火星の対流励起重力波の加熱強制パラメータへの依存性
Forcing parameter dependence of convectively-generated gravity waves on Mars

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1. Introduction

Gravity waves that are generated in the troposphere and propagate to the upper atmosphere are considered to play key roles in the momentum and energy transport and turbulence generation in the Martian atmosphere. Here we investigate convective generation of gravity waves using a nonlinear 2-D model and study the dependence of the wave characteristics on the parameters of the thermal forcing that initiates convection.

2. Two-dimensional convection model

Two types of thermal forcing distributions are tested: ‘localized heating’ representing a local dust storm, and ‘uniform heating’ representing boundary-layer convection. The model used is CReSS (Cloud Resolving Storm Simulator) version 2.3. The model parameters are given in Table 1. In the initial state the temperature is a function of altitude only as shown in Fig. 1 and the atmosphere is at rest. The bottom 5 km is neutrally stable considering convection occurring in this region.

Table 1: Model parameters

Dynamics	CReSS (Cloud Resolving Storm Simulator) 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

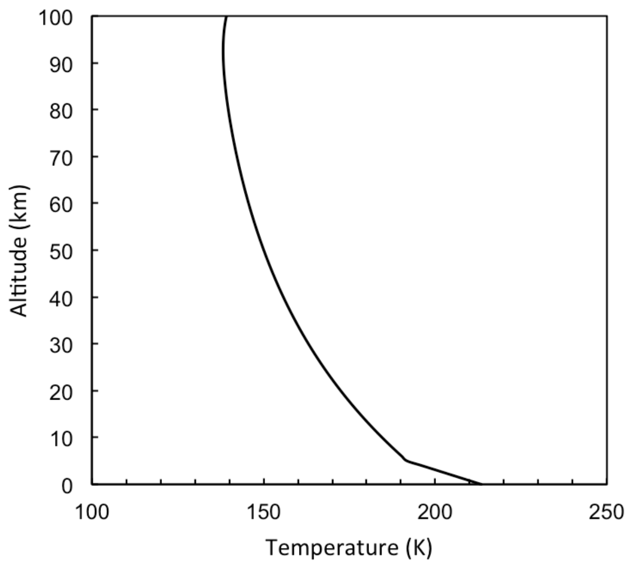

Fig. 1: Initial temperature profile

2.1 Localized heating

Based on the paper by Spiga et al. (JGR, 2013), who studied localized convection forced by solar heating of a dust cloud located near the surface using a three-dimensional regional model, a thermal forcing localized both in space (60 km x 3 km) and time (120 minutes) with the peak heating rate of 20 K/h is given as shown in Fig. 2.

