*ISSI Venus working group meeting, September 29, 2008*

# Venus Atmospheric Modeling based on CCSR/NIES GCM

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# Japanese Venus GCM research group

Yamamoto and Takahashi (2003; …)
Ikeda et al. (2008)
Kido and Wakata (2008)
*Based on CCSR/NIES GCM (Numaguti 1997)*

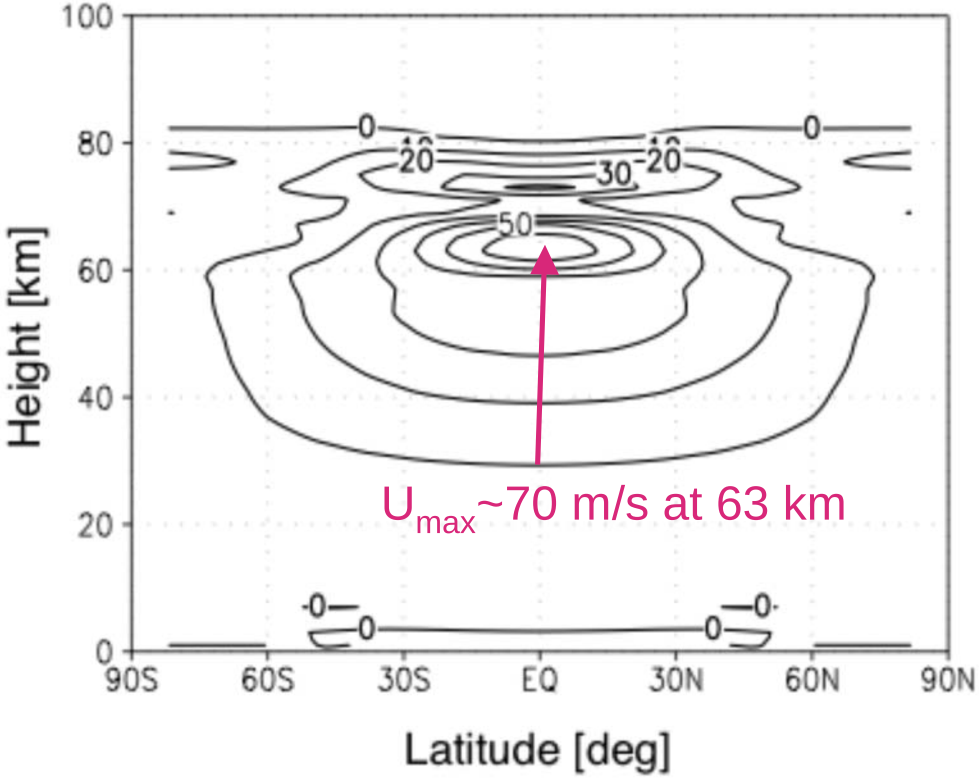
Takagi and Matsuda (2007)
*Based on a 3D mechanistic model ,*
*similar to Hoskins and Simmons (1975),*
*including atmospheric tides.*
→Next slide!

# Takagi and Matsuda (2007)

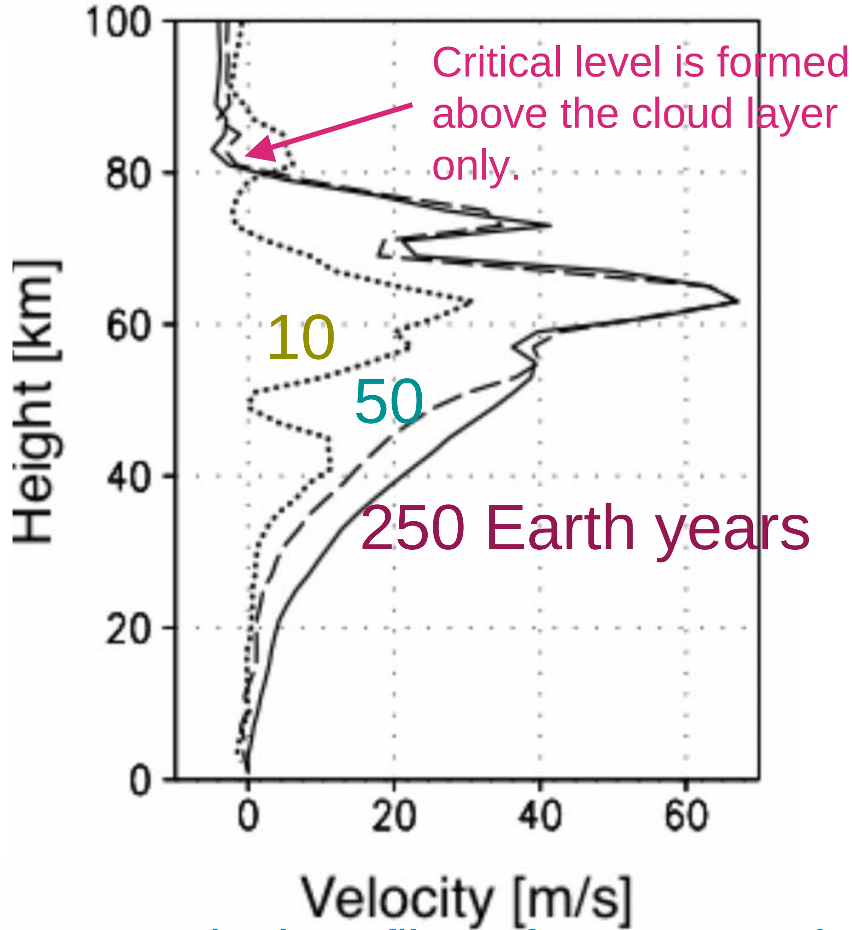
**Mean zonal flow generated by the tidal mechanism**

**Meridional circulation is not included.**

Mean zonal flow: U(y, z)




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.

# Japanese Venus GCM research group

Yamamoto and Takahashi (2003; …)
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*Based on CCSR/NIES GCM (Numaguti 1997)*
→Today's talk

Takagi and Matsuda (2007)
*Based on a 3D mechanistic model ,*
*similar to Hoskins and Simmons (1975),*
*including atmospheric tides.*

# Venus modeling by CCSR/NIES GCM

## Contents

1. Simplified Venus GCM using Newtonian cooling

Application to Venus superrotation
(Yamamoto and Takahashi, 2003, 2006 JAS)
Polar Vortex ?

Application to parametric experiments
(Yamamoto and Takahashi, EPSC2008)

2. Venus middle atmosphere GCM (VMAGCM)

Preliminary experiments
(Yamamoto and Takahashi, 2007 EPS)

3. Venus GCM including radiative process

(Ikeda et al., EPSC2008)

# Recent simplified Venus GCMs using Newtonian cooling

## SR is classified by two mechanisms

**Zonal mean heating**

**SR by meridional circulation**

Yamamoto and Takahashi (2003)
Lee et al. (2005)
Hollingsworth et al. (2007)
Richardson et al. (2007)

**<problem>**

**Thermal tides are not included in this model.**

**Solar heating rate is not realistic.**

**Thermal tide forcing**

**SR by thermal tides**

Takagi and Matsuda (2007)

**<problem>**

**Zonal flow near 20 km is weaker than observation.**

**Meridional circulation (zonal mean heating) is not included.**

# Recent simplified Venus GCMs using Newtonian cooling

## SR is classified by two mechanisms

**Zonal mean heating**

**SR by meridional circulation**

Yamamoto and Takahashi (2003)
Lee et al. (2005)
Hollingsworth et al. (2007)
Richardson et al. (2007)

**Thermal tide forcing**

**SR by thermal tides**

Takagi and Matsuda (2007)

↓

**3D heating (including zonal mean heating & thermal tide forcing)**

**Yamamoto & Takahashi (2006) includes both merdional circulation and thermal tides**

# Recent simplified Venus GCMs using Newtonian cooling

## Model description (Yamamoto & Takahashi 2006)

- T21L52 CCSR/NIES AGCM ver.5.6 (*Numaguti et al.* 1995)

(Tech. Rep. http://www-cger.nies.go.jp/cger-e/e_report/r_index-e.html I025-'97 )

- Simplified physical process (using Newtonian cooling)

3D solar heating profile with the maximum level of 65 km.

Latitude difference of 10 K between the equator and the pole at the surface.

Frictional drag of 3 days in the thin undermost layer ($\Delta\sigma$ = 0.01).

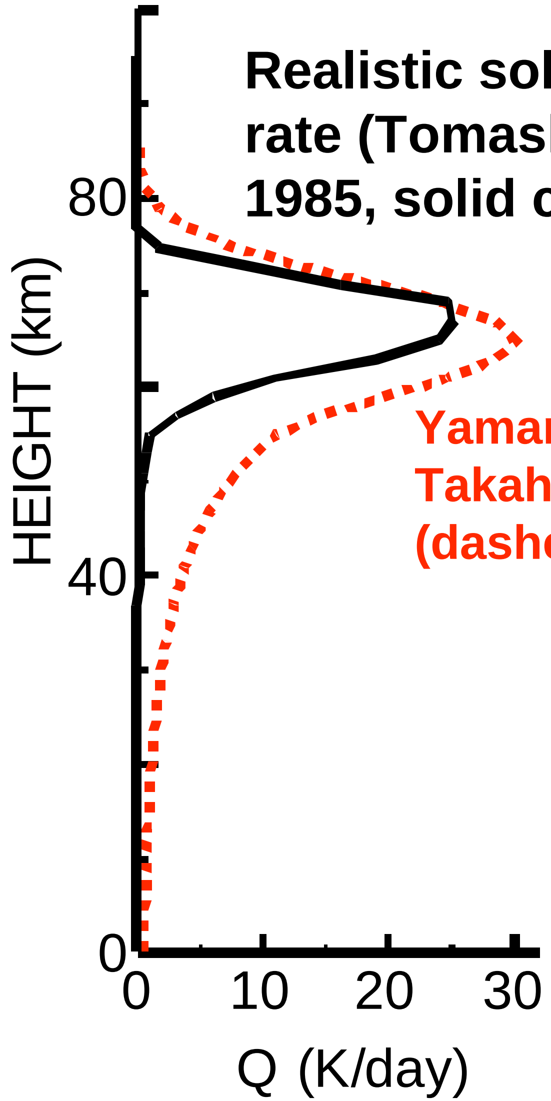
The 4th order horizontal diffusion of 4 days at the maximum wavenumber.

Rayleigh friction of 30 days near the top boundary.

Constant vertical eddy diffusion with Kv = 0.15$m^2$/s is set.

Rayleigh friction for eddy horizontal flow with the same time constant of Newtonian cooling.

# 3D solar heating rate (K/day) and SR




**Realistic solar heating rate (Tomasko et al. 1985, solid curve)**

**⇒ SR is NOT formed in the lower atmosphere.**

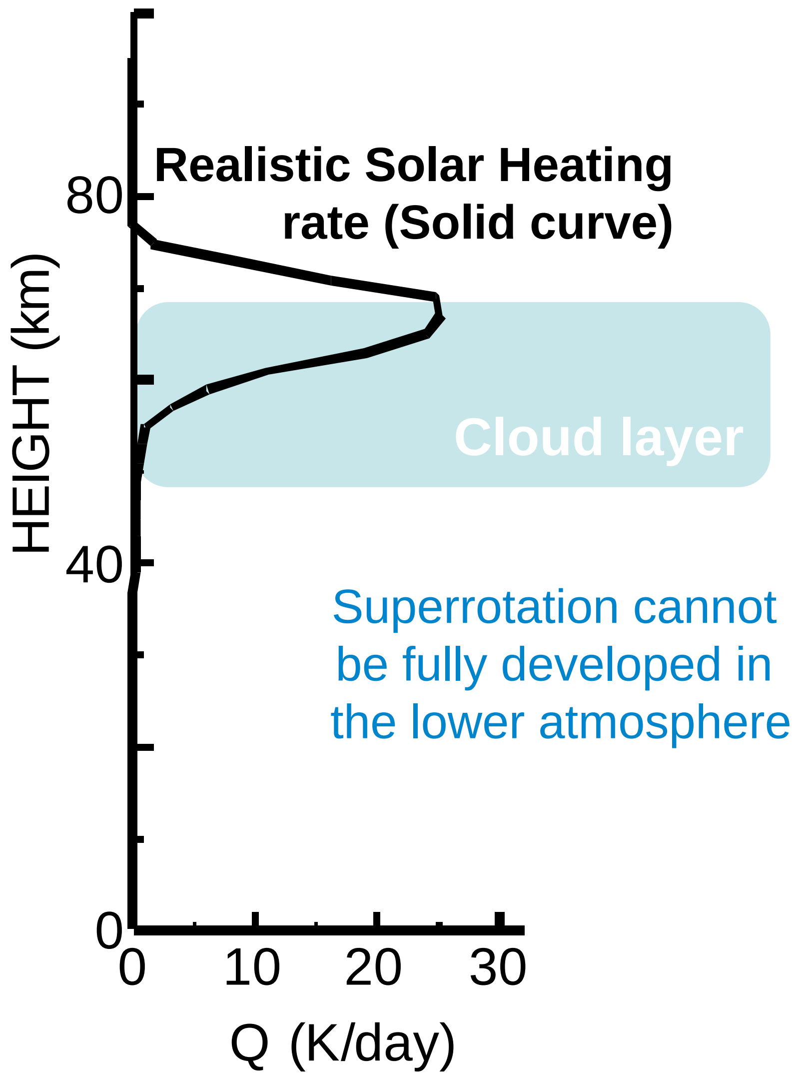
**Yamamoto and Takahashi (2006) (dashed curve)**

**⇒ SR is formed in the lower atmosphere.**

**At the present stage, additional heating is required in order to reproduce SR in the lower atmosphere. This is open issue as commented by Hollingsworth et al. [2007]**

