火星の対流励起重力波
Convective generation and vertical propagation of fast gravity waves on Mars

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Generation of gravity waves by convection was studied using a nonlinear two-dimensional model. A boundary-layer convection forced by a horizontally-uniform heating and a plume forced by a localized heating representing a local dust storm were tested. The results suggest that vigorous convection occurs due to the low density of the Martian atmosphere and that short-period waves having frequencies near the buoyancy frequency can be preferentially generated. The propagation of those gravity waves to thermospheric heights was studied using a linearized one-dimensional model. Because of the fast vertical propagation the waves attain large amplitudes in the lower thermosphere, being consistent with Mars Global Surveyor and Mars Odyssey's accelerometer measurements and MAVEN's neutral and ion measurements. The heating and cooling caused by the waves are expected to be significant in the energy budget of the thermosphere, and the vertical mixing induced by those gravity waves should influence the homopause height. Since the thermospheric densities of light, minor species increase with the lowering of the homopause, a lower homopause may have enhanced the escape of such species to space for early Mars, where slower, weaker gravity waves should dominate.

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経緯

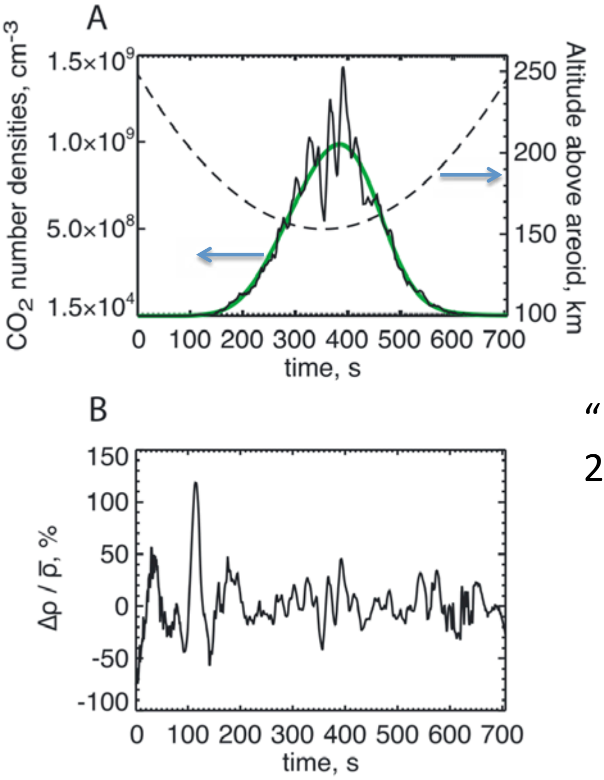
- 渡邊歩佳　東京大学大学院修士論文 「火星における対流励起重力波と熱圏への影響」 2014年2月
- NASA MAVENによる火星上層大気観測で火星熱圏の波動がクローズアップ

  “Orbit-to-orbit variability may be driven from below owing to gravity wave interactions with the global wind structure and small-scale mixing processes. This combined density and temperature variability at this exobase altitude ultimately has a direct impact upon volatile escape rates.” -- Bougher et al. (2015, *Science*)

- 上記を踏まえ

  Imamura, T., A. Watanabe, Y. Maejima, Convective generation and vertical propagation of fast gravity waves on Mars: one- and two-dimensional modeling, *Icarus*, 267, 51-63, 2016.

Measurement by Neutral Gas Ion Mass Spectrometer (NGIMS) instrument on board MAVEN



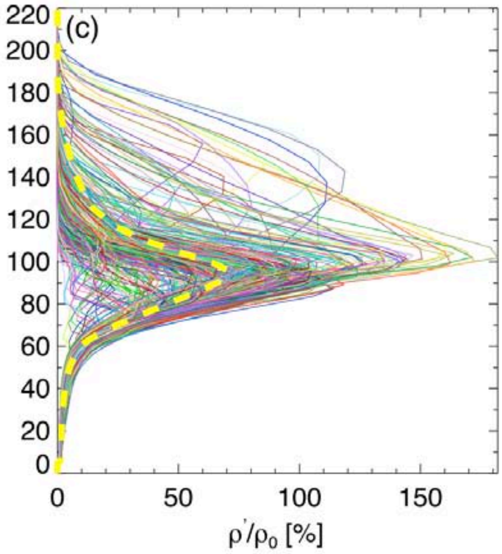
Yigit et al. (2015)

