Anomalous solar heating dependence of Venus's cloud-level convection

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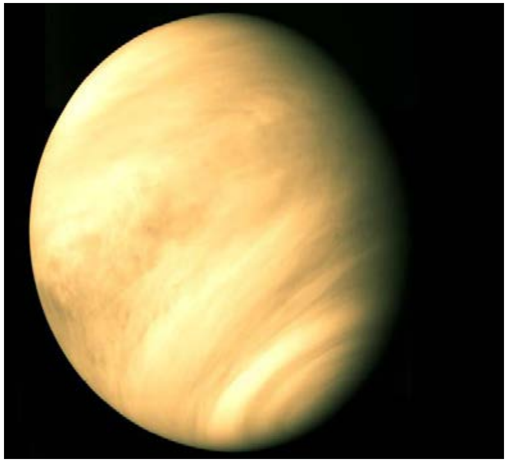
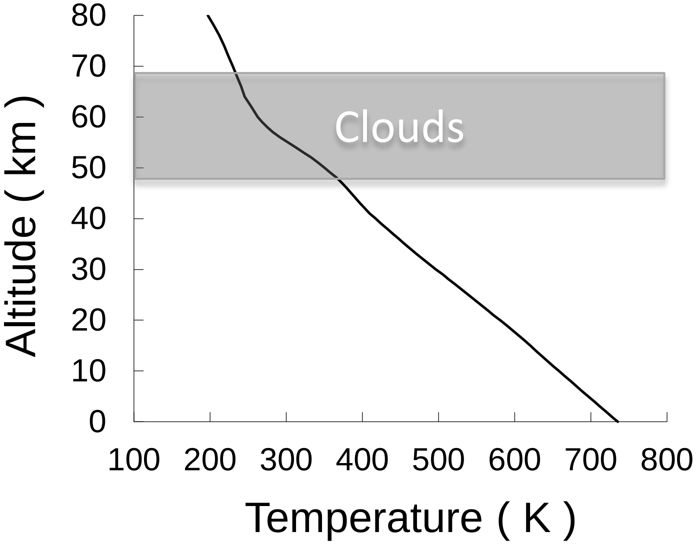
Clouds on Venus



Ultraviolet image of Venus taken from Pioneer Venus

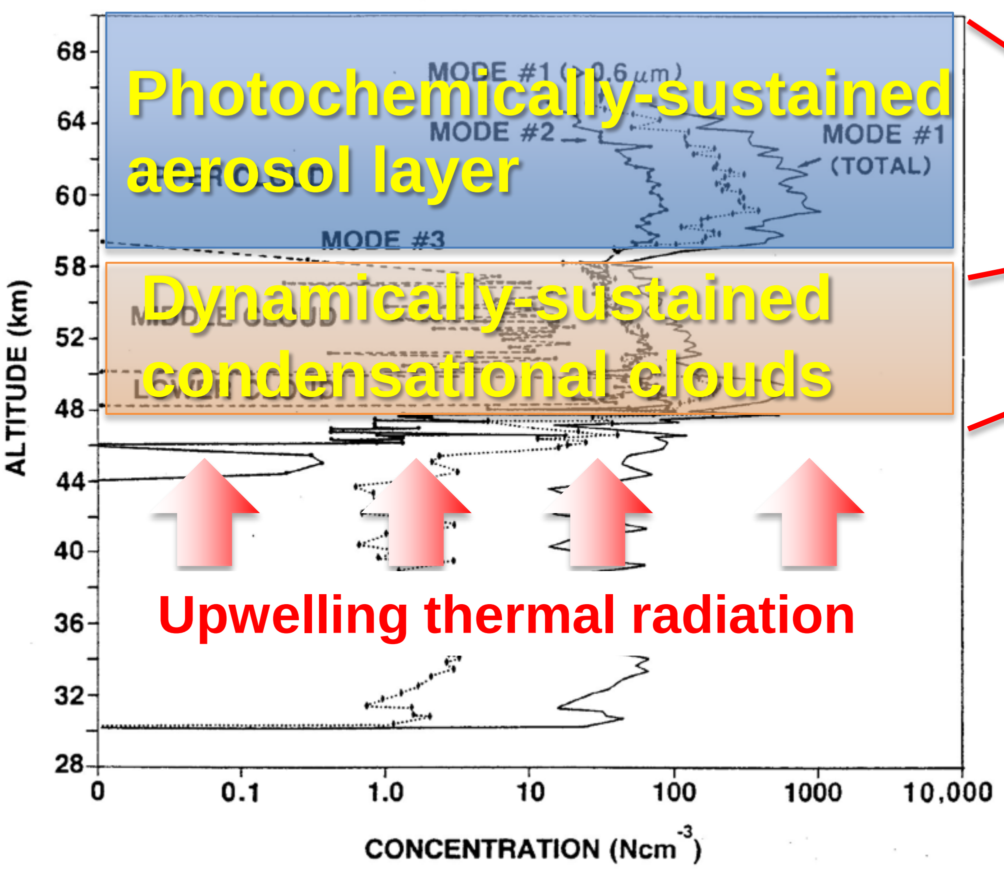
- Venus is covered by clouds of H_2SO_4-H_2O which float in the altitude region from 48 to 70 km.

- The clouds play a major role via reflection of sunlight (albedo of 0.78) and absorption of upwelling thermal radiation.



Vertical temperature distribution of the Venus atmosphere

Vertical structure



Photochemically-sustained aerosol layer

Dynamically-sustained condensational clouds

Upwelling thermal radiation

Pioneer Venus LCPS
(Knollenberg and Hunten, 1980)

