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1 **Imaging of Martian circulation patterns and atmospheric tides**
2 **through MAVEN/IUVS nightglow observations**
3

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16 **Key Points:**

- 17 • The MAVEN spacecraft orbiting Mars has obtained a new type of nightside imaging data
18 which reveals the effects of global-scale winds and waves in the upper atmosphere.
- 19 • Ultraviolet nightglow emissions confirm the expected change of circulation patterns with
20 season and pinpoint an unusually bright spot on Mars' nightside.
- 21 • A Mars General Circulation Model successfully matches many of the observed features
22 and allows an examination of the underlying physical causes.
23

24 Abstract

25 We report results from a study of two consecutive Martian years of imaging observations
26 of nitric oxide ultraviolet nightglow by the Imaging Ultraviolet Spectrograph (IUVS) on the
27 Mars Atmosphere and Volatile Evolution (MAVEN) mission spacecraft. The emission arises
28 from recombination of N and O atoms in Mars' nightside mesosphere. The brightness traces the
29 reaction rate as opposed to the abundance of constituents, revealing where circulation patterns
30 concentrate N and O and enhance recombination. Emissions are brightest around the winter
31 poles, with equatorial regions brightening around the equinoxes. These changes offer clear
32 evidence of circulation patterns transitioning from a single cross-equatorial cell operating during
33 solstice periods to more symmetric equator-to-poles circulation around the equinoxes. Prominent
34 atmospheric tides intensify the emissions at different longitudes, latitude ranges and seasons. We
35 find a strong eastward-propagating diurnal tide (DE2) near the equator during the equinoxes,
36 with a remarkably bright spot narrowly confined near (0°, 0°). Wave features at the opposite
37 winter poles are dissimilar, reflecting different circulation patterns at perihelion versus aphelion.
38 LMD-MGCM simulations agree with the patterns of most observed phenomena, confirming that
39 the model captures the dominant physical processes. At the south winter pole, however, the
40 model fails to match a strong wave-1 spiral feature. Observed brightnesses exceed model
41 predictions by a factor of 1.9 globally, probably due to an underestimation of the dayside
42 production of N and O atoms. Further study of discrepancies between the model and
43 observations offer opportunities to improve our understanding of chemical and transport
44 processes controlling the emission.

45 Plain Language Summary

46 The MAVEN spacecraft orbiting Mars has obtained a new type of imaging data which
47 reveals the effects of global-scale winds and waves in the upper atmosphere. Ultraviolet
48 emissions confirm the expected change of wind patterns with season, and pinpoint an unusually
49 bright spot on Mars' nightside. Computer model runs successfully match many of the observed
50 features, and allow an examination of the underlying physical causes. Differences between the
51 model and observations offer insights on how to improve the model.

52 1 Introduction

53 The structure, composition and dynamics of the upper atmosphere of Mars are controlled
54 by its interactions with solar radiation and the lower atmosphere (*e.g.*, *Bougher et al.*, 2015,
55 2017). Nitric oxide nightglow is a good remote tracer of these properties. This emission was first
56 observed at Mars with the Spectroscopy for Investigation of Characteristics of the Atmosphere of
57 Mars (SPICAM) spectrograph (*Bertaux et al.*, 2005, 2006) on board the ESA Mars Express
58 spacecraft and more recently with the Imaging Ultraviolet Spectrograph (IUVS) (*McClintock et*
59 *al.*, 2015, *Stiepen et al.*, 2017) on board NASA's Mars Atmosphere and Volatile Evolution
60 (MAVEN) spacecraft (*Jakosky et al.*, 2015). Although nightglow measurements were not part of
61 the MAVEN mission requirements, observations have proven to be straightforward and valuable.
62 These nightglow NO emissions are not to be confused with dayside NO emissions (*Stevens et al.*
63 2019) which originate through a different physical process.

64 Nitric oxide ultraviolet nightglow reveals the recombination of N and O atoms on Mars'
65 nightside through the reaction

66



68 which leaves the molecule in an excited state that subsequently radiates. The observed brightness
 69 therefore traces the reaction rate as opposed to the abundance any specific constituent, revealing
 70 where dynamics, chemistry, and other factors enhance recombination. In essence, nightglow
 71 traces how dynamical processes create compositional differences in atomic species on Mars
 72 nightside. The reaction is essentially fueled by solar extreme ultraviolet radiation which
 73 photodissociates CO_2 and N_2 molecules in the dayside thermosphere, leaving the atomic
 74 fragments to be transported by global circulation patterns. Photoelectron impact on these
 75 molecules can also produce $\text{O}(^3\text{P})$ and $\text{N}(^4\text{S})$ ground state atoms and lead to nightglow.

76 Conditions around the solstices give a clear example. Global circulation is strong, so
 77 thermospheric winds carry N and O atoms towards the dark winter pole, where they descend into
 78 the mesosphere. As densities increase downward into the mesosphere, $\text{O}(^3\text{P})$ and $\text{N}(^4\text{S})$ atoms
 79 can recombine to form $\text{NO}(\text{C}^2\Pi)$. Nightglow emission is generated by the deexcitation of this
 80 state. These excited NO molecules relax by emitting photons in the UV δ and γ bands through
 81 cascades via the $\text{A}^2\Sigma(v' = 0)$ state. Nightglow from the NO ultraviolet δ and γ bands are
 82 therefore indicators of the atomic N and O fluxes from the dayside to the nightside and down
 83 into the mesosphere. Due to the higher abundance of O compared to N in the nightside
 84 mesosphere, the limiting factor for this emission is the atomic nitrogen flux descending toward
 85 the atmospheric layer where N atoms recombine with O to produce NO in the excited ($\text{C}^2\Pi$)
 86 state. In the simplest approximation, the emission rate equals the downward flux of atomic
 87 nitrogen: one atom, one photon, as originally pointed out by *Stewart et al.* (1980) and confirmed
 88 by the model of *Bougher et al.* (1990). A summary of key reactions, branching ratios and rates is
 89 presented in *Stiepen et al.* (2017), hereafter *Stiepen17*.

90 NO recombination nightglow was discovered at Mars by *Bertaux et al.* (2005), with limb
 91 observations showing an emission peak reaching 2.2 kR at an altitude of ~ 70 km. The emission
 92 required an estimated downward flux of 2.5×10^8 N atoms $\text{cm}^{-2} \text{s}^{-1}$, about one third of the
 93 estimated production of N atoms by EUV photodissociation of N_2 molecules on the dayside.
 94 Based on the analysis of 21 SPICAM limb scans, *Cox et al.* (2008) performed a first study of the
 95 correlation between the emission peak brightness and altitude versus geographical factors
 96 (latitude and local time), and external factors (the interplanetary magnetic field and solar
 97 activity). They reported a large variability in NO nightglow and a lack of apparent correlation
 98 between these factors, probably a consequence of the small size of the dataset. SPICAM also
 99 serendipitously observed the NO nightglow emission while making stellar occultation
 100 observations. *Gagné et al.* (2013) identified 128 SPICAM stellar occultation NO emission
 101 detections out of 2215 observations. They compared their seasonal and latitudinal distribution to
 102 calculations from the Mars general circulation model developed at the *Laboratoire de*
 103 *Météorologie Dynamique* (LMD-MGCM) and described by *Forget et al.* (1999) and *González-*
 104 *Galindo et al.* (2009). *Gagné et al.* showed that the model predicted brighter NO nightglow
 105 during winter at polar latitudes, while during equinoxes it predicted maximum emission at both
 106 poles with an equatorial enhancement during equinoxes. The observations were too limited to
 107 offer strong support to the conclusion, though. *Stiepen et al.* (2015) compiled 10 years of
 108 SPICAM stellar occultation and limb observations of NO nightglow to study the variability of
 109 the summer-to-winter hemispherical circulation in the upper atmosphere of Mars. Their data set
 110 extended the observations used by *Cox et al.* (2008) and *Gagné et al.* (2013). They found that the
 111 NO nightglow layer is centered at 72 ± 10.4 km and that the number of NO nightglow detections

112 increased during periods of higher solar activity, in agreement with the paradigm of the dayside
113 production of N and O atoms. They produced maps of the brightness and altitude of the
114 emission, though with large gaps in coverage due to observational limitations.

115 The first MAVEN/IUVS study of the nitric oxide nightglow was based on limb scans
116 (*Stiepen17*). They analyzed IUVS observations of NO nightglow over the northern hemisphere
117 during three seasons: winter in the north, fall equinox in the south, and northern summer at
118 equatorial latitudes. They characterized the brightness (from 0.2 to 30 kR) and altitude (from 40
119 to 115 km) of the nightglow layer, as well as its average topside scale height (11 km). They
120 discovered the signature of atmospheric waves forcing longitudinal variability, associated with
121 an increased airglow brightness peaking near longitudes 10° and 170° in the northern hemisphere
122 winter ($240^\circ < L_s < 295^\circ$), and longitudes -75° , 20° , and 140° during northern summer ($75^\circ < L_s <$
123 115°). In contrast, the limb data suggested an absence of longitudinal intensity variation during
124 fall equinox in the southern hemisphere. They also showed that the LMD-MGCM globally
125 reproduces some of the trends of the NO nightglow emission and its seasonal variation, but also
126 indicated large discrepancies in brightness, by as much as a factor of 50 fainter in the model
127 during northern winter at low- to mid- latitudes.

128 Nightglow emissions from other species have also been observed on the Martian
129 nightside. O_2 and OH emissions are concentrated in the polar night region and result from
130 transport of O and H atoms produced on the dayside by photodissociation. Both are carried into
131 the dark winter polar regions where they flow down and recombine to produce $O_2(^1\Delta)$ and
132 vibrationally excited OH. The O_2 nightglow at $1.27 \mu\text{m}$ corresponding to the infrared
133 atmospheric $a^1\Delta \rightarrow X^3\Sigma(0,0)$ forbidden transition was observed from Mars Express with the
134 OMEGA (*Bertaux et al., 2012*) and SPICAM IR (*Federova et al., 2012*) instruments, from the
135 Mars Reconnaissance Orbiter (MRO) CRISM instrument by *Clancy et al. (2012, 2013a)* and
136 Rosetta by *Migliorini (2013)*. This emission bears some resemblance to the NO nightglow as it
137 arises from three-body recombination of O atoms ($O + O + CO_2 \rightarrow O_2(^1\Delta) + CO_2$) carried from
138 the dayside to the nightside. The results from all instruments indicate that the emission layer is
139 located between 40 and 60 km in both winter and equinoctial polar regions. Simulations with the
140 LMD model (*Gagné et al., 2012; Clancy et al., 2012, 2013a*) showed good agreement with LMD
141 simulations of the vertical and latitudinal distribution, especially when including interactive
142 aerosol forcing. *Clancy et al. (2013b)* also measured the characteristics of the OH $\Delta v = 0$ and 1
143 Meinel bands with the CRISM instrument between 70° and 90° near the winter pole. They found
144 the location and vertical profile to be very similar to the $O_2(^1\Delta)$ emission. They reached good
145 agreement with LMD simulations, confirming the ability of the model to adequately reproduce
146 the mean features of the odd oxygen and hydrogen photochemistry and their transport by global
147 circulation in this altitude range. In addition to nightglow remote sensing, MAVEN/NGIMS *in*
148 *situ* helium bulge measurements paint a similar picture of the important of nightside polar
149 downwelling (*Elrod et al., 2017*).

150 Comparable processes create nitric oxide nightglow on Earth (e.g., *Tennyson et al.,*
151 *1986; Eastes et al. 1992*) and Venus (e.g., *Stewart et al., 1980*), where it has been observed and
152 extensively studied. The Venus case, with its CO_2 -dominated atmosphere, offers the most
153 insightful comparison into Mars. Both CO_2 and N_2 are dissociated on the Venus dayside and
154 carried to the nightside by subsolar to antisolar global circulation, where they recombine and
155 produce the NO δ and γ bands. Bright spots have been observed with Pioneer Venus (*Bougher et*
156 *al., 2006*) and Venus Express instruments (*Stiepen et al., 2013; Royer et al., 2010*) at varying

157 locations in the vicinity of the antisolar point (midnight on the equator) with brightness changing
158 from day to day. When combined into long-term statistical maps (*Stewart et al.*, 1980; *Bougher*
159 *et al.*, 1990; *Royer et al.*, 2016; *Stiepen et al.*, 2013; *Gérard et al.*, 2017)) a bright, nearly-circular
160 region appears spanning about 5 hours in local time and has a full-width at half-maximum of
161 about 50° in latitude. It is located near the equator and shifted toward dawn by about 2 to 3
162 hours of local time. The driving circulation pattern at these altitudes is a single Hadley cell
163 circulating from the dayside to nightside, apparently with an offset caused by the Venus
164 atmosphere's super-rotation. In the absence of seasons, the circulation appears relatively stable.
165 GCM simulations by *Bougher et al.* (2006) and *Brecht et al.* (2011) have confirmed the validity
166 of the general concept. They were able to reproduce the main characteristics of the observed
167 nightglow. Gravity waves and planetary waves (*i.e.*, Kelvin and Rossby waves) have been
168 suggested as the sources of the observed fluctuations of brightness and morphology for both the
169 Venus NO and O₂ nightglow emissions. GCM modeling efforts combining these sources have
170 recently been able to reproduce a significant portion of the amplitude of these fluctuations
171 (*Brecht et al.*, 2019).

172 In the study that follows, we use IUVS's disk imaging capabilities during the apoapse
173 phase of the MAVEN orbit to obtain ultraviolet images of the Mars NO nightglow emission.
174 These represent the first observations of Mars nightglow in nadir view. The dataset offers far
175 more complete coverage of latitude, longitude, season and local time than was previously
176 possible, allowing expanded insights into global circulation and the factors that control it. This
177 initial study focusses on long-term seasonal averages, and therefore cannot address shorter-term
178 phenomena. Those will be addressed in a subsequent publication.

179 2 Instrument, observations, and data analysis

180 2.1 MAVEN's Imaging UltraViolet Spectrograph

181 The Imaging UltraViolet Spectrograph is MAVEN's sole instrument for remote sensing of Mars
182 and its atmosphere (*McClintock et al.*, 2015]). This study uses the mid-ultraviolet (MUV)
183 channel spanning 180 to 340 nm at ~ 1.2 nm spectral resolution. IUVS uses a long, narrow slit
184 ($10^\circ \times 0.06^\circ$) placed in the focal plane of the telescope as an entrance to the spectrograph, which
185 defines the instrument field of view. The instrument uses image intensifiers for UV sensitivity,
186 using high voltages when viewing the nightside and using low voltages when viewing the
187 dayside. The instrument is mounted on the Articulated Payload Platform (APP) which can orient
188 its field of view relative to Mars. During the apoapse portion of the MAVEN orbit (~ 6000 km
189 above the surface), IUVS uses its scan mirror to obtain multiple swaths across the planet as the
190 spacecraft moves. The swaths can be combined to produce an image of the planet with pixel
191 resolution of about 20 km at the sub-spacecraft point at apoapsis (Figure 1a). Spectral range and
192 binning are optimized for the science objectives of the observation and adapted to the available
193 data rate. This study uses IUVS nightside apoapse disk observations taken between 30 March
194 2016 and 31 July 2018, corresponding to MAVEN orbits 2915 through 7468. To accommodate
195 high spatial resolution data when the available data rate was low, data products from orbits 3925
196 to 6932 (4 October 2016 to 24 April 2018) used 40 spectral bins (195 to 221 nm) instead of 174
197 spectral bins (185 to 299 nm) while keeping the spectral resolution unchanged. The wavelength
198 range for the 40 spectral bins records the three strong delta bands ($\Delta v = 1,2,3$) in Figure 1b).
199 IUVS level 1B data used are available in the Planetary Data System, labeled v13_r02 tagged
200 with "apoapse".

