Study of gravity waves distribution and propagation in the thermosphere of Mars based on MGS, ODY, MRO and MAVEN density measurements

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Key Points:

- Perturbations of relative density caused by gravity wave activity in the Martian thermosphere are analyzed.
- MGS aerobraking data, and ODY aerobraking data in polar regions, exhibit a similar correlation between gravity wave activity and inverse background temperature as evidenced in MAVEN measurements and expected in an isothermal thermosphere.
- Density measurements during MRO aerobraking in polar regions show a correlation with static stability instead, which is expected for a non-isothermal thermosphere.
- Correlation to neither inverse temperature, nor static stability, is found for ODY and MRO aerobraking at lower latitudes, which suggests a more complex interplay of saturation, critical levels and gravity-wave sources.
Abstract
By measuring regular oscillations of the density of CO$_2$ in the upper atmosphere (between 120 and 190 km), the mass spectrometer MAVEN/NGIMS (Atmosphere and Volatile Evolution/Neutral Gas Ion Mass Spectrometer), reveals local effects of gravity waves, and conversely, yields precious information on the conditions for propagation and activity of gravity waves. Indeed, the intensity of gravity waves in the upper atmosphere measured by MAVEN has been shown to be dictated by saturation processes in isothermal conditions and is correlated to the evolution of the inverse of the background temperature. Previous data gathered during aerobraking by the accelerometers on board MGS (Mars Global Surveyor), ODY (Mars Odyssey) and MRO (Mars Reconnaissance Orbiter) are analyzed in the light of those recent findings with MAVEN. The anti-correlation between GW-induced density perturbations and background temperature is also found in MGS data, and in the ODY data acquired in the polar regions, but not in the MRO data. MRO data in polar regions exhibit a correlation between the density perturbations and the Brunt-Väisälä frequency (or, equivalently, static stability), obtained from Global Climate Modeling compiled in the Mars Climate Database. At lower altitude levels (between 100 and 120 km), although wave saturation is still dominant, isothermal conditions are no longer verified. In this case, theory predicts that the variability of the gravity waves intensity is no more correlated to background temperature, but to static stability. At lower latitudes in the ODY and MRO datasets, the GW-induced relative density perturbations are correlated with neither inverse temperature nor static stability; in this particular case, the observed activity of gravity waves is not only controlled by saturation, but also by the effects of gravity-wave sources, and wind filtering through critical levels.

1 Introduction
Gravity waves propagate as perturbations of the stratified atmospheric fluid [Gossard and Hooke, 1975], with the buoyancy force being the restoring mechanism giving rise to the waves [cf. Fritts and Alexander, 2003; Alexander et al., 2010, for a review]. While being essentially regional-scale phenomena, gravity waves can be responsible for significant dynamical and thermal forcing of the global atmospheric state, as they transfer their momentum and energy upon their saturation and breaking in the upper atmosphere [Lindzen, 1981; Palmer et al., 1986; McFarlane, 1987].

Gravity waves are ubiquitous in the Martian atmosphere and were actually one of the first atmospheric phenomenon to be witnessed by orbiting spacecraft [Briggs and Leovy, 1974]. As is the case on Earth [O’sullivan and Dunkerton, 1995; Vincent and Alexander, 2000; Plougouven et al., 2003; Spiga et al., 2008], those waves may be triggered in the Martian lower atmosphere by different sources: topography [Pickersgill and Hunt, 1979; 1981], convection [Spiga et al., 2013; Imanura et al., 2016], or jet-streams and fronts in ageostrophic evolution. Amongst all those sources, only the impact of the first one on the global circulation is accounted for in all Martian Global Climate Models [GCM, e.g. Barnes, 1990; Collins et al., 1997; Forget et al., 1999; Hartogh et al., 2005], although the exploration of the impact of an additional non-orographic source is a topic of current active research [Medvedev et al., 2015; Gilli et al., 2018].