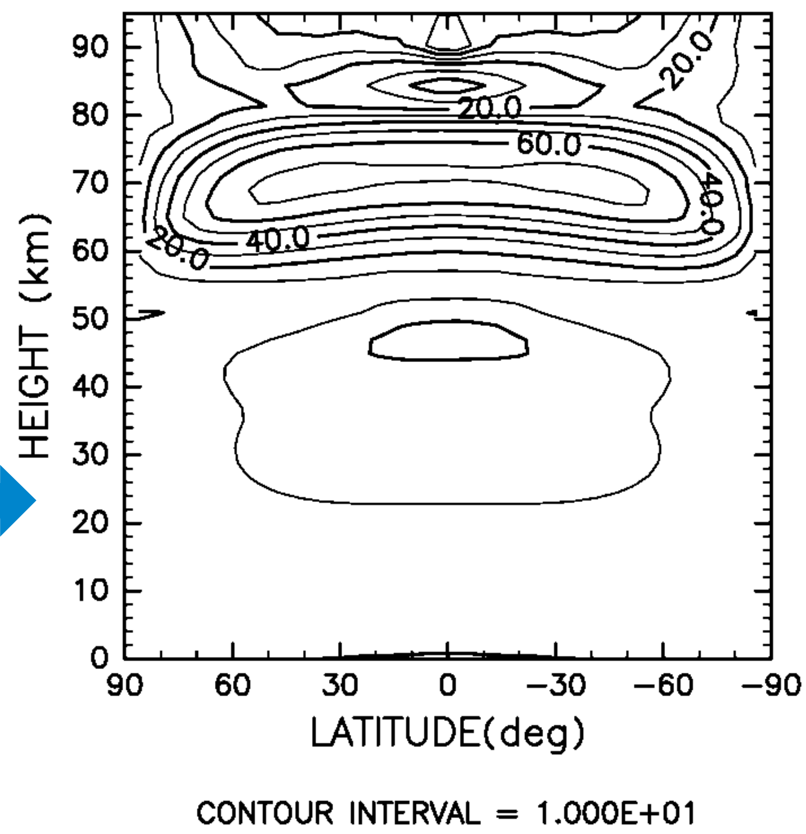
# 3D solar heating rate (K/day) and SR

Tomasko et al. (1985)



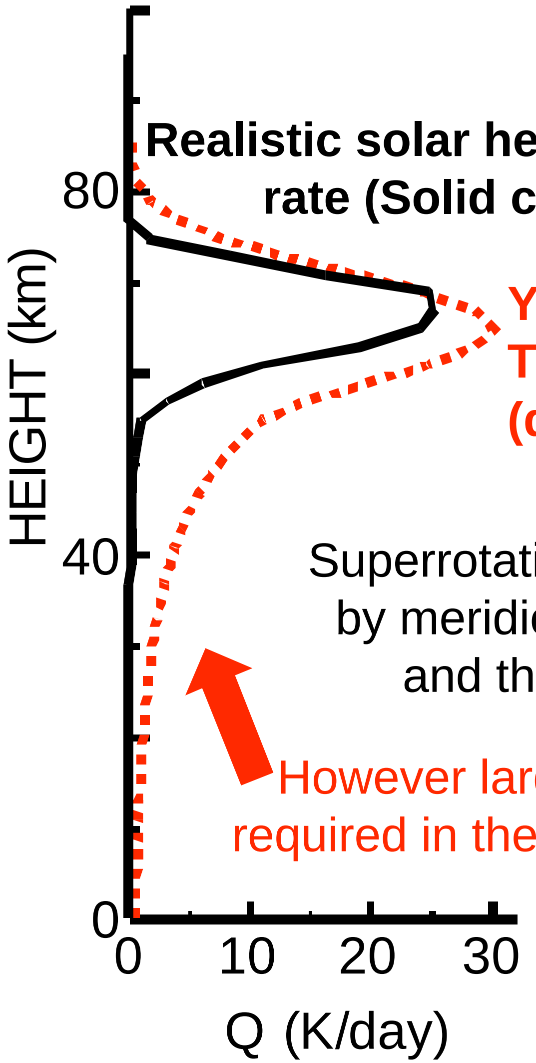

Superrotation cannot be fully developed in the lower atmosphere

**Mean Zonal Flow** (m/s)



# <u>3D solar heating rate</u> (K/day) and SR

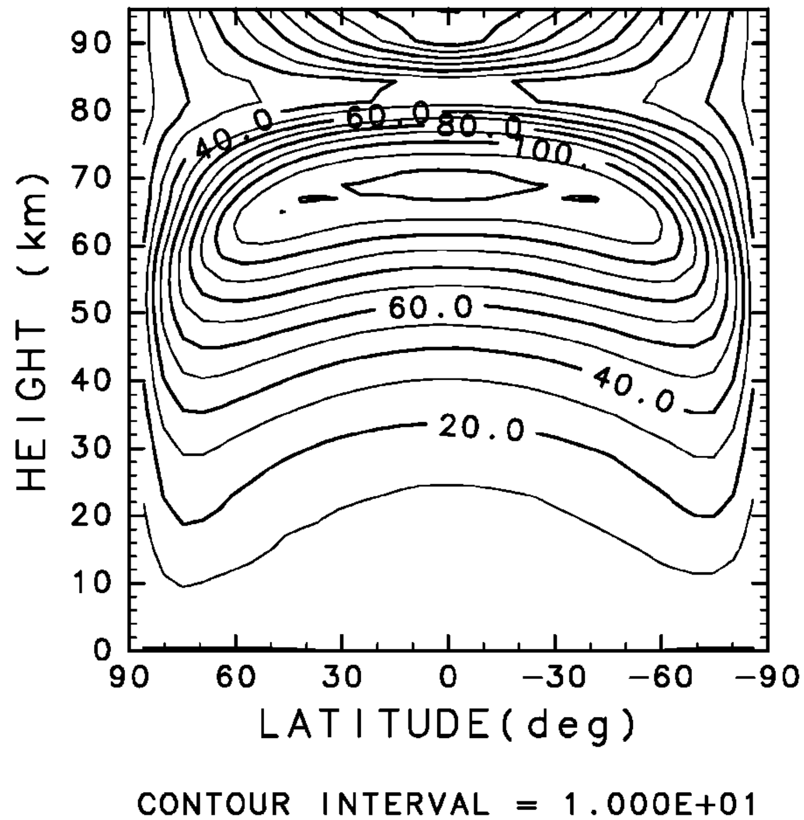
Yamamoto & Takahashi (2006)




Superrotation is maintained by meridional circulation and thermal tides.

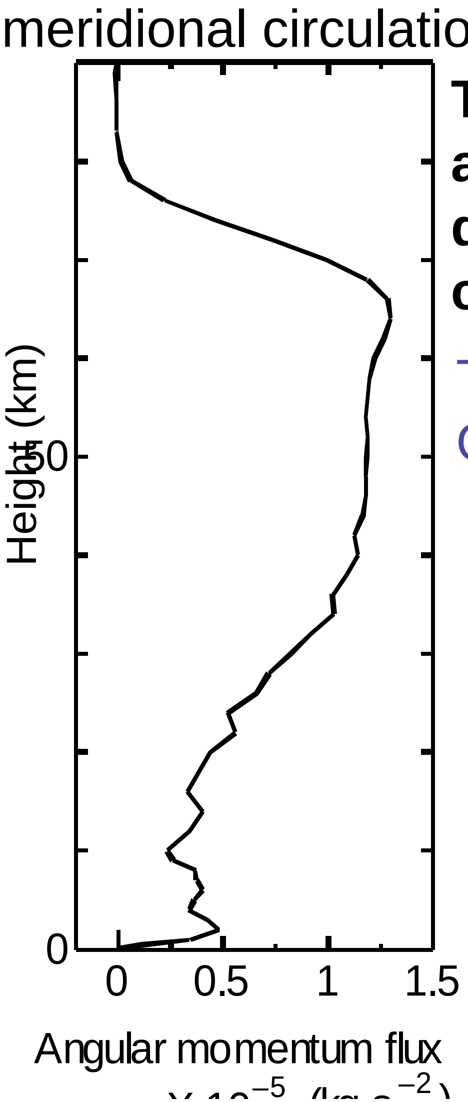
However large heating rate is required in the lower atmosphere

Mean Zonal Flow (m/s)



# Yamamoto & Takahashi (2006)

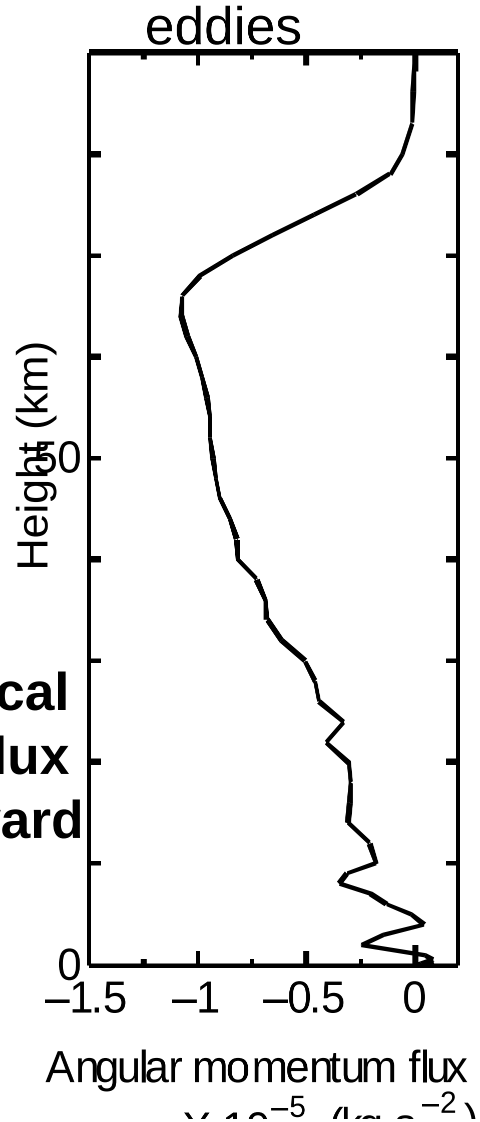
## *Global mean angular momentum fluxes*