Static stability measured by entry probes

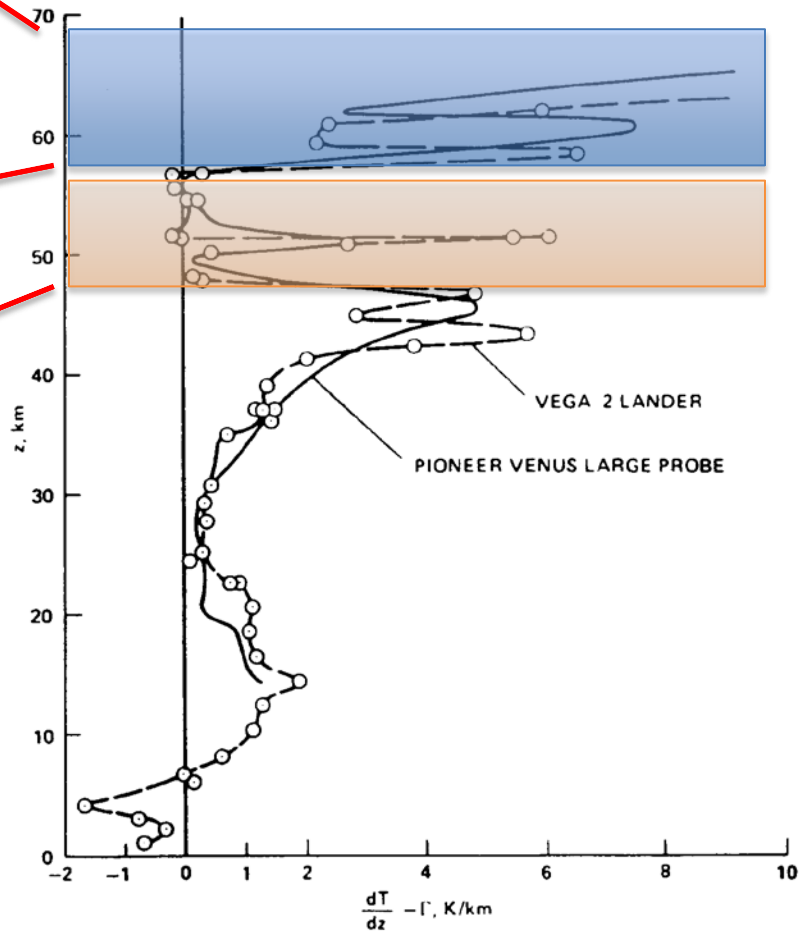
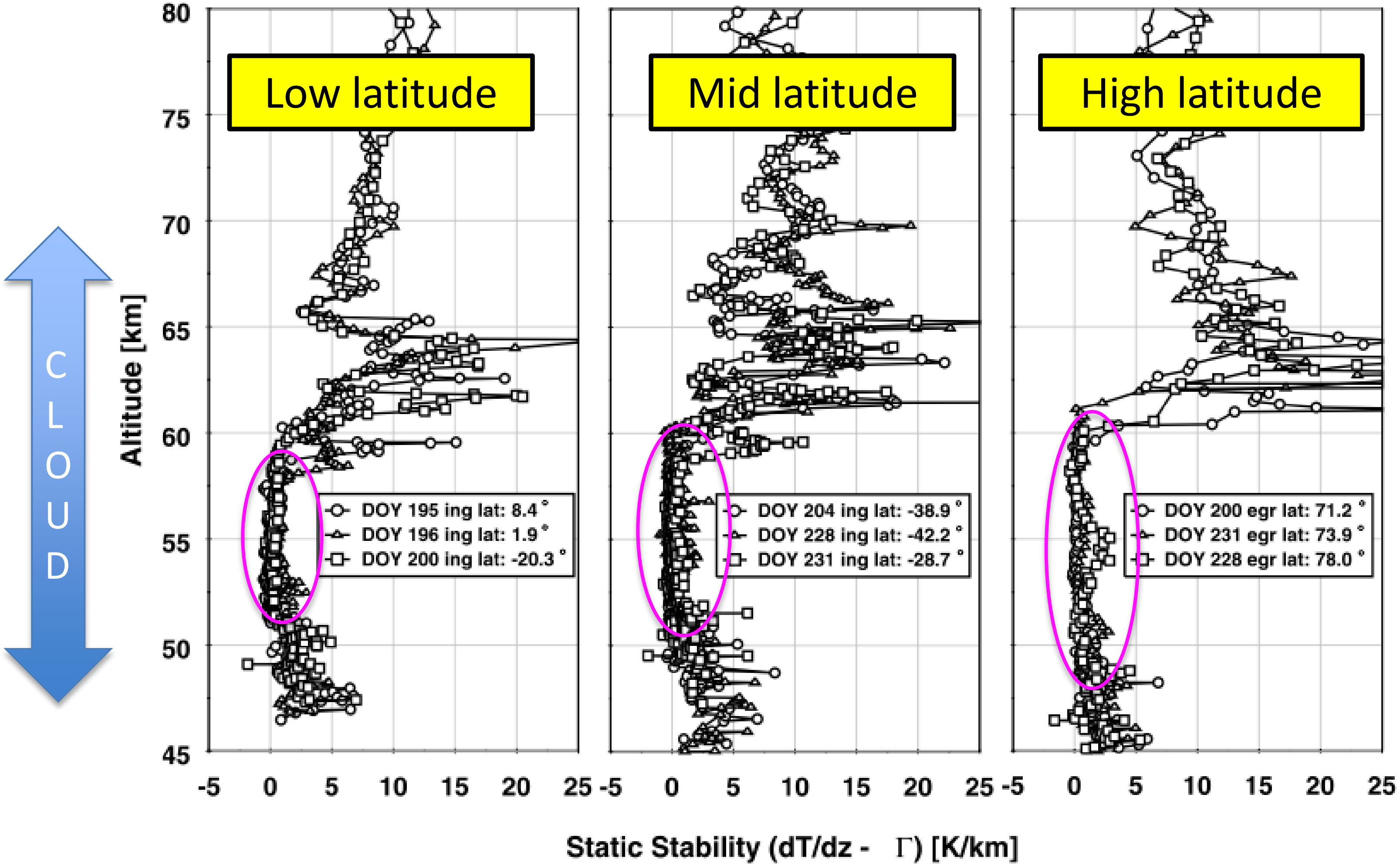


Figure 2. Static stability ($dT/dz - \Gamma$) of the Venus lower atmosphere from the Pioneer Venus sounder probe (solid) and the Vega-2 lander (⊙) (figure from Seiff et al. 1987).

Latitudinal variation

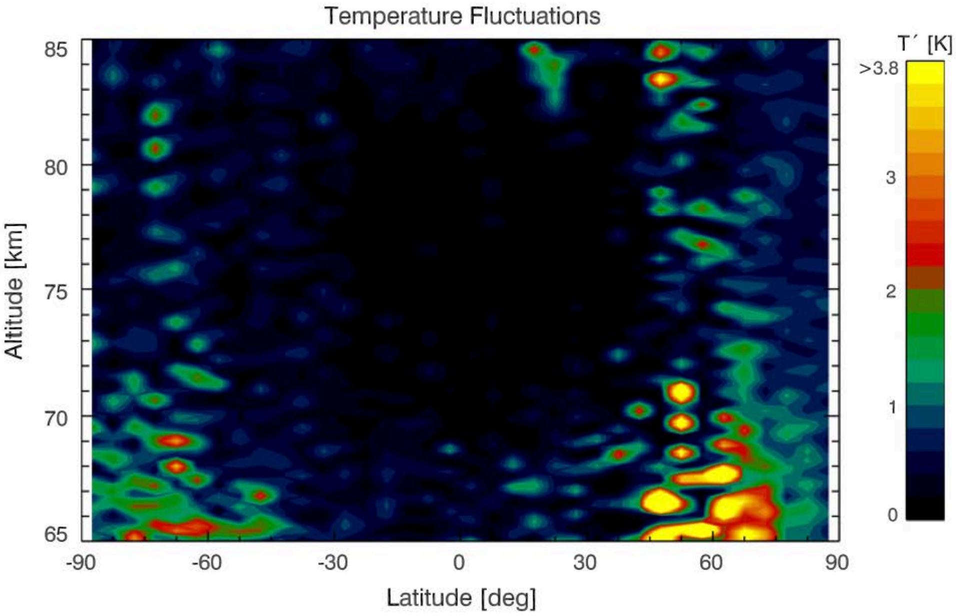
Static stability profiles obtained by radio occultation (Tellmann et al. 2009)



- The depth of convection layer increases with latitude.
  → More vigorous convection at higher latitudes ?

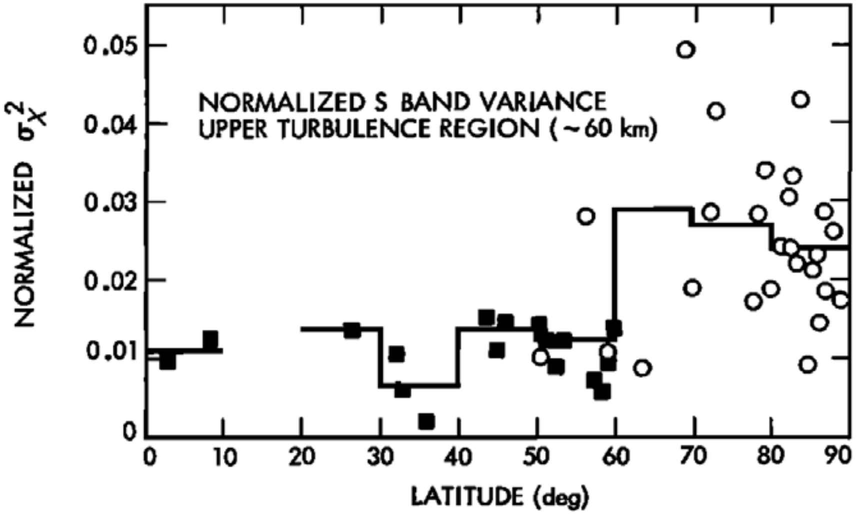
Latitudinal variation

Amplitude of small-scale temperature fluctuation deduced by radio occultation



Tellmann et al. (2012)

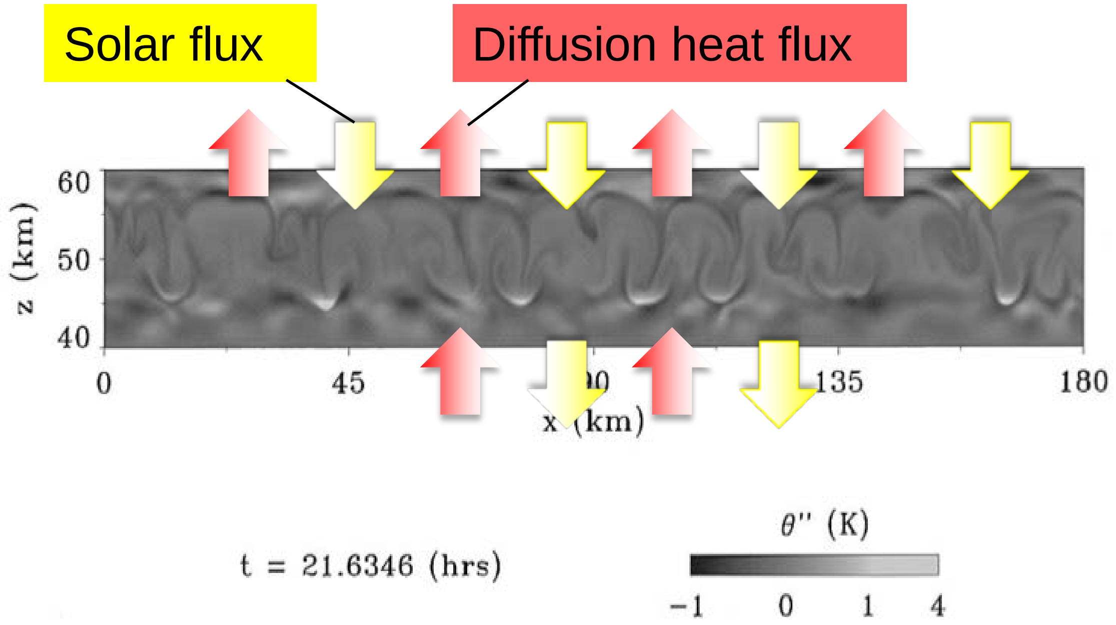
Variance of radio scintillation power observed during radio occultation



Woo et al. (1980)

- Amplitude of small-scale temperature/density fluctuation tends to be larger at higher latitudes. → More vigorous wave excitation at higher latitudes ?

