed justification for this linear trending, and associated error analysis, are provided in Section 4.1.

The method of extracting temperatures through vertical integration of the hydrostatic equation allows the derivation of entire profiles. However, this technique is laborious and time consuming when applied to thousands of NGIMS orbits. Instead, its application to a limited number of orbits (e.g., Deep Dip campaigns) for detailed vertical structure studies is preferred (e.g., Stone et al., 2018). An independent method for calculation of exospheric temperatures is given in Section 2.2.1, based upon local scale heights in the near isothermal region above about ~ 180 km. This simpler method allows much faster processing of the large number of NGIMS orbits. We have used such scale height derived Texo values in Figures 1 and 2.

2.2.3. Specific Campaigns of L2 Data Sets: Detailed Studies of Extremes

Two specific intervals are chosen for detailed study of the extremes of the exospheric temperatures owing to the combination of solar cycle and seasonal variations. The two campaigns chosen are as follows: (a) the Deep Dip 2 extended campaign (orbits 1059–1200) for low SZA and early MAVEN solar maximum conditions approaching vernal equinox ($L_s \sim 328$ – 341) and (b) the post solar conjunction 2019 (orbits 9926–10017) for low SZA and late MAVEN solar minimum conditions near aphelion ($L_s \sim 85.0$). These cases are chosen to investigate the M-GITM performance during Mars seasonal/solar cycle extreme conditions and to be consistent with deep dayside sampling ($SZA \leq 60^\circ$) for comparison to NGIMS statistical exospheric temperature trends illustrated in Figures 1 and 3.

3. Three-Dimensional Modeling of Texo Variations Using M-GITM

M-GITM is a 3-D spherical code that was developed to address the physics of the whole Mars atmosphere system, capturing the basic observed features of the dynamical, thermal, and composition of the atmosphere from the surface to ~ 250 km (S. W. Bougher, Pawlowski, et al., 2015). The M-GITM code was built from the terrestrial GITM framework (Ridley et al., 2006), now including Mars fundamental physical parameters, ion-neutral chemistry, key radiative processes, and solar (insolation/particle) and dynamical (wave/tidal) drivers unique to Mars (S. W. Bougher, Pawlowski, et al., 2015). Typically, the M-GITM nonhydrostatic model is setup to run with a $5^\circ \times 5^\circ$ latitude-longitude grid and a 2.5 km vertical resolution. Thus far, it has been used to interpret Mars upper atmosphere features observed from several MAVEN instruments (i.e., NGIMS, IUVS, and ACC measurements). This includes thermospheric temperatures and key densities throughout Mars seasons and SC24, lighter species density distributions (i.e., helium), mass density distributions during Deep Dip campaigns, thermospheric winds during short campaigns, and 2018 global dust storm impacts on the upper atmosphere (e.g., S. W. Bougher, Jakosky, et al., 2015; S. W. Bougher, Roeten, et al., 2017; Elrod et al., 2017, 2020; Gupta et al., 2021; Jain et al., 2020; Roeten et al., 2019; Zurek et al., 2017).

This ground to exosphere numerical model is constructed using existing parameterizations and physical formulations found in other modern GCMs (see details in S. W. Bougher, Pawlowski, et al. (2015)). For instance, a correlated-k radiative transfer code is used to compute LTE CO_2 15-micron cooling and near IR heating rates, both employed in the calculation of lower atmosphere temperatures (0–80 km) (Haberle et al., 1999). For the Mars upper atmosphere (~ 80 – 250 km), a fast and modern formulation for non-LTE CO_2 15-micron cooling is now used within the M-GITM code from González-Galindo et al. (2013) to accurately capture the CO_2 cooling rates (S. W. Bougher, Roeten, et al., 2017), especially near the mesopause and on the nightside.

In order to better understand Mars' lower and upper atmosphere coupling, an existing gravity wave momentum and energy deposition code (e.g., Medvedev et al., 2015; Yiğit et al., 2008) has been incorporated, implemented, and fully tested within the M-GITM framework (Roeten et al., 2022). It is a spectral nonlinear scheme for the treatment of nonorographic gravity waves that reach the thermosphere from their launching point at the top of the planetary boundary layer. This scheme is one of the most recent parameterizations appropriate for gravity waves that propagate to thermospheric altitudes. It accounts for wave dissipation due to molecular viscosity in the upper atmosphere, molecular thermal conduction, radiative damping, and breaking-saturation (Roeten et al., 2022). This gravity wave scheme is now utilized when conducting new M-GITM simulations described in this paper. Standard gravity model parameters utilized in M-GITM are discussed in detail in Roeten et al. (2022). The most important thermospheric impacts resulting from application of this new GW scheme are twofold: (a) the reduction of global winds by nearly a factor of two for all Mars seasons and (b) the cooling of temperatures above ~ 100 km at all latitudes, with most pronounced cooling at high/polar latitudes. It is important to emphasize that modern M-GITM simulations utilizing this new gravity wave formulation are able to capture these stated mean impacts on winds and temperatures, but not the individual impacts of gravity waves launched upward and breaking at thermospheric heights. Thus, M-GITM cannot capture any large stochastic variability that may be present in the NGIMS temperatures.

Inputs for two extreme cases are prescribed for new M-GITM simulations in this paper (see Section 2.2.3): (a) a solar maximum near perihelion case capturing Deep Dip 2 conditions (and beyond) early in the MAVEN mission (2015) and (b) a solar minimum aphelion case appropriate to post solar conjunction conditions in late 2019. These cases are specifically chosen to capture afternoon conditions ($SZA \leq 60^\circ$) for comparison to the extremes of the

NGIMS statistical Texo trend illustrated in Figure 3. In addition, the same dust scenario was purposefully chosen for all M-GITM simulations (globally uniform $\tau = 0.5$ optical opacity for averaged non dust storm conditions throughout the Mars year). This avoids the issue of the changing impact of dusty events on Texo values that is still a focus of intense research (e.g., Fang et al., 2020; Jain et al., 2020). Finally, the maximum eddy diffusion coefficient was set to be slightly larger (1.3 factor enhancement) for solar minimum conditions, in line with weakened solar control of the thermosphere and stronger wave variability overall (Jain et al., 2021).

4. Results

4.1. Analysis of NGIMS Derived Texo

First, this section provides a broad statistical picture of Texo variations over SC24. Then it shows both seasonal and SZA dependencies. Ultimately, an empirical expression for the NGIMS $\Delta\text{Texo}/\Delta\text{EUV}$ sensitivity is computed. This sensitivity will be used to detrend the entire Texo data set, revealing SZA and Ls (seasonal) dependencies. Finally, a comparison of both MAVEN and MGS trends and sensitivities is made.

The question of using a linear (least squares) fit to capture the Mars solar cycle/seasonal trend of dayside Texo is important to address because the NGIMS scale height temperature data has a rather large scatter as shown in Figure 1. The adequacy and uniqueness of a computed linear fit for such a large scatter would be legitimate for a data distribution that is both homogenous and representative (enough data points to capture the full distribution). Thus, a robust NGIMS linear fit must meet two criteria. First, the data must follow the same distribution along the independent variable domain (EUV radiation in Figure 1 and SZA in Figure 2). If the data distribution looks the same for any subsample along the X direction then the data has a homogenous distribution. In that case, one can apply the classical statistical metrics such as mean, variance, etc. Second, if an adequate sample size is available for the distribution (i.e., if the sample is large enough), then the statistical metrics are unique. In this regard, the NGIMS scale height temperatures were analyzed and found to be statistically homogeneous along the EUV and SZA scales (see Figure S1). In both cases, the data obey a normal-like distribution with varying mean but constant variance. Statistical homogeneity and the large size of the data set allow us to apply a linear regression and moving averaging in our analysis.

