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Dynamical effects of the thermal tides in the Venus atmosphere

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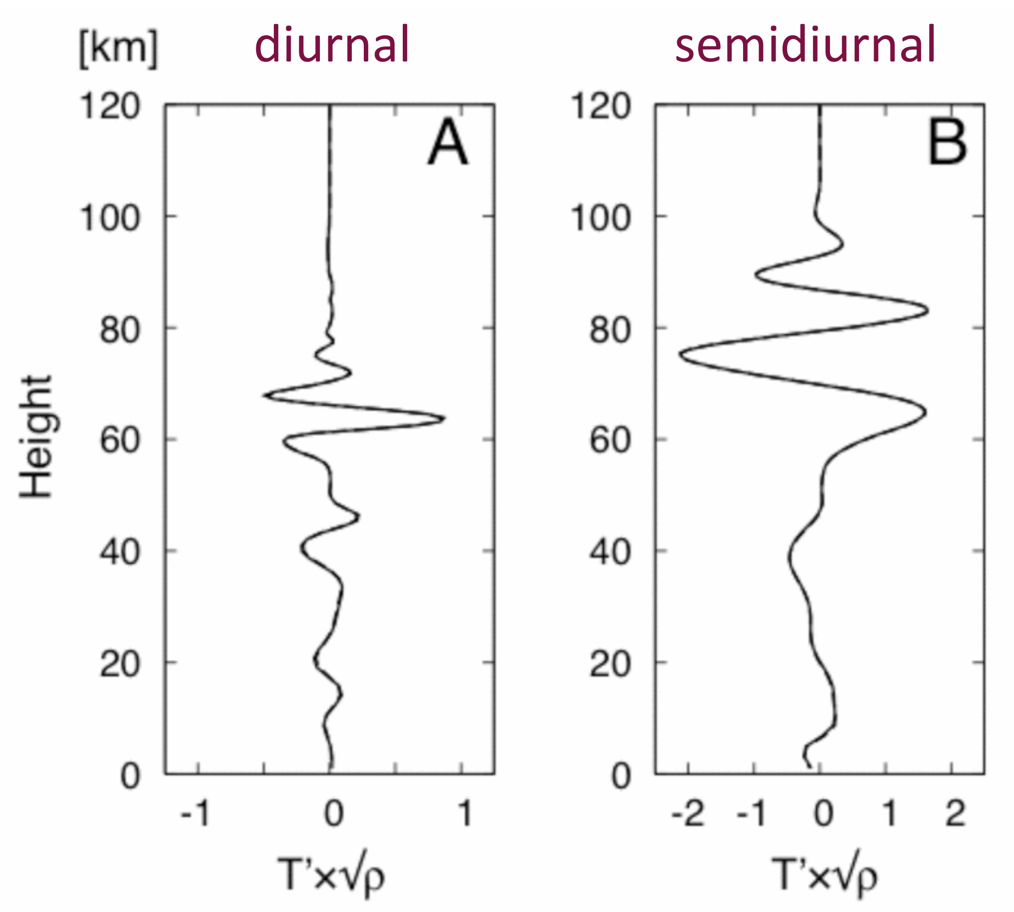
Linear model of thermal tides

- In order to examine structure of thermal tides, a linear model on the spherical geometry is constructed.
- Based on the linearized primitive equations on a sphere
  - 10 modes of Legendre functions (symmetry to the equator)
  - 250 levels in the vertical domain (0-120 km)
- Basic state field and parameters:
  - Mean zonal flow (superrotation)
    - With vertical shear consistent with observations.
    - With and without the midlatitude jets.
  - Newtonian cooling
    - Based on Crisp (1989)
    - Dependent on the vertical wavenumbers of disturbances
  - Static stability
    - VIRA (Seiff et al. 1985)
  - Solar heating
    - Crisp (1986, 1989) and Tomasko et al. (1980)

Downward propagation of thermal tides



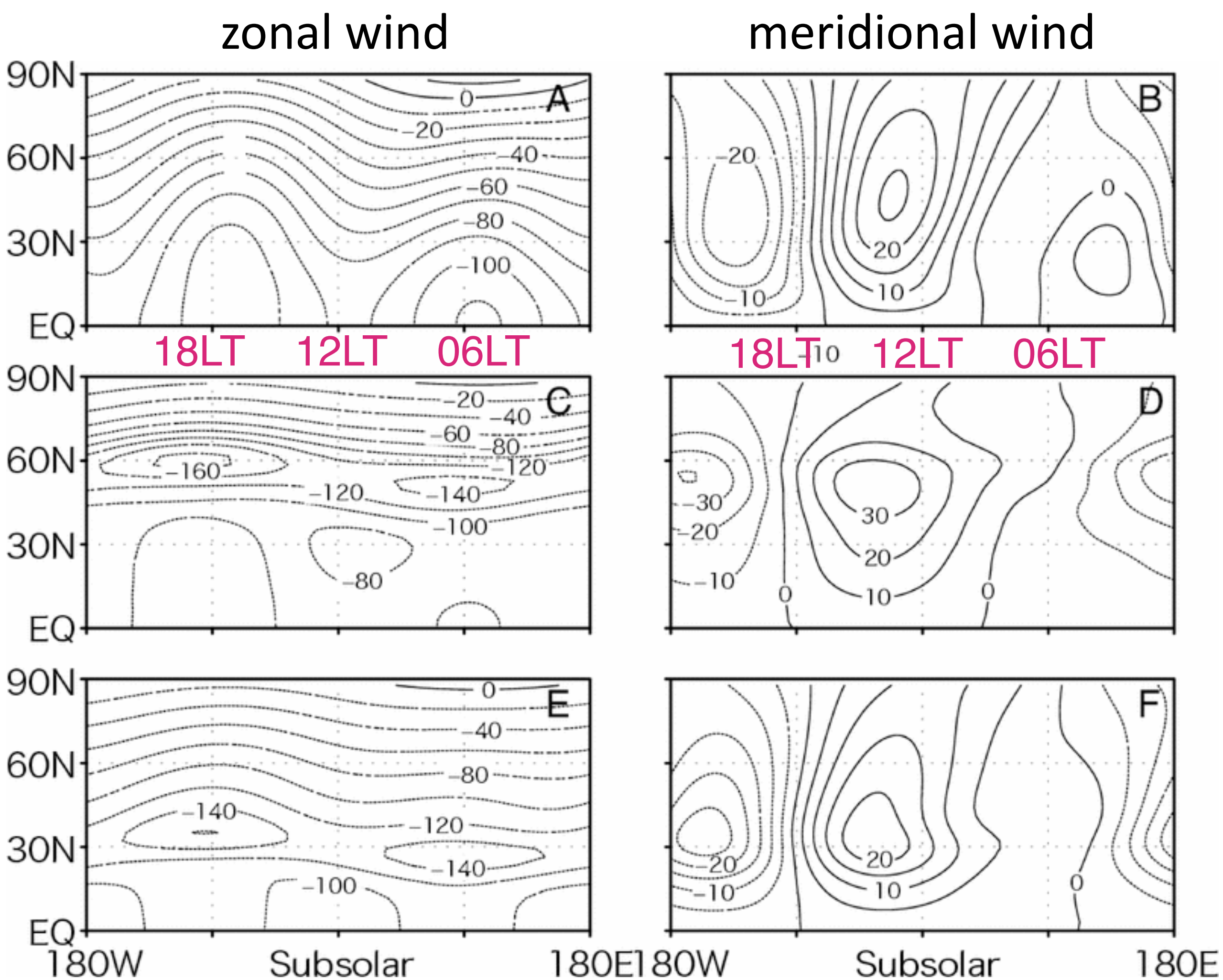
Vertical profiles of the temperature deviation multiplied by the square root of the basic atmosphere density.

- Both the diurnal and semidiurnal tides excited in the cloud layer propagate to the ground.
  - Their amplitude is determined almost by the solar heating at the cloud levels.
  - The effect of the ground heating is negligible except in the lowest layer.
- This result suggests that zonal momentum is transported vertically by the thermal tides and exchanged between the cloud layer and lower layers near the ground.

Takagi and Matsuda (GRL 2005)

Total wind fields ($U+u_1+u_2$) at z=70 km

Horizontal distributions of zonal and meridional winds obtained by superimposing the diurnal and semidiurnal tides on the corresponding basic winds.