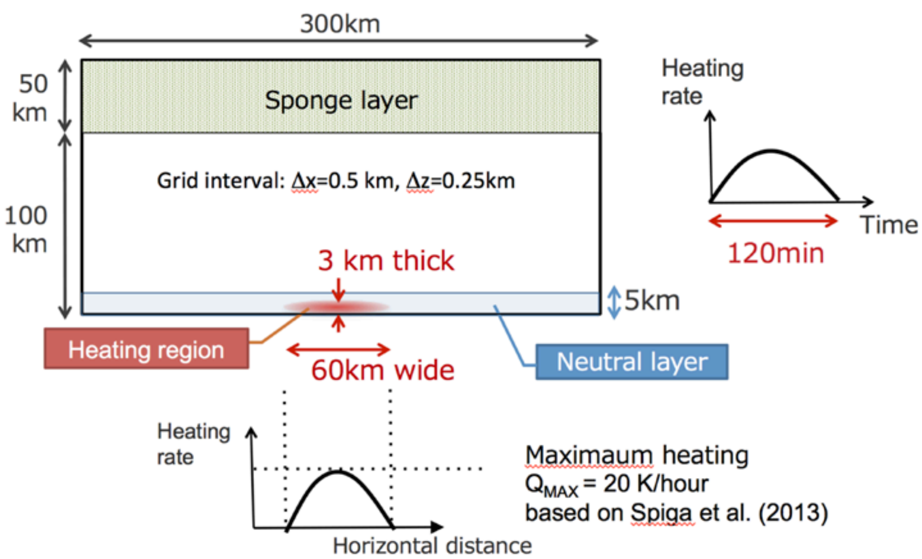

Fig. 2: Schematic of the localized heating experiment

The thermal forcing initiates upward motion of a plume near the surface, and the penetration of the plume into the overlying statistically-stable layer generates gravity waves. The plume develops into smaller convection cells with time, and these cells also generate gravity waves. The wind speed in the convection reaches ~20 m s^{-1}. Snapshots of the vertical velocity field and the temperature perturbation field around the time where the amplitude of gravity waves in the upper part of the physical domain (50-100 km) reaches maximum are given in Fig. 3.

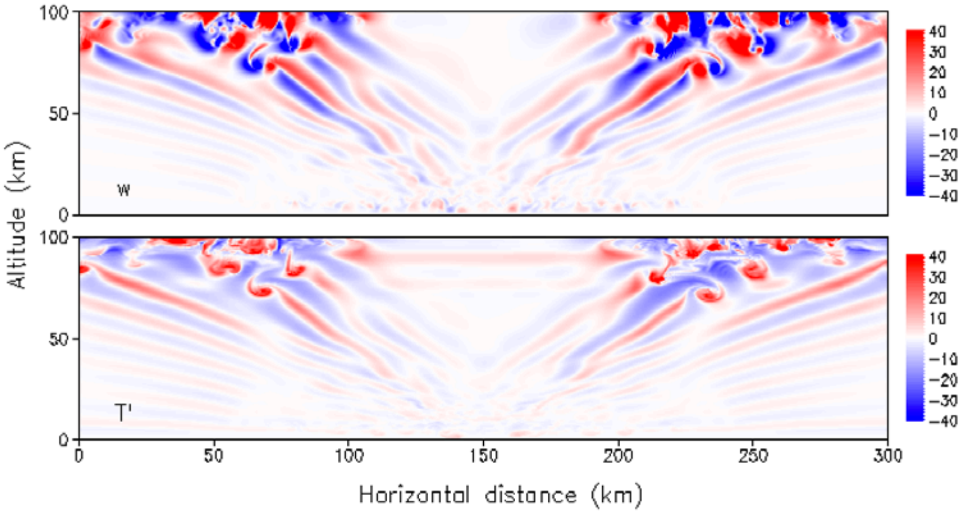

Fig. 3: Distribution of the vertical velocity (upper) and the temperature perturbation (lower) at 180 minutes in the nominal run of the localized forcing experiment.

The two-dimensional spectrum of the vertical velocity at 60 km altitude in the time interval of 120-248 minutes is shown in Fig. 4. The dominant wavenumber is 0.02-0.07 km^{-1} (wavelength ~ 15-50 km) and the dominant frequency is (0.6-2) x 10^{-3} Hz (period ~ 500-1600 s). These spatial and temporal scales are near the width of convection cells and the overturning time of convection, respectively.