Figure 1 shows NGIMS scale height derived exospheric temperatures (Texo) as a function of the Lyman- α index (measured at Mars) over most of the MAVEN mission (i.e., solar cycle #24). Sampling is restricted to SZA = 0°–60° and LT = 06:00–18:00 and spans ~12,000 orbits. Ls (season) is color coded as indicated by the color bar. A linear regression (least squares) empirical trend in these Texo values is computed and superimposed (black line) spanning the 2.0–4.5 mW/m² solar fluxes. The dashed curves represent the uncertainty of the NGIMS linear fit due to the errors in the scale height Texo values themselves. These errors are larger for solar high conditions. It is noteworthy that a large variation in extracted Texo values about the linear trend is observed at all seasons. This variability seen in the reconstructed temperatures is mainly due to the presence of GWs, and this is fully consistent with the uncertainty of the scale height extraction fits and associated temperatures (approximately ± 50 K) as shown in Figure 1. This gravity wave variation is stochastic in nature.

In addition, an empirical trend using MGS Texo values (Forbes et al., 2008) and a similar (Mars based) Lyman- α index (now for SC23) is shown (red curve) for comparison to MAVEN. This MGS linear regression is calculated using an excellent database of Lyman- α fluxes obtained at Earth (LISIRD) (Machol et al., 2019), scaled by the Mars heliocentric distance, and rotated to Mars for this MGS sampling period (1 February 1999 to 7 July 2005). Corresponding Texo values are obtained from the MGS POD technique used to extract densities and derive Texo values at ~390 km (Forbes et al., 2008). Endpoints near aphelion/solar minimum and perihelion/solar maximum conditions were utilized in computing this MGS regression (2.0–4.5 mWm⁻², the same as used for the NGIMS data set). The resulting $\Delta\text{Texo}/\Delta\text{EUV}$ sensitivities that emerge from these two linear regressions are as follows: $\sim 45 \pm 1.0$ and $\sim 38 \pm 3.4$ K m² mW⁻¹ for MGS and MAVEN, respectively. It is notable that a small temperature offset exists between these MAVEN and MGS trend curves. This small discrepancy between their computed sensitivities ($\Delta\text{Texo}/\Delta\text{EUV}$) suggests differences in heat balance physics in the Mars dayside thermosphere during SC23 and SC24 (i.e., MGS vs. MAVEN sampling periods). The major difference in the two data sets is that the EUV heating is likely larger as MGS mean Texo values approach ~300 K, while those for MAVEN approach ~260 K. This 40 K difference is due to the fact that SC23 period is more robust (active) than SC24. See a summary of solar cycle activity in Table 2.

Table 2

Solar Cycle 21–24 Indices at Earth for Comparison of Proxies Indicating Changing Solar EUV-UV Fluxes Over Time

Solar cycle #	Sunspot #	F10.7-cm	Lyman- α
21 (PVO)	184	229	9.82
22 (PVO)	218	247	10.3
23 (MGS)	175	236	9.94
24 (MVN)	94	154	8.3

Note. Taken from monthly averaged peak values archived in the LISIRD database at LASP. PVO refers to Pioneer Venus Orbiter sampling, 1979–1992. MGS refers to Mars Global Surveyor sampling, 1999–2005. MVN coincides with the first 3-Mars years of MAVEN sampling, 2014–2019. Units of Lyman- α fluxes are mW m^{-2} .

The EUVM solar occultation (terminator) derived ($\Delta\text{Texo}/\Delta\text{EUV}$) sensitivities in Table 3 are about a factor of 1.3–1.5 smaller than those corresponding ones for MGS and MAVEN (E. M. Thiemann et al., 2018). These tabulated EUVM values are corrected for the Lyman- α index instead of the original integrated EUV flux index (0–94-nm). This Table 3 comparison suggests that dawn and dusk terminator heat balances may be different from those at low SZAs explored in this paper. This is to be expected since the solar EUV control of the high SZA (terminator) region is likely weaker than that at low SZAs (0° – 60°). In fact, dynamical influences may also play a role in terminator heat balances (Pilinski et al., 2018).

Figure 2 presents NGIMS scale height detrended temperatures versus SZA over the same $\sim 12,000$ orbits of the MAVEN mission. Both morning (LT = 06:00–12:00) and afternoon (LT = 12:00–18:00) sector temperatures (SZA = 0° – 90°) are combined and colored coded to illustrate Ls (seasonal) behavior. The solar cycle trend line from Figure 1 is removed, yielding this

detrended exospheric temperature behavior as a function of SZA. This new detrended curve is further characterized using a 20° moving average (black curve). It is evident that a $\sim 25^\circ\text{K}$ drop in running mean exospheric temperature over the dayside (from SZA = 0° to the terminators) is present in this NGIMS data set. Furthermore, two SZA bins are selected to highlight SZA behavior: 0° – 60° and 60° – 90° . For SZA = 0° – 60° , the temperature variations are weakest (± 5 – 10 K) about the zero line. Most importantly, the large scatter in temperatures seen in Figure 1 still exists in the NGIMS scale height temperature data in Figure 2, once the solar cycle linear trend is extracted and temperatures are organized in SZA. This remaining scatter (up to ± 50 K FWHM) is similar to the typical NGIMS scale height temperature uncertainty of ± 50 K over 0° – 60° SZA outlined above in Table 1. This variability still seen in both EUV and SZA sorted data sets is mainly due to the presence of gravity waves, which are stochastic in nature. The difference between afternoon (LT = 12:00–18:00) and morning (LT = 06:00–12:00) sensitivities is given in Figure 3 (see discussion below).

Figure 2 also shows that the variability of individual orbit Texo values about the 20° moving average increases as SZA = 90° is approached. This clearly reveals that the smallest variations are realized at low SZA (0° – 60°), presumably where the solar EUV heating maintaining temperatures is the strongest. Once again, as the terminator is approached, other factors play a larger role in the control of topside thermospheric temperatures (i.e., global winds, gravity, and planetary waves, etc.). See Pilinski et al. (2018).

4.2. Comparison of the Two NGIMS Texo Methods of Extraction

NGIMS dayside exospheric temperatures are plotted versus the EUVM Lyman- α index in Figure 3 for eight-specified periods (campaigns) over the MAVEN mission for SZA = 0° – 60° (see Section 2.2.2 and Table 1). The hydrostatic integration method is applied here for Texo extraction over CO_2 densities spanning 10^8 – 10^7 cm^{-3} .

Mean Texo values (black dots) plus $1\text{-}\sigma$ variations (vertical bars) are illustrated for these eight-campaigns. In addition, the NGIMS scale height temperature trend is extracted (dashed curve) from Figure 1 (LT = 06:00–18:00) and contrasted (solid curve) with a second trend (LT = 12:00–18:00) for afternoon SZA conditions only. Finally, a third curve is added to illustrate morning (LT = 06:00–12:00) temperatures, now enabling comparison of afternoon versus morning temperature variations.

This figure illustrates that exospheric temperatures extracted by the hydrostatic integration method correspond closely to the linear trend derived from the scale height method (afternoon conditions) for extreme solar minimum to solar maximum conditions. Table 1 also specifically compares eight-period values of scale height temperatures and corresponding hydrostatic integration method derived values, revealing agreement within about ± 6 K throughout SC24. Notably, Texo values for periods #2 and #3 (i.e., from both techniques) show departures from the linear trend. Period #3 may be associated with nonsolar forcing during the decay phase of the regional

Table 3

Mars ΔTexo Versus ΔEUV Sensitivities From Mars Global Surveyor and MAVEN Sampling for SC#23 and SC#24, Respectively

Mission (instrument)	Solar cycle (MY)	$\Delta\text{Texo}/\Delta\text{EUV}$
MGS (POD)	23 (MY24–27)	45.0 ± 1.0
MAVEN (NGIMS)	24–25 (MY32–35)	38.0 ± 3.4
MAVEN (EUVM-SO)	24–25 (MY33–35)	30.0 ± 1.4
PVO (ONMS and OUVS)	21	17.5 ± 4.2

Note. The EUVM solar occultation sensitivity is converted from an integrated EUV flux index (0.94-nm) to the Lyman- α index and provides a mean value independent of dawn or dusk location. Finally, the PVO based Venus sensitivity is presented spanning SC#21. The \pm values indicate the uncertainty in the fits (computed slopes) due to uncertainty in the solar fluxes and/or the temperature measurements themselves.