J0 case:
Solid body rotation

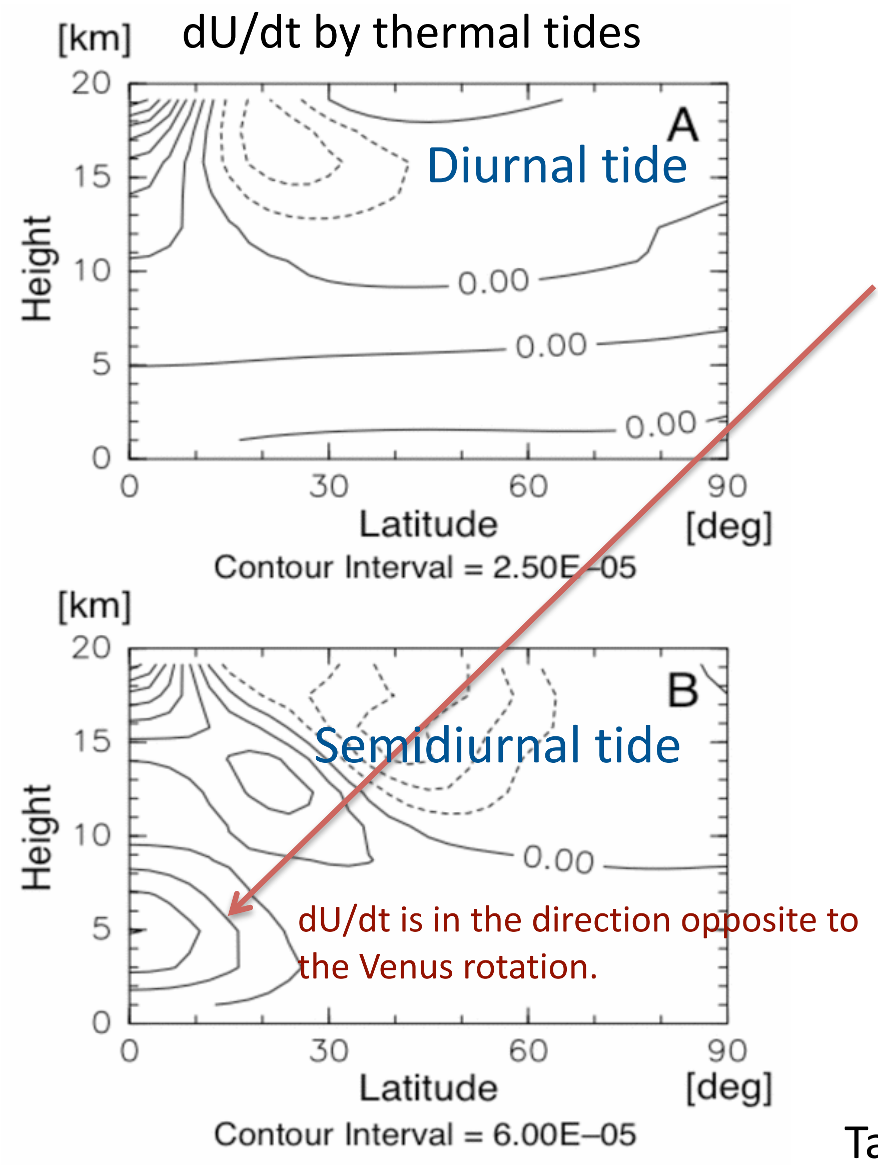
J1 case:
High latitudes jets

J3 case:
Low latitudes jets

Local minimum at noon.
Jets are weakened at midlatitudes.

Not sensitive to midlatitude jets.
Poleward in the day side, and equatorward in the night side.

Dynamical effects of thermal tides



- The diurnal tide does not affect on the mean zonal flow in the lowest layer (0-10 km).
- The semidiurnal tide decelerates the mean zonal flow in the low latitudes of the lowest layer (dU/dt: 2.4E-4 m/s/day).
- This result implies that mean zonal flow in the direction opposite to the Venus rotation is induced by the semidiurnal tide in the lowest layer.
- If the surface friction acts on this counter flow, the net angular momentum required for the superrotation may be supplied from the solid part of Venus.

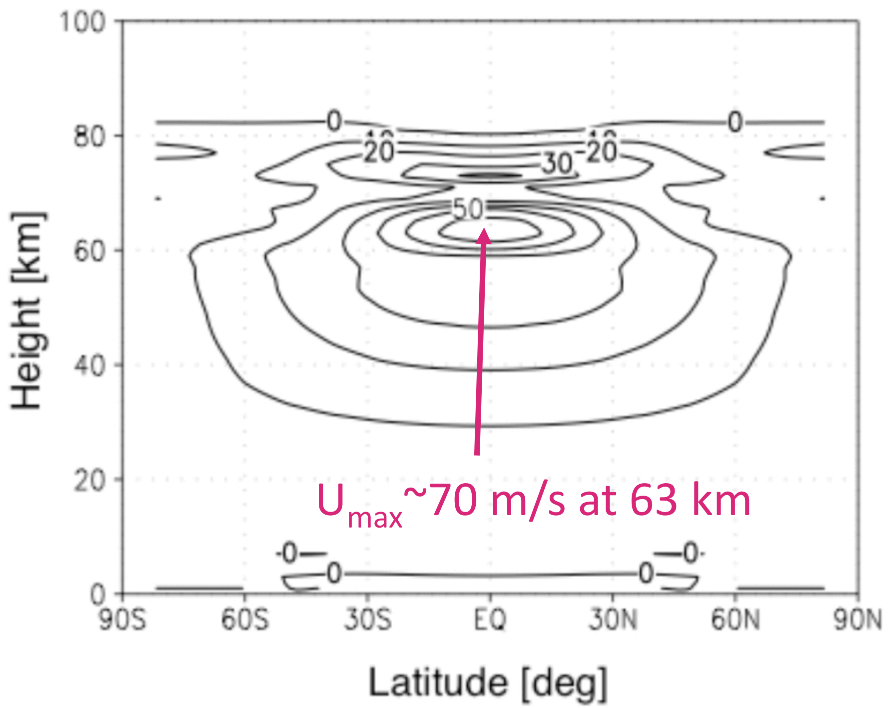
Takagi and Matsuda (GRL 2006)

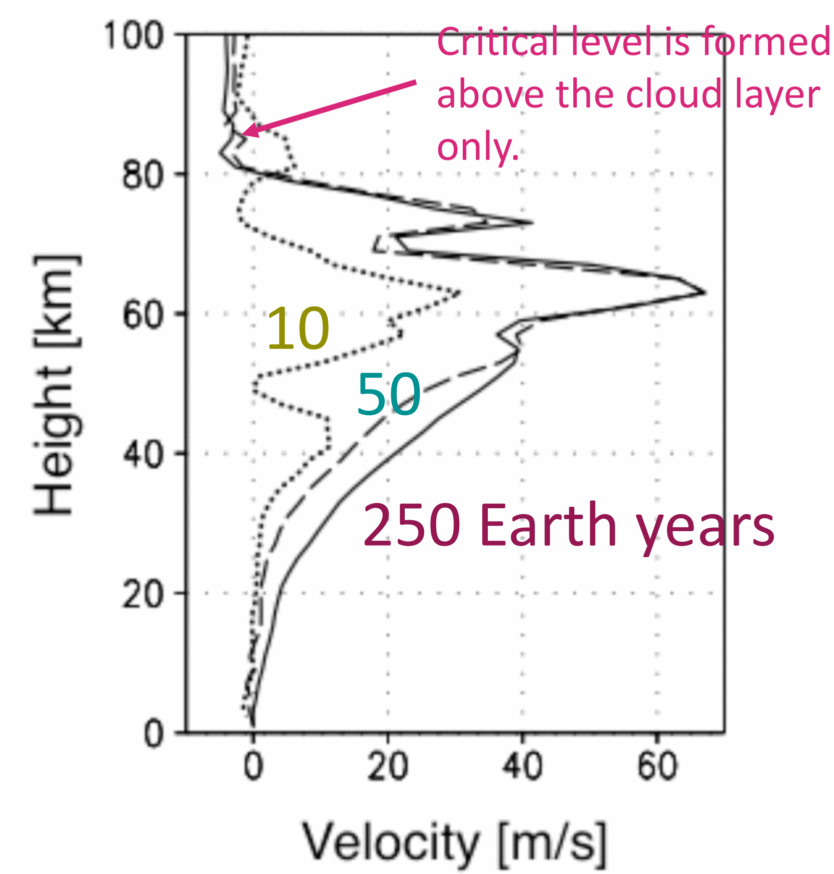
Nonlinear model

- A simple GCM
  - Constructed to examine the dynamical effects of the thermal tides inferred from the linear model.
  - Based on Hoskins and Simmons (1975)
  - T21L60 (vertical domain: 0–120 km)
  - Time integrated for 300 Earth years from a rest state.
- Solar heating
  - Based on Crisp (1986, 1989) and Tomasko et al. (1980)
    - The mean zonal component is removed to focus on the effects of the thermal tides.
    - The ground heating is neglected.
- Damping
  - Newtonian cooling (Seiff et al. 1985)
  - Rayleigh friction only in the lowest level (to mimic the surface friction).