The upward propagation of gravity waves from their tropospheric sources to the upper atmosphere leads to large departures of density, temperature and winds in the thermosphere, owing to the exponential increase of gravity wave amplitude with height [Fritts and Alexander, 2003; Parish et al., 2009]. Measurements of CO$_2$ density through accelerometers, gathered during the aerobraking of Mars Global Surveyor (MGS), Mars Odyssey (ODY) and Mars Reconnaissance Orbiter (MRO) evidenced the sustained gravity wave activity in the Martian thermosphere between 90 and 130 km [Fritts et al., 2006; Creasey et al., 2006; Tolson et al., 2007b]. Those measurements also demonstrated the large variability of the gravity-wave amplitudes with season, local time, latitude and longitude.
The Mars Atmosphere and Volatile Evolution (MAVEN) mission to Mars [Jakosky et al., 2015], operating since 2014, is dedicated to studying the upper atmosphere of Mars and, as such, is a unique opportunity to broaden the knowledge of gravity wave activity on Mars. The mass spectrometer NGIMS (Neutral Gas Ion Mass Spectrometer) on board MAVEN [Mahaffy et al., 2015] recently delivered new and more accurate measurements of density fluctuations at upper altitudes between 120 and 300 km, identified as typical gravity-wave signatures [Yiğit et al., 2015; England et al., 2017]. Based on those MAVEN / NGIMS measurements, Terada et al. [2017] demonstrated that gravity-wave amplitudes in the Martian thermosphere are anti-correlated with the background temperature.

The goal of this paper is to build on those recent findings by MAVEN and to expand this analysis by comparing all available aerobraking data from other orbiting spacecraft. Thus, we obtain a broader dataset of the variability of gravity wave activity with altitude, latitude and season. This allows us to compare the available measurements with diagnostics obtained by GCM through the Mars Climate Database [MCD Lewis et al., 1999; Forget et al., 1999; Milour et al., 2015].

This paper is organized as follows. In section 2, we provide information on the datasets. Section 3 features a discussion of the MAVEN / NGIMS measurements, while section 4 features a comparative discussion of the aerobraking datasets. We conclude in section 5.

2 Data and Method

2.1 Datasets used in this study

During aerobraking operations in the Martian thermosphere, the accelerometers of MGS, ODY and MRO [Lyons et al., 1999; Smith and Bell, 2005; Tolson et al., 2008] acquired data during 850 passes for MRO (since September 1997, Martian Year [MY] 23) [Keating et al., 2002], 320 passes for ODY (since October 2001, MY 25) [Tolson et al., 2007a], and 430 passes for MGS (from April to August 2006, MY 28) [Tolson, 2007], covering latitude ranges from 60°N to 90°S for MRO, 30°N to 90°N for ODY, and 0° to 90°S for MGS. Periapsis altitudes varied from about 95 km to 150 km.

In addition to those aerobraking datasets, the CO2 density variations from 3124 orbits are available from MAVEN / NGIMS mass spectrometer data reported in the NASA Planetary Data System from October 2014 (MY32) to February 2017 (MY34) [Benna and Lyness 2014]. We chose to focus on datasets issued from February 2015 to February 2017; the instrument is still in operation at the time of writing and the present study can be complemented in the future by an analysis of the interannual variability. MAVEN covers (high-periapsis) altitude ranges between about 120 and 190 km. The latitudinal coverage of MAVEN is spread all over the planet.

Data issued from a mass spectrometer such as MAVEN / NGIMS are more accurate than other density estimates, since the instrument directly counts the amount of molecules. Mass spectrometer acquisitions also present the advantage to be reliable over the whole orbital track, from the periapsis (the deepest part of the orbit trajectory) to the highest altitudes; accelerometer data, which are retrieved from the acceleration measurements during the aerobraking phase, are often very noisy at highest altitudes.