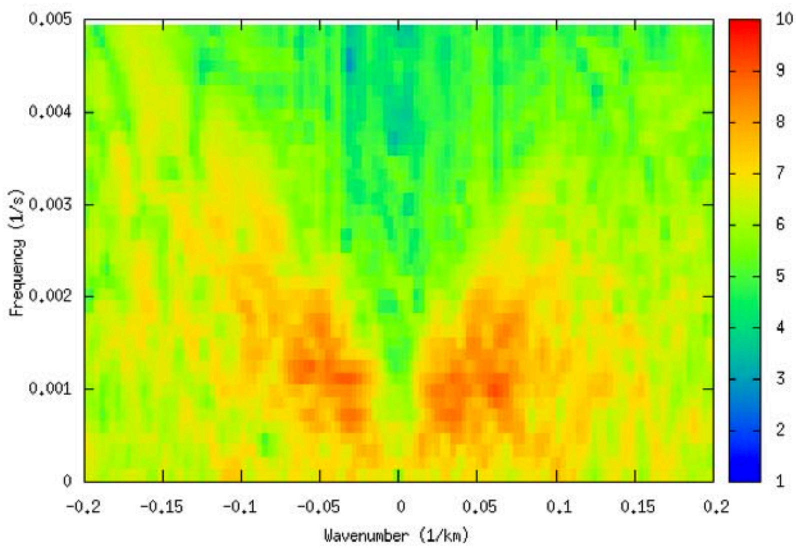

Fig. 4: Two-dimensional spectrum of the vertical velocity at 60 km altitude in the nominal run of the localized forcing experiment. Colors represent $\log_{10}$ of the spectral density in relative scale.

A test run with a 10 times weaker forcing, i.e. the peak heating rate of 2 K/h, was conducted to investigate the dependence on the forcing strength. In this case the convection and gravity waves develop more slowly, the waves propagate in more oblique directions, and the wave amplitude reaches maximum around 360 minutes. Snapshot are shown in Fig. 5, indicating that shorter wavelength waves are generated in more oblique directions. The two-dimensional spectrum at 60 km altitude for the time interval of 300-428 minutes is shown in Fig. 6, indicating that the dominant wavenumber is now 0.05-0.13 km^{-1} (wavelength ~ 8-20 km) and the dominant frequency is (0.5-1) x 10^{-3} Hz (period ~ 1000-2000 s). The shorter horizontal wavelength than the nominal run is attributed to the smaller scales of convective cells: the typical height of the cells is ~8 km in the nominal run and ~5 km in the weak forcing run, and the horizontal scale of the cells is approximately twice the height in both cases. The lower frequency than the nominal run is attributed to the slower motions in the convection.

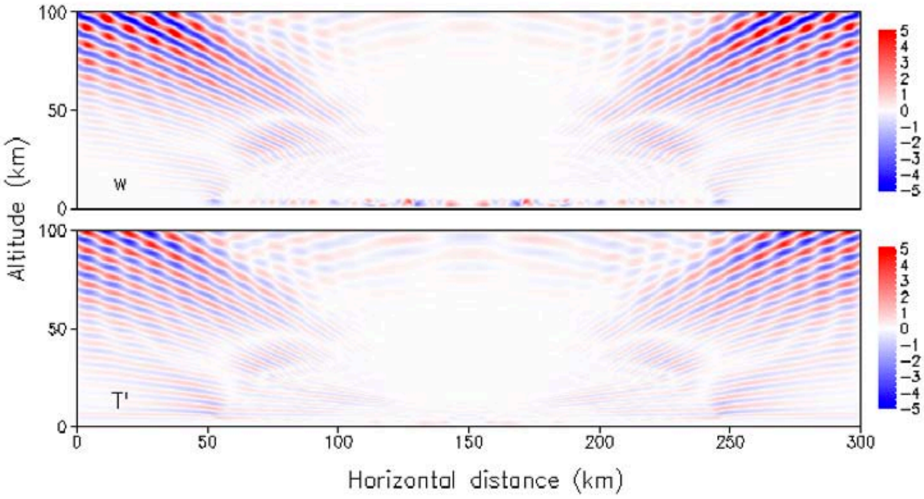

Fig. 5: Same as Fig. 3, but at 360 minutes in the 10 times smaller heating rate case of the localized heating experiment.