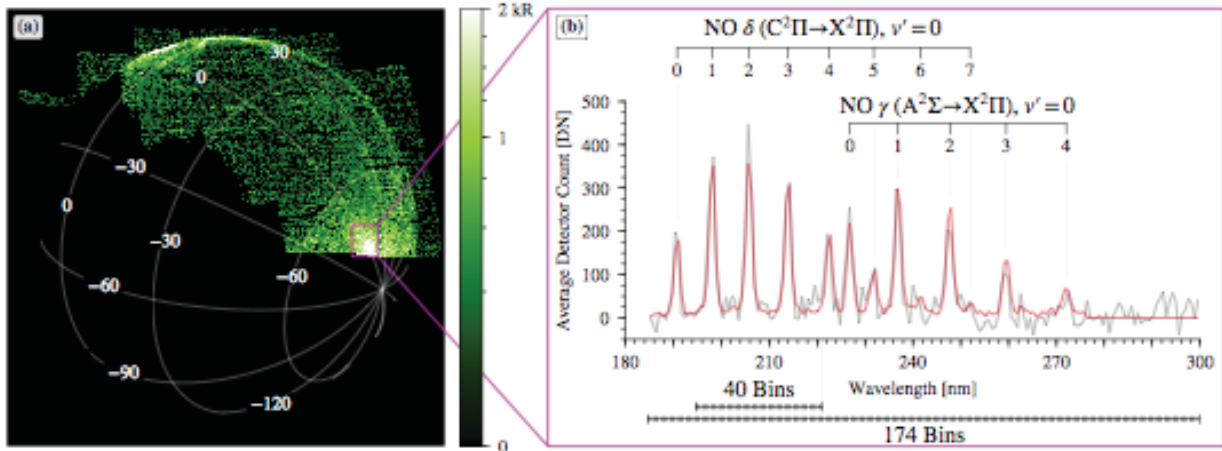
201 2.2 Spectral analysis

202 Nightside spectra consist primarily of emissions from nitric oxide, though solar
203 continuum can contaminate the spectrum near the terminator, and auroral emissions can occur
204 anywhere during an auroral event (*e.g.*, *Schneider et al.*, 2015). We minimize the error
205 introduced from dark current and its subtraction by using the average dark image per orbit
206 created by coadding multiple dark images taken during a single orbit.

207 To isolate the NO emission brightness, we use a multilinear regression technique (MLR)
208 to fit the observed spectrum (*Stevens et al.*, 2015). The method is functionally equivalent to that
209 used by *Stiepen17*, including the use of identical templates and spectral ranges. We used
210 templates derived from IUVS observations isolating the individual spectral components with
211 negligible levels of the other components. The fit yields spectral component contributions for
212 NO nightglow, solar continuum, and a constant term indicating the presence of high background
213 or other artifacts. The observed contributions from the CO Cameron bands (175-270nm) and the
214 Ultraviolet Doublet (289 nm) were negligible in the dataset, due to the lack of aurora in this time
215 frame, and were not included from the fit. (A short period of known auroral activity (*Schneider*
216 *et al.*, 2018) was excluded from the dataset.) Examination of high SNR data over the course of
217 the dataset demonstrated that no wavelength zero-point corrections were necessary.

218 We quantified the NO nightglow ultraviolet emission in instrumental units by summing
219 the nightglow fit over the wavelength range of the NO δ and γ bands (Figure 1b). The three NO δ
220 band features captured with 40 spectral bins (Figure 1b) account for less than half of the total NO
221 radiance observed by the MUV channel and must be corrected. The validity of combining

222 datasets at the two binnings was tested by comparing fits to a 40-bin subset of 174-bin data vs.
 223 fits from the full 174-bin data, and finding negligible differences.
 224



225
 226 **Figure 1a.** Spherical projection of level 1C NO nightglow brightnesses observed during orbit
 227 3241 on 30 May 2016 at $L_s = 161^\circ$ during Mars Year 33. The colormap shows the total NO
 228 nightglow brightness obtained by fitting the NO δ and γ band spectral template. The image
 229 shows the expected enhancement near the southern winter pole, but also patchy equatorial
 230 enhancements of comparable magnitude.

231 **Figure 1b.** MUV spectral fit of NO nightglow. The black line shows the spectrum observed
 232 within the box near the terminator in Figure 1a containing about 100 spatial pixels. Other fitted
 233 spectral components have been subtracted; the template is shown in red. The fitted brightness is
 234 1.68 ± 0.04 kR. The two spectral regimes used for binning and fitting for different observations
 235 are shown along the bottom.

236 In the final step of spectral analysis, we converted brightnesses in instrumental units to
 237 kiloRayleighs (kR) using a calibration curve. We correct for the different binnings described
 238 above by scaling 40-spectral-bin data up by factor of 2.2 in order to combine them 174-spectral-
 239 bin data. IUVS was calibrated using UV-bright stellar observations, scaled by instrument
 240 geometric factors appropriate for extended source observations. Intensities presented in this
 241 study are linearly dependent on the absolute calibration. The intensity values are affected by a
 242 30% systematic wavelength-independent uncertainty due to the calibration. The MUV detectors
 243 have recently been recalibrated using bright stars in the airglow slit (the central portion) resulting
 244 in a wavelength-dependent 10 to 20% reduction in intensities for most of the MUV emissions
 245 compared to previous stellar observations made in the occultation keyhole at one end of the slit.
 246 This recalibration also affects the prior MAVEN/IUVS NO nightglow results (*Stiepen17*) in
 247 which the reported nightglow intensities must be reduced by about 17%. The updated calibration
 248 curve will be applied to all IUVS data products on the Planetary Data System (including the 17%
 249 correction to those in this work) at a future date.

250 2.3 Data coverage and quality

251 IUVS nightside apoapse disk observations span from March 2016 to 31 July 2018 (orbits
 252 2915-7468). The selected observations started at $L_s = 130^\circ$ during Mars Year 33 (MY 33) and
 253 continued through to $L_s = 221.5^\circ$ during MY 34. Data gaps exist when MAVEN's evolving orbit

254 did not place apoapse at a suitable location for nightside observations. We eliminated data with
255 solar zenith angles (SZA) $< 110^\circ$ to restrict solar or dayglow contamination of nightglow spectra.
256 We further eliminated individual spectra which produced MLR fitted values for solar continuum
257 or a constant term exceeding thresholds we determined as contributing significant contamination
258 to the nitric oxide signal. For data with 40 spectral bins (about 75% of the data), we eliminated
259 pixels with a solar continuum component greater than 1.15 kR or a constant term greater than 2
260 kR. For data with 174 spectral bins (about 25% of the data), we eliminated pixels with a solar
261 continuum greater than 5 kR or a constant term greater than 9.2 kR. Data do not cover all
262 latitudes at all solar longitudes due to orbital limitations. The SZA cutoff prevents observations
263 during daytime and at the summer poles. These cutoffs prevent contaminated data from entering
264 the analysis, as verified by visual examination of the data while selecting the threshold values.
265 No systematic effects on fitted brightness were detected even near the planet's terminator due to
266 the conservative cutoffs used.

267 The filtered dataset based on 2941 apoapse images contains more than 41 million
268 independent measurements of vertically integrated NO brightness, each tagged with latitude,
269 longitude, local time and solar longitude. We only used pixel locations on the Mars disk (lines of
270 sight intercepting the disk instead of passing above the limb) with a correction for emission
271 angle. For emission angles less than 50° we multiply by the cosine of the emission angle, to
272 diminish the brightness to what would be observed at exact nadir viewing. For emission angles
273 between 50° and 85° we use a numerical Chapman correction (*Smith and Smith, 1972*) with a
274 Mars radius of 3390 km, NO nightglow layer altitude of 80 km, and atmospheric scale height of
275 11 km. Pixels lying above Mars' physical limb cannot be corrected in the same manner, and we
276 will use them in a later study.

277 Data quality has been ensured by visual inspection of sample data under the full range of
278 observed radiances and observing conditions. This applies at the faintest levels reported in this
279 work (25 R), where the unique spectral structure of NO is readily discernable in spatial or
280 temporal averages of 5000 samples or more. This number of samples corresponds to areal
281 averages over a square area ~ 300 by 300 km in a single integration of 3.4 seconds, or
282 corresponding temporal integral over our 20 km diameter spatial resolution element in about 15
283 minutes. At the brightest levels (about a hundred times brighter) the spectral shape is distinct in
284 correspondingly smaller areas and timespans. All plots and figures employ summations over
285 much greater areas and timespans, such that all the observation geophysical variations are far
286 larger than statistical noise. The figures in following sections confirm this conclusion in the
287 relatively smooth variation over the independently calculated pixels in maps and line plots.

288 Figure 1a conveys a sense of the excellent data quality in an individual image, but cannot
289 convey the substantial variability frame-to-frame or day-to-day. Given this variability, it is all the
290 more remarkable that strong patterns emerge from seasonal averages, as discussed in Section 3.

291 2.4 Model description

292 In this study we compare observational results to vertically-integrated NO nightglow
293 brightness simulations from the Mars Global Climate Model developed at the *Laboratoire de*
294 *Météorologie Dynamique* (LMD-MGCM) (*Forget et al., 1999; Gonzalez-Galindo et al., 2009*).
295 We use the same version used by *Stiepen17*, which was also used to build the Mars Climate
296 Database version 5.3 (*Millour et al., 2018*). The main difference between our simulations and
297 those in *Stiepen17* is that we have used the solar activity and dust load observed during the

298 period of IUVS observations described here as inputs, while *Stiepen17* used a generic scenario
299 for average solar conditions and a climatological dust scenario appropriate for years without a
300 global dust storm. In particular, the solar variability during MY 33 and 34 have been included as
301 described in *González-Galindo et al. (2015)*. For the dust scenario, we included the observed
302 dust load variability during MY 33 using the procedure described in *Montabone et al. (2015)*.
303 For MY 34 we used the climatological dust scenario, appropriate for the period analyzed here
304 before the onset of the global dust storm beginning in May 2018 at a solar longitude of
305 approximately 180° . The model does not include effects of non-orographic gravity waves.

306 The LMD-MGCM was adapted to include key physical processes relevant to the
307 nightglow emission process: photochemical creation of atomic nitrogen and oxygen on the
308 dayside, horizontal and vertical transport to the nightside, and recombination reaction rates based
309 on densities and temperature. The influence of changing EUV flux controlling dissociation and
310 ionization is included in the model. The model currently includes only production by
311 photodissociation, and omits N_2 electron-impact dissociation, identified by *Bougher et al. (1990)*
312 as an important source of odd nitrogen. The model brightness is linearly dependent on the
313 production of atomic N on Mars' dayside, so this limitation will affect quantitative agreement.

314 As a check, we calculated two forms of model output to examine potential observational
315 bias: output spanning all latitudes, longitudes, nightside local times and solar longitudes, and
316 point-by-point model calculations matched to the exact geometry of individual data points. There
317 were no discernible differences between the two where observations exist, giving confidence that
318 conclusions reached with this dataset are not artifacts of the observational coverage. With the
319 exception of Figures 2b and 4, all model outputs are point-for-point matches to observational
320 data.

321 **3 Results**

322 3.1 Latitudinal and seasonal control of NO nightglow emission

323 Latitude and season are the strongest influences on global circulation patterns, and Figure
324 2a confirms they exert strong control on the brightness of nightglow. The winter poles show very
325 strong enhancements with steep latitudinal gradients towards the equator spanning nearly two
326 orders of magnitude. While *Stiepen17* measured a strong latitudinal gradient up to 60° north and
327 south latitude, the imaging observations presented here are the first to span the full polar regions.
328 Observational limits do not allow estimates of the timing of the seasonal onset or decline of the
329 polar enhancements. We note an asymmetry between the northern winter pole and the southern
330 winter pole brightness, with the north brighter by a factor of 2 to 3. Part of this asymmetry is
331 probably attributable to the higher solar flux at perihelion. During northern winter, MAVEN's
332 EUV Monitor (*Eparvier et al. 2015*) measured total irradiance between 1-45 nm a factor 1.43
333 larger than that during the southern winter, attributable almost entirely to the reduced distance,
334 with no significant difference in solar activity. The observed increase in insolation and
335 corresponding dissociation rate is not enough to explain the entire effect. Models show that
336 increased insolation and a dustier atmosphere drive more rapid meridional circulation during
337 southern summer (*Bougher et al., 2006; Bell et al., 2007, González-Galindo et al., 2009*), which
338 would transport dissociation products more rapidly to the northern summer pole. These two
339 effects combined are plausibly sufficient to explain the brightness asymmetry, but a more
340 quantitative analysis is beyond the scope of this work.