“Relative density perturbations of 20–40% between 180 and 220 km”

Homopause control

- We take the homopause to be the altitude where the eddy diffusion coefficient and the molecular diffusion coefficients are equal, although large-scale dynamics also influences the homopause height.
- The homopause is typically located near 100 nbar (105 km) on Earth, near 10 nbar (135 km) on Venus, and near 1 nbar (125 km) on Mars (Mueller-Wodarg, 2008). The relatively low pressure at the Martian homopause implies strong turbulent mixing in the Martian upper atmosphere.
- The location of the homopause influences the composition of the exosphere, thereby influencing the species escaping to space.

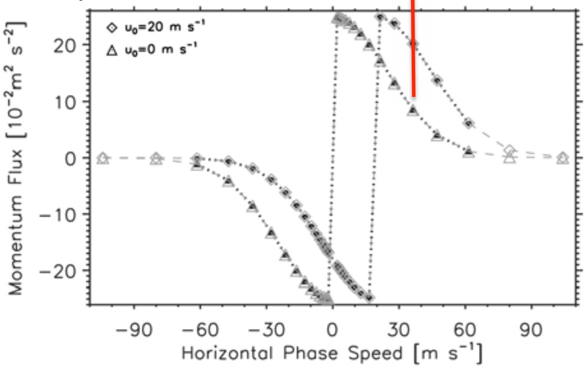
Altitude profiles of gravity wave effects
calculated by nonlinear gravity wave scheme



Yigit et al. (2015)

Typical period
~ 300(km) / 30(m/s)
~ 2.8 hours

Wave source
parameterization



> "Overall, the wave-like density perturbations have been observed at all altitudes up to 250 km. This is significantly higher than in previous observations of such waves on Mars, and even higher than in the theoretical estimates using the GW parameterization."

Wave sources

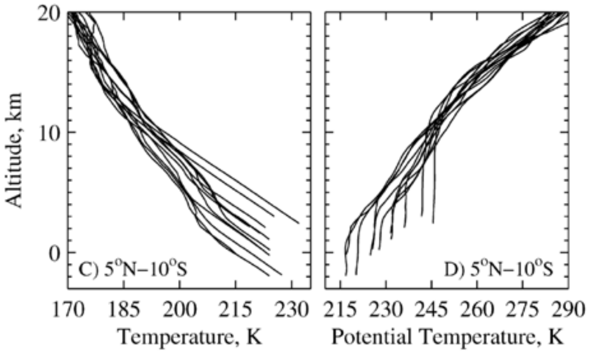
- Convective excitation / topographic excitation / geostrophic adjustment ?
- Tenuous atmosphere of Mars favors strong large-scale winds near the surface, which lead to strong topographic generation, and strong convective activity, which leads to strong convective generation.

- Convective generation has been less studied than topographic generation for Martian atmosphere.

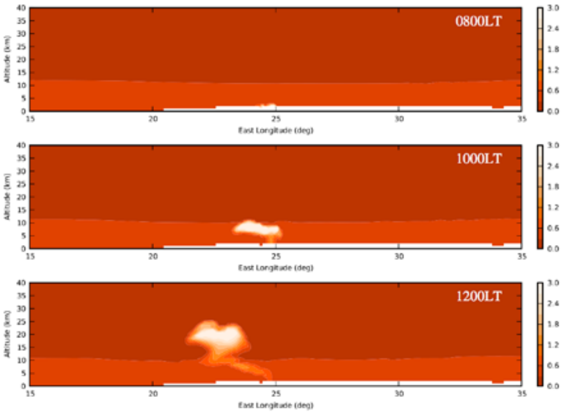
Convection on Mars

Convection can be driven by uniform heating in the boundary layer and by localized heating of dust clouds

Temperature profiles by radio occultation (Hinson et al., 2008)



Regional model of dust plume ‘Rocket dust storm’ (Spiga et al., 2013)



* Nighttime detached convective layers are also suggested by radio occultations (Hinson et al., 2013)

Purpose of this study

- To clarify how efficiently convection generates gravity waves on Mars
- To explain the large-amplitude density fluctuations observed in Martian thermosphere
- To understand how the homopause height is controlled
- To assess the contribution of convectively-generated waves on the energy budget of the thermosphere

Method

- Combination of a nonlinear convection model and a linear wave solution in the upper atmosphere
  - The period, the wavelength and the amplitude of the waves generated by convection are found by using a 2-D regional-scale convection model based on CReSS (Cloud Resolving Storm Simulator).
  - The estimated wave parameters are used as the input to a linear wave model extending to the thermosphere.