**The global mean vertical angular momentum flux due to mean meridional circulation is upward.**

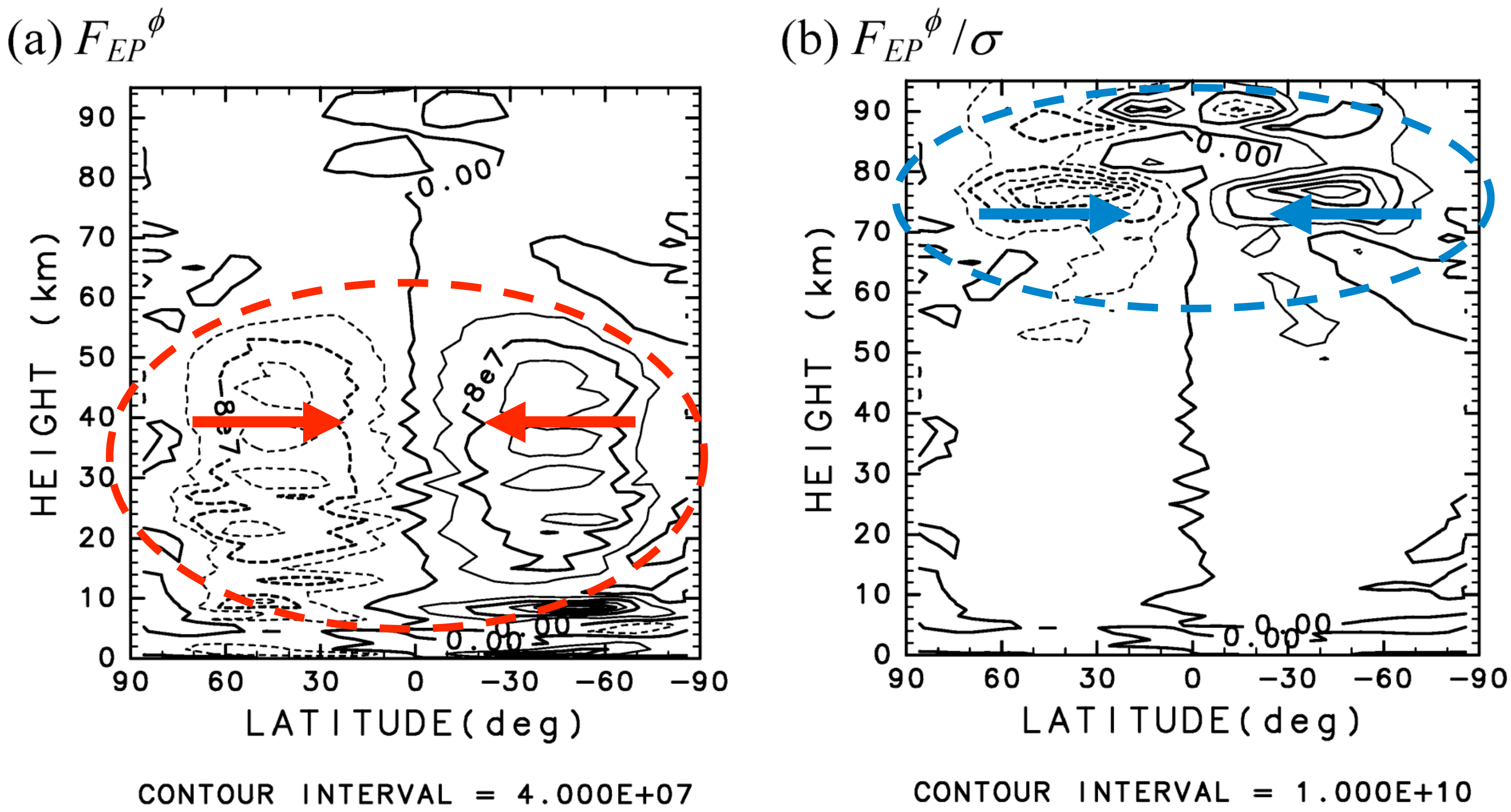
This supports the Gierasch mechanism

**The global mean vertical angular momentum flux due to eddies is downward**



# Yamamoto & Takahashi (2006)

## Horizontal eddy angular momentum transport

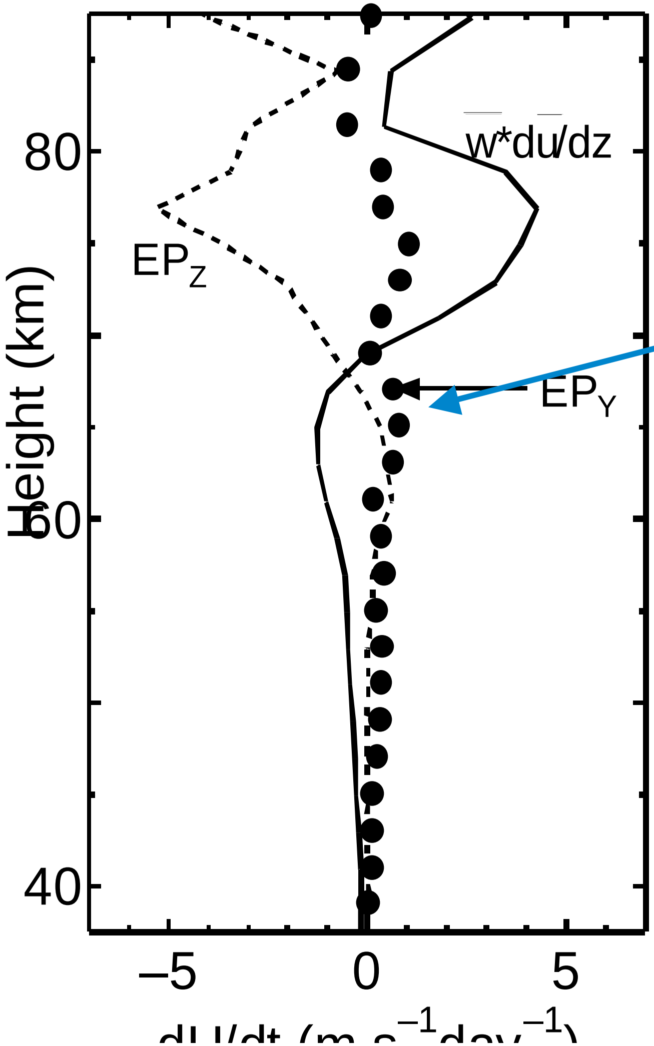



Shear instability
Kelvin wave & Rossby wave

Thermal tides

# Yamamoto & Takahashi (2006)

## Equatorial acceleration balance near the cloud top




**EPY and EPZ of thermal tide maintain SR near the cloud top.**

## Yamamoto & Takahashi (2006)

## Comparison with observations

(1) SR is reproduced in the middle and lower atmosphere

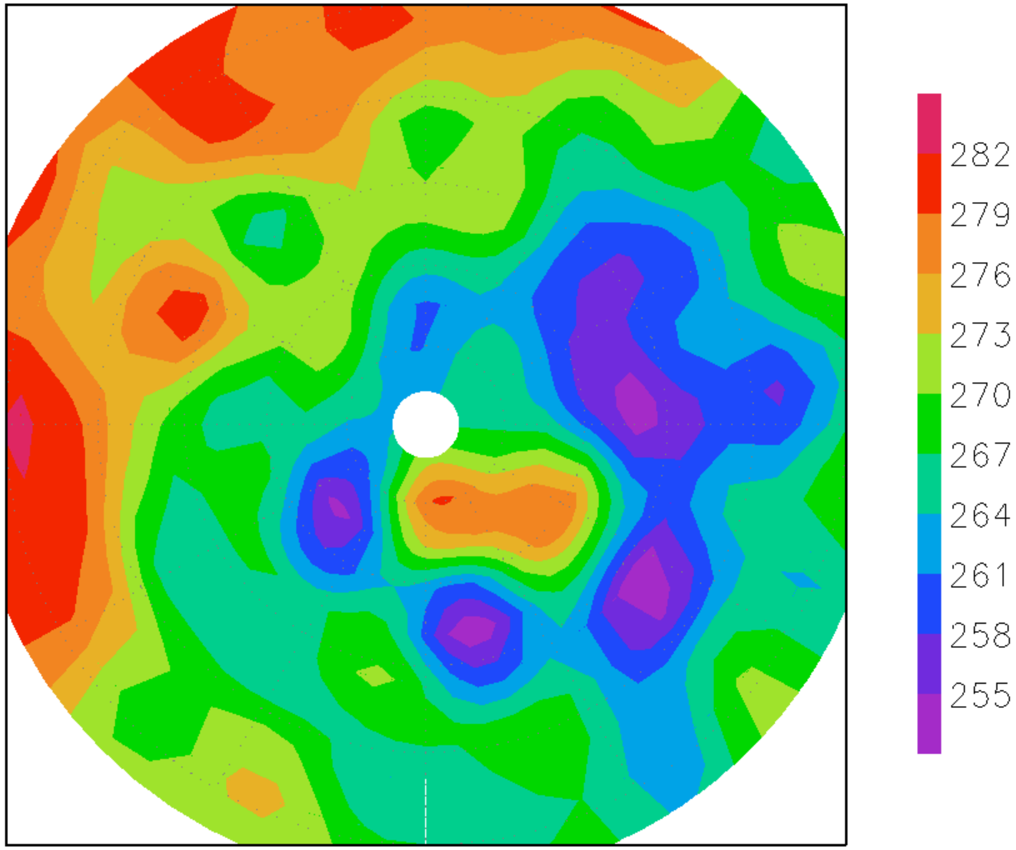
(2) Diurnal thermal tides are similar to the OIR observation

(3) Semidiurnal thermal tides are smaller than the OIR observation

(4) NIR 5.5 day markings (Crisp et al 1991) correspond to the Kelvin wave

Now we are investigating the polar vortex.

# Polar vortex simulated in Yamamoto and Takahashi (2006)




T (K) at 61 km

Next purpose is to elucidate dynamics of ***polar dipole*** and ***polar collar***.

Large amplitude modulation (single eye ↔ dipole)

# Parametric GCM experiments based on Yamamoto & Takahashi (2006)

1. Sensitivities of SR to astronomical parameters
(Yamamoto & Takahashi 2007, GRL)
(Yamamoto & Takahashi 2008, Astron. Astrophys.)

Not shown now, because this is not directly related to Venus.

2. Sensitivities of SR to lower-atmospheric heating
(Yamamoto & Takahashi , EPSC2008)

Hollingsworth et al (2007,GRL) have already examined two cases and discussed the importance of the lower-atmospheric heating

In our study, the wide range of the heating rate is applied

# Open issue

At the present stage, the formation mechanism of Venus Super-Rotation (SR) is still unknown.

*In particular, the driving force of SR (Thermal tides? additional radiative forcing?) in the lower atmosphere is open issue.*

# Recently, several GCM studies are conducted:

**IR radiative forcing in a Venus LMD GCM [Lebonnois et al. 2007]**

**Downward propagation of thermal tides *in the absence of meridional circulation* [Takagi & Matsuda 2007]**

**Upward propagation of gravity waves in a Venus CCSR/NIES GCM [Ikeda et al. 2008]**

# Objectives

1. To elucidate whether thermal tides can drive fully developed SR in the lower atmosphere.

**<Takagi & Matsuda , 2007>**
**Only thermal tide is included,**
**but meridional circulation is NOT.**

**<Present study>**
**Both thermal tide & meridional circulation are included in a GCM.**

2. To determine the heating rates required to reproduce the SR in the lower atmosphere

**Sensitivity of SR to lower-atmospheric heating in a simplified AGCM**

# Sensitivity to lower-atmospheric heating Qmin

## Model

**Yamamoto and Takahashi [2006]**

Changes in the present study

**Heating rate of Tomasko et al. [1985] is used in standard case.**

**Kv = 0.025 m2/s**

[Takagi & Matsuda ,2007]

**$dT_{0-90}$ = 3 K**
**at the surface and**
**in the atmosphere**

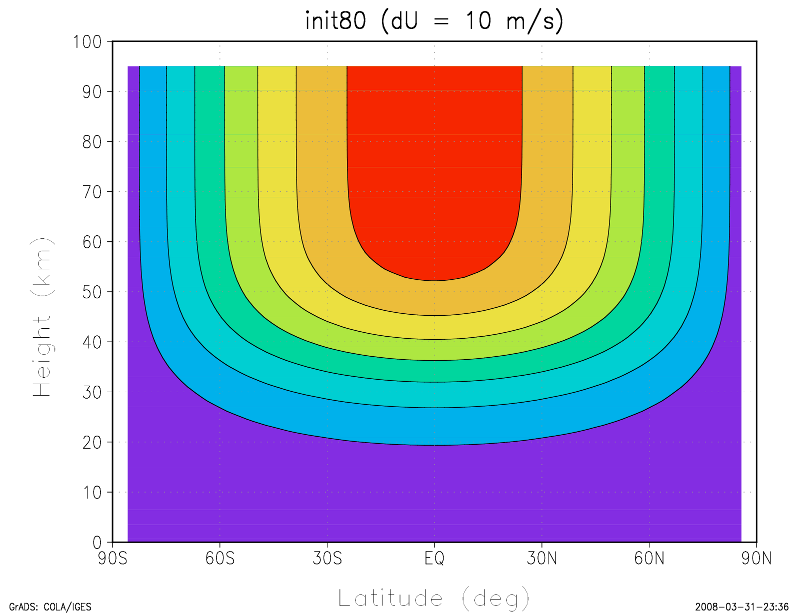
## Initial condition

**Exp. Init00**

Initial motionless state

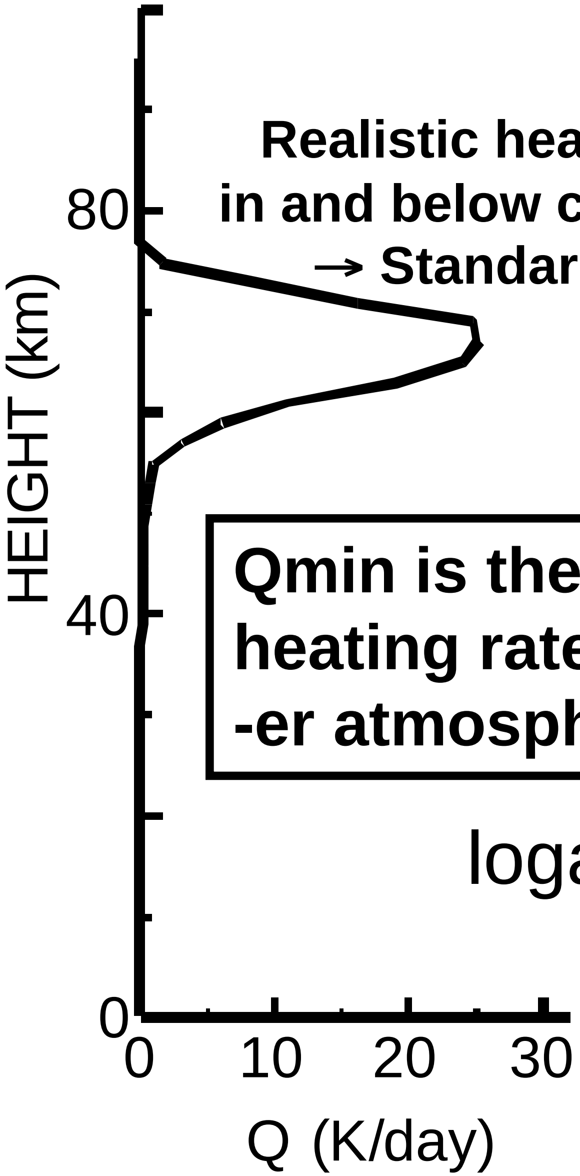
**Exp. Init80**

Initial SR state of 80 m/s



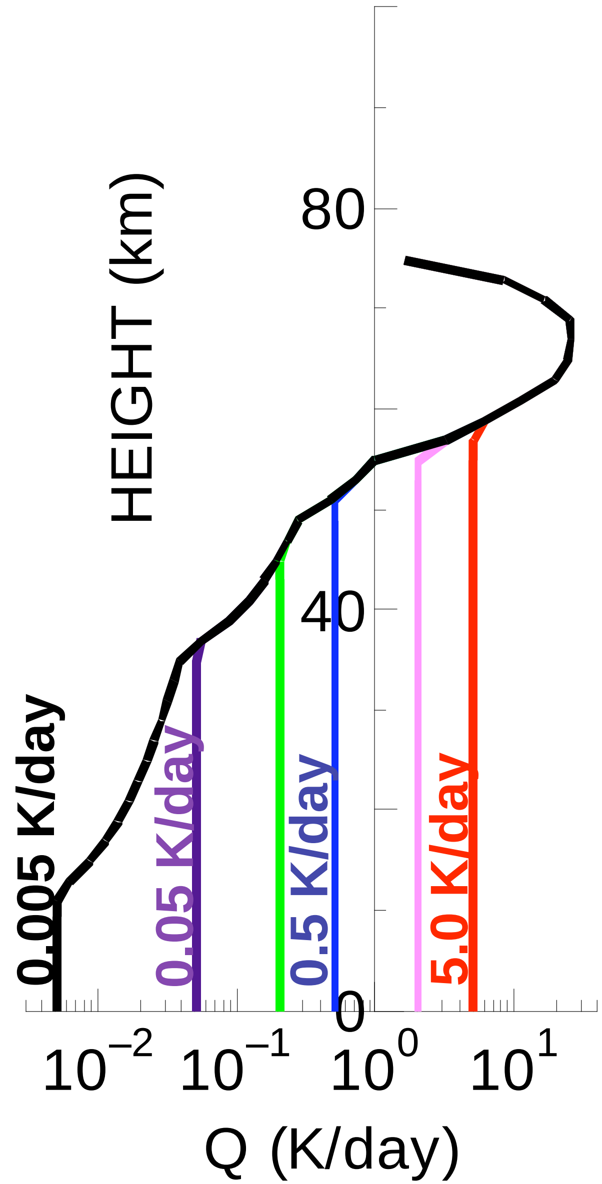
# Sensitivity to lower-atmospheric heating
# Qmin