Mean zonal flow (250 Earth years)

Takagi and Matsuda (JGR 2007)



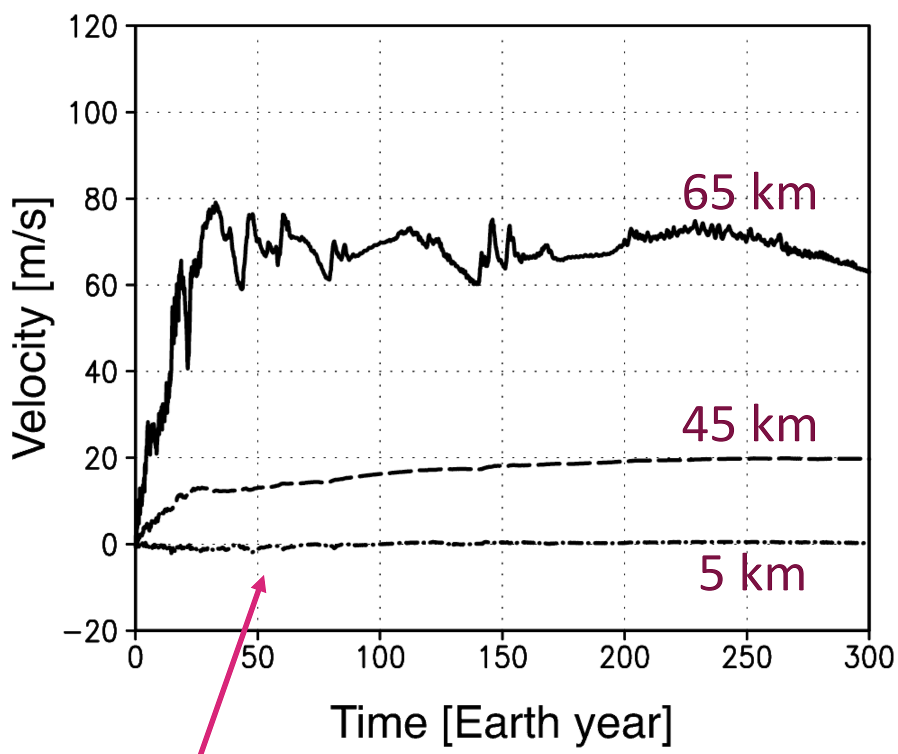


Fast zonal flow extending from the ground to 80 km have been generated. Above the cloud top, it decreases with altitude sharply.

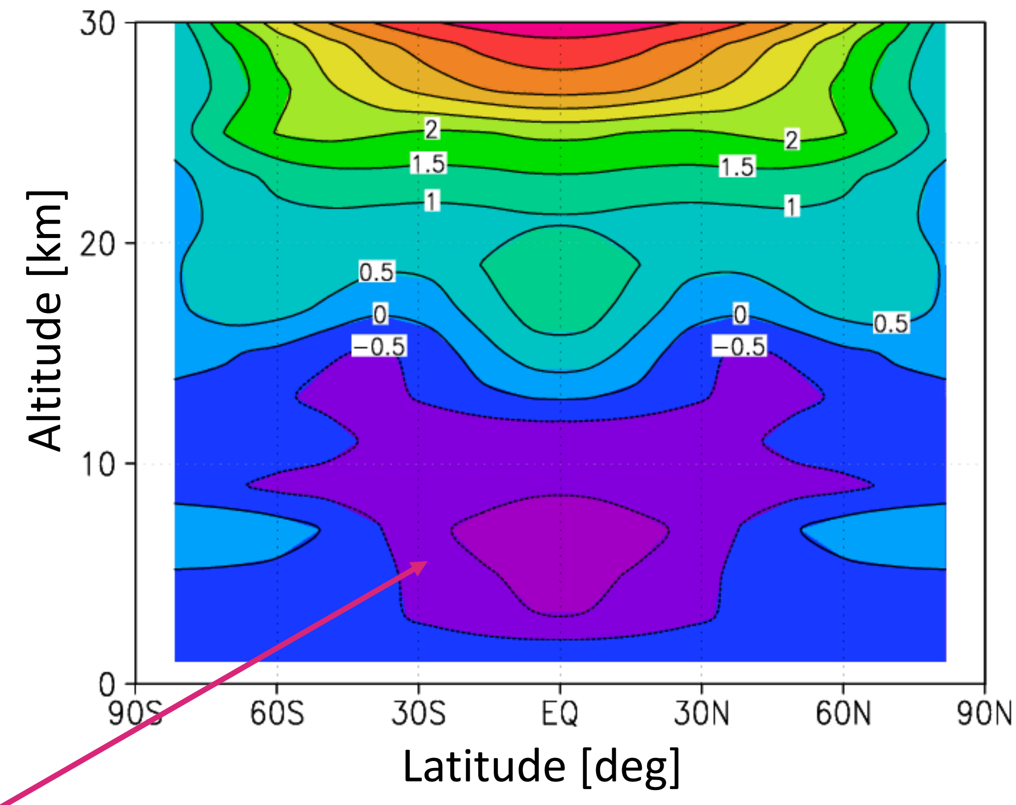
Vertical profiles of mean zonal flow on the equator at 10, 50 and 250 Earth years.

Counter flow in the lowest layer

U on the equator



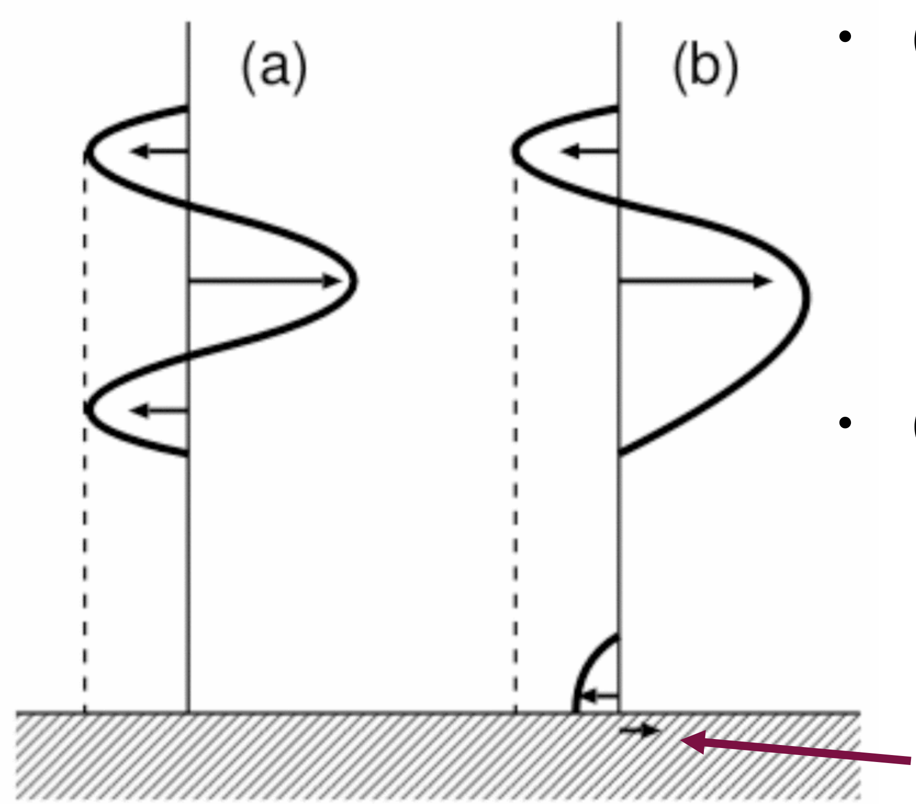
U(y,z) at 50 Earth years



U<0 is observed in the lowest layer in the early stage of the time integration.