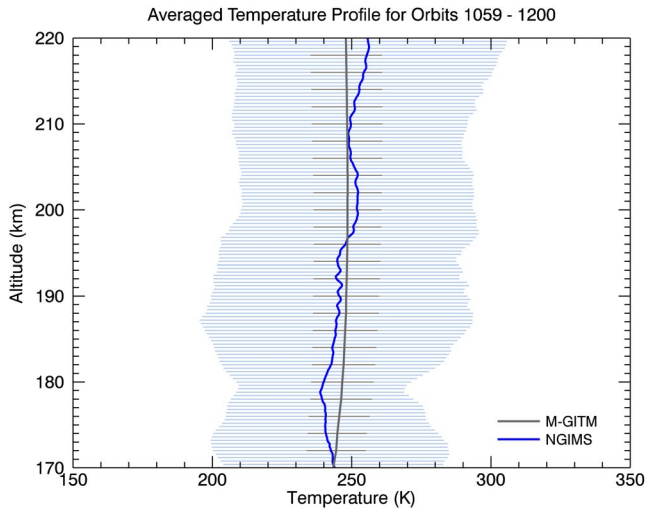


Figure 4. Neutral Gas and Ion Mass Spectrometer (NGIMS) and Mars Global Ionosphere-Thermosphere Model (M-GITM) dayside exospheric temperatures during the extended DD2 campaign are illustrated (see Table 1, first campaign). Mean NGIMS extracted temperatures (dark blue curve) are surrounded by cross-hatched (light blue) lines indicating 1σ orbital variations about the mean. A mean temperature of 252 ± 43.3 K is derived over 200–220 km. Corresponding M-GITM campaign mean temperatures (solid black curve) are presented for a standard gravity wave case. Here, the computed mean temperature (over 200–220 km) is 248 ± 12 K.

C-dust storm in MY33. Indeed, warmer thermosphere temperatures have been inferred during this dust event (e.g., Fang et al., 2020). Nevertheless, the overall strong linear trend suggests that the scale height method can be applied for general usage to extract Mars dayside exospheric temperatures. Moreover, the afternoon extracted temperatures are ~ 10 – 25 K warmer than those extracted over morning local times for Lyman- α fluxes less than 3.5 mW/m^2 . This trend of warmer afternoon topside thermosphere temperatures is observed in other MAVEN data sets (e.g., Jain et al., 2021) and predicted by pre-MAVEN model simulations (e.g., S. W. Bougher, Pawlowski, et al., 2015).

4.3. Study of Two Temperature Extreme Cases: DD2E Plus PC19 Periods

It is instructive to investigate the performance of the M-GITM code for capturing the MAVEN solar cycle trend of dayside Texo illustrated in Figure 3. The goal is to determine the underlying heat balances that are required to reproduce observed Texo variations over the solar cycle. We have selected two extreme cases for conducting new M-GITM simulations in this paper. These cases are found in Table 1 as follows: (Period 1) a solar maximum/near-perihelion case capturing extended Deep Dip 2 conditions early in the MAVEN mission (2015) and (Period 8) a solar minimum/aphelion case appropriate to post solar conjunction conditions (late 2019). M-GITM outputs from these two cases are extracted along the NGIMS sampling trajectories appropriate to deep dayside conditions ($\text{SZA} \leq 40^\circ$). Interpolation is conducted from the model's coarse nominal grid to the location of each NGIMS sampling location. This is in effect a flythrough of the M-GITM model output along the NGIMS orbit trajectory. Mean temperatures and their 1σ orbital variations throughout the campaign about the mean are plotted in Figure 3 for both the NGIMS and M-GITM profiles.

It is noteworthy that standard Mars gravity wave parameters are used for the momentum and energy deposition code that is incorporated within these M-GITM simulations and utilized for these two extreme cases (Roeten et al., 2022). The corresponding momentum deposition was previously found to impact the ~ 90 – 160 km region of the simulated thermosphere, thereby slowing winds by up to a factor of 2, reducing the day-to-night transport of atomic O (leaving more on the Mars dayside) and ultimately providing enhanced CO_2 $15\text{-}\mu\text{m}$ cooling in the lower dayside thermosphere (Roeten et al., 2022). See Section 3.

Figure 4 shows both mean DD2 temperature profiles over 170–220 km, demonstrating that the simulated (M-GITM) and measured (NGIMS) mean profiles match very well. The model 1σ values in Figure 4 (black horizontal bars) represent the dispersion of the Texo values about the computed mean. Similarly, the blue cross hatched bars represent the 1σ variability of the NGIMS (hydrostatic method) derived Texo values about the mean. The measured exosphere temperature of 252 ± 43.3 K is quite close to the corresponding computed mean temperature of 248 ± 12 K over 180–200 km. Notice that the real atmosphere orbital 1σ temperature variability is much larger (factor of ~ 3.5) than that calculated by M-GITM. This is largely because M-GITM is a climate model that does not capture all the gravity, planetary, and tidal waves that contribute to orbit-to-orbit variability that is present in the real atmosphere. Specifically, modern M-GITM simulations utilizing the new gravity wave formulation (see Section 3) are able to capture the mean impacts on winds and temperatures but not the individual impacts of gravity waves launched upward and breaking at thermospheric heights. M-GITM cannot capture this large stochastic variability due to gravity waves observed in NGIMS Texo values illustrated in Figure 4. However, the variability that is captured by M-GITM includes changes in the evolving orbital trajectories over ~ 140 orbits, plus the changing solar fluxes (EUVM provided) that are used to drive the EUV heating simulated by M-GITM.

Figure 5 illustrates the heat balance terms that maintain the simulated DD2 extended mean temperature profile of Figure 4. The altitude scale covers 135–220 km in order to capture the CO_2 $15\text{-}\mu\text{m}$ cooling layer that peaks

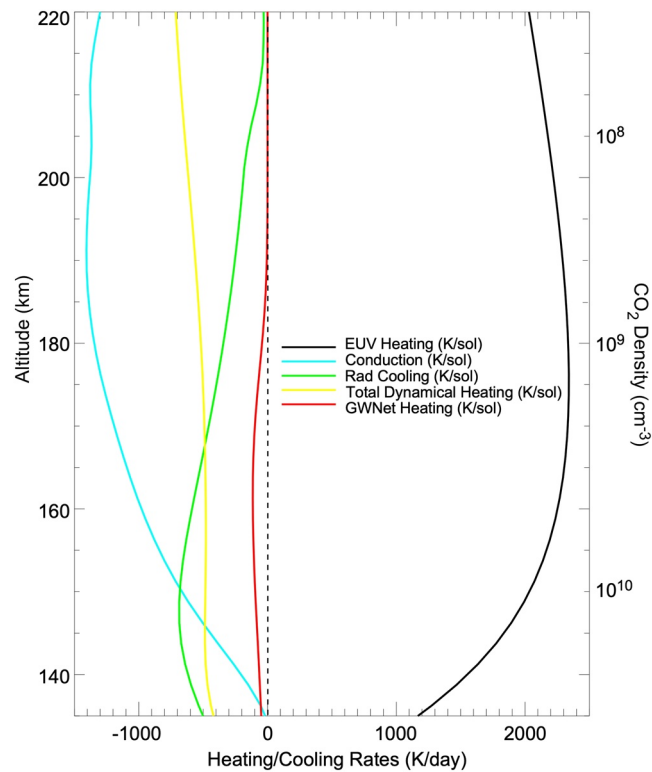


Figure 5. Mars Global Ionosphere-Thermosphere Model extracted heat balance terms are provided for the DD2 extended campaign, corresponding to the mean computed temperature profile from Figure 4. This is the extreme case where solar maximum—post perihelion conditions prevailed. The averaged EUV solar forcing over this DD2 extended campaign is used to select a corresponding specific orbit to yield a set of campaign averaged heat balance terms for plotting. Altitudes span ~ 135 – 220 km (above the near IR heating layer). Terms include EUV heating (EUVHeating), CO_2 15- μm cooling (Radcooling), molecular thermal conduction (Conduction), net dynamical heating (TotalDynamicalHeating), and gravity wave net heating (GWNetHeating). Units are K/day (Earth day).

near 150 km. Notice that molecular thermal conduction largely balances EUV heating above ~ 150 km (approximately where the CO_2 density is 10^{10} cm^{-3}), while CO_2 15- μm cooling plus net dynamical cooling (i.e., adiabatic cooling due to upwelling winds) together dominate cooling below 150 km. It is also evident that net gravity wave cooling (i.e., owing to gravity energy deposition effects) approaches ~ 100 K/day near 160 km but is otherwise negligible in its net impact on the heat budget. Thus, for solar maximum conditions, molecular conduction is not the dominant cooling mechanism at all altitudes. Rather, the emission of CO_2 15- μm photons to space provides thermosphere cooling that plays an important role in radiating away the heat conducted downward to lower thermospheric altitudes. Will this modest CO_2 15- μm cooling effect also hold for solar minimum/aphelion conditions when thermospheric temperatures are cooler? PC19 simulations below will answer this question.

