

# Mars Dust Storm Effects in the Ionosphere and Magnetosphere and Implications for Atmospheric Carbon Loss

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## Key Points:

- The dayside main ionosphere is lifted in accordance with dust-induced atmospheric expansion, with peak electron densities unchanged.
- Dust-induced perturbations propagate upward from the ionosphere to the magnetosphere and extend from the dayside to the nightside.
- Strong dust storms may enhance CO<sub>2</sub><sup>+</sup> loss by a factor of ~3 and increase total carbon loss (neutrals and ions) by ~20% or more.

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**Abstract**

Mars regional and global dust storms are able to impact the lower/upper atmospheres through dust aerosol radiative heating and cooling and atmospheric circulation. Here we present the first attempt to globally investigate how the dust impact transfers from the neutral upper atmosphere to the ionosphere and the induced magnetosphere above 100 km altitude. This is achieved by running a multifluid magnetohydrodynamic model under non-dusty and dusty atmospheric conditions for the 2017 late-winter regional storm and the 1971-1972 global storm. Our results show that the dayside main ionospheric layer (below  $\sim 250$  km altitude) undergoes an overall upwelling, where photochemical reactions dominate. The peak electron density remains unchanged, and the peak altitude shift is in accordance with the upper atmospheric expansion ( $\sim 5$  km and  $\sim 15$  km for the regional and global storms, respectively). Controlled by the day-to-night transport, the nightside ionosphere responds to the dust storms in a close connection with what happens on the dayside but not apparently with the ambient atmospheric change. At higher altitudes, dust-induced perturbations propagate upward from the ionosphere to the magnetosphere and extend from the dayside to the nightside, within a broad region bounded by the induced magnetospheric boundary. It is found that the global dust storm is able to dramatically enhance the  $\text{CO}_2^+$  loss by a factor of  $\sim 3$ , which amounts to an increase of  $\sim 20\%$  or more for total carbon loss (in the forms of neutrals and ions). Strong dust storms are a potentially important factor in atmospheric evolution at Mars.

**1 Introduction**

Today's Mars is a dry and dusty planet, on which dust storms frequently occur mainly during southern hemisphere spring and summer seasons [e.g., *Zurek*, 1982]. When dust storms happen, a significant amount of dust particles are injected into the atmosphere by wind-related processes. The most common are local dust storms that have limited occurrence scale (size and duration) and relatively low intensity and extent of dust opacity. Sometimes local storms merge and develop into a continent-sized, regional dust storm, which may last for weeks or more. Beyond local and regional storms, Mars has some of the greatest dust storms in the solar system, which occur infrequently but are able to obscure the planet's surface and last for several months. This type of planet-encircling dust storm is called a great/global dust storm or a global dust event, and receives much atten-

54 tion from the scientific community and the public. More detailed discussions on local,  
55 regional, and global dust storms have been given by, e.g., *Cantor et al.* [2001].

56 Mars dust storms are well known to cause perturbations in the neutral temperature,  
57 wind, and density of the lower and even upper atmosphere [e.g., *Haberle et al.*, 1982;  
58 *Zurek*, 1992; *Bougher et al.*, 1997; *Keating et al.*, 1998; *Bougher et al.*, 1999; *Smith et al.*,  
59 2002; *Forget et al.*, 2009; *Medvedev et al.*, 2013; *Withers and Pratt*, 2013; *Bougher et al.*,  
60 2017; *Kahre et al.*, 2017; *Toigo et al.*, 2018; *Liu et al.*, 2018; *Montabone and Forget*, 2018].  
61 The dust-induced atmospheric disturbance is associated with a series of complex direct  
62 and indirect processes: initially involved with dust aerosol radiative heating and cool-  
63 ing, followed by significant alteration of the atmospheric thermal structure and circula-  
64 tion. These dust-related radiative and dynamical processes result in profound atmospheric  
65 changes, which may be roughly regarded as an expansion of the entire atmospheric col-  
66 umn particularly at high altitudes [e.g., *Kliore et al.*, 1973; *Withers and Pratt*, 2013]. It is  
67 recognized that dust storms play an important role in governing the atmosphere and cli-  
68 mate of Mars. It is worth noting that although dust particles may be carried by vertical  
69 transport to altitudes as high as 80 km [*Clancy et al.*, 2010], there is no evidence sup-  
70 porting that direct dust loading would happen higher. The dust impact in the upper atmo-  
71 sphere (>80 km) is basically an indirect effect resulting from the coupling with the lower  
72 atmosphere [*Bougher et al.*, 1997].

73 Unlike extensive studies on the neutral atmospheric effectiveness of dust storms,  
74 their impact on the charged particle radiation environment near Mars remains poorly un-  
75 derstood. *Kliore et al.* [1973], *Hantsch and Bauer* [1990], and *Zhang et al.* [1990] analyzed  
76 radio occultation measurements by the Mariner 9 spacecraft and reported that the main  
77 ionospheric layer of Mars (which typically peaks at ~120 km altitude or higher, owing to  
78 the absorption of the solar extreme ultraviolet, EUV, radiation) behaved differently dur-  
79 ing the 1971-1972 global dust storm. They reported that the ionospheric peak altitude was  
80 considerably upward lifted by ~20 km, although the peak electron density was normal  
81 and in line with Chapman theory predictions. *Wang and Nielsen* [2003] used a 1-D photo-  
82 chemical model to simulate the ionospheric response during this specific dust storm. Their  
83 results showed that the ionospheric altitude profile underwent an overall upward lift, main-  
84 taining the similar peak intensity at a significantly elevated altitude. The numerical work  
85 of *Wang and Nielsen* [2003], consistent with the Mariner 9 data interpretation, implies  
86 that it is the expanded upper neutral atmosphere that is responsible for the ionospheric

87 anomaly during the dust storm, a process controlled by the altitude-varying energy depo-  
88 sition by the solar EUV irradiance (i.e., photoionization) and subsequent photochemical  
89 reactions. In addition, a handful of studies have been reported on the dust influence in the  
90 regions other than the main ionospheric layer. *Haider et al.* [2010] and *Nemec et al.* [2015]  
91 found that ion/electron concentrations at low altitudes (<60 km) may be significantly de-  
92 pleted during dust storms due to the reduction of ionizing galactic cosmic rays as a result  
93 of the enhanced optical depth. *Liemohn et al.* [2012] analyzed dayside photoelectron flux  
94 observations of the Mars Global Surveyor (MGS, at ~400 km altitude), and found that  
95 statistically significant correlations were achieved with the dust-modulated solar EUV in-  
96 tensity after taking into account the dust opacity over the preceding 7-month time history.  
97 The work speculates that the long-lived dust influence on photoelectrons may be attributed  
98 to the composition/density change of the upper atmosphere, which is also supported by *Xu*  
99 *et al.* [2014].

100 Despite these early efforts, there is still no global picture of how and the extent to  
101 which the entire Mars plasma environment (including the ionosphere and the induced  
102 magnetosphere) reacts to dust storms that develop and arise from the surface. Besides  
103 what we have learned from those sparse spatial and temporal sampling, what other dis-  
104 turbances are there during dust storms? In particular, little is known about how high in  
105 altitude dust storms are capable of extending their impact beyond the low-altitude part  
106 of the ionosphere. It is natural to expect that upper atmospheric density changes in dust  
107 storms would result in photoionization rate perturbations and then have an impact on the  
108 ionosphere and ultimately manifest themselves at higher altitudes through the interaction  
109 of the Mars conductive obstacle with the solar wind. The main difficulty, however, is on  
110 a quantitative assessment of how important these potential consequences are and whether  
111 they may be distinguishable from other sources of variability. In contrast with the highly  
112 collisional bottomside ionosphere (which is in relatively closer proximity to dust activity  
113 regions), the plasma distribution at high altitudes is in a collisionless regime and is domi-  
114 nated by transport processes, that is, is more dynamic in nature. The continuous change of  
115 observational sites and conditions in reality, together with the lack of simultaneous multi-  
116 point measurements, constitute a practical challenge of organizing data and extracting the  
117 effects that may be reliably associated with dust activity.

118 Our current strategy to overcome the limitations in observational data analysis is to  
119 apply a state-of-the-art global magnetohydrodynamic (MHD) model [*Najib et al.*, 2011;

120 *Dong et al., 2018a*] using physically realistic background and boundary conditions for spe-  
121 cific dust storm events. Numerical simulations are conducted under observationally con-  
122 strained atmospheric conditions, separately corresponding to nondusty and dusty scenarios,  
123 with all the other model parameters held unchanged. By making direct comparison of the  
124 results between these controlled runs, this study represents the first attempt to assess the  
125 ionospheric and magnetospheric disturbances on a planetary scale during dust storms and  
126 to discuss the implications for total atmospheric loss.

## 127 **2 The Global and Regional Dust Storms for Case Studies**

128 Figure 1 gives an overview of the zonally-averaged dust opacity in infrared over 11  
129 Martian years (MYs, from MY 24 to currently MY 34), as a function of the solar longi-  
130 tude ( $L_s$ ) and planetary latitude. The column dust optical depth (CDOD) is derived using  
131 combined infrared radiance observations from several Mars orbiters: the Thermal Emis-  
132 sion Spectrometer (TES) onboard Mars Global Surveyor [*Christensen et al., 2001*], the  
133 Thermal Emission Imaging System (THEMIS) onboard Mars Odyssey [*Christensen et al.,*  
134 *2004*], and the Mars Climate Sounder (MCS) onboard Mars Reconnaissance Orbiter [*Mc-*  
135 *Cleese et al., 2004*]. The algorithms for synthesizing these measurements to derive dust  
136 opacity products have been described in detail by *Montabone et al. [2015]* and are not re-  
137 peated here. Note that Figure 1 is a replot of Figure 16 of *Montabone et al. [2015]* for  
138 MYs 24-31, updated with latest results for MYs 32 and 33 using the same data processing  
139 technique. MY 34 is produced using specific processing described in detail by *Montabone*  
140 *et al. [2019]* within this special issue. Due to the differences in data processing techniques  
141 (see the Appendix of *Montabone et al. [2019]* for further details), particular caution is  
142 required for a direct comparison of the zonal means between MY 34 and other Martian  
143 years (particularly MYs 28-33).

144 The time series of the dust opacity presented in Figure 1 clearly demonstrates that  
145 Mars atmospheric dust loading in general follows an annual repeatable pattern with a  
146 strong seasonal dependence. A Martian year can be roughly divided into two seasons in  
147 terms of atmospheric dust loading [e.g., *Montabone and Forget, 2018*]. A “low dust load-  
148 ing” season starts sometimes after the northern hemisphere vernal equinox ( $L_s \sim 10$ ) and  
149 ends sometimes before the autumnal equinox ( $L_s \sim 140$ ). Mars generally is calm within  
150 this season except for local dust storms and dust devils. During the rest of the time, Mars  
151 is inside a “high dust loading” season, when the planet receives intensified solar heating

152 particularly near its perihelion ( $L_s=251$ ). Regional dust storms start to happen within  
153 the dust season. Outside annually repeatable patterns of dust opacity, planet-encircling  
154 or global dust storms are episodic, powerful meteorological phenomena, which lift a con-  
155 siderable amount of dust particles into the atmosphere and obscure most of the planet's  
156 surface. Their exact timing of occurrence is (so far) unpredictable, on an intermittent basis  
157 of roughly every two to three Martian years [e.g., *Zurek and Martin*, 1993]. Three global  
158 dust storms are visible in Figure 1, showing distinct optical depth enhancement over nearly  
159 all latitudes in years 2001 (MY 25), 2007 (MY 28), and 2018 (MY 34), respectively. See  
160 *Montabone and Forget* [2018] and references therein for more discussions of the two-dust-  
161 season partition and more specificity of global dust events. Figure 2 gives a 3-D view of  
162 CDOD global distributions at an  $L_s$  cadence of  $30^\circ$  during MY 34. The overall seasonal  
163 evolution of dust loading during this specific MY is consistent with other MYs (Figure 1).  
164 The 2018 planet-encircling dust storm is readily seen in Figure 2 in the dramatic dust  
165 optical depth increase, in both magnitude and spatial extent, particularly at  $L_s=210^\circ$  and  
166  $240^\circ$ .

167 In this study, we select one relatively weak regional storm and one strong global  
168 storm for numerical simulation. The comparison of the Mars ionospheric and magneto-  
169 spheric responses to different storm levels enables an assessment of the range of potential  
170 dust consequences. Considering that it is the plasma regime rather than the neutral at-  
171 mospheric regime that our current dust impact study focuses on, we rely on previously  
172 published works on atmospheric changes from nondusty to dusty scenarios, which serve  
173 as direct inputs to our MHD model. For a regional storm, we select the one in year 2017  
174 (hereinafter referred to as event 1), highlighted by the red box in Figure 1. The upper at-  
175 mospheric conditions within the regional storm have been available, which were reported  
176 by *Liu et al.* [2018] using the in-situ measurements from the NASA Mars Atmosphere and  
177 Volatile EvolutionN (MAVEN) mission [*Jakosky et al.*, 2015]. On the other hand, an ideal  
178 global storm case for study would be the recent one in year 2018 (MY 34), which receives  
179 the most comprehensive measurements and is the focus of the current special issue. Unfor-  
180 tunately, the evaluation of the dust atmospheric impact for the 2018 global storm is still an  
181 ongoing process and the results are not yet publicly available. As an alternative, we select  
182 the 1971-1972 global dust storm (hereinafter referred to as event 2), whose atmospheric  
183 changes have been estimated by *Wang and Nielsen* [2003] and are available for direct use.  
184 By limiting our case studies to those storms whose neutral atmospheric estimates are al-

185 ready available, the current work is able to maintain a focused scope on studying the dust  
186 impact on the charged particle regime.

### 187 **3 Multifluid MHD Model of Mars**

#### 188 **3.1 Model Description**

189 The primary research tool for this work is the 3-D multifluid MHD model of *Na-*  
190 *jib et al.* [2011] and *Dong et al.* [2018a,b]. After two decades of code development and  
191 improvement since *Liu et al.* [1999] and *Ma et al.* [2004], the MHD model provides a  
192 state-of-the-art solution of the interaction between the incoming solar wind and the Mars  
193 conductive obstacle (consisting of the ionosphere and planet-attached crustal magnetic  
194 anomalies). The MHD continuity, momentum, and pressure equations are solved sepa-  
195 rately for each of the major ion species ( $H^+$ ,  $O_2^+$ ,  $O^+$ ,  $CO_2^+$ ) under the multifluid approx-  
196 imation. The sources for planetary ions include photoionization of a prescribed global  
197 atmosphere ( $CO_2$ ,  $O$ ,  $H$ ), charge exchange collisions, and electron impact ionizations.  
198 The effect of the neutral wind is currently neglected in the MHD model. The magnetic  
199 field is self-consistently calculated with the plasma distribution, dominated by the crustal  
200 magnetic field on the inner model boundary of 100 km altitude and by the interplanetary  
201 magnetic field (IMF) in the upstream. The MHD equations are solved in the classic Mars-  
202 centered Solar Orbital (MSO) coordinate system. The simulation domain is sufficiently  
203 broad to allow for the interaction of the plasma and fields of the solar and planetary ori-  
204 gins:  $-36R_M \leq X \leq 12R_M$ ,  $-24R_M \leq Y, Z \leq 24R_M$ , where  $R_M$  stands for the mean  
205 Martian radius of 3396 km. To ensure adequate sensitivity for the ionospheric response to  
206 upper atmospheric changes, we adopt the highest spatial resolutions that have ever been  
207 realized in the MHD model:  $1.5^\circ$  in both longitudinal and latitudinal directions and an  
208 altitude resolution of 2.5 km in the ionosphere. At altitudes higher than  $\sim 1000$  km, the  
209 angular resolution is relaxed to  $3^\circ$ , and the radial resolution doubles and then gradually  
210 increases with altitude as in typical MHD runs.

211 Our current investigation focuses on spatial rather than temporal variability of the  
212 dust impact. Accordingly, the background conditions for our model runs are set to be  
213 static, or time independent. This is not possible in reality but is a particular advantage  
214 of numerical experiments. This is also a strategy commonly used by the global Mars-solar  
215 wind interaction modeling community, not mentioning that running the multifluid MHD

216 model in a time-varying fashion is prohibitive at present in terms of computation time.  
217 The nominal solar wind has a number density of  $n_{sw}=4 \text{ cm}^{-3}$  and an antisunward flow  
218 speed of  $U_{sw}=400 \text{ km/s}$ , corresponding to a dynamic pressure of 1.07 nPa. The IMF is a  
219 Parker spiral of  $(B_X, B_Y, B_Z)=(-1.634, 2.516, 0) \text{ nT}$ , making the MSO coordinate system  
220 for MHD calculation identical to the Mars-Solar-Electric field (MSE) coordinate system.  
221 The planetary axis is tilted in the MSO direction of  $(-0.224, 0.362, 0.905)$  and  $(-0.412,$   
222  $0.106, 0.905)$  for event 1 and event 2, respectively, using representative time points of  
223 2017-03-06 and 1971-11-01. The subsolar longitude, and thus the planet's orientation to  
224 the Sun, are specified in such a way that the strongest crustal magnetic field region (near  
225  $178^\circ\text{E}, 53^\circ\text{S}$ ) is located on the nightside with the maximum solar zenith angle (SZA).  
226 This ensures that the potentially important crustal field influence on plasma distributions is  
227 minimized [cf., e.g., *Ma et al.*, 2014; *Fang et al.*, 2015, 2017]. In addition, ionizing solar  
228 irradiance is parameterized by 10.7-cm radio fluxes at the Mars' orbit, which are estimated  
229 by scaling Earth observations with inverse square of the Sun-Mars distance in AU. The  
230 Mars equivalent  $F_{10.7}$  values are 32.6 (in event 1) and 54.9 (in event 2), which are used to  
231 interpolate  $\text{CO}_2$  and O photoionization frequencies according to Table 9.2 of *Schunk and*  
232 *Nagy* [2009]. Note that the MHD model in its current form adopts  $F_{10.7}$ -parameterized  
233 photoionization frequencies, and thus cannot take advantage of the detailed solar flux mea-  
234 surements from MAVEN EUV Monitor [*Eparvier et al.*, 2015].

### 235 **3.2 Atmospheric Conditions for Model Input**

236 MHD calculations are performed twice for each of the two dust events to be stud-  
237 ied, under nondusty and dusty atmospheric conditions, respectively. For the two controlled  
238 runs of each event, the parameters other than neutral species distributions are specified to  
239 be the same to exclude unnecessary interference and thus to effectively concentrate on dust  
240 effects. Note that all the four atmospheric conditions (two events by two nondusty-dusty  
241 settings) need to be specifically characterized, given the fact that the timing (i.e., seasonal  
242 effects) and solar irradiance of the events are different. There is no need for considering  
243 dust aerosols in our MHD simulations, because direct dust effects are negligible beyond  
244 100 km altitude (which is the location of the bottom boundary of our model). At high al-  
245 titudes, dust storms act in such an indirect way that the dust-induced perturbations in neu-  
246 tral species distributions impact the plasma regime via ion-involved chemical reactions and  
247 ion-neutral momentum/energy transfer collisions. Since neutral concentrations are many



orders of magnitude greater than those of charged particles, the atmospheric distribution serves as a static input to the model. Without any specific knowledge of the 3-D atmospheric distributions, we make an assumption of a horizontally uniform spherically symmetric atmosphere. This is a reasonable first-order approximation, given that dust storm effects in the upper atmosphere are found to have much broader horizontal scales [Withers and Pratt, 2013].

Figure 3 shows the specification of the nondusty and dusty atmospheric conditions for event 1. The circles indicate estimates from the MAVEN instrument of the Neutral Gas and Ion Mass Spectrometer (NGIMS) [Mahaffy et al., 2014]. The dusty CO<sub>2</sub> and O densities (red and dark blue circles, respectively) are the average over 15 MAVEN orbits (~3 days) near  $L_s=328$ , which corresponds to the third dust increase episode in Liu et al. [2018] and is marked by dashed line in Figure 1. For nondusty conditions, we choose not to use the average levels of pre-storm densities. The study of Liu et al. [2018] demonstrates that due to the continuous change of the MAVEN periapsis segments in longitude, latitude, local time, and SZA, the density contrast between the storm and pre-storm local values is not necessarily primarily caused by dust activity. Therefore we take a conservative approach for estimating the nondusty atmosphere by using the 25th percentile within the  $L_s$  range of 310-360, as denoted by the red box in Figure 1.

Next we fit and extrapolate these MAVEN data products into both lower and higher altitudes to fill in the MHD simulation domain under a globally symmetric approximation. A multi-component approximation is adopted to fit the MAVEN data, with various atmospheric thermal and hot components considered as follows. A  $m$ -component structure ( $m=2/4/2$  for CO<sub>2</sub>/O/H, respectively) is defined as  $n(h) = \sum_{i=1}^m n_{0i} \cdot \exp(-(h - 100)/H_i)$ , where  $n$  is the total number density of an atmospheric species (CO<sub>2</sub>, O, H) at altitude  $h$ . On the right hand side of the equation,  $n_{0i}$  and  $H_i$  stand for the density at  $h=100$  km and the scale height in units of km for the  $i$ th ( $i=1, \dots, m$ ) component. The nominal, solar minimum atmosphere that is typically adopted by the MHD model is superposed in Figure 3 for reference, with dashed lines for CO<sub>2</sub>/O and a green line for H [Ma et al., 2004]. Recall that the average solar EUV levels during both dust events are much closer to solar minimum than to solar maximum (see section 3.1). For simplicity, this study directly takes the reference H profile for nondusty and dusty conditions at all altitudes for two considerations. Firstly, the proton contribution from planetary hydrogen is dominated by that of solar wind origin at high altitudes [Najib et al., 2011]. Secondly, at low altitudes, iono-

281 spheric  $H^+$  is a minor species in comparison with abundant  $O_2^+$  and  $CO_2^+$ . Therefore, no  
282 important errors would be expected from the simplification on the planetary H distri-  
283 bution. Below the MAVEN periapsis altitude where no specifics are available for  $CO_2$   
284 and O, we assume that their minimum scale heights in the  $m$ -component approximation  
285 (that is, for the dominant components near 100 km) approach those of the reference atmo-  
286 sphere. To self consistently describe the oxygen corona above  $\sim 250$  km altitude, we take  
287 an iterative approach. In the first iteration run, we assume the hot O components from  
288 the reference atmosphere and make multi-component O and  $CO_2$  atmospheric fits on a  
289 least-squares scheme over the entire altitude range ( $\geq 100$  km). We use these estimated at-  
290 mospheric profiles to perform an exploration MHD run and obtain ionospheric properties.  
291 The Mars Adaptive Mesh Particle Simulator (AMPS) of *Lee et al.* [2015a, 2019] is applied  
292 to account in detail for the dissociative recombination of ionospheric  $O_2^+$  ( $O_2^+ + e^- \rightarrow O$   
293 + O) and thus energetic O production and collisions with ambient neutrals. The AMPS-  
294 calculated, high-altitude oxygen distributions are seen in Figure 3c. We then perform the  
295 second iteration run, which is similar to the first one except that the AMPS results rather  
296 than the reference O corona are used for atmospheric fits. The final atmospheric  $CO_2$  and  
297 O specifications are presented in solid lines in Figure 3, which serve as background input  
298 conditions for the MHD model. More detailed discussions of the AMPS-calculated hot  
299 oxygen corona for these specific cases have been given by *Lee et al.* [2019].

300 The above procedures are followed separately to derive both nondusty and dusty at-  
301 mospheric profiles. Below the altitude of MAVEN data availability, we make an ad-hoc  
302 adjustment for the dusty estimation. It is assumed that for both  $CO_2$  and O, the nondusty-  
303 to-dusty density enhancement factors at  $\sim 160$  km are extended unchanged down to the  
304 lower boundary of the model (i.e., 100 km). Using the scale heights of the density dis-  
305 tributions, we calculate neutral temperatures of each species and then thermal pressures.  
306 Figure 3b shows the atmospheric pressure and bulk temperature results under nondusty  
307 and dusty conditions in event 1. It is seen that the entire upper atmosphere is approxi-  
308 mately lifted by  $>5$  km in altitude in response to this regional storm, and there is no im-  
309 portant change in the bulk temperature. The low-altitude temperature overlap is caused  
310 by the aforementioned ad-hoc approximation. A more careful examination is needed for  
311 the validity of the temperature difference above  $\sim 160$  km altitude, given the uncertainties  
312 due to our NGIMS data averaging (which is independently performed at altitude levels)  
313 and the simplistic fitting. Nevertheless, our numerical experiments showed that the MHD

314 results are not sensitive to the neutral temperature setup. It is also found by *Wang and*  
315 *Nielsen* [2003] that the neutral temperature makes an insignificant impact on the iono-  
316 spheric density. Although the atmospheric expansion (in total pressure/density) effectively  
317 stops at  $\sim 300$  km altitude (Figure 3d), significant compositional changes (specifically in  
318 the O corona) take place at higher altitudes up to  $\sim 500$  km (Figure 3c).