2.2 Computing the amplitude of gravity wave perturbations

Along each orbit trajectory, we extract the longitudes, latitudes, solar longitudes, local times, altitudes, CO2 density measurements, as well as the elapsed time from the periapsis. The geodesic distance from the periapsis is calculated from the latitude and longitude displacements. A relative density perturbation \(\delta \rho_l\) is obtained by subtracting the mean density \(\rho_m\) [considered here to be a 40-second rolling averaged density, as in [Tolson et al., 1999, 2005, 2007a, 2008; Creasey et al., 2006] from the instantaneous density \(\rho_l\), and by normal-
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Figure 1. Vertical (km) and seasonal (Solar Longitude in degrees) coverage of Mars Global Surveyor (MGS), Mars Odyssey (ODY), Mars Reconnaissance Orbiter (MRO) and MAVEN (MVN) spacecrafts, each bullet corresponds to the periapsis location of one orbit.

Figure 2. Latitudinal (degrees) and seasonal (Solar Longitude in degrees) coverage of Mars Global Surveyor (MGS), Mars Odyssey (ODY), Mars Reconnaissance Orbiter (MRO) and MAVEN (MVN) spacecrafts, each bullet corresponds to the periapsis location of one orbit.

Typical examples of orbit trajectory, absolute and relative density variations, obtained for the two MAVEN orbits 1046 and 3641 are shown in Figure 3. Considering the relative density perturbations, rather than the absolute value, enables a direct diagnostic of the effect of grav-
ity waves, with the underlying assumption that the 40-second average provides an acceptable estimate of the “background” atmospheric state upon which the gravity waves propagate.

In order to quantify the amplitude (i.e. the intensity) of the observed gravity waves on a single orbit, and to assess the spatial and seasonal variability of the gravity wave activity, we calculate for each orbit the Root Mean Square (RMS) of the fluctuations of relative densities $\delta \rho_r$ along the trajectory.

Figure 4 (MAVEN / NGIMS data) and Figure 5 (aerobraking data) show the seasonal variations of the GW activity as quantified by this RMS quantity. A distinctive pattern of amplitude fluctuations with season is found in the MAVEN data in Figure 4, in agreement with the tendencies discussed in England et al. [2017] and Terada et al. [2017].

2.3 Temperature estimates

Temperature is obtained from density and pressure by using ideal gas law and hydrostatic equilibrium. This method is straightforward where the spacecraft altitude is varying, i.e. for MAVEN measurements, and for the inbound (points located before the periapsis) and outbound (points located after the periapsis) legs of MGS/ODY/MRO aerobraking orbits [Tolson et al., 2008]. Determining background temperature by this method is challenging where the spacecraft displacement is nearly horizontal, notably in the middle leg of the aerobraking orbits [Tolson et al., 1999, 2005]. Thus the middle leg of the MAVEN measurements is excluded from the comparative analysis, and we only keep the inbound and outbound profiles for MAVEN / NGIMS measurements. We found that in the inbound and outbound legs, the temperature profiles follow a similar vertical gradient. We thus study the variability of temperature from one orbit to another with a single representative value for both the inbound and outbound legs, chosen as the average value on each leg.

Those temperatures estimated from aerobraking and MAVEN / NGIMS measurements are compared in Figure 6 and Figure 7 with the temperature in the Mars Climate Database.
Figure 4. Seasonal variability of GWs amplitudes measured by MAVEN / NGIMS. Each point corresponds to the RMS of the relative densities calculated over each orbit. In this figure the RMS has been calculated on the points around the periapsis, where the trajectory is close to be horizontal, on a frame of -700 to 700 km. This restriction reduces the altitude range to around 15 km above the periapsis.

Figure 5. Seasonal variability of GWs amplitudes measured by aerobraking instruments MGS, ODY and MRO. Each point corresponds to the RMS of the relative densities calculated over each orbit. In this figure the RMS has been calculated on the points around the periapsis, where the trajectory is close to be horizontal, on a frame of -400 to 400 km. This restriction reduces the altitude range to around 10 km above the periapsis.