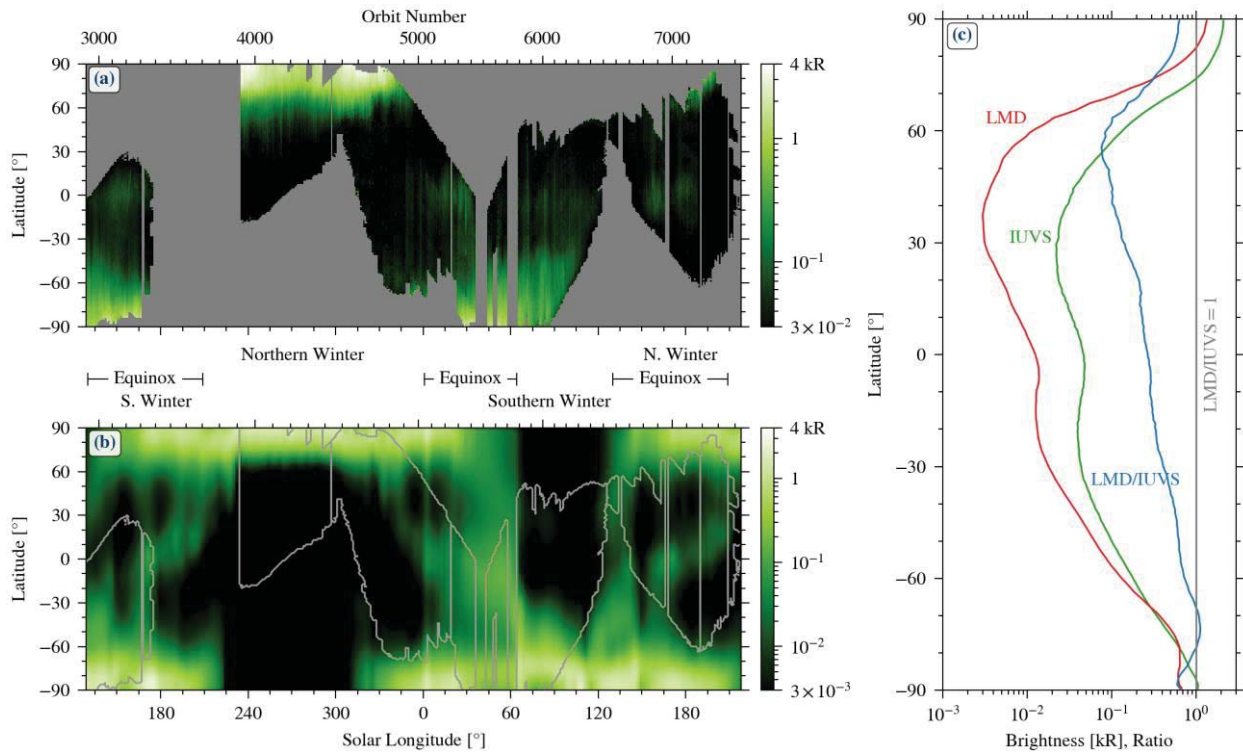
341 Imaging measurements identify equatorial enhancements during equinox seasons. This
342 differs slightly from the equatorial enhancements first noted by *Stiepen17* during southern
343 winter. In both cases, the emission primarily takes the form of patchy enhancements as seen in
344 Figure 1a, as opposed to a uniform equatorial belt. We discuss the nature and distribution of
345 these patches in the subsequent sections.

346 Figure 2b shows LMD-MGCM nightglow predictions for the solar and dust conditions
347 appropriate to the season and Mars year. Note the color bar extends downward one additional
348 order of magnitude, indicating the model predicts extremely faint emissions away from the
349 seasonal enhancements. The overall structure is similar between observations and model,
350 especially the winter pole brightenings and the northern winter enhancement. Equatorial
351 equinoctial brightenings are present in both observations and model, though the observed
352 equatorial peak is a factor of several brighter than the modeled peak. The model enhancements
353 are generally more extended in solar longitude and latitude, but observational limits prevent a
354 deeper comparison.

355 Figure 2c quantifies the brightness differences between Figures 2a and 2b. We find that
356 the model underestimates emissions by factors between 2 and 10 at northern- and mid-latitudes,
357 while brightnesses in the south are comparable. This differs from the conclusions of *Steipen17*,
358 who found the model was brighter near the north pole, while fainter elsewhere, though this may
359 have been biased by less complete observational coverage in latitude and solar longitude. The
360 area-weighted integrals of the curves in Figure 2c show that the observations' average brightness
361 is 1.9 times brighter than the models. The likely cause of this discrepancy is the net production of
362 atomic nitrogen on the dayside, rather than any profound error or incompleteness in the physics
363 of transport or subsequent chemistry. The deficit could be met through inclusion of additional
364 dayside sources such as electron impact dissociation, changes in reaction rate coefficients,
365 branching ratios, or solar activity inputs.

366

367



368

369 **Figure 2a.** Climatology map of NO nightglow brightness from the full disk dataset binned by 1°
 370 in latitude and solar longitude. The data are averaged over all observed longitudes and local
 371 times. Note polar brightening during northern winter ($L_S \sim 270^\circ$), southern winter ($L_S \sim 90^\circ$) and
 372 the equinoxes ($L_S \sim 160^\circ, 40^\circ$, and again $\sim 160^\circ$). The edges of the dataset are determined by
 373 observational coverage and solar stray light limits. Seasonal demarcations are based on
 374 similarities in observed behavior rather than formal solar longitude limits.

375 **Figure 2b.** LMD-MGCM calculations of the zonal mean NO brightness at all latitudes and solar
 376 longitudes during the observation period. The grey outline indicates the data boundaries from
 377 figure 2a, showing that the observations sampled the majority of key phenomena including both
 378 polar nights and the transition periods during the equinoxes. Note that the color bar extends one
 379 order of magnitude lower and for the panel above.

380 **Figure 2c.** Zonally averaged NO nightglow brightness across all solar longitudes plotted vs.
 381 latitude in 1° bins. The grey line marks 1 kR for the red and green curves, and indicates a ratio of
 382 unity for the blue curve. Statistical uncertainties in these mission-long averages are negligible on
 383 the scale of these plots, while the observed variability among observations at the same latitude is
 384 substantial. The faintest level of emission (25 R observed at about 30° N) is a confirmed
 385 detection as opposed to an upper limit, so the difference from the LMD curve is significant.

386 3.2 Local-time control of the NO nightglow

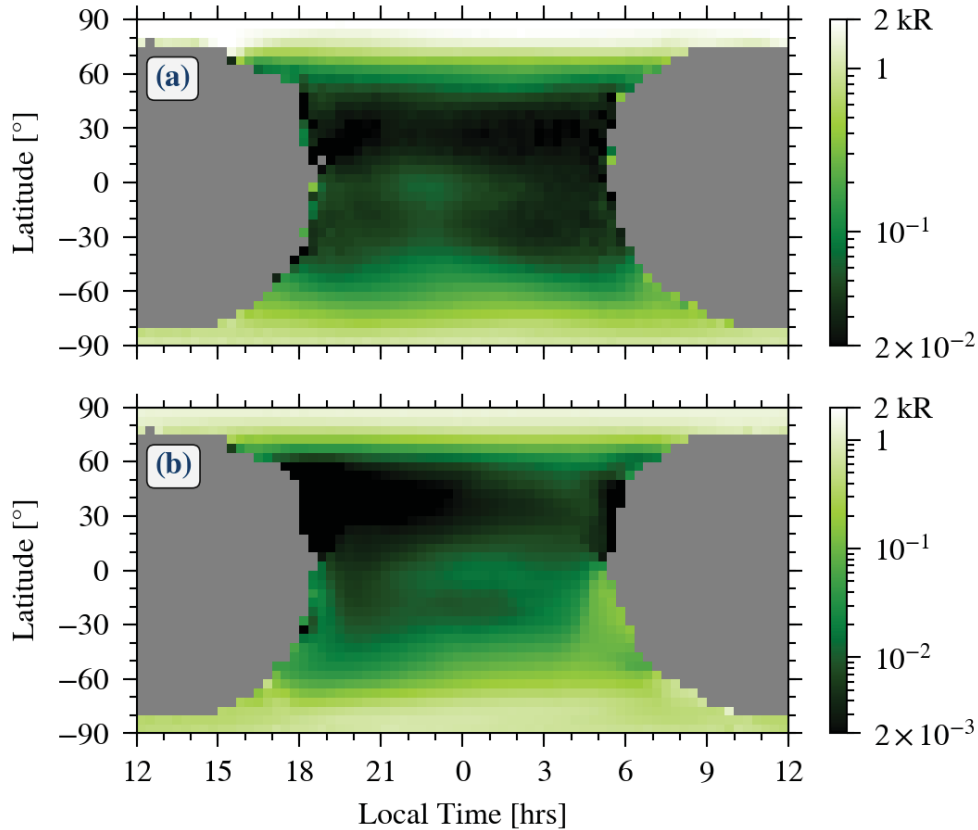
387 Next, we examine local time behavior of the emission, with an emphasis on
 388 understanding the effect that the transition from day to night makes on the emission. Figure 3a
 389 shows all observations as functions of local time and latitude, averaging over all observed
 390 geographic and solar longitudes. The data show that polar emissions are bright and relatively

391 constant in local time due to the persistent darkness. At equatorial latitudes, the data show a peak
392 in emission in the evening hours and a strong decline towards the morning terminator.
393 Combining the results shown in Figure 2a and 3a, the equinox enhancements at the equator peak
394 in the evening hours.

395 Figure 3b shows point-for-point simulations from the LMD-MGCM model in the same
396 format. The polar regions exhibit minimal local time variation, as expected since winter pole
397 latitudes do not experience daytime. At the equator, the model predicts a continuous brightness
398 increase through the evening, peaking in the late morning hours just before sunrise. This effect
399 enhanced at mid-southern altitudes. While it is reassuring that both observation and model
400 indicate an equatorial nightside enhancement, the disagreement between the observed equatorial
401 pre-midnight peak and the modeled pre-dawn peak indicates a substantial gap in our
402 understanding of what drives equatorial circulation at equinox seasons.

403 The LMD-MGCM provides diagnostic information on the conditions that drive the
404 emissions. The most probable cause for the nightside equatorial spot of Figure 3a or 3b is
405 vertical winds carrying the atomic species downward to higher densities where they recombine.
406 Figure 4 shows the LMD-MGCM prediction of vertical winds during equinox seasons. The
407 model reproduces the basic expectation of equatorial upwelling on the dayside during equinox
408 seasons and downwelling on the night side, though maximum downwelling occurs at a later local
409 time than observed. The local time and altitude variability of the emission and the vertical winds
410 in the model (Figures 4c and 4d) below about 100 km are similar to that expected from the
411 vertical propagation of the migrating diurnal tide. This suggests that the different local time peak
412 of the emission in the model compared to the observations is produced by an incorrect
413 representation of the diurnal tide in the model. A possible cause is the lack of non-orographic
414 gravity waves effects in the model. Previous studies (*e.g.*, *Medvedev et al.*, 2011) have shown the
415 importance of the inclusion of the effects of such waves in 3D models for matching the thermal
416 and dynamical structure of the mesosphere. In particular, *Gilli et al.* (2020) have shown that their
417 inclusion in the LMD-MGCM significantly improves comparisons with observations of the
418 amplitude of the diurnal migrating tide from Mars Climate Sounder (MCS) on the Mars
419 Reconnaissance Orbiter (MRO).

420 A similar analysis of the polar brightenings also indicates that atmospheric circulation is
421 the driver, but the correspondence with downwelling is less clear. Figure 4a shows that the
422 equinox model predicts bright emission at both poles, even though nightside local times are
423 experiencing upwelling. Detailed analysis of model output offers some clues. First, the zonally-
424 averaged vertical velocity does indicate downwelling on average, as must be the case with
425 transport from the thermosphere to mesosphere. Furthermore, the model indicates a buildup of
426 atomic N on the nightside in a region of very long lifetime against loss processes. In the absence
427 of nightside production mechanisms or downwelling, the buildup must be caused by horizontal
428 transport. The same condition is true during the solstices, where the polar regions are further
429 complicated by the dynamics of the polar vortex. The model again finds a substantial buildup of
430 nightside N consistent with the observed polar brightenings. A deeper investigation of the model
431 to study these polar processes is beyond the scope of this synoptic effort, but is likely to bear
432 fruit as a separate project.



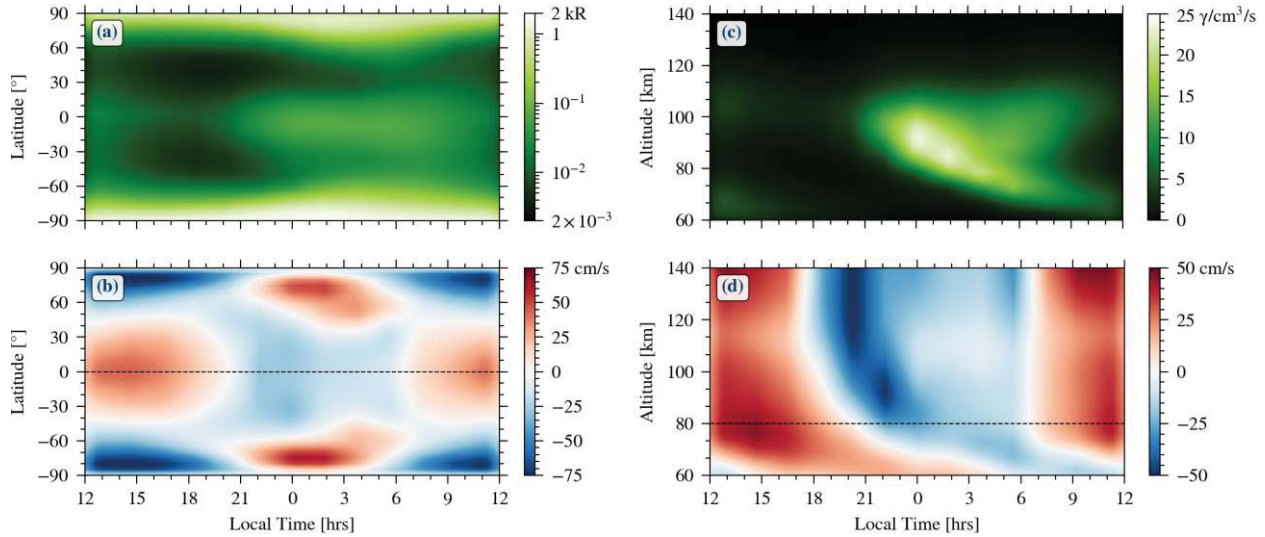
433

434 **Figure 3a.** Observed NO nightglow emission by latitude and local time averaged over our
 435 dataset. Different latitude ranges are filled in over different seasons: High-latitude emissions are
 436 observed at all local times during each polar night, filling both poles. We observed the equatorial
 437 enhancement primarily during equinox seasons. Local time bins are 20 minutes and latitude bins
 438 are 5°.

439 **Figure 3b.** Average LMD-MGCM calculations for the same conditions as Figure 3a. Note the
 440 extra order of magnitude in color scale necessary to display equatorial brightness in the model
 441 compared to observations above.

442 3.3 Wave structures and atmospheric tides

443 Atmospheric tides are widespread phenomena throughout the solar system. Diurnal solar
 444 heating of planetary atmospheres, modulated by topography, surface thermal inertia, albedo, and
 445 dust loading in the atmosphere can produce tides and global-scale thermal oscillations with
 446 periods that are subharmonics of the planetary rotation period (*Forbes et al., 2002*). These tides
 447 can be generally classified as migrating (those components that track the Sun's motion) and non-
 448 migrating. Tides can produce significant deviations from equilibrium values in atmospheric state
 449 variables, such as density, pressure, and temperature, and in doing so can affect atmospheric
 450 circulation and the horizontal and vertical transport of energy. Tides have important effects on the
 451 momentum balance in Mars' atmosphere (*Wilson and Hamilton, 1996, Moudden and Forbes,*
 452 *2008*). These far-reaching effects imply that an understanding of the atmosphere is incomplete
 453 without an understanding of atmospheric tides.



454

455 **Figure 4a.** LMD-MGCM predictions of vertically-integrated nightglow for the equinox season
 456 ($L_s=0-30$). It shows a nightside equatorial enhancement, though less spatially confined and later
 457 in local time than observed. Note that these plots show a global seasonal average (*i.e.*, not
 458 restricted to observed times & locations), so it is not an exact match to Figure 3b.