319 A similar approach is applied to specify atmospheric conditions during the 1971-  
320 1972 global storm, except that the density estimates between 100-180 km are directly  
321 adopted from Figure 3 of *Wang and Nielsen* [2003]. Our estimation results over the MHD  
322 spatial domain are presented in Figure 4. Several differences in the upper atmospheric re-  
323 sponses between the regional and global dust storms are noticeable in the comparison of  
324 Figure 4 to Figure 3. The atmosphere expands more significantly in event 2 showing an  
325 upwelling of 10-15 km in altitude (Figure 4b), which is expected owing to enhanced lower  
326 atmospheric dust load and solar radiation absorption. The neutral temperature change,  
327 which decreases with altitude, indicates that direct dust aerosol heating happens mostly in  
328 the lower atmosphere. In addition, an important density drop of about 35% happens in the  
329 O corona, nearly altitude independent above  $\sim 650$  km (Figure 4c), which is mainly due  
330 to the enhanced collisional loss of energetic O in the thicker CO<sub>2</sub> atmosphere [*Lee et al.*,  
331 2018, 2019].

## 332 4 Multifluid MHD Results

### 333 4.1 Dust Impact on the Ionosphere and Magnetosphere

334 We conduct multifluid MHD simulations using the estimated boundary conditions  
335 (in solar radiation, solar wind, IMF, crustal magnetic anomalies) and background atmo-  
336 spheric conditions, which are described in section 3. The model is run sufficiently long  
337 until a dynamic equilibrium is achieved in the Mars system. A total of 4 steady-state  
338 model runs have been obtained in correspondence with 2 nondusty/dusty atmospheric set-  
339 tings for 2 dust events. Figure 5 and Figure 6 show the comparison of the ionospheric  
340 properties at the subsolar point (SZA=0°) between nondusty and dusty conditions for the  
341 regional and global dust storms, respectively. One prominent feature in both Figures 5a  
342 and 6a is that the main ionosphere may be roughly seen as being subject to an upward lift  
343 in response to dust-induced atmospheric expansion. The charged particle density peaks  
344 are located at significantly higher altitudes during the dusty scenarios, with their peak

345 intensities barely affected (except for  $O^+$  in event 2). This result is consistent in quality  
346 with the report of *Wang and Nielsen* [2003], which used a simplified 1-D photochemical  
347 ionospheric model. Our MHD results show a subsolar peak altitude lift of approximately  
348 5/5/5/15 km and 15/12.5/17.5/17.5 km for  $e^-/O_2^+/CO_2^+/O^+$  in event 1 and in event 2, re-  
349 spectively. As a consequence, density increases (decreases) occur at altitudes above (be-  
350 low) their peak locations.

351 A close look at Figure 5b reveals that over a broad altitude range in event 1, the  
352 two major ionospheric ions of  $O_2^+$  (in blue) and  $CO_2^+$  (in red) share a similar percentage  
353 density change of about 30% – 40% with  $e^-$  (or total ions, in black); in other words, the  
354 mixing ratios and thus the ionospheric composition of the major ions are insignificantly  
355 affected during the regional dust storm. To test the hypothesis that the ionosphere seems  
356 to exhibit a simple upwelling in event 1, the results are reorganized according to atmo-  
357 spheric thermal pressure levels (in place of altitude levels) and are presented in Figures 5c  
358 and 5d. As speculated, the ionospheric profiles become nearly identical with respect to  
359 the neutral pressure. Figure 5d illustrates that in the main ionosphere (corresponding to  
360 neutral pressure higher than  $10^{-8}$  Pa, or at altitudes lower than 220 km, see Figure 3b),  
361 almost all charged particles have a negligible density change within  $\pm 10\%$ . Noticeable  
362 exceptions happen at higher altitudes, particularly for  $O^+$  (in brown). Even in terms of  
363 neutral pressure as vertical coordinate, the  $O^+$  density shows an increase by up to a factor  
364 of 3, which, nevertheless, is considerably smaller than that in the altitude coordinate as  
365 seen in Figure 5b. The different responses of  $O^+$  than the heavier ions to the atmospheric  
366 lift are understandable. The ion production of  $CO_2^+/O_2^+$  is concentrated at low altitudes,  
367 which originates from the solar EUV absorption by heavy atmospheric  $CO_2$  molecules.  
368 Photoionization rates are directly determined by local quantities of neutral densities and  
369 ionizing solar fluxes, the latter of which are controlled by the optical depth. Being a proxy  
370 of the overlying atmospheric column mass, the neutral pressure regulates the optical depth  
371 of solar radiation and is thus (nonlinearly) correlated with ion production. Given that the  
372 primary  $CO_2^+/O_2^+$  production is within a photochemical equilibrium region, it is not sur-  
373 prising to see that these heavier ions vertically shift their density profiles in accordance  
374 with the moderate shift of the neutral pressure. The vertical distribution of  $O^+$ , however,  
375 is much more complex, which peaks at high altitudes where vertical transport starts to  
376 dominate over the photochemical process. Because the  $O^+$  production itself peaks at low  
377 altitudes [e.g., *Fox*, 2004], the dust-induced vertical shift of the atmospheric pressure does

indeed affect the location of  $O^+$  production but cannot solely account for the distribution of the ion density. This is the reason why we see the smaller but still significant change for  $O^+$  in Figure 5d than in Figure 5b. It should be pointed out that the great percentage differences for  $CO_2^+/O_2^+$  densities at the top of Figure 5d (with  $<1$  nPa pressures, or  $>600$  km altitudes) are not that meaningful for two reasons. First, their abundances are dominated by the lighter species like  $H^+$  and  $O^+$ . Second, global transport is so important at high altitudes as to require a careful evaluation over a broad spatial scale instead of being limited to along the radial direction as examined here.

Figure 6 shows the results of event 2 using a similar format as Figure 5. Several distinct differences stand out during the global dust storm. First, while the peak locations of ionospheric ions are also lifted in consistence with the upper atmospheric expansion, the concentration of  $O^+$  significantly decreases at all altitudes: up to about  $-80\%$  near 210 km. This is mainly caused by the enhanced ion loss through charge exchange collisions with ambient  $CO_2$  neutrals ( $O^+ + CO_2 \rightarrow O_2^+ + CO$ ). Second, as illustrated by Figure 6b,  $CO_2^+$  densities show a critical increase by approximately a factor of 5 above  $\sim 200$  km altitude. Besides the direct photoionization increase for  $CO_2^+$ , the reduced loss rate also helps, which is due to reduced charge exchange collisions with atomic oxygen (see Figure 4a):  $CO_2^+ + O \rightarrow O_2^+ + CO$ ;  $CO_2^+ + O \rightarrow O^+ + CO_2$ . Undoubtedly, photochemical reactions become less important in competition with the transport process at such high altitudes, which, however, is neglected by 1-D photochemical models. Our work represents the first attempt to take advantage of global MHD models to consider transport processes for a dust impact study. Third, Figure 6b reveals that different ionospheric species have different percentage changes in density, suggesting that the ionospheric composition is subject to important perturbations during the global storm. Fourth, after being organized using atmospheric pressure levels in Figures 6c and 6d, the ionospheric density profiles (except for  $e^-$ ) do not coincide with each other between the nondusty and dusty scenarios, which is remarkably different from what we have seen in Figure 5 for the regional storm. Nevertheless, the ionospheric density profiles in terms of neutral pressure do show an overlap at low altitudes. These observations suggest that the significant upper atmospheric compositional change in the severe global dust storm (see Figure 4) indeed results in a profound impact on the ionospheric densities and compositions. By considering general neutral distributions but neglecting the detailed atmospheric compositions, neutral pressures may still

410 be helpful to account for the overall location change of the main ionospheric layer but fail  
411 for individual ionospheric species even in photochemical equilibrium regions.

412 The examination of the MHD results along the Sun-Mars line is useful to shed light  
413 on the Mars system's response to dust activities originating near the surface. However,  
414 the plasma environment at the subsolar point is subject to the maximum solar wind surp-  
415 pression, which in turn leads to limited vertical transport along the radial direction. To  
416 utilize the 3-D MHD model capability of self consistently simulating the solar wind-Mars  
417 interaction, we extend our analysis to make comparisons from a global perspective. Fig-  
418 ure 7 shows the global dust-induced ionospheric impact in event 2, as a function of SZA  
419 and altitude. These 2-D density distributions are obtained by arithmetically averaging the  
420 MHD radial profiles rotating about the Sun-Mars line at any given SZA location, ranging  
421 from subsolar at  $SZA=0^\circ$  to antisubolar at  $SZA=180^\circ$ . Before examining the dust im-  
422 pact, we take a look at the global ionospheric distributions themselves. A few interesting  
423 ionospheric features that are not seen in a classic Chapman photochemical picture are il-  
424 lustrated.

425 First, while the ionosphere generally follows the Chapman theory below  $\sim 200$  km  
426 altitude, important deviation takes place at high altitudes. It is more prominent above  
427  $\sim 300$  km altitude near the terminator region for all the planetary ions, shown as a rapid  
428 density increase mainly due to the combined effects of the ambipolar electric field ac-  
429 celeration and the  $J \times B$  drag during the magnetic field draping process. There is another  
430 density bulge close to the subsolar region near  $SZA=10^\circ$ , which is attributed to plume-  
431 like escaping ions under the convection electric field acceleration [e.g., *Fang et al.*, 2008;  
432 *Dong, Y., et al.*, 2015; *Dong et al.*, 2018a]. Note that the ion plume is a regional feature  
433 and is aligned approximately with the convection electric field direction, which is along  
434  $+Z$  direction upstream of Mars in our simulation cases. Therefore, the plume feature in  
435 Figure 7 is not that prominent as it is (which will be discussed in more detail later), ow-  
436 ing to our averaging manner, in which all radial profiles having the same angle from the  
437  $X$  axis are equally weighted. Furthermore, the geometry of the ion plume makes its ap-  
438 pearing location in SZA increase with altitude, which is readily seen when examined over  
439 a greater altitude range as in Figure 8 (see particularly the density bulges shown as blue  
440 shading).

441 Second, while ionospheric densities quickly drop after crossing the terminator plane  
442 and approaching the optical shadow of ionizing solar irradiance, a significant nightside  
443 ionosphere is effectively maintained even at the antisubsolar point (SZA=180°). This is  
444 driven by the transterminator ionospheric flow due to the day-night plasma pressure gra-  
445 dient, part of which descends to replenish the nightside ionosphere that is short of pho-  
446 toionization. Such a day-to-night transport effect manifests itself more visibly in the O<sub>2</sub><sup>+</sup>  
447 “tongue”, which is extended throughout the entire nightside region near 150 km altitude in  
448 Figure 7. Note that in the MHD model, the electron impact ionization is generally consid-  
449 ered and parameterized using thermal electrons. That is, the kinetic ionization from pre-  
450 cipitating energetic electrons along open magnetic field lines [e.g., *Lillis and Fang, 2015,*  
451 and references therein] is neglected in our MHD approximations. The relative importance  
452 of particle precipitation to the day-to-night transport in the nightside ionosphere is not  
453 well understood.

454 The right column of Figure 7 provides a quantitative evaluation of ionospheric den-  
455 sity changes below 400 km altitude on a planetary scale in response to the 1971-1972  
456 global dust storm. Similar to what has been observed at SZA=0° in Figure 6b, we see  
457 the altitude profiles of all ionospheric species are subject to an upward lift over the entire  
458 dayside (SZA < 90°). As a result, the densities of O<sub>2</sub><sup>+</sup>/CO<sub>2</sub><sup>+</sup>/e<sup>-</sup> above their peak altitudes  
459 increase and those below the peaks decrease. Among them, CO<sub>2</sub><sup>+</sup> has the most pronounced  
460 increase, which is up to a factor of 5, over a broad altitude range. Moreover, their per-  
461 centage changes on the dayside show a moderate SZA dependence. The patterns are more  
462 consistent below ~200 km altitude (where the Chapman photochemical approximation is  
463 reasonable): being maximum at SZA=0° and then gradually decreasing with SZA. Iono-  
464 spheric O<sup>+</sup> ions show distinctly different characteristics from the other planetary ions. The  
465 O<sup>+</sup> density on average decreases over all altitude levels (see the discussions of Figure 6),  
466 and the degree of reduction below ~200 km increases with SZA. Above ~250 km altitude,  
467 where transport processes start to dominate over photochemical processes, the relative dust  
468 impact exhibits complex features in the SZA dependence.

469 Besides the dayside impact, the plasma environment on the nightside is also dis-  
470 turbed by the global dust storm but more importantly in terms of a relative difference.  
471 Unlike an overall upwelling of the dayside ionosphere in response to the upper atmo-  
472 spheric expansion, the impact on the nightside shows a dramatically different character-  
473 istics given that photoionization by solar EUV becomes insignificant toward the optical

474 shadow. In consistence with the MHD perspective that the nightside ionosphere is main-  
475 tained by transterminator and descending ionospheric fluxes, the nightside dust-induced  
476 ionospheric impact shows a clear connection with what happens on the dayside but not  
477 apparently with the ambient atmospheric change. Because ionospheric densities on the  
478 nightside are considerably lower than on the dayside by orders of magnitude, the enhance-  
479 ment factors are greatly amplified as shown in Figure 7 when more ionospheric species  
480 transport from the dayside and inject into the nightside. Accordingly, we see the percent-  
481 age change gradually increases away from the terminator region and reaches the maxima  
482 near the antisubsolar point. The relative increases in the nightside density are as high as  
483 a factor of 6 for  $O_2^+$  and  $e^-$  and up to two orders of magnitude for the minor species of  
484  $CO_2^+$ .

485 It is a natural expectation that the tight coupling between the ionosphere and mag-  
486 netosphere enables the upward propagation of dust-induced, low-altitude perturbations into  
487 the magnetosphere. By self-consistently simulating plasma transport within the context  
488 of the Mars-solar wind interaction, the MHD model goes beyond the limitation of sim-  
489 plistic photochemical approximations and offers a comprehensive global view. Figure 8  
490 presents similar results as Figure 7 but in a much broader altitude range of up to 2000  
491 km. To guide the understanding of the plasma flow distribution and its interaction with the  
492 solar wind, we derive and superpose in the figure the location of the bow shock (BS) and  
493 induced magnetospheric boundary (IMB) by applying the algorithm of *Fang et al.* [2015,  
494 2017]. It is seen that the BS is approximately at 2000 km altitude at the subsolar point for  
495 this specific case (as indicated). This is also reflected by the proton density enhancement  
496 when the solar wind is slowed down, compressed, and heated downstream of the BS. It  
497 should be pointed out that 3-D MHD results enable the determination of global bound-  
498 ary shapes and locations with spatial asymmetry, as demonstrated by *Fang et al.* [2015,  
499 2017]. However, in order to be consistent with the reduced 2-D plot in Figure 8, we make  
500 axial symmetric conic section fits and project the average boundary locations for the ref-  
501 erence purpose. Our results suggest that the boundaries in general show insensitivity even  
502 toward a strong global dust storm. It is found that the dust impact at high altitudes is con-  
503 centrated mostly on plasma densities but little on the dynamics (i.e., velocity) or magnetic  
504 field distributions.

505 As illustrated in the right column of Figure 8, the dust-induced plasma density dis-  
506 turbance occupies a very broad spatial domain, spanning not only the ionosphere but also



507 the magnetosphere. However, perturbations in electron density (i.e., total ion density) are  
508 mostly confined inside the ionosphere, which may explain in part why the high-altitude  
509 IMB and BS are barely affected. For individual ion species, on the other hand, the dust  
510 impact is extended by means of plasma transport from the ionosphere to the magneto-  
511 sphere, from the dayside to the nightside, but great changes are basically limited and bounded  
512 by the IMB. Note that the large percentage differences of planetary ion densities outside  
513 of the IMB on the dayside (particularly near subsolar) are less important, given that so-  
514 lar wind protons are dominant in density by orders of magnitude. As a shielding barrier  
515 that weakens the solar wind penetration [e.g., see Figure 5 of *Fang et al.*, 2015], the IMB  
516 together with the nearby piled-up magnetic field effectively inhibit upward propagation  
517 of the dust-induced disturbance. Figure 8 clearly demonstrates the enormous complexity  
518 of the dust storm consequences in the near-Mars plasma environment and the need for a  
519 global Mars-solar interaction model (like what we are using) to make assessments from a  
520 system's perspective.

521 Figure 9 reorganizes the comparison of the MHD results for dust event 2 using at-  
522 mospheric pressure levels (see Figure 4). These assessments of the dust effects are an ex-  
523 tension of what we have examined along the subsolar line in Figures 6c and 6d to cover  
524 the entire global domain. A few features stand out, consistent with what have been dis-  
525 cussed before. First, within the low-altitude atmosphere of pressure greater than  $\sim 10^{-7}$   
526 Pa (approximately 200 km altitude), the ionospheric electron density on the dayside is  
527 subject to an insignificant change in the atmospheric pressure coordinate frame. In con-  
528 trast, the dayside dust impact on the densities of individual planetary ion species remains  
529 important and is different from each other, although the strength of the relative change  
530 is greatly reduced from what has been seen in Figures 7 and 8 in the altitude coordinate  
531 frame. Second, in these photochemical equilibrium regions, the dust-induced percentage  
532 changes show little dependence with SZA at pressure levels, on the contrary to the appar-  
533 ently strong SZA dependence at altitude levels in Figure 7. It is illustrated that the day-  
534 side main ionospheric layer reacts to the solar absorption and photoionization location  
535 change in accordance with the upper atmospheric expansion, in which plasma transport is  
536 not efficient and photochemical reactions determine the vertical structure of ionospheric  
537 ion abundances. Owing to significant atmospheric compositional changes, the ionospheric  
538 composition is greatly altered, regardless of whether altitude or neutral pressure grids are  
539 used. Third, at higher altitudes, the upper atmosphere becomes insensitive to dust activi-

540 ties (Figure 4) and plasma transport dominates over photochemical reactions. As a result,  
541 the importance of local atmospheric concentrations drops, and using neutral pressure lev-  
542 els is not helpful in explaining the dust impact. Fourth, the nightside ionospheric distur-  
543 bance cannot be accounted for in terms of neutral pressures. This is because under the  
544 MHD approximations, the nightside ionosphere is replenished by ions that are of the day-  
545 side origin and are carried across the terminator by the day-to-night transport. That is, the  
546 nightside ionospheric disturbance is more closely connected with the counterpart on the  
547 dayside than with the ambient neutral perturbation.

548 To have a straightforward picture of the dust-induced global consequences, we show  
549 in Figure 10 a 3-D view of the Martian ionosphere and magnetosphere under nondusty  
550 and dusty atmospheric conditions. The  $e^-$  density distribution is presented at 140 km al-  
551 titude, which is approximately the ionospheric peak location at subsolar under the dusty  
552 condition (see Figure 6a and Figure 7). As expected from axial symmetric setup of the at-  
553 mospheric and solar irradiance conditions about the Sun-Mars line, we see an overall sym-  
554 metry inside the ionospheric photochemical equilibrium region. The relatively weak but  
555 noticeable asymmetric features are attributed to the combined influence from the intrinsic  
556 asymmetry due to multifluid MHD approximations together with the highly nonuniformly  
557 distributed crustal magnetic field. It has been found that the crustal field has a control on  
558 the dayside ionospheric density distribution [e.g., *Andrews et al.*, 2015]. It is readily seen  
559 from the comparison of the nondusty and dusty results that the  $e^-$  density is greatly en-  
560 hanced, particularly near subsolar. Also superposed in Figure 10 are planar cuts of the  
561  $\text{CO}_2^+$  density distributions inside the ionosphere and magnetosphere and beyond (specifi-  
562 cally on the dayside). The most prominent feature is the dayside plume-like ion population  
563 on the meridional ( $X$ - $Z$ ) plane, which is distinct from the tailward-escaping population.  
564 Accelerated by the convection electric field, which is aligned with the  $+Z$  direction up-  
565 stream of Mars, ion plume represents an important nonthermal ion escape channel for at-  
566 mospheric erosion [e.g., *Fang et al.*, 2008; *Dong, Y., et al.*, 2015] and is captured by our  
567 MHD multifluid approximations [*Dong et al.*, 2018a]. Note that the IMF direction setup  
568 in this work makes the MSO and MSE coordinate systems coincide. The comparison in  
569 Figure 10 reveals that the  $\text{CO}_2^+$  density remarkably increases due to the global dust storm,  
570 inside not only the ionosphere but also the magnetosphere, including both the plume and  
571 tail population regions.

## 4.2 Dust Impact on Atmospheric Loss

The density disturbances at high altitudes as illustrated in Figures 8 and 10 suggest an important implication of dust storms for total planetary ion loss. We make an assessment of how the amounts of escaping ions react to the global dust storm. The comparison is conducted in Figure 11, sufficiently far away from Mars ( $r = 6R_M$ ) to ensure that outward moving particles are lost to space. The two ion escape channels are prominent in Figure 11: the plume escape over the polar region (mainly on the dayside and swept through the nightside) and the downstream escape of plasma sheet particles (concentrated near the nightside meridional plane). The detailed comparison in the right column of Figure 11 reveals that all of these major planetary heavy ions suffer important escaping flux perturbations at least locally, resulting in net relative changes in the integrated loss amounts:  $-5.6\%$  ( $O_2^+$ ),  $-32.6\%$  ( $O^+$ ), and  $161.6\%$  ( $CO_2^+$ ). The important dust impact on the total loss of  $O^+$  and  $CO_2^+$  are consistent with what we have seen in the magnetosphere in Figure 8, in support of the picture that dust-induced perturbations are propagated upward by plasma transport processes.

While MHD-estimated oxygen escape in the form of ions is minor in comparison with neutral escape through dissociative recombination of molecular ions  $O_2^+$  and  $CO_2^+$  [e.g. *Lee et al.*, 2015a], the net increase of MHD  $CO_2^+$  escape by a factor of  $\sim 2.6$  as shown here has profound implications. According to the work of *Groller et al.* [2014], the neutral carbon loss rate is about  $7.9 \times 10^{23} \text{ s}^{-1}$  for low solar activity, the condition comparable to the solar irradiance conditions of our current MHD simulations (see section 3.1). Another independent work by *Lee et al.* [2015b] gives a total carbon loss estimate of  $9.7 \times 10^{23} \text{ s}^{-1}$  under perihelion and low solar conditions. The estimate of the carbon loss by *Cui et al.* [2019] is  $10^{24} \text{ s}^{-1}$  on average, under low to moderate solar conditions. Taking the neutral loss into account and artificially assuming a stable level of about  $9 \times 10^{23} \text{ s}^{-1}$ , our results imply that the strong global dust storm may increase the total carbon loss (in the forms of neutrals and ions) from  $1.0 \times 10^{24} \text{ s}^{-1}$  to  $1.2 \times 10^{24} \text{ s}^{-1}$ , which amounts to a relative increase of 20%. However, this represents a lower bound estimate and the potential increase for total carbon loss may have been greater, given that neutral loss itself probably increases as well. In association with upper atmospheric expansion, more CO molecules are expected, and thus more hot carbon atoms are produced from photodissociation [*Fox & Bakalian*, 2001]. When assessing the implication of global dust storms for atmospheric loss, we need to consider another equally important factor, i.e., time scale. Note that global

605 dust storms typically last for months (see Figures 1 and 2), and the work of *Liemohn et al.*  
606 [2012] suggests that the dust impact on the upper atmosphere may last even longer by up  
607 to 7 months. All together, Mars global dust storms are more than just a powerful meteo-  
608 rological phenomenon. Its potential importance in atmospheric evolution (particularly for  
609 carbon loss) should be further studied.

## 610 **5 Discussion and Conclusion**

611 In summary, we apply the state-of-the-art multifluid MHD model to investigate how  
612 the dust-induced upper atmospheric perturbations transfer to the surrounding plasma envi-  
613 ronment over a global scale. A broad spatial domain of the model (above 100 km altitude)  
614 is examined, including not only the main ionosphere (which suffers direct influence due  
615 to photochemical reactions and tight neutral-ion coupling) but also the induced magneto-  
616 sphere (which is more subject to indirect influence through plasma transport processes).  
617 By choosing the 2017 late-winter regional dust storm and the stronger 1971-1972 global  
618 dust storm for our case studies, our quantitative evaluation enables an assessment of the  
619 range of potential dust consequences. The discussions above focus more on the analysis  
620 of the MHD results for the 1971-1972 global dust storm. The impact of the 2017 late-  
621 winter regional dust storm has been similarly analyzed and included in the supporting in-  
622 formation of this paper. It is found that important dust consequences also happen in the  
623 ionosphere and magnetosphere during the regional storm, but to a less degree as expected.  
624 The impact of the regional dust storm on planetary ion loss is basically negligible.