## Heating of Tomasko et al. [1985]



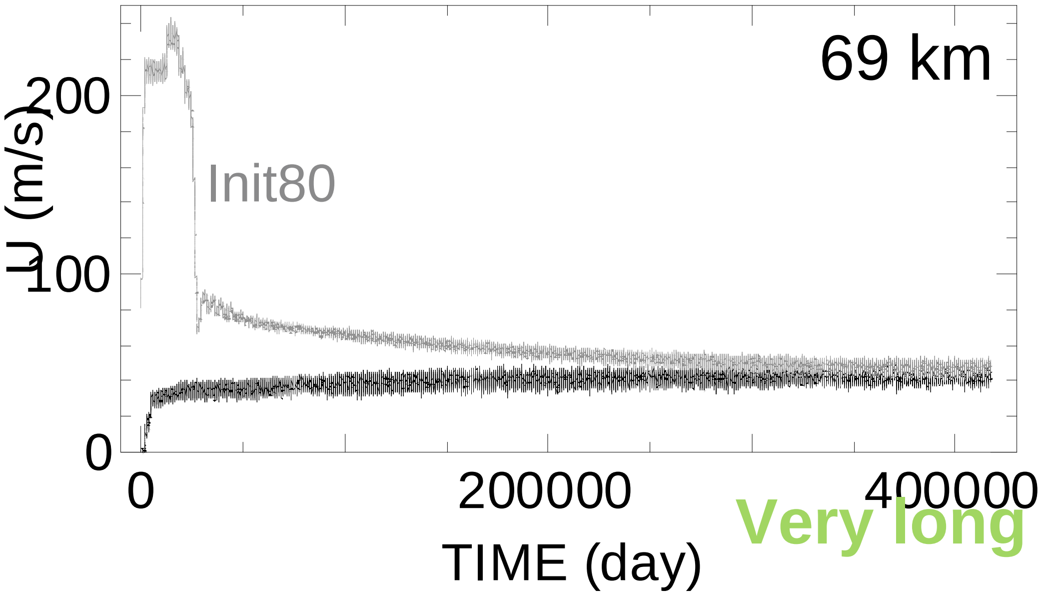

**Qmin is the minimum heating rate in the low -er atmosphere.**

logarithmic scale



# Sensitivity to weak Qmin

Qmin=0.005 K/day

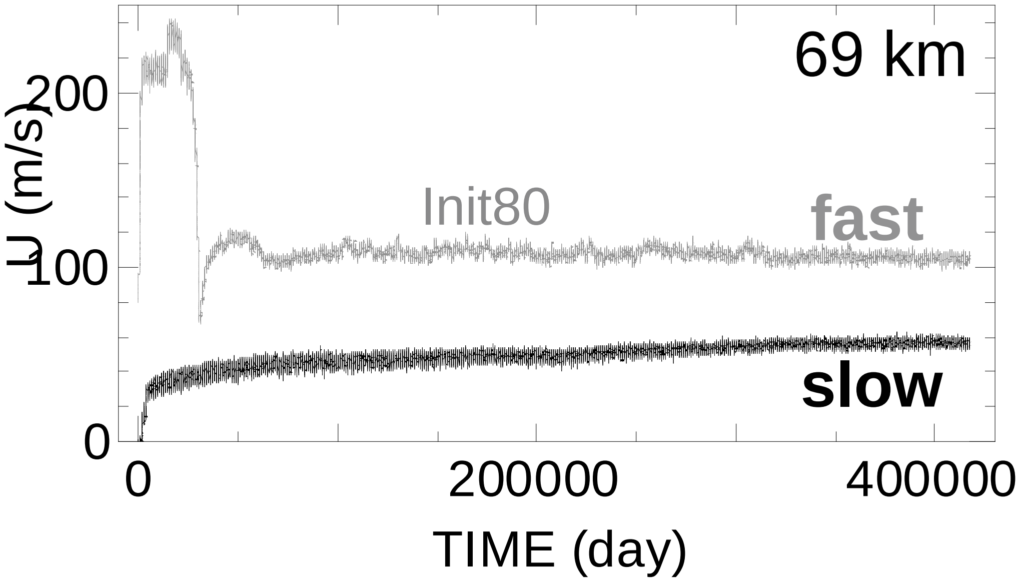



**Standard case**
Qmin=0.005 K/day at the subsolar point

<Single equilibrium>
(Del Genio et al. 1993)

Very long time!

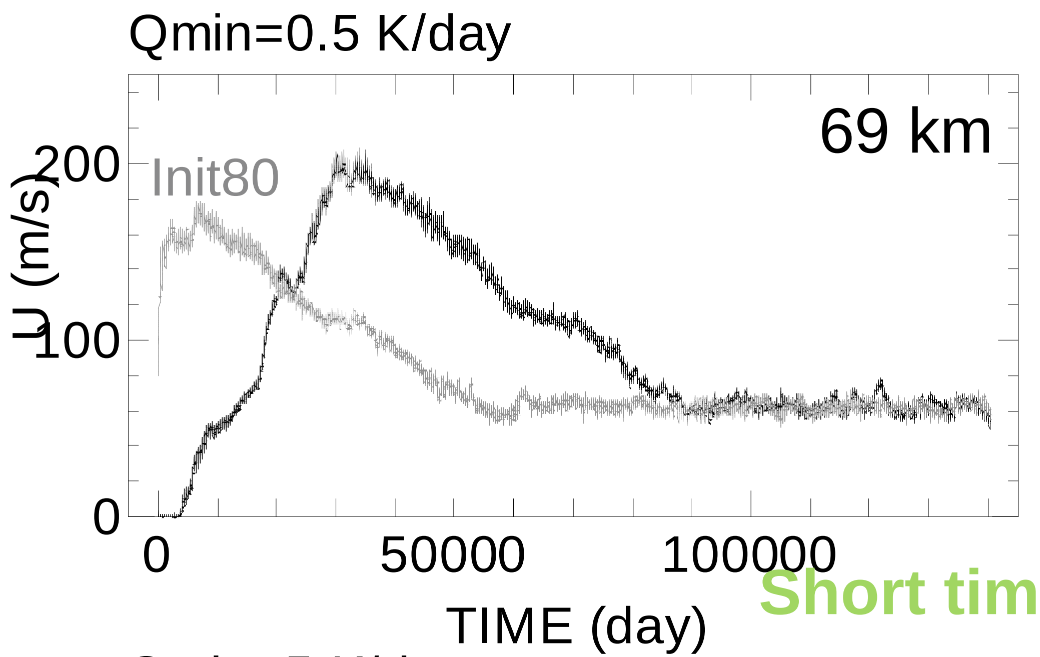
Qmin=0.05 K/day




Qmin=0.05 K/day at the subsolar point

<Multiple equilibrium>
(Suarez & Duffy 1992)
*also recent works of Kido & Wakata and Lebonnois et al.*

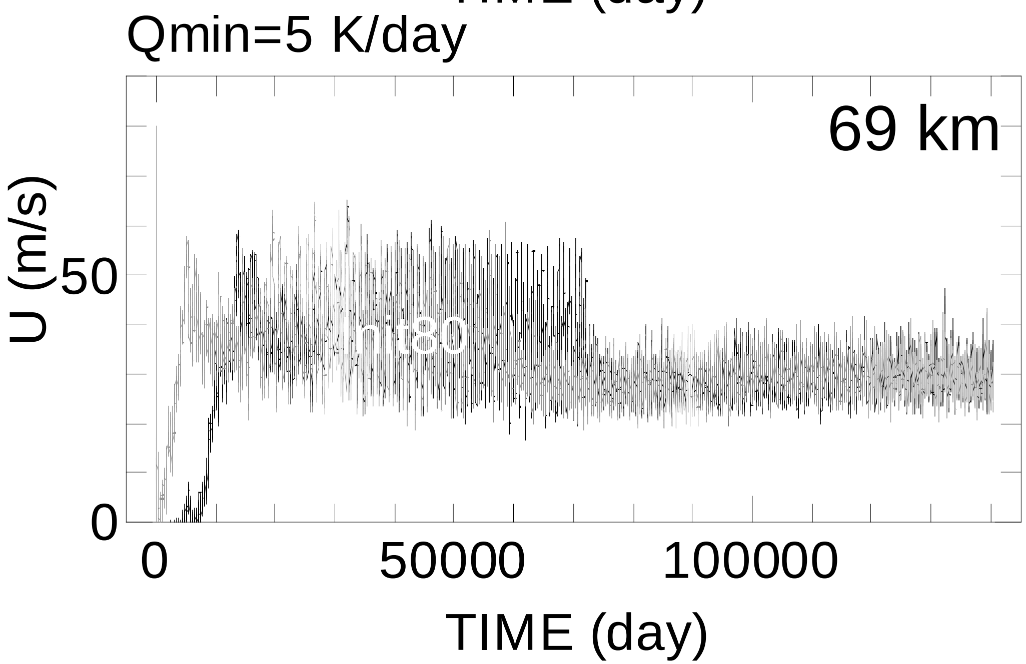
# Sensitivity to strong Qmin




Qmin: 0.5 K/day at the subsolar point

<Single equilibrium>
(Del Genio et al. 1993)

**Short time, compared on weak Qmin**

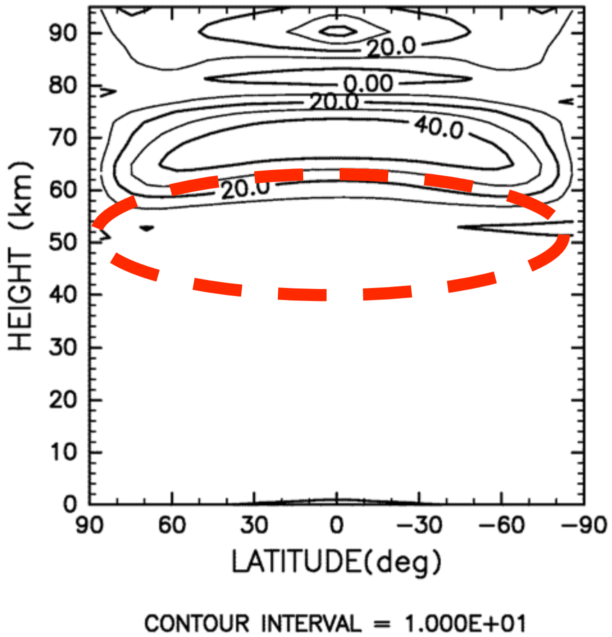



Qmin: 5.0 K/day at the subsolar point

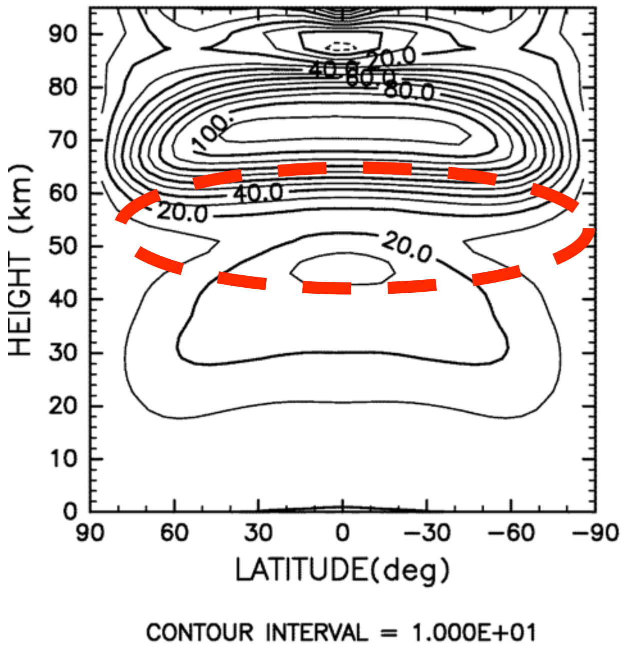
<Oscillation>
periods of ~1000 days
Year-to-year variation ?
(Rossow et al. 1990)

# Sensitivity to lower-atmospheric heating Qmin

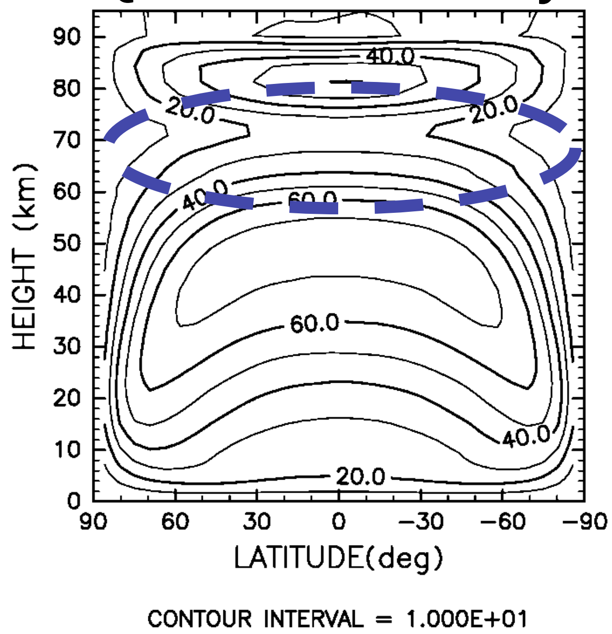
Qmin: 0005 K/day




Qmin: 0.05K/day




Qmin: 5.00K/day




SR is not formed below the cloud.

⇩

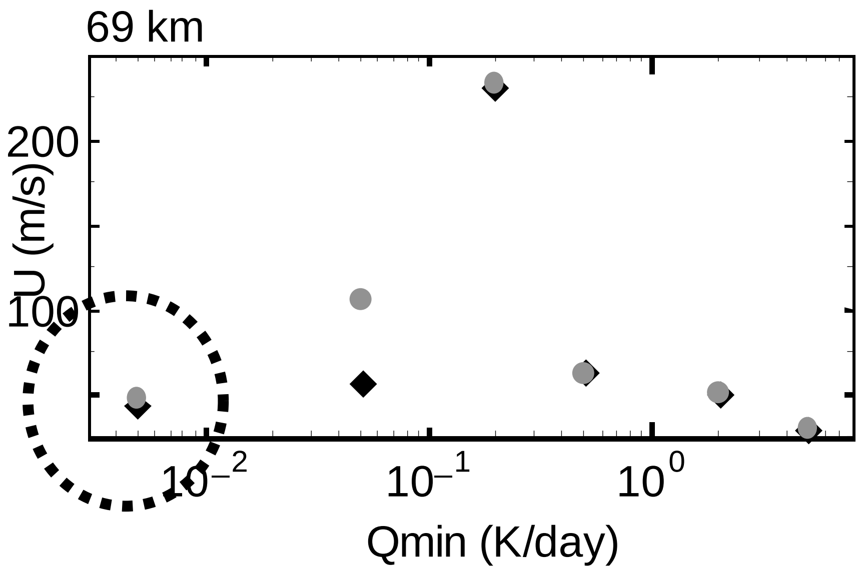
It is difficult for thermal tides to reproduce the SR below the cloud.