[built from Global Climate Model (GCM) simulations\cite{Millour2015} for the same spatio-temporal coordinates (Ls, longitude, latitude, altitude, local time). Only the comparisons of temperatures measured on outbound legs versus temperature modeled in the MCD are displayed for the sake of brevity; the analysis for inbound legs is similar. The MCD tem-
Figure 6. Mean background temperature estimated over the outbound leg and calculated from the CO2 density observations (blue bullets) and estimated with the MCD (red bullets) as a function of Solar Longitude; from the left to the right column: MGS, ODY and MRO

Figure 7. Mean background temperature estimated over the outbound leg and calculated from the CO2 density observations of NGIMS instrument (blue bullets) and estimated with the MCD (red bullets) as a function of Solar Longitude

...temperatures are systematically lower than those observed by MAVEN and aerobraking, and there is also much more variability in the observation data points; however, the overall seasonal variability is well reproduced, except the $L_s = 290^\circ$ maximum observed by ODY. This gives us confidence that using a value of background temperature averaged over the inbound and outbound legs is suitable to carry out an analysis of the seasonal (climatological) trends.

3 Vertical Propagation of Gravity Waves: analysis of the MAVEN observations in the thermosphere

In the absence of additional wave sources and dissipation processes [e.g., radiative damping [Eckermann et al., 2011]], the amplitude of gravity waves is expected to grow exponentially with altitude as the atmospheric density decreases. Conversely, the amplitudes of gravity waves appear to anti-correlate with altitude, according to the altitudes of the MAVEN measurements shown in Figure 1 and the amplitudes $\delta \rho$ of the perturbations shown in Fig-
ure. In other words, in the MAVEN observations, gravity-wave amplitude seems to correlate with density, as opposed to an anti-correlation expected if the amplification of gravity-wave amplitude with altitude (and reduced density) was the only controlling factor. This is confirmed by considering the seasonal variations of density perturbations $\delta \rho$ at a constant pressure level, e.g. at pressures $4 \times 10^{-8} < P < 6 \times 10^{-8}$ Pa in Figure 8. The observed variability in gravity-wave amplitude must be controlled by either the sources of those waves and/or the impact of saturation and critical levels.

![Figure 8](image-url)

**Figure 8.** Seasonal variability of GWs amplitudes measured by MAVEN / NGIMS at a constant pressure level P such as $4 \times 10^{-8} < P < 6 \times 10^{-8}$ Pa. Each point corresponds to the RMS of the relative densities calculated over each orbit.

In the MAVEN measurements, gravity wave activity in the thermosphere is randomly distributed with longitude and latitude (figures not shown). No correlation appears to exist between this gravity wave activity and either the position of topographical highs and lows (mountains and craters), or the position of mesospheric jet-streams. This suggests that the regional distribution of the intensity of gravity waves is more controlled by propagation effects [e.g., filtering by saturation or critical levels, Fritts and Alexander, 2003] than by the distribution of the sources triggering those waves.

The background horizontal wind plays a particularly crucial role in impacting the conditions for the upward propagation of gravity waves emitted in the troposphere. A critical level occurs when and where the background horizontal wind velocity $\bar{u}$ almost equals the gravity wave phase speed $c$ [first Eliassen-Palm theorem, Lindzen, 1981]. A gravity wave that reaches a critical level can no longer propagate towards the thermosphere: hence horizontal circulations may filter out gravity waves emitted in the troposphere from the mesosphere and the thermosphere.

Considering, for the sake of simplicity, a gravity-wave phase speed $c = 0$ (typical of orographic gravity waves), we explored the regional and seasonal variability of background horizontal winds $\bar{u}$ simulated in the MCD from the troposphere to the lower mesosphere (since no measurements of such winds are available). We found no correlation between this variability, and the regional and seasonal variability of the gravity wave amplitudes observed by MAVEN. Hence it appears difficult to explain the variability of the observed gravity wave amplitudes solely with the occurrence of critical levels.
It follows from the above discussions that the most likely possibility to explain the observed variability of gravity wave amplitude in the MAVEN observations is the breaking/saturation due to convective instability. This shall lead to, according to Terada et al. [2017], the gravity wave amplitudes to be inversely proportional to the background temperature. Let us propose an alternate, yet equivalent, derivation of the theoretical arguments in [Terada et al. 2017] that we will use in section 4.