625 It should be stressed that dust storms are typically characterized with different tim-  
626 ing (season), duration, spatial coverage, and magnitude (see Figure 1), and at the same  
627 time the corresponding upstream solar wind, IMF, and solar irradiance conditions are  
628 largely stochastic. In this respect, dust storms are different and somehow unique from  
629 each other, not only in dust activities themselves but also in the background atmospheric  
630 and solar conditions. To add to the complexity of modeling the dust impact on the near-  
631 Mars space environment, localized crustal magnetic anomalies are an important factor.  
632 The crustal field distribution in the MSO coordinate system is determined by the season-  
633 dependent Mars' orientation to the Sun (see Figure 2) and its continuous rotation, signif-  
634 icantly contributing to the complexity and variability of the solar wind-Mars interaction  
635 [*Fang et al.*, 2010, 2015, 2017; *Ma et al.*, 2014].

636 In this study, which represents the first attempt to theoretically predict the dust im-  
637 pact on a global scale including both the ionosphere and magnetosphere, we make a few  
638 simplified approximations. For example, we rely on previously published results to de-  
639 scribe the atmospheric profiles under nondusty and dusty conditions, which serve as input  
640 to the MHD model. Except for background atmospheric conditions, all the other driv-  
641 ing factors are held identical in our controlled MHD runs. The model runs until a quasi  
642 steady state is reached; by this means, we neglect fluctuations over short periods of time.  
643 Nevertheless, by using conditions as physically realistic as possible, it suffices for us to  
644 perform a first-order assessment of whether and how dust storms could extend their effects  
645 thousands of kilometers from the bottom side of the ionosphere into space. It is left to fu-  
646 ture study to include self-consistently configured 3-D atmospheres (including thermal and  
647 hot components) and allow for time variation of the system and its drivers.

648 It is found that the ionosphere can be significantly disturbed during dust storms. On  
649 the dayside, the net effect on ionospheric vertical profiles of electron densities or total  
650 ion densities basically is upwelling of the main ionospheric layer (below  $\sim 250$  km alti-  
651 tude). The peak altitudes are upward lifted by  $\sim 5$  km and  $\sim 15$  km for the regional and  
652 global dust storm, respectively. This occurs nearly uniformly on the dayside, in accordance  
653 with the assumed expansion of the entire upper atmosphere. Similar vertical shifts hap-  
654 pen to individual planetary  $O_2^+/CO_2^+/O^+$  ion distributions, although relatively light  $O^+$  ions  
655 (which peak at high altitudes) are subject to a greater elevation. During ionospheric up-  
656 welling, there is little change in the peak densities of electrons and ions. As an exception,  
657 the whole  $O^+$  density profile may be significantly reduced in the global dust storm, due  
658 to more severe ion loss through charge exchange collisions with enhanced ambient  $CO_2$   
659 neutrals. Consistent with the upward lift, charged particle densities increase (decrease) at  
660 altitudes above (below) their peak locations. The ionospheric composition is significantly  
661 altered in the global storm, as a result of dust-induced perturbations in the neutral com-  
662 position. In contrast, the ionospheric composition basically is stable during the regional  
663 storm. In these photochemical equilibrium regions (below  $\sim 250$  km), using neutral pres-  
664 sure levels in place of altitude levels is helpful to explain the ionospheric upwelling in  
665 response to the regional storm, but fails in the case of the global storm except for elec-  
666 tron density profiles. This supports that photochemical reactions still play a dominant role  
667 in determining the main ionospheric layer, but sufficiently large compositional changes in  
668 neutrals would in turn result in noticeable ion mixing ratio changes.

669 Unlike the direct and straightforward reactions of the dayside ionosphere to the up-  
670 per atmospheric perturbations, the nightside ionosphere responds to the dust storm in  
671 an indirect sense. From the MHD perspective, the source of the nightside ionosphere  
672 comes from the plasma of the dayside origin, which is carried by the day-to-night trans-  
673 port across the terminator and then descends to low altitudes. As a result, the nightside  
674 ionospheric change shows a close connection with what happens on the dayside but not  
675 apparently with the ambient atmospheric change. Because of considerably lower plasma  
676 abundances on the nightside, the percentage change due to dust storms is greatly amplified  
677 in comparison with the dayside part. Consistent with the day-to-night transport, the max-  
678 imum relative change appears deep in the optical shadow, even over orders of magnitude.  
679 However, it has been suggested by previous studies [e.g., *Nemec et al.*, 2010; *Duru et al.*,  
680 2011; *Cui et al.*, 2015; *Girazian et al.*, 2017; *Adams et al.*, 2018] that particle precipitation  
681 constitutes an important, direct ionization source to the ionosphere in addition to the day-  
682 to-night transport, particularly far into the nightside. In this scenario, dust-induced atmo-  
683 spheric expansion on the nightside would more effectively prevent particle penetration and  
684 therefore enhance energy deposition and particle impact ionization rates at higher altitudes  
685 and reduce them at lower altitudes. The resulting upward shift of the nightside ionosphere  
686 due to particle precipitation would be mixed with the indirect changes that we have seen  
687 in this study due to the day-to-night transport. Untangling the relative importance of par-  
688 ticle precipitation and transterminator transport, with the crustal magnetic field taken into  
689 account, is an important topic for future work.

690 At altitudes higher than  $\sim 250$  km, the transport process becomes important and  
691 takes over the control of plasma distributions from local photochemical reactions. As a  
692 result, we see that dust-induced perturbations propagate upward from the ionosphere to the  
693 magnetosphere, and extend from the dayside to the nightside. While the electron density  
694 or the total ion density seems to have their disturbances limited to altitudes below  $\sim 500$   
695 km, the densities of planetary ions ( $\text{O}_2^+$ ,  $\text{CO}_2^+$ ,  $\text{O}^+$ ) react to the dust storms throughout the  
696 entire magnetosphere generally bounded by the IMB. This suggests that the IMB and the  
697 nearby magnetic field pileup not only weaken the solar wind penetration but also consti-  
698 tute a barrier to effectively inhibit the upward propagation of low-altitude perturbations.  
699 Despite probable strong local changes to densities at high altitudes, the total ion escape  
700 rates are hardly impacted during the regional storm. On the contrary, the total loss of  $\text{O}_2^+$   
701 and  $\text{CO}_2^+$  in the global storm may change by  $-32.6\%$  and  $161.6\%$ , respectively. Taking

702 neutral carbon loss into account, our results imply that total carbon loss, in the forms of  
703 neutrals (mainly through photodissociation of CO) and ions (through CO<sub>2</sub><sup>+</sup> in this study),  
704 may be subject to a net increase of ~ 20% or higher during strong dust storms. Consider-  
705 ing that global dust storms are an event over a time scale of months and their disturbances  
706 on the upper atmosphere may last even longer [Liemohn *et al.*, 2012], this work suggests  
707 that the potential importance of intense dust storms in Mars atmospheric evolution needs  
708 further study.

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787 narios are available through the Mars Climate Database (MCD) project at [http://www-](http://www-mars.lmd.jussieu.fr)  
788 [mars.lmd.jussieu.fr](http://www-mars.lmd.jussieu.fr).

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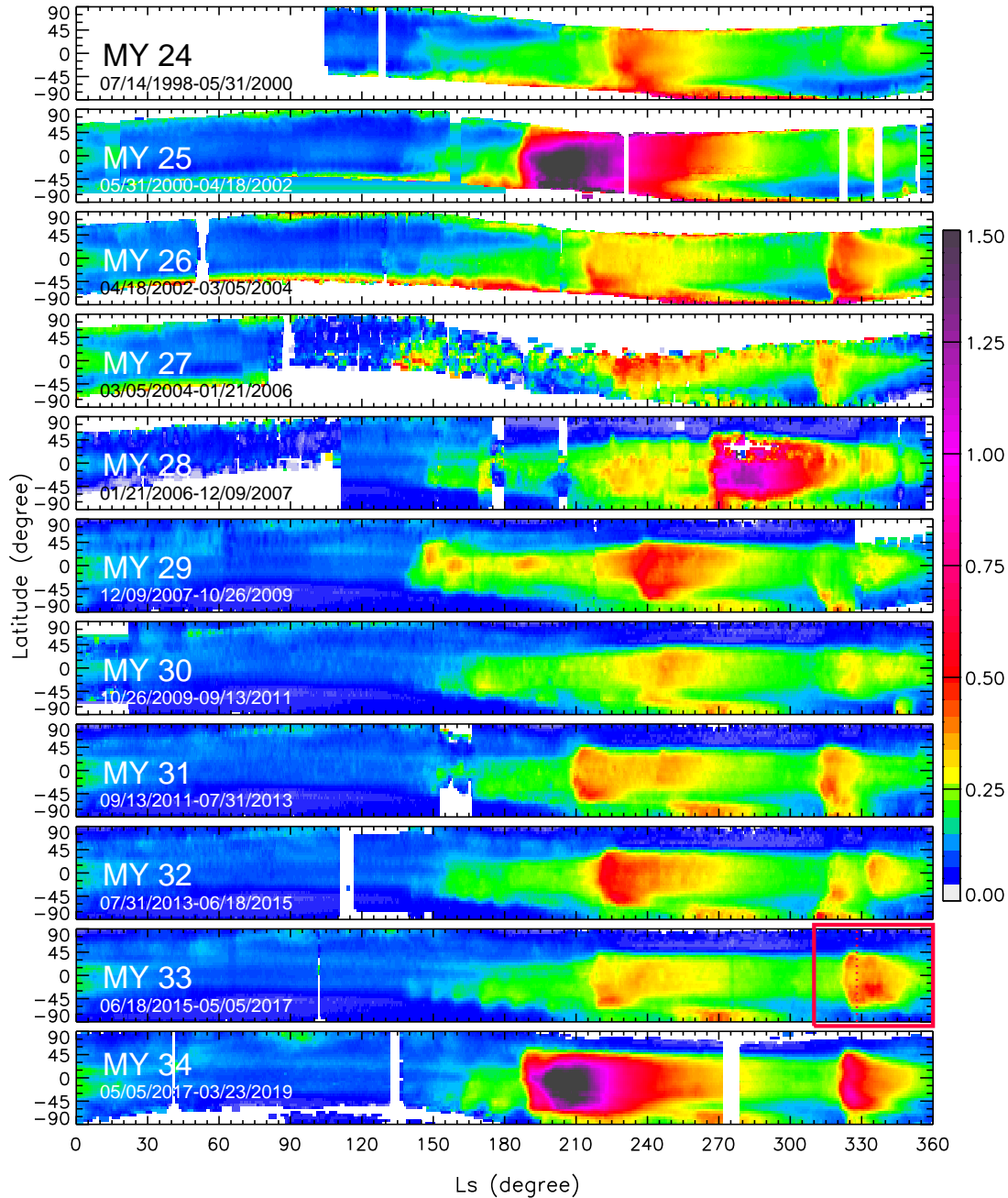
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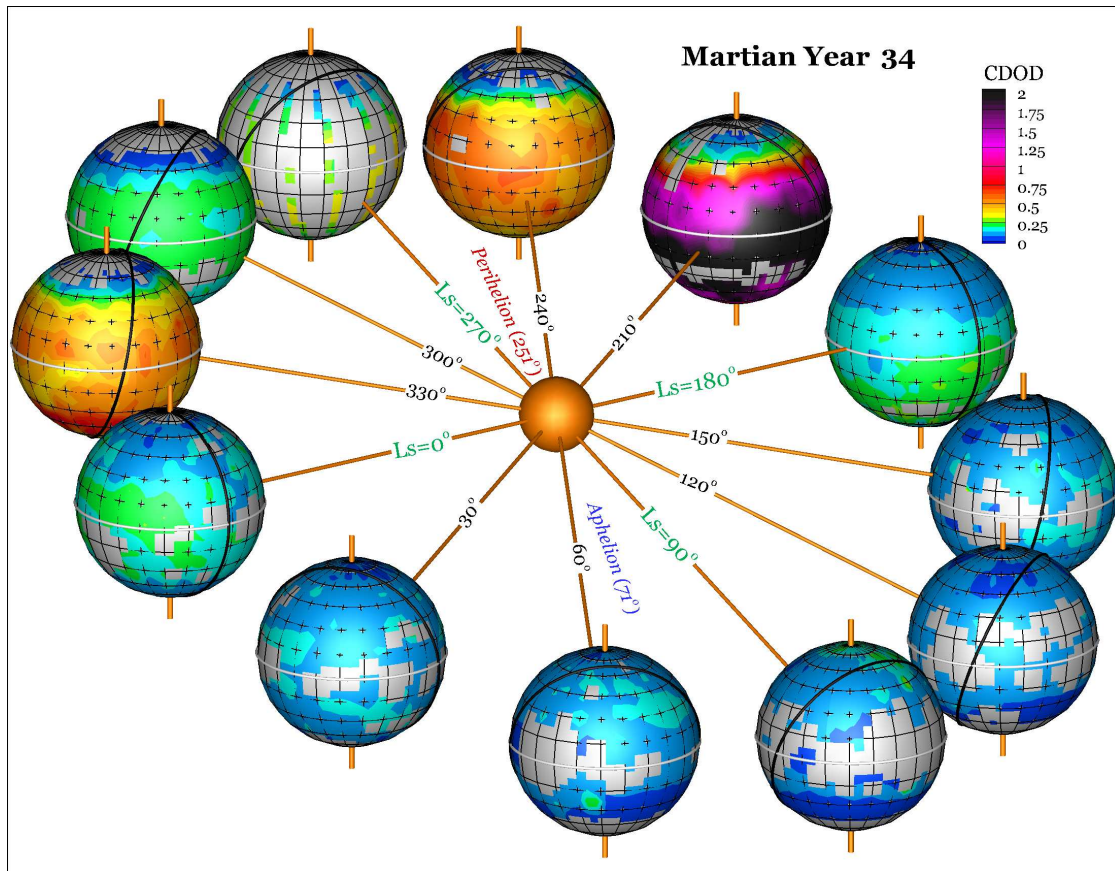
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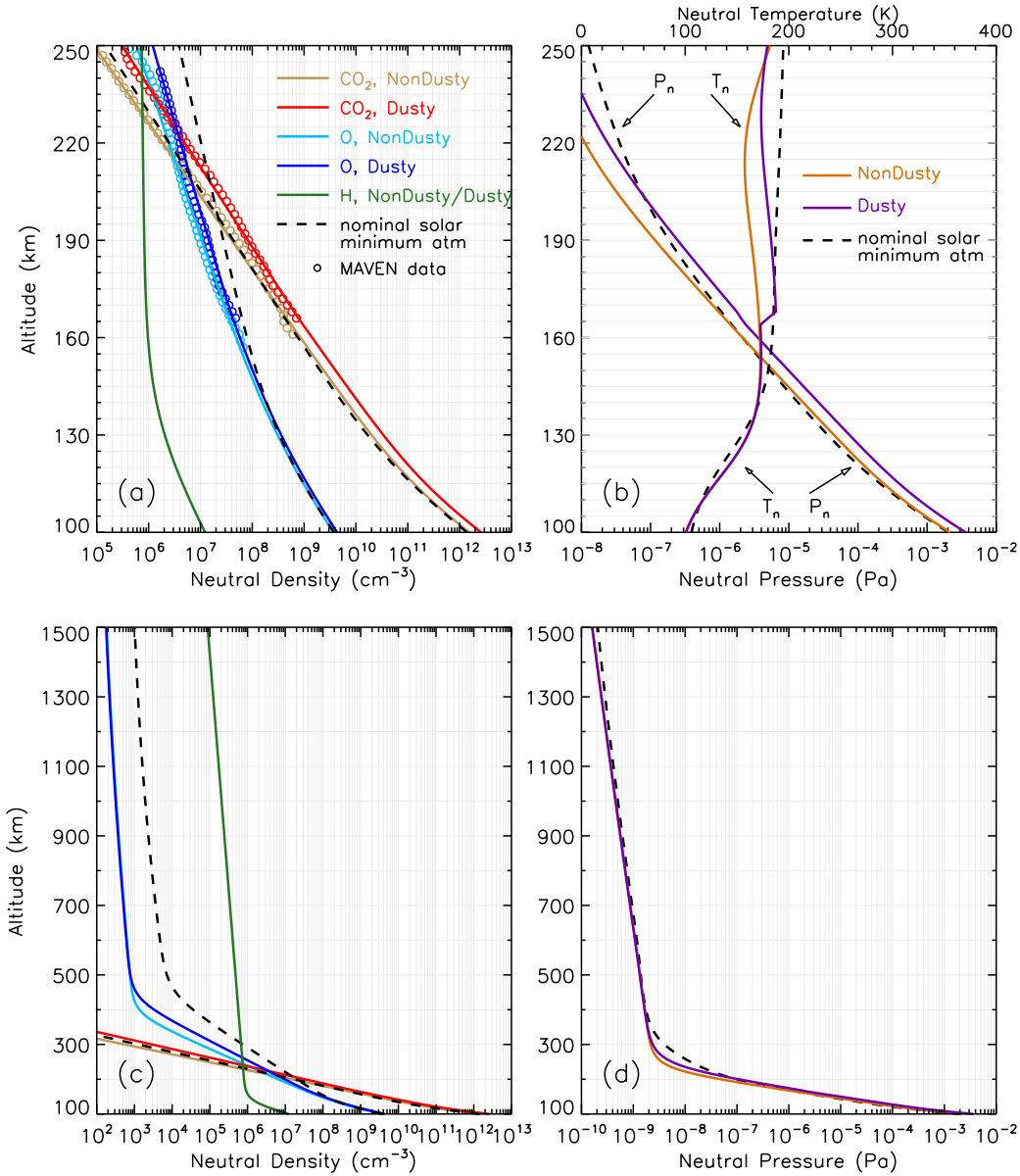
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709 **Figure 1.** Mars zonally-averaged column dust optical depth at the infrared wavelength of about  $9.3\mu\text{m}$   
 710 during 11 Martian years. The dust opacity, scaled to the atmospheric pressure level of 610 Pa, is shown as  
 711 a function of solar longitude ( $L_s$ ) and geographic latitude. The start and end dates on Earth are given for  
 712 each Martian year, and white areas indicate missing data. The red box in the second to last panel denotes the  
 713 currently investigated 2017 regional dust storm period, and the vertical dashed line indicates the time when a  
 714 dusty condition is taken for this study. Note that while MY 24-33 zonal means are created using the Mars Cli-  
 715 mate Database gridded dust climatology versions 2.0 and 2.1, MY 34 zonal mean is created using an updated  
 716 version (as described in *Montabone et al. [2019]*). Therefore, caution is required when directly comparing  
 717 MY 34 and the other years (particularly MYs 28-33).

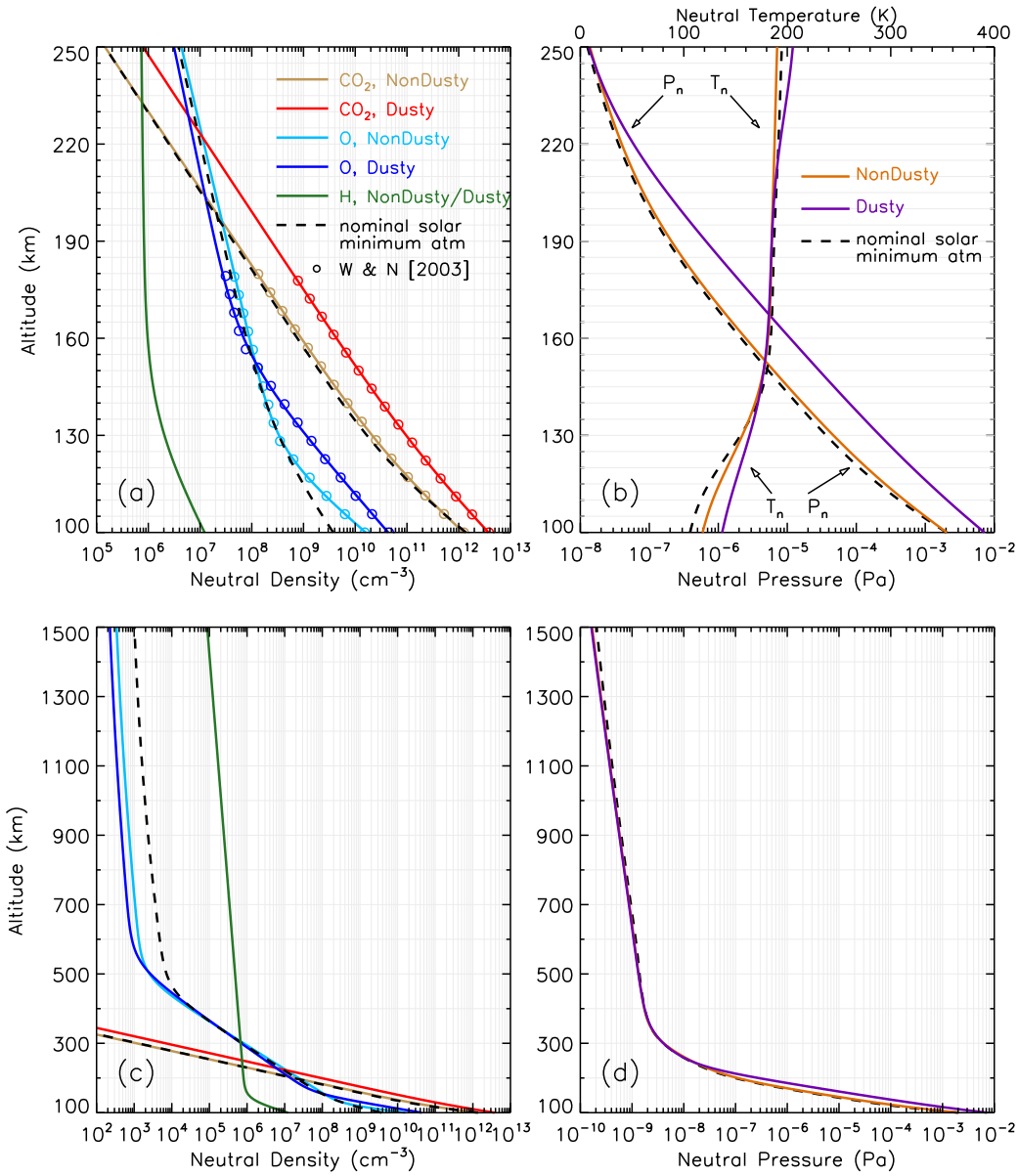


718 **Figure 2.** Global distributions of column dust optical depth at the wavelength of  $9.3\mu\text{m}$  during Martian  
 719 Year 34. The dust opacity has been scaled to the atmospheric pressure of 610 Pa. Gray areas indicate missing  
 720 data. The planetary rotational axis is shown in yellow, and the equatorial and terminator circles are super-  
 721 posed as thick white and black curves, respectively. While the sizes of the solar and Martian bodies are not  
 722 scaled in comparison with the distances between them, the planetary orientations and orbital positions are  
 723 based on calculations using NAIF-SPICE. Note that the color scale is different from Figure 1.

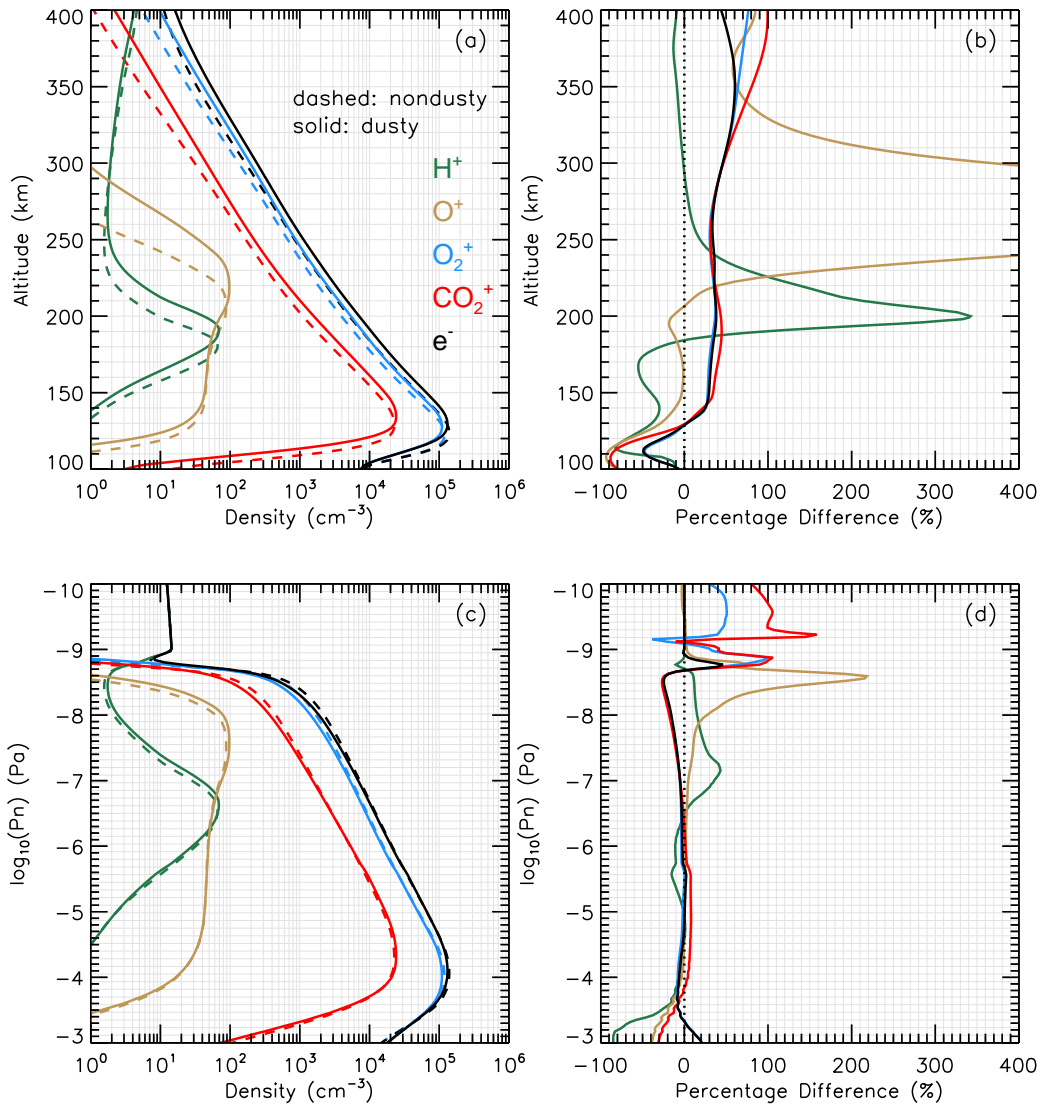


724 **Figure 3.** Altitude profiles of the upper atmospheric density (left) and temperature and pressure (right)  
 725 under nondusty and dusty conditions for the simulation of the 2017 regional dust storm period (event 1). The  
 726 circles in panel (a) represent the density of  $\text{CO}_2$  and O inferred from MAVEN measurements. The solid lines  
 727 for these two species are our fit and extension into the simulation domain of the MHD model (see the text).  
 728 The green line shows the H density profile, regardless of nondusty or dusty conditions, which are adopted  
 729 from a typical MHD setting for a nominal solar minimum atmosphere. The dashed lines are the nominal  $\text{CO}_2$   
 730 and O distributions for reference. Panel (b) shows the total neutral pressure (bottom axis) and bulk neutral  
 731 temperature (top axis) under nondusty and dusty conditions, with the nominal altitude profiles shown in  
 732 dashed line. Panels (c) and (d) are the zoom out of panels (a) and (b), respectively, showing the hot oxygen  
 733 and hydrogen coronas in an extended altitude range.