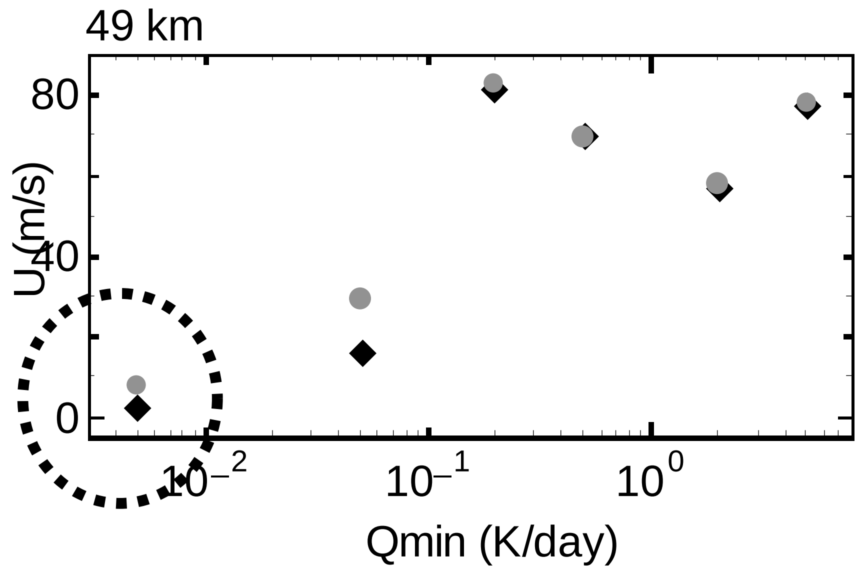
Meridional circulation reproduces the SR below the cloud.

SR is not formed at the cloud top.

# Summary(1)

## <Sensitivity to lower-atmospheric heating>



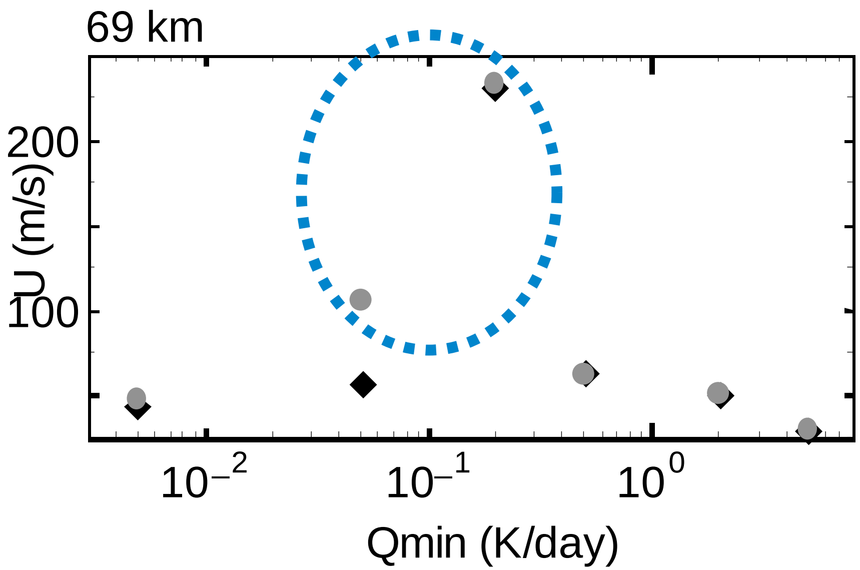

1. It is difficult for thermal tide and meridional circulation to reproduce realsitic SR for weak solar heating rate.

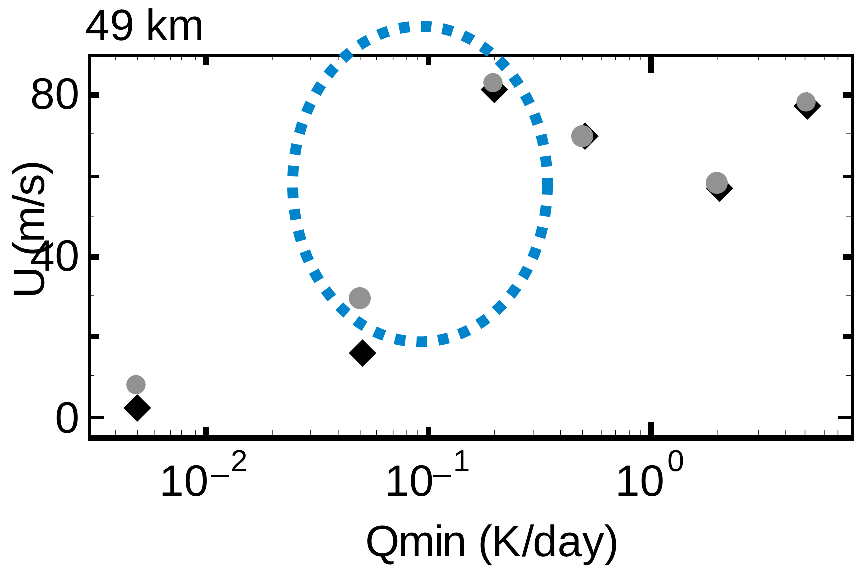
**We must consider additional driving forces of SR as follows:**

**Radiative forcing (e.g., *IR or NIR heatings*)**

**Eddy momentum sources (e.g., gravity waves)**

# Summary(2)
## <Sensitivity to lower-atmospheric heating>

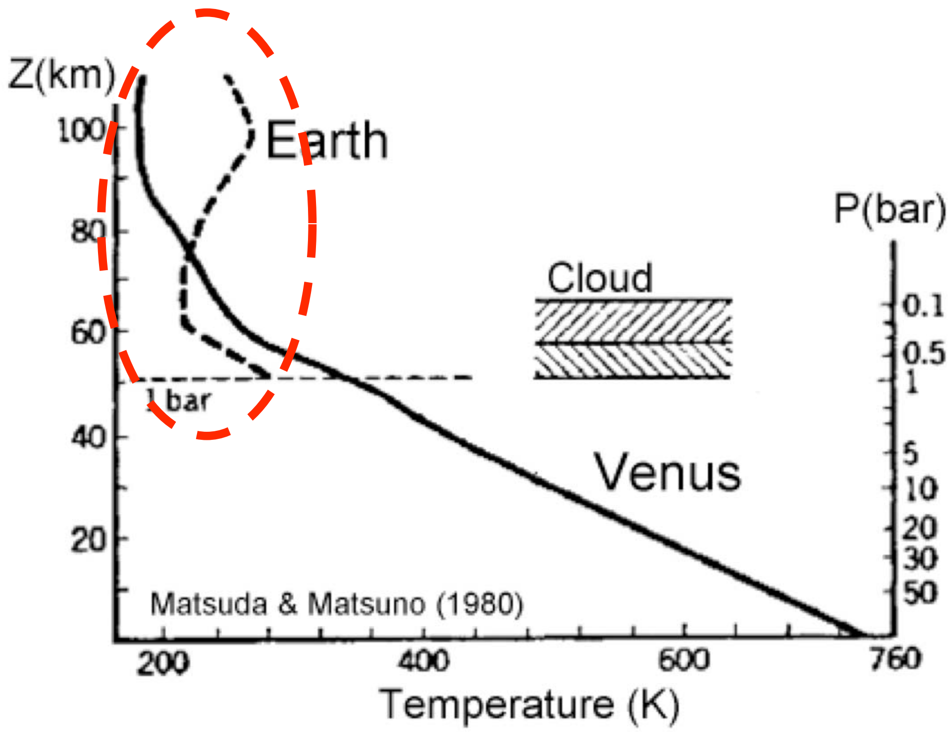



2. Under the condition that additional radiative forcing of Qmin~ 0.1 K/day (~ 0.02 K/day for the global mean),
SR is fully developed in our Venus GCM.

3. The time scale for reaching equilibrium and the bifurcation of the general circulation depend on the lower atmospheric heating rate.

# Venus Middle Atmosphere GCM(VMAGCM)




The Venus middle atmosphere are similar to the Earth atmosphere for temperature and pressure.

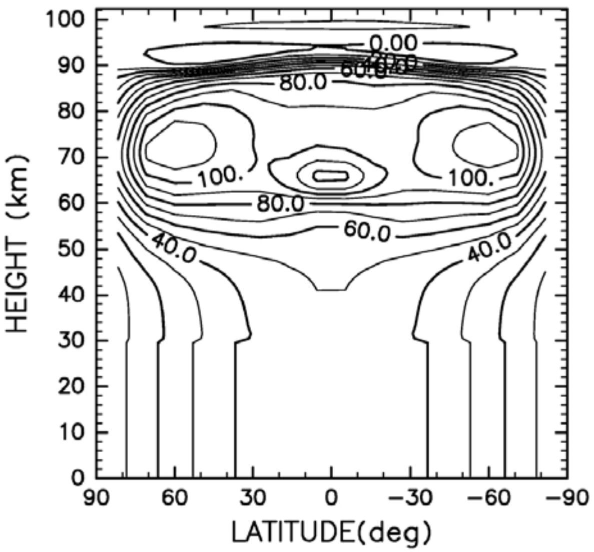
**We can apply Earth's GCM to the Venus middle atmosphere.**

**1. VMAGCM_NC (using Newtonian Cooling)**

**2. VMAGCM_RP (including radiative process) (Yamamoto and Takahashi 2007, EPS)**

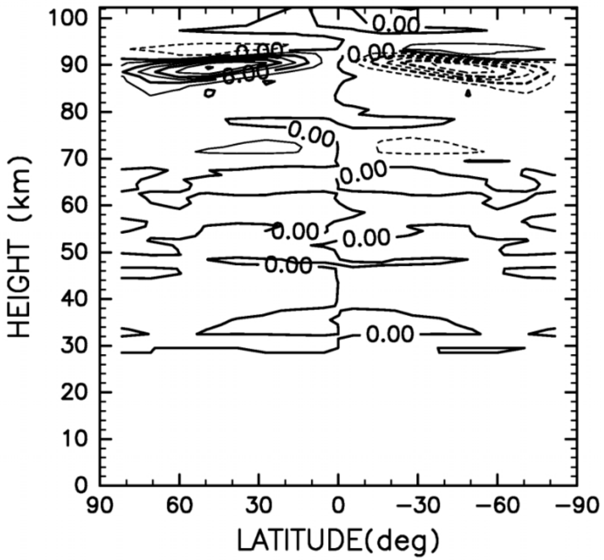
# T10L100 VMAGCM_RP (using radiative process)
# (Yamamoto and Takahashi 2007, EPS)

U



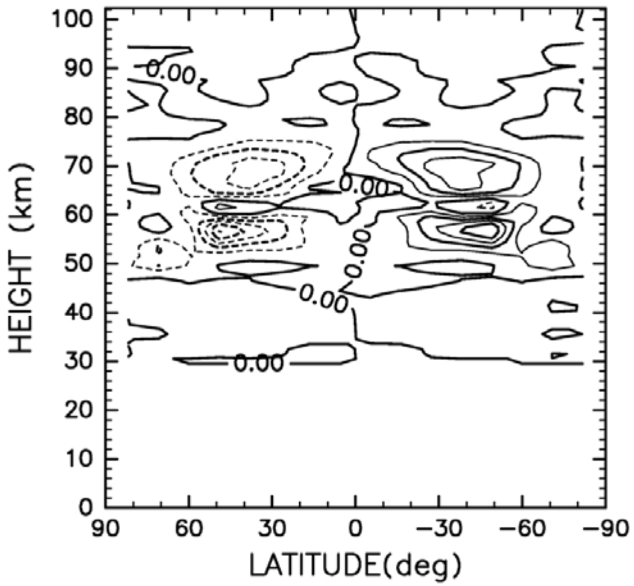

CONTOUR INTERVAL = 1.000E+01

V




CONTOUR INTERVAL = 3.000E+00

Horizontal EP flux




CONTOUR INTERVAL = 5.000E+06

We can simulate the middle atmospheric structures of Venus.

Furthermore, we can estimate the eddy momentum fluxes;
e.g. [u’v’] = 9.57 m2/s2 for diurnal tide at 71 km & 38deg lat.
[u’v’] = 4.14 m2/s2 for semiduirnal tide at 71 km & 38deg lat

# Venus Middle Atmosphere GCM(VMAGCM)

**At the present stage of VMAGCM**

**If the observational grid data are produced, we expected to simulate more realistic simulation in the middle atmosphere by using the 3D nudging method.**

⬇

**This contributes to the estimate of meridional circulation and eddy momentum flux**

# Toward realistic Venus modeling
(Ikeda, Yamamoto, and Takahashi 2008)

## Simplified Venus GCMs

Radiative processes are simplified by solar heating
and Newtonian cooling.
⇒ SR induced by IR and NIR forcing cannot be simulated

⬇

## Development of a GCM including radiation

In this study, we develop a new Venus AGCM
(based on CCSR/NIES/FRCGC AGCM).
In our model, radiative transfer is calculated.
We try to reproduce the Venus atmospheric superrotation
under the realistic condition.