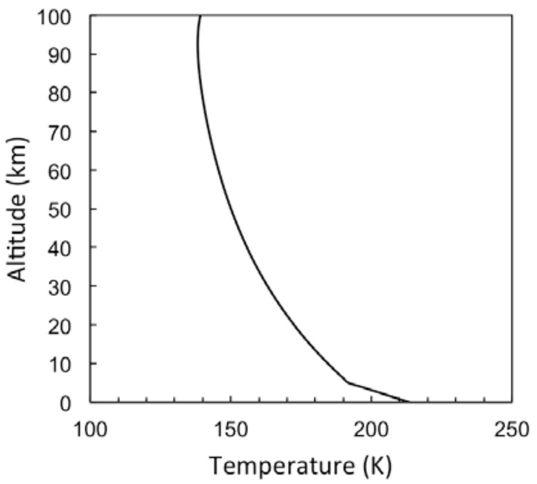
2-D regional model

Two types of forcing:

(1) Uniform heating near the surface

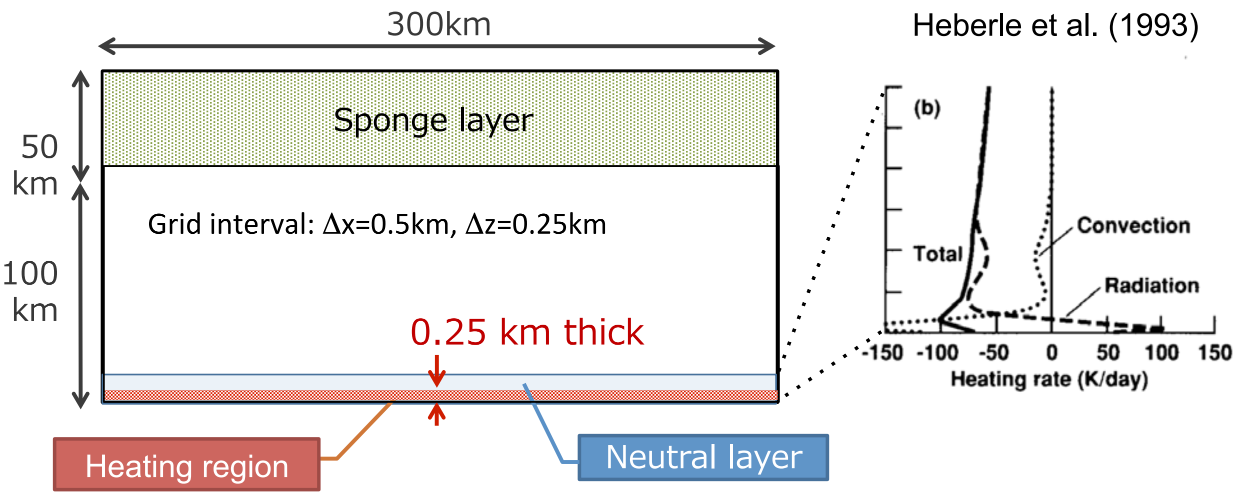
(2) Localized heating representing a local dust storm

Dynamics	CReSS version 2.3
Model domain	Horizontal: 600 km Vertical: 0-100 km (sponge layer at 100-150 km)
Grid interval	Horizontal: 0.5 km Vertical: 0.25 km
Boundary condition	Side: Radiation (Localized heating) or Periodic (Uniform heating) Top and bottom: Rigid wall
Diffusivity	Calculated from turbulence kinetic energy by 1.5th order closure scheme
Initial condition	6 hPa at the surface Neutral stratification below 5 km altitude **No background wind**