2-D convection model (Baker, Schubert & Jones, 1998; 2000)

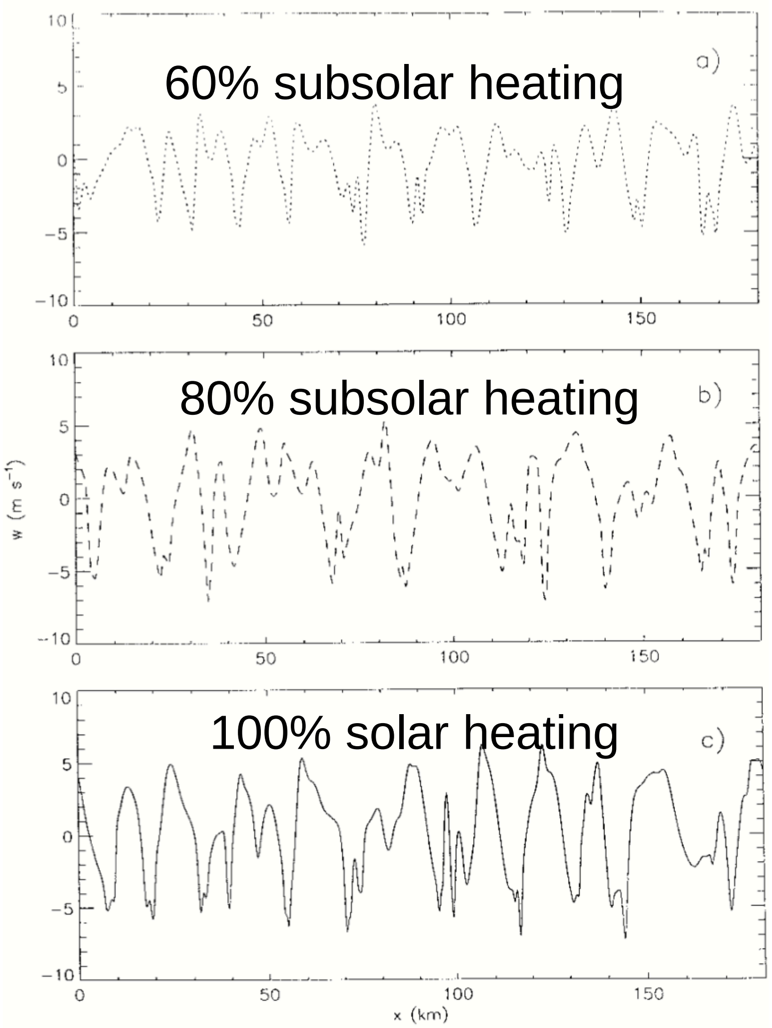


Solar flux

Diffusion heat flux

Baker et al. introduced upward eddy diffusion heat flux at the upper and lower boundaries to drive convection. The value of the eddy diffusion heat flux at the boundaries is equal to (but opposite in sign from) the solar heat flux at that altitude.

The results show more vigorous convection for stronger solar fluxes.



60% subsolar heating

80% subsolar heating

100% solar heating

FIG. 5. Vertical velocity at 54-km altitude as a function of horizontal position for (a) 60% subsolar heating, t = 15.0 h, (b) 80% subsolar heating, t = 24.1 h, and (c) 100% subsolar heating, t = 13.8 h. The velocities were sampled at times corresponding to peaks in the kinetic energy density.

Origin of the latitudinal dependences of convection depth and gravity wave activity

- Baker et al. argues occurrence of more vigorous convection at lower latitudes.

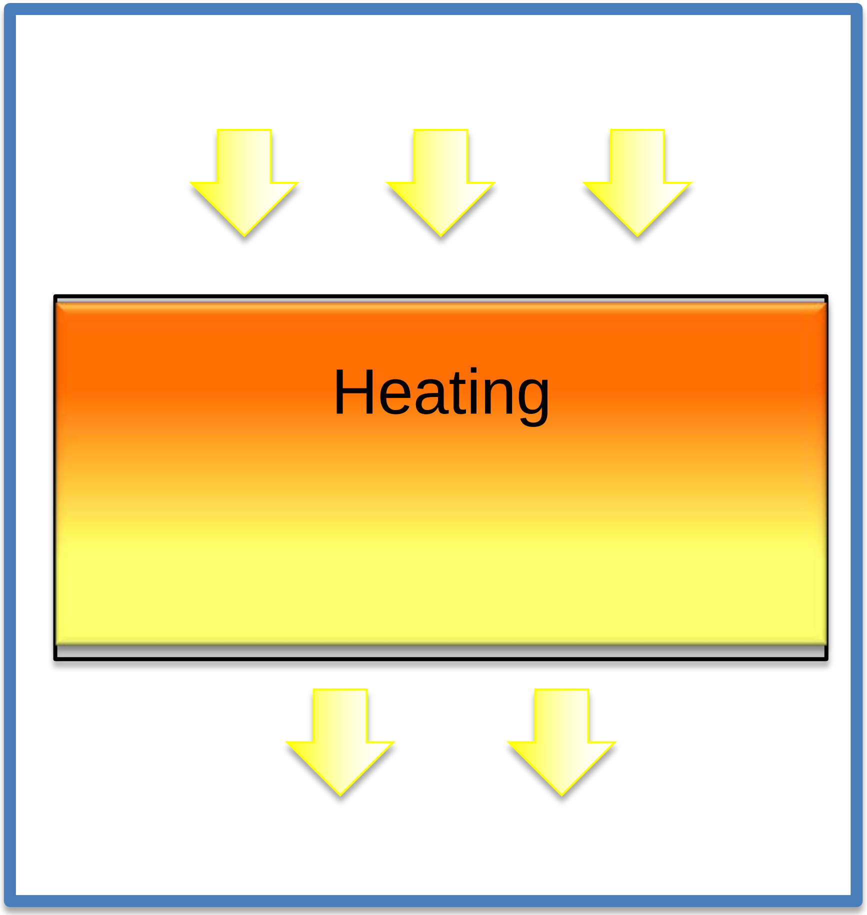
→ Gravity wave generation by other mechanisms ? (for example, fluctuation of high-latitude jets, shear instability, topographyically-generated waves)

→ How about the latitudinal variation of convection depth ?

