Convectively-generated Gravity Waves on Mars and Their Influence on the Upper Atmosphere

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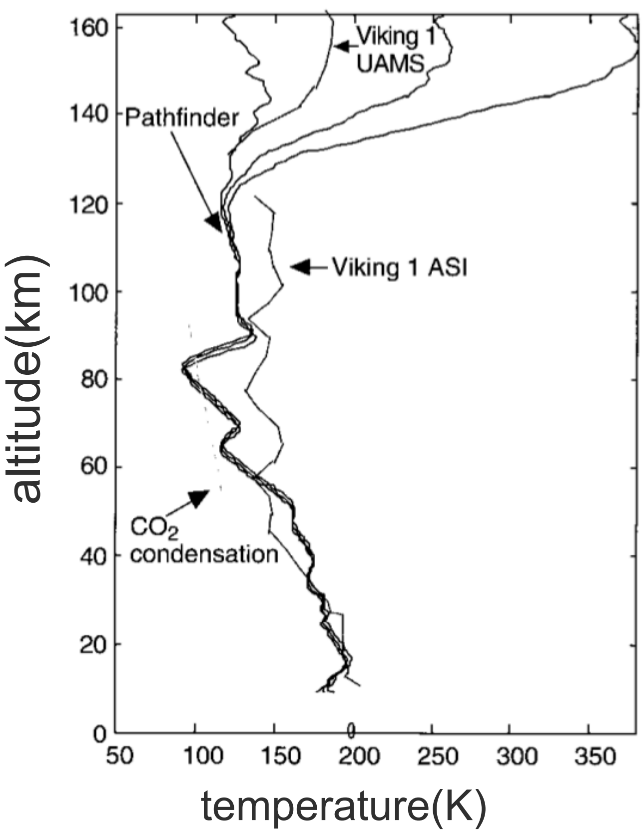
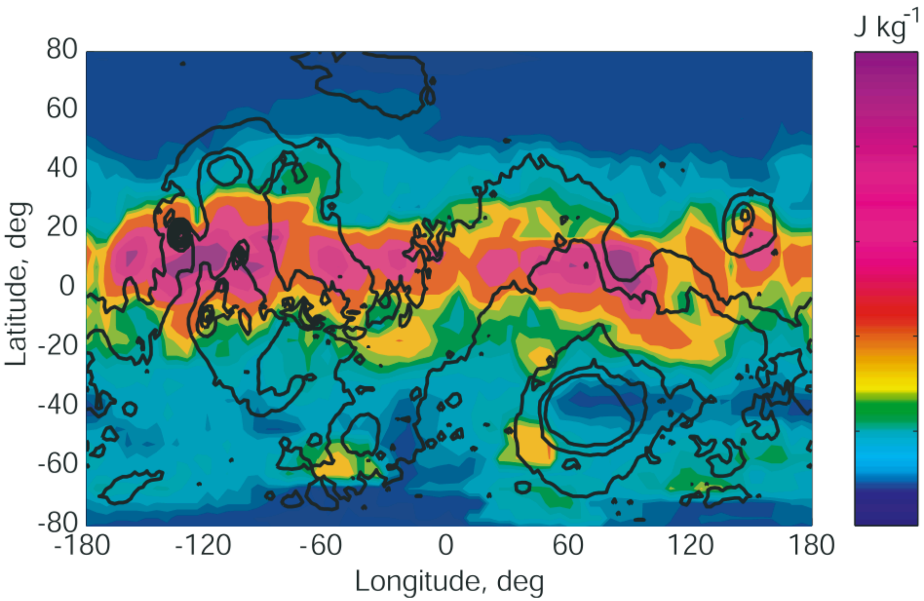
Gravity waves on Mars

Gravity waves which are generated in the troposphere and propagate to the upper atmosphere are considered to play key roles in momentum and energy transport in the Martian atmosphere.

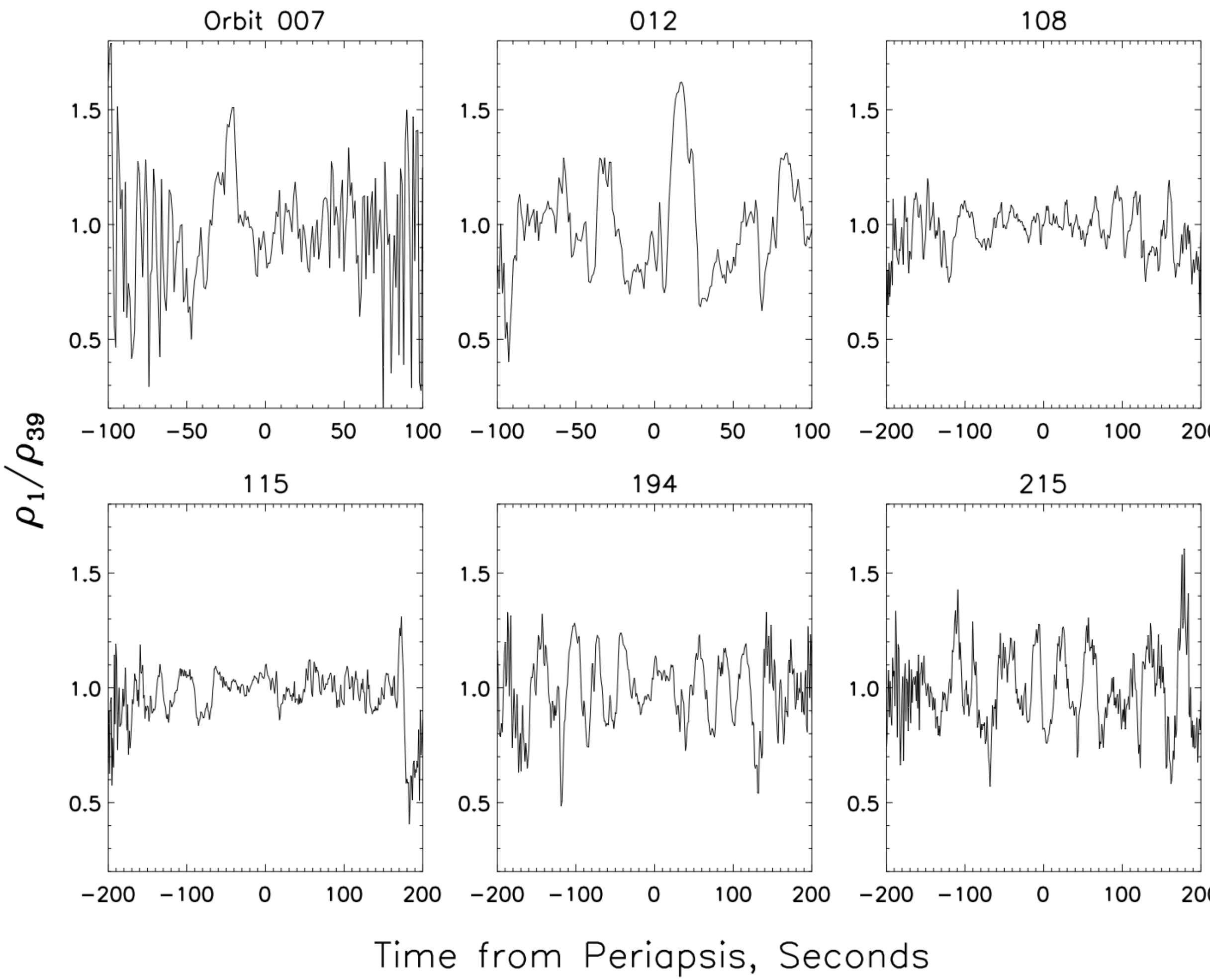
Vertical wavelike structures of temperature (Schofield et al., 1997)





GW energy distribution according to radio occultation (Creasey et al. 2006)

Horizontal wavelike structure of atmospheric density in the lower thermosphere (Fritts et al. 2006)



The accelerometer measurements revealed density fluctuations of 5-50% on horizontal scales of 20-200 km in the lower thermosphere (100-130 km)

Wave sources

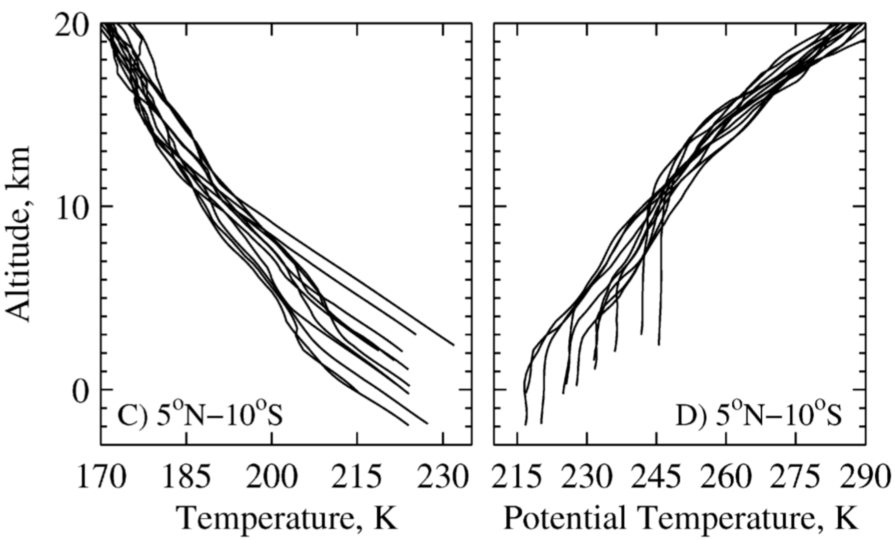
- Convective excitation / topographic excitation / geostrophic adjustment ?
- Previous Mars GCMs assumed wave spectra in the source region based on experience in the Earth's atmosphere (e.g., Medvedev et al. 2011).
- Tenuous atmosphere of Mars favors strong large-scale winds near the surface, which lead 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.