459 **Figure 4b.** Vertical winds at 80 km, confirming the intuitive pattern of dayside upwelling (red)
 460 and nightside downwelling (blue) where emission is maximized. The dashed line indicates where
 461 this panel intersects Figure 4d.

462 **Figure 4c.** LMD-MGCM predictions of nightglow volume emission rate in a vertical slice at the
 463 equator for the equinox season ($L_s=0-30$).

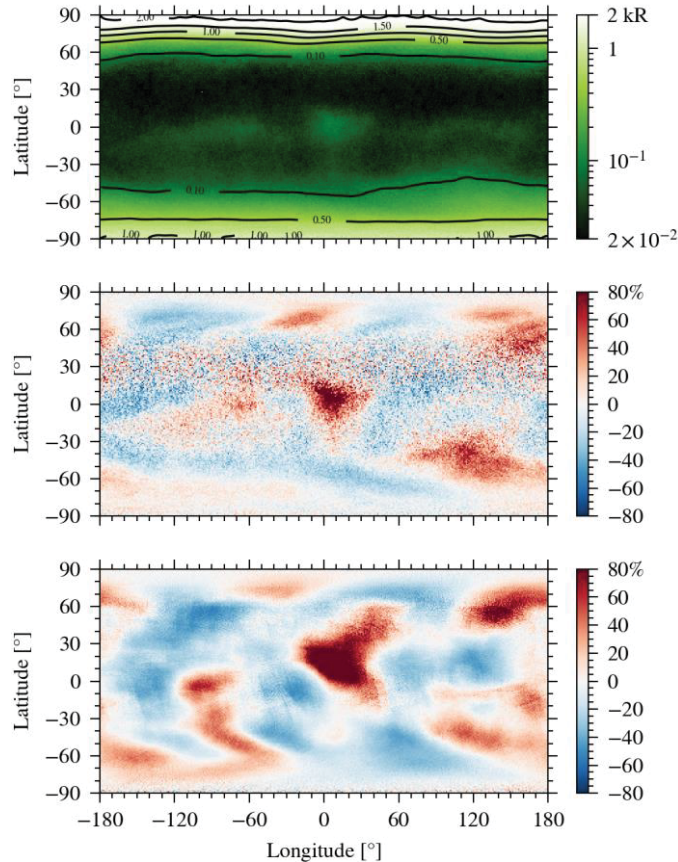
464 **Figure 4d.** Vertical wind velocity as a function of local time and altitude. Note that the
 465 maximum downwelling shifts from pre- to post-midnight looking lower in the atmosphere,
 466 indicating the importance of zonal winds in deflecting vertical flow. Note the correlation
 467 between downwelling (blue) and volume emission rate (green) in Figure 4c. The dashed line
 468 indicates where this panel intersects Figure 4b.

469 Previous studies have found that atmospheric tides and associated wave features affect
 470 different latitude and altitude ranges during different seasons. Mars' mid-latitudes are affected by
 471 planetary waves including standing and traveling waves (*e.g.*, *Banfield et al.*, 2003, 2004; *Hinson*
 472 *2006*; *Lewis et al.*, 2016). Other studies have reported longitudinally-dependent wave and tide
 473 activity in the upper atmosphere of Mars during northern hemisphere summer, fall and winter
 474 seasons (*Keating et al.*, 1998; *Wilson et al.*, 2002; *Bougher et al.*, 2004; *Angelats i Coll*, 2004; *Lo*
 475 *et al.*, 2015; *England et al.*, 2016; *Stiepen17*; *Gröller et al.*, 2018; *Bougher et al.*, 2017). *Lo et al.*
 476 (2015) and *Medvedev et al.* (2016) have discussed nonmigrating tides observed in
 477 MAVEN/IUVS airglow observations between altitudes of 130 and 180 km on the dayside, while
 478 *England et al.* (2016) sample the 165 to 205 km dayside altitude region using MAVEN/IUVS
 479 airglow measurements and MAVEN Neutral Gas Ion Mass Spectrometer (MAVEN/NGIMS)
 480 measurements. At mesospheric altitudes, waves and tides have been previously studied using two
 481 different datasets. First, *Withers et al.* (2011) identified strong wave-2 and wave-3 nonmigrating
 482 eastward-propagating tides using densities from SPICAM/UV occultations, identifying them as
 483 diurnal Kelvin waves DK1 and DK2. (DK2 is also referred to in the literature as DE2, which we
 484 discuss below.) Second, *Guzewich et al.* (2012) analyzed the MRO/MCS temperature dataset,

485 finding that tropical latitudes were dominated by non-migrating tides, while stationary planetary
486 waves with wavenumbers 1 and 2 dominated mid and high latitudes of both hemispheres.

487 The substantial IUVS dataset offers a new opportunity to study wave structures and
488 atmospheric tides. Many prior studies have been based on observations from orbiting platforms
489 fixed in local time (*e.g.*, Mars Climate Sounder on the Mars Reconnaissance Orbiter (*Guzewich*
490 *et al.*, 2012)), or precessing in local time (*e.g.*, MAVEN/NGIMS and IUVS limb scans, as in
491 *England et al.* (2019)). These measurements follow a repeating ground track that ties together
492 latitude, longitude, and local time. Other observations have been made from surface assets fixed
493 in latitude and longitude (*e.g.*, the Viking Landers (*Hess et al.*, 1977)). IUVS imaging provides a
494 significant improvement in coverage over past studies by offering simultaneous coverage in both
495 longitude and local time, while also mapping over a range of latitudes. The IUVS dataset offers
496 two significant advantages with respect to previous mesospheric datasets. First, for the first time
497 the polar regions are fully covered (at least during the winter periods). The MCS dataset is
498 restricted to latitudes between $\pm 70^\circ$ (*Guzewich et al.*, 2012), while the SPICAM stellar
499 occultations dataset only included four narrow latitudinal and seasonal ranges, none of them
500 extending further than 60° in latitude (*Withers et al.*, 2011). Second, our dataset offers good local
501 time coverage which avoids aliasing problems, in contrast with MCS measurements which are
502 obtained at only two local times.

503 We begin with an overview of wave structures identified in the full IUVS imaging dataset
504 spanning more than one Mars year. Figures 5a and 5b show significant longitudinal variability at
505 all latitudes, but more pronounced at the equator, northern polar and southern polar regions. Note
506 in particular the brightening near $(0^\circ, 0^\circ)$, and strong features at high northern and southern
507 latitudes. In the following sections we analyze these three regions separately, finding that the
508 wave features are strongly correlated with season and exhibit different behaviors with local time.
509 Nonetheless, the features are so strong and distinct that they still appear in the full dataset
510 average. Many of the observed features are replicated in the LMD-MGCM model simulations
511 (Figure 5c), but analysis will benefit from consideration of the specific seasonal conditions for
512 the occurrence of the wave structure.



513

514 **Figure 5a.** Full dataset average brightness of NO nightglow.

515 **Figure 5b.** Average brightness of NO nightglow above divided by the mission-long zonal
 516 average brightness (Figure 2c) to show the deviations from the mean brightness at all latitudes.
 517 The color scale is now shown blue-to-red to indicate variations about the mean.

518 **Figure 5c.** LMD-MGCM simulations of the same data from Figure 4a divided by the model's
 519 zonal average brightness (also from Figure 2c) to show the deviation from the mean brightness at
 520 all latitudes.

521

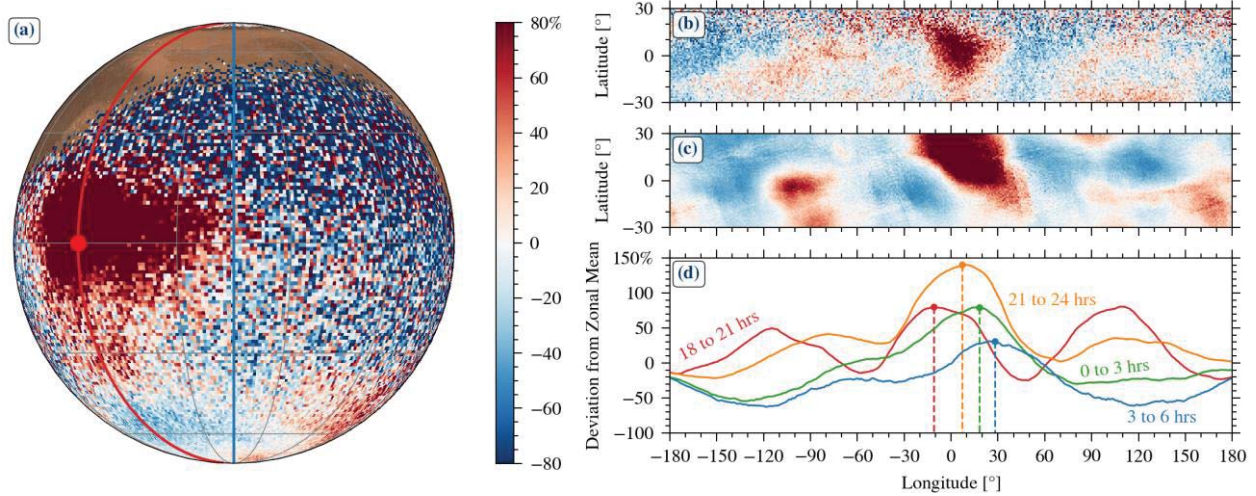
3.3.1 Equatorial wave-3 atmospheric tides

522 Figure 6 takes a closer look at the equatorial wave structure evident in the mission-long
 523 average in Figure 5a. Here we average only the equinox data when the structure was observed:
 524 $130^\circ < L_s < 175^\circ$ during MY 33 (orbits 2917 to 3379, 30 March to 24 June 2016) and $0^\circ < L_s < 60^\circ$
 525 during MY 34 (orbits 5036 to 5727, 5 May to 12 September 2017). Figure 6a shows a simulated
 526 nightside image constructed from all equinox data, with local time varying across the image.
 527 Each latitude is divided by its corresponding zonal mean across the entire data set (figure 2c),
 528 showing a strong enhancement near $(0^\circ, 0^\circ)$. Figure 6b shows the data from which this was
 529 constructed with data from all local times co-added. Two changes from the filtering are evident:
 530 first, the intensity of the enhancement near $(0^\circ, 0^\circ)$ is amplified; second, side lobes become
 531 evident in Figures 6b and 6d, indicating the presence of a wave-3 structure in addition to the
 532 bright maximum. Animations of this dataset are provided in the Supporting Information. (It bears

533 noting that *Stiepen17*'s reported equatorial wave-3 structure mentioned above occurs at a
 534 different season not directly comparable to the observations here.)

535

536



537

538 **Figure 6a.** Nightside image constructed from all equinox data with appropriate geometry from
 539 $L_s = 130-175$ in MY33 and 0-60 in MY34. The anti-solar point lies at the disk center; the red line
 540 indicates the location of the prime meridian; the blue line indicates midnight, with the evening
 541 terminator to the left and morning to the right. The local time at $(0^\circ, 0^\circ)$, indicated by the red dot,
 542 is 21 hours, when the spot is near its brightest. At each location, we smoothed the data by
 543 averaging ± 1.5 hours around the instantaneous local time.

544 Figure 6b. Cylindrical projection of the zonal mean variation of NO nightglow brightness for the
 545 same equinox period. Note the reddish regions on either side of central red peak constituting
 546 secondary maxima around $\pm 120^\circ$. The side peaks are more visible in this seasonally-restricted
 547 plot than in Figure 5a.

548 **Figure 6c.** Cylindrical projection of the zonal mean variation of the LMD-MGCM model NO
 549 nightglow brightness matching observational parameters, approximately replicating the three-
 550 peaked structure seen in the data (in Figure 6b). Note that the $(0^\circ, 0^\circ)$ spot appears even brighter
 551 in the model than the data.

552 **Figure 6d.** Observed local-time relative variation of the NO nightglow brightness for equatorial
 553 latitudes between 30° S and 30° N. The complex structure suggests a combination of wave-3 and
 554 wave-1 features, and probably some additional modes varying with time. Dashed lines mark the
 555 longitudes of the peaks of the curves, showing the eastward progression of the peaks.

556 The LMD-MGCM model simulations for these conditions are shown in Figure 6c,
 557 offering a good match to the observations. An examination of the variables controlling emission
 558 in the model confirms a spatially confined region of strong downwelling around $(0^\circ, 0^\circ)$ carrying
 559 N and O atoms down to lower altitudes where they can recombine.

560 Figure 6d shows the changing position of the wave-3 structure over four local time
 561 ranges. Different non-migrating tides can produce an apparent longitudinal wave-3 structure,

562 such as a stationary planetary wave-3 (SPW3), a diurnal eastward-propagating wave-2 (DE2),
 563 and semi-diurnal eastward-propagating wave-1 (SE1). These tides can be distinguished by their
 564 motion (if any) in local time. The observed average motion of the central peak is about 4.7°/hour
 565 eastward, consistent with the DE2 wave's 5°/hour rate and inconsistent with other non-migrating
 566 tides. In fact, it is the eastward motion of a wavenumber-2 diurnal tide that turns it into a wave-3
 567 structure when plotted vs. longitude. A tidal decomposition performed on the LMD-MGCM
 568 predicted emission (Figure 6c) also indicates that the wave-3 structure is dominated by DE2,
 569 with a much smaller contribution by SW1.

570 The clear identification of DE2 tides in the middle atmosphere at low latitudes is
 571 significant in the context of other tide identifications. DE2 has been previously identified as a
 572 dominant contributor to observed temperature variability in the lower atmosphere at low latitudes
 573 (*Wilson, 2000*). Wave-3 structures previously observed in the upper atmosphere (such as those
 574 derived from MGS aerobraking or ionospheric observations at high northern latitudes near
 575 aphelion) have usually been interpreted as the product of the semidiurnal wave-1 SE1 tide
 576 (*Bougher et al., 2004*). However, a significant contribution of the DE2 wave was acknowledged
 577 in the tropics (*Withers et al., 2003, 2011; Angelats i Coll et al., 2004*). Our result indicates that at
 578 low latitudes in the mesosphere, DE2 is still the dominant source of variability, in good
 579 agreement with the previous analysis of MCS temperature measurements in a similar altitude
 580 region (*Guzewich et al., 2012*). This result helps connect previous lower- and upper-atmosphere
 581 observations of this tidal component, providing information about the vertical propagation of the
 582 tidal modes (e.g., *Moudden and Forbes, 2008; Lee et al. 2009*).

583 The tight confinement of the (0°, 0°) spot (and its implication of highly localized
 584 downwelling) is one of the most surprising results of this work, including the excellent match
 585 with the LMD-MGCM. This suggests that the model captures the driving physics of circulation
 586 and tides in the upper mesosphere and lower thermosphere at equinox. The nightside nightglow
 587 spot is reminiscent of the statistically averaged NO nightglow brightening observed near the anti-
 588 solar point on Venus (e.g., *Stewart et al., 1979; Bougher et al., 1990; Stiepen et al., 2012; Royer*
 589 *et al., 2016*). It suggests that the circulation pattern of Mars' mesosphere during equinox has
 590 similarities to Venus's dayside-to-nightside circulation pattern.