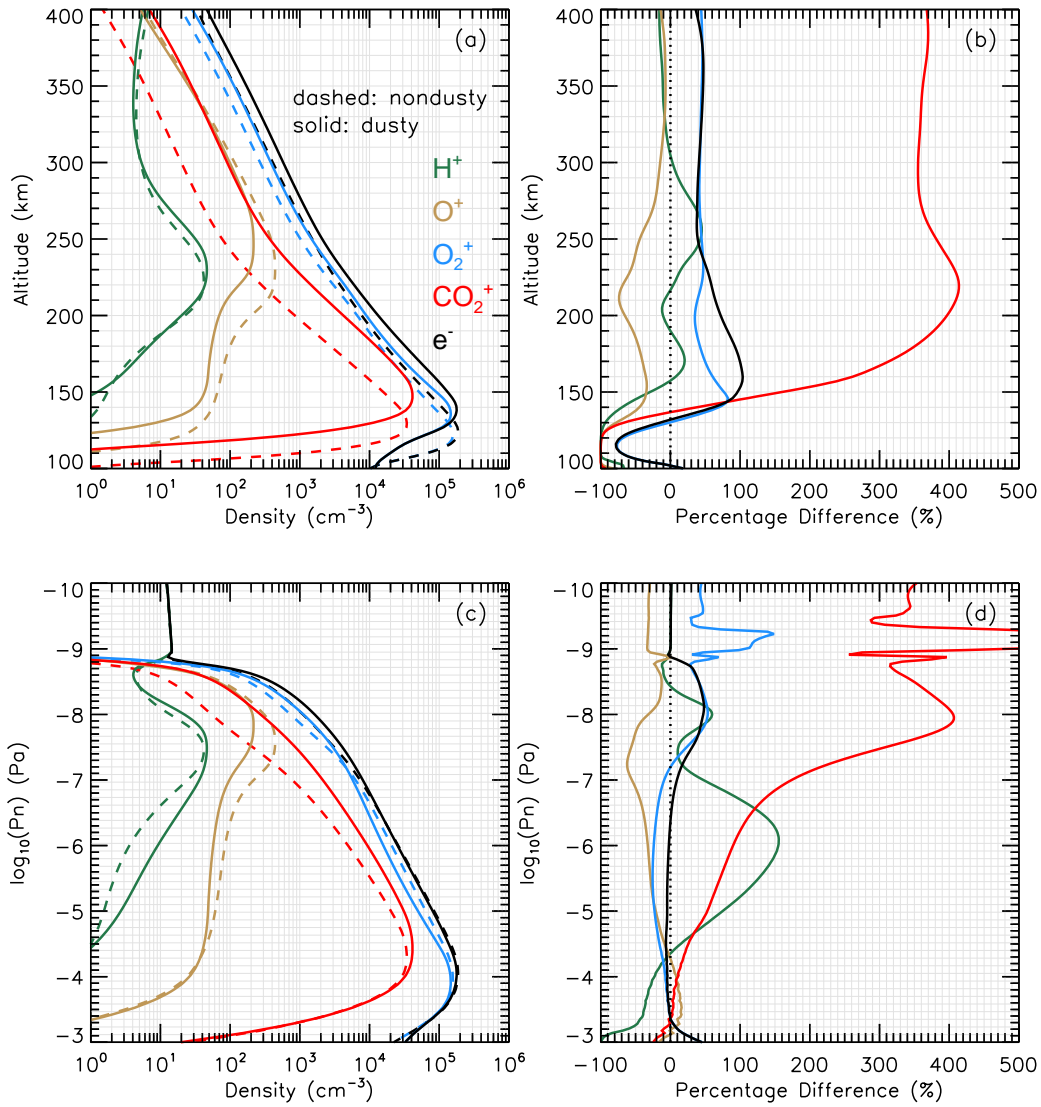




734 **Figure 4.** Similar to Figure 3 but for the 1971-1972 global dust storm period (event 2). The circles indicate  
 735 the estimates obtained by Wang and Nielsen [2003].

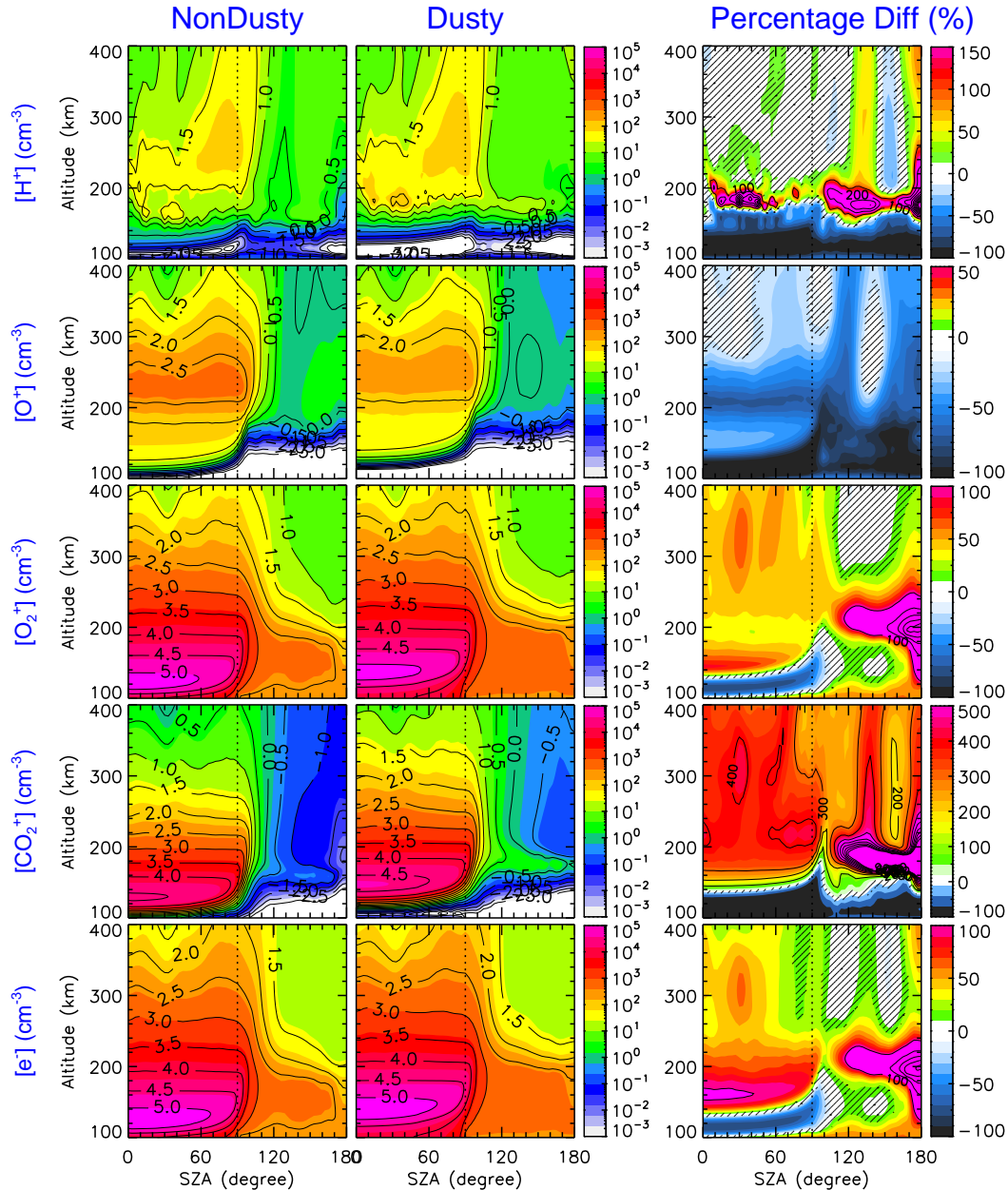


736 **Figure 5.** MHD-calculated ionospheric density disturbances along the subsolar line for dust event 1. Panel  
 737 (a) shows the altitude profiles of ion and electron densities under nondusty (in dashed) and dusty (in solid)  
 738 atmospheric conditions. Panel (b) shows the percentage change of the densities due to the dust storm. The  
 739 second row is similar to the first row, expect that the results are presented at atmospheric pressure levels. The  
 740 pressure axis has been reversed to show increasing altitude from the bottom to the top. Also note that the  
 741 pressure axis covers a much broader altitude range than in the first row. For example, the topside atmospheric  
 742 pressure of  $10^{-10}$  Pa is at an altitude higher than 1500 km.

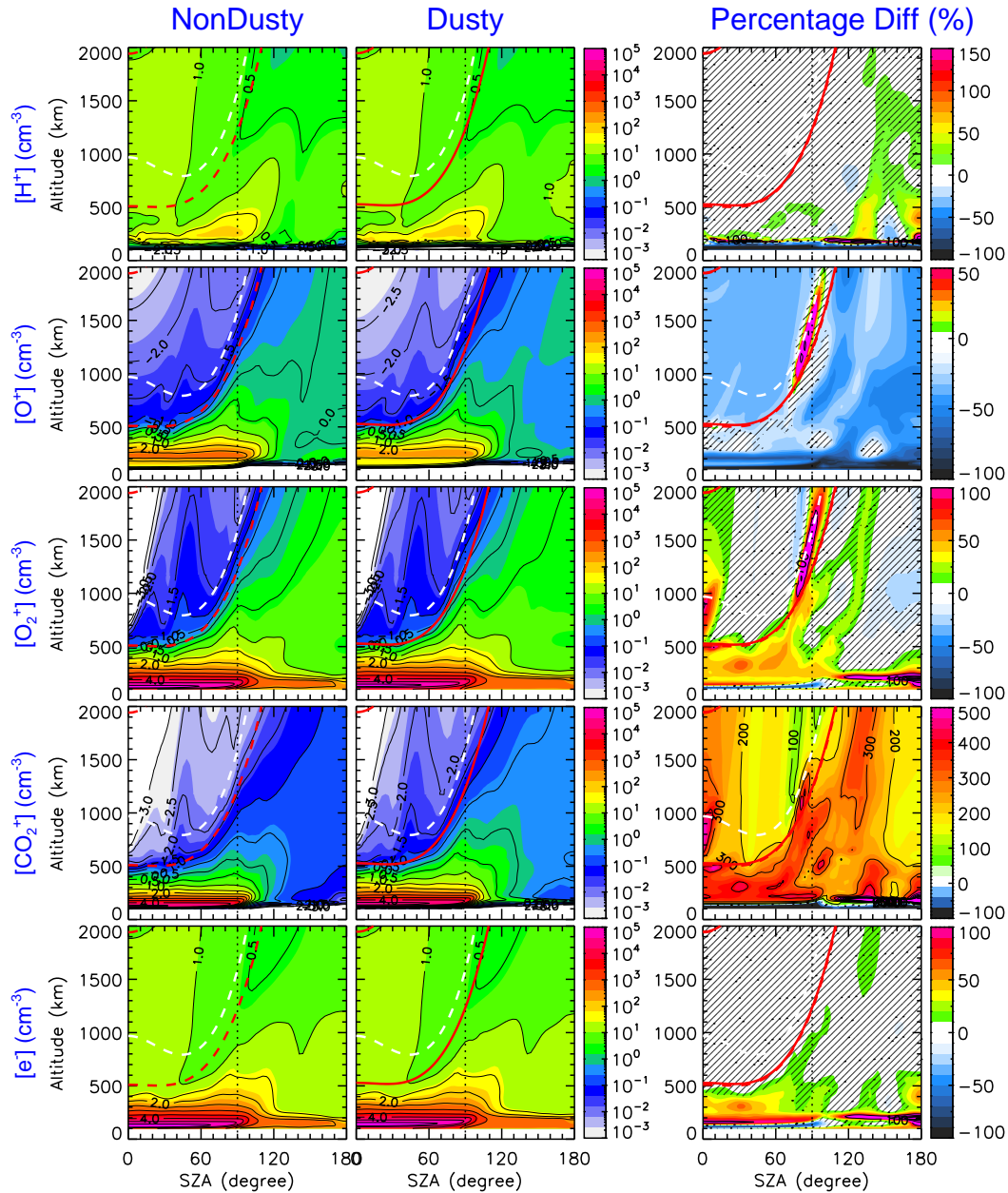


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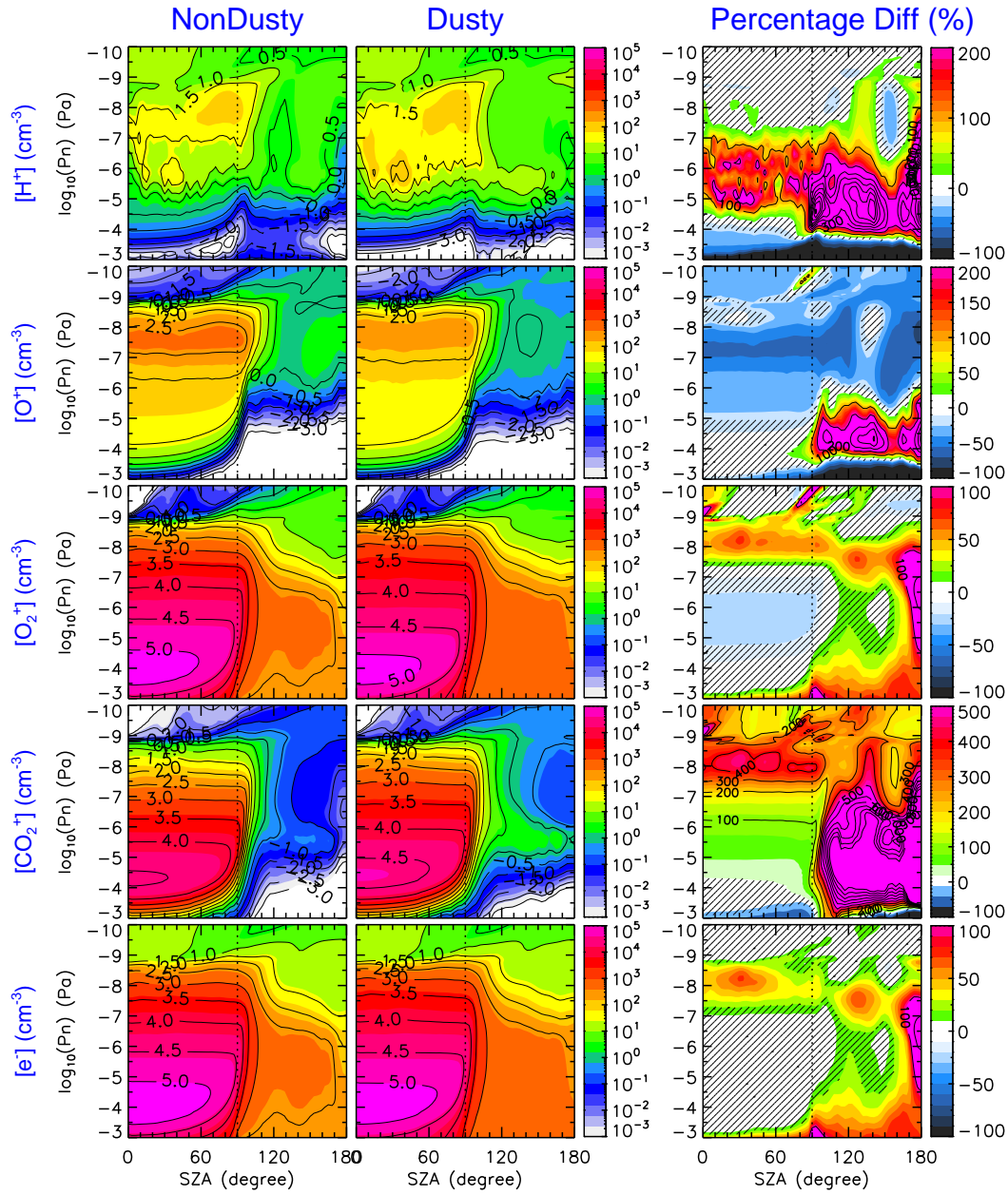
**Figure 6.** Subsolar ionospheric density disturbances for dust event 2, in a format similar to Figure 5.



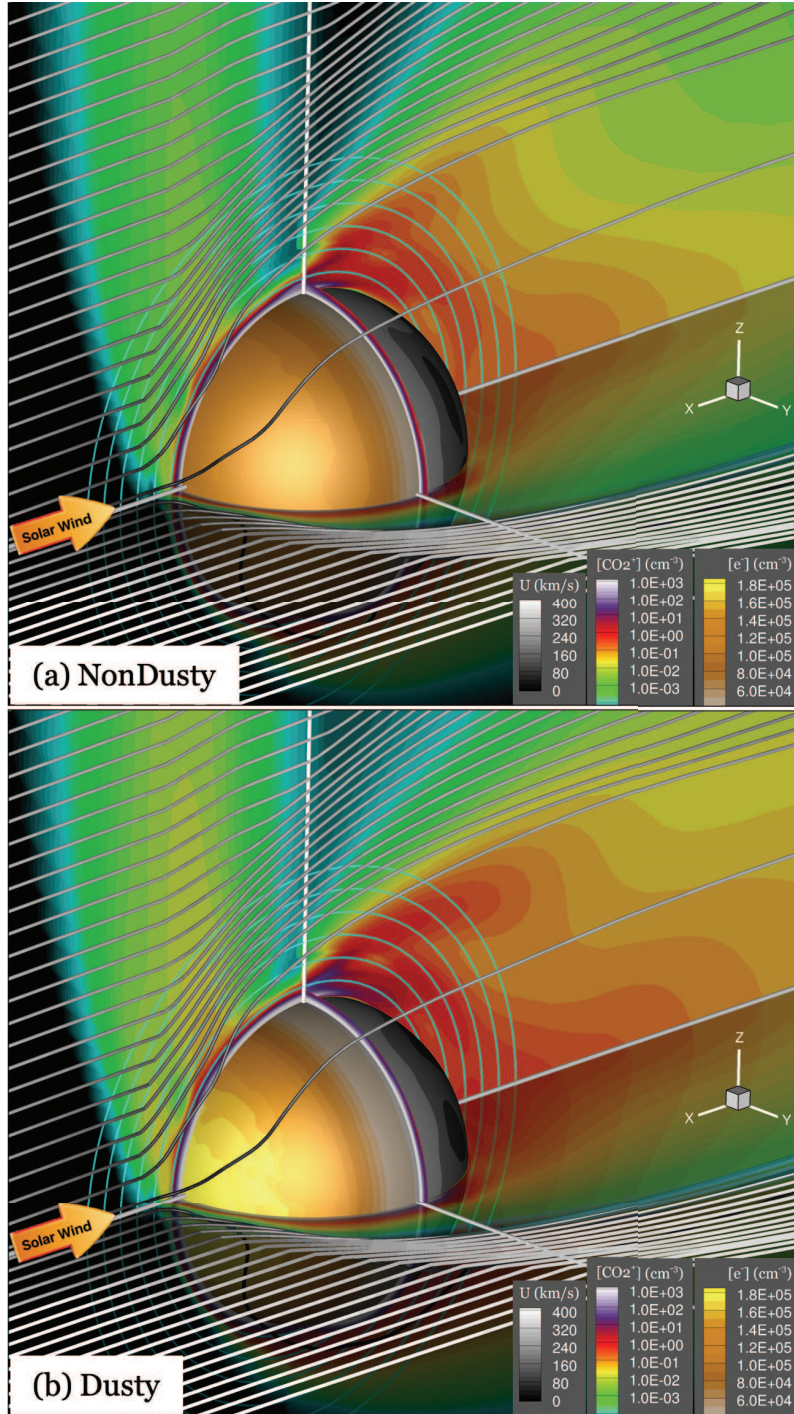
744 **Figure 7.** MHD-calculated ionospheric density disturbances for dust event 2 as a function of SAZ and  
 745 altitude. The left two columns present the SAZ-averaged ionospheric densities under nondusty and dusty  
 746 atmospheric conditions, respectively. The right column shows their percentage differences, i.e., dusty values  
 747 minus nondusty divided by nondusty. From top to bottom, the panels show the results for different iono-  
 748 spheric species, using different color scales for the percentage changes. In the right column, the contour lines  
 749 indicate a percentage change of every 100% interval, particularly useful on the nightside where the relative  
 750 difference may be sufficiently high to make the color scale saturated. The hatched areas mark the places  
 751 having a modest change, where the absolute percentage difference is less than 20%.



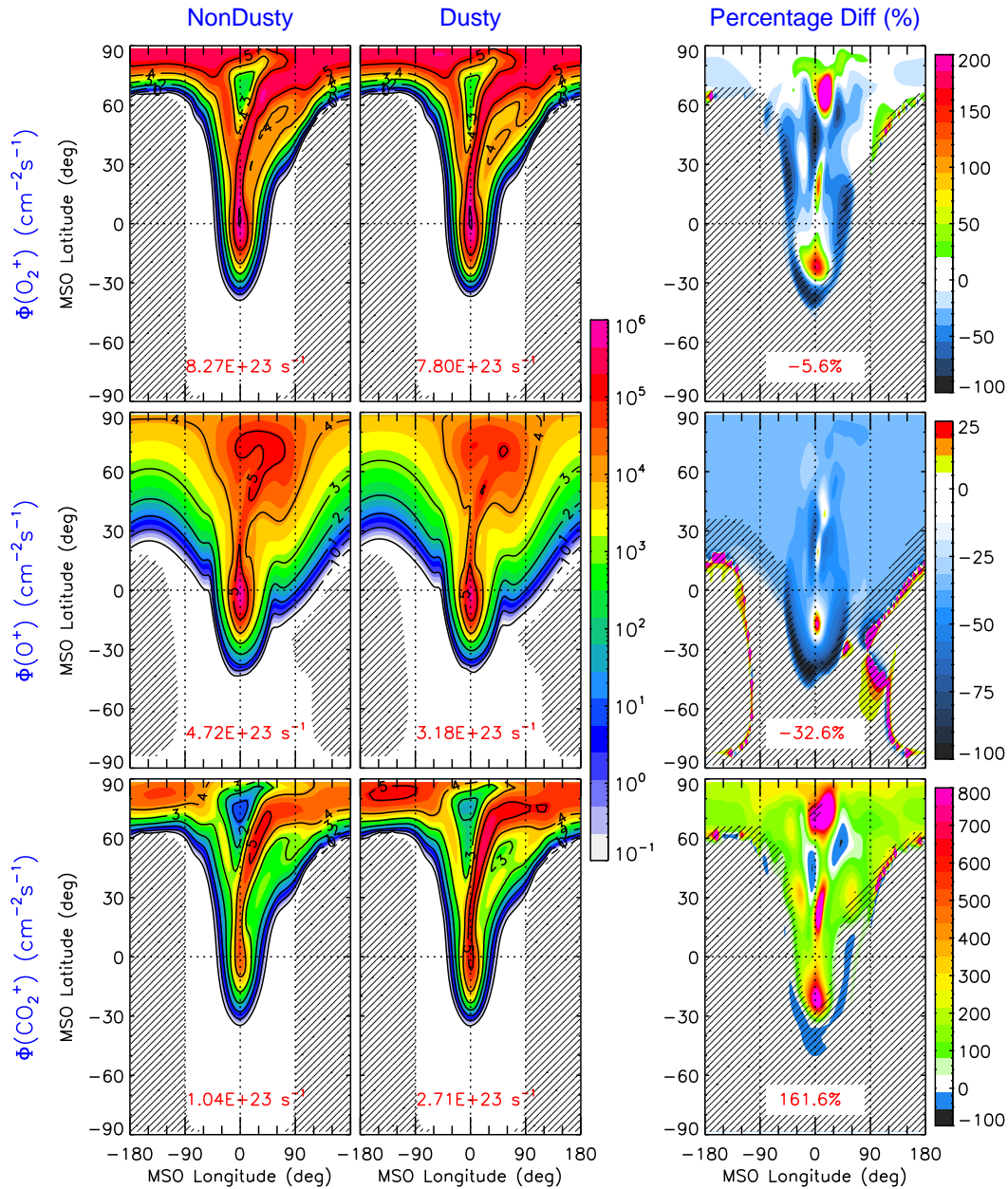
752 **Figure 8.** Similar to Figure 7 but including the results of the induced magnetosphere during dust event  
 753 2, with the altitude limit extended up to as high as 2000 km. The average location of the induced magneto-  
 754 spheric boundary, which is obtained using a conic section fit, is shown as red dashed (solid) lines for nondusty  
 755 (dusty) conditions. The empirical location by *Vignes et al.* [2000] is superposed as white dashed lines for  
 756 reference. Note that our MHD-derived bow shock is also shown but partly at the upper left corners of the  
 757 panels, which is located mostly higher than 2000 km altitude except near subsolar in this specific case. As a  
 758 comparison, the lowest altitude of the empirical bow shock is  $\sim 2190$  km.