Figure 6 illustrates both mean PC19 temperature profiles over 170–220 km, showing that the simulated (M-GITM) and measured (NGIMS) profiles match reasonably well. Nevertheless, the measured exosphere temperature of 185 ± 40.9 K is a bit cooler than the corresponding computed mean temperature of 193.7 ± 4.6 K over 180–200 km. In addition, there is a slight cooling of the computed mean temperature profile with increasing altitude that corresponds to dynamical cooling (upwelling flow) that contributes near 200 km (see Figure 7). More importantly, the real atmosphere orbit-to-orbit 1σ temperature variability is much larger (factor of ~ 9) than that calculated by M-GITM. This discrepancy is even larger than for DD2 conditions (see Figure 4). Indeed, the solar forcing (EUV heating) for PC19 conditions is much weaker than for DD2 conditions (see Figure 5). This implies that the impacts of upward propagating waves (i.e., tides, planetary, and gravity waves) will be larger for PC19 than for DD2 conditions. For instance, the larger impact of tidal forcing at lower thermospheric altitudes during solar minimum conditions is clearly observed using IUVS measurements (see Jain et al. (2021) and Thaller et al. (2021)). These NGIMS solar minimum temperatures (and their 1σ temperature variability) provide

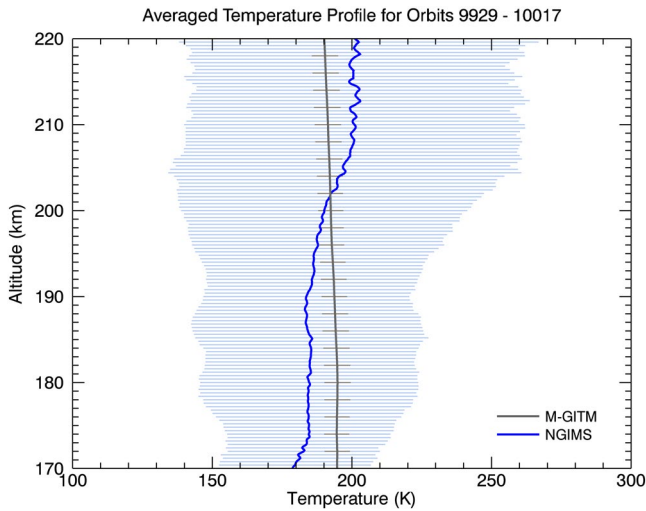


Figure 6. Neutral Gas and Ion Mass Spectrometer (NGIMS) and Mars Global Ionosphere-Thermosphere Model (M-GITM) dayside exospheric temperatures during the extended PC19 campaign are illustrated (see Table 1, last campaign). Mean NGIMS extracted temperatures (dark blue curve) are surrounded by cross-hatched (light blue) lines indicating 1σ orbital variations about the mean. A mean temperature of 185 ± 40.9 K is derived over 180–200 km. Corresponding M-GITM campaign mean temperatures (solid black curve) are presented for a standard gravity wave case. Here, the computed mean temperature (over 180–200 km) is 193.7 ± 4.6 K.

further support for this claim of stronger wave activity impacts during solar minimum conditions.

Figure 7 illustrates the heat balance terms that maintain the simulated PC19 extended mean temperature profile of Figure 6. Notice that molecular thermal conduction largely balances EUV heating over nearly the entire domain (~ 135 – 210 km), while dynamical cooling plays a stronger role at higher altitudes. Notably, CO_2 15- μm cooling is not important anywhere in this altitude region. It is also evident that net gravity wave cooling (i.e., owing to gravity energy deposition effects) approaches ~ 300 K/day over ~ 150 – 165 km. This value is larger than for DD2 conditions, indicating that GW effects are more pronounced in the solar minimum thermosphere than for solar maximum. Nevertheless, the net impact on the overall heat budget is still small. Thus, for solar minimum conditions, molecular conduction is mostly dominant as a cooling mechanism at altitudes below ~ 205 km, while CO_2 15- μm cooling is weak. This is much different than computed for solar maximum conditions as seen in Figure 5. Why is this so?

Figure 8 shows NGIMS extracted profiles of O abundances (i.e., O/CO_2 ratios) for both DD2 and DD8 Deep Dip campaign periods (see Table 1). In addition, 1σ orbital variations about the mean O/CO_2 profiles are provided as cross-hatched lines. It is noted that DD8 is used as a proxy for PC19, since derived exospheric temperatures are very similar (see Table 1), and DD8 extends to lower periapsis altitudes where O abundances are available for study. These are new MAVEN measurements spanning the solar cycle that help to constrain the CO_2 cooling rates at Mars for the first time.

The comparison here between DD2 and DD8 abundances (over solar high to solar low conditions) shows that at the common highest CO_2 density of $\sim 10^{10} \text{ cm}^{-3}$, the O/CO_2 ratios are much the same (~ 0.03 – 0.035). This corresponds to ~ 150 and ~ 135 km for DD2 and DD8 sampling, respectively. In addition, this implies that the collision of O atoms with CO_2 molecules for enhancing Mars CO_2 15- μm cooling is similarly efficient during both solar low and solar high conditions in the lower thermosphere (Huestis et al., 2008). Nevertheless, the magnitude of CO_2 15- μm cooling is greatly reduced for solar minimum conditions (see Figure 7). This is due to the much weaker solar EUV forcing and resulting cooler temperatures at these PC19 thermospheric altitudes. Recall that CO_2 cooling is highly nonlinearly temperature dependent (S. W. Bougher et al., 1994; Huestis et al., 2008).

Table 4 provides a detailed comparison between NGIMS (measured) and M-GITM (computed) O/CO_2 ratios for these DD2 and DD8 sampling periods. These Deep Dip campaign values are displayed at a constant CO_2 density (where CO_2 15- μm cooling peaks) to best illustrate variations that are driven by in situ thermospheric drivers and not hydrostatic variations linked to the changing seasons. Results show a reasonable comparison for DD2 conditions in the lower thermosphere (equivalent to ~ 145 km) where CO_2 cooling dominates. Likewise, a good comparison for DD8 conditions also appears in the lower thermosphere (equivalent to ~ 135 – 138 km) where CO_2 cooling peaks but does not dominate the heat budget. This reasonable data-model match of O/CO_2 ratios in the lower thermosphere supports our finding that CO_2 15- μm cooling does play a modest role in regulating the heat budget in the Mars thermosphere for solar high conditions. However, CO_2 cooling does not play any significant role in balancing EUV heating for solar low conditions at Mars. This CO_2 thermostatic cooling effect is much weaker at Mars than for Venus (see Section 5).