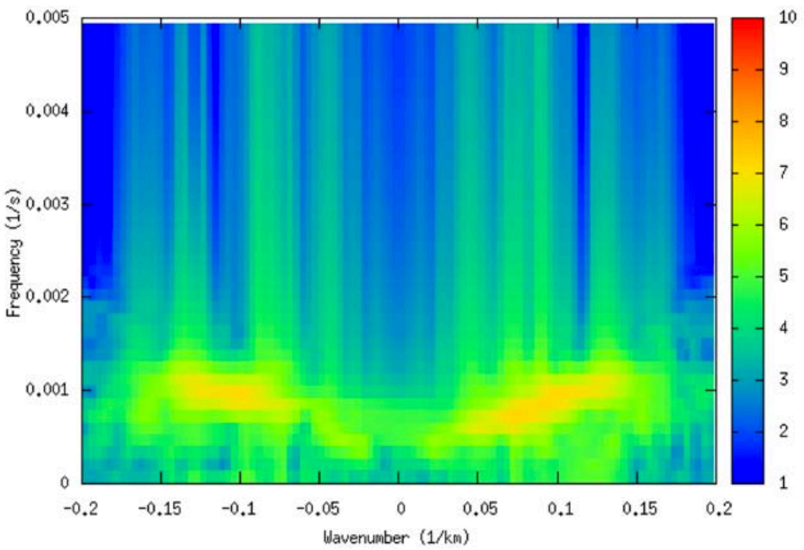

Fig. 6: Same as Fig. 4, but in the 10 times smaller heating rate case of the localized heating experiment.

The sensitivity to the horizontal scale of the forcing is studied by changing the width of the heating to 30 km and 120 km. The results are shown in Figs. 7-10. It is suggested that the wavelength and the frequency are largely unchanged, although there is a tendency that the horizontal extent of the wave packet at each altitude increases with increasing the horizontal scale of the heating. This is explained by the temporal development the plume: convective cells with horizontal scales of 10-20 km always develop irrespective of the horizontal scale of the heating, and they generate gravity waves having similar scales.

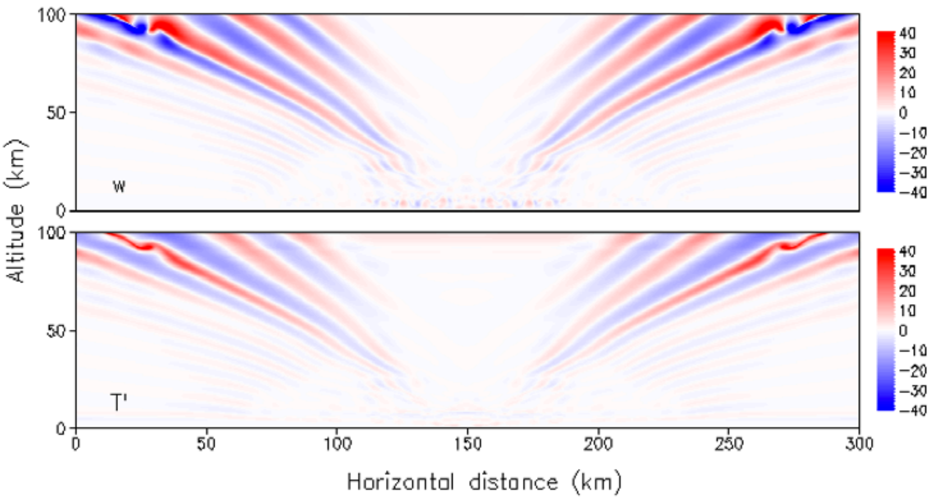

Fig. 7: Same as Fig. 3, but in the test run with the forcing width of 30 km.