759 **Figure 9.** Similar to Figures 7 and 8 except that the results for dust event 2 are presented at atmospheric  
 760 pressure levels. The pressure axis has been reversed in correspondence with altitude increase from the bottom  
 761 to the top.



762 **Figure 10.** The 3-D view of the Martian ionospheric and magnetospheric disturbances during dust event  
 763 2 by comparing the MHD results under (left) nondusty and (right) dusty atmospheric conditions. The gray  
 764 curves show streamlines of mass-averaged plasma flow (color coded by the speed), originating in the upstream  
 765 on the MSO  $X-Z$  (meridional) and  $X-Y$  (equatorial) planes. The spherical surface shows the ionospheric  $e^-$   
 766 density at 140 km altitude. On the  $X-Z$ ,  $X-Y$ , and  $Y-Z$  (terminator) planes, we superpose the color contours  
 767 of the  $CO_2^+$  density. Note that the  $CO_2^+$  distribution on the terminator plane is shown up to 400 km altitude in  
 768 order not to block the view. The cyan concentric circles on the  $X-Z$  plane indicate the altitudes from 500 km  
 769 to 3000 km at an interval of 500 km.



770 **Figure 11.** Comparison of the MHD-calculated planetary ion fluxes escaping through the spherical surface  
 771 at a radial distance of  $6 R_M$  from the Mars center during dust event 2. The panels from top to bottom show  
 772 the results for  $O_2^+$ ,  $O^+$ , and  $CO_2^+$ , respectively. The left two columns present the results under nondusty and  
 773 dusty atmospheric conditions, respectively, as a function of MSO longitude and latitude. The MSO latitude  
 774 is measured from the MSO equatorial plane, on which  $0^\circ$  longitude and  $\pm 180^\circ$  longitude point toward the  
 775 antisonward and sunward directions, respectively. The hatched areas mark negative fluxes, that is, for ion  
 776 velocities having a radially inward component. The spherically integrated loss rates are indicated on the bot-  
 777 tom of the panels. In the right column, we show the percentage difference between the left two columns. The  
 778 hatched areas correspond to insignificant ion fluxes of less than  $10 \text{ cm}^{-2} \text{ s}^{-1}$ , where the relative comparison is  
 779 less meaningful. The percentage differences of the total loss rates are indicated on the panels.



Figure 1.

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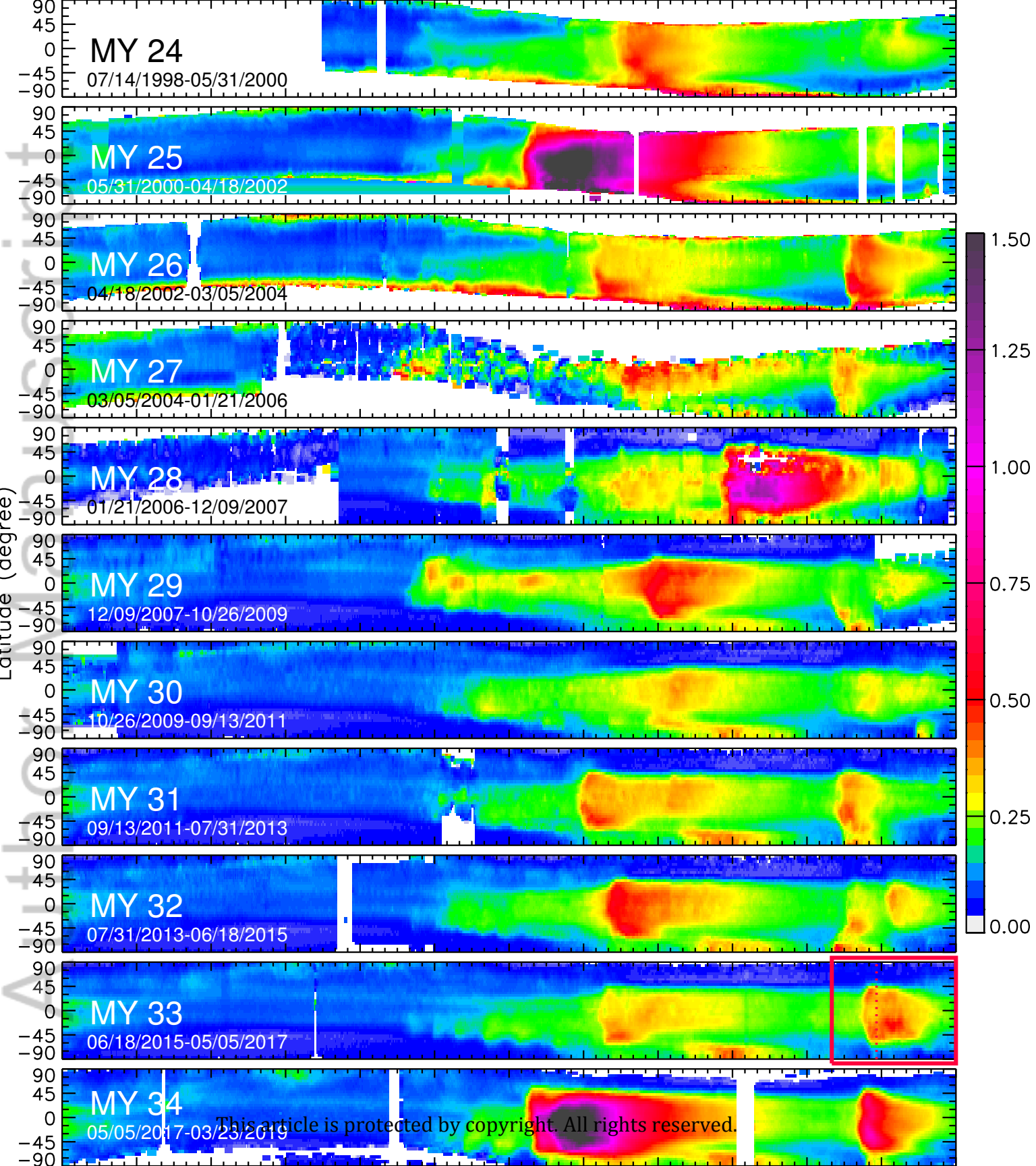


Figure 2.

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# Martian Year 34

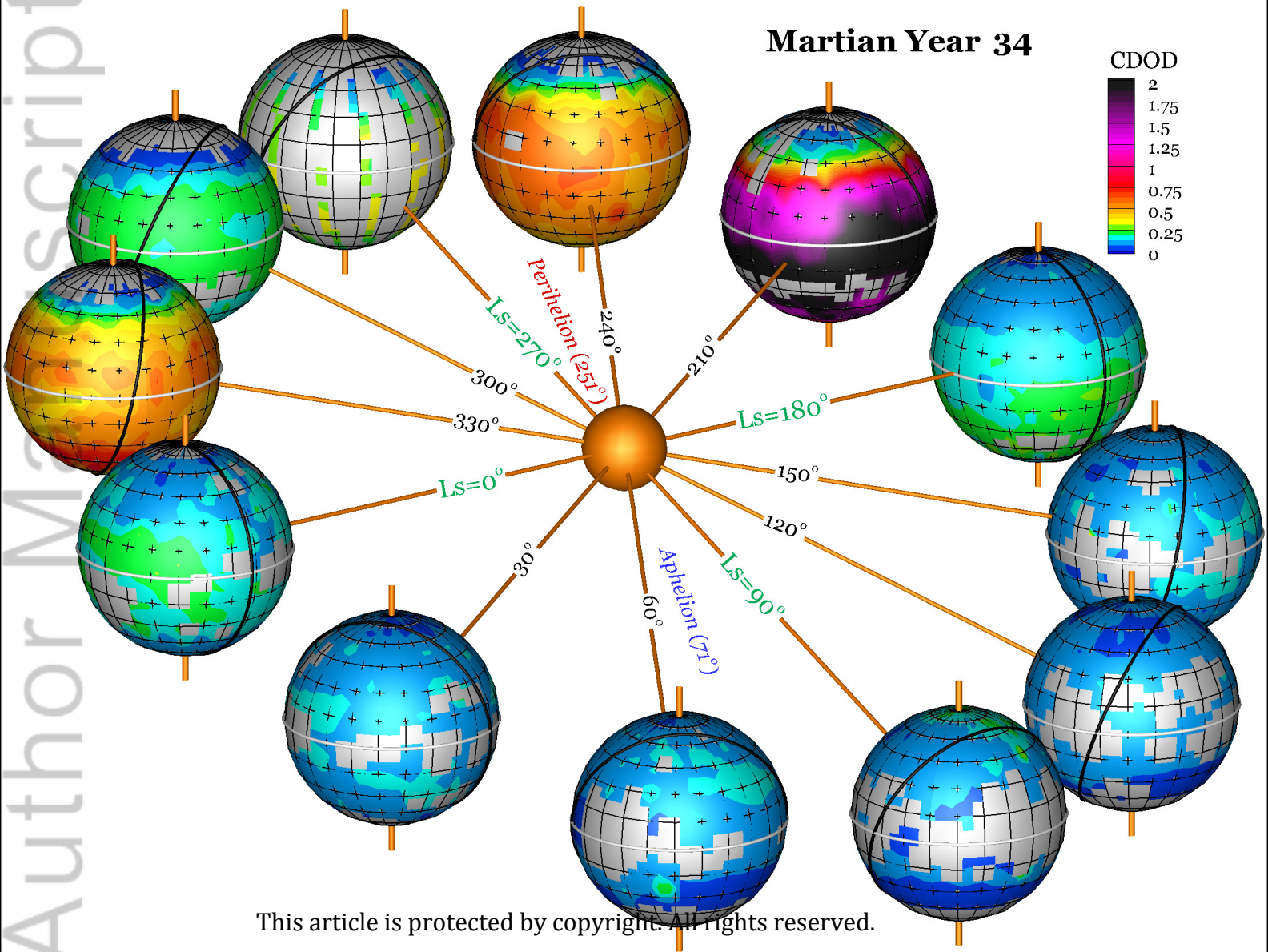
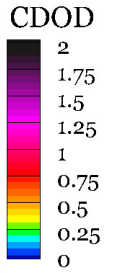


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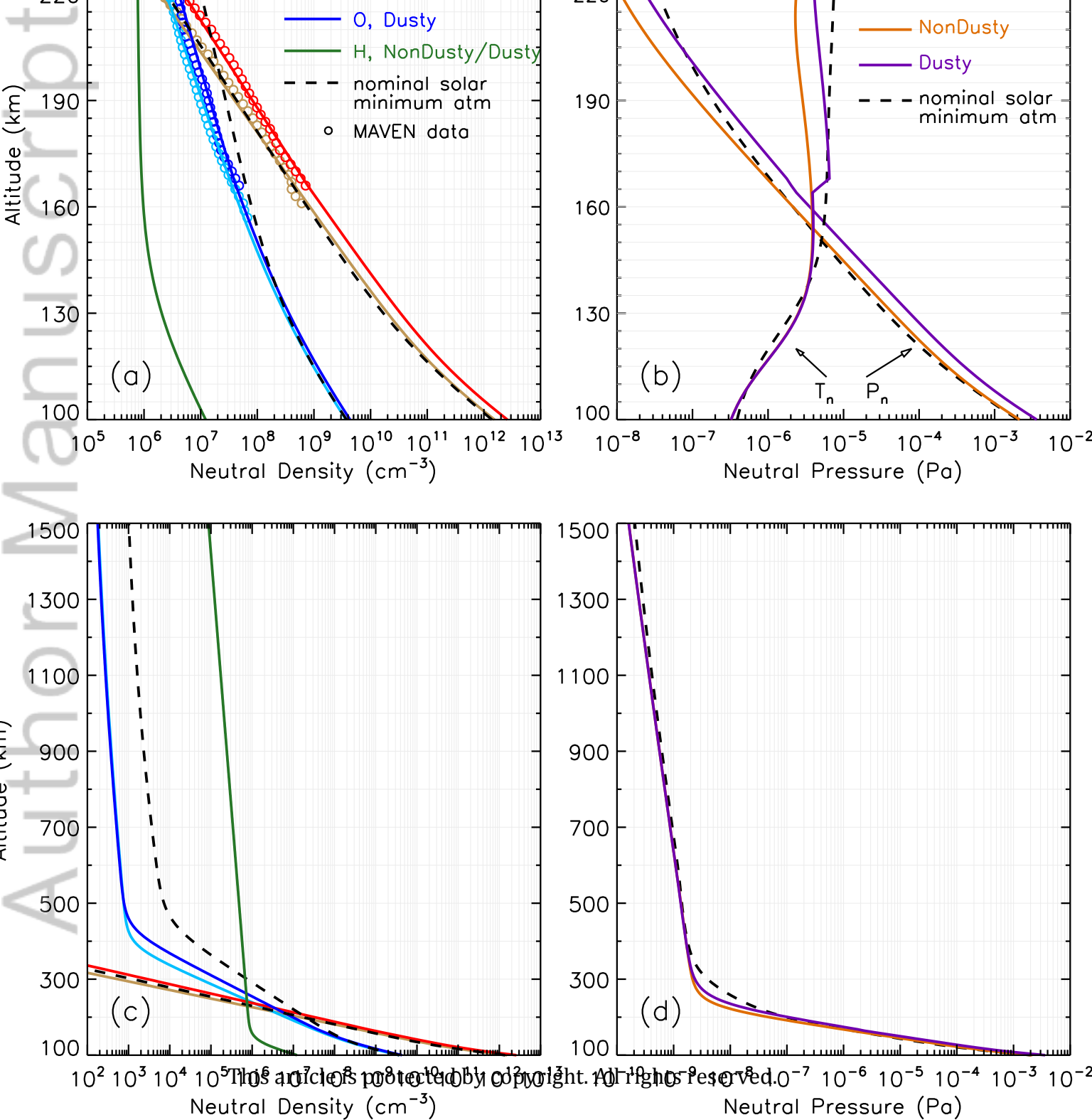


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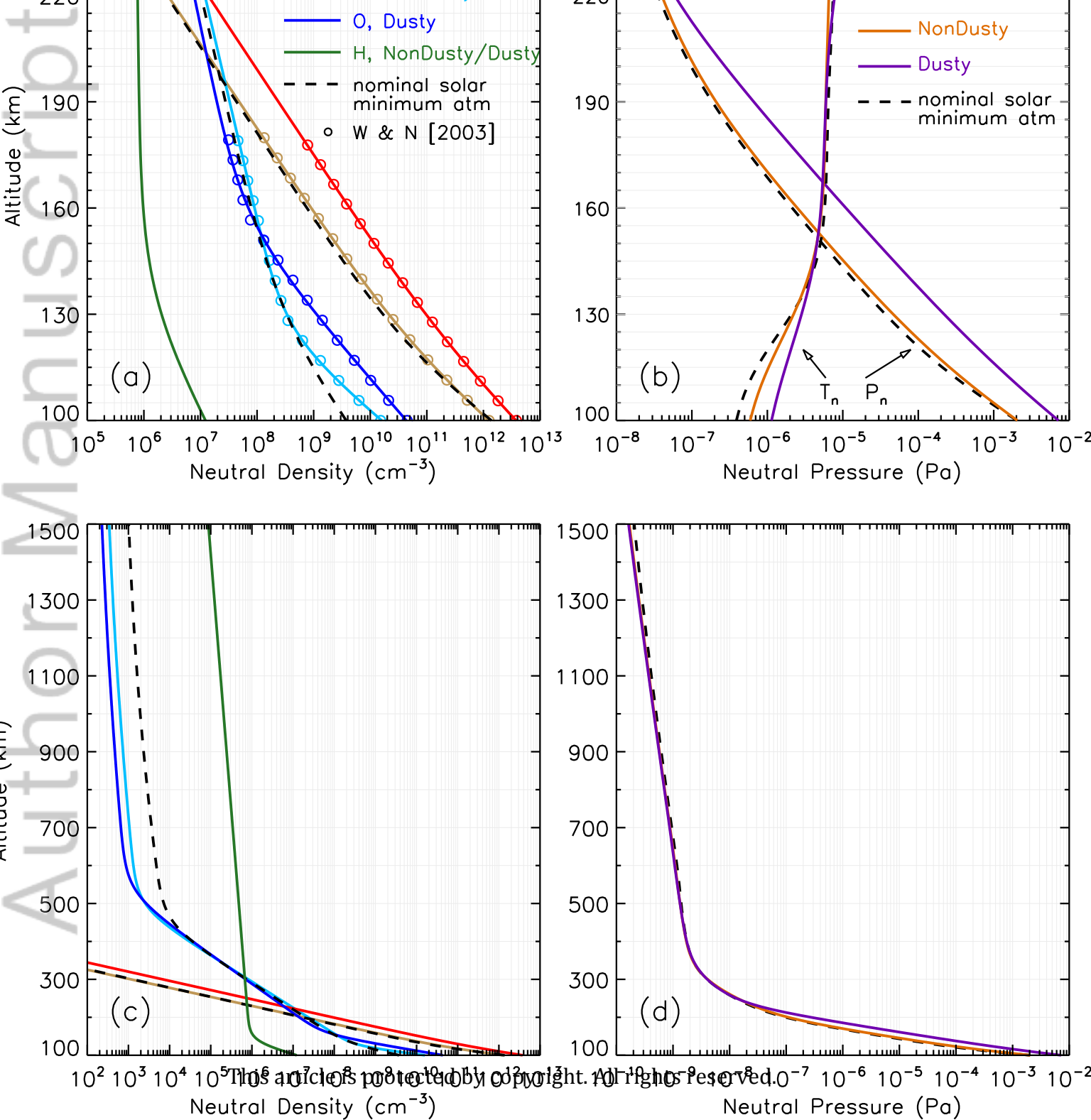
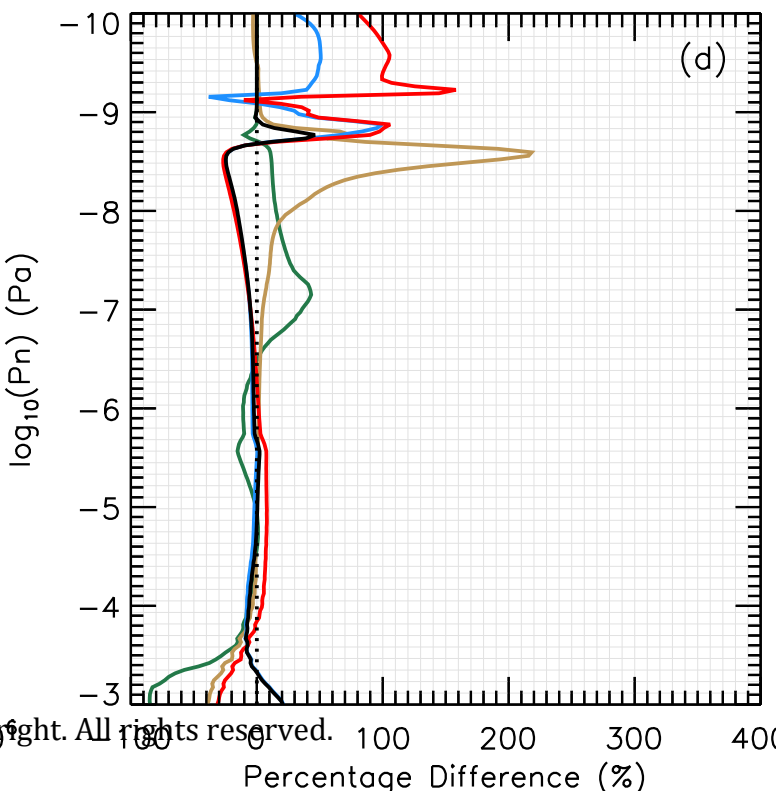
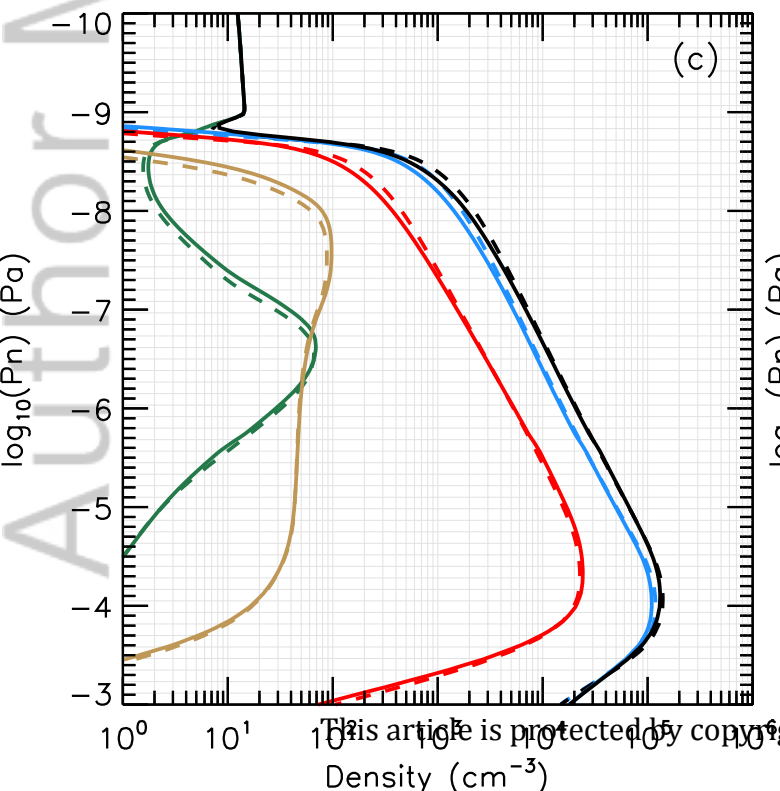
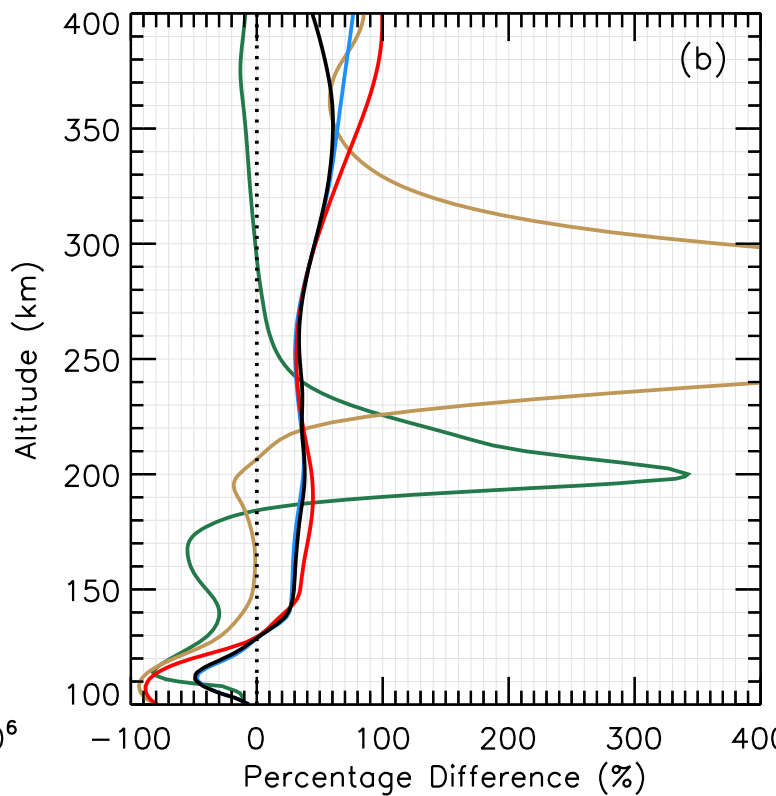
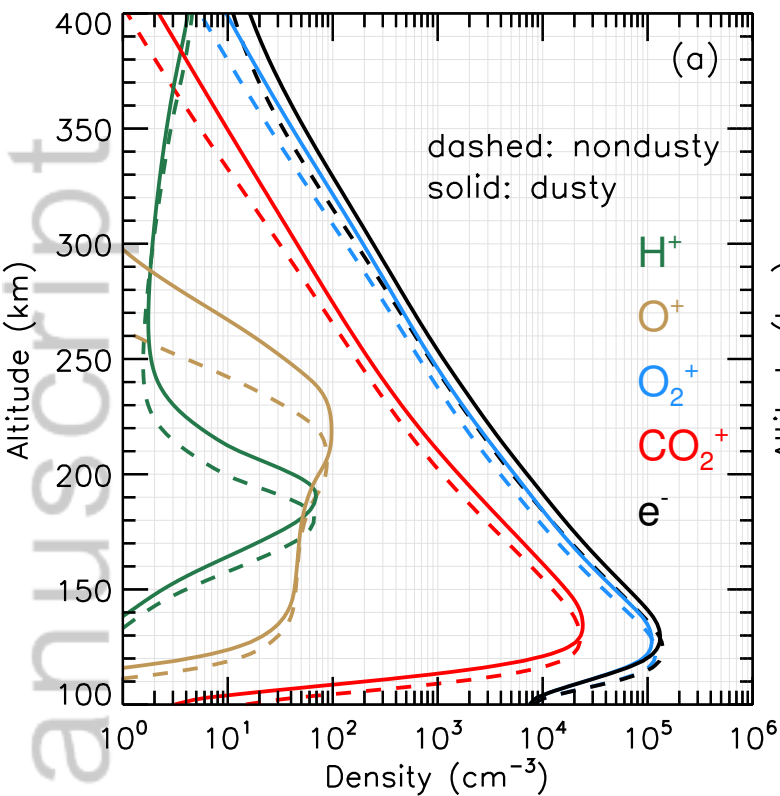




Figure 5.