591 3.3.2 Wave-2 structure at the northern winter pole

592 The poles are regions of intense NO emission during the extended winter night, with very
 593 strong latitudinal gradients which make wave structures challenging to detect. Figure 7a shows
 594 the averaged northern polar brightness for $240^\circ < L_s < 360^\circ$. Contours show an elliptical
 595 distribution around the pole. The long axis of the 1.5 kR contour is about 50% greater than the
 596 short axis, extending southward towards longitudes -15° and 150° . Examination of the images
 597 contributing to this seasonal mean shows high variability, with a strong tendency for bright
 598 patches or fingers of emission near these longitudes at 5-10° away from the pole. The pole itself
 599 is consistently brighter than lower latitudes, but is rarely the brightest location on the planet.

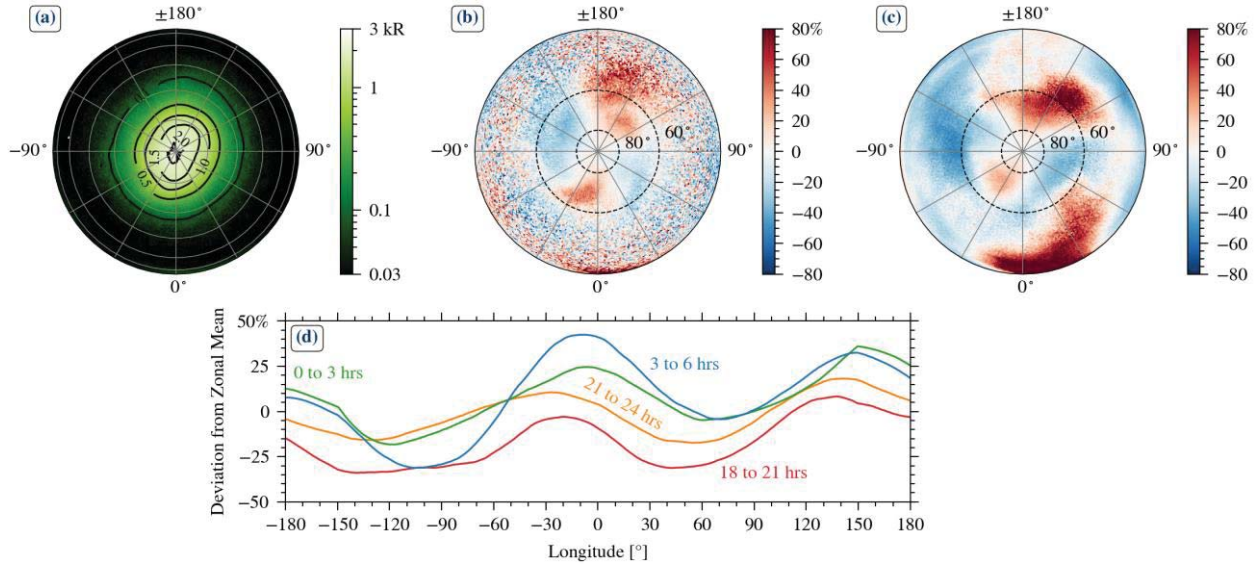
600 Figure 7b shows the average brightnesses divided by the zonal mean, such that the oval
 601 structure appears as a longitudinal wave-2 structure, with a hint of a spiral structure extending
 602 westward farther from the pole. The wave amplitude is less than 25% around the zonal mean,
 603 much less than that observed in equatorial regions.

604 Figure 7c shows the LMD model simulations corresponding to these observations,
605 presenting a very good wave-2 match to the observations, with two peaks offset to the west by
606 about 15° relative to the observations. At this level, the model is evidently capturing the
607 dominant physics.

608 Figure 7d examines the local time behavior of the wave structure, showing a general
609 increase in average brightness as local time progresses. Evidence for tidal motion is ambiguous,
610 as the motion of the peaks is not regular. While the peaks move significantly between the earliest
611 and latest local times, the spiral structure evident in the data links latitudinal structure to
612 longitudinal motion and inhibits further analysis. We therefore cannot distinguish at this level
613 whether the structure is a stationary wave or a non-migrating tide. The potential identification of
614 stationary waves should not be construed as evidence against other wave types such as planetary
615 waves. The seasonal means used here of necessity average out shorter term variations, and it
616 remains possible that such waves are superposed on the stationary waves. In fact, preliminary
617 analysis of model output suggests baroclinic waves are expected, and a subsequent study will
618 search for them in the observations.

619 The behavior at the nightglow peak altitude can be compared to phenomena at other
620 altitudes, such as ozone in the troposphere. *Clancy et al.* (2016) observed a prominent wave-2
621 feature in late northern winter (their Figure 8), but it propagated eastward over a period of days,
622 characteristic of a planetary wave. They also identified a wave-1 stationary wave (their Figure 5)
623 peaking around -45° in late northern spring. While this matches one of the NO features at higher
624 altitude, there is no second maximum corresponding to the NO peak at 135° . Further modeling,
625 beyond the scope of this work, will be needed to tie together these phenomena at different
626 altitudes, seasons, and years.

627 Waves induced by the northern hemisphere topography are well known on Mars at high
628 latitudes and have been shown to propagate well through the eastward jet stream present in the
629 Martian atmosphere at high northern latitudes during spring and summer (*Barnes et al.*, 1996).
630 An analysis of the stationary variations in the temperature fields observed by MGS/TES
631 confirms the presence of a strong wave-2 during northern winter and spring combined with a
632 stationary wave-1 which may explain the observed asymmetry between the hemisphere centered
633 around 30° E and the opposite hemisphere centered around -150° E in Figure 7a. MCS
634 observations show that a stationary wave-2 signature was present at all northern latitudes up to
635 70° N (*Guzewich et al.*, 2012). Our result confirms for the first time the dominance of this wave
636 mode in the mesosphere in the North polar region, at least during the polar winter.
637



638

639 **Figure 7a.** Northern polar projection of the mean brightness of the NO nightglow in the period
 640 around northern winter. Polar latitudes were observed exclusively in winter ($L_s=235^\circ$ - 350°
 641 during MY33 and 150° - 210° during MY 34), while midlatitudes were observed over a broader
 642 range of L_s solar longitudes. These differences do not affect the wave structure.

643 **Figure 7b.** Variation in NO nightglow brightness relative to the zonal mean across all local
 644 times. The region selected for the wave analysis in 7d is indicated with two dashed parallels at
 645 60° N and 80° N, respectively. The larger variation at latitudes less than 60° N is caused by the
 646 significantly lower zonal mean brightness (see Figure 2c).

647 **Figure 7c.** Same as Figure 7b, but for the LMD model simulations sampled to match the data.
 648 The model matches well within the dashed lines. (The red spot at the bottom of the image is the
 649 equatorial spot discussed in the previous section.)

650 **Figure 7d.** Local-time zonal mean variation of the northern polar NO nightglow brightness
 651 averaged between 60° N and 80° N latitude. Each curve shows 3-hour averages.

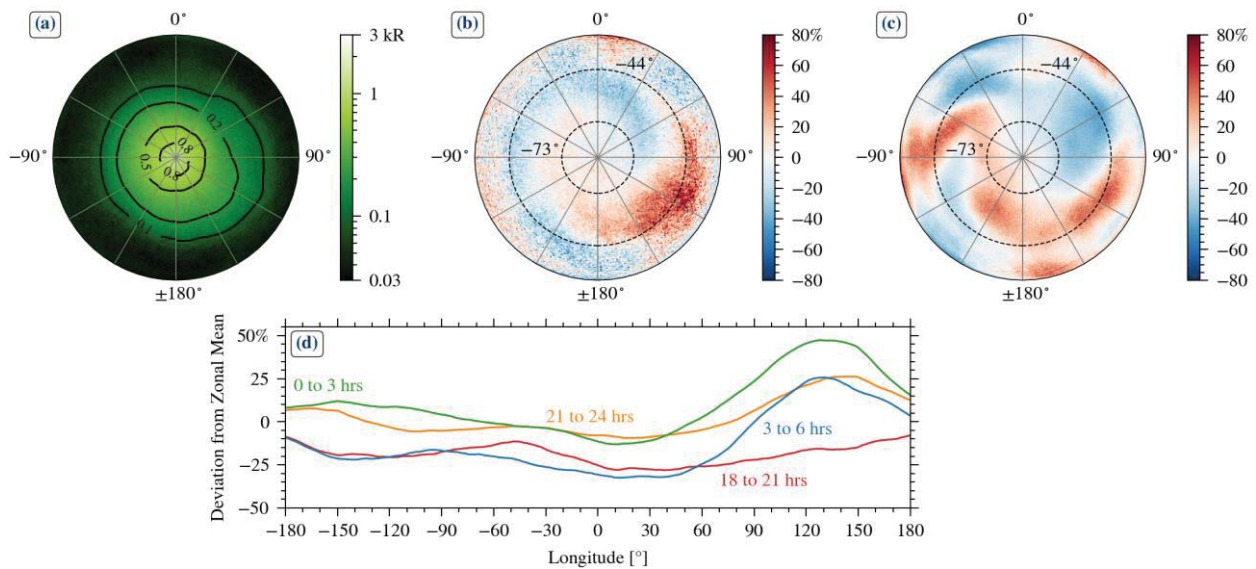
652 3.3.3 Wave-1 structure at the southern winter pole

653 During southern polar winter, the average brightness structure also appears as an oval but
 654 slightly off-center from the pole (Figure 8a), representing an average of a spatially patchy and
 655 temporally variable appearance from orbit-to-orbit. When divided by the zonal mean, we observe a
 656 wave-1 feature and a clear spiral pattern in the variation about the zonal mean (Figure 8b), notably
 657 different from the north pole wave structure. There is a large positive deviation around 120°
 658 longitude, and a corresponding negative deviation near 30° longitude.

659 Figure 8c shows the LMD model simulations for these observations. At most latitudes the
 660 model predicts a wave-2 structure differing from the observed wave-1 structure. One model
 661 maximum lies in the longitude range from -150° to $+120^\circ$, in good correspondence to the
 662 observations, but an additional peak around -60° has no observed counterpart. Whatever physics
 663 drives the wave-1 versus wave-2 difference between the poles is apparently not captured in the
 664 model.

665 Figure 8d shows the local-time decomposition of the average amplitude of the zonal
 666 mean variation between latitudes 73° S and 44° S. The average intensity starts very low in the
 667 early evening. It increases with local time past midnight, as it does at the north, but then falls
 668 slightly in the last interval. The wave-1 structure is most prominent after midnight, but there is
 669 no discernable motion. This leads us to conclude that the observed peak is likely caused by a
 670 stationary planetary wave-1. Analysis of the model results at 70° S, where model predictions are
 671 most similar to observations, show a combination of a wave-1 quasi-stationary wave with the
 672 influence of the diurnal tide and a baroclinic wave-1 with a period of about 7 to 10 sols. As for
 673 the northern winter case, the seasonal average masks the signature of the shorter period waves,
 674 emphasizing the importance of the stationary wave.

675 Strong wave-1 stationary waves signatures have been previously observed in the lower
 676 atmosphere by the Thermal Emission Spectrometer (TES) on Mars Global Surveyor, (*e.g.*,
 677 *Barnes et al.* (2003)) and in the mesosphere by MCS (*Guzewich et al.*, 2012). Our measurements
 678 present complete latitudinal coverage offering new insights into the structure of the stationary
 679 waves in both winter polar regions.



680 **Figure 8a.** Southern polar projection of the NO nightglow brightness in the period around
 681 southern winter (same as Figure 7 for the north). Data poleward of 60° S were obtained between
 682 $L_s=130^\circ$ - 175° in during MY 33 and 24° - 106° during MY 34 while midlatitudes were observed
 683 over a broader range of solar longitudes.

685 **Figure 8b.** Southern polar projection of the zonal mean variation of the NO nightglow
 686 brightness. Dashed lines indicate the latitude region between 73° S and 44° S selected for wave
 687 analysis in 8d. This range captures the bulk of the observed variability while minimizing the
 688 influence from other mid-latitude features.

689 **Figure 8c.** Same as figure 8b, but for the LMD model simulations sampled to match the data.
 690 The model matches adequately at longitudes around 120° , but exhibits a second feature around
 691 -60° that was not observed.

692 **Figure 8d.** Local-time zonal mean variation of the southern polar NO nightglow brightness
 693 averaged between 73° S and 44° S latitude. Each curve shows 3-hour averages.

694 4 Conclusions and future work

695 IUVS nitric oxide nightglow disk images are an unanticipated bonus of the MAVEN
696 mission. They are unique among Mars datasets in providing good coverage in latitude, longitude,
697 local time and season (solar longitude). This four-dimensional coverage removes biases and
698 ambiguities inherent in observations fixed in local time (as many orbiters) or latitude and
699 longitude (specifically landed assets). The images have proven to be a powerful tool for the
700 identification of atmospheric downwelling regions and their modulation by waves and tides.
701 Furthermore, they highlight seasonal transitions in circulation patterns. The observed effects are
702 of such large amplitude and high signal-to-noise ratio that subsequent analyses could subdivide
703 the dataset more finely than attempted in this synoptic approach.

704 The dataset presented here, by virtue of this extensive coverage, offers the most complete
705 observations to date bearing on mesospheric circulation and tides. The main results can be
706 succinctly stated as seasonal changes in latitudinal structure modulated by tides in longitude and
707 local time: During the equinoxes, an emission peak due to equatorial downwelling forms with
708 very strong DE2 tidal modulation. Polar brightenings occur throughout much of the year and are
709 strongest around the winter solstices. They are caused by downwelling from the thermosphere
710 and subsequent horizontal transport to the nightside; the polar emissions are further modulated
711 by waves that differ between north and south poles. These top-level results stand alone for their
712 direct insights into the mesosphere, though more important implications will come when
713 integrated with our understanding of circulation, waves, and tides in the troposphere below and
714 thermosphere above. In particular, future analyses should examine the connections in circulation
715 patterns between these layers and the propagation of tides from the bottom to the top of the
716 atmosphere. Together, these should allow advances in understanding the mechanisms behind
717 these phenomena.

718 The LMD-MGCM matches most features of the observations with remarkable accuracy.
719 The match is especially significant because the model did not require any tuning or optimization
720 based on the observations. A good match to polar winter enhancements was expected after the
721 comparison in *Stiepen17*, though their lack of data poleward of $\pm 70^\circ$ latitude prevented as
722 complete an analysis as here. Similarly, the equatorial equinox enhancements were present in
723 both observations and models presented in *Stiepen17*, so the good match presented here is
724 consistent. The good match in tidal modes presented here is a new result, and the quality of
725 agreement is arguably better than would be expected without tuning of the model. This is
726 especially true for the match to the geographic location of the $(0^\circ, 0^\circ)$ spot. A closer look at the
727 underlying physics in the model behind the polar enhancements should be undertaken in the
728 future.