The distribution of the negative mean zonal flow (shaded by blue and violet colors) is consistent with that of the deceleration rates due to the semidiurnal tide. The surface friction acts on this counter flow, and the net positive angular momentum is supplied.

New thermal tide mechanism



Generation mechanisms of the superrotation: (a) Fels and Lindzen (1974), (b) present results.

- (a) Old interpretation
  - The critical levels formed above and below the heating layer prevent the thermal tides from redistributing zonal momentum.
  - Net momentum cannot be supplied.
  - Fast mean flow cannot be generated.
- (b) Present result
  - The semidiurnal tide propagates downward and induces mean zonal flow in the direction opposite to the Venus rotation in the lowest layer.
  - Surface friction acting on $U<0$ supplies the Venus atmosphere with net angular momentum.
  - Fast mean zonal flow (superrotation) is generated in the heating layer.

Influence of CO_2 line profiles on the equilibrium temperatures in the Venus lower atmosphere`

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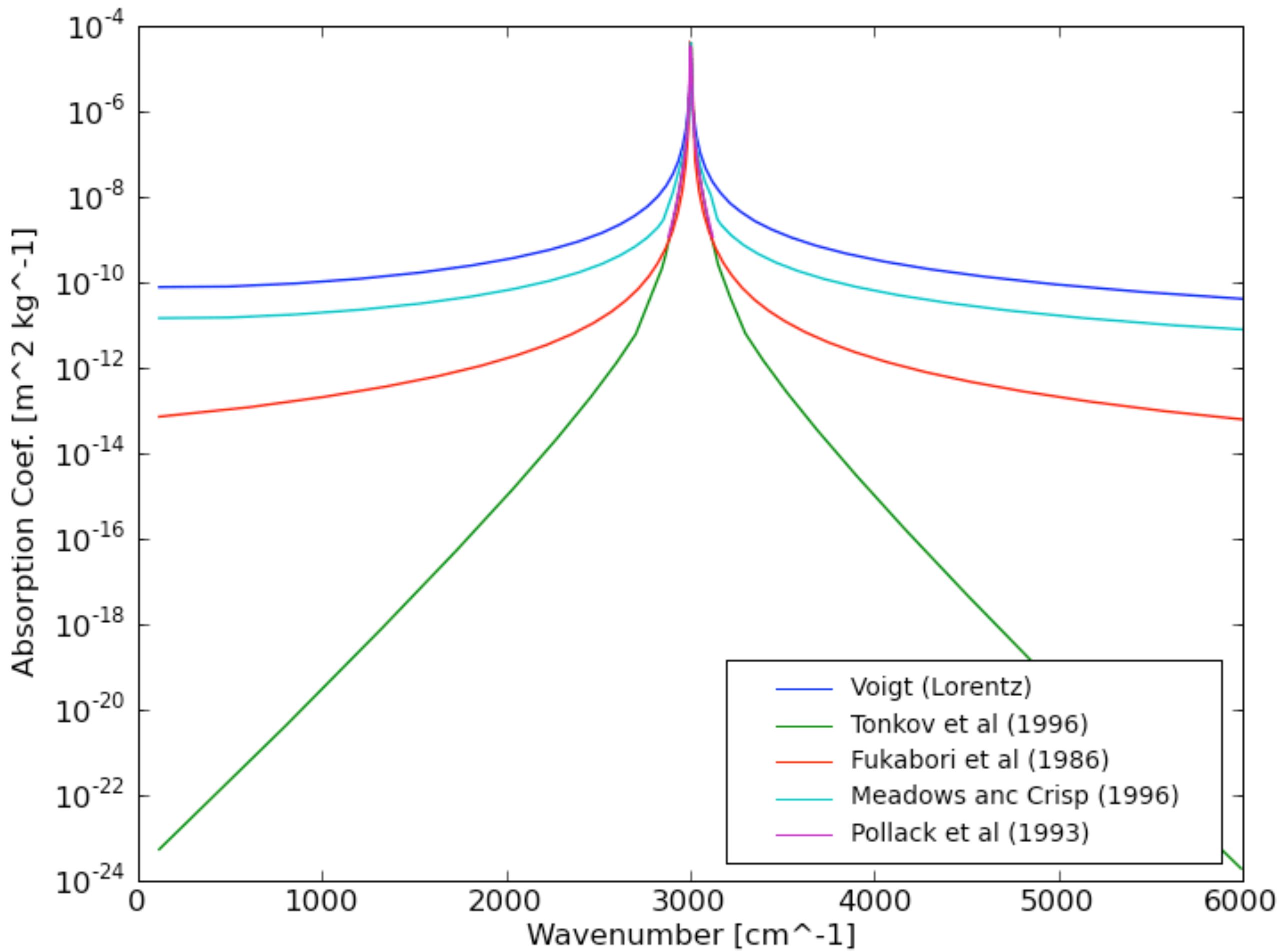
Takagi et al. (2010, submitted to JGR Planet)

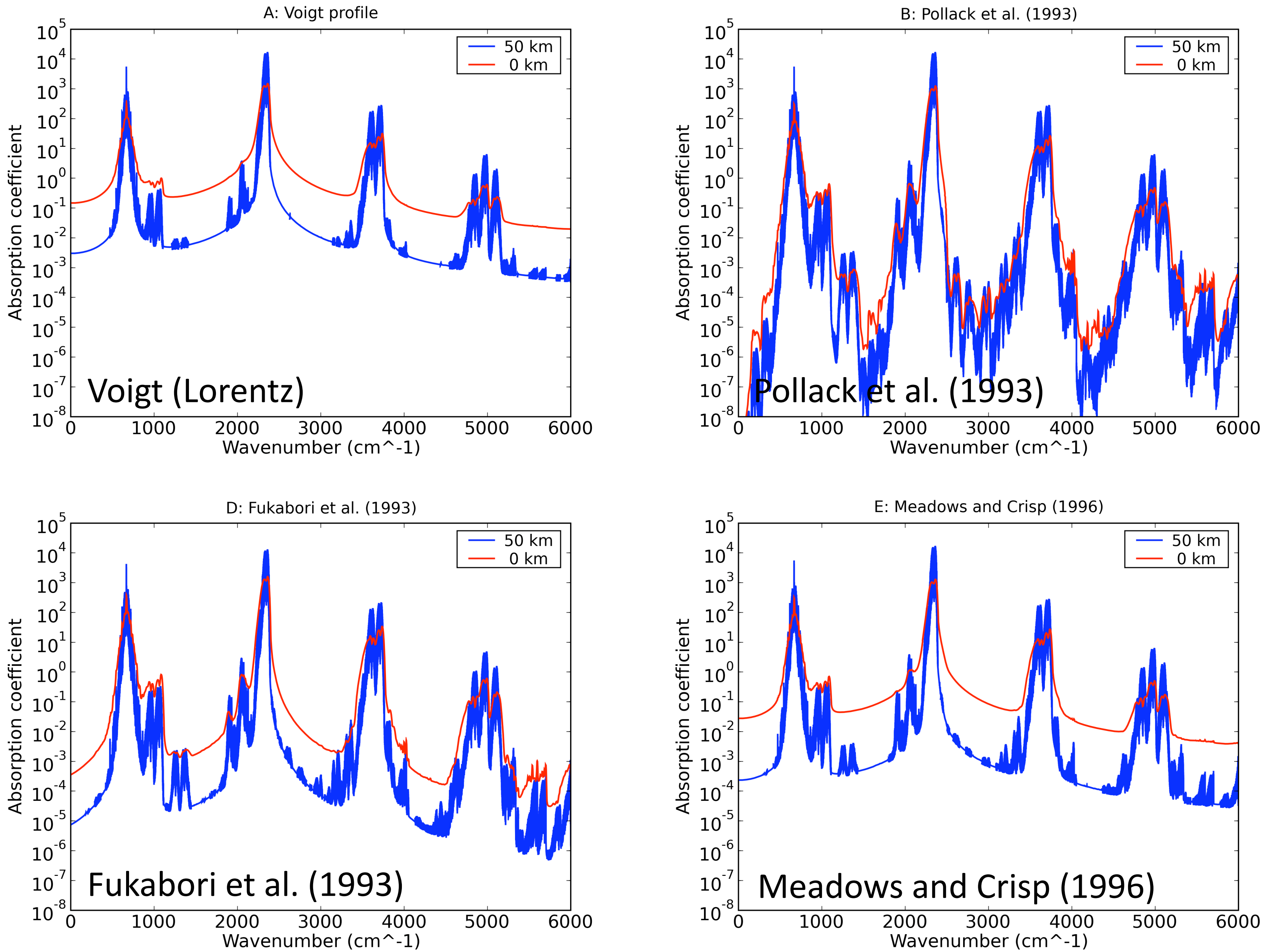
Objectives

- Improvement of the dynamical model of the Venus atmosphere requires a radiative transfer model.
- In order to determine the CO_2 line profile, temperatures in the radiative and radiative-convective equilibrium states in the Venus lower atmosphere are calculated for the following CO_2 line profiles:
  - Voigt profile
  - Pollack et al. (1993)
  - Tonkov et al. (1996)
  - Fukabori et al. (1986)
  - Meadows and Crisp (1996)