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Figure 6.

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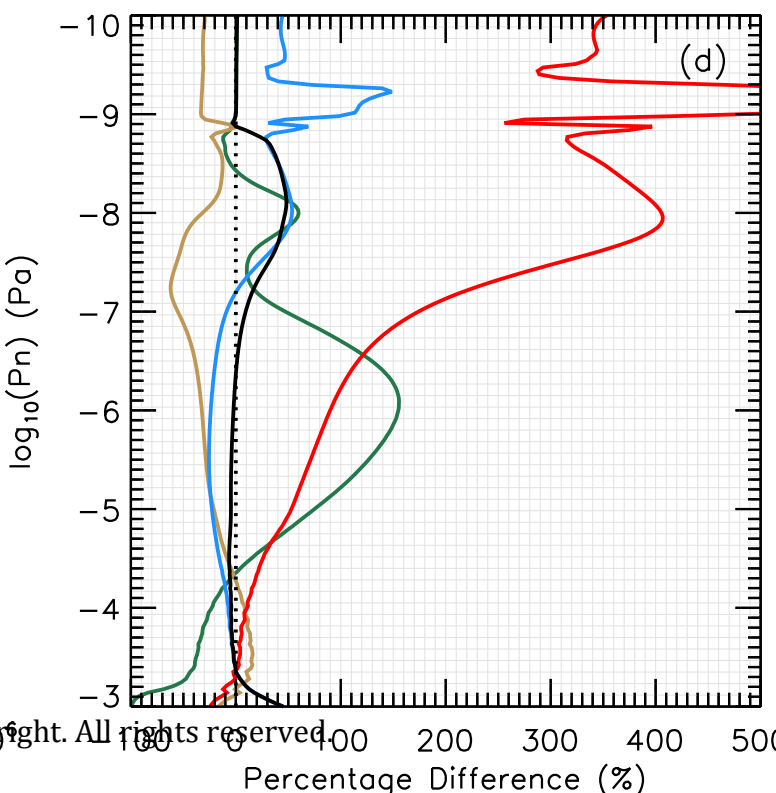
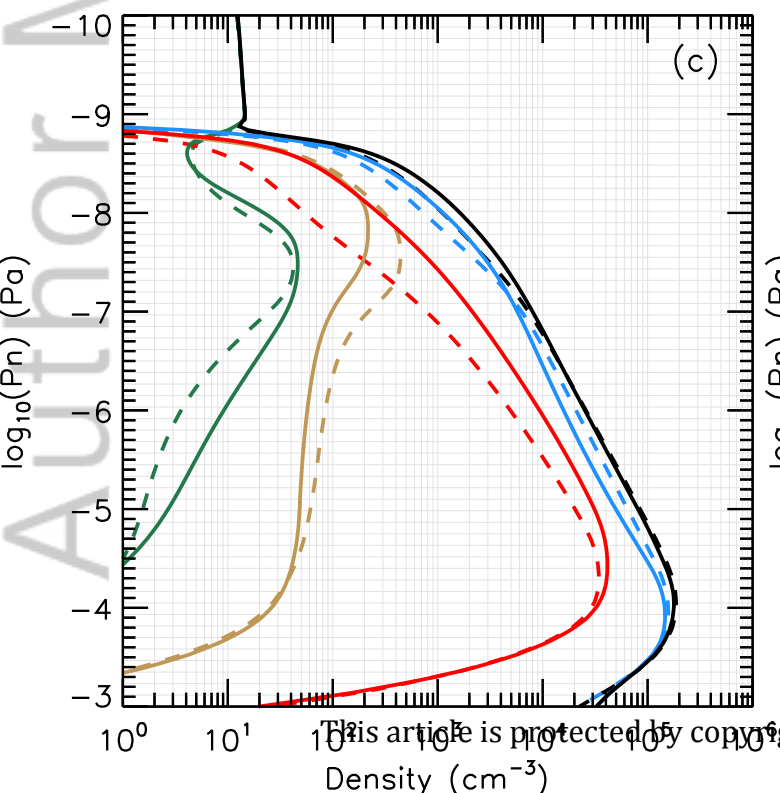
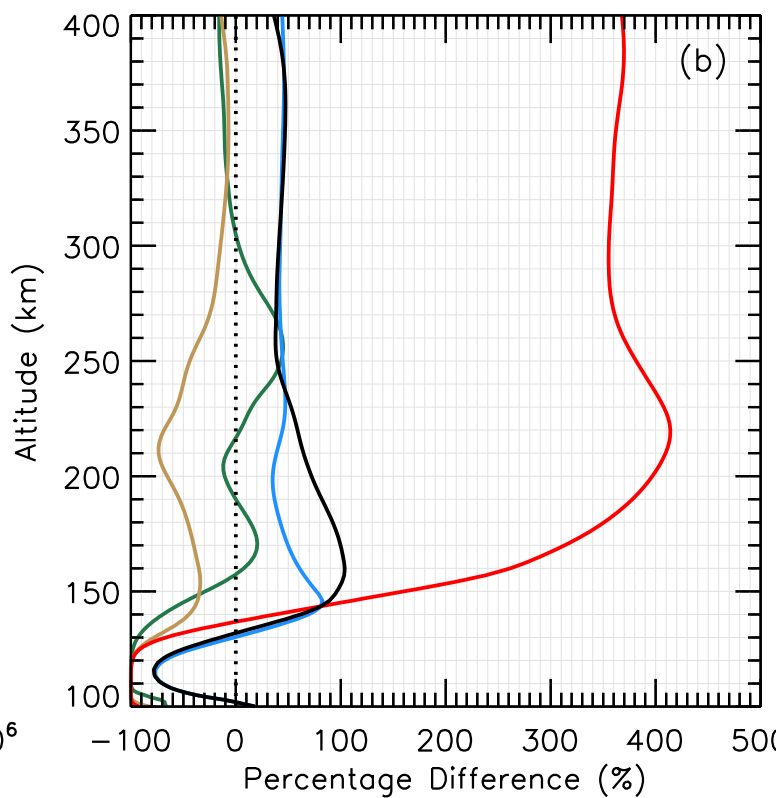
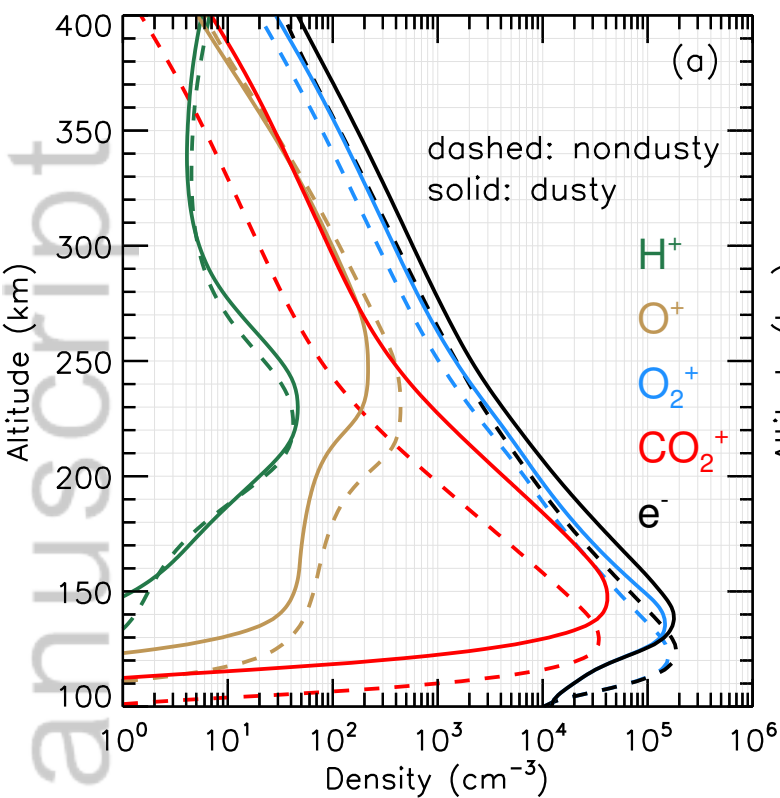


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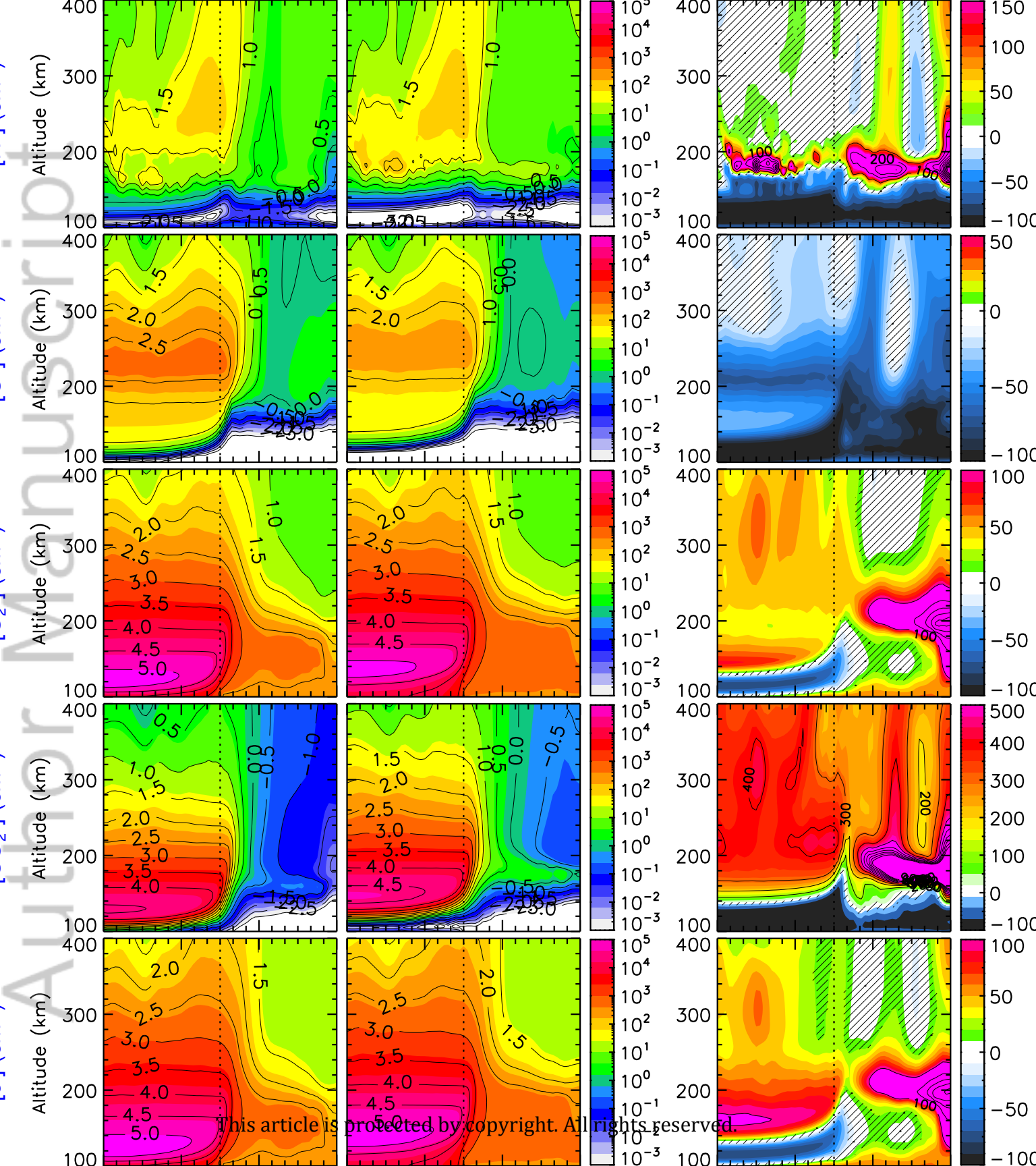


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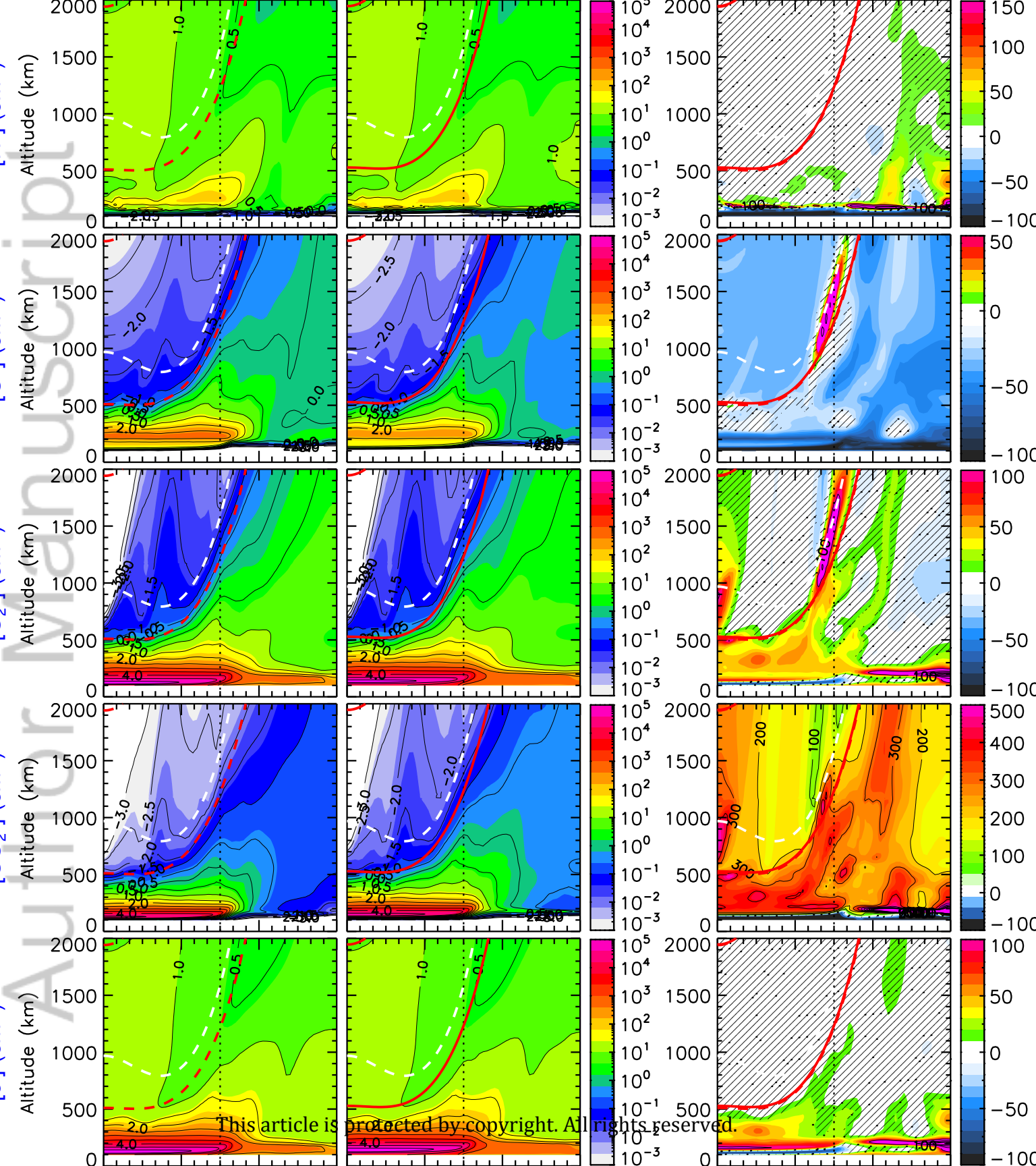




Figure 9.

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Figure 10.