729 Despite the overall good match by the LMD-MGCM, several significant data/model
730 discrepancies stand out and offer opportunities for model improvements. First, the observed
731 global average nightglow intensity is higher than the model value by a factor of 1.9. The model
732 either underestimates the creation of atomic N and O, or overestimates their loss through non-
733 radiative paths. In either case, there are likely to be ramifications for other aspects of
734 atmospheric chemistry once the model matches the observed brightnesses. Since the largest
735 mismatches occur well away from the poles, a search for mechanisms to boost emission there in
736 the model will be needed. Second, the model fails to match the local time behavior of the
737 strongest tide feature observed, the $(0^\circ, 0^\circ)$ spot associated with the DE2 tide. The spot peaks
738 well before midnight in the observations and well after midnight in the model. Our model run

739 examination offers the possibility that predicting emission too low in altitude shifts the peak too
740 late in the night. Alternatively, the implementation of diurnal tides in the relevant altitude range
741 may be incorrect, not being constrained by any other observations. Since prior IUVS results on
742 NO nightglow altitude profiles found that the model predicts emission too high, the error in
743 diurnal tides seems more plausible. Finally, the observed south polar wave structure is not well
744 matched by the LMD-MGCM. The model mechanism driving the second longitudinal maximum
745 around -60° needs to be identified, and reasons for its overestimation investigated. It may be that
746 higher model resolution, as used in *Pottier et al. (2017)* will be useful.

747 We have presented here only the top-level conclusions from IUVS observations using
748 heavily averaged data, so many paths present themselves for deeper analysis. First, the wave and
749 tide analysis should be greatly expanded through detailed harmonic analysis of the wave
750 structures including tidal decomposition and Hovmöller analyses. Similar approaches could
751 search for ultra-fast Kelvin waves; such waves with periods more than one sol are suppressed by
752 the methods used in this work. Second, much can be learned from a study of the day-to-day
753 variability of NO nightglow images. In polar regions, a search should be carried out for Rossby
754 waves comparable to those seen in ozone distributions lying tens of kilometers below. The high
755 frequency of IUVS images could also help precisely quantify the impact of changes in solar
756 activity on the NO nightglow emission and a GCM could be coupled to observations to track
757 back the emission to the production rates of N and O in the dayside and their transport to the
758 nightside. This would benefit from IUVS observations over larger variations of solar activities.
759 The higher-level data products used in this paper would be suitable for all these studies, and are
760 made available to the community as described the following section.

761 **Acknowledgments and Data Availability**

762 The MAVEN mission is supported by NASA through the Mars Exploration Program in
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764 level 1B data (spatially-resolved spectra) are available in the Planetary Data System (PDS),
765 labeled v13_r02 tagged with "apoapse" at [https://pds-](https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/MAVEN/maven_iuvs.html)
766 [atmospheres.nmsu.edu/data_and_services/atmospheres_data/MAVEN/maven_iuvs.html](https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/MAVEN/maven_iuvs.html). This
767 work used high-level data products (MLR brightnesses derived from PDS products) which will
768 be archived in the FAIR-compliant CU Scholar Repository (<https://doi.org/10.25810/fke8-7z93>).
769 The LMD-MGCM model results used in this paper are also available at the CU Scholar
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781 **References**

- 782 Angelats i Coll, M. (2004). Upper atmosphere of Mars up to 120 km: Mars Global Surveyor
 783 accelerometer data analysis with the LMD general circulation model. *Journal of*
 784 *Geophysical Research*, *109*(E1). doi: 10.1029/2003je002163
- 785 Banfield, D., Conrath, B. J., Smith, M. D., Christensen, P. R., & Wilson, R. J. (2003). Forced
 786 waves in the martian atmosphere from MGS TES nadir data. *Icarus*, *161*(2), 319–345.
 787 doi: 10.1016/s0019-1035(02)00044-1
- 788 Banfield, D., Conrath, B. J., Gierasch, P. J., Wilson, R. J., & Smith, M. D. (2004). Traveling
 789 waves in the martian atmosphere from MGS TES Nadir data. *Icarus*, *170*(2), 365–403.
 790 doi: 10.1016/j.icarus.2004.03.015
- 791 Barnes, J. R., Haberle, R. M., Pollack, J. B., Lee, H., & Schaeffer, J. (1996). Mars atmospheric
 792 dynamics as simulated by the NASA Ames general circulation model: 3. Winter quasi-
 793 stationary eddies. *Journal of Geophysical Research: Planets*, *101*(E5), 12753–12776.
 794 doi: 10.1029/96je00179
- 795 Barnes, J.R. (2003). Mars Weather Systems and Maps: FFSM Analyses of MGS TES
 796 Temperature Data. Sixth International Conference on Mars, July 20-25 2003, Pasadena,
 797 California, abstract no.3127
- 798 Bell, J.M., S.W. Bougher, J.R. Murphy (2007). Vertical dust mixing and the interannual
 799 variations in the Mars thermosphere. *Journal of Geophysical Research*: 112 (E12), doi:
 800 10.1029/2006JE002856
- 801 Bertaux, J.-L., Leblanc, F., Perrier, S., Quemerais, E., Korablev, O., Dimarellis, E., ... Sandel, B.
 802 (2005). Nightglow in the Upper Atmosphere of Mars and Implications for Atmospheric
 803 Transport. *Science*, *307*(5709), 566–569. doi: 10.1126/science.1106957
- 804 Bertaux, J.-L., Korablev, O., Perrier, S., Quémerais, E., Montmessin, F., Leblanc, F., ... Guibert,
 805 S. (2006). SPICAM on Mars Express: Observing modes and overview of UV
 806 spectrometer data and scientific results. *Journal of Geophysical Research*, *111*(E10). doi:
 807 10.1029/2006je002690
- 808 Bertaux, J. L., Gondet, B. P., Lefèvre, F. undefined, Bibring, J. undefined, & Montmessin, F.
 809 undefined. (2012). First detection of O 21.27 μm nightglow emission at Mars with
 810 OMEGA/MEX and comparison with general circulation model predictions. *Journal of*
 811 *Geophysical Research: Planets*, *117*(E11). doi: 10.1029/2011je003890
- 812 Bougher, S. W., Gérard, J. C., Stewart, A. I. F., & Fesen, C. G. (1990). The Venus nitric oxide
 813 night airglow: Model calculations based on the Venus thermospheric general circulation
 814 model. *Journal of Geophysical Research*, *95*(A5), 6271. doi: 10.1029/ja095ia05p06271

- 815 Bougher, S. W., Engel, S., Hinson, D. P., & Murphy, J. R. (2004). MGS Radio Science electron
 816 density profiles: Interannual variability and implications for the Martian neutral
 817 atmosphere. *Journal of Geophysical Research*, *109*(E3). doi: 10.1029/2003je002154
- 818 Bougher, S. W., Rafkin, S., & Drossart, P. (2006). Dynamics of the Venus upper atmosphere:
 819 Outstanding problems and new constraints expected from Venus Express. *Planetary and*
 820 *Space Science*, *54*(13-14), 1371–1380. doi: 10.1016/j.pss.2006.04.023
- 821 Bougher, S. W., Pawlowski, D., Bell, J. M., Nelli, S., Mcdunn, T., Murphy, J. R., ... Ridley, A.
 822 (2015). Mars Global Ionosphere-Thermosphere Model: Solar cycle, seasonal, and diurnal
 823 variations of the Mars upper atmosphere. *Journal of Geophysical Research:*
 824 *Planets*, *120*(2), 311–342. doi: 10.1002/2014je004715
- 825 Bougher, S. W., D. A. Brain, J. L. Fox, F. Gonzalez-Galindo, C. Simon-Wedlund, and P. G.
 826 Withers (2017). Chapter 14: Upper Neutral Atmosphere and Ionosphere, in *The*
 827 *Atmosphere and Climate of Mars*, ed. B. Haberle, M. Smith, T. Clancy, F. Forget, R.
 828 Zurek, Cambridge University Press, doi:10.1017/9781107016187
- 829 Brecht, A. S., Bougher, S. W., Gérard, J.-C., Parkinson, C. D., Rafkin, S., & Foster, B. (2011).
 830 Understanding the variability of nightside temperatures, NO UV and O2IR nightglow
 831 emissions in the Venus upper atmosphere. *Journal of Geophysical Research*, *116*(E8).
 832 doi: 10.1029/2010je003770
- 833 Brecht, A. S., S. W. Bougher, E. Yigit, H.-L. Liu (2019). Understanding the Impact of Waves on
 834 Venus' Upper Atmosphere through General Circulation Model Simulations, International
 835 Venus Conference 2019, 74th Fujihara Seminar, abstract, Hokkaido, Japan, 31-May to 3-
 836 June 2019.
- 837 Clancy, R. T., Sandor, B. J., Wolff, M. J., Smith, M. D., Lefèvre, F., Madeleine, J.-B., ...
 838 Heavens, N. (2012). Extensive MRO CRISM observations of 1.27 μ m O2airglow in Mars
 839 polar night and their comparison to MRO MCS temperature profiles and LMD GCM
 840 simulations. *Journal of Geophysical Research: Planets*, *117*(E11). doi:
 841 10.1029/2011je004018
- 842 Clancy, R. T., Sandor, B. J., Wolff, M. J., Smith, M. D., Lefèvre, F., Madeleine, J.-B., ...
 843 Heavens, N. (2013a). Correction to “Extensive MRO CRISM observations of 1.27 μ m
 844 O2airglow in Mars polar night and their comparison to MRO MCS temperature profiles
 845 and LMD GCM simulations.” *Journal of Geophysical Research: Planets*, *118*(5), 1148–
 846 1154. doi: 10.1002/jgre.20073
- 847 Clancy, R. T., Sandor, B. J., García-Muñoz, A., Lefèvre, F., Smith, M. D., Wolff, M. J., ... Nair,
 848 H. (2013b). First detection of Mars atmospheric hydroxyl: CRISM Near-IR measurement
 849 versus LMD GCM simulation of OH Meinel band emission in the Mars polar winter
 850 atmosphere. *Icarus*, *226*(1), 272–281. doi: 10.1016/j.icarus.2013.05.035

- 851 Clancy, R. T., Wolff, M. J., Lefèvre, F., Cantor, B. A., Malin, M. C., & Smith, M. D. (2016).
 852 Daily global mapping of Mars ozone column abundances with MARCI UV band
 853 imaging. *Icarus*, 266, 112–133. doi: 10.1016/j.icarus.2015.11.016
- 854 Cox, C., Saglam, A., Gérard, J.-C., Bertaux, J.-L., González-Galindo, F., Leblanc, F., & Reberac,
 855 A. (2008). Distribution of the ultraviolet nitric oxide Martian night airglow: Observations
 856 from Mars Express and comparisons with a one-dimensional model. *Journal of*
 857 *Geophysical Research*, 113(E8). doi: 10.1029/2007je003037
- 858 Eastes, R.W., R.E Huffman, F.J. Leblanc (1992). NO and O₂ ultraviolet nightglow and
 859 spacecraft glow from the S3–4 satellite. *Planetary and Space Science*, 40, 481-493.
 860 doi: 10.1016/0032-0633(92)90168-N
- 861 Elrod, M. K., S. W. Bougher, J. M. Bell, P. R. Mahaffy, M. Benna, S. Stone, R. Yelle, and B. M.
 862 Jakosky (2017). He bulge revealed: He and CO₂ diurnal and seasonal variations in the
 863 upper atmosphere of Mars as detected by MAVEN NGIMS, *J. Geophys. Res. Space*
 864 *Physics*, 122, 2564-2573. doi:10.1002/2016JA023482
- 865 England, S. L., Liu, G., Withers, P., Yiğit, E., Lo, D., Jain, S., ... Jakosky, B. M. (2016).
 866 Simultaneous observations of atmospheric tides from combined in situ and remote
 867 observations at Mars from the MAVEN spacecraft. *Journal of Geophysical Research:*
 868 *Planets*, 121(4), 594–607. doi: 10.1002/2016je004997
- 869 England, S. L., Liu, G., Kumar, A., Mahaffy, P. R., Elrod, M., Benna, M., et al. (2019).
 870 Atmospheric tides at high latitudes in the Martian upper atmosphere observed by
 871 MAVEN and MRO. *Journal of Geophysical Research: Space Physics*, 124, 2943–2953.
 872 doi.org/10.1029/2019JA026601
- 873 Eparvier, F., P. Chamberlin, T. Woods, and E. Thiemann (2015), The solar extreme ultraviolet
 874 monitor for MAVEN, *Space Sci. Rev.*, **195**(1–4), 293– 301.
- 875 Fedorova, A. A., Lefèvre, F., Guslyakova, S., Korablev, O., Bertaux, J.-L., Montmessin, F., ...
 876 Gondet, B. (2012). The O₂ nightglow in the Martian atmosphere by SPICAM onboard of
 877 Mars-Express. *Icarus*, 219(2), 596–608. doi: 10.1016/j.icarus.2012.03.031
- 878 Forbes, J. M., Bridger, A. F. C., Bougher, S. W., Hagan, M. E., Hollingsworth, J. L., Keating, G.
 879 M., & Murphy, J. (2002). Nonmigrating tides in the thermosphere of Mars. *Journal of*
 880 *Geophysical Research: Planets*, 107(E11). doi: 10.1029/2001je001582
- 881 Forget, F., F. Hourdin, R. Fournier, C. Hourdin, O. Talagrand, M. Collins, S. R. Lewis, P. L.
 882 Read, and J.-P. Huot (1999), Improved general circulation models of the Martian
 883 atmosphere from the surface to above 80 km, *J. Geophys. Res.*, 104, 24,155–24,176.
 884 doi: 10.1029/1999JE001025