- **Shoud convection be really stronger at lower latitudes ?** (This study)

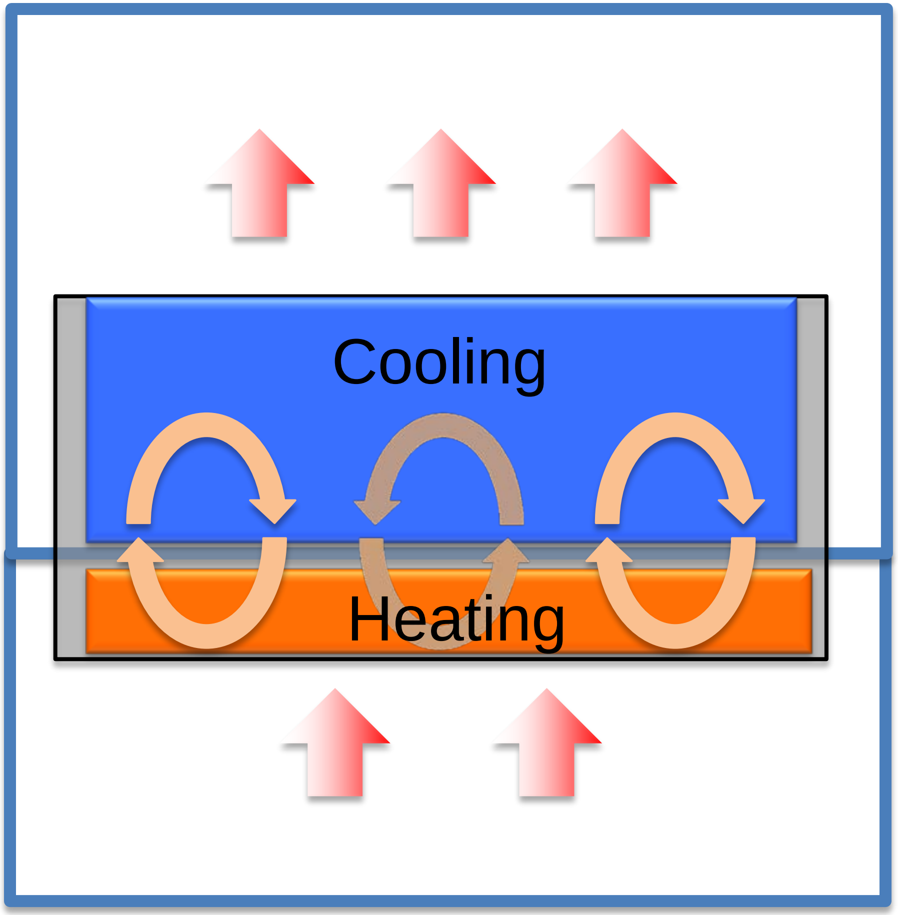
Energy input to the cloud layer

Shortwave heating



Heating

Longwave heating and cooling



Cooling

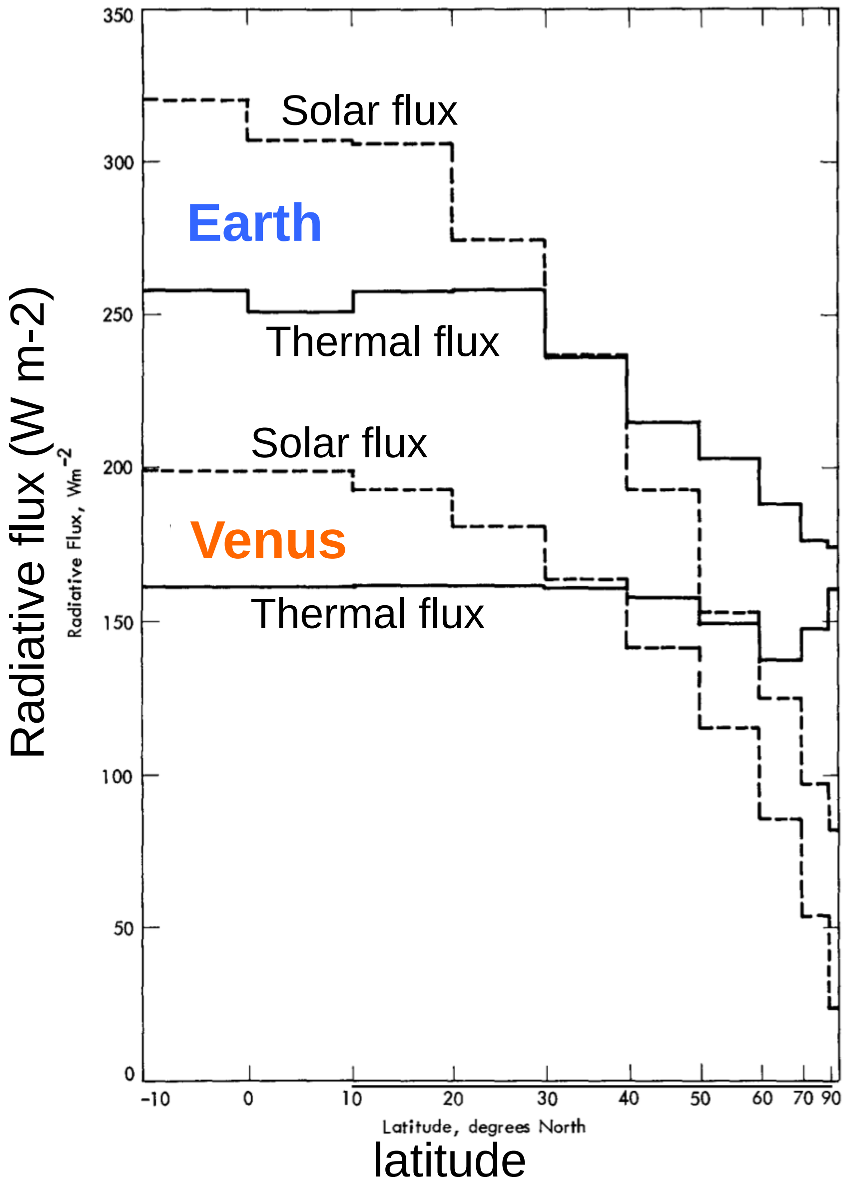
Heating

Statement in Baker et al. (2000)

“ Because solar heating is strongest at the top of the domain, one may initially conclude that absorption of solar radiation provides a stabilizing influence in Venus’s atmosphere. However, the Venus profile of solar heating actually provides a destabilizing influence on the atmosphere. Since the atmosphere behaves diffusively below 60-km altitude, negative potential temperature gradients are established to transfer the absorbed solar radiation. Larger values of solar heating result in steeper (more negative) potential temperature gradients, and convectively unstable regions are produced. The situation is somewhat analogous to a uniformly internally heated system in which convection occurs even though heating is uniformly distributed. “

→ However, this seems to be true only when the net heat flux is zero at the bottom boundary. This is not the case in the real atmosphere.

Latitude dependence of the zonally-averaged radiative energy flux

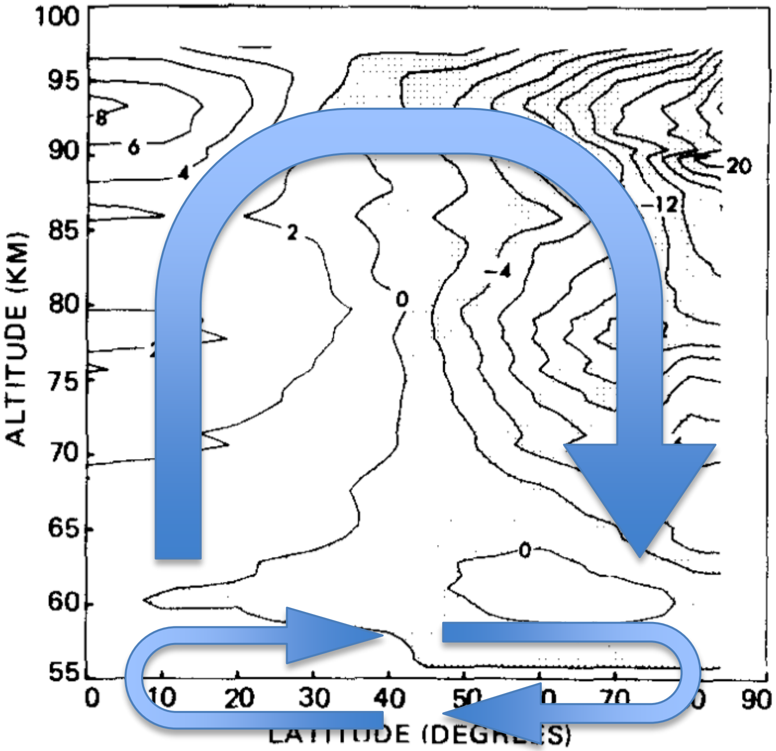


- Excess solar flux in the low latitude
- Excess thermal flux in the high latitude

Moroz et al. (1985)

Energy transport by atmospheric circulation

Net radiative heating rate
(Crisp 1989)



unit: K/day

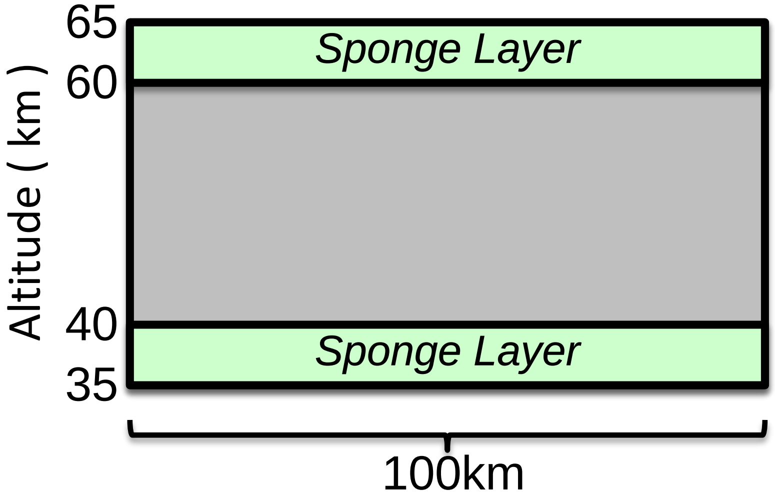
- Mean heating/cooling of the cloud-level atmosphere by atmospheric dynamics is expected to occur mostly through
  - adiabatic heating/cooling associated with large-scale descent/ascent in stably-stratified region (Crisp 1989; Imamura 1997)
  - diffusive flux by convection in neutral stability region