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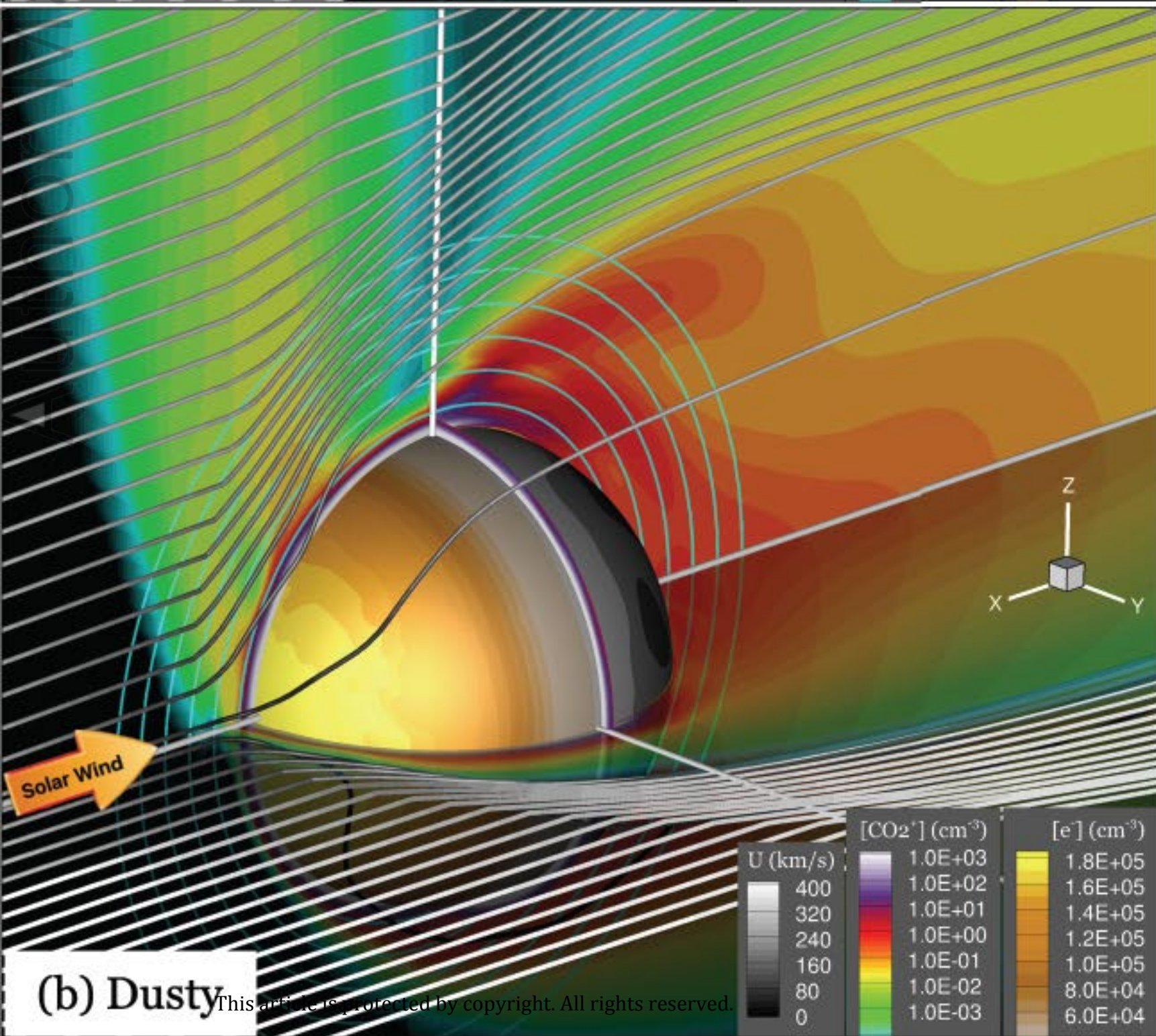
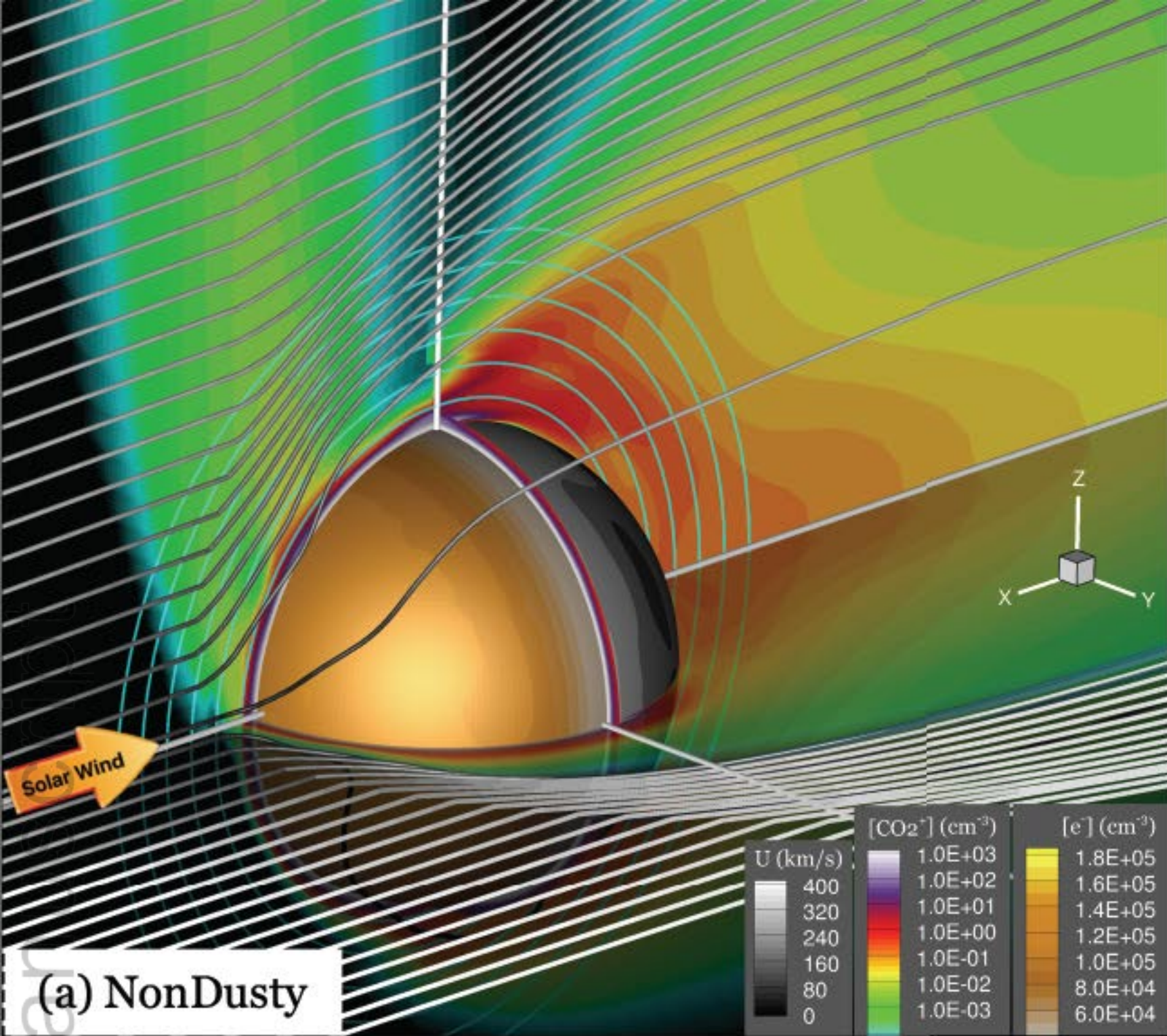
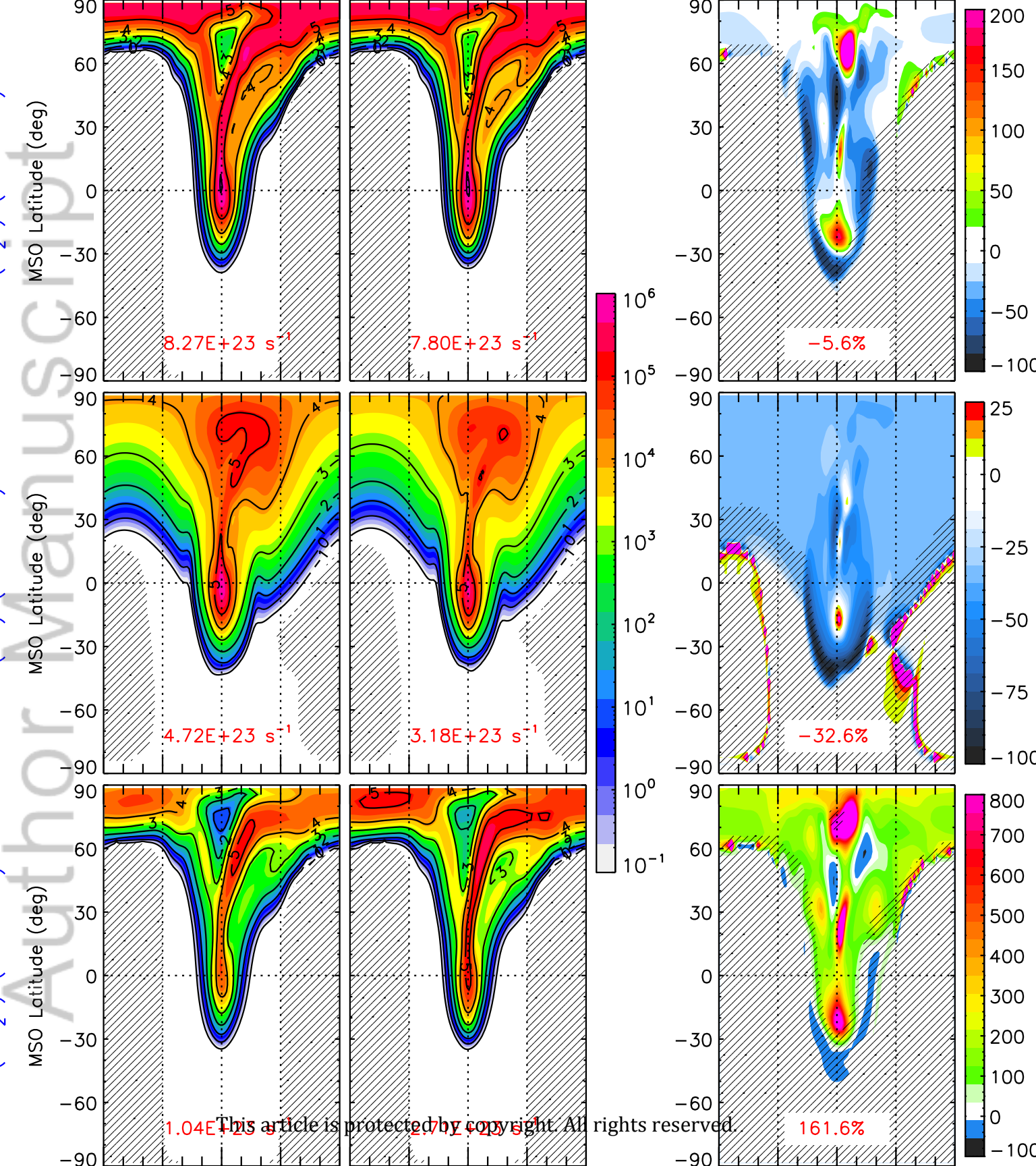
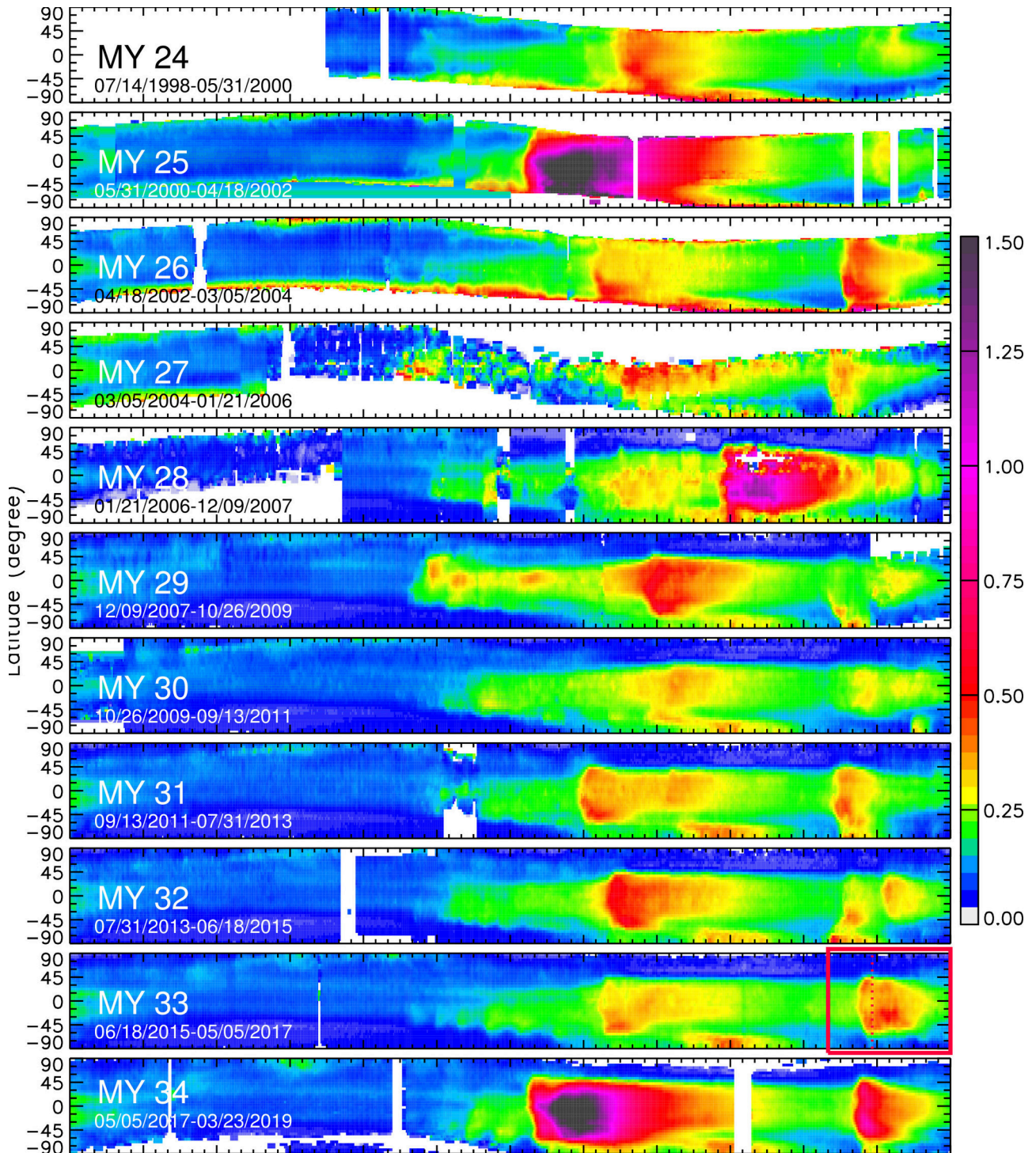


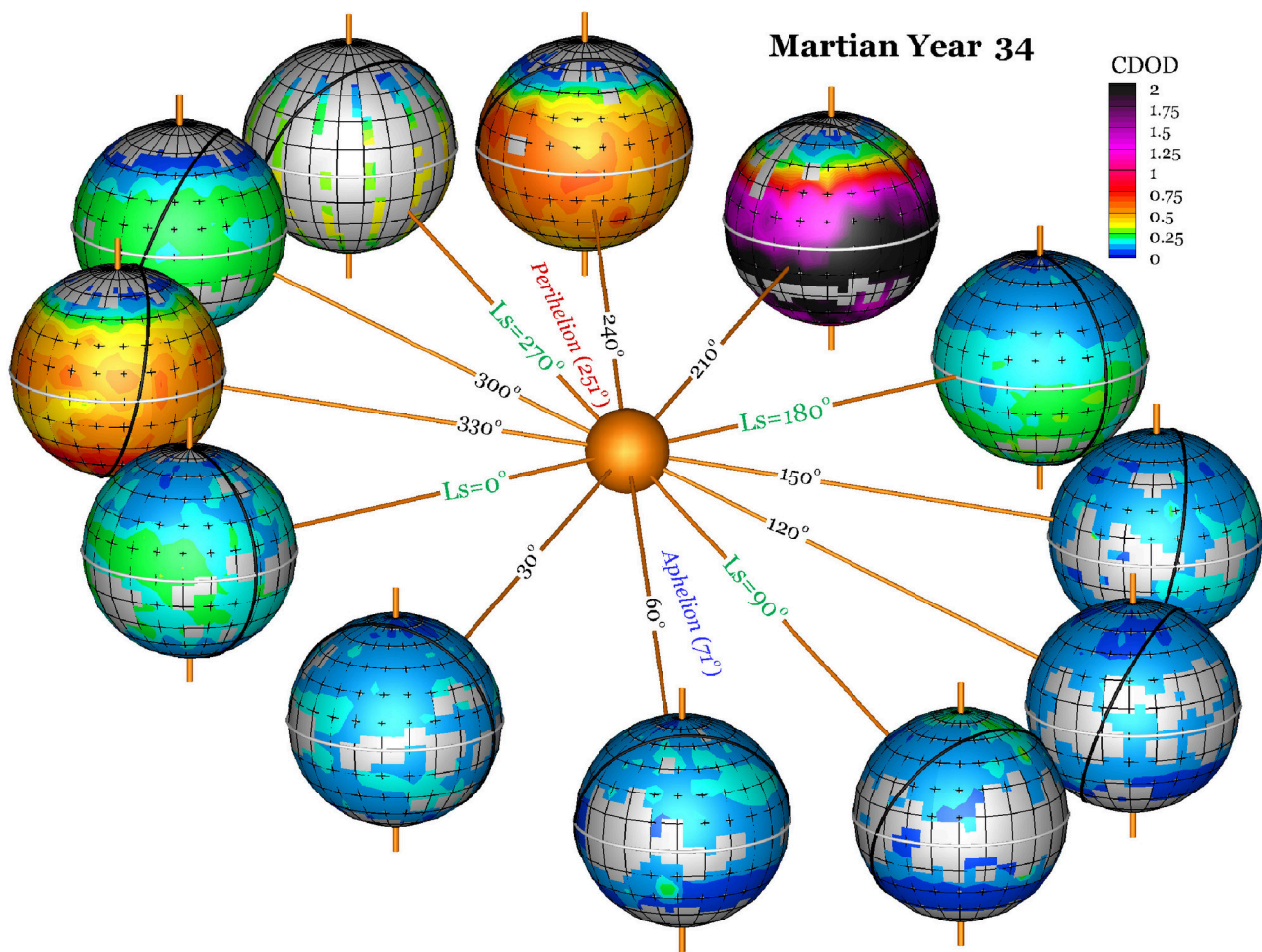
Figure 11.

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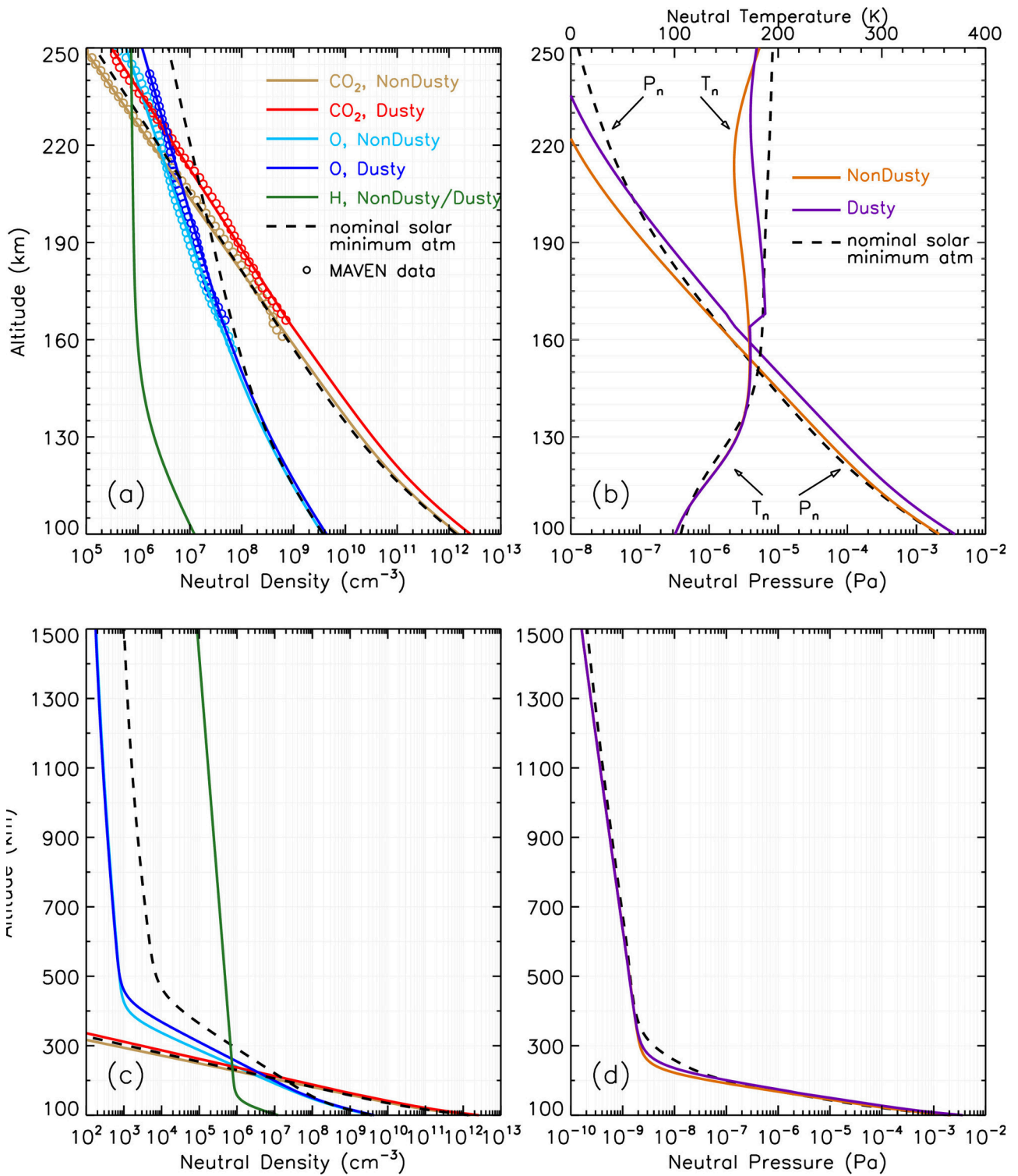


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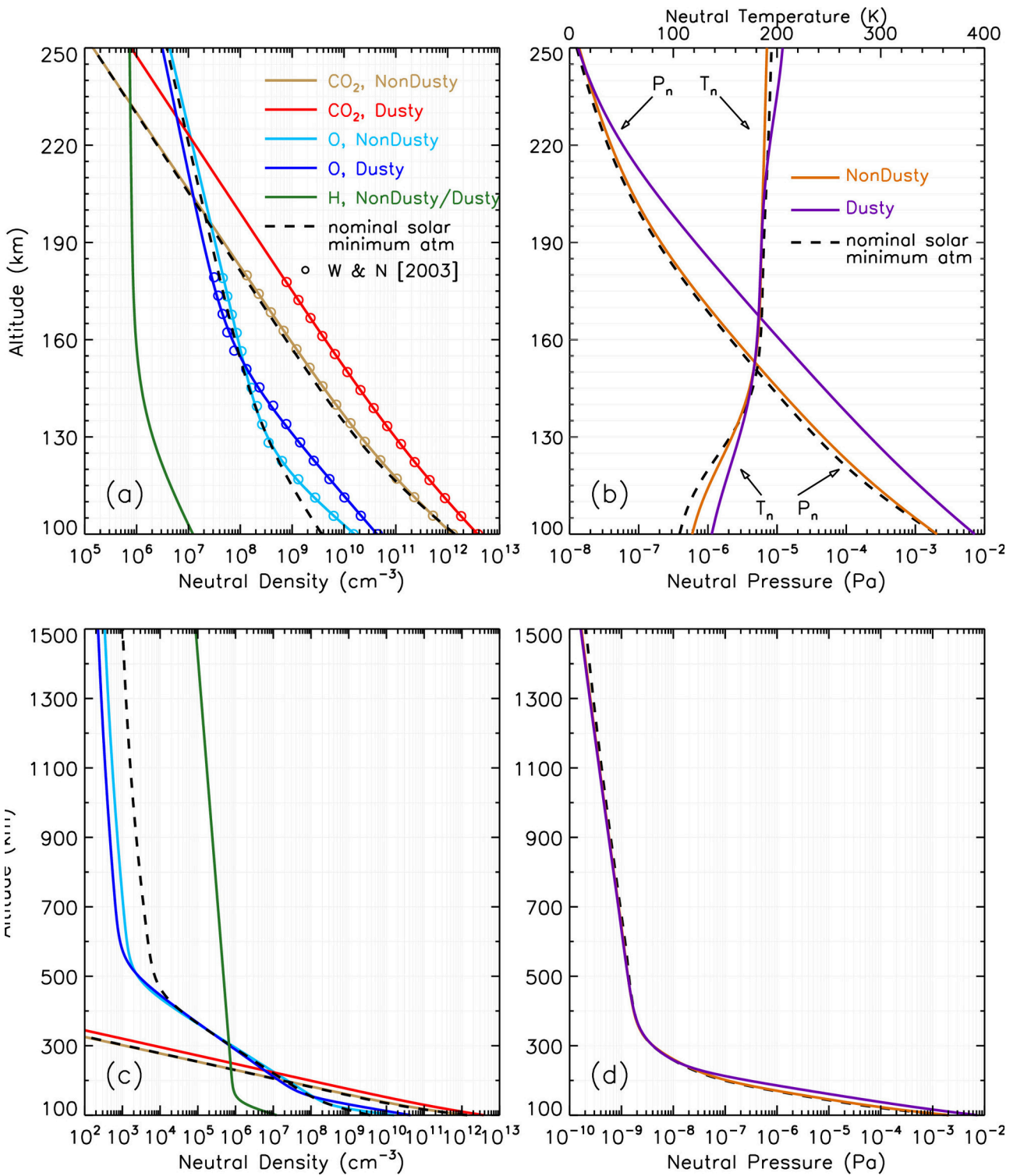


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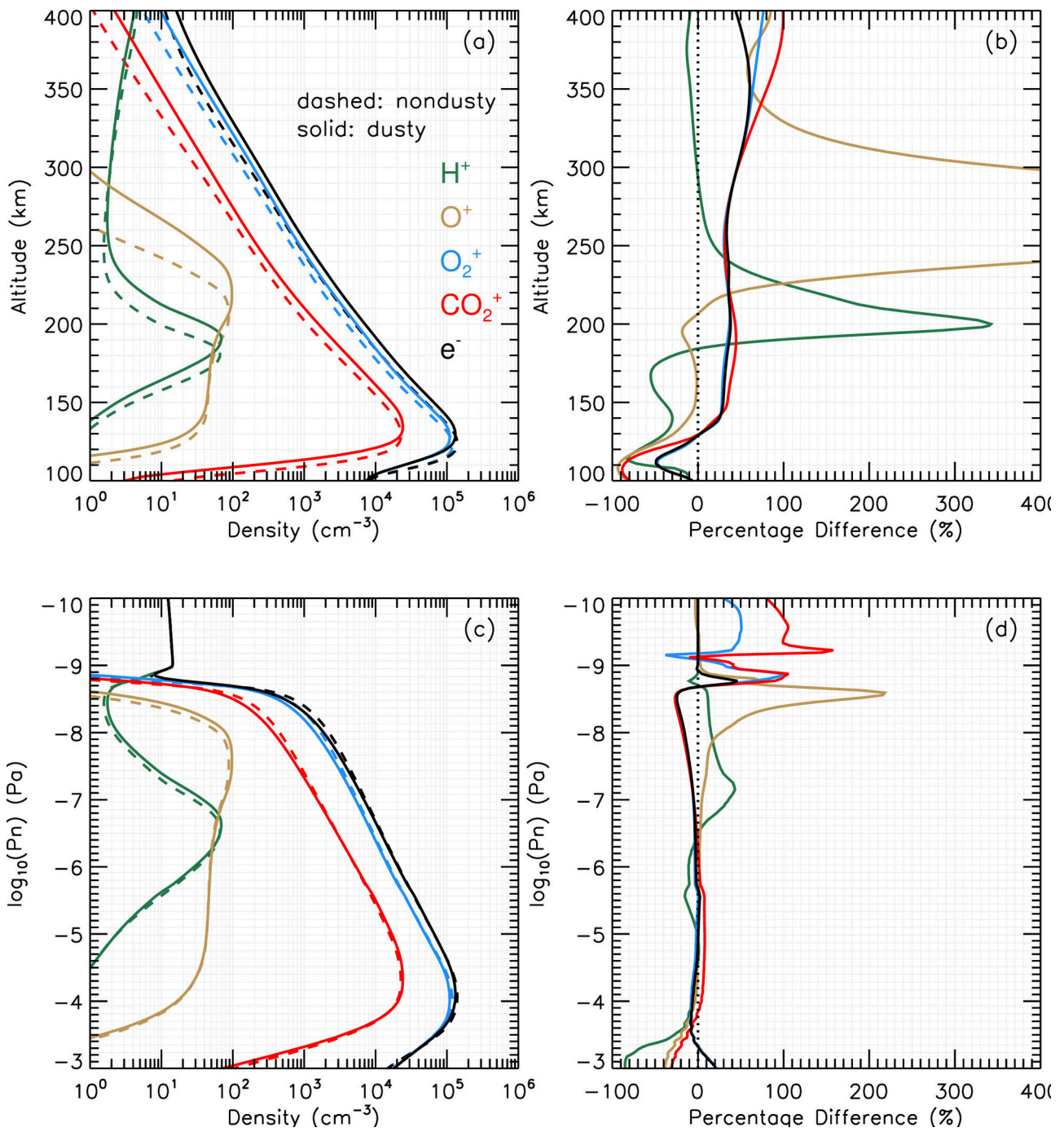