CO_2 line profiles



Absorption coefficients due to CO_2

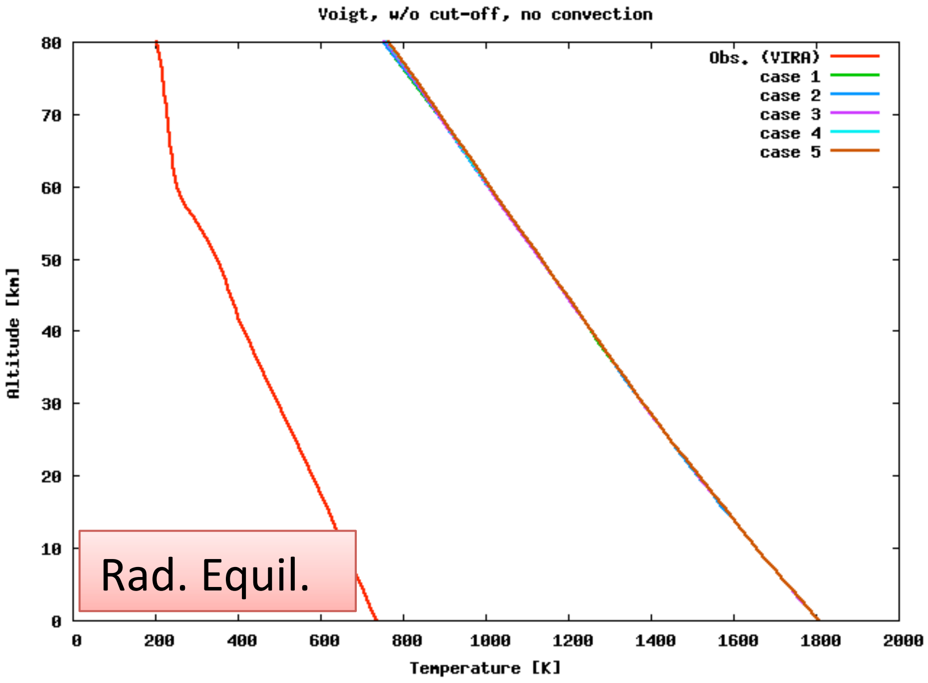


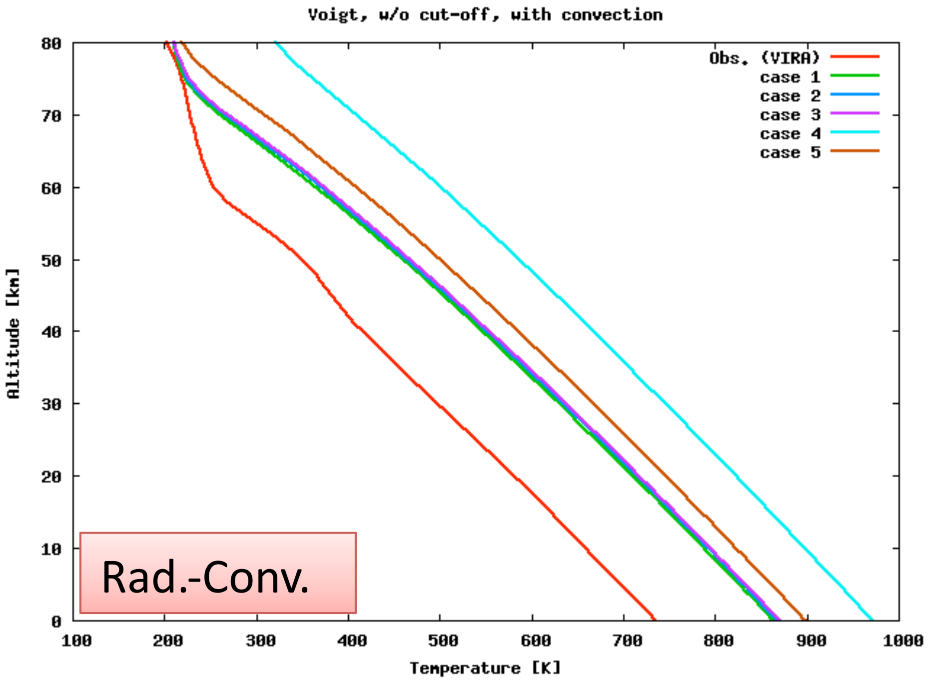
Conditions

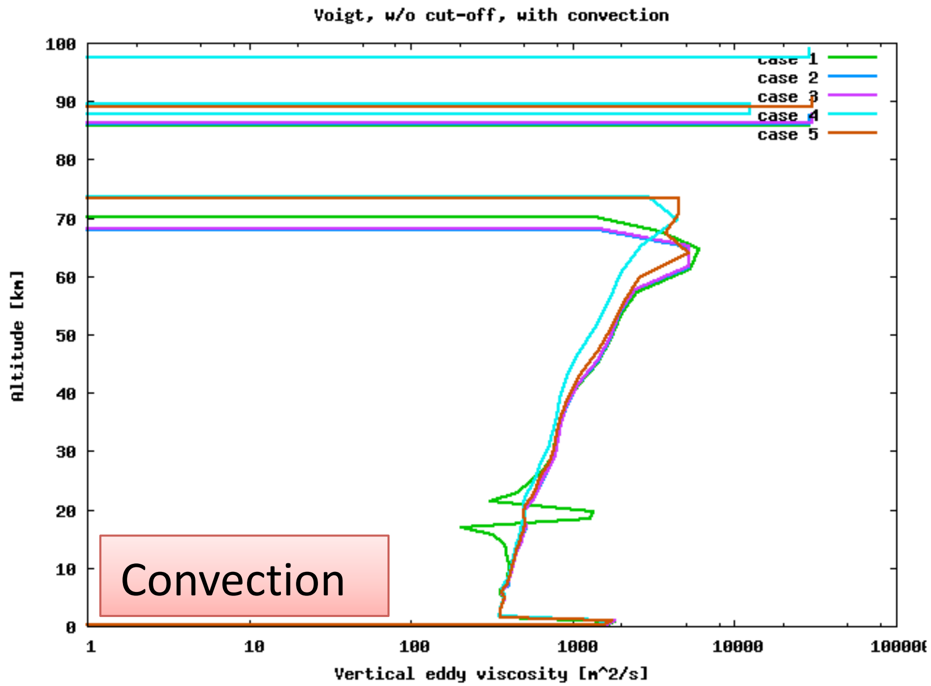
- Case 1: Absorption due to CO_2 only.
- Case 2: Case 1 + pressure induced absorption caused by CO_2 pairs.
- Case 3: Case 2 + absorption due to H_2O
- Case 4: Case 3 + cloud (k*ρ const.)
  - Samuelson et al. (1975)
  - Matsuda and Matsuno (1978)
- Case 5: Case 3 + cloud (k const.)

- Total opacity of the cloud is fixed to 10.