5. Broader Implications: Comparative Planetology

Previously, the role of CO_2 15- μm cooling was found to be substantially different for the simulated 3-D model heat budgets of the upper atmospheres of Venus, Earth, and Mars (e.g., S. Bougher et al., 1999; S. W. Bougher et al., 1994; S. W. Bougher et al., 1999, 2000; Huestis et al., 2008). In light of the new findings from MAVEN for Mars (above), how does the new MAVEN derived dayside temperature sensitivity ($\Delta\text{Texo}/\Delta\text{EUV}$) compare to that at Venus, another CO_2 dominated planet? This sensitivity comparison can now be made using measured

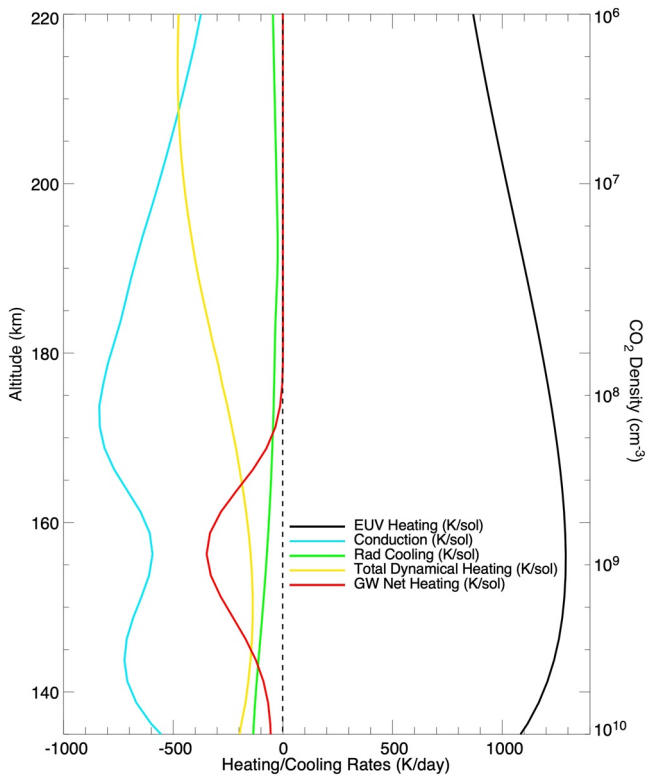


Figure 7. Mars Global Ionosphere-Thermosphere Model extracted heat balances terms are provided for the PC19 campaign, corresponding to the mean computed temperature profile from Figure 6. This is the extreme case where solar minimum—aphelion conditions prevailed. Altitudes span ~ 130 – 220 km (above the near IR heating layer). Notice the revised CO_2 density vertical scale here, in contrast to that for DD2E in Figure 5. Terms include EUV heating (EUVHeating), CO_2 15- μm cooling (Radcooling), molecular thermal conduction (Conduction), net dynamical heating (TotalDynamicalHeating), and gravity wave net heating (GWNetHeating). Units are K/day (Earth day).

solar Lyman- α fluxes obtained in situ at Venus and Mars for the first time. It is also important to constrain the relative role of O enhanced CO_2 15- μm cooling at Mars in the context of its much different (unique) role at Venus, especially that measured O abundances in the dayside thermospheres of both planets are now available.

The photo-electron current (Ipe) from the PV OETP (Brace et al., 1988), when measured outside the atmosphere, was found to be generated by the solar EUV-UV flux spanning wavelengths ranging from about 55.0 to 130.0-nm. Approximately 51% of the spectral contribution for Ipe comes from Lyman- α . This Ipe was calibrated to total solar EUV flux and Lyman- α flux by Brace et al. (1988). Correspondingly, one estimate of the dayside exospheric temperature over the solar cycle was made by fitting 39-orbits of PV-Orbiter UVS (Orbiter Ultraviolet Spectrometer [OUVS]) Lyman- α limb profiles with a model for three-hydrogen components, one of which was a cold component (thermal hydrogen) whose temperature was adjusted to provide a best fit. The trend of increasing temperature with the advance of the solar cycle (minimum to maximum) was clearly derived, with a relative temperature change of about 80 K. Alternatively, empirical models and various data sets (Fox & Bougher, 1991; Kasprzak et al., 1997) estimate a relative temperature change up to 70 K over the solar cycle. Thus, we have a measure of dayside exospheric temperature variation at Venus, spanning solar cycle #21 (SC21), that can be linearly fit to the changing Lyman- α flux measured at Venus.

The resulting SC21 Venus dayside temperature sensitivity ($\Delta T_{\text{exo}}/\Delta \text{EUV}$) is about $\sim 17.5 \pm 4.2 \text{ K m}^2 \text{ mW}^{-1}$. This Venus sensitivity approaches $\sim 40\%$ – 50% of that derived from MAVEN NGIMS and MGS POD values (see Table 3). This is a revised calculation for Venus sensitivity based upon Lyman- α fluxes received at the planet. This sensitivity comparison between Venus and Mars now approaches a factor of 2–3 enhancement for Mars, in contrast to a factor of 5 computed previously using F10.7-cm fluxes as the solar index (Forbes et al., 2008). Why are these sensitivities so different for Venus and Mars even though both are CO_2 dominated planets?

S. W. Bougher et al. (1999) and S. W. Bougher et al. (2008) make use of the Venus Thermospheric General Circulation Model (VTGCM) to compute the solar minimum to maximum dayside temperature profiles and correctly capture the measured exospheric temperature changes over the solar cycle. The underlying thermal balances suggest that CO_2 15- μm emission is the dominant cooling mechanism that balances the peak of the EUV heating layer near ~ 150 km (approximately where the CO_2 density is $\sim 10^{10} \text{ cm}^{-3}$). Furthermore, this strong cooling is regulated by enhanced O/ CO_2 ratios measured at solar maximum (SC21) by the ONMS instrument ($\sim 65\%$) which are much larger than corresponding O/ CO_2 ratios at Mars (3%–5%) at the same constant CO_2 density level. In essence, a CO_2 cooling thermostat is in operation at Venus that is very efficient at regulating dayside temperatures over the solar cycle. By contrast, Mars O/ CO_2 ratios are much smaller and the O- CO_2 enhancement of CO_2 15- μm cooling is much weaker than at Venus. Instead, molecular thermal conduction is simulated to balance the bulk of the dayside EUV heating at Mars.

6. Summary and Conclusions

MAVEN NGIMS measured dayside exospheric temperatures ($\text{SZ} \leq 60^\circ$) are shown to vary by up to ~ 80 K (~ 180 – 260 K) over solar cycle #24 (SC24). This linear least squares empirical trend corresponds to an EUV sensitivity ($\Delta T_{\text{exo}}/\Delta \text{EUV}$) of $\sim 38 \text{ K m}^2 \text{ mW}^{-1}$. Lyman- α fluxes are used in this calculation for computing the EUV sensitivity.

This MAVEN dayside sensitivity ($\Delta T_{\text{exo}}/\Delta \text{EUV}$) is slightly smaller than that derived from MGS solar cycle #23 (SC23) measurements ($45 \text{ K m}^2 \text{ mW}^{-1}$). The main difference between the two is that SC23 is much stronger

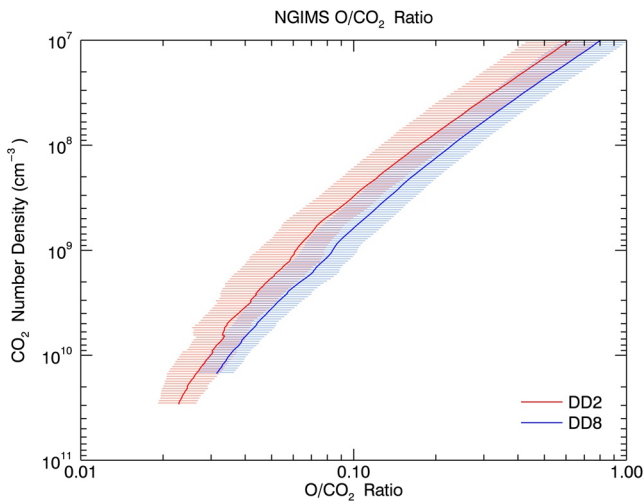


Figure 8. Neutral Gas and Ion Mass Spectrometer (NGIMS) O abundance profiles for both DD2 and DD8 conditions. Orbit to orbit 1- σ variations about the mean are also plotted as cross-hatched lines. Plotted vertical coordinate is CO_2 density (cm^{-3}). There is a close match of Mars Global Ionosphere-Thermosphere Model (M-GITM) and NGIMS O/CO_2 ratios about 1-scale height above the peak CO_2 cooling layer but larger ratios are computed by M-GITM than observed at higher altitudes, where CO_2 cooling has negligible impact on the heat budget for solar high and low conditions.

these NGIMS studies (i.e., Lyman- α fluxes less than 3.5 mW/m^2) constrained similar seasonal variations to be 185–230 K. Finally, IUVS studies concluded that Texo values are highly variable with respect to local time when solar forcing, Mars-sun distance and dust effects are removed (Jain et al., 2021). Similar constraints are found in NGIMS data for the extreme aphelion/solar low conditions (see Figure 3). Here morning and afternoon Texo values vary by up to $\sim 30 \text{ K}$ (for $\text{SZA} \leq 60^\circ$). This value is comparable to $\sim 50 \text{ K}$ for a wider range ($\text{SZA} \leq 85^\circ$) of IUVS dayside conditions. In short, for these three dayside thermospheric features, IUVS and NGIMS measurements for Texo are complementary and generally consistent.