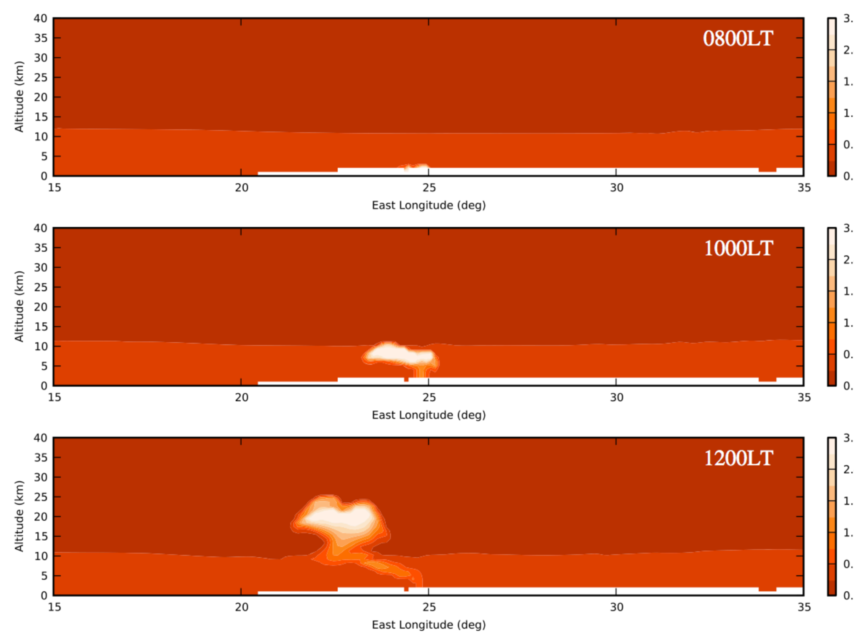
Convection on Mars

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)

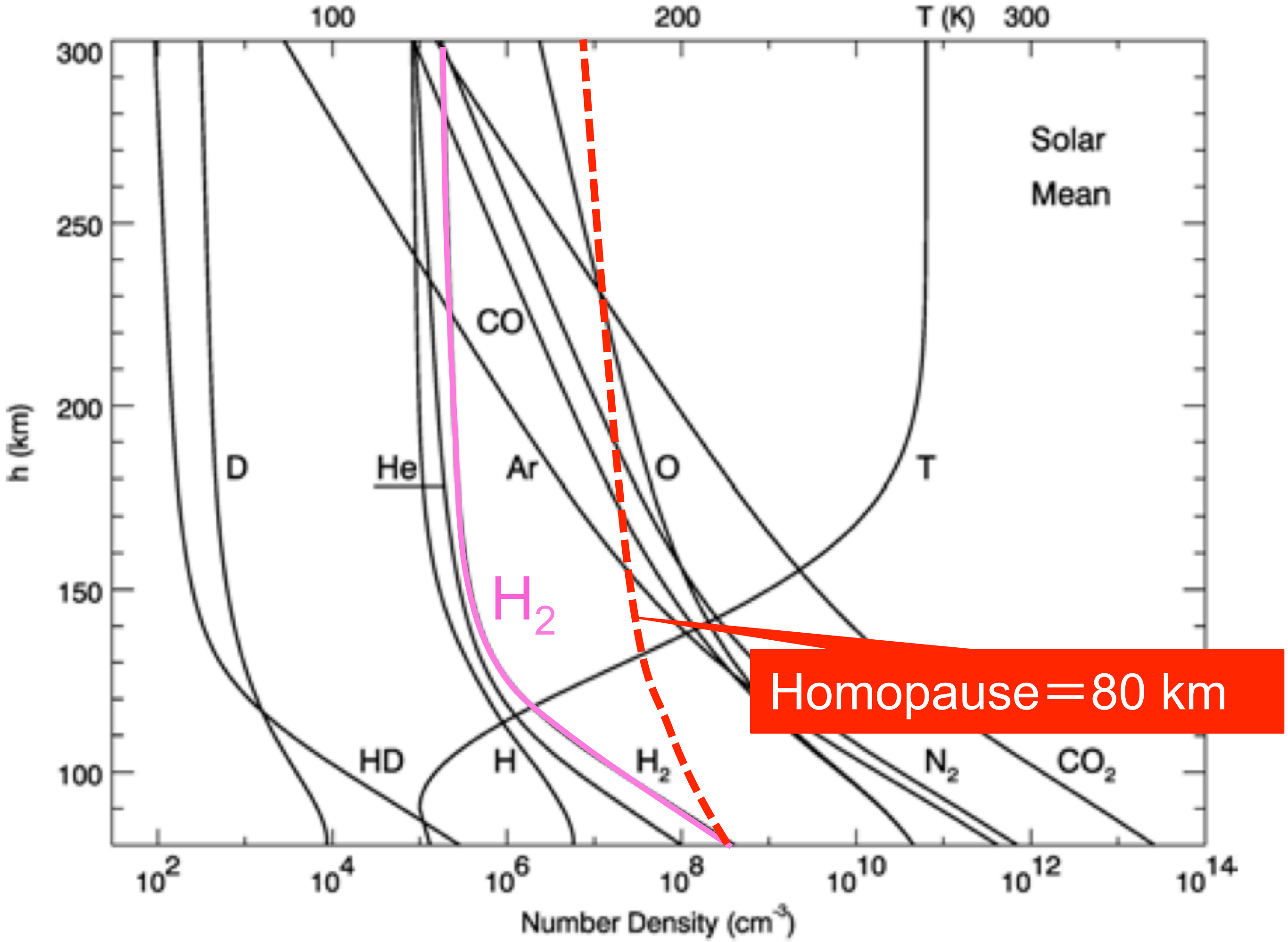


* Nighttime detached convective layers are also suggested by radio occultations (Hinson et al., 2013)

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 105 km altitude (100 nbar) on Earth, near 135 km (10 nbar) on Venus, and near 125 km (1 nbar) 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.

1-D photochemical model by Krasnopolsky (2002)



Purpose of this study

- To clarify how efficiently convection generates gravity waves on Mars
- To explain the large-amplitude density fluctuations observed during aerobraking of Mars orbiters
- 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 regional-scale model of convection and a linear solution of wave propagation 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 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.

- (Limitations of 2-D modeling will be discussed later)

2-D regional model

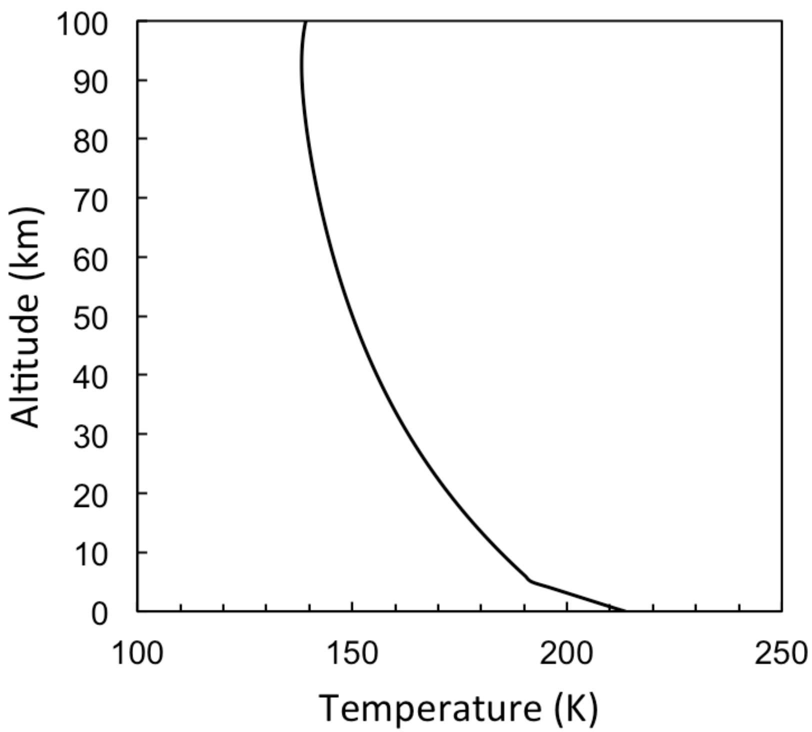
Two types of forcing:

(1) Uniform heating near the surface

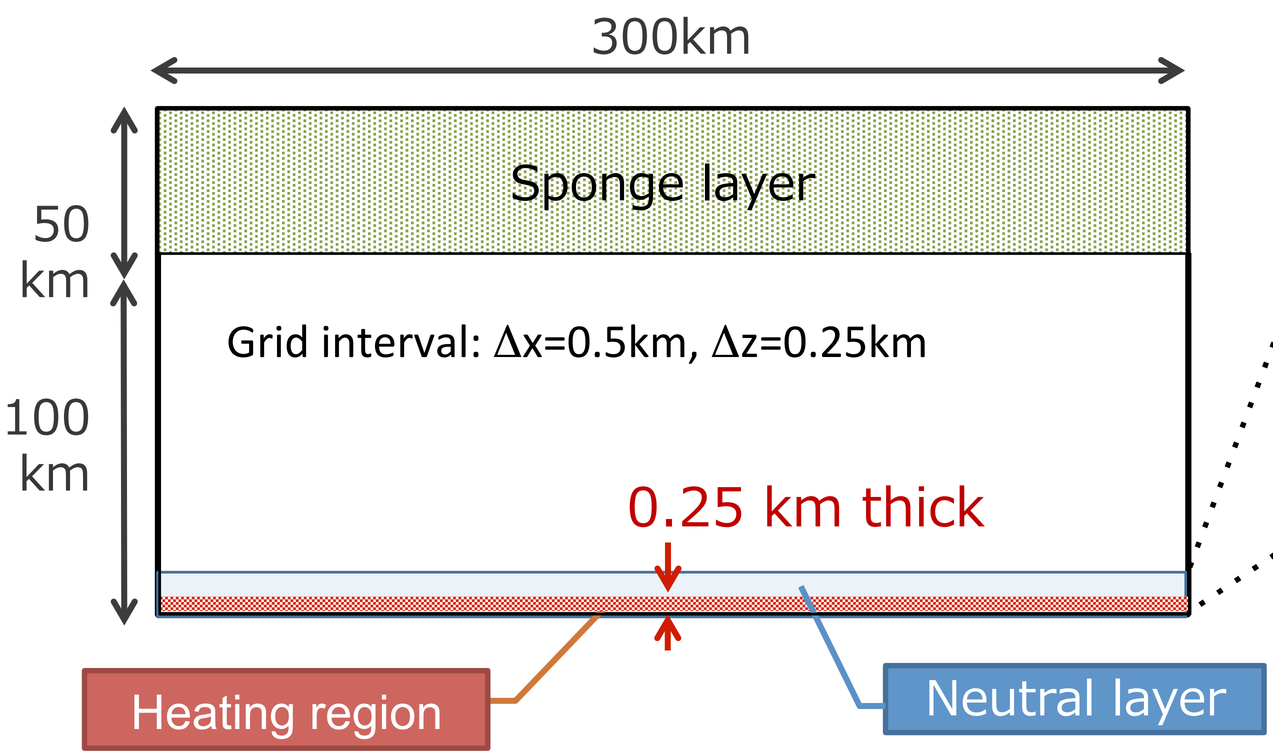
(2) Localized heating representing a local dust storm

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**

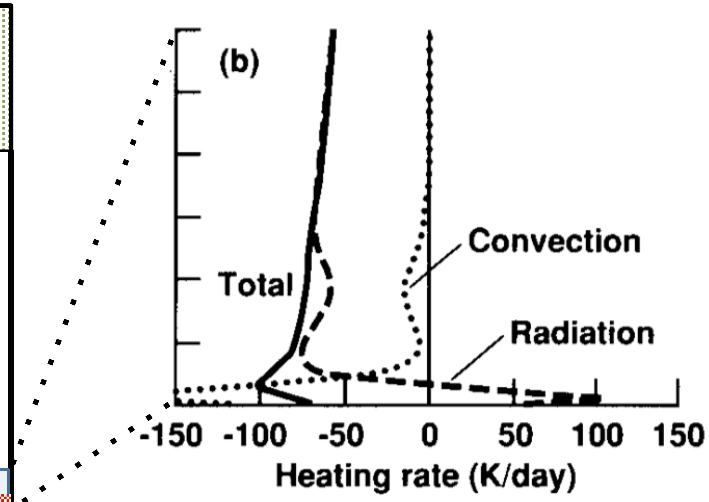
Initial temperature profile



(1) Uniform heating



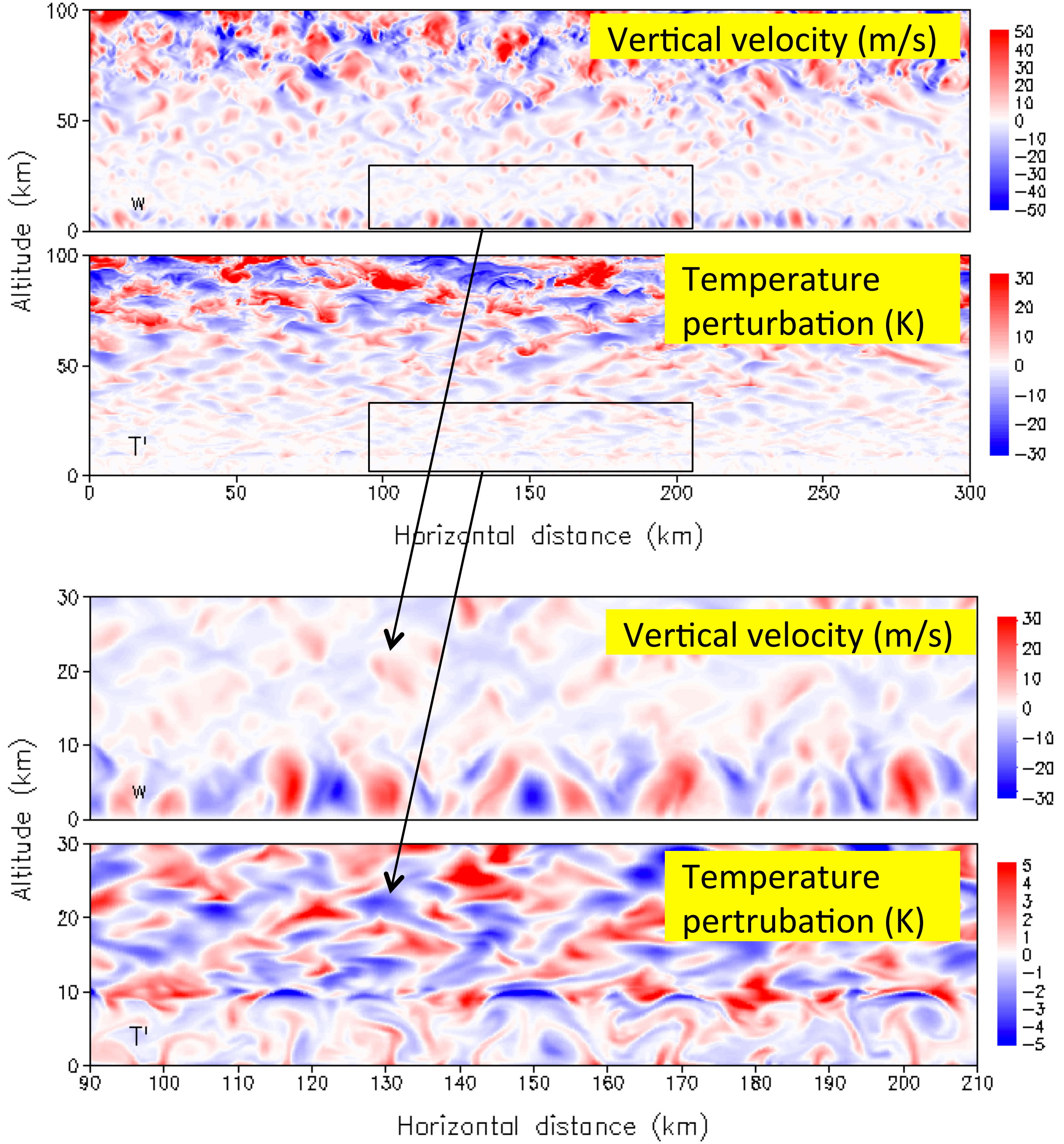
Heberle et al. (1993)



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)