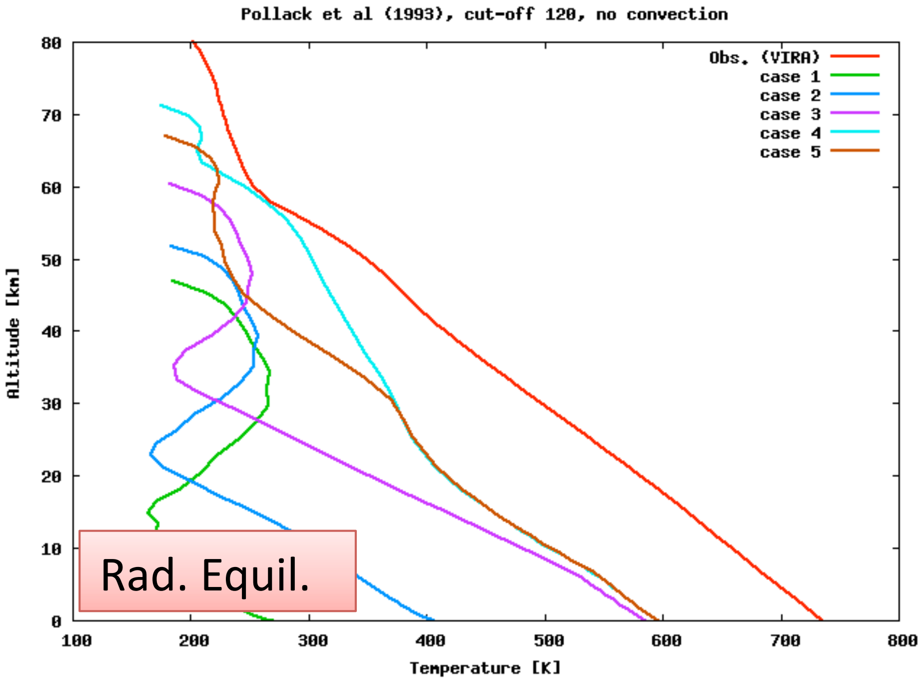
Equil. temperatures Voigt (Lorentz) w/o line cut-off

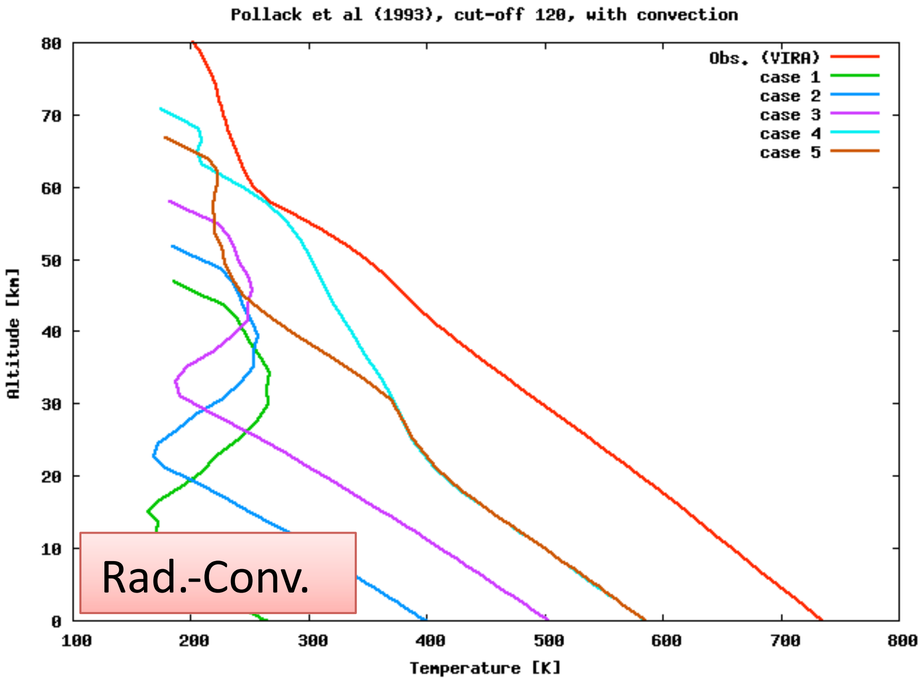


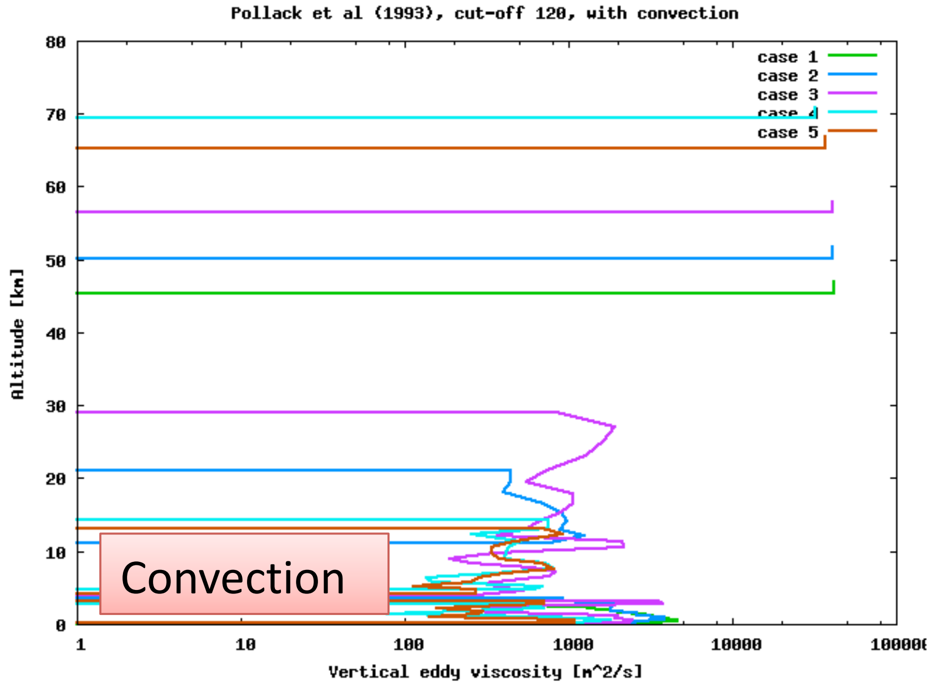




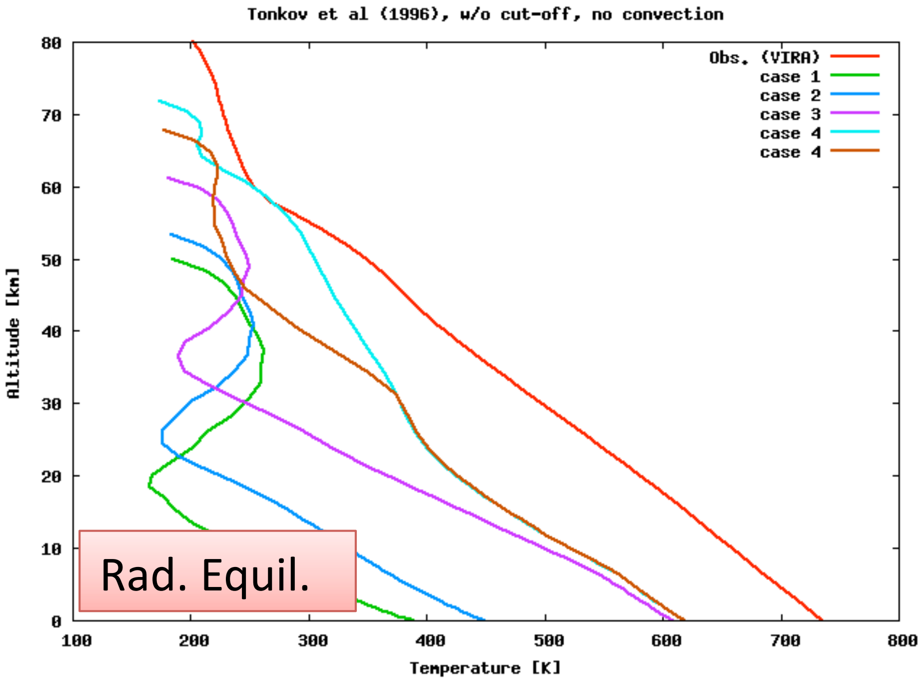
Equil. temperatures Pollack et al. (1993) 120 cm^{-1} cut-off