Initial temperature profile

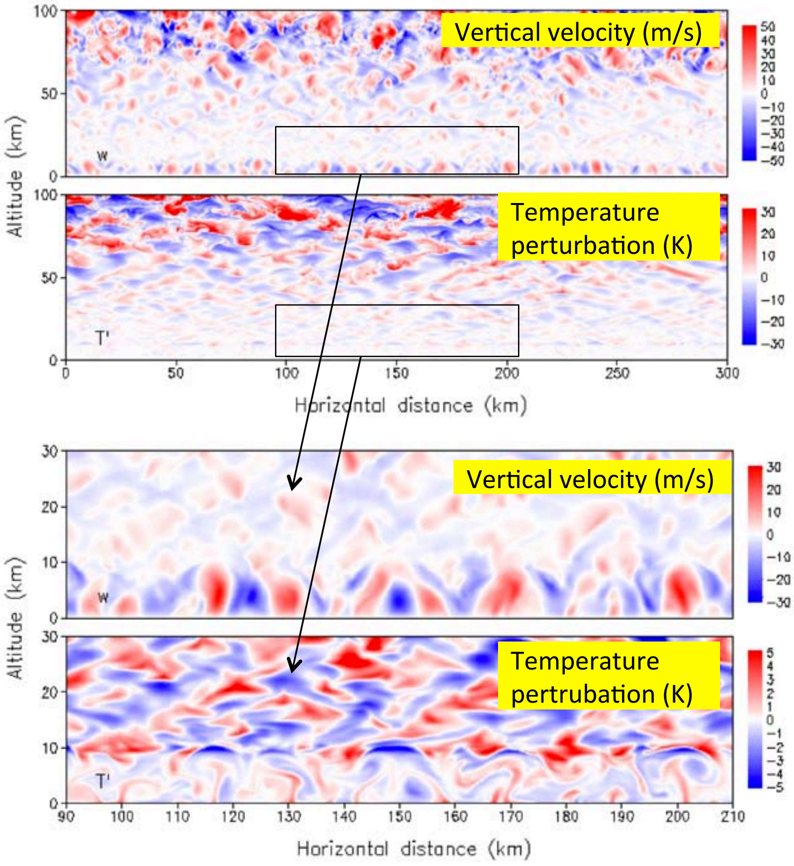
(1) Uniform heating



Heating is given in the lowest layer (0.25 km thick) by
Q_{MAX} = 40 K/hour
to be consistent with the nighttime radiative cooling rate of the
5 km-thick boundary layer estimated by Heberle et al. (1993).

＊The convective heat flux is similar to Odaka et al. (1998).

Structure of convection (200 min)



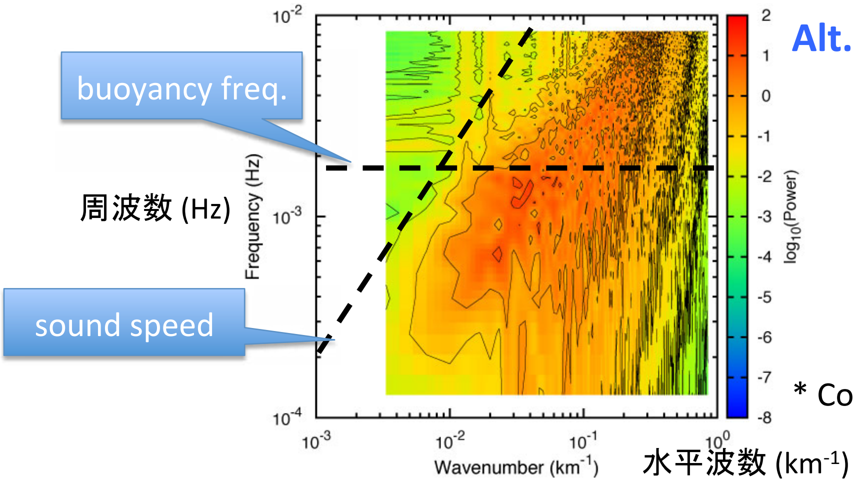
Convective velocities are consistent with Odaka et al. (1998).