Mars Global Ionosphere-Thermosphere Model has been used to simulate extreme MAVEN cases (DD2E and PC19), corresponding to solar high and low conditions, respectively. Mean temperature profiles and corresponding heat balances are computed for interpreting the extreme dayside exospheric temperatures shown in Figure 3. It is shown that the primary dayside EUV heating is largely balanced by molecular thermal conduction throughout SC24. However, CO_2 15- μm cooling does play a modest role in regulating the heat budget in the Mars thermosphere for solar high conditions. This occurs as dayside thermal conduction transfers EUV heat to lower altitudes below $\sim 150 \text{ km}$ (i.e., for CO_2 densities higher than 10^{10} cm^{-3}) where 15- μm emission largely provides NLTE cooling to space. CO_2 15- μm cooling does not play any appreciable role for solar low conditions. The global winds also contribute mildly to dayside cooling at low SZA, owing in part to adiabatic cooling due to upwelling winds and also horizontal transport from divergent flow.

From a comparative planetology perspective, the MAVEN newly derived dayside temperature sensitivity ($\Delta\text{Texo}/\Delta\text{EUV}$) can be contrasted to that computed at Venus from measurements obtained during the PV (PVO) mission. Furthermore, CO_2 cooling rates can be constrained for both planets now that measured O abundances in their dayside thermospheres are now available for the first time. These solar cycle #21 (SC21) measurements make use of both PV-OUVS exospheric temperature measurements (~ 250 – 330 K) and PV-ONMS measurements as well as in situ solar Lyman- α fluxes derived from the photo-electron current of the PV-Orbiter Electron Temperature Probe (OETP) instrument. The resulting SC21 Venus dayside temperature

Table 4
Comparison Between Neutral Gas and Ion Mass Spectrometer (Measured) and Mars Global Ionosphere-Thermosphere Model (Computed) O/CO_2 Ratios for DD2 and DD8 Sampling Periods in the Lower Thermosphere

CO_2 Density (cm^{-3}) (altitude)	Period	NGIMS	M-GITM
10^{10} ($\sim 150 \text{ km}$)	DD2 (only)	0.032	0.050
10^{10} ($\sim 135 \text{ km}$)	DD8	0.035	0.040

sensitivity ($\Delta T_{\text{exo}}/\Delta E_{\text{UV}}$) is about $\sim 17.5 \text{ K m}^2 \text{ mW}^{-1}$, which is about $\sim 40\%$ – 50% of that derived from MAVEN NGIMS (SC24) and MGS (SC23) values. This sensitivity comparison between Venus and Mars now approaches a factor of 2–3 enhancement for Mars, in contrast to a factor of 5 computed previously using F10.7-cm fluxes as the solar index (Forbes et al., 2008). VTGCM model simulations suggest that the underlying thermal balances determine that CO_2 15- μm emission is the dominant cooling mechanism that balances the bulk of the EUV heating in the Venus thermosphere. This is in stark contrast to Mars, for which molecular thermal conduction is instead dominant and CO_2 cooling is much weaker. This explains why the temperature-EUV sensitivity ($\Delta T_{\text{exo}}/\Delta E_{\text{UV}}$) is larger for Mars than Venus. Furthermore, it yields a larger exospheric temperature variation over a robust solar cycle for Mars (~ 180 – 300) than for Venus (~ 250 – 330 K).

These conclusions serve to interpret the MAVEN NGIMS measurements in the context of previous Mars measurements from MGS and in light of other PV measurements. Dayside exospheric temperature variations for Venus and Mars are indeed controlled by their respective underlying thermal balances. However, the role of CO_2 15- μm cooling for each planet's thermosphere is much different, being much stronger for Venus than for Mars.

Data Availability Statement

The NGIMS densities and scale heights used for this study are available on the PDS (Benna & Lyness, 2014). These data sets are also discussed in the NGIMS Software Interface Specification (Benna & Elrod, 2020). The scale height temperatures are an NGIMS Level 3, Version 6, Revision 1 data product while the neutral densities are an NGIMS Level 2, Version 8, Revision 1 data product. In addition, solar fluxes used for data analysis and model simulations are taken from the MAVEN/EUVM FISM-M empirical model corresponding to a Level 3, Version 14, Revision 3 data product on the PDS (Eparvier, 2022). Finally, data cubes and orbital tables containing M-GITM computed outputs from simulations used in this study are available on the University of Michigan Deep Blue Data repository (Bougher & Roeten, 2022).

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References

- Benna, M., & Elrod, M. (2020). MAVEN neutral gas and ion mass spectrometer (NGIMS) PDS software Interface (SIS), version 1.12, DOC number MAVEN-NGIMS-SIS-0001.
- Benna, M., & Lyness, E. (2014). MAVEN neutral gas and ion mass spectrometer data [Dataset]. NASA Planetary Data System. <https://doi.org/10.17189/1518931>
- Benna, M., Mahaffy, P. R., Grebowsky, J. M., Fox, J. L., Yelle, R. V., & Jakosky, B. M. (2015). First measurements of composition and dynamics of the Martian ionosphere by MAVEN's neutral gas and ion mass spectrometer. *Geophysical Research Letters*, 42(21), 8958–8965. <https://doi.org/10.1002/2015GL066146>
- Bougher, S., Keating, G., Zurek, R., Murphy, J., Haberle, R., Hollingsworth, J., & Clancy, R. (1999). Mars Global Surveyor aerobraking: Atmospheric trends and model interpretation. *Advances in Space Research*, 23(11), 1887–1897. [https://doi.org/10.1016/S0273-1177\(99\)00272-0](https://doi.org/10.1016/S0273-1177(99)00272-0)
- Bougher, S. W., Blelly, P.-L., Combi, M., Fox, J. L., Mueller-Wodarg, I., Ridley, A., & Roble, R. G. (2008). Neutral upper atmosphere and ionosphere modeling. *Space Science Reviews*, 139(1–4), 107–141. <https://doi.org/10.1007/s11214-008-9401-9>
- Bougher, S. W., Brain, D. A., Fox, J. L., Gonzalez-Galindo, F., Simon-Wedlund, C., & Withers, P. G. (2017). Upper neutral atmosphere and ionosphere. In R. M. Haberle, R. T. Clancy, F. Forget, M. D. Smith, & R. W. Zurek (Eds.), *The atmosphere and climate of mars*. Cambridge University Press. <https://doi.org/10.1017/9781139060172.014>
- Bougher, S. W., Engel, S., Roble, R. G., & Foster, B. (1999). Comparative terrestrial planet thermospheres 2. Solar cycle variation of global structure and winds at equinox. *Journal of Geophysical Research*, 104I(E7), 16591–16611. <https://doi.org/10.1029/1998JE001019>
- Bougher, S. W., Engel, S., Roble, R. G., & Foster, B. (2000). Comparative terrestrial planet thermospheres 3. Solar cycle variation of global structure and winds at solstices. *Journal of Geophysical Research*, 105(E7), 17669–17692. <https://doi.org/10.1029/1999JE001232>
- Bougher, S. W., Hunten, D. M., & Roble, R. G. (1994). CO_2 cooling in terrestrial planet thermospheres. *Journal of Geophysical Research*, 99(E7), 14609–14622. <https://doi.org/10.1029/94JE01088>
- Bougher, S. W., Jakosky, B. M., Halekas, J., Grebowsky, J., Luhmann, J. G., Mahaffy, P., et al. (2015). Early MAVEN dip deep campaign reveals thermosphere and ionosphere variability. *Science*, 350(6261), 1–7. <https://doi.org/10.1126/science.aad0459>
- Bougher, S. W., McDunn, T. M., Zoldak, K. A., & Forbes, J. M. (2009). Solar cycle variability of Mars dayside exospheric temperatures: Model evaluation of underlying thermal balances. *Geophysical Research Letters*, 36(5), L05201. <https://doi.org/10.1029/2008GL036376>
- Bougher, S. W., Pawłowski, D., Bell, J. M., Nelli, S., McDunn, T., Murphy, J. R., et al. (2015). Mars Global Ionosphere-Thermosphere Model: Solar cycle, seasonal, and diurnal variations of the Mars upper atmosphere. *Journal of Geophysical Research: Planets*, 120(2), 311–342. <https://doi.org/10.1002/2014JE004715>
- Bougher, S. W., Roble, R. G., & Fuller-Rowell, T. (2002). Simulations of the upper atmospheres of the terrestrial planets. *Geophysical Monograph Series*, 130, 261–288. <https://doi.org/10.1029/130GM17>
- Bougher, S. W., & Roeten, K. J. (2022). Mars thermospheric temperature and density distributions: M-GITM simulated datasets for comparison to MAVEN/NGIMS measurements [Dataset]. University of Michigan - Deep Blue Data. <https://doi.org/10.7302/4rck-ds11>
- Bougher, S. W., Roeten, K. J., Olsen, K., Mahaffy, P. R., Benna, M., Elrod, M., et al. (2017). The structure and variability of Mars dayside thermosphere from MAVEN NGIMS and IUVS measurements: Seasonal and solar activity trends in scale heights and temperatures. *Journal of Geophysical Research: Space Physics*, 122(1), 1296–1313. <https://doi.org/10.1002/2016JA023454>