The saturation of a gravity wave occurs as soon as it encounters convective instability [Lindzen, 1981; Hauchecorne et al., 1987; Terada et al., 2017]. Local mixing occurs as the gravity wave breaks, inducing an adiabatic (neutral) temperature lapse rate. We consider the case of a medium-frequency gravity wave $f \ll \omega \ll N$ (where $f$, $\omega$ and $N$ are respectively the Coriolis, the gravity-wave and the Brunt-Väisälä frequencies, with $N$ such that

$$N^2 = \frac{g}{T} \left[ \frac{\partial T}{\partial z} + \frac{g}{C_p} \right]$$

assuming the short-wavelength approximation $2Hk_z \gg 1$, where $k_z$ is the vertical wave number). which are reasonable assumptions for most gravity waves observed in planetary upper atmospheres [Fritts and Alexander, 2003]. In those conditions, according to Hauchecorne et al. [1987], the saturated conditions lead to

$$k_z \theta_s' = \frac{N^2 \bar{\theta}}{g} \quad \Rightarrow \quad \frac{\theta_s'}{\bar{\theta}} = \frac{N^2}{g k_z} \quad (2)$$

where $\theta_s'$ is the amplitude of the wave at saturation (expressed in perturbations of potential temperature), $\bar{\theta}$ the background potential temperature and $g$ the acceleration of gravity. Besides, the linearized fluid equations applied to the propagation of gravity waves [Fritts and Alexander, 2003] lead to:

$$\frac{\theta'}{\bar{\theta}} = \frac{1}{c_s^2} \frac{P'}{\bar{\rho}} - \frac{\rho'}{\bar{\rho}} \quad (3)$$

where $\rho$ is the density, $P'$ and $\rho'$ the pressure and density perturbations, and $c_s$ the sound speed. We can neglect the compressibility term related to the background density gradient, which is equivalent to filter out acoustic gravity waves ($c_s \rightarrow \infty$). This entails:

$$\left| \frac{\rho'}{\bar{\rho}} \right| = \left| \frac{\theta'}{\bar{\theta}} \right| \quad (4)$$

Combining equations 2 and 4, we obtain the equation expressing the relative density perturbations by gravity waves:

$$\delta \rho = \frac{|\rho'|}{\bar{\rho}} = \frac{N^2}{k_z g} \quad (5)$$

which corresponds to the observed diagnostic described in equation 1. Isothermal background profiles $T = T_0$ are often observed in the Martian thermosphere, where EUV heating is offset by molecular conduction [Bougher et al., 1990]. In the specific case of isothermal profiles, $N^2$ can be reduced to:

$$N^2 = \frac{g}{C_p T_0} \frac{\partial \bar{\theta}}{\partial z} = \frac{g^2}{C_p T_0} \quad (6)$$

which yields the “inverse temperature” dependency [Terada et al., 2017] in the case of isothermal profiles at saturation:

$$\delta \rho = \frac{|\rho'|}{\bar{\rho}} = \frac{g}{k_z C_p T_0} \quad (7)$$

MAVEN data are acquired high in the Martian thermosphere (above 150 km) even for deep dip acquisitions; hence the temperature profiles retrieved by MAVEN are approximately isothermal [England et al., 2017; Terada et al., 2017]. The temperature profiles modeled and compiled in the MCD also indicate widespread isothermal profiles at the altitudes...
probed by MAVEN. Comparing Figures 4 and 9 confirms qualitatively equation 7, i.e. the correlation between the amplitude of gravity wave perturbations and the inverse background temperature. Quantitatively, in the case of the inbound leg of each orbit, a correlation coefficient \( R \approx 0.70 \) between the average of the relative density and the calculated temperature is found (see Figure 10). Our analysis of the MAVEN is thus compliant with the one conducted by [Terada et al., 2017], and we now turn to the analysis of aerobraking data in the lower thermosphere.