2-D spectrum of vertical velocity

- The unit of the spectral density used here is

  $m^2 s^{-2} / \log_2(\text{wavenumber}) \log_2(\text{frequency})$

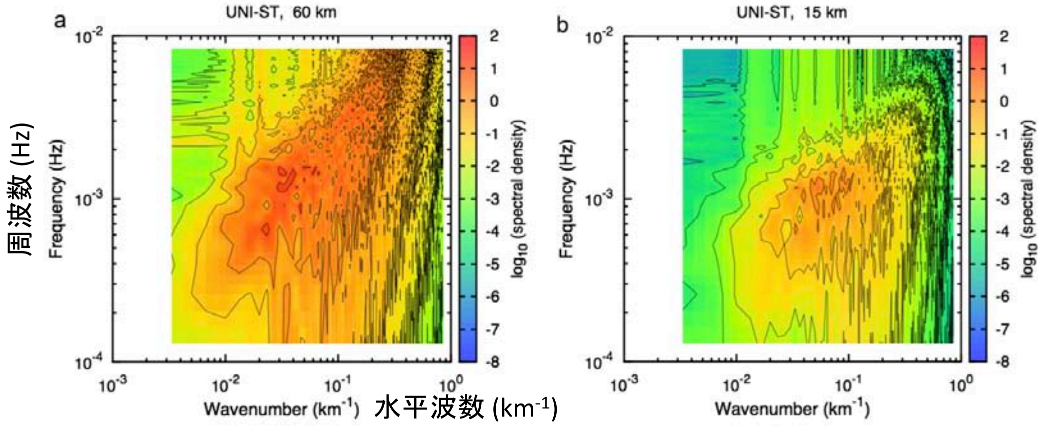
  i.e. the squared amplitude in each power of two of the wavenumber and frequency.
- We take the square root of this quantity as the amplitude for each wavenumber and frequency mode.



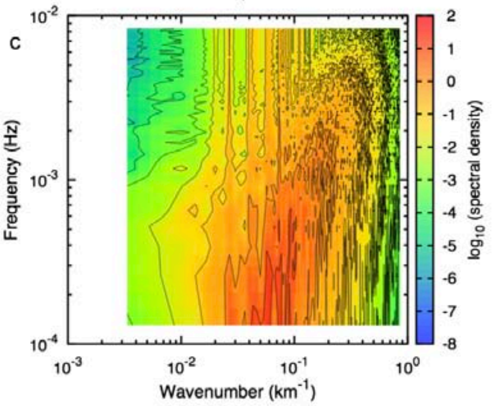
Alt. = 60 km

* Color scale is $\log_{10}$(power)