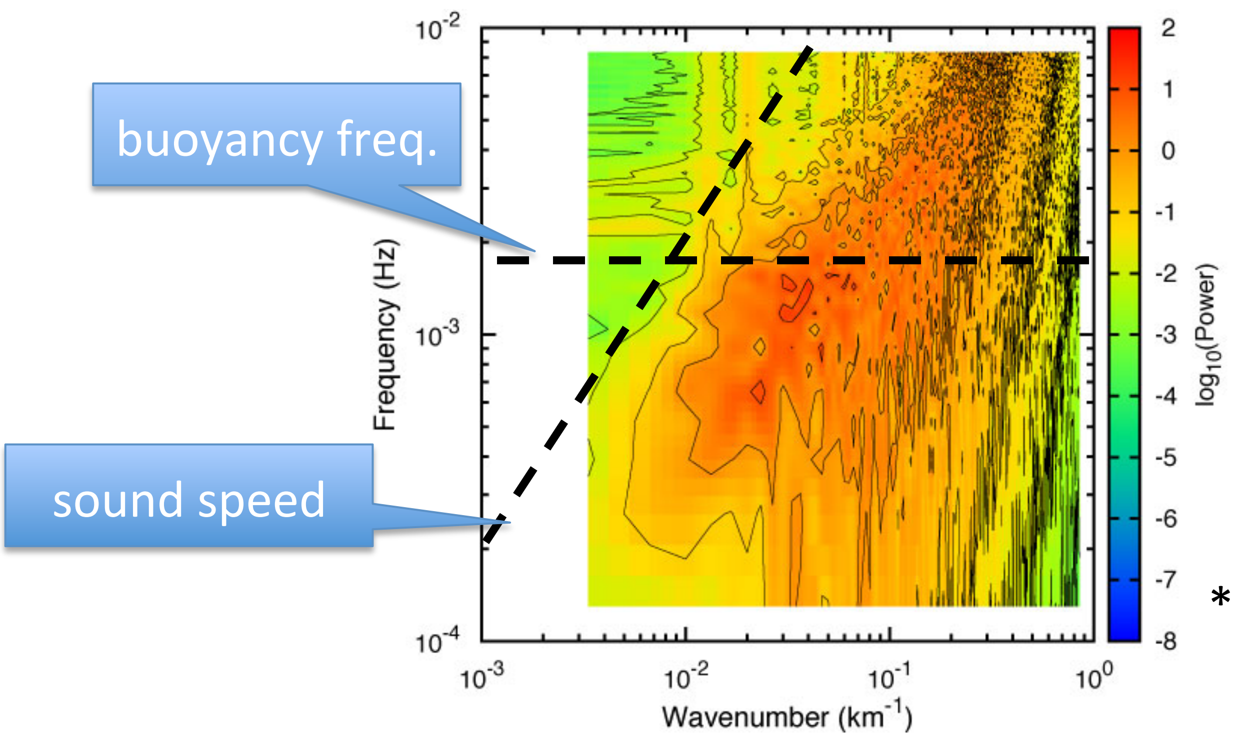
Convective velocities are consistent with Odaka et al. (1998).

2-D spectrum of vertical velocity

- The unit of the spectral density used here is

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



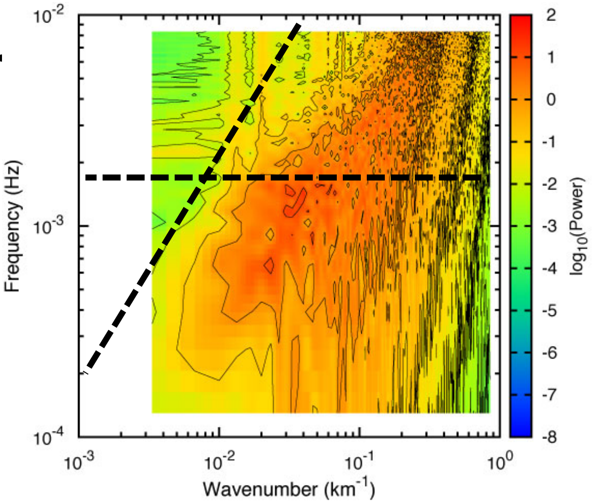
2-D spectrum of w' at 60 km altitude

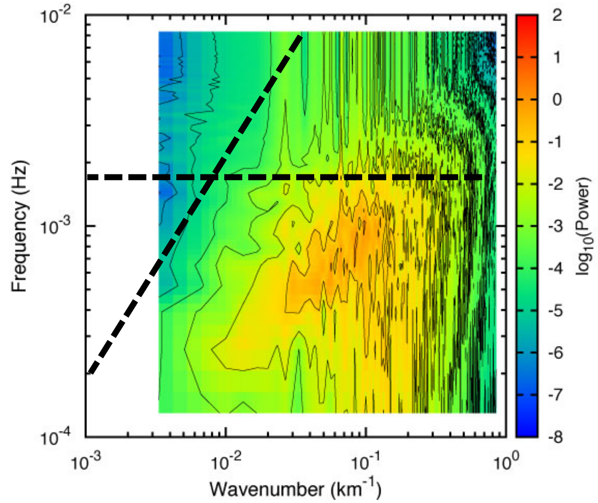
* Color scale is $\log_{10}$(power)