**Figure 9.** Seasonal variability of the background temperature estimated from MAVEN / NGIMS density measurements (ideal gas law and hydrostatic equilibrium). Each point corresponds to the inverse of the mean background temperature calculated over the outbound leg of each orbit.

4 Gravity Waves in the Lower Thermosphere: Aerobraking Data

4.1 Analysis

Aerobraking data have been studied in the past to observe the activity of gravity waves in the lower thermosphere, either to discuss the variability of potential sources [Creasey et al., 2006] or to assess wave filtering by zonal jets and how large-amplitude GWs could penetrate to high altitudes [Fritts et al., 2006]. Here we assess if the “inverse temperature” correlation inferred from the MAVEN / NGIMS data [Terada et al., 2017] and section 3 of this paper can be extended to those lower-thermosphere aerobraking observations obtained by the three accelerometers of MGS, ODY and MRO.

In the aerobraking observations, as is emphasized by [Tolson et al., 2005] and [Tolson et al., 2008], the intensity of density perturbations are systematically lower when the spacecraft enters the polar vortex (e.g. MRO during the Southern Hemisphere Winter and ODY during the Northern Hemisphere Winter). Figure 11 shows two examples: ODY orbit 155, which goes through the Northern Hemisphere Winter vortex at \( Ls = 298.30° \) and latitude 82.43°N, and MRO orbit 250, going through the Southern Hemisphere Winter vortex at \( Ls = 90.01° \) and latitude=69.50°S. These variations of density perturbations within the same orbital track can be explained by the anti-correlation between temperature and gravity wave activity explained above [an explanation that was not provided in Tolson et al., 2008]. Polar warming at thermospheric altitudes [first observed by ODY during aerobraking, Keat-
Figure 10. Correlation between the average of the absolute relative density and the average of the background temperature calculated over the inbound leg of each orbit. Temperature is obtained from the density observations by means of the ideal gas law and the hydrostatic equilibrium.

Figure 11. Examples of orbit 155 of ODY and orbit 250 of MRO. Density variations in kg km$^{-3}$ in function of the distance from periapsis in km.

Results from the adiabatic heating generated by the subsidence of air over the winter pole produced by strong interhemispheric transport [González-Galindo et al., 2009]. The entry of the spacecraft inside the polar vortex is then expected to be associated with an increase of temperature, leading to a decrease of gravity wave activity according to equation 7.

In Figure 12, the observed RMS of the relative density variations is compared to the inverse of the background temperature, calculated for each orbit of each instrument over the outbound leg. (For the sake of brevity, similar results over the inbound leg are not shown.) Latitudinal variability is displayed in Figure 12. Seasonal variability for aerobraking acquisitions is not shown: contrary to upper-thermosphere MAVEN observations, which have complete seasonal coverage, aerobraking data are limited to only one season (two for MGS).
The amplitude of gravity waves is reasonably correlated with the inverse temperature in the MGS observations, with an amplitude increase at latitudes 60°S, 50°N and particularly at 20°S, where inverse temperature is higher. This anti-correlation is more difficult to identify in ODY data, except at polar latitudes around 80°N, where a clear decrease of GWs amplitude is correlated with the polar warming (see previous paragraphs). Conversely, there is no obvious correlation between density perturbations and inverse temperature in the MRO aerobraking data: there is an increase in gravity waves activity from latitude -90° to -70°, while the tendency for inverse temperature is unclear. Furthermore, the former decreases towards the equator while the latter is approximately uniform.