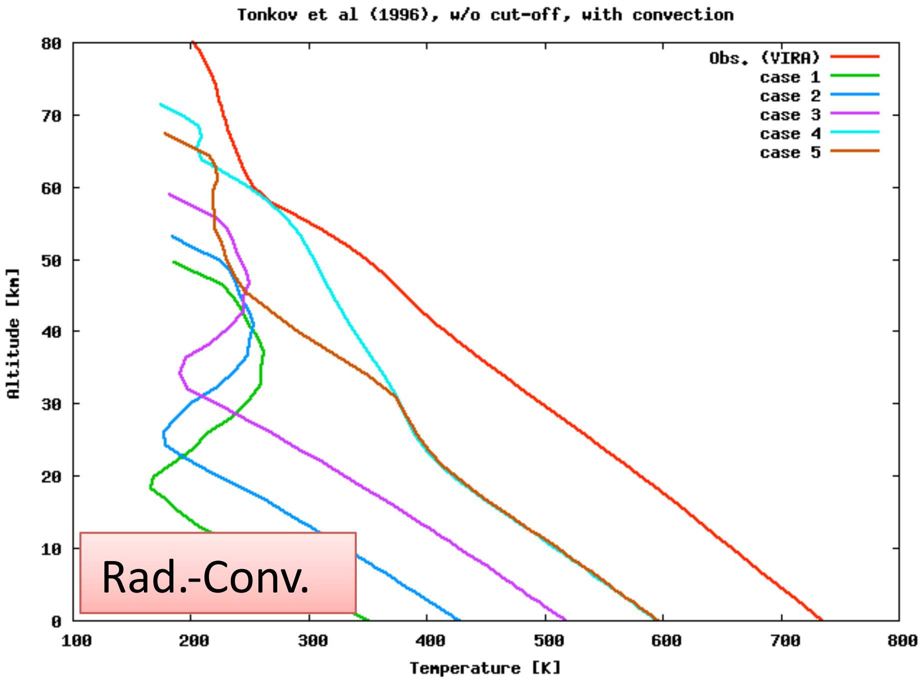


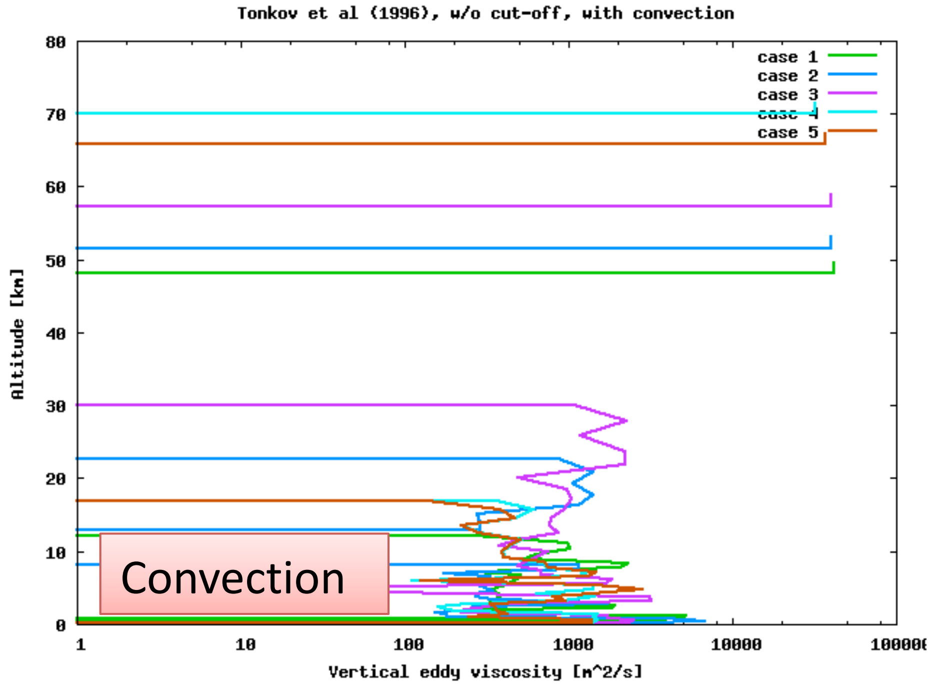




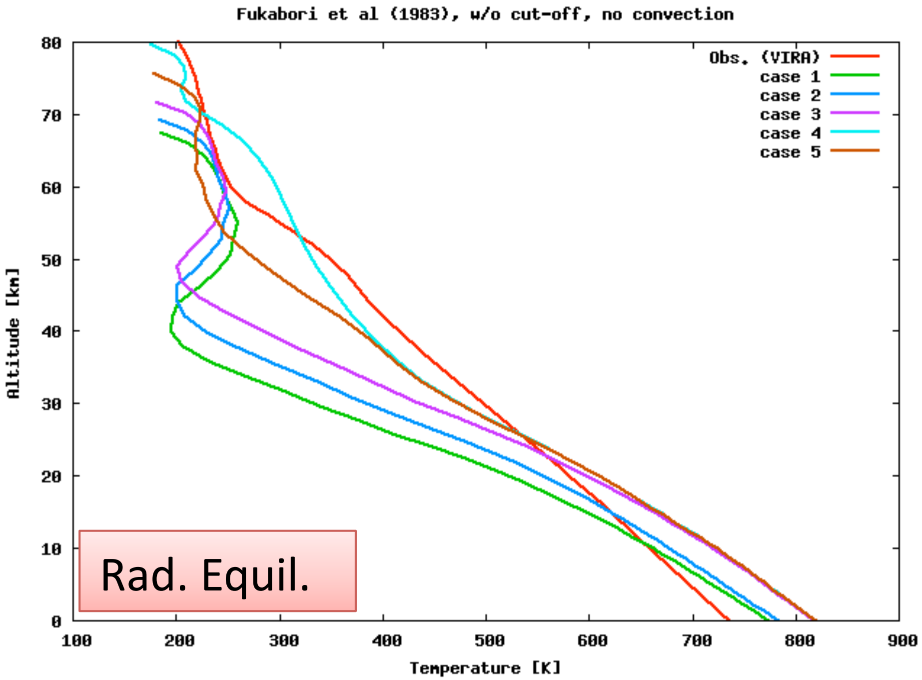
Equil. temperatures
Tonkov et al. (1996)
w/o line cut-off