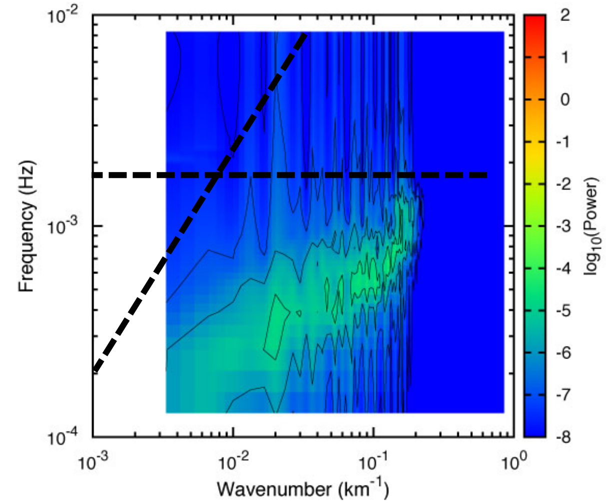
2-D spectra

Heating rate = 40 K/h | **4 K/h** | **0.4 K/h**

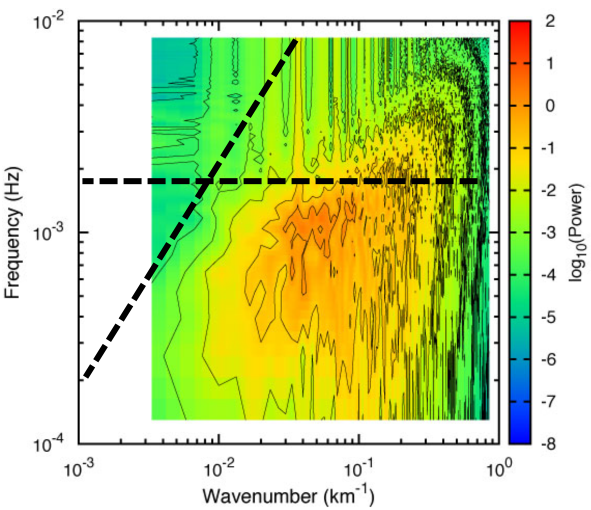
Alt. 60 km





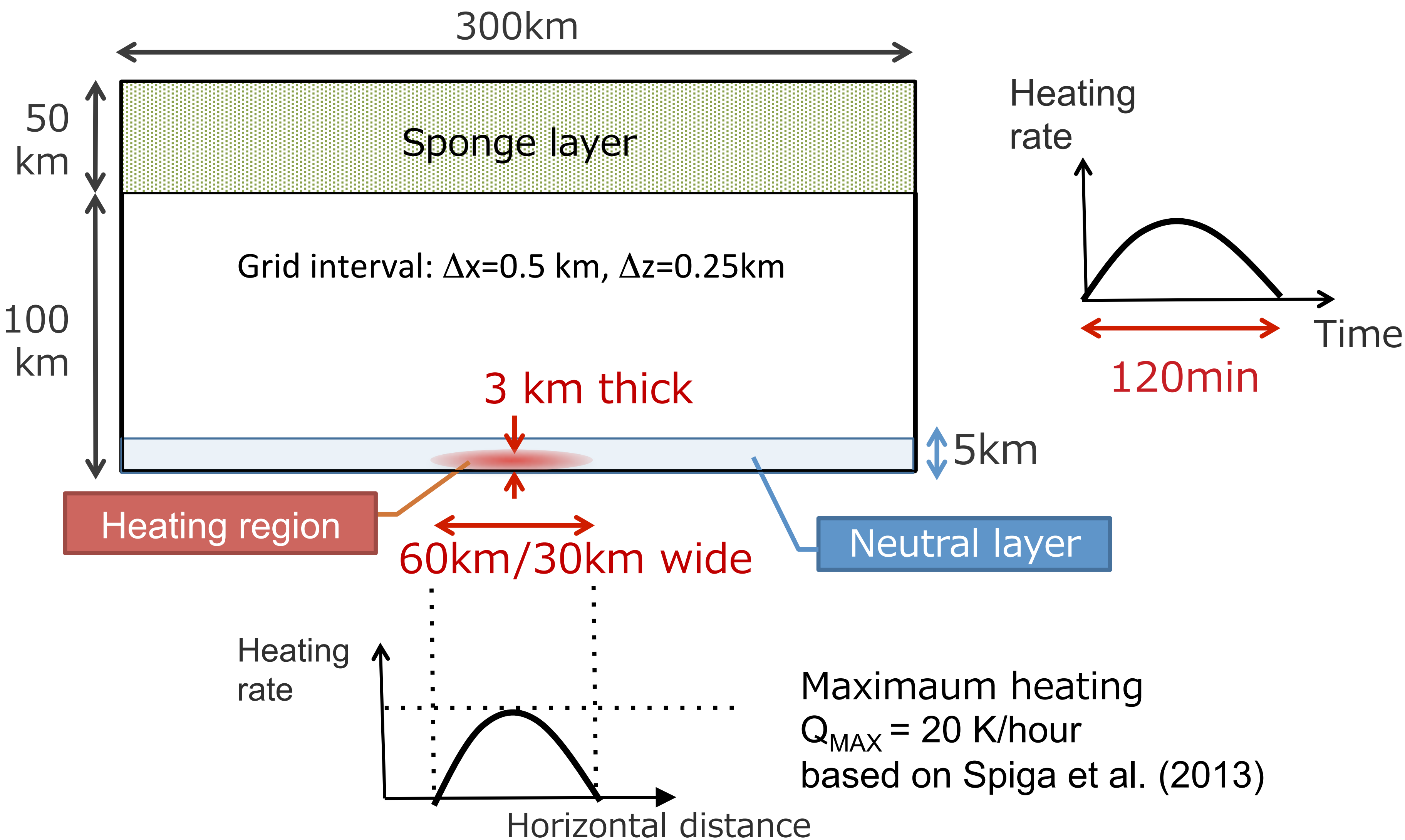


20 km



- The significant power seen at frequencies higher than the buoyancy frequency at 60 km is attributed to turbulent eddies generated via nonlinearity of primary waves.
- 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.

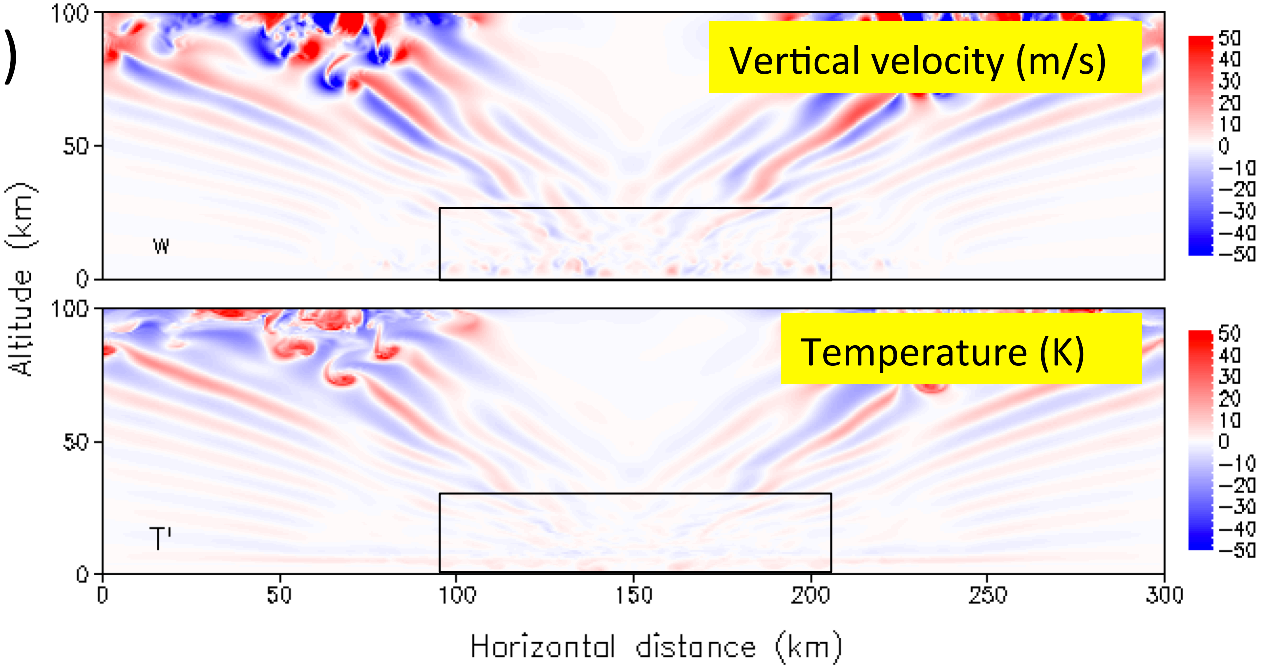
(2) Localized heating



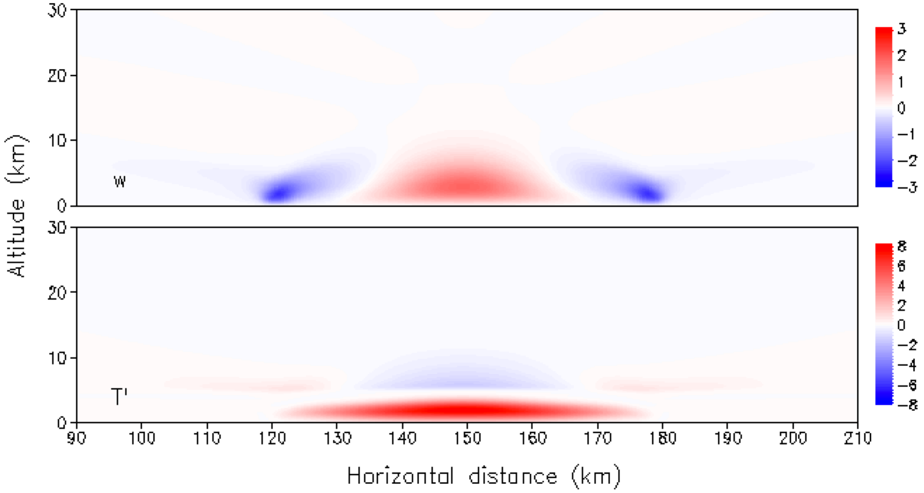
No radiatively-active dust is included

Structure of convection

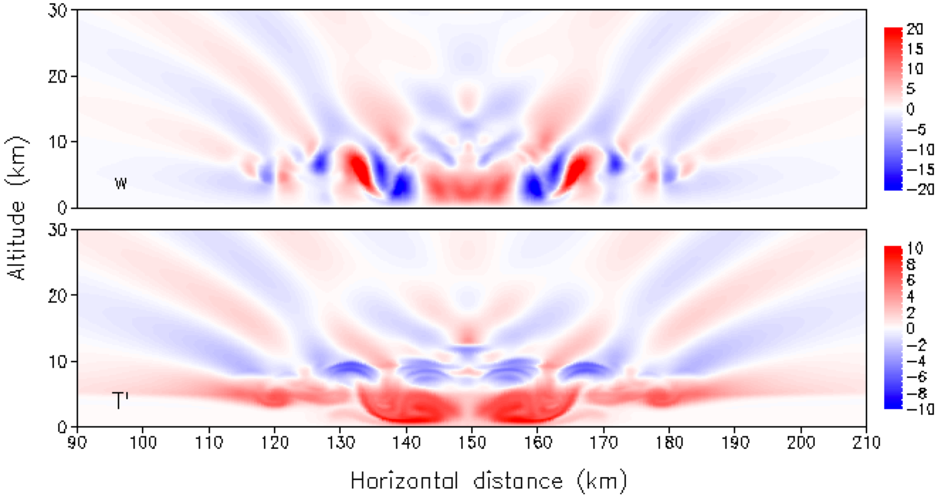
(200 min)



(50 min)



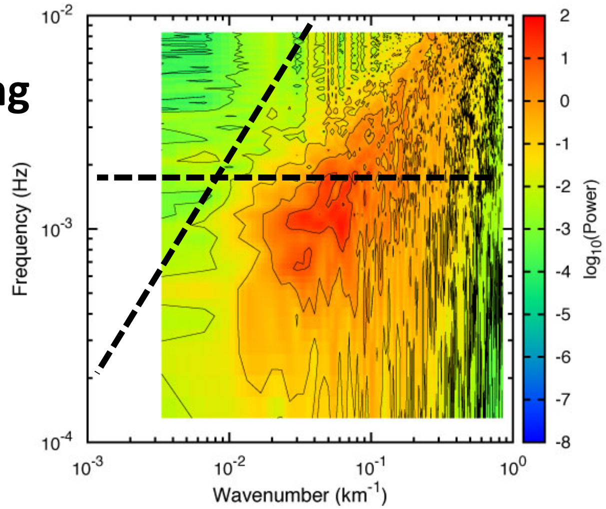
(100 min)