- Brace, L. H., Hoegy, W. R., & Theis, R. F. (1988). Solar EUV measurements at Venus based on photoelectron emission from the Pioneer Venus Langmuir probe. *Journal of Geophysical Research*, 93(A7), 7282–7296. <https://doi.org/10.1029/JA093iA07p07282>
- Elrod, M. K., Bougher, S., Bell, J., Mahaffy, P. R., Benna, M., Stone, S., et al. (2017). He bulge revealed: He and CO₂ diurnal and seasonal variations in the upper atmosphere of Mars as detected by MAVEN NGIMS. *Journal of Geophysical Research: Space Physics*, 122(2), 2564–2573. <https://doi.org/10.1002/2016JA023482>
- Elrod, M. K., Bougher, S. W., Roeten, K., Sharrar, R., & Murphy, J. (2020). Structural and compositional changes in the upper atmosphere related to the PEDE-2018 dust event on Mars as observed by MAVEN NGIMS. *Geophysical Research Letters*, 47(4), e2019GL084378. <https://doi.org/10.1029/2019GL084378>
- Eparvier, F. G. (2022). MAVEN EUV modeled data bundle [Dataset]. NASA Planetary Data System. <https://doi.org/10.17189/1414173>
- Fang, X., Bougher, S. W., Johnson, R. E., Ma, Y., Liemohn, M. W., & Wang, Y. (2013). The importance of pickup oxygen ion precipitation to the Mars upper atmosphere under extreme solar wind conditions. *Geophysical Research Letters*, 40(10), 1922–1927. <https://doi.org/10.1002/grl.50415>
- Fang, X., Ma, Y., Lee, Y., Bougher, S. W., Liu, G., Benna, M., et al. (2020). Mars dust storm effects in the ionosphere and magnetosphere and implications for atmospheric carbon loss. *Journal of Geophysical Research: Space Physics*, 125(3), e2019JA026838. <https://doi.org/10.1029/2019JA026838>
- Forbes, J. M., Lemoine, F. G., Bruinsma, S. L., Smith, M. D., & Zhang, X. (2008). Solar flux variability of Mars' exosphere densities and temperatures. *Geophysical Research Letters*, 35(1), L01201. <https://doi.org/10.1029/2007GL031904>
- Fox, J. L. (2004). Response of the Martian thermosphere/ionosphere to enhanced fluxes of solar soft X rays. *Journal of Geophysical Research*, 109(A11), A11310. <https://doi.org/10.1029/2004JA010380>
- Fox, J. L., & Bougher, S. W. (1991). Structure, luminosity, and dynamics of the Venus thermosphere. *Space Science Reviews*, 55, 357–489. https://doi.org/10.1007/978-94-011-3300-5_7
- González-Galindo, F., Chaufray, J.-Y., López-Valverde, M. A., Gilli, G., Forget, F., Leblanc, F., et al. (2013). 3D Martian ionosphere model: I. The photochemical ionosphere below 180 km. *Journal of Geophysical Research: Planets*, 118, 2105–2123. <https://doi.org/10.1002/jgre.20150>
- González-Galindo, F., Forget, F., López-Valverde, M., Angelats i Coll, M., & Millour, E. (2009). A ground-to-exosphere Martian general circulation model: I. Seasonal, diurnal, and solar cycle variation of thermospheric temperatures. *Journal of Geophysical Research*, 114(E4), E04001. <https://doi.org/10.1029/2008JE003246>
- González-Galindo, F., López-Valverde, M. A., Forget, F., García-Comas, M., Millour, E., & Montabone, L. (2015). Variability of the Martian thermosphere during eight Martian years as simulated by a ground-to-exosphere global circulation model. *Journal of Geophysical Research: Planets*, 120(11), 2020–2035. <https://doi.org/10.1002/2015JE004925>
- Gupta, N., Rao, N. V., Bougher, S. W., & Elrod, M. K. (2021). Latitudinal and seasonal asymmetries of the helium bulge in the Martian upper atmosphere. *Journal of Geophysical Research: Planets*, 126(10), e2021JE006976. <https://doi.org/10.1029/2021JE006976>
- Haberle, R. M., Joshi, M. M., Murphy, J. R., Barnes, J. R., Schofield, J. T., Wilson, G., et al. (1999). General circulation model simulations of the Mars Pathfinder atmospheric structure investigation/meteorology data. *Journal of Geophysical Research*, 104(E4), 8957–8974. <https://doi.org/10.1029/1998JE900040>
- Huestis, D. L., Bougher, S. W., Fox, J. L., Galand, M., Johnson, R. E., Moses, J. I., & Pickering, J. C. (2008). Cross sections and reaction rates for comparative planetary aeronomy. *Space Science Reviews*, 139(1–4), 63–105. <https://doi.org/10.1007/s11214-008-9383-7>
- Huestis, D. L., Slinger, T. G., Sharpee, B. D., & Fox, J. L. (2010). Chemical origins of the Mars ultraviolet dayglow. *Faraday Discussions*, 147, 307–322. <https://doi.org/10.1039/c003456h>
- Jain, S. K., Bougher, S. W., Deighan, J., Schneider, N. M., González Galindo, F., Stewart, A. I. F., et al. (2020). Martian thermospheric warming associated with the planet encircling dust event of 2018. *Geophysical Research Letters*, 47(3), e2019GL085302. <https://doi.org/10.1029/2019GL085302>
- Jain, S. K., Soto, S., Evans, J. S., Deighan, J., Schneider, N. M., & Bougher, S. W. (2021). Thermal structure of Mars' middle and upper atmospheres: Understanding the impacts of dynamics and of solar forcing. *Icarus*, 114703. <https://doi.org/10.1016/j.icarus.2021.114703>
- Jain, S. K., Stewart, A. I. F., Schneider, N. M., Deighan, J., Stiepen, A., Evans, J. S., et al. (2015). The structure and variability of Mars upper atmosphere as seen in MAVEN/IUVS dayglow observations. *Geophysical Research Letters*, 42(21), 9023–9030. <https://doi.org/10.1002/2015GL065419>
- Kasprzak, W. T., Keating, G. M., Hsu, N. C., Stewart, A. I. F., Coldwell, W. B., & Bougher, S. W. (1997). Solar cycle behavior of the thermosphere. In S. W. Bougher, D. Hunten, & R. J. Phillips (Eds.), *Venus II: Geology, geophysics, atmosphere and solar wind environment*. University of Arizona: University of Arizona Press.
- Keating, G. M., Bougher, S. W., Theriot, M. E., & Tolson, R. H. (2008). Properties of the Mars upper atmosphere derived from accelerometer measurements. In *Proceedings of the 37th Cospar scientific assembly*.
- Keating, G. M., Theriot, M. E., Tolson, R. H., Bougher, S. W., Forget, F., i Coll, M. A., & Forbes, J. M. (2003). Recent detection of winter polar warming in the Mars upper atmosphere. In *The third international mars polar science conference* (p. 8033).
- Krasnopolsky, V. A. (2010). Solar activity variations of thermospheric temperatures on Mars and a problem of CO in the lower atmosphere. *Icarus*, 207(2), 638–647. <https://doi.org/10.1016/j.icarus.2009.12.036>
- Leblanc, F., Chaufray, J. Y., Lilensten, J., Witasse, O., & Bertaux, J.-L. (2006). Martian dayglow as seen by the SPICAM UV spectrograph on Mars Express. *Journal of Geophysical Research*, 111(E9), E09S11. <https://doi.org/10.1029/2005JE002664>
- Lee, Y., Combi, M. R., Tenishev, V., Bougher, S. W., & Lillis, R. J. (2015). Hot oxygen corona at Mars and the photochemical escape of oxygen: Improved description of the thermosphere, ionosphere and exosphere. *Journal of Geophysical Research: Planets*, 120(11), 1880–1892. <https://doi.org/10.1002/2015JE004890>
- Machol, J., Snow, M., Woodraska, D., Woods, T., Viereck, R., & Coddington, O. (2019). An improved Lyman-alpha composite. *Earth and Space Science*, 6(12), 2263–2272. <https://doi.org/10.1029/2019EA000648>
- Mahaffy, P. R., Benna, M., Elrod, M., Yelle, R. V., Bougher, S. W., Stone, S. W., & Jakosky, B. M. (2015). Structure and composition of the neutral upper atmosphere of Mars from the MAVEN NGIMS investigation. *Geophysical Research Letters*, 42(21), 8951–8957. <https://doi.org/10.1002/2015GL065329>
- Medvedev, A. S., González-Galindo, F., Yiğit, E., Feofilov, A. G., Forget, F., & Hartogh, P. (2015). Cooling of the Martian thermosphere by CO₂ radiation and gravity waves: An intercomparison study with two general circulation models. *Journal of Geophysical Research: Planets*, 120(5), 913–927. <https://doi.org/10.1002/2015JE004802>
- Nier, A., & McElroy, M. B. (1977). Composition and structure of Mars' upper atmosphere: Results from the neutral mass spectrometers on Viking 1 and 2. *Journal of Geophysical Research*, 82(28), 4341–4349. <https://doi.org/10.1029/JS082i028p04341>
- Pilinski, M., Bougher, S. W., Greer, K., Thiemann, E., Andersson, L., Benna, M., & Elrod, M. (2018). First evidence of persistent night-time temperature structures in the neutral thermosphere of Mars. *Geophysical Research Letters*, 45(17), 8819–8825. <https://doi.org/10.1029/2018GL078761>