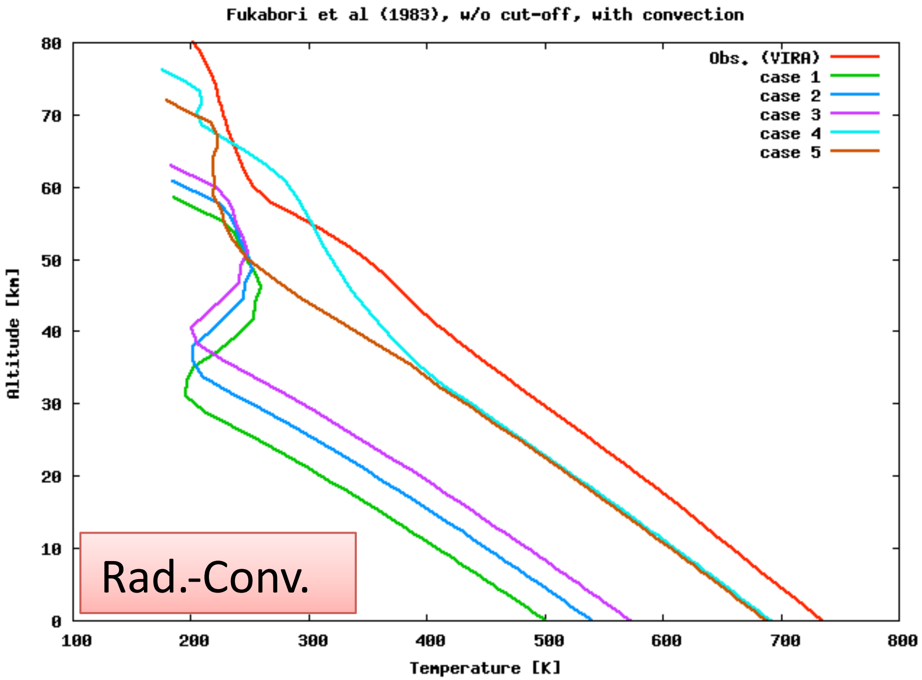


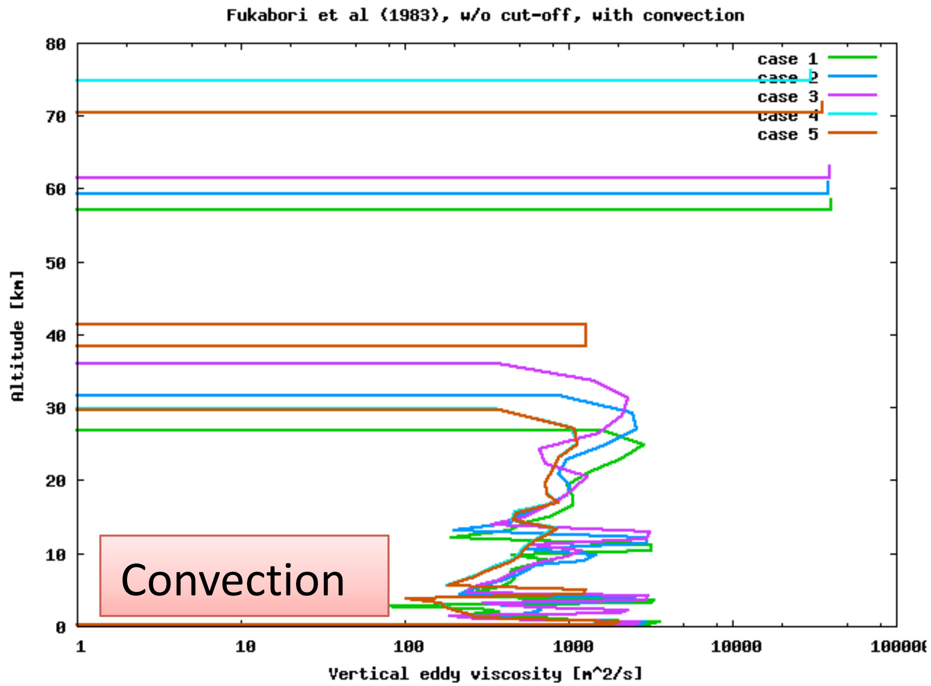




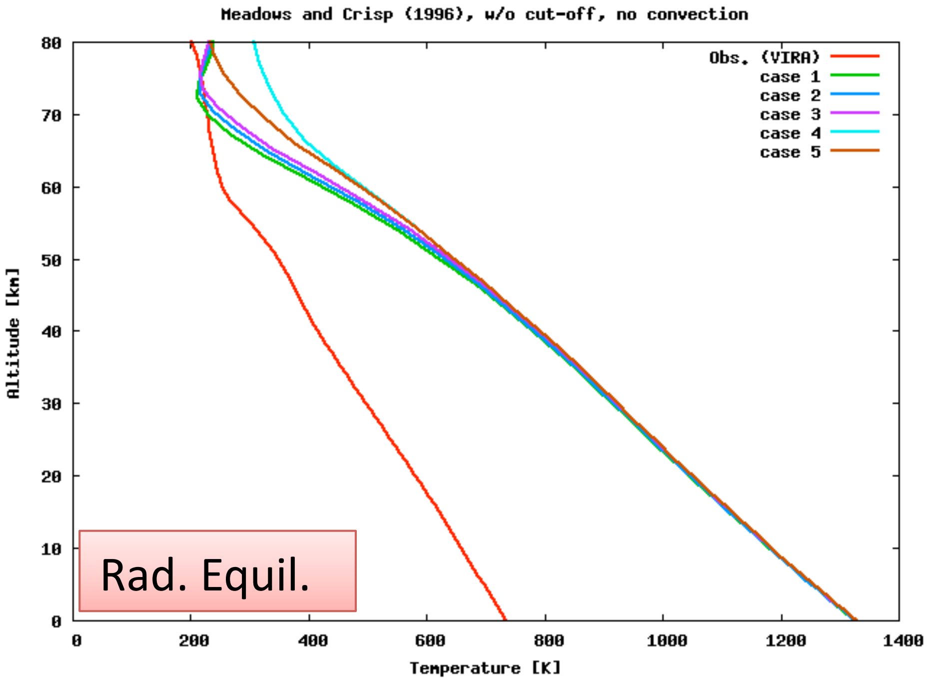
Equil. temperatures Fukabori et al. (1983) w/o line cut-off

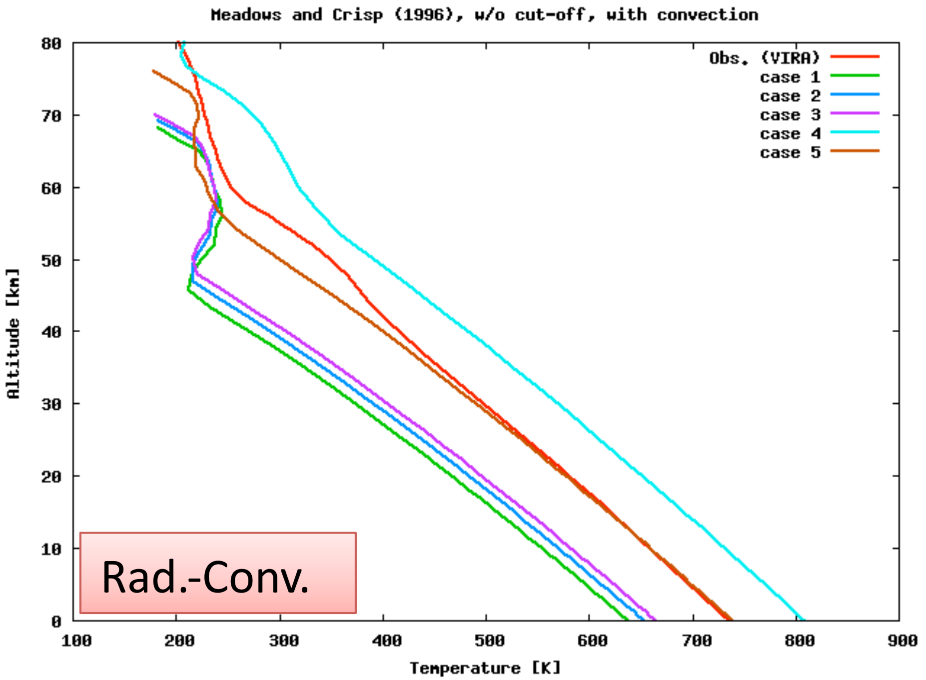


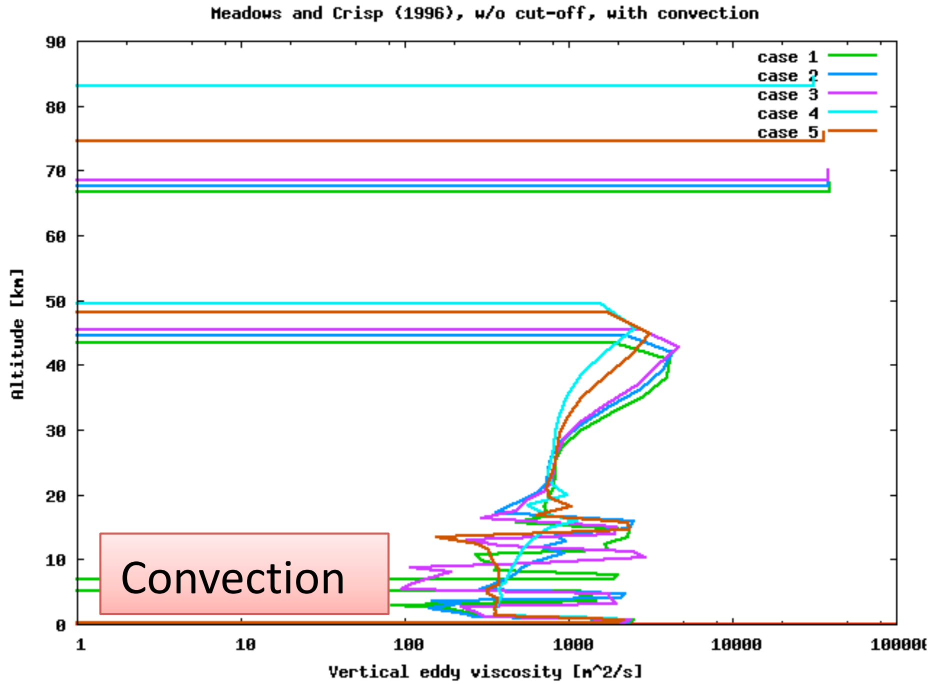




Equil. temperatures Meadows & Crisp (1996) w/o line cut-off







Summary

- Temperature profile close to the VIRA data can be obtained by the CO2 line profiles of Fukabori et al. (1983) and Meadows and Crisp (1996).
- Radiative equil. temperatures are:
  - Super-adiabatic from the surface to 10-80 km altitudes (depends on the assumed CO_2 line profiles).
  - Considerably higher than the VIRA temperatures (820-1300 K at the surface).
- Rad.-Conv. equil. temperatures are:
  - Convective from the surface to 30-50 km altitudes for the Fukabori and Meadows profiles.
  - Strongly affected by the temperature at the bottom of the cloud layer (in contrast to those in the rad. equil.).
- The detailed structure of the cloud must be taken into account in order to construct a realistic radiative transfer model for the Venus lower atmosphere.