We focus on the convection layer and ignore contributions of large-scale dynamics

Two-dimensional convection model

- 2-D numerical experiments based on the non-hydrostatic meteorological model CReSS (Cloud Resolving Storm Simulator) Version 2.3.
- No cloud microphysics (dry convection)

Computational domain

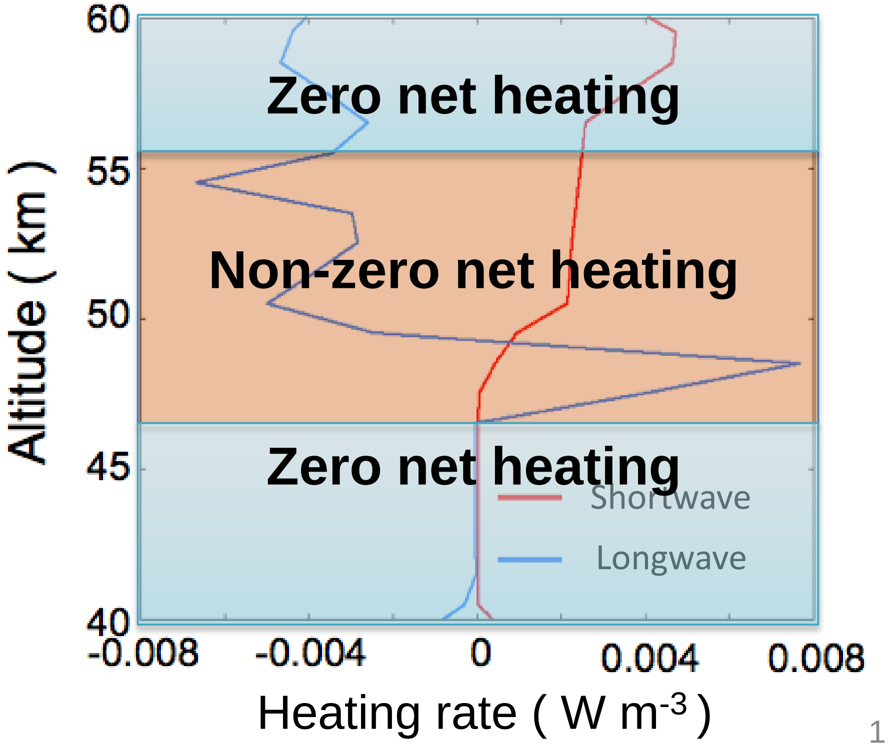


Grid size	dx = 200m dz = 125m
Boundary condition	lateral：Periodic Top and bottom：Fixed wall
Time step	HE-VI, Long : 1.0 s Short : 0.2 s
Initial perturbation	Random perturbation (Maximum value : 10-3 K)
Eddy diffusion	1.5-order turbulent kinetic energy closure

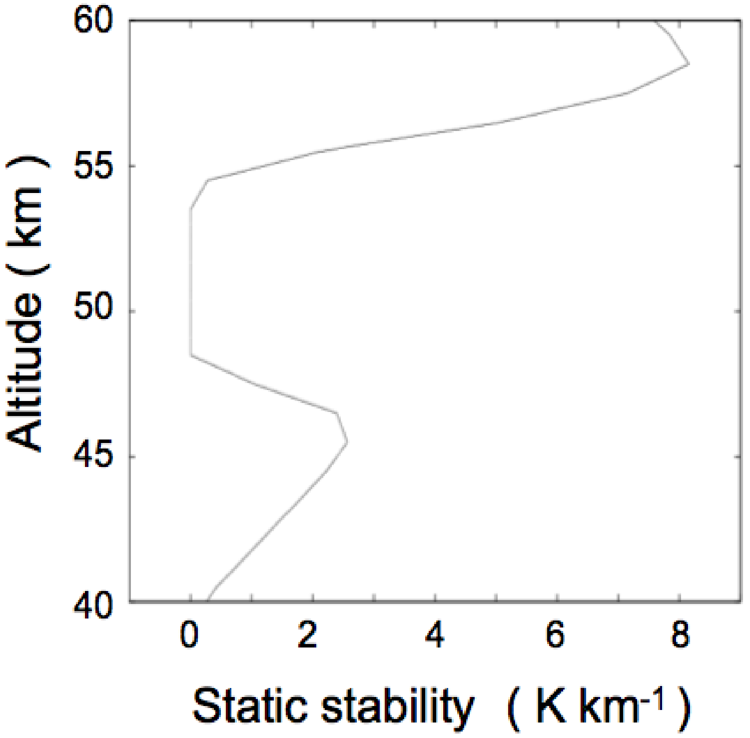
Thermal forcing

Shortwave heating rate is taken from Tomasko et al. (1980).

Longwave heating/cooling rate is taken from the one-dimensional radiative-convective equilibrium calculation by Ikeda (2010).