- Ridley, A., Deng, Y., & Töth, G. (2006). The global ionosphere-thermosphere model. *Journal of Atmospheric and Solar-Terrestrial Physics*, 68(8), 839–864. <https://doi.org/10.1016/j.jastp.2006.01.008>
- Roeten, K. J., Bougher, S. W., Benna, M., Elrod, M., Medvedev, A., & Yigit, E. (2022). Impacts of gravity waves in the Martian thermosphere using M-GITM coupled with a whole atmosphere gravity wave scheme. *Journal of Geophysical Research: Planets*, 127(12). e2022JE007477. <https://doi.org/10.1029/2022JE007477>
- Roeten, K. J., Bougher, S. W., Benna, M., Mahaffy, P. R., Lee, Y., Pawlowski, D., et al. (2019). MAVEN/NGIMS thermospheric neutral wind observations: Interpretation using the M-GITM general circulation model. *Journal of Geophysical Research: Planets*, 124(12), 3283–3303. <https://doi.org/10.1029/2019JE005957>
- Seiff, A., & Kirk, D. B. (1977). Structure of the atmosphere of Mars in summer at mid-latitudes. *Journal of Geophysical Research*, 82(28), 4364–4378. <https://doi.org/10.1029/J082i028p04364>
- Snowden, D., Yelle, R.-V., Cui, J., Wahlund, J.-E., Edberg, N. J. T., & Agren, K. (2013). The thermal structure of Titan's upper atmosphere: 1. Temperature profiles from Cassini INMS observations. *Icarus*, 226, 552–582. <https://doi.org/10.1016/j.icarus.2013.06.006>
- Stewart, A. I. (1972). Mariner 6 and 7 ultraviolet spectrometer experiment: Implications for CO₂⁺, CO and O airglow. *Journal of Geophysical Research*, 77(1), 54–68. <https://doi.org/10.1029/JA077i001p00054>
- Stewart, A. I., Barth, C., Hord, C., & Lane, A. (1972). Mariner 9 ultraviolet spectrometer experiment: Structure of Mars' upper atmosphere. *Icarus*, 17(2), 469–474. [https://doi.org/10.1016/0019-1035\(72\)90012-7](https://doi.org/10.1016/0019-1035(72)90012-7)
- Stewart, A. I. F. (1987). Revised time dependent model of the Martian atmosphere for use in orbit lifetime and sustenance studies. In *LASP-JPL internal report*. NQ-802429. Jet Propulsion Laboratory.
- Stone, S. W., Yelle, R. V., Benna, M., Elrod, M., & Mahaffy, P. R. (2018). Thermal structure of the Martian upper atmosphere from MAVEN NGIMS. *Journal of Geophysical Research: Planets*, 123(11), 2842–2867. <https://doi.org/10.1029/2018JE005559>
- Thaller, S. A., Andersson, L., Thiemann, E., Pilinski, M. D., Fang, X., Elrod, M., et al. (2021). Martian nonmigrating atmospheric tides in the thermosphere and ionosphere at solar minimum. *Icarus*, 114767. <https://doi.org/10.1016/j.icarus.2021.114767>
- Thiemann, E. M., Eparvier, F. G., Bougher, S. W., Dominique, M., Andersson, L., Girazian, Z., et al. (2018). Mars thermospheric variability revealed by MAVEN/EUV solar occultations: Structure at aphelion and perihelion, and response to EUV forcing. *Journal of Geophysical Research: Planets*, 123(9), 2248–2269. <https://doi.org/10.1029/2018JE005550>
- Thiemann, E. M. B., Chamberlin, P. C., Eparvier, F. G., Templeman, B., Woods, T. N., Bougher, S. W., & Jakosky, B. M. (2017). The MAVEN EUVM model of solar spectral irradiance variability at Mars: Algorithms and results. *Journal of Geophysical Research: Space Physics*, 122(3), 2748–2767. <https://doi.org/10.1002/2016JA023512>
- Withers, P. (2006). Mars Global Surveyor and Mars Odyssey accelerometer observations of the Martian upper atmosphere during aerobraking. *Geophysical Research Letters*, 33(2), L02201. <https://doi.org/10.1029/2005GL024447>
- Yigit, E., Aylward, A. D., & Medvedev, A. S. (2008). Parameterization of the effects of vertically propagating gravity waves for thermosphere general circulation models: Sensitivity study. *Journal of Geophysical Research*, 113(D19), D19106. <https://doi.org/10.1029/2008JD010135>
- Zurek, R. W., Tolson, R. A., Bougher, S. W., Lugo, R. A., Baird, D. T., Bell, J. M., & Jakosky, B. M. (2017). Mars thermosphere as seen in MAVEN accelerometer data. *Journal of Geophysical Research: Space Physics*, 122(3), 3798–3814. <https://doi.org/10.1002/2016JA023641>