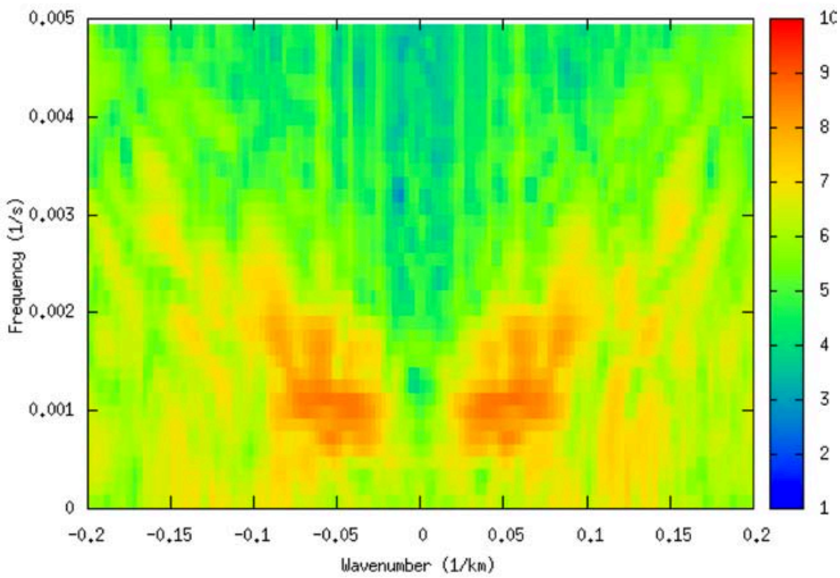

Fig. 8: Same as Fig. 4, but in the test run with the forcing width of 30 km.

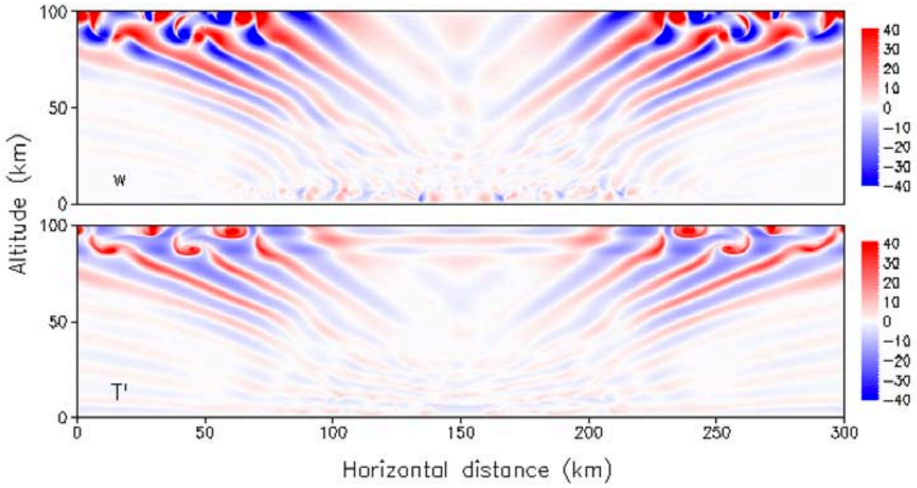

Fig. 9: Same as Fig. 3, but in the test run with the forcing width of 120 km.