- 885 Gagné, M.-È., Melo, S. M. L., Lefèvre, F., González-Galindo, F., & Strong, K. (2012). Modeled
 886 O₂ airglow distributions in the Martian atmosphere. *Journal of Geophysical Research:*
 887 *Planets*, 117(E6). doi: 10.1029/2011je003901
- 888 Gagné, M.-È., Bertaux, J.-L., González-Galindo, F., Melo, S. M. L., Montmessin, F., & Strong,
 889 K. (2013). New nitric oxide (NO) nightglow measurements with SPICAM/MEx as a
 890 tracer of Mars upper atmosphere circulation and comparison with LMD-MGCM model
 891 prediction: Evidence for asymmetric hemispheres. *Journal of Geophysical Research:*
 892 *Planets*, 118(10), 2172–2179. doi: 10.1002/jgre.20165
- 893 Gérard, J.-C., Bougher, S. A., López-Valverde, M., Pätzold, M., Drossart, P., & Piccioni, G.
 894 (2017). Aeronomy of the Venus Upper Atmosphere. *Space Science Reviews*, 212(3-4),
 895 1617–1683. doi: 10.1007/s11214-017-0422-0
- 896 Gilli, G., Forget, F., Spiga, A., Navarro, T., Montabone, L., Millour, E. (2020). Impact of gravity
 897 waves on the middle atmosphere of Mars: a non-orographic gravity wave
 898 parameterization based on Global Climate modeling and MCS observations, accepted in
 899 *J. Geophys. Res.* Doi: 10.1029/2018JE005873
- 900 González-Galindo, F., Forget, F., López-Valverde, M. A., Angelats i Coll, M., & Millour, E.
 901 (2009). A ground-to-exosphere Martian general circulation model: 1. Seasonal, diurnal,
 902 and solar cycle variation of thermospheric temperatures. *Journal of Geophysical*
 903 *Research*, 114(E4). doi: 10.1029/2008je003246
- 904 González-Galindo, F., López-Valverde, M. A., Forget, F., García-Comas, M., Millour, E., &
 905 Montabone, L. (2015). Variability of the Martian thermosphere during eight Martian
 906 years as simulated by a ground-to-exosphere global circulation model. *Journal of*
 907 *Geophysical Research: Planets*, 120(11), 2020–2035. doi: 10.1002/2015je004925
- 908 Gröller, H., Montmessin, F., Yelle, R. V., Lefèvre, F., Forget, F., Schneider, N. M., et al. (2018).
 909 MAVEN/IUVS stellar occultation measurements of Mars atmospheric structure and com-
 910 position. *Journal of Geophysical Research: Planets*, 123, 1449–1483. doi:
 911 10.1029/2017JE005466
- 912 Guzewich, S. D., Talaat, E. R., & Waugh, D. W. (2012). Observations of planetary waves and
 913 nonmigrating tides by the Mars Climate Sounder. *Journal of Geophysical Research:*
 914 *Planets*, 117(E3). doi: 10.1029/2011je003924
- 915 Hess, S. L., Henry, R. M., Leovy, C. B., Ryan, J. A., & Tillman, J. E. (1977). Meteorological
 916 results from the surface of Mars: Viking 1 and 2. *Journal of Geophysical*
 917 *Research*, 82(28), 4559–4574. doi: 10.1029/js082i028p04559
- 918 Hinson, D. P. (2006). Radio occultation measurements of transient eddies in the northern
 919 hemisphere of Mars. *Journal of Geophysical Research*, 111(E5). doi:
 920 10.1029/2005je002612

- 921 Jakosky, B. M., R. P. Lin, J. M. Grebowsky, J. G. Luhmann, D. F. Mitchell, G. Beutelschies, ...
 922 R. Zurek (2015). The Mars Atmosphere and Volatile Evolution (MAVEN) Mission.
 923 *Space Science Reviews*, 195(1–4), 3–48. doi: 10.1007/s11214-015-0139-x
- 924 Keating, G. M., Bougher, S. W., Zurek, R. W., Tolson, R. H., Cancro, G. J., Noll, S. N., ...
 925 Babicke, J. M. (1998). The Structure of the Upper Atmosphere of Mars: In Situ
 926 Accelerometer Measurements from Mars Global Surveyor. *Science*, 279(5357), 1672–
 927 1676. doi: 10.1126/science.279.5357.1672
- 928 Lee, C., et al. (2009), Thermal tides in the Martian middle atmosphere as seen by the Mars
 929 Climate Sounder, *J. Geophys. Res.*, 114, E03005, doi:10.1029/2008JE003285.
- 930 Lewis, S. R., Mulholland, D. P., Read, P. L., Montabone, L., Wilson, R. J., & Smith, M. D.
 931 (2016). The solsticial pause on Mars: 1. A planetary wave reanalysis. *Icarus*, 264, 456–
 932 464. doi: 10.1016/j.icarus.2015.08.039
- 933 Lo, D. Y., Yelle, R. V., Schneider, N. M., Jain, S. K., Stewart, A. I. F., England, S. L., ...
 934 Jakosky, B. M. (2015). Nonmigrating tides in the Martian atmosphere as observed by
 935 MAVEN IUVS. *Geophysical Research Letters*, 42(21), 9057–9063. doi:
 936 10.1002/2015gl066268
- 937 McClintock, W. E., Schneider, N. M., Holsclaw, G. M., Clarke, J. T., Hoskins, A. C., Stewart, I.
 938 V., ... Deighan, J. (2015). The Imaging Ultraviolet Spectrograph (IUVS) for the
 939 MAVEN Mission. *Space Science Reviews*, 195(1-4), 75–124. doi: 10.1007/s11214-014-
 940 0098-7
- 941 Medvedev, A. S., Yiğit, E., Hartogh, P., & Becker, E. (2011). Influence of gravity waves on the
 942 Martian atmosphere: General circulation modeling. *Journal of Geophysical*
 943 *Research*, 116(E10). doi: 10.1029/2011je003848
- 944 Medvedev, A. S., et al. (2016), Comparison of the Martian thermospheric density and
 945 temperature from IUVS/MAVEN data and general circulation modeling, *Geophys. Res.*
 946 *Let.*, 43, 3095–3104, doi:10.1002/2016GL068388.
- 947 Millour et al. (2018). Exploring the interannual variability of the Martian atmosphere with the
 948 Mars Climate Database v5.3. *42nd COSPAR Scientific Assembly*, C4.3-6-18.
- 949 Montabone, L., Forget, F., Millour, E., Wilson, R. J., Lewis, S. R., Cantor, B., et al. (2015).
 950 Eight-year climatology of dust optical depth on Mars. *Icarus*, 251, 65–95.
 951 <https://doi.org/10.1016/j.icarus.2014.12.034>
- 952 Montmessin, F., Forget, F., Rannou, P., Cabane, M., & Haberle, R. M. (2004). Origin and role of
 953 water ice clouds in the Martian water cycle as inferred from a general circulation
 954 model. *Journal of Geophysical Research*, 109(E10). doi: 10.1029/2004je002284
 955

- 956 Moudden, Y. and J. M. Forbes (2008). Effects of vertically propagating thermal tides on the
 957 mean structure and dynamics of Mars' lower thermosphere. *Geophysical Research*
 958 *Letters*, 35, L23805, doi:10.1029/2008GL036086
- 959 Pottier, A., Forget, F., Montmessin, F., Navarro, T., Spiga, A., Millour, E., ... Madeleine, J.-B.
 960 (2017). Unraveling the Martian water cycle with high-resolution global climate
 961 simulations. *Icarus*, 291, 82–106. doi: 10.1016/j.icarus.2017.02.016
- 962 Royer, E., Montmessin, F., & Bertaux, J.-L. (2010). NO emissions as observed by SPICAV
 963 during stellar occultations. *Planetary and Space Science*, 58(10), 1314–1326. doi:
 964 10.1016/j.pss.2010.05.015
- 965 Royer, E. M., Montmessin, F., & Marcq, E. (2016). Variability of the nitric oxide nightglow at
 966 Venus during solar minimum. *Journal of Geophysical Research: Planets*, 121(5), 846–
 967 853. doi: 10.1002/2016je005013
- 968 Schneider, N. M., Deighan, J. I., Jain, S. K., Stiepen, A., Stewart, A. I. F., Larson, D., ...
 969 Jakosky, B. M. (2015). Discovery of diffuse aurora on Mars. *Science*, 350(6261). doi:
 970 10.1126/science.aad0313
- 971 Schneider, N. M., Jain, S. K., Deighan, J., Nasr, C. R., Brain, D. A., Larson, D., et al. (2018).
 972 Global aurora on Mars during the September 2017 space weather event. *Geophysical*
 973 *Research Letters*, 45, 7391–7398. <https://doi.org/10.1029/2018GL077772>
- 974 Smith, F. L., & Smith, C. (1972). Numerical evaluation of Chapman's grazing incidence integral
 975 Ch(X, χ). *Journal of Geophysical Research*, 77(19), 3592–3597. doi:
 976 10.1029/JA077i019p03592
- 977 Stevens, M. H., Evans, J. S., Schneider, N. M., Stewart, A. I. F., Deighan, J., Jain, S. K., ...
 978 Jakosky, B. M. (2015). New observations of molecular nitrogen in the Martian upper
 979 atmosphere by IUVS on MAVEN. *Geophysical Research Letters*, 42(21), 9050–9056.
 980 doi: 10.1002/2015gl065319
- 981 Stevens, M. H., Siskind, D. E., Evans, J. S., Fox, J. L., Deighan, J., Jain, S. K., & Schneider, N.
 982 M. (2019). Detection of the nitric oxide dayglow on Mars by MAVEN/IUVS. *Journal of*
 983 *Geophysical Research: Planets*, 124. <https://doi.org/10.1029/2019JE005945>
- 984 Stewart, A. I., & Barth, C. A. (1979). Ultraviolet Night Airglow of Venus. *Science*, 205(4401),
 985 59–62. doi: 10.1126/science.205.4401.59
- 986 Stewart, A. I. F., Gérard, J.-C., Rusch, D. W., & Bougher, S. W. (1980). Morphology of the
 987 Venus ultraviolet night airglow. *Journal of Geophysical Research*, 85(A13), 7861–7870.
 988 doi: 10.1029/ja085ia13p07861

- 989 Stiepen, A., Soret, L., Gérard, J.-C., Cox, C., & Bertaux, J.-L. (2012). The vertical distribution of
990 the Venus NO nightglow: Limb profiles inversion and one-dimensional
991 modeling. *Icarus*, 220(2), 981–989. doi: 10.1016/j.icarus.2012.06.029
- 992 Stiepen, A., Gérard, J.-C., Dumont, M., Cox, C., & Bertaux, J.-L. (2013). Venus nitric oxide
993 nightglow mapping from SPICAV nadir observations. *Icarus*, 226(1), 428–436. doi:
994 10.1016/j.icarus.2013.05.031
- 995 Stiepen, A., Gérard, J.-C., Gagné, M.-È., Montmessin, F., & Bertaux, J.-L. (2015). Ten years of
996 Martian nitric oxide nightglow observations. *Geophysical Research Letters*, 42(3), 720–
997 725. doi: 10.1002/2014gl062300
- 998 Stiepen, A., Jain, S. K., Schneider, N. M., Deighan, J. I., González-Galindo, F., Gérard, J.-C., ...
999 Jakosky, B. M. (2017). Nitric oxide nightglow and Martian mesospheric circulation from
1000 MAVEN/IUVS observations and LMD-MGCM predictions. *Journal of Geophysical
1001 Research: Space Physics*, 122(5), 5782–5797. doi: 10.1002/2016ja023523
- 1002 Tennyson P. D., P.D. Feldman, P. D. G.F. Hartig, R.C. Henry (1986). *Journal of Geophysical
1003 Research*, 91, 12291, 10141-10146. doi: 10.1029/JA091iA09p10141
- 1004 Wilson, R. J., & Hamilton, K. (1996). Comprehensive Model Simulation of Thermal Tides in the
1005 Martian Atmosphere. *Journal of the Atmospheric Sciences*, 53(9), 1290–1326. doi:
1006 10.1175/1520-0469(1996)053<1290:cmsott>2.0.co;2
- 1007 Wilson, R. J. (2000). Evidence for Diurnal Period Kelvin Waves in the Martian Atmosphere
1008 from Mars Global Surveyor TES Data. *Geophysical Research Letters*, 27(23). doi:
1009 10.1029/2000GL012028
- 1010 Wilson, R. J. (2002). Evidence for nonmigrating thermal tides in the Mars upper atmosphere
1011 from the Mars Global Surveyor Accelerometer Experiment. *Geophysical Research
1012 Letters*, 29(7). doi: 10.1029/2001gl013975
- 1013 Withers, P., Bougher, S. W., & Keating, G. M. (2003). The effects of topographically-controlled
1014 thermal tides in the martian upper atmosphere as seen by the MGS
1015 accelerometer. *Icarus*, 164(1), 14–32. doi: 10.1016/s0019-1035(03)00135-0
- 1016 Withers, P., Pratt, R., Bertaux, J.-L., & Montmessin, F. (2011). Observations of thermal tides in
1017 the middle atmosphere of Mars by the SPICAM instrument. *Journal of Geophysical
1018 Research*, 116, E11005. <https://doi.org/10.1029/2011JE003847>
- 1019

Figure 1.

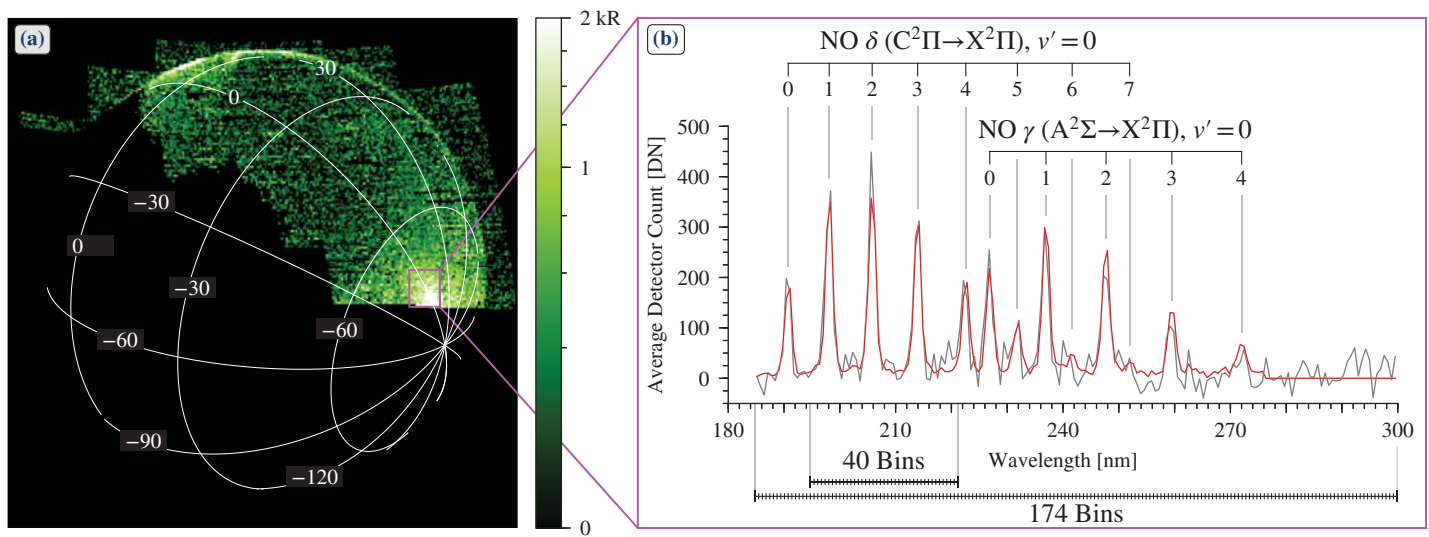


Figure 2.