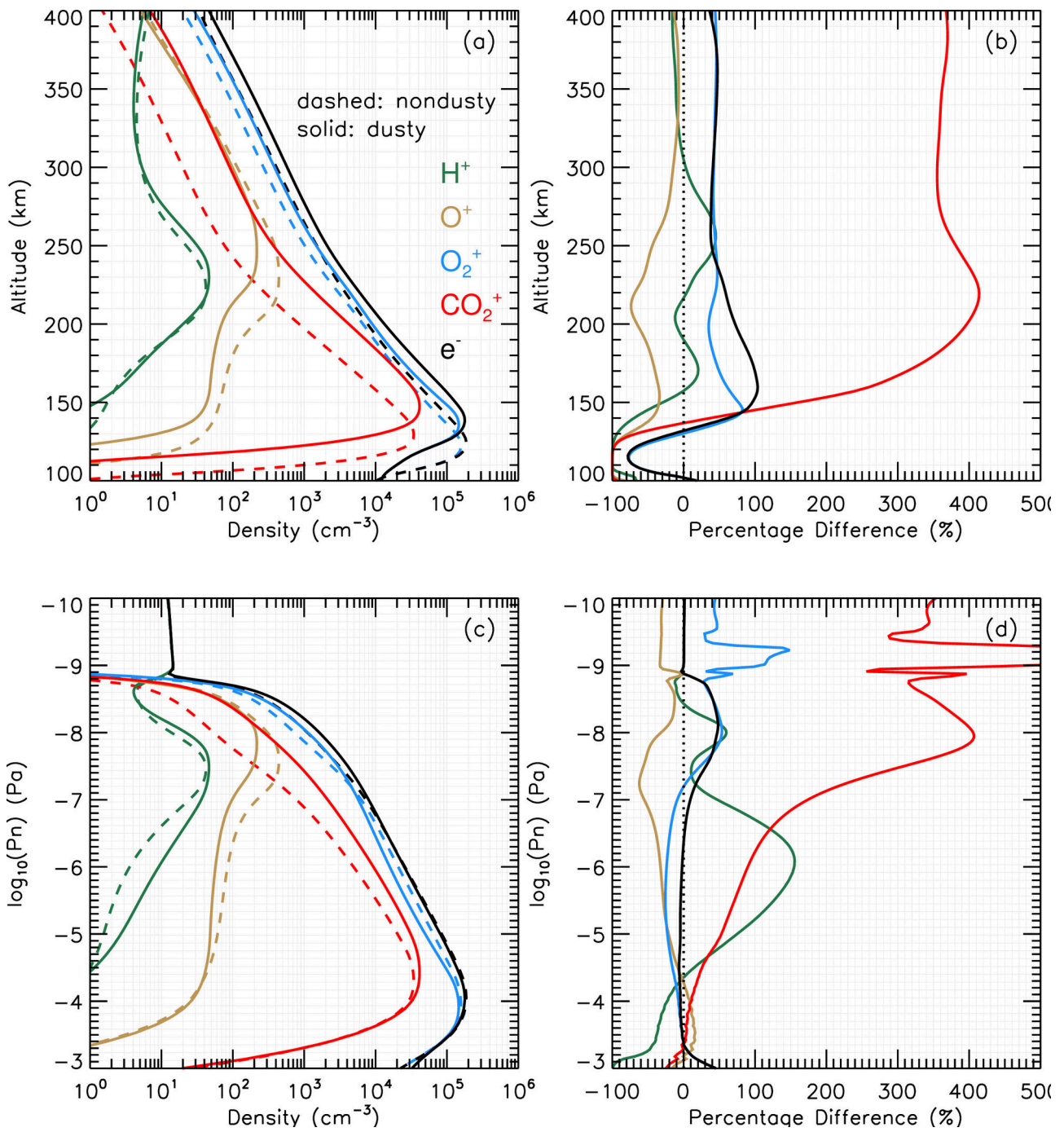
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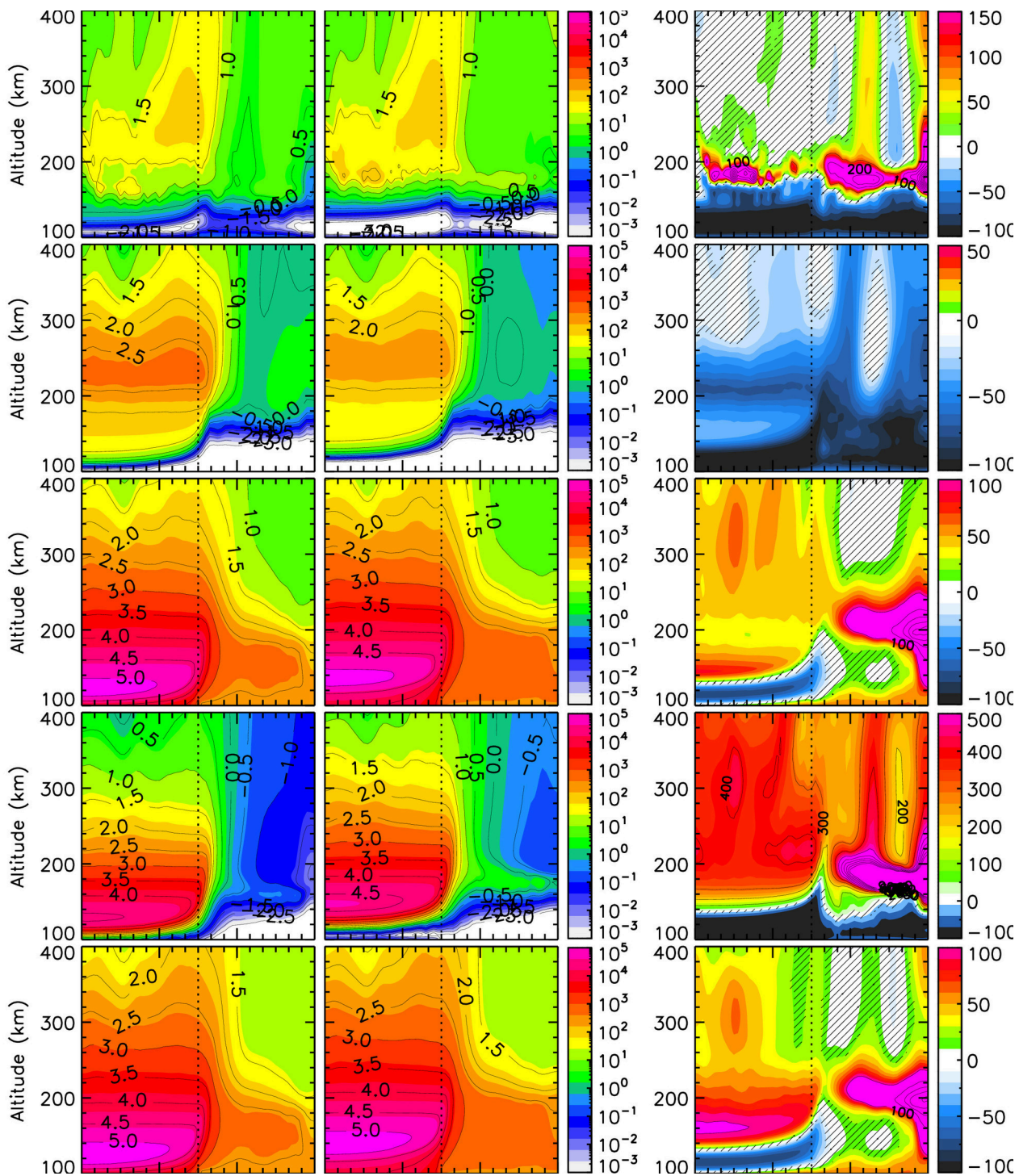
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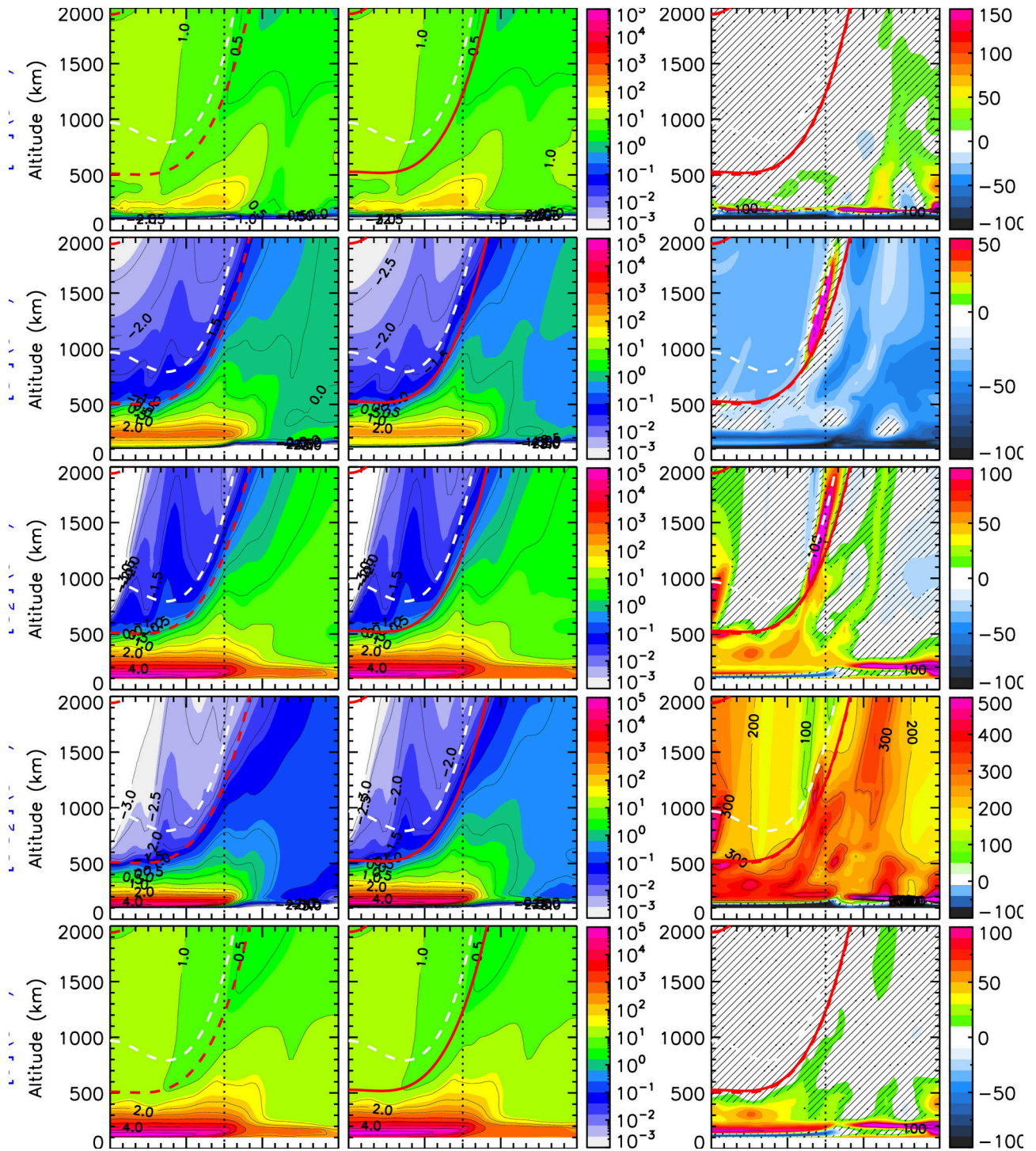
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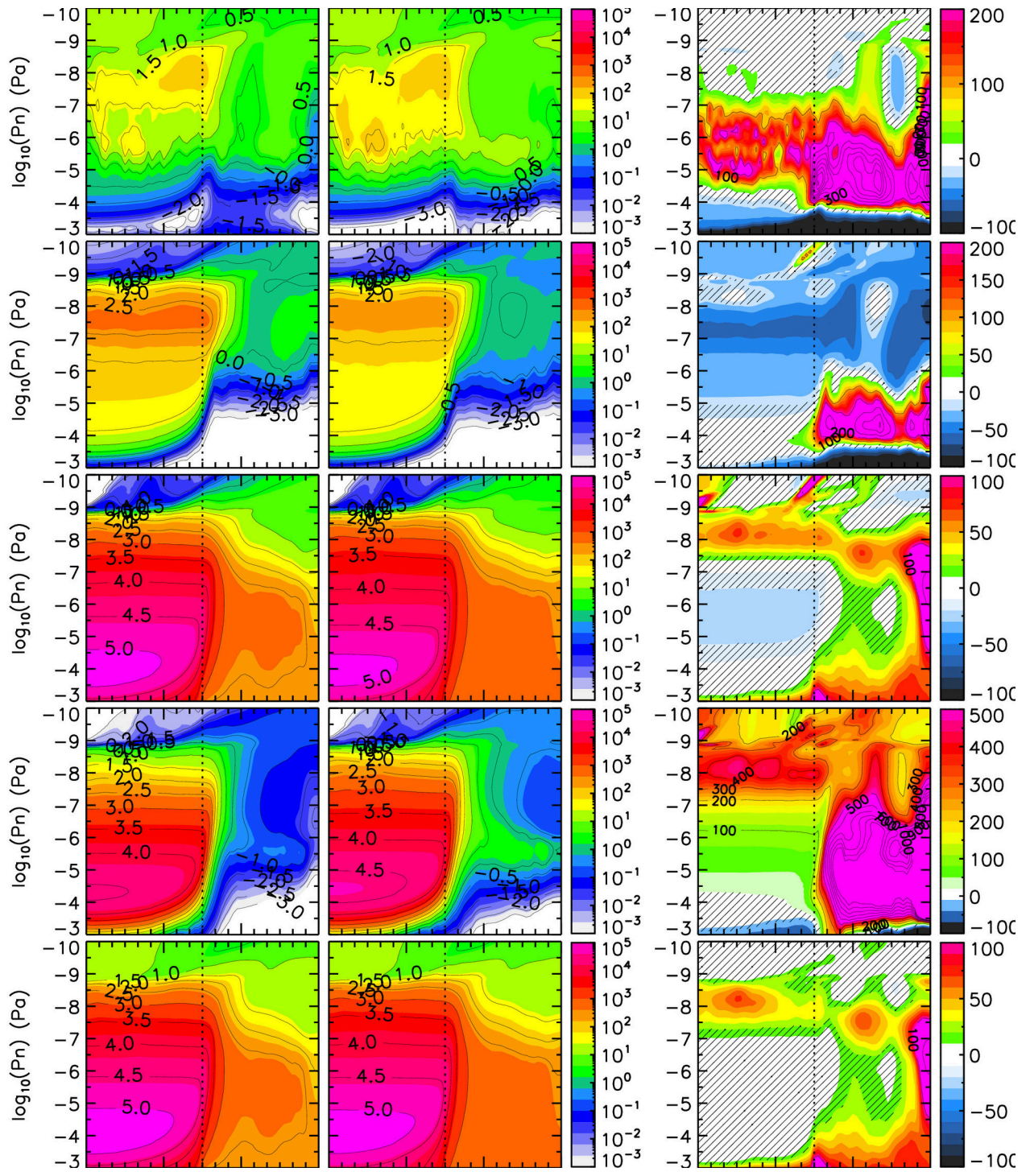
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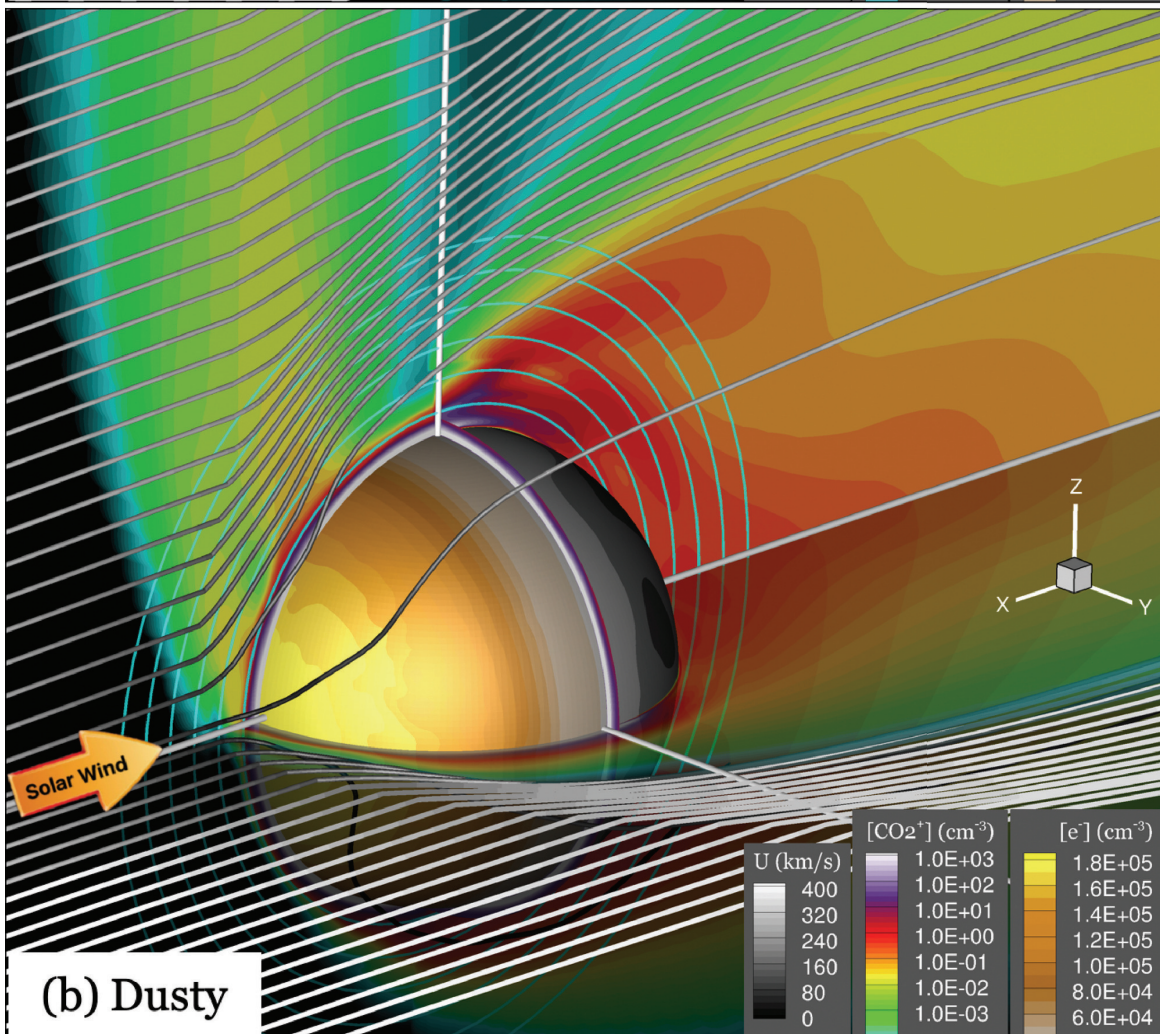
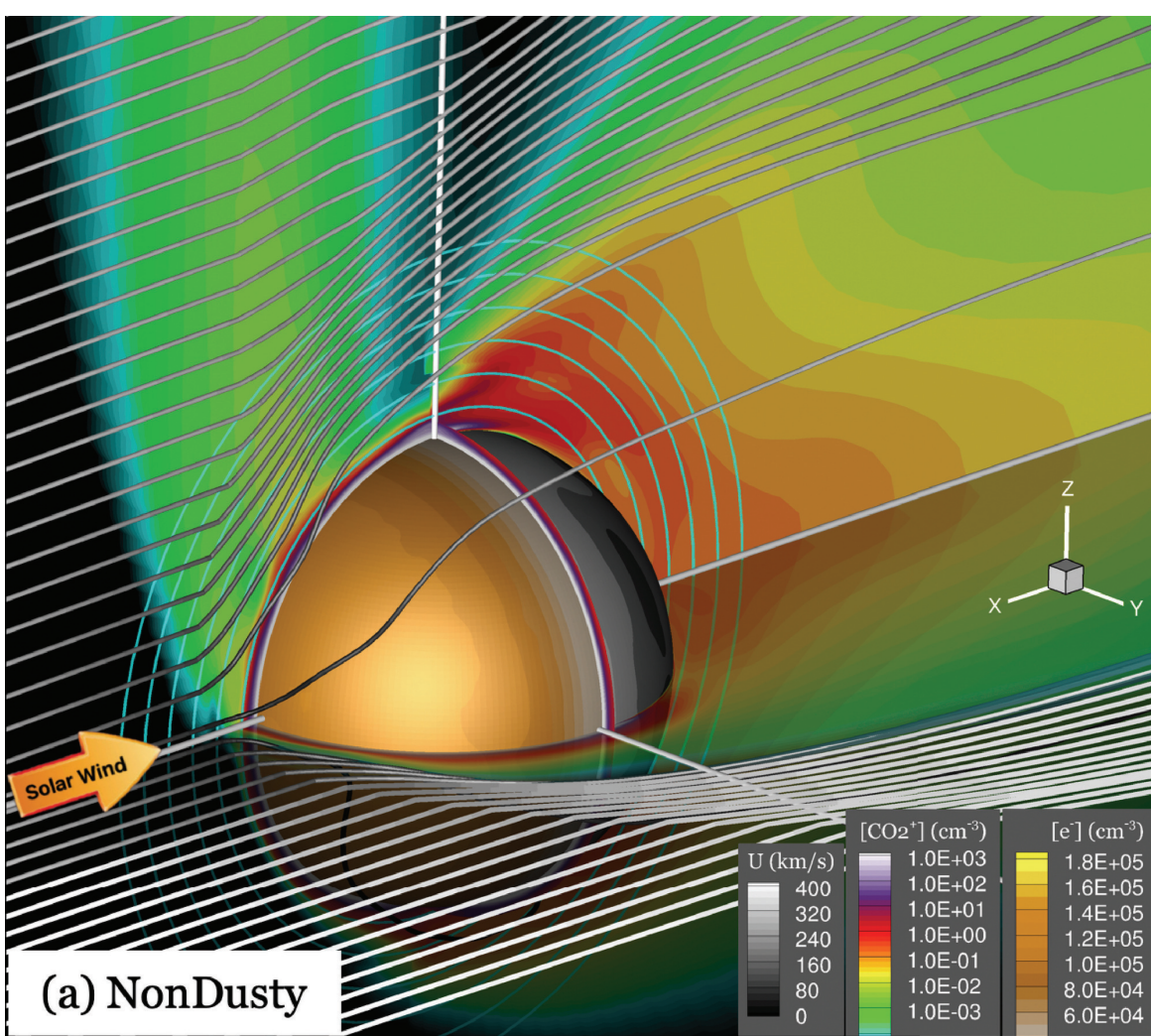
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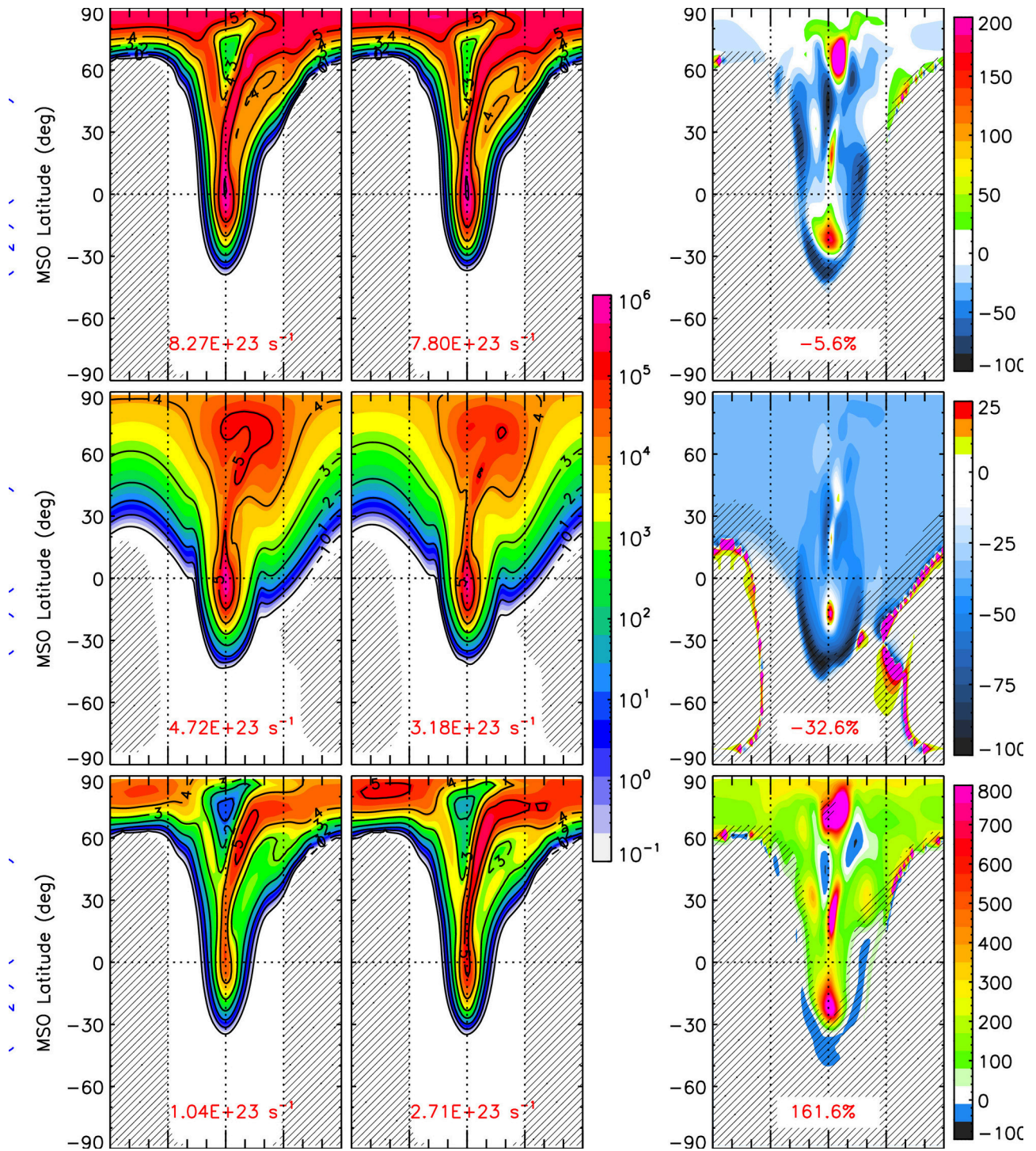
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