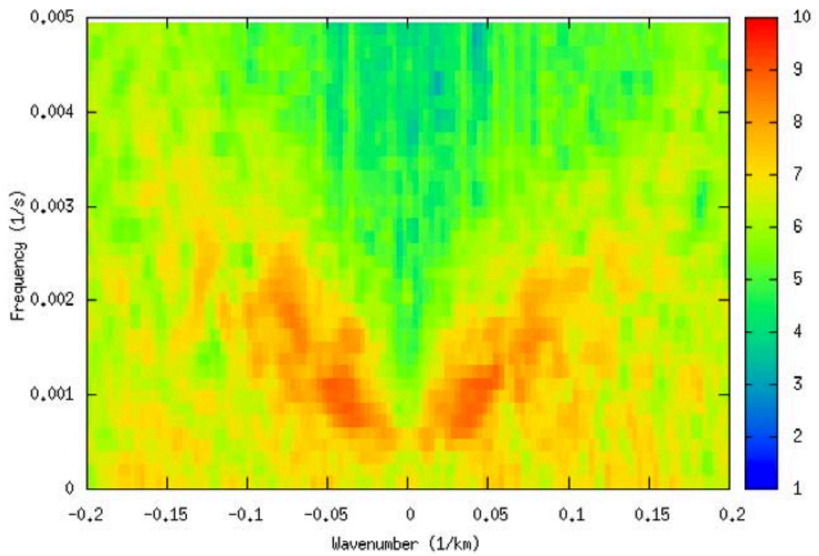

Fig. 10: Same as Fig. 4, but in the test run with the forcing width of 120 km.

2.2 Uniform heating

In the uniform heating experiment, a steady heating rate of 40 K/h is given in the bottom layer (0.25 km thickness) as illustrated in Fig. 11. The heating rate was chosen so that the energy to be lost through radiative cooling with a rate of 50 K/day during night in the 5 km-thick boundary layer (Heberle et al., JAS, 1993) is replenished by the heating of the bottom layer during daytime.

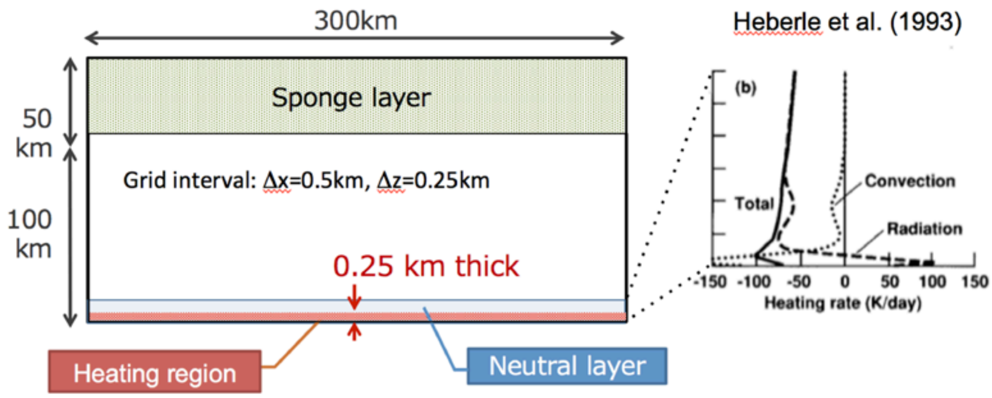

Fig. 11: Schematic of the localized heating experiment

The thermal forcing initiates convection below ~7 km, and the penetration of the plume into the overlying stable layer generates gravity waves as shown in Fig. 12. The strengths of convection and gravity waves reach quasi-steady states around 180 minutes. The wind speed in the convection reaches ~20 m s^{-1}.

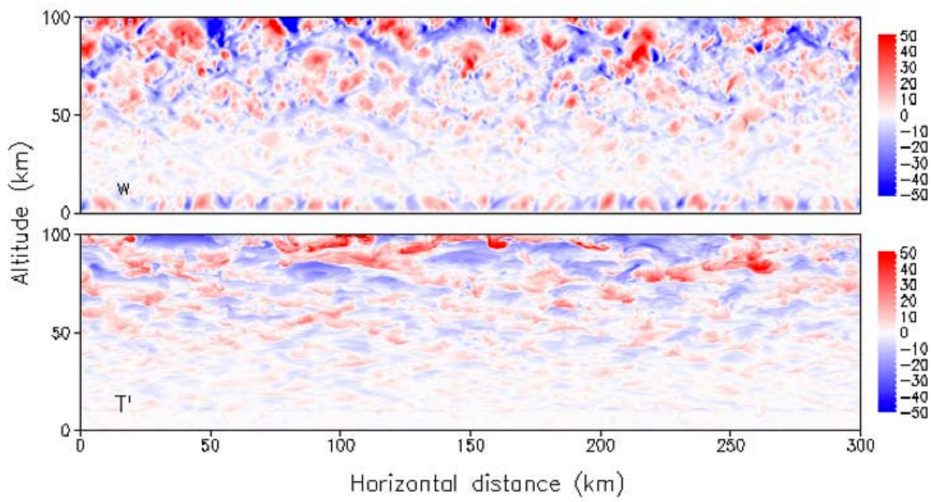

Fig. 12: Same as Fig. 3, but at 240 minutes in the uniform heating experiment.