# Model

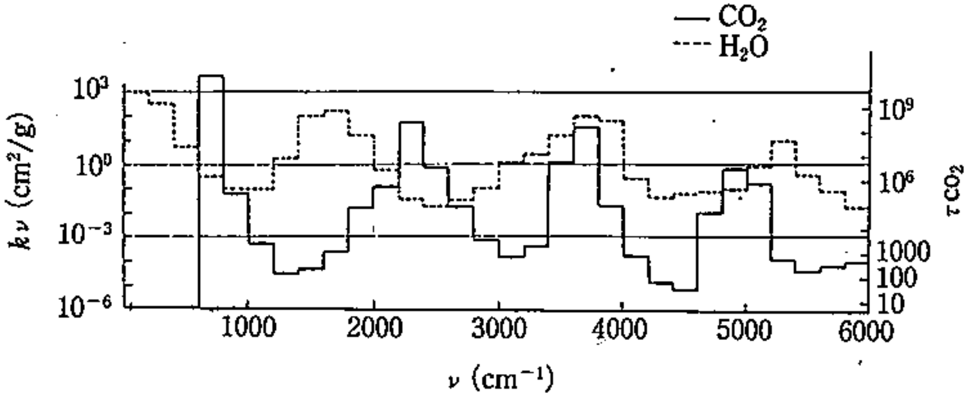
## CCSR/NIES/FRCGC AGCM ver. 5.7b

- Resolution: T21L52 (0-95 km)
- Radiative code: Two-stream with 18 ch. (Nakajima et al., 2000)
- Absorption coefficients in the infrared region of $CO_2$ and $H_2O$:
  Matsuda and Matsuno (1978)
- Cloud optical properties and vertical distributions :
  Crisp (1986, 1989)
- Vertical distribution of water vapor: Crisp (1986)
- Vertical diffusion coefficient: 0.8 $m^2\ s^{-1}$
- Dry convective adjustment
- One solar day: 117 Earth days
- Initial condition: Isothermal atmosphere (730K) at rest.
  Surface pressure is $9.2\times10^4$ hPa.

# Absorption by gas in the infrared region

- Absorption coefficients in the infrared region of $CO_2$ and $H_2O$
  - Matsuda and Matsuno (1978) : Radiative-convective equiribrium in the Venus atmosphere
  - Absorption coefficients are determined by their works and set in bands of CCSR/NIES/FRCGC AGCM radiative transfer code.
  - Absorption coefficients are proportional to the pressure.

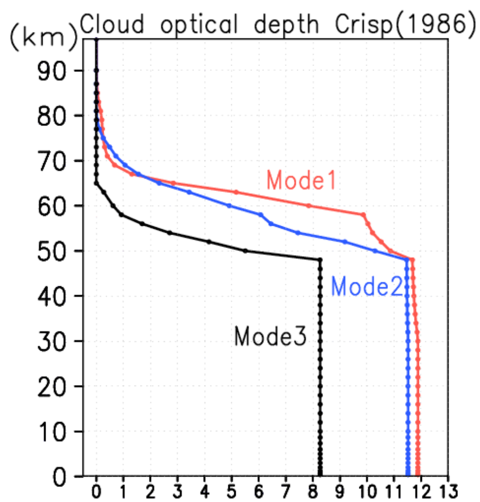
Matsuda and Matsuno (1978)



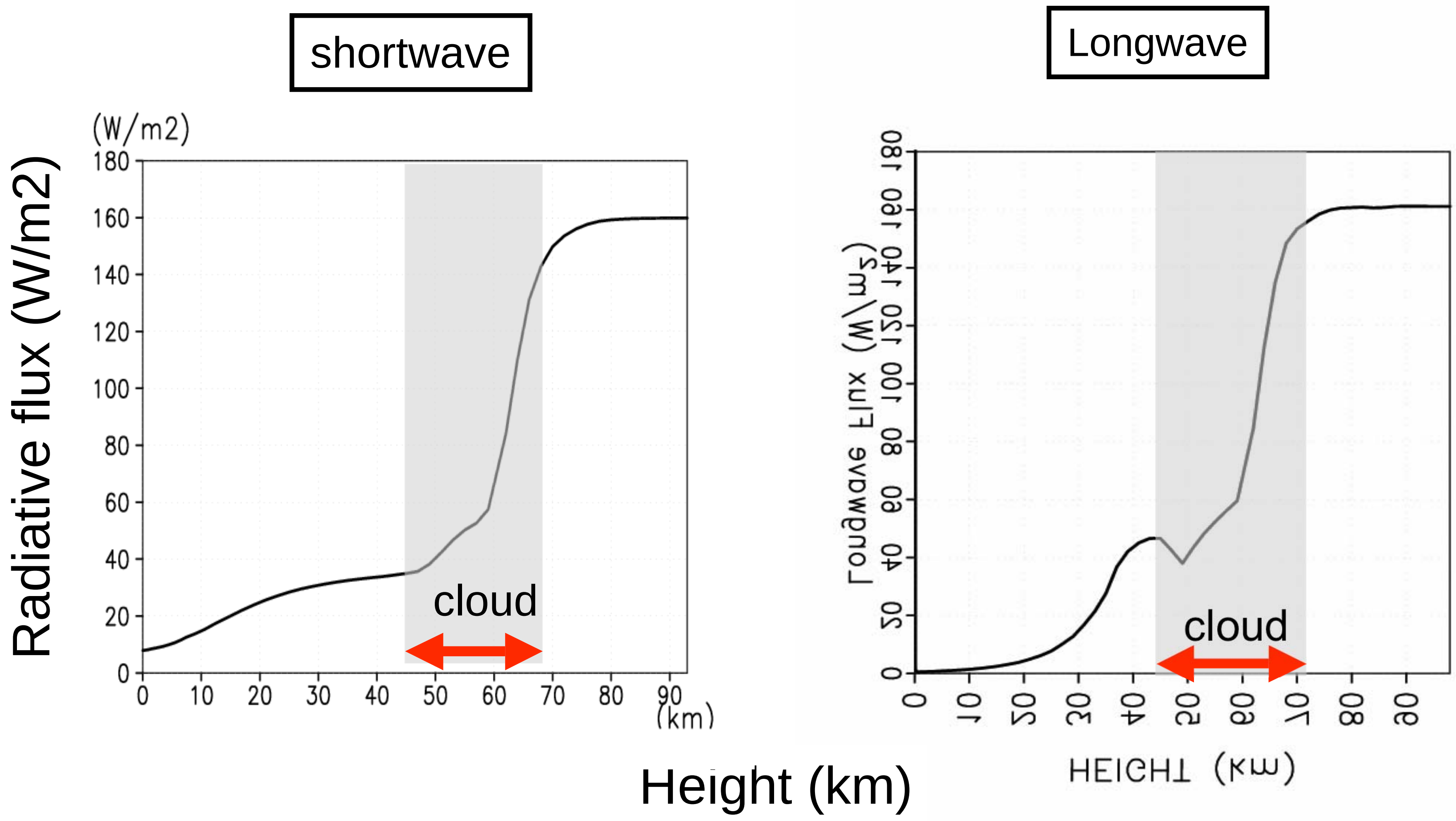

Infrared absorption coefficients of $CO_2$ and $H_2O$ at standard pressure (Matsuda and Matsuno, 1978).

# Absorption and scattering by Venus cloud

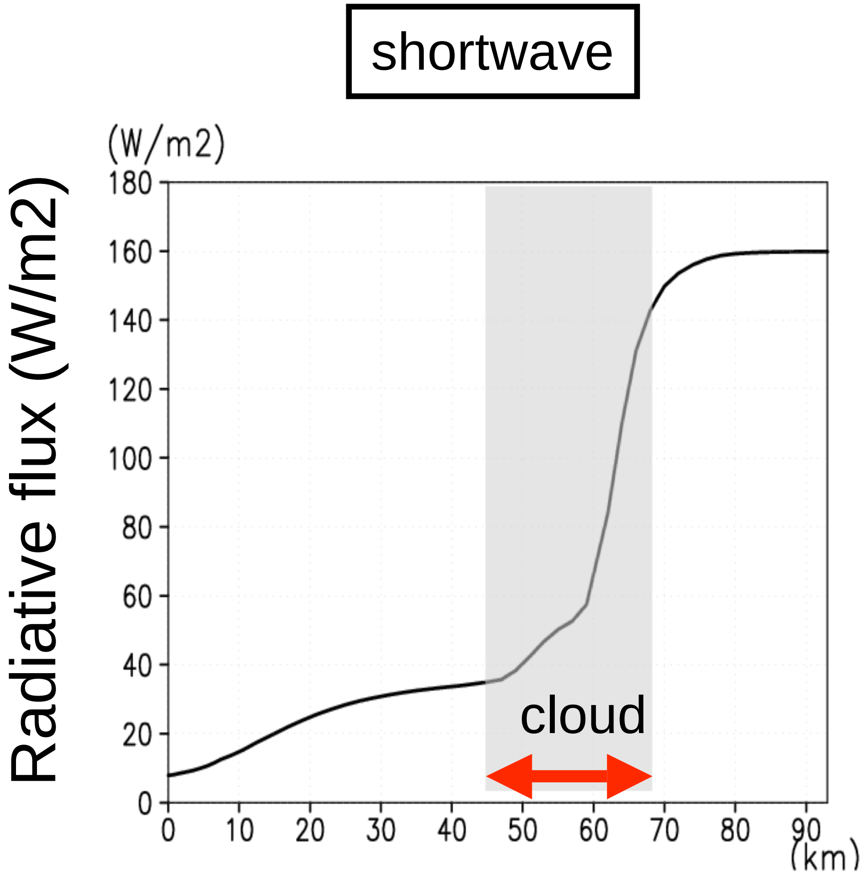
- Crisp (1986,1989)
  - Venus cloud is composed of $H_2SO_4$ aerosol with there distinct size distributions.
  - Size distribution: log-normal distribution (Pollack et al., 1980)
  - Refractive index: $H_2SO_4$(75%)
    - Palmer and Williams (1975)
    - Pinkley and Williams (1976)
  - Extinction efficiencies ($Q_e$), absorption efficiencies ($Q_a$), and scattering asymmetry parameters (g) are set in 18 bands.
  - Vertical distribution: Optical depth at 0.63μm (Tomasko et al., 1980)
- We assume that the cloud is horizontally uniform.

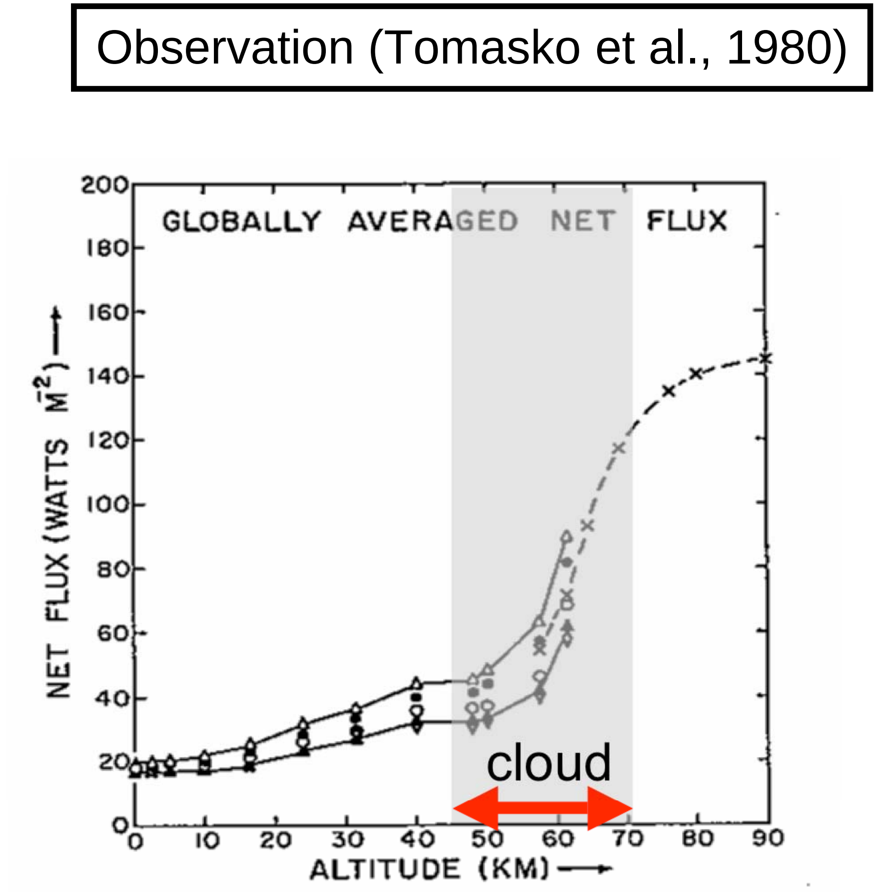


# Globally averaged net radiative flux



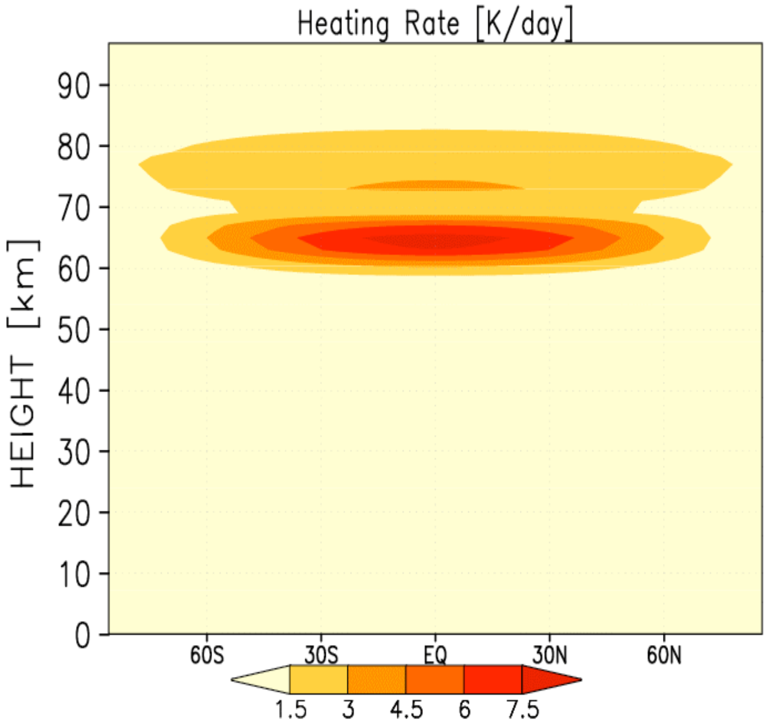
# Globally averaged net shortwave flux

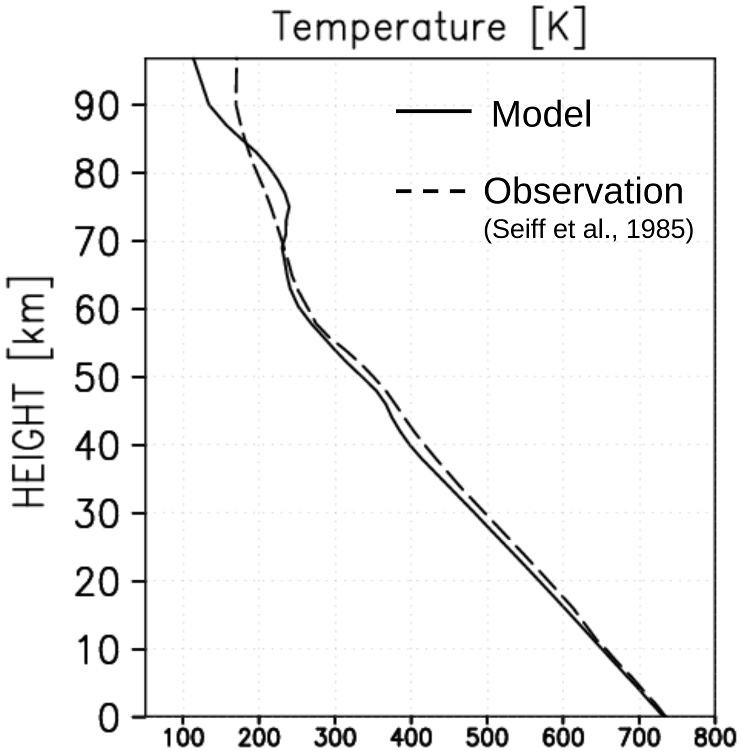



- Much of the solar flux is absorbed in the upper cloud.
- The net shortwave flux is consistent with the observations (Tomasko et al., 1980)