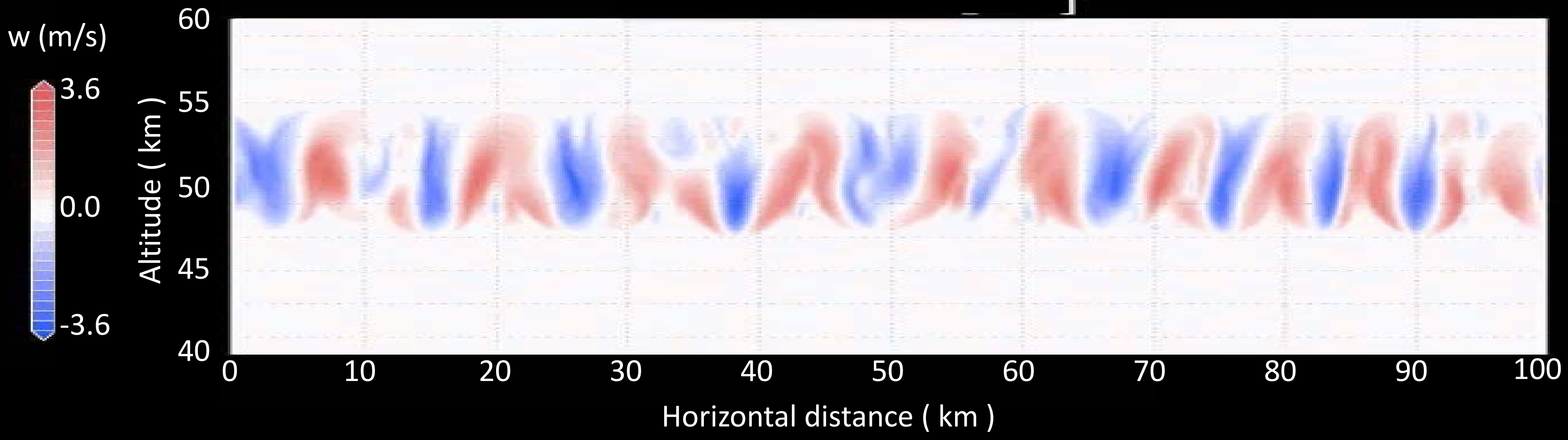


Static stability calculated by Ikeda (2010) → used as the initial state

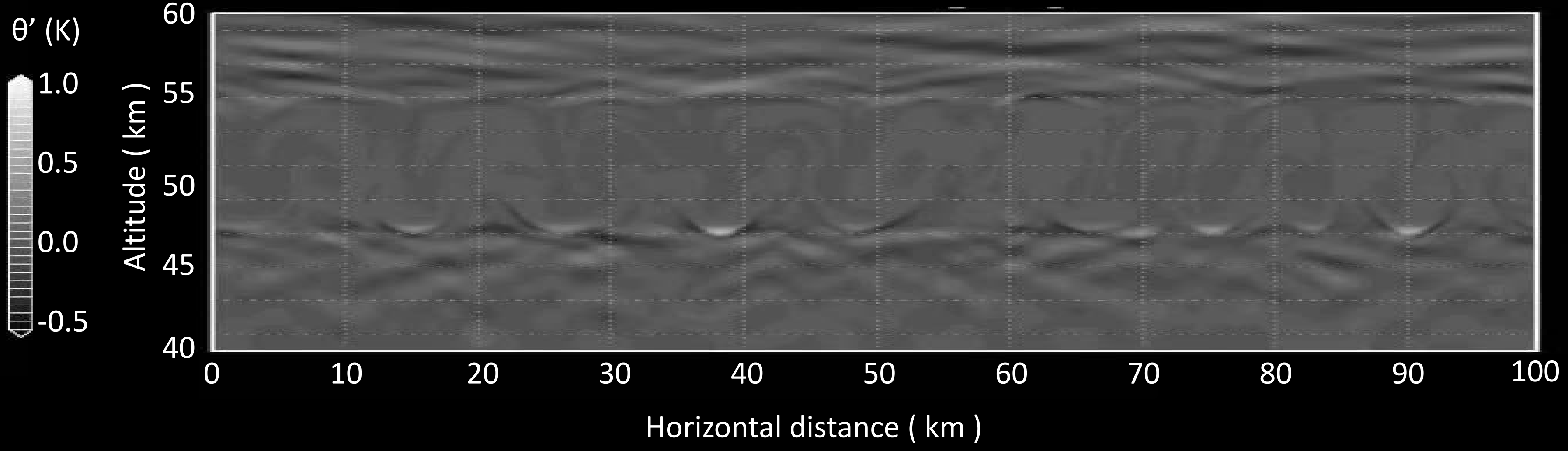


Structure of convection

Vertical velocity

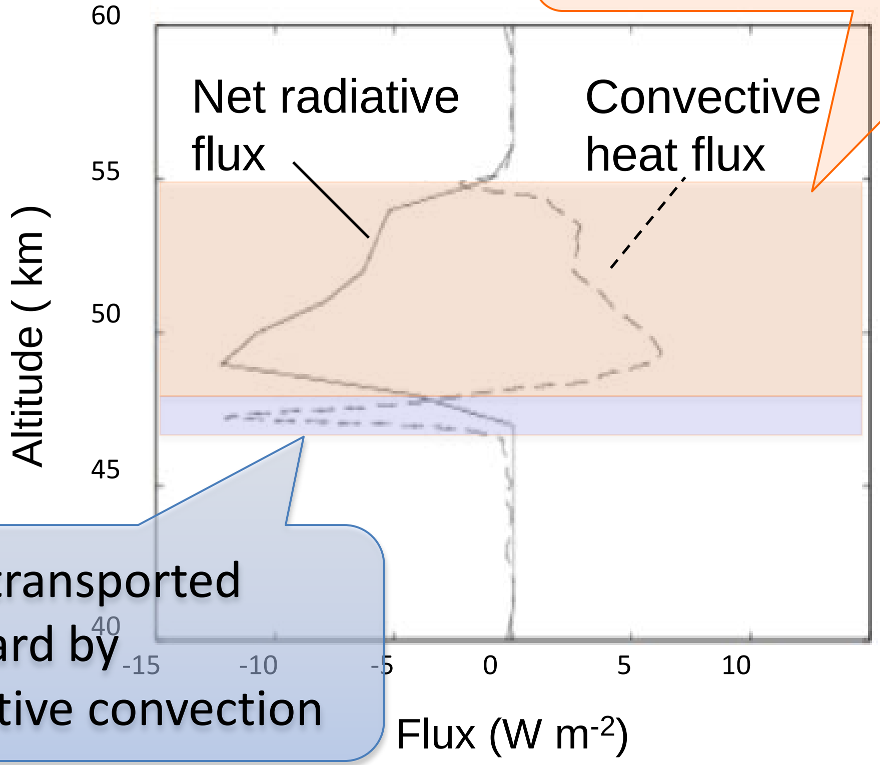


Potential temperature perturbation



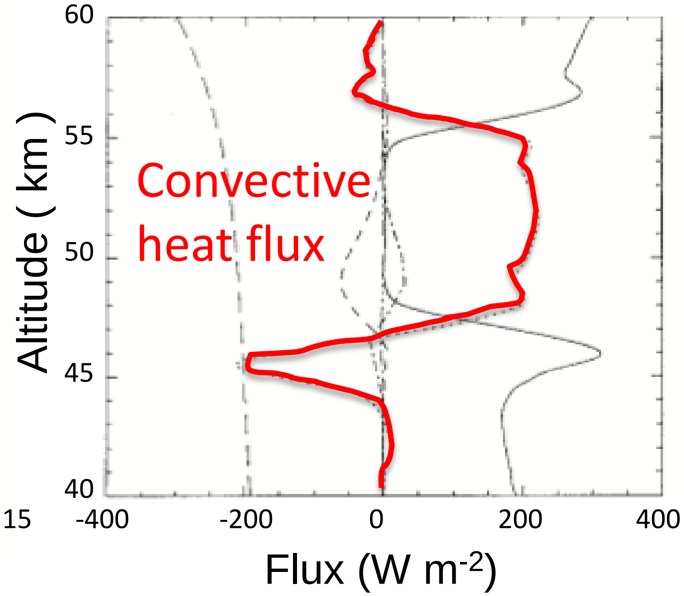
Heat flux

Heat is transported upward by convection



Heat is transported downward by penetrative convection

Heat flux calculated by Baker et al. (1998)

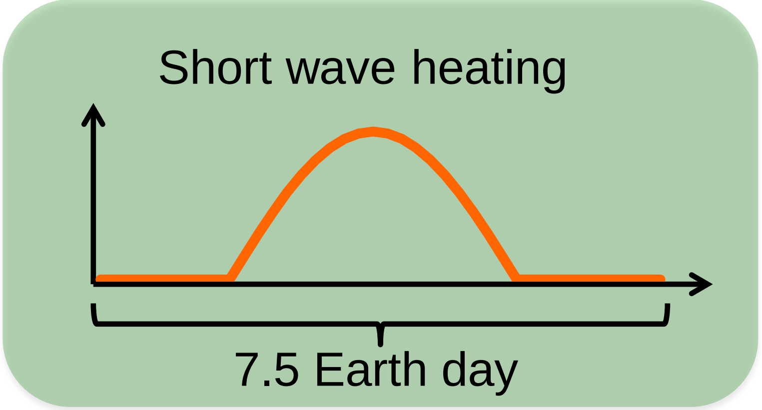


A part of the energy supplied to the convection zone by longwave heating is transported downward by penetrative compressible convection.

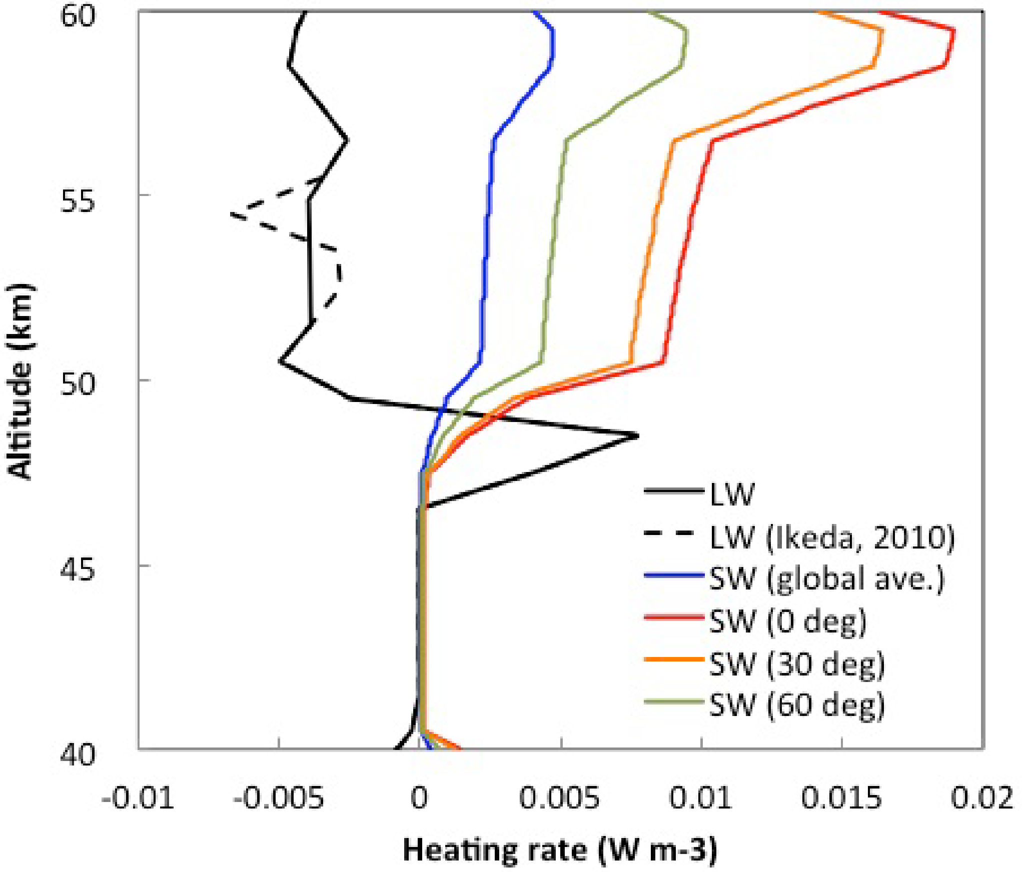
Modeling the latitudinal dependence and diurnal variation

- The clouds make a circuit of Venus in 7.3 Earth days that are the mean circulatory period at 50km altitude.