Alt. = 60 km **Alt. = 15 km**

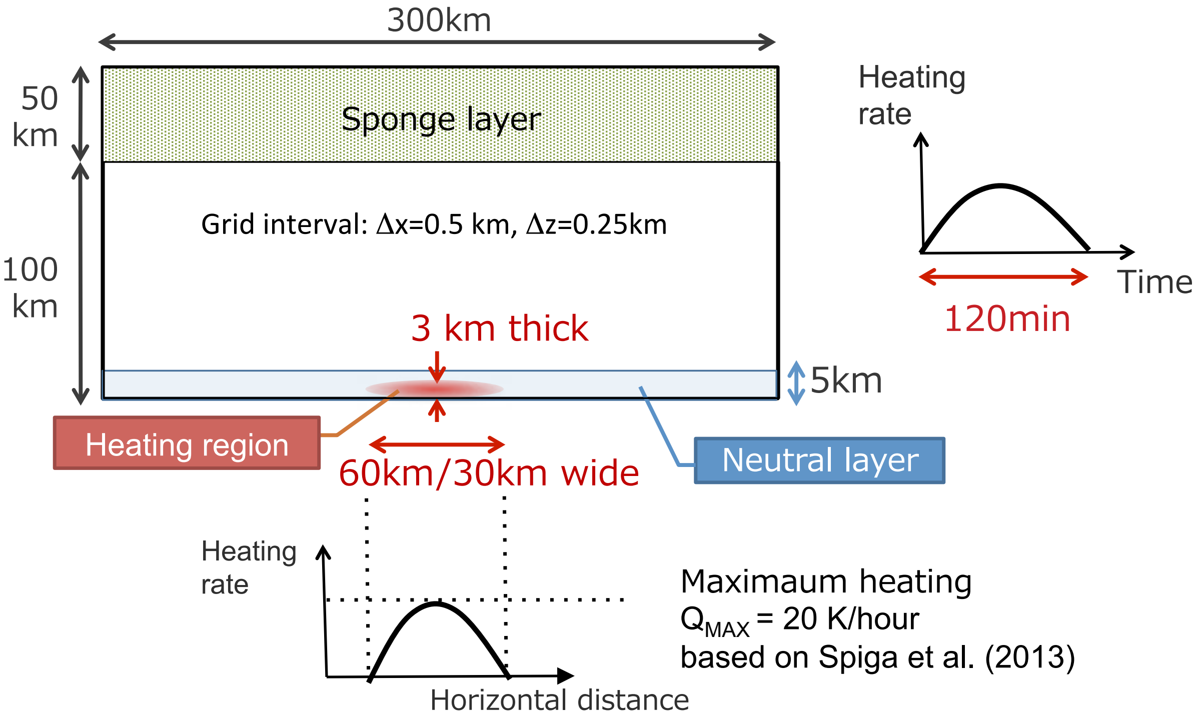


Alt. = 5 km



The maximum power occurs at wavelengths of 10-50 km, being consistent with the horizontal scales of the boundary-layer convective cells, and at periods of 700-2000 s, being consistent with the turnover time of convection.

(2) Localized heating



300km

50 km

Sponge layer

100 km

Grid interval: Δx=0.5 km, Δz=0.25km

3 km thick

5km

Heating region

60km/30km wide

Neutral layer

Heating rate

Time

120min

Heating rate

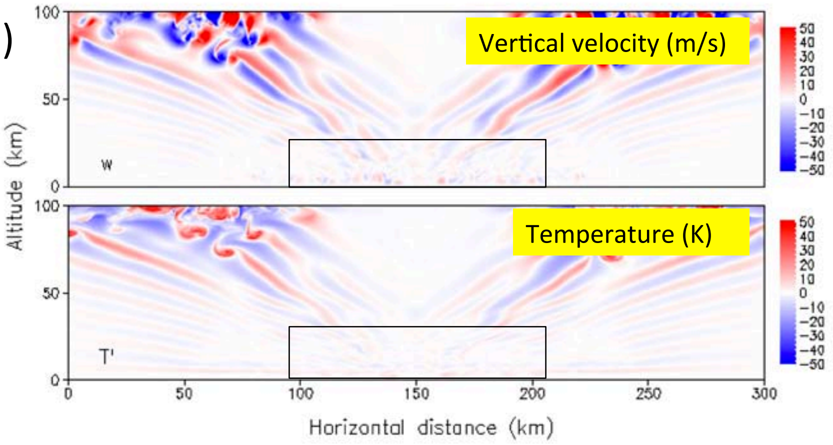
Horizontal distance

Maximaum heating
Q_{MAX} = 20 K/hour
based on Spiga et al. (2013)

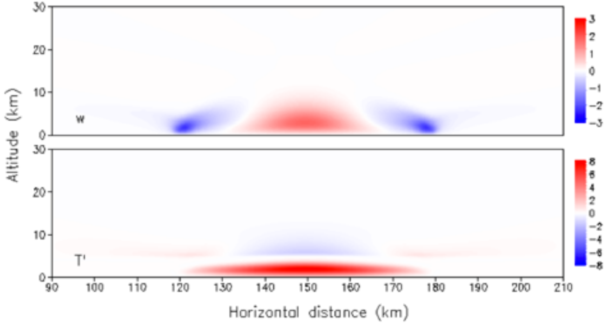
No radiatively-active dust is included

Structure of convection

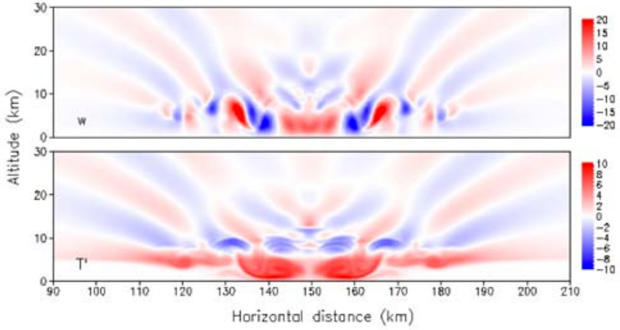
(200 min)



(50 min)



(100 min)



1-D linear wave solution

- The vertical structures of specific wave modes seen in the convection models are solved using a full-wave model (e.g., Hickey et al. 2000; Schubert et al. 2003). The model solves the linearized equations of continuity, momentum, and energy for a compressible atmosphere. Waves are forced near the surface by a periodic heating.
- Wave amplitudes are scaled so that the maximum amplitude of the horizontal wind in the model domain is equal to the horizontal phase velocity. Since the wave modes studied in this study all have amplitudes large enough for saturation at high altitudes, giving marginally-saturated amplitudes enables evaluation of wave dissipation in the region where the influence of molecular dissipation dominates.
- The physical domain extends from 0 km to 500 km.
- Radiative damping is considered (Eckermann et al. 2011).