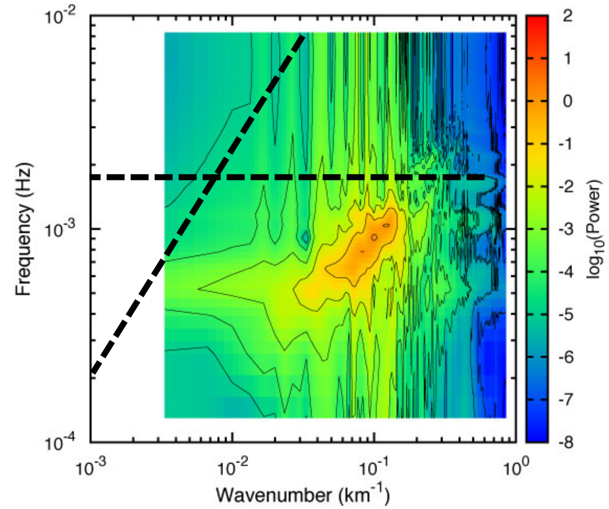


2-D spectra

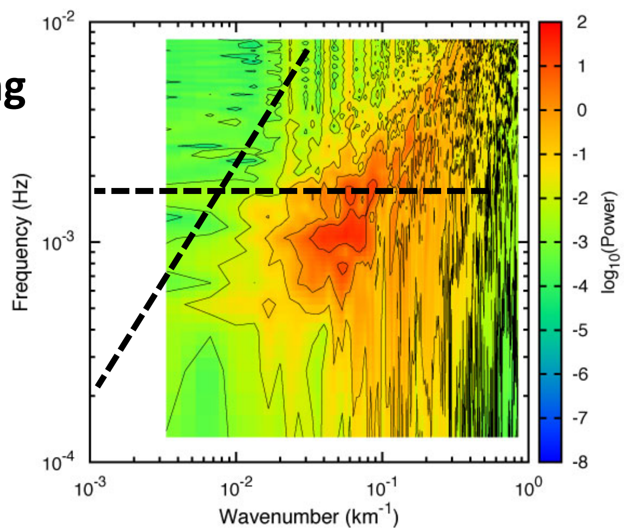
Peak heating rate = 20 K/h **2 K/h**

Width of heating region = 60 km





Width of heating region = 30 km



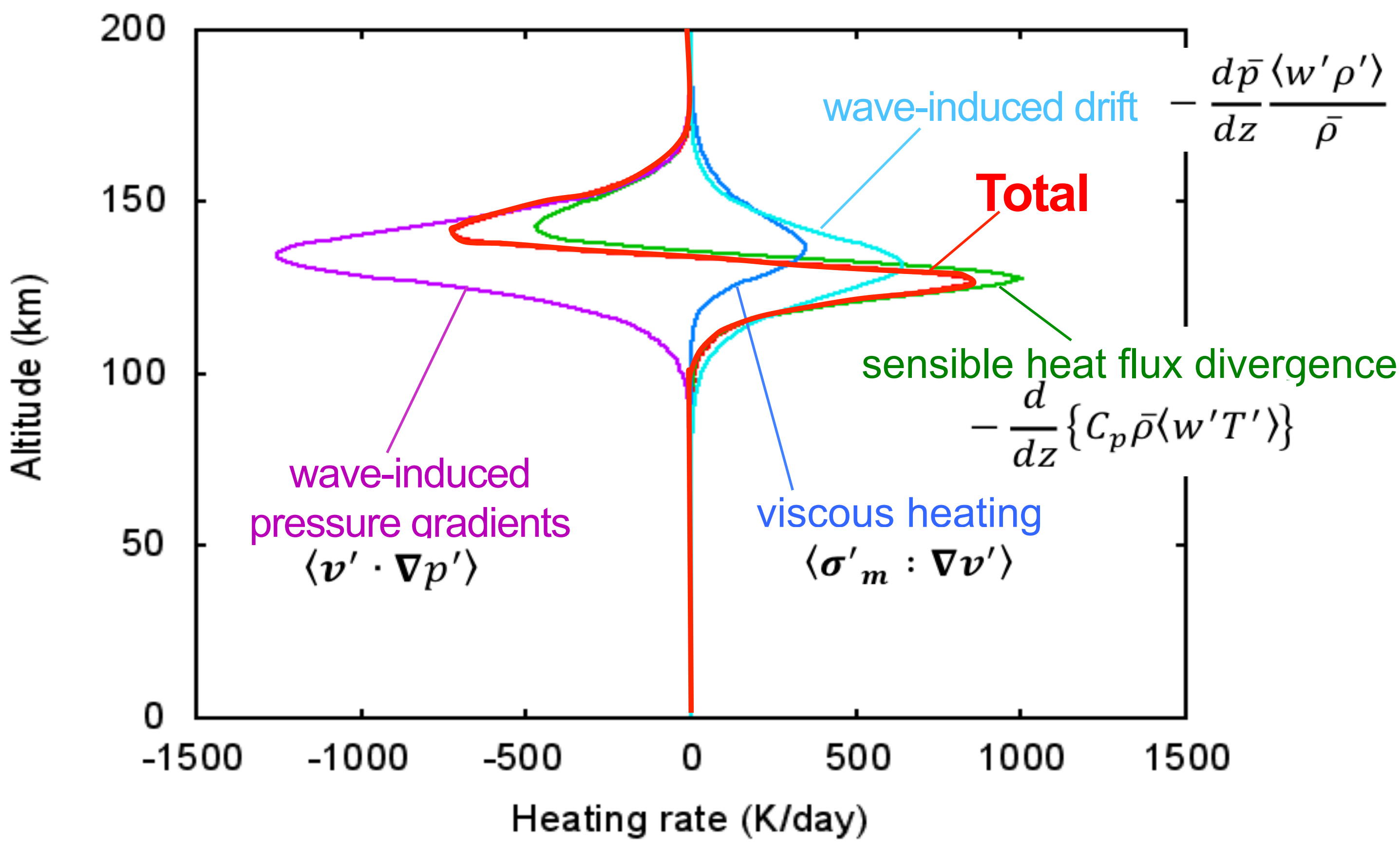
- Similar to the uniform heating model, but the contribution in a 3-D atmosphere should be much less.

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).

Heating rate

$$\bar{\rho} c_p Q = \langle \underline{\underline{\sigma}}'_m : \underline{\nabla}\, \underline{v}' \rangle - \frac{d}{dz}\{c_p \bar{\rho} \langle w' T' \rangle\} + \langle \underline{v}' \cdot \underline{\nabla} p' \rangle - \frac{d\bar{p}}{dz} \frac{\langle w' \rho' \rangle}{\bar{\rho}}$$



Finding the homopause

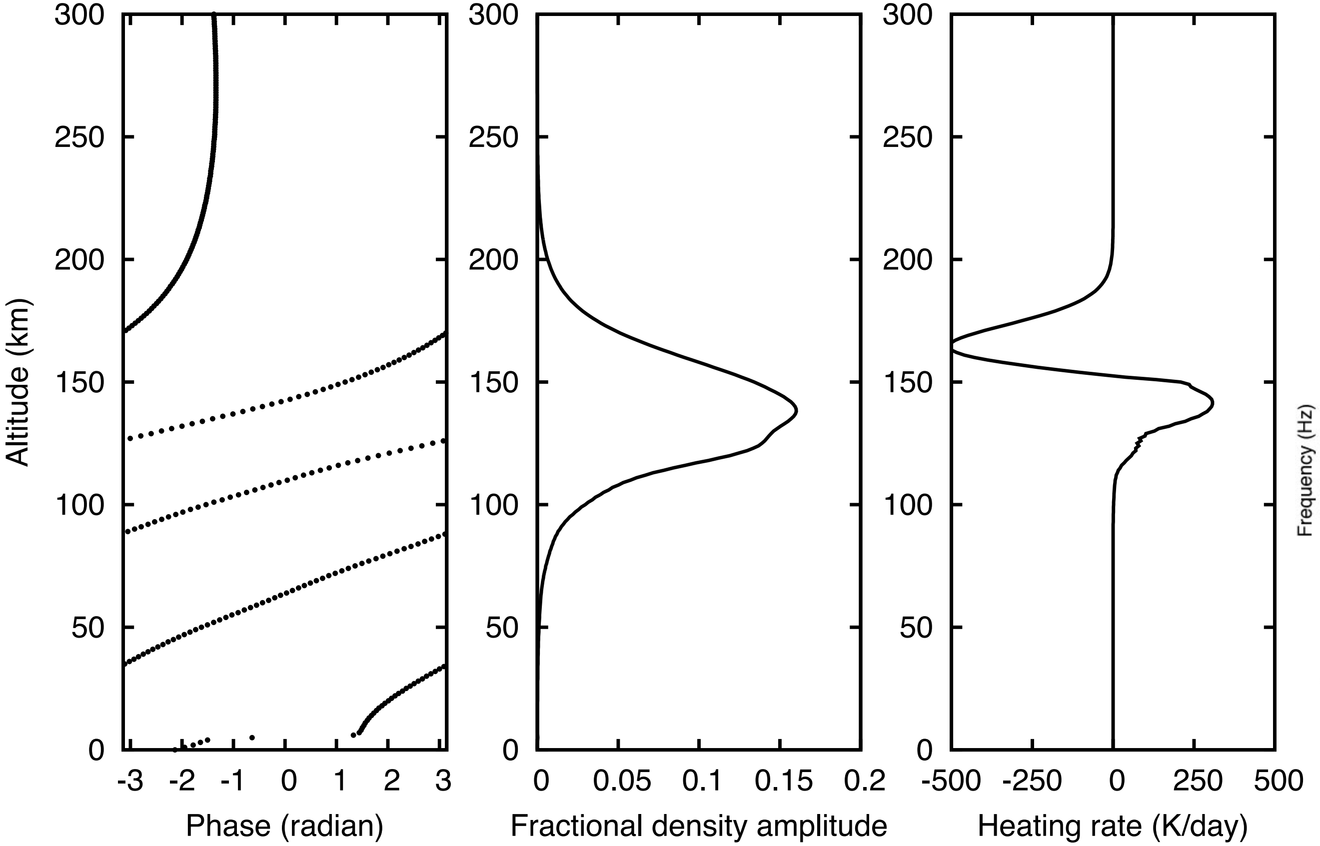
- Given a gravity wave saturated via convective breaking, the wave-induced turbulent diffusion coefficient is given by (Lindzen 1981)