# Solar heating rate and temperature



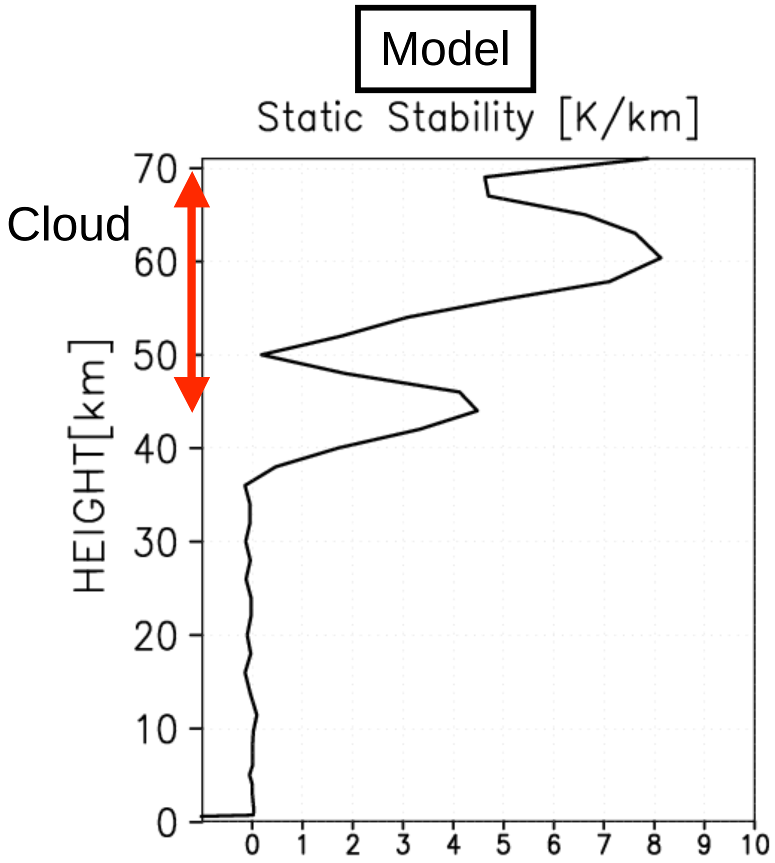




- Maximum is at 65 km altitude.
- Consistent with Crisp (1986) and Tomasko et al. (1985)

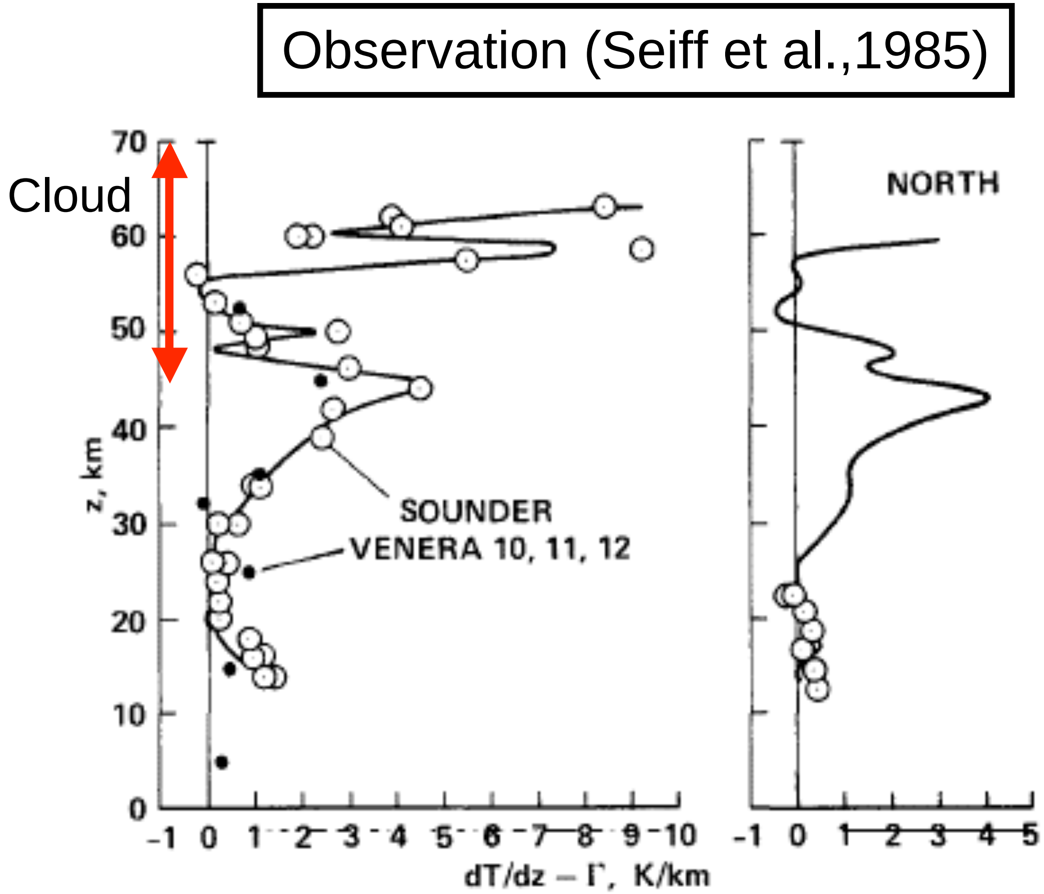
Vertical distribution of temperature at the equator

- The temperature at the lowest layer is 735K.
- The vertical structure of the temperature below 70 km is consistent with observations

# Static stability

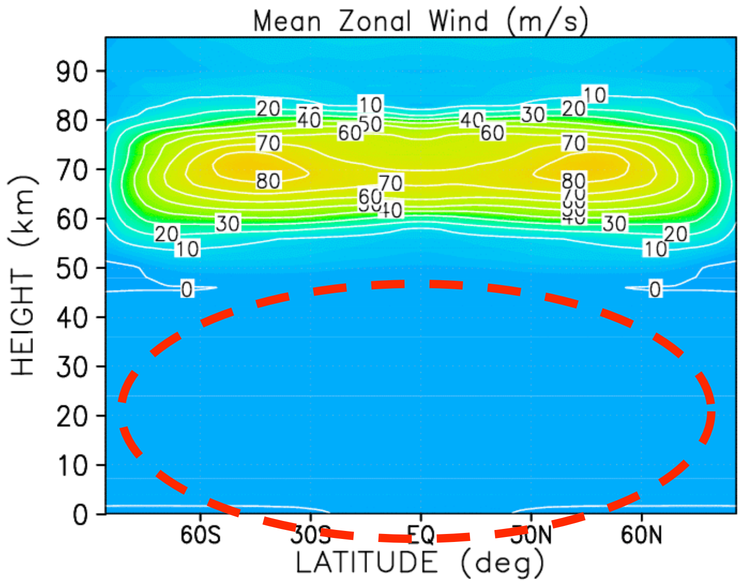


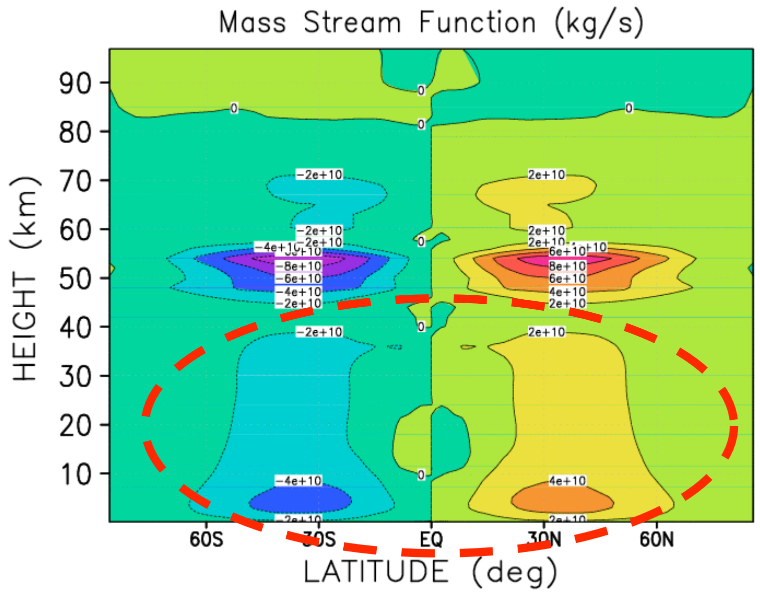

- 0–35km: neutral
- 35–45km : stable
- near 50km : neutral
- > 50km : stable




- 28–45km: stable
- near 50km : neutral
- >50km : stable

# Zonal flow and stream function




**SR is formed in the middle atmosphere**

**SR is NOT reproduced in the lower atmosphere**

**Meridional circulation is separated into two cells; Strong cloud-induced cell and weak surface cell.**

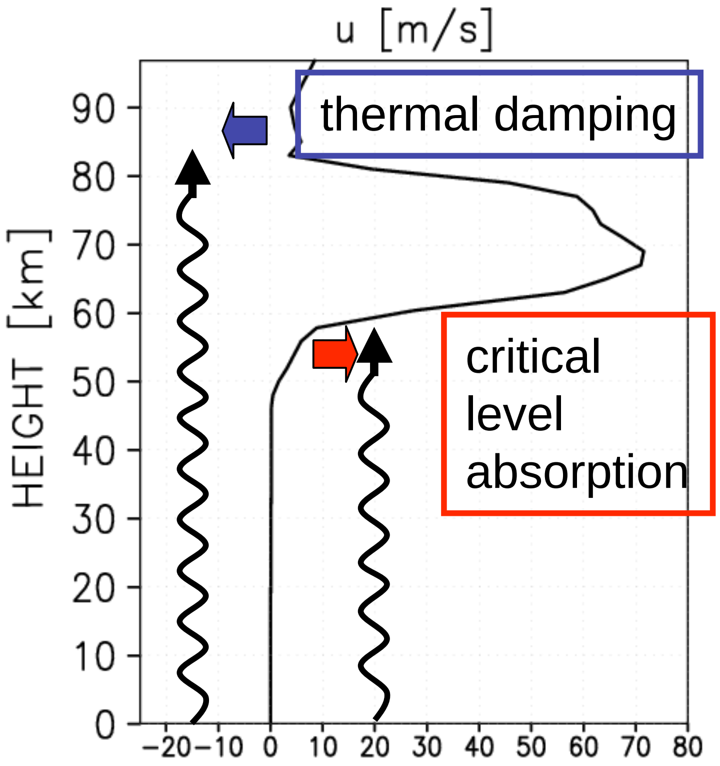
# Gravity wave forcing

- Internal gravity waves with a horizontal wavelength of 200 km are forced at the bottom of the model.
- Gravity waves with phase speeds of 15, 25, 35, 45, –15 m $s^{-1}$ are forced.
- Momentum fluxes at the bottom (F(0)) are based on Hou and Farrell (1987).
- Momentum fluxes (F(z)) are dissipated by Newtonian cooling (Holton and Lindzen, 1972) and vertical diffusion (Matsuno, 1982).