The two-dimensional spectrum of the vertical velocity at 60 km altitude in the time interval of 180-308 minutes is shown in Fig. 13. The dominant wavenumber is 0.005-0.05 km^{-1} (wavelength ~ 20-200 km) and the dominant frequency is (0.2-1.6) x 10^{-3} Hz (period ~ 600-5000 s).

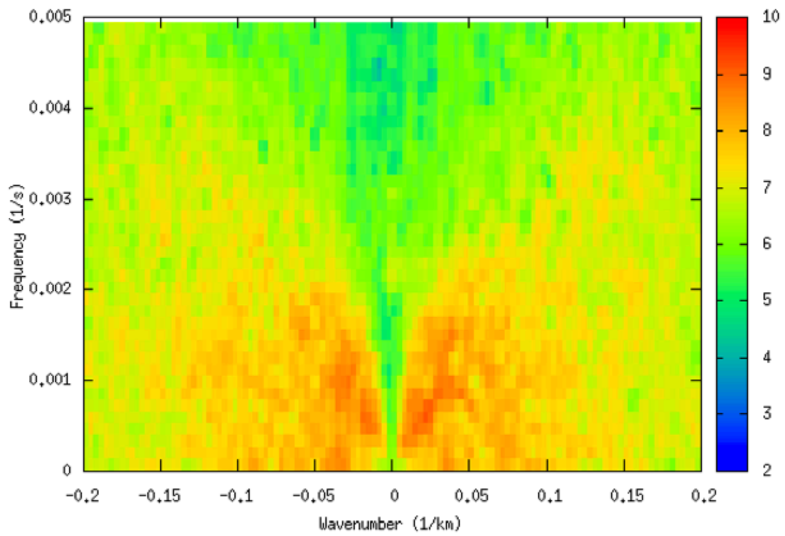

Fig. 13: Same as Fig. 4, but in the uniform heating experiment.

A test run with a 10 times weaker forcing, i.e. the heating rate in the bottom layer of 4 K/h, was conducted to investigate the dependence on the forcing strength. In this case the convection and gravity waves develop more slowly, and reach quasi-steady states around 400 minutes. A snapshot is shown in Fig. 14, indicating shorter vertical wavelengths of gravity waves. The two-dimensional spectrum at 60 km altitude for the time interval of 360-488 minutes is shown in Fig. 15, indicating that the dominant wavenumber is 0.005-0.1 km^{-1} (wavelength ~ 10-200 km) and the dominant frequency is (0.2-0.8) x 10^{-3} Hz (period ~ 1200-5000 s). The shorter horizontal wavelength than the nominal run is attributed to the smaller scales of convective cells, and the lower frequency than the nominal run is attributed to the slower motions in the convection.