Locating the homopause

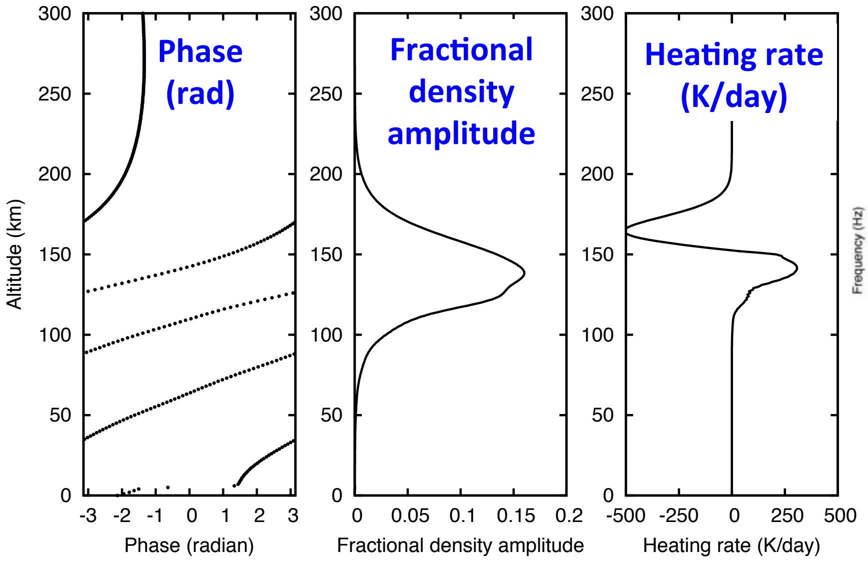
- Given a gravity wave saturated via convective breaking, the wave-induced turbulent diffusion coefficient is given by (Lindzen 1981)

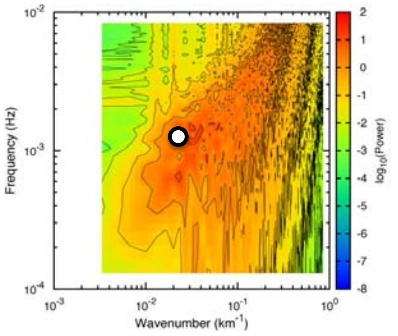
$$D = \gamma \frac{kc^4}{2HN^3}$$

- where *k* is the horizontal wavenumber, *c* is the horizontal phase velocity, *H* is the scale height, and *N* is the buoyancy frequency.
- The efficiency parameter γ, which was not included in Lindzen's (1981) original formulation, accounts for the spatially and temporally localized character of the turbulence. Although the value of γ is highly uncertain, previous modeling studies adopted γ = 0.2 (Barnes 1990; Theodore et al 1993; Joshi 1995). Here we further consider the spatially and temporally localized character of gravity waves, and tentatively adopt γ = 0.1.
- Finding the altitude where the turbulent diffusion coefficient *D is* equal to the molecular diffusion coefficient, we obtain the homopause height.

Vertical structure

horizontal wavelength = 50 km, period = 900 s





The amplitude seen in the convection model is 10 times larger than that required for saturation. → Amplitude in the thermosphere is determined by saturation at lower altitudes. Turbopause height is calculated to be 132 km

Summary

- It was suggested that vigorous convection occurs due to the low density of the Martian atmosphere and that short-period waves having frequencies near the buoyancy frequency can be preferentially generated. Such waves are potentially important in the upper atmosphere due to less damping.
- The suggested amplitudes in the thermosphere are consistent with the mass spectrometer observation by MAVEN and the aerobraking experiments by other Martian orbiters.
- Wave breaking seems to explain the observed homopause height, although other dynamical processes can also contribute.