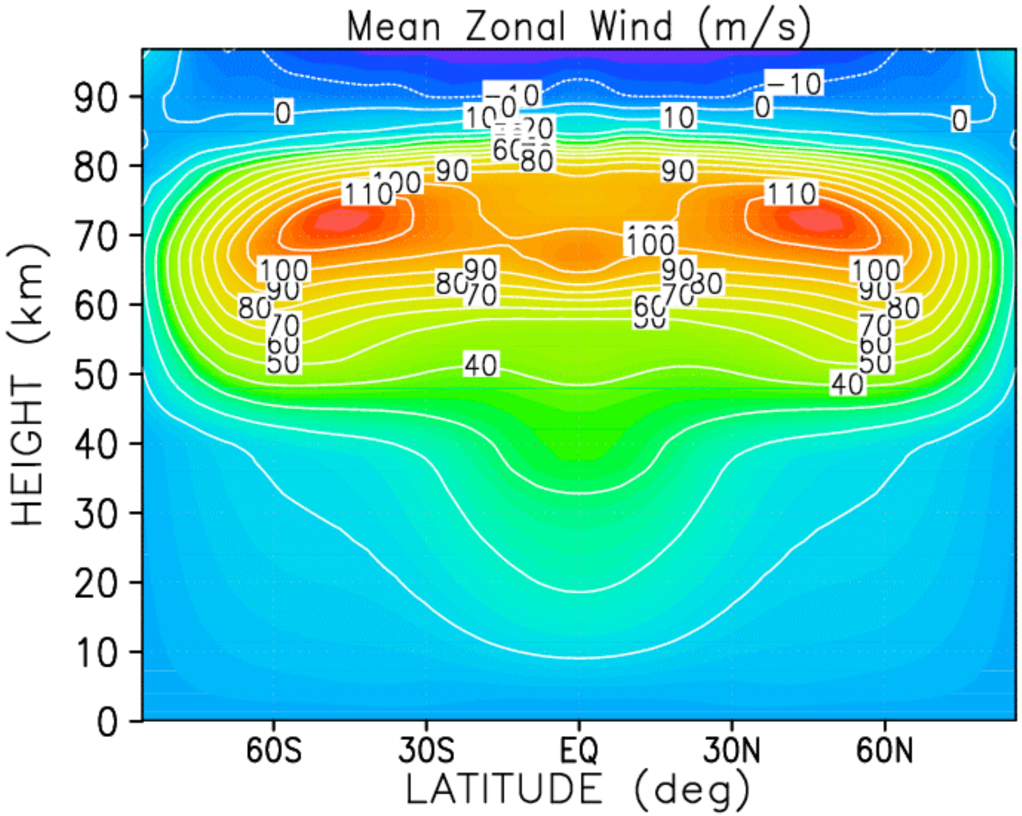
$$F(z) = F(0)\exp\left(-\int_0^z \tau(z')dz' - \int_0^z g(z')dz'\right)$$

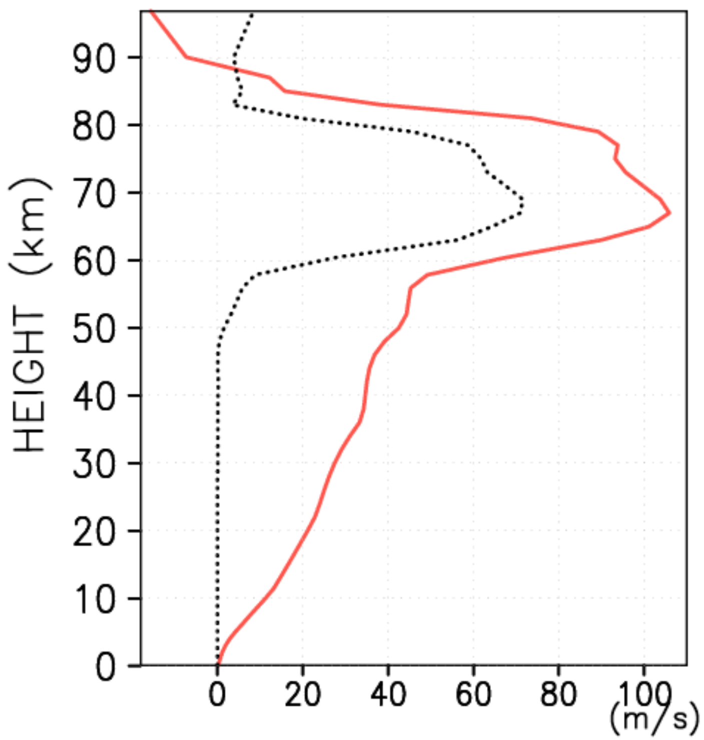
$$\tau = \frac{2\nu N^3}{k(\bar{u}-c)^4}$$ (Matsuno, 1982)

$$g = \frac{\alpha N}{k(\bar{u}-c)^2}$$ (Holton and Lindzen, 1972)



# Mean zonal wind: case with gravity wave forcing

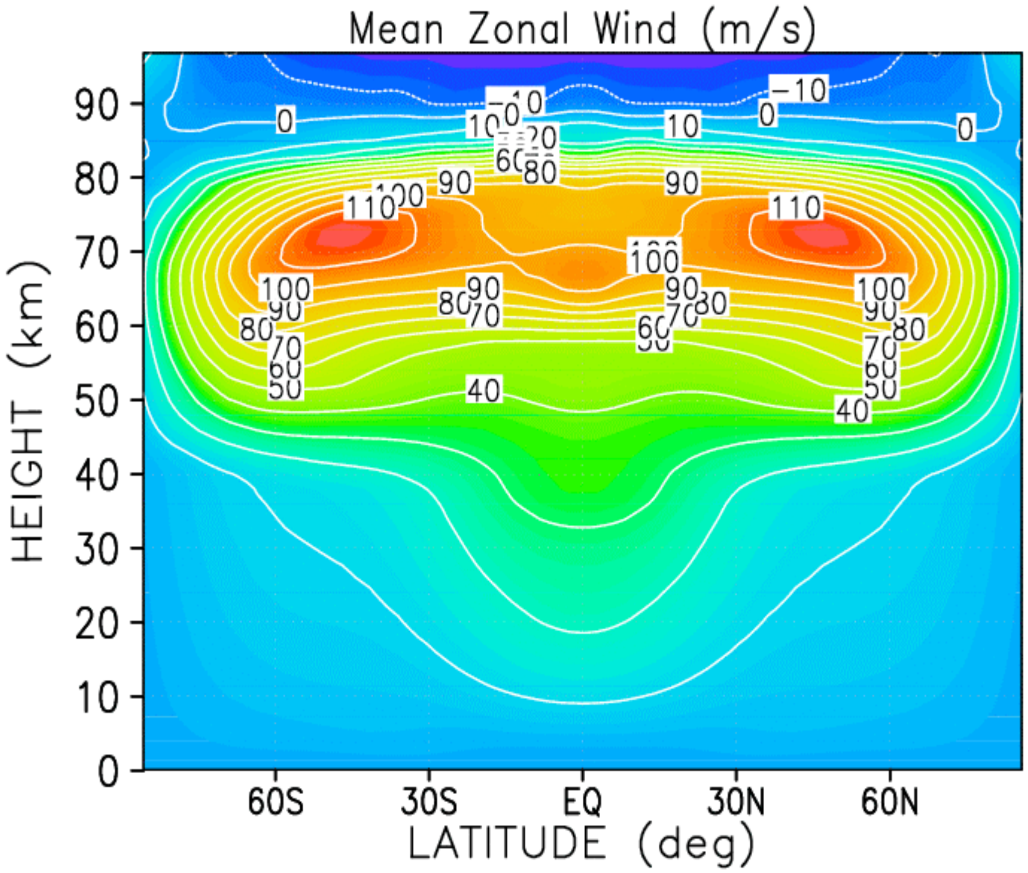


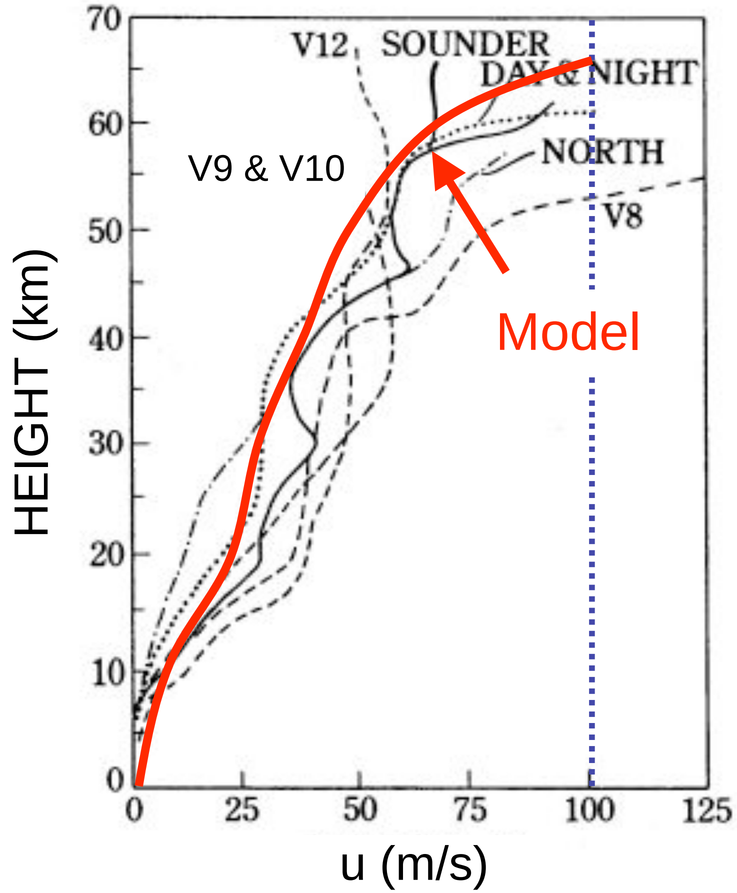

- Latitude-height distribution of the mean zonal wind in case with gravity wave forcing.
- The mean zonal wind is 100 m s$^{-1}$ at equatorial cloud top.
- Mid-latitude jets of about 120 m s$^{-1}$ are seen above the cloud.

- Vertical profiles of the mean zonal wind at the equator.
- The atmospheric superrotation below the cloud is reproduced in the case with gravity forcing (red line).

# Mean zonal wind: case with gravity wave forcing

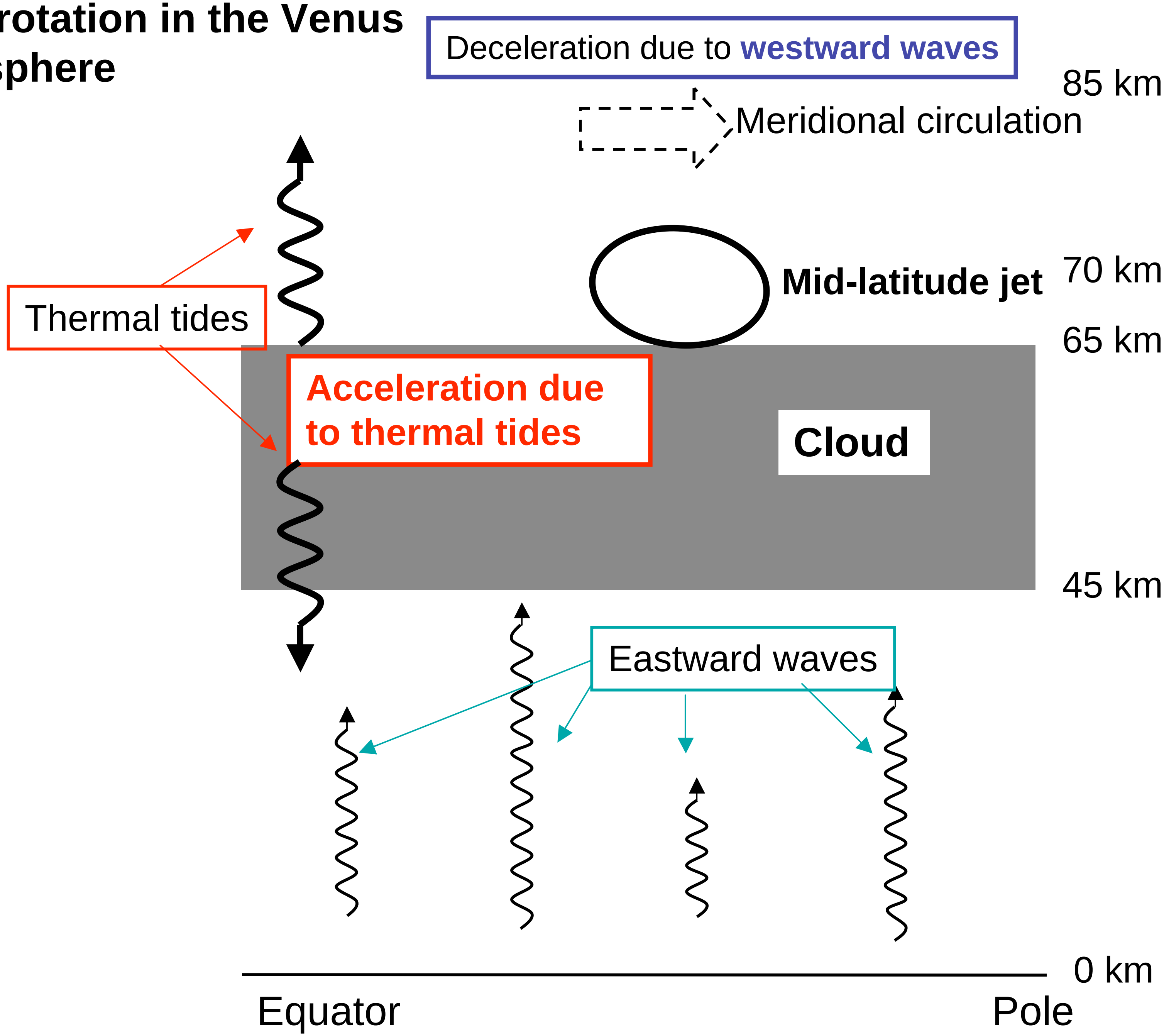



**Observation (Schubert et al.,1980)**




The superrotation simulated in the experiment with the gravity wave parameterization is consistent with observations.

## Maintenance mechanism of the superrotation in the Venus atmosphere



# Summary

<Venus AGCM including radiative processes>

1. Simulated thermal structures are consistent with observations

2. The superrotational flow of about 70 m/s is maintained at the equatorial cloud top.

⇒Thermal tide mechanism is predominant in the middle atmosphere

3. Mean zonal flow is much weaker below 55 km compared with observations.

⇒ There is no mechanism of SR in the lower atmosphere

# Summary

<Venus AGCM including sub-grid gravity wave>

4. Superrotation of about 100 m $s^{-1}$ is reproduced in the case with gravity wave forcing.

Superrotational flow is maintained in the lower atmosphere in contrast to the case with no gravity wave forcing.

↓ Instead of thermal tides

**Small-scale gravity wave is a possible momentum source of SR in the lower atmosphere under the realistic thermal structure.**

# Open issues and perspectives

**(1) Venus lower atmosphere SR**

What parameter controls the SR?

The radiative and sub-grid physical processes?

⇒ We can elucidate the driving forces of the SR (heating? or/and eddy momentum sources ?)

**(2) Data assimilation in the middle atmosphere**

Gridded product of observational data?

⇒ This product can be useful for practical application of VMAGCM to observation

**(3) Different results among GCMs**

⇒ comparison with Venus GCMs