→ Shortwave heating changes with a period of 7.5 Earth days.

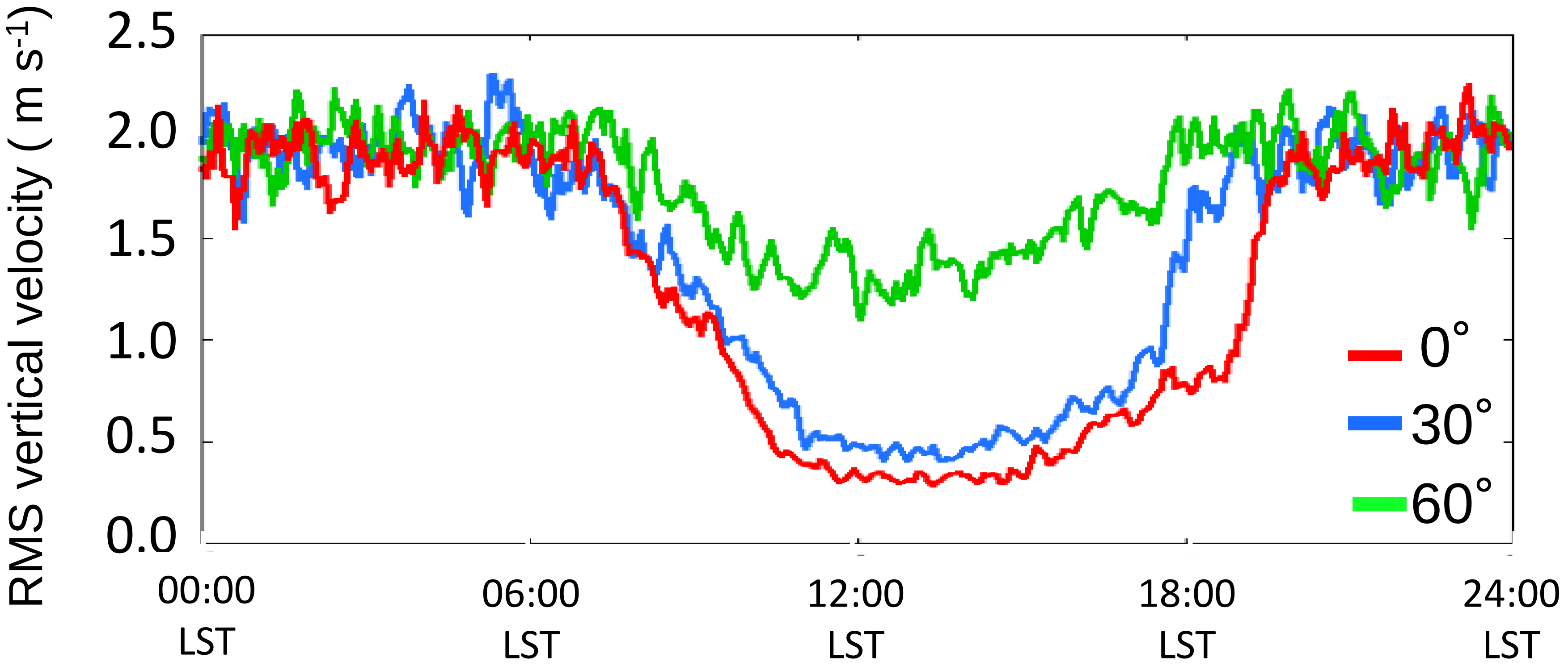


Heating rate at local noon



- A constant profile of longwave heating and cooling is given based on the observations that the latitudinal and local time dependences of the temperature are small below the cloud top.

Latitudinal dependence and diurnal variation



Diurnal variation of vertical velocity at 50km altitude

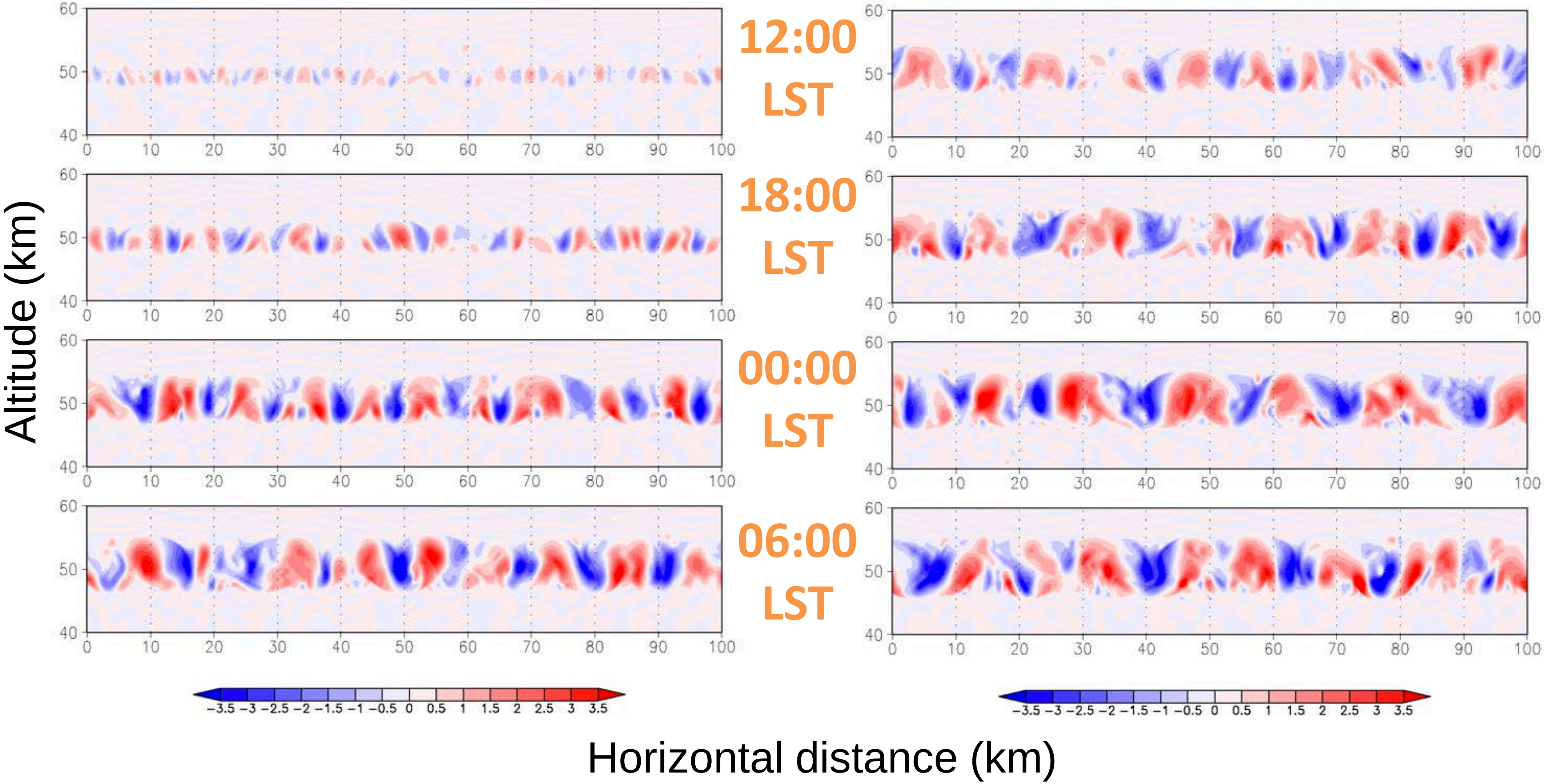
☐ The diurnal variation is more prominent in the low latitude than in the high latitude.