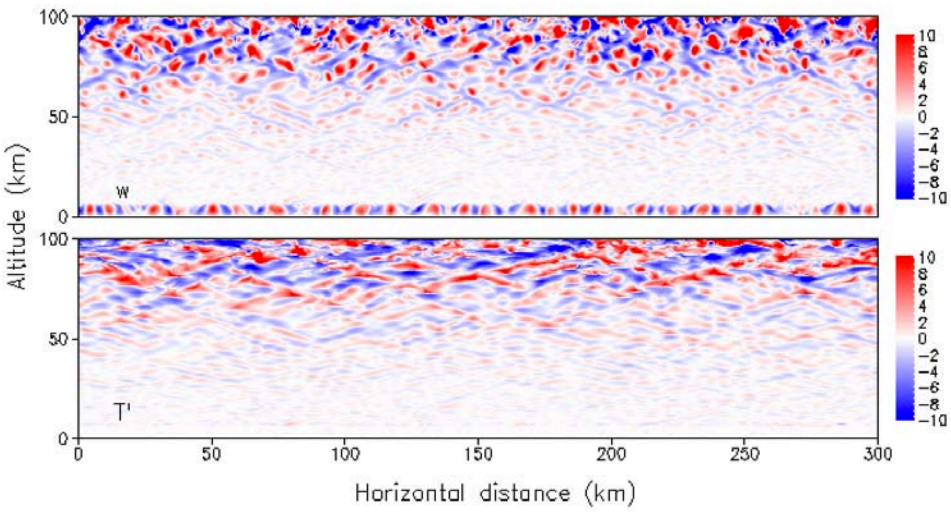

Fig. 14: Same as Fig. 12, but at 420 minutes in the 10 times smaller heating rate case of the uniform heating experiment.

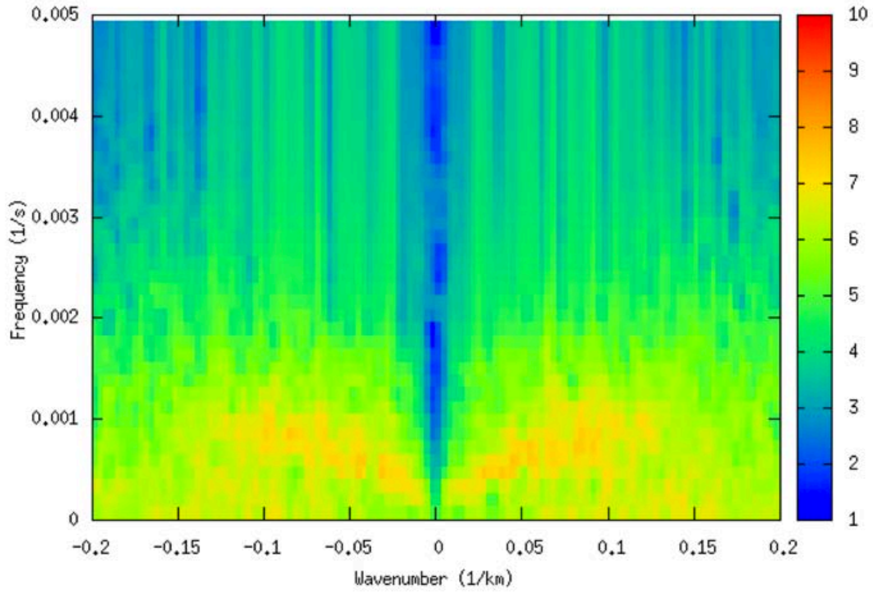

Fig. 15: Same as Fig. 13, but in the 10 times smaller heating rate case of the uniform heating experiment.

3. Summary

The model results suggest that high-frequency (near buoyancy frequency) gravity waves can be predominantly generated by convection during daytime on Mars. Such waves are relatively unaffected by radiative damping and molecular viscosity, and thus they are potentially important in the energy/momentum balance and turbulence generation in the upper atmosphere. Both in the local heating and the uniform heating experiments, there is a clear tendency that the dominant frequency is higher for larger heating rates. This tendency suggests that the low density of the Martian atmosphere, which leads to large heating rates, sustains high-frequency gravity waves. The large amplitudes of Martian graity waves observed in the lower thermosphere by spacecraft drag experiments (Fritts et al., JGR, 2006) might be attributed to such high frequencies. The horizontal wavelength is relatively unchanged in the sensitivity tests probably because the wavelength is largely determined by the spatial scale of the convection, which is limited by the depth of the prescribed neutral stability layer and largely unaffected by the heating function.