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

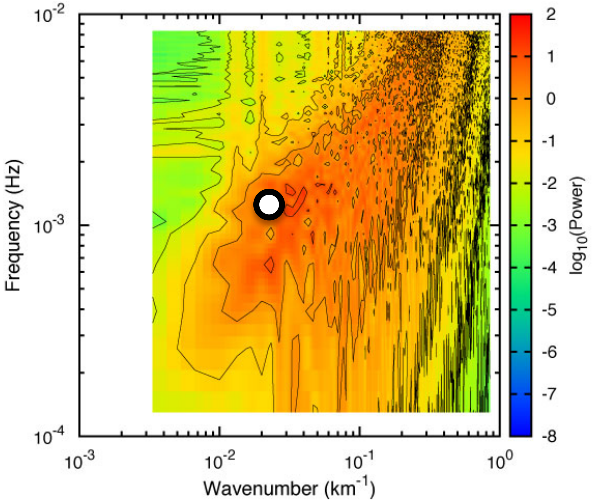
- where *k* is the horizontal wavenumber, *c* is the horizontal phase velocity, *H* is the scale height, and *N* is the buoyancy frequency.
- The efficiency parameter γ, which was not included in Lindzen's (1981) original formulation, accounts for the spatially and temporally localized character of the 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

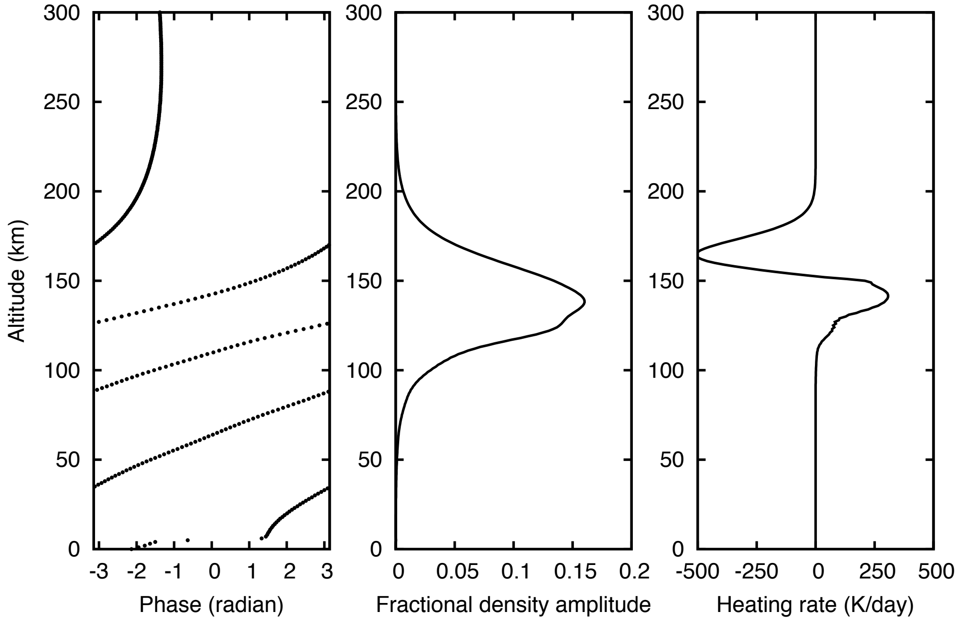


Uniform heating model with nominal heating rate



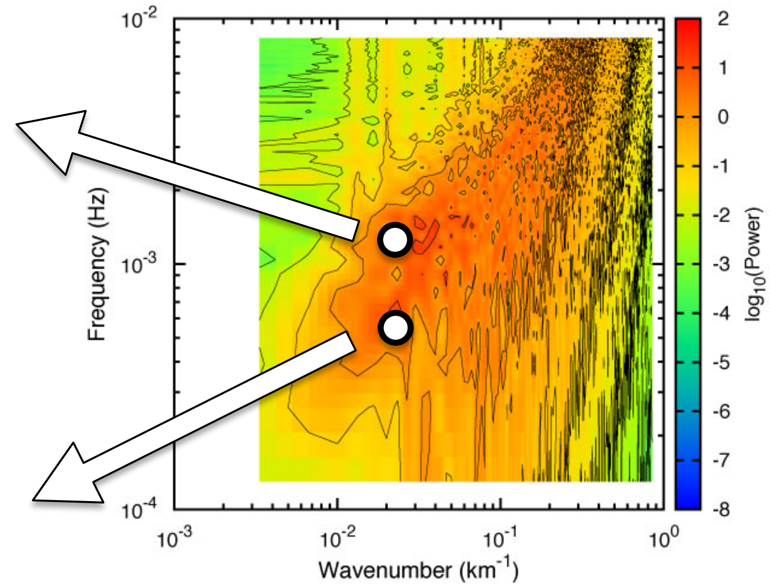
The amplitude seen in the convection model is 10 times larger than that required for saturation. → Amplitude in the thermosphere is determined by saturation at lower altitudes.

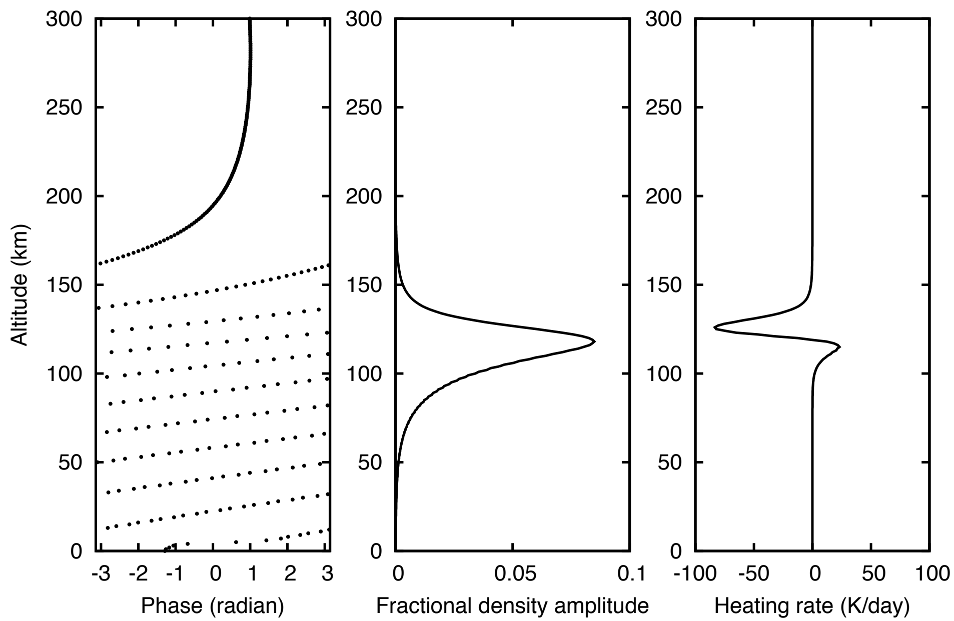
Turbopause height is calculated to be 132 km