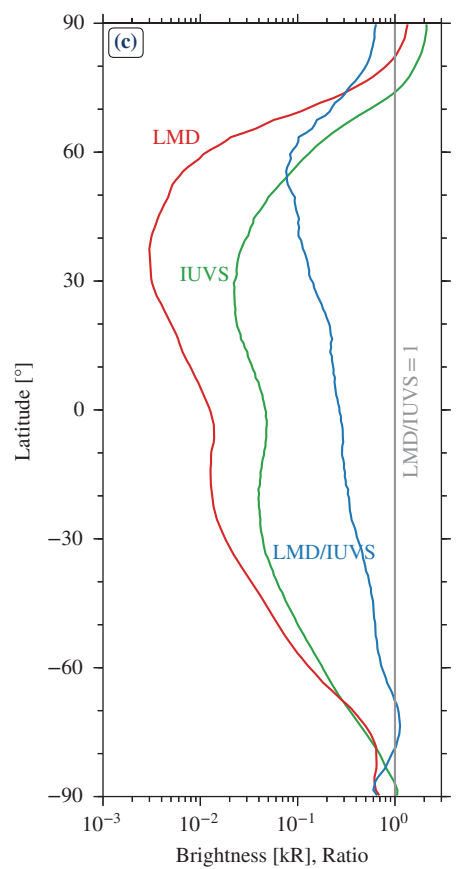
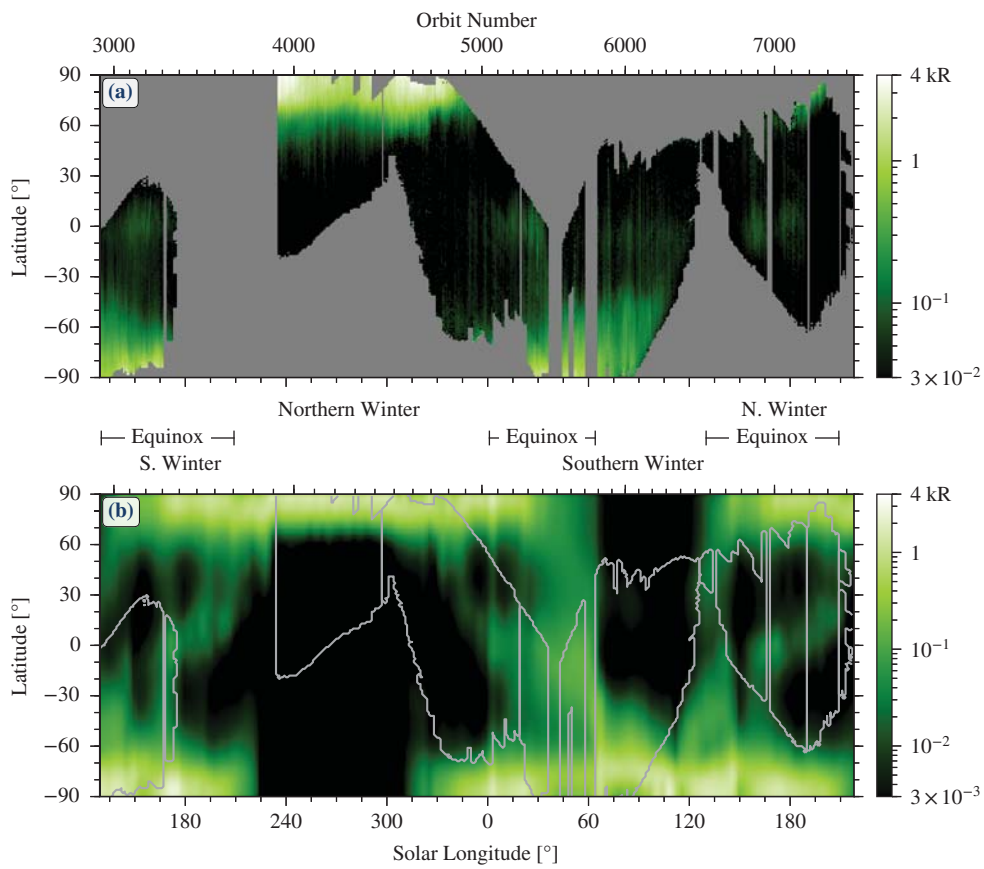


Figure 3.

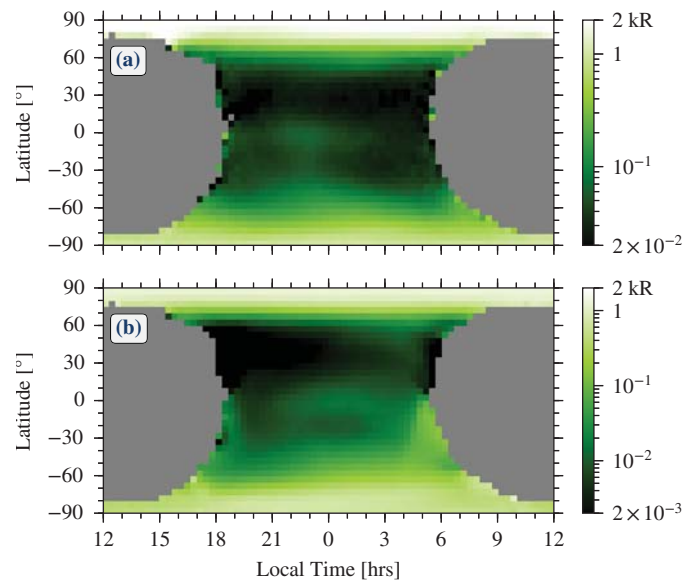


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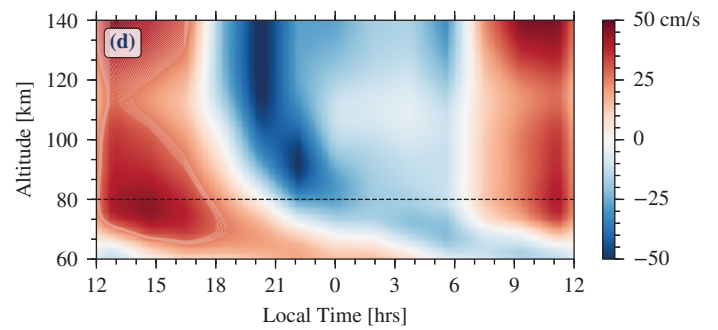
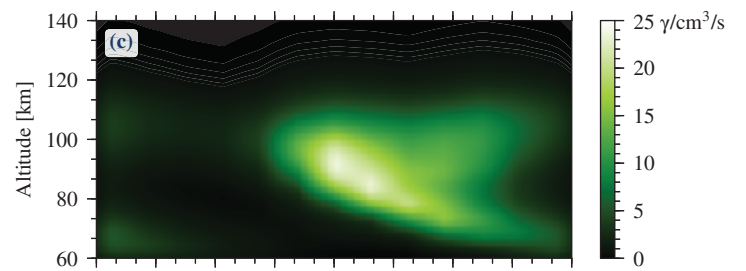
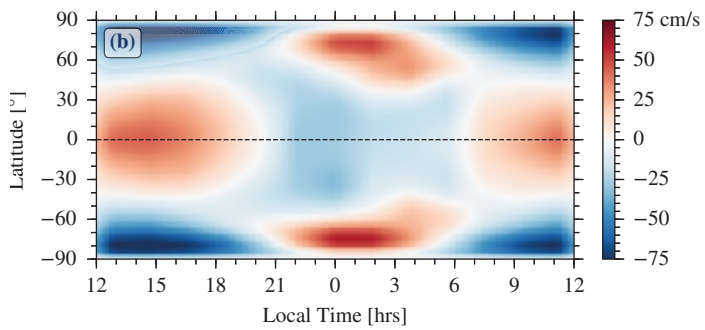
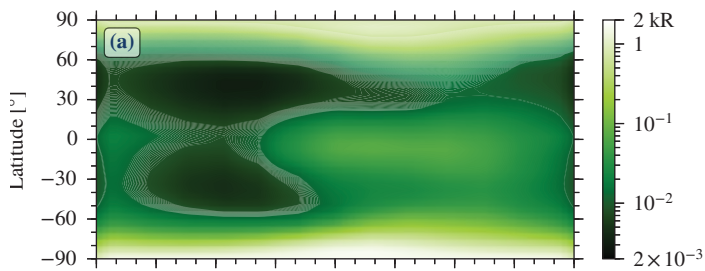


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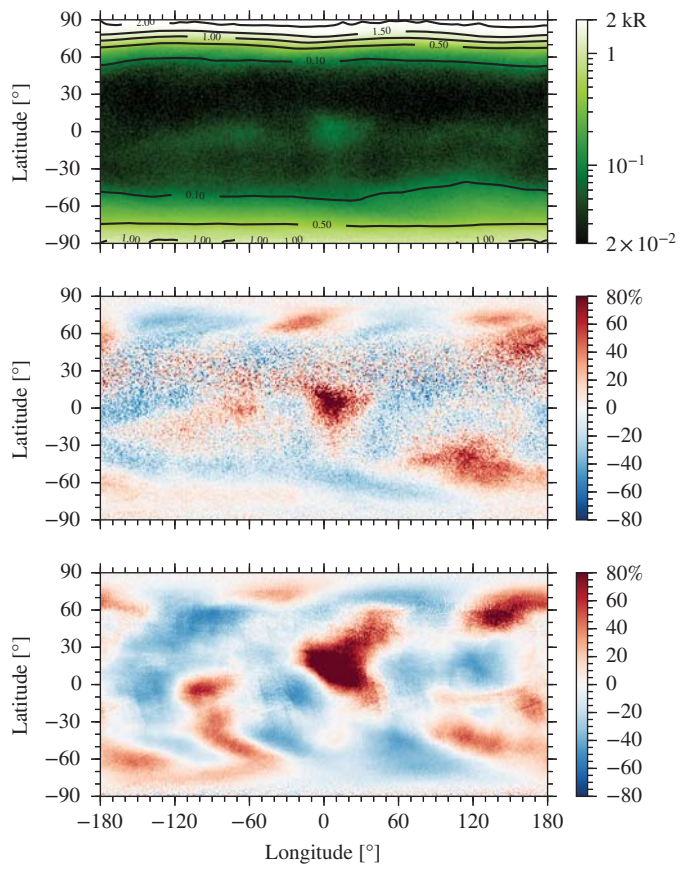


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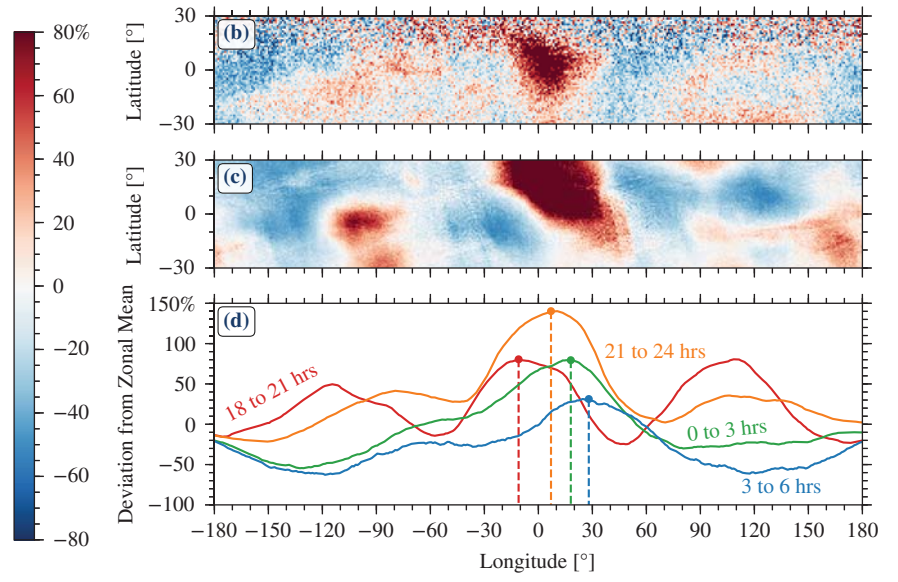
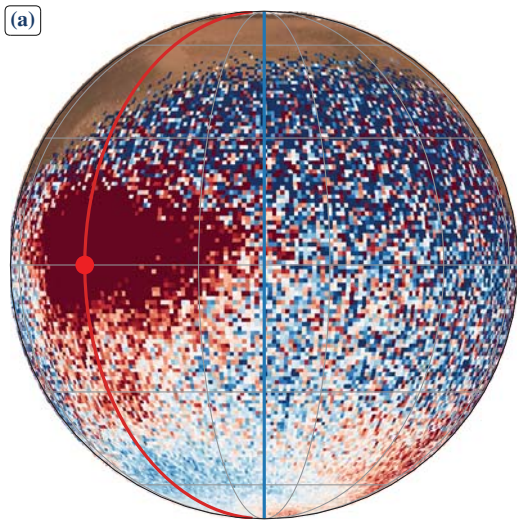


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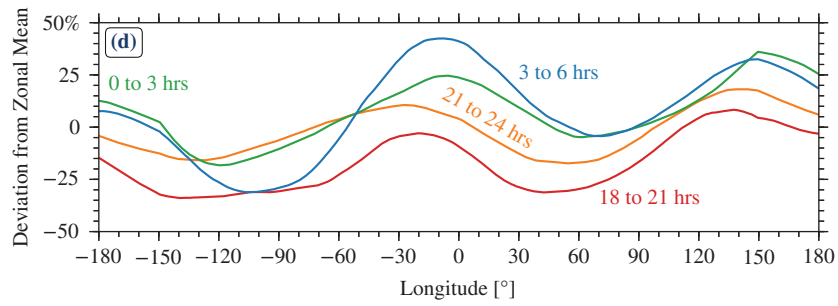
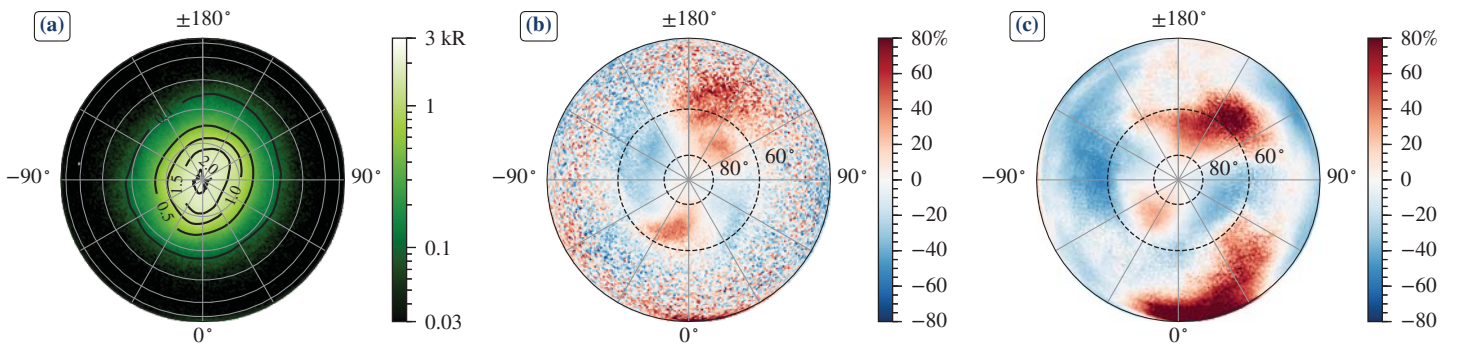


Figure 8.