☐ The vertical velocity is depressed at daytime and at low latitude.

Structure of convection

Equator (0°)

High latitude (60°)

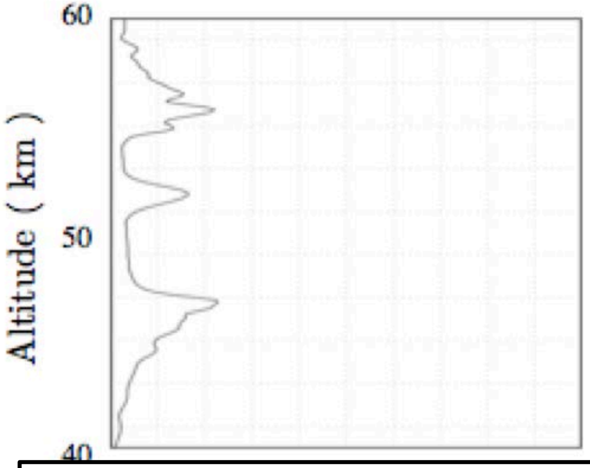


Stronger and deeper convection occurs during nighttime rather than daytime, and at high latitudes rather than at low latitudes.

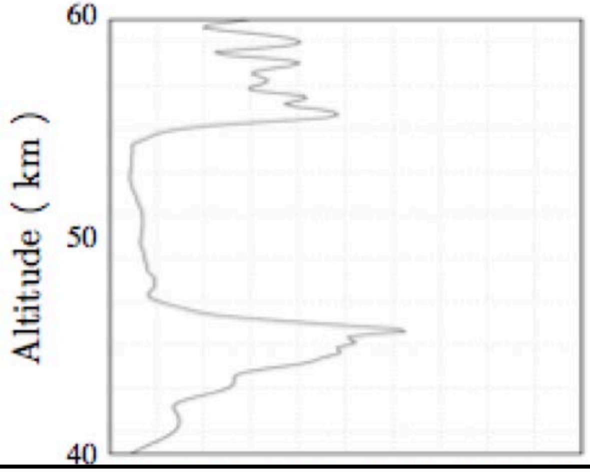
Amplitude of temperature fluctuation

Equator (0°)

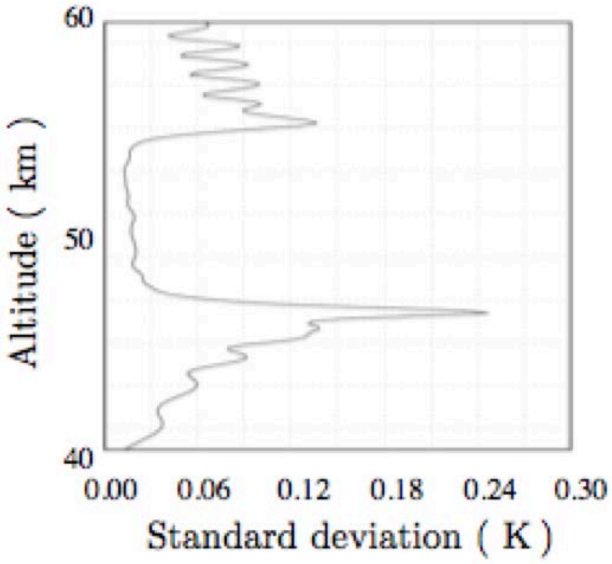
High latitude (60°)



12:00 LST



Stronger gravity wave excitation at higher latitudes



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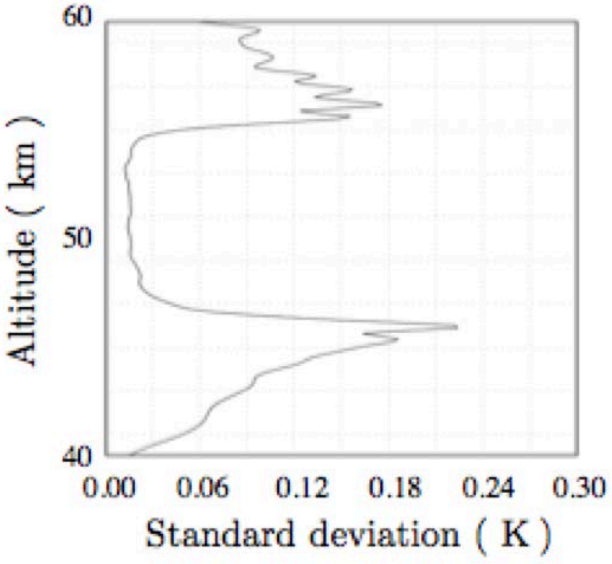
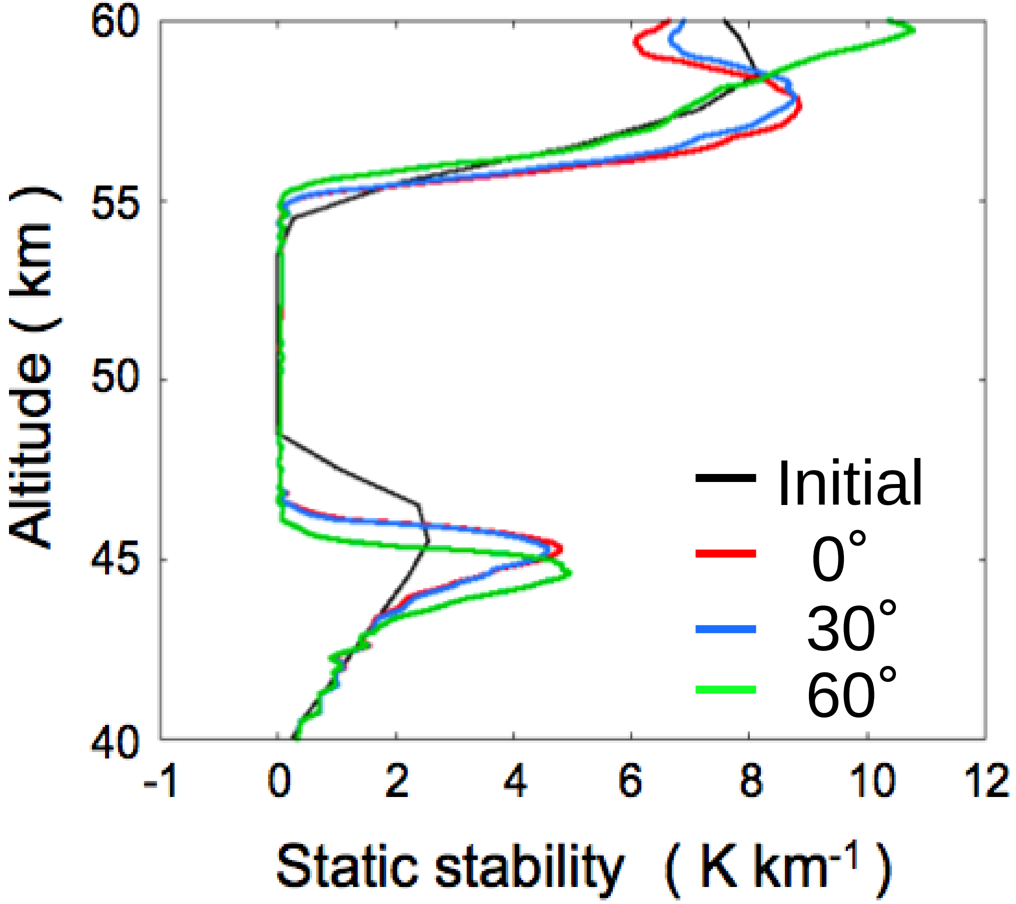


Depth of neutral stability layer

Zonally-averaged static stability 14.6 Earth days after start of the calculation



More deepening of the neutral stability layer at higher latitudes

Summary

- The newly-developed Venus’s cloud-level convection model showed that stronger and deeper convection occurs at high latitudes rather than at low latitudes, and during nighttime rather than daytime. This is qualitatively consistent with the observed latitudinal tendencies of the convective layer depth and the amplitudes of small-scale waves.
- In the Earth’s convection layer, incoming solar radiation is quickly converted to heat which drives convection. In the case of Venus’s cloud-level convection, on the other hand, the solar energy supplied to the lower atmosphere is well mixed in latitude and longitude due to the long radiative timescale before being delivered to the cloud level. Because of this difference the latitudinal tendency becomes different.
- The suggested latitudinal tendency is expected to be common to planets having a thick aerosol layer detached from the ground and a radiatively-thick lower atmosphere.