horizontal wavelength = 50 km
period = 900 s

→Turbopause height= 132 km

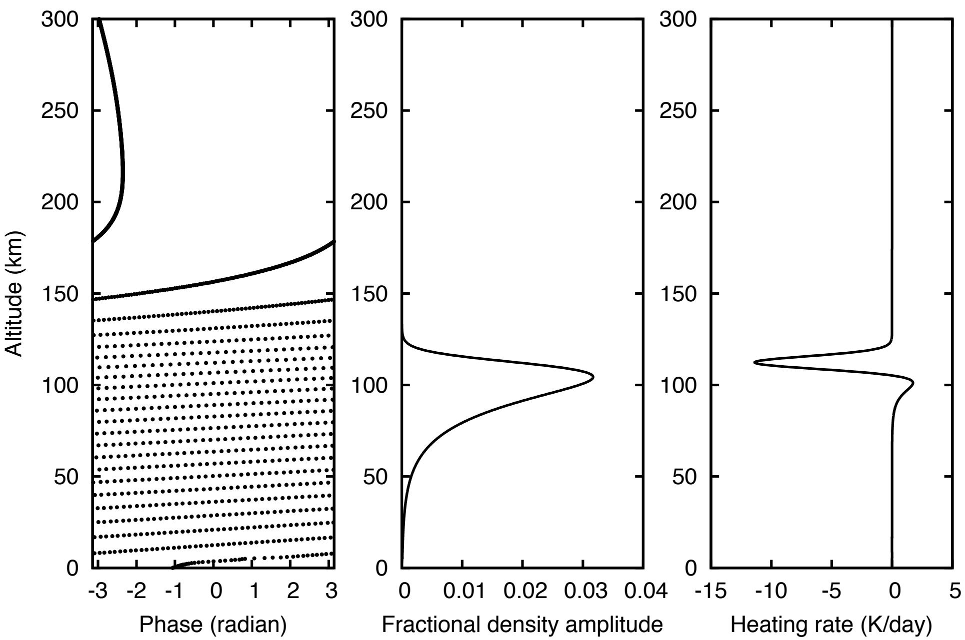




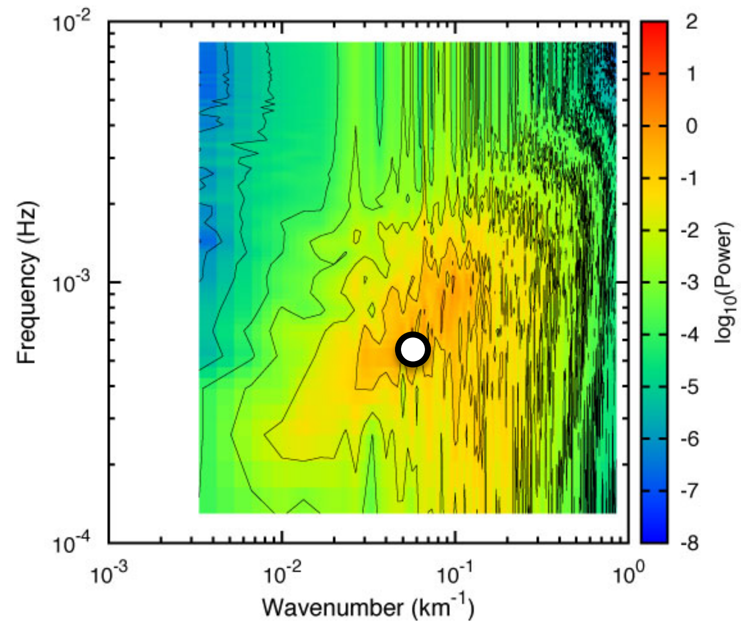
horizontal wavelength = 50 km
period = 2000 s

→Turbopause height= 110 km

Waves in weaker heating case



Uniform heating model with 10% heating rate



horizontal wavelength = 20 km
period = 2000 s

→Turbopause height= 93 km

Medvedev et al. (2011)

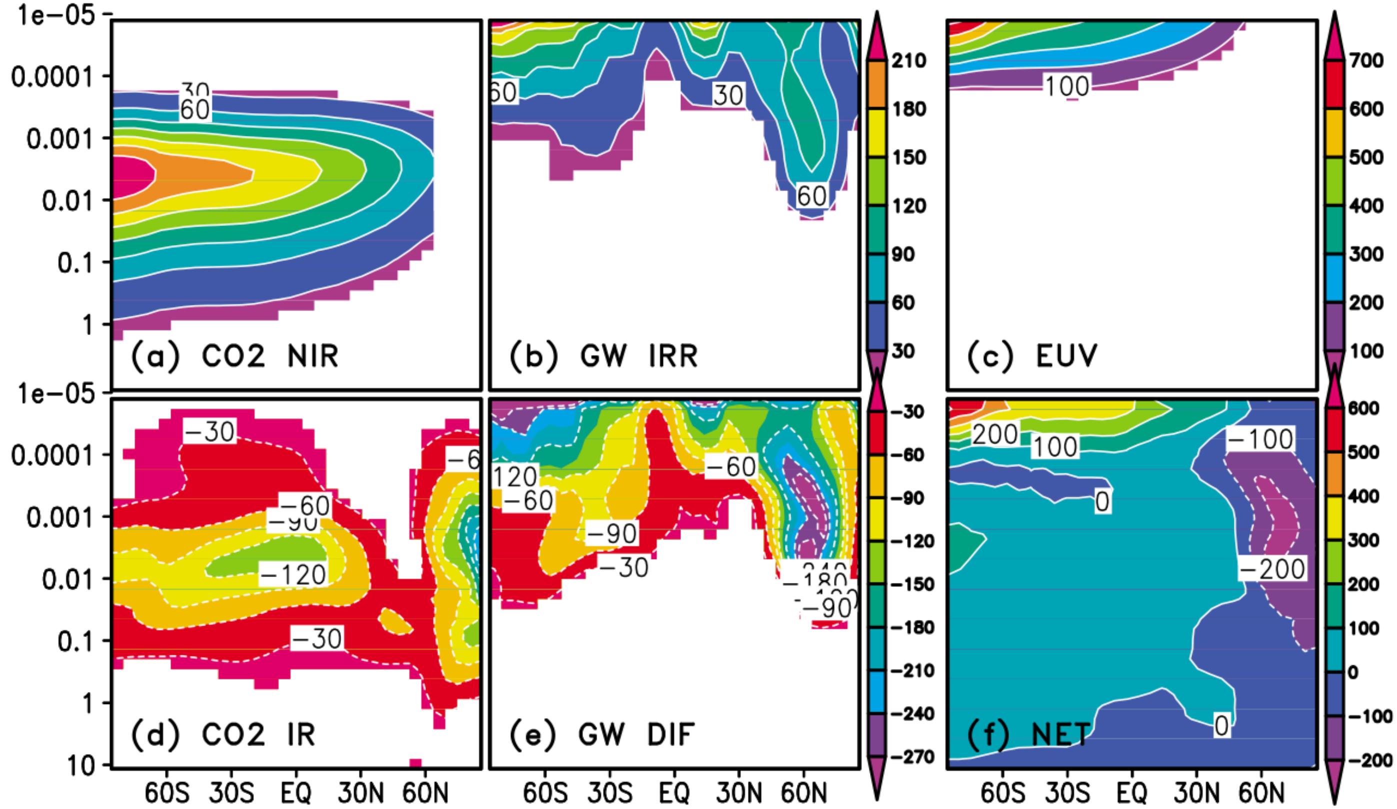


Figure 3. Zonal mean heating and cooling rates (in K sol^{-1}) due to various physical mechanisms: (a) radiative heating by near-IR CO_2 bands; (b) irreversible GW heating; (c) EUV heating by CO_2 molecules; (d) cooling by 15-m bands; (e) differential heating and cooling by GWs; (f) net heating and cooling rates.

Limitation of 2-D modeling

- The dominant horizontal wavelength (tens of kilometers) and the period (tens of minutes) are determined by the basic characteristics of convection, which would be largely unchanged in the three-dimensional atmosphere.
- The amplitude in the thermosphere is limited by saturation in most of the cases. Once saturated, the result in the altitude region where molecular diffusion dominates does not depend on the source strength.
- Considering these points, the conclusions drawn from the current 2-D model are expected to be largely unchanged in a 3-D atmosphere.

  (Of course, 3-D modeling is indispensable for determining the realistic source spectrum and the wave amplitude over all altitudes. Nonlinear cascade in convection should generate other spatial scales and resultant other wave modes.)

Summary

- Generation of fast gravity waves by intense convection due to low atmospheric density was suggested. Such waves are potentially important in the upper atmosphere due to less damping.
- The suggested amplitudes of atmospheric density are consistent with the observations during aerobraking of Mars orbiters.
- Convectively-generated waves seem to explain the observed homopause height, although other dynamical processes can also contribute.
- The heating and cooling caused by the gravity waves can be significant in the lower thermosphere.
- The suggested fast waves have vertical wavelengths of several tens of kilometers, and thus they are difficult to be detected in vertical profiles of temperature and winds.