4.2 Discussion

The correlation between density perturbations, caused by gravity waves, and the inverse background temperature, suggested by equation 7 appears to be observed by MAVEN/NGIMS, and during MGS aerobraking phases. This correlation is not clear in the case of ODY aerobraking phase, and does not exist at all in the case of MRO aerobraking phase. Those two aerobraking density measurements (both ODY and MRO) correspond to periapsis conditions at lower altitudes than the MGS measurements and the MAVEN/NGIMS measurements (cf. Figure 1). There the assumption of isothermal profiles is not valid anymore — especially at polar latitudes, where polar warming shifts the threshold for isothermal conditions to higher in the mesosphere. In such conditions, the more general equation 5 shall prevail instead of equation 7 which means that the amplitude of gravity waves is proportional to the static stability $N^2$ rather than the inverse background temperature.

The possible correlation with static stability $N^2$ can be tested in the case of MRO data, for which no correlation has been found between observed gravity-wave amplitudes and the inverse background temperatures. Figure 13 displays the comparison between the RMS of the relative density acquired at different MRO orbits and the static stability calculated from

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**Figure 12.** From the left to the right: MGS, ODY, MRO. From the upper to the lower: RMS of the relative density calculated over the outbound leg according to the latitude of the orbit’s periapsis, inverse of the mean background temperature calculated from the observations over the outbound leg according to the latitude of the orbit’s periapsis.
Figure 13. Left: RMS of the relative density calculated over the outbound leg of each orbit of MRO according to the latitude of the orbit’s periapsis; Right: Mean static stability $N^2$ calculated over the outbound leg of each orbit of MRO according to the latitude of the orbit’s periapsis, $N^2$ has been calculated by means of the Mars Climate Database (MCD) at the different orbital characteristics and with the corresponding dedicated MCD dust scenarios of Mars Year (MY) 25 (MCD detailed document, Montabone et al. [2015]).

There might be multiple reasons for MRO measurements not following equation 5 in the low and mid latitudes. Firstly, while no correlation was found with potential sources of gravity wave, it is still possible that outside the polar regions, propagation effects would compete with the regional variability of gravity-wave sources. Secondly, following a similar argument, the filtering by critical levels was ruled out for a lack of clear tendency, but might be of peculiar importance for specific regions [see Spiga et al., 2012]. Thirdly, the regional variability of vertical wavelength $k_z$, a parameter found in equations 5 and 7, in principle could impact density perturbations, which then would be less clearly correlated to static stability $N^2$.

5 Conclusion

We have studied the seasonal and regional variability of density perturbations, putatively caused by the propagation of gravity waves in the thermosphere, in different sets of data issued from the aerobraking phases of MGS, ODY and MRO (accelerometers) and the observations of the NGIMS instrument on board MAVEN. The modeling compiled in the Mars Climate Database has been used to complement background atmospheric conditions obtained by observations. Our conclusions are as follows:

1. The correlation found in the MAVEN observations by Terada et al. [2017] between the inverse background temperature and the density perturbations extends to the MGS aerobraking observations. This corresponds to conditions dictated by wave saturation processes in isothermal conditions (equation 7). The seasonal variability of inverse background temperature measured by MAVEN is reproduced in the Mars Climate Database.

2. Aerobraking data acquired at lower altitude by ODY and MRO do not exhibit this correlation of density perturbations with inverse background temperature. However, a correlation of density perturbations monitored by MRO during aerobraking in polar conditions...
regions with static stability $N^2$ indicates that wave saturation is still dominant, but the isothermal conditions are no longer verified (equation 5).

3. The spatial variability of gravity-wave-induced density perturbations for ODY and MRO aerobraking are more difficult to explain in lower latitudes, where correlation with neither inverse temperature nor static stability is found. The effects of gravity-wave sources, or wind filtering effects through critical levels, were ruled out as explanations for most of the measured variability, yet might play a stronger role in the low-to-mid latitudes.

Future studies will employ measurements during the aerobraking phase of the ExoMars Trace Gas Orbiter, as well as new measurements by MAVEN, to confirm the conclusions drawn in this study and the existing literature. Broadening the knowledge of gravity wave activity in the mesosphere and thermosphere is crucial to understand the large-scale heat and momentum budget of this part of the Martian atmosphere.

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