Dynamics of the Super-Rotation of Venus Atmosphere

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(1)Introduction

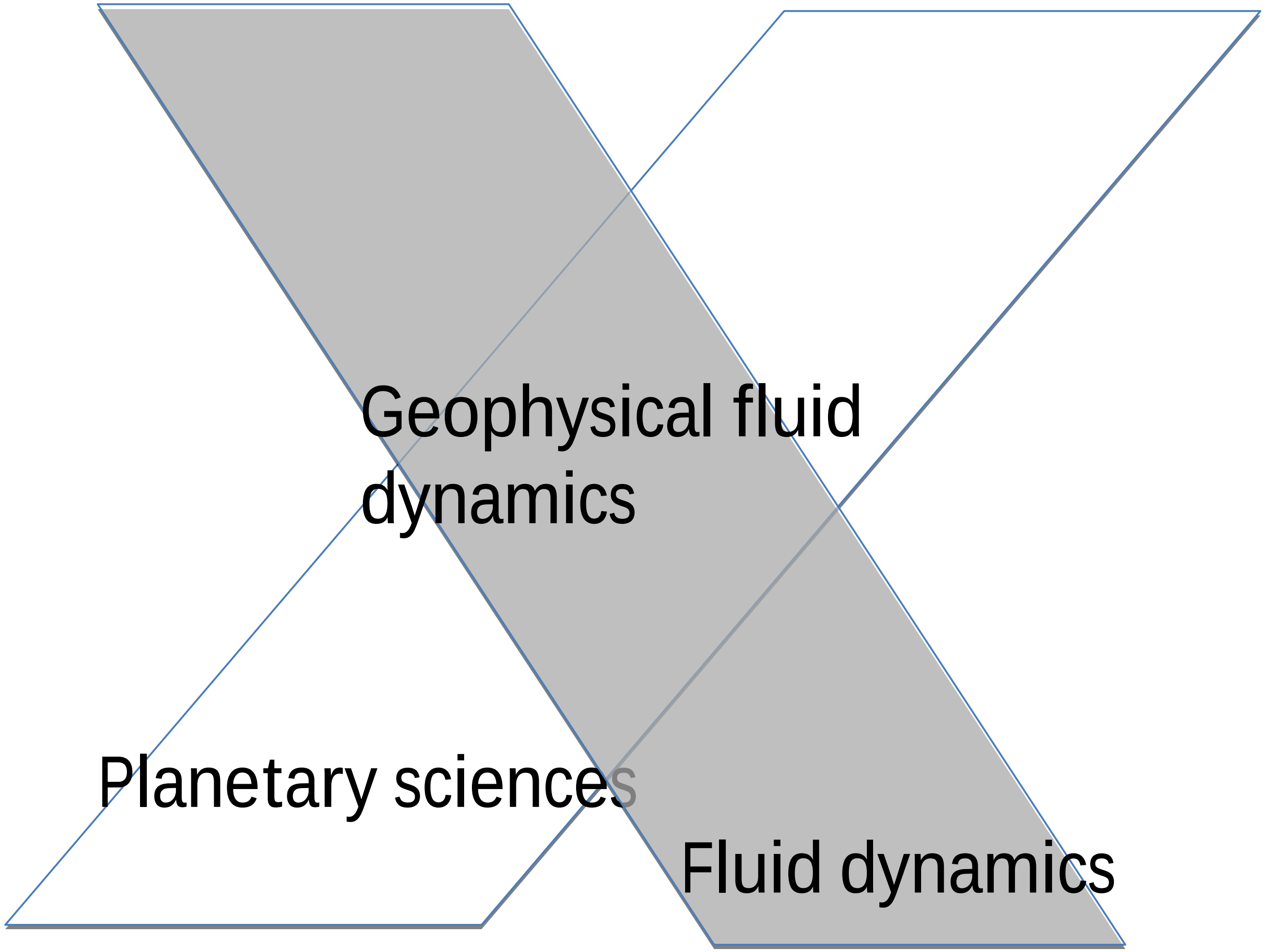
(2)Mechanism based on the circulation between day and night sides

(3)Mechanism based on thermal tides

(4)Mechanism based on meridional circulation

(5)Conclusion

Planetary sciences and geophysical fluid dynamics



(1) Introduction

Review of

(A) Some important aspects of the Venus atmosphere

(B) Observation of the Super-rotation

(C) Mechanism so far proposed for explaining the Super-rotation

Basic parameters of Venus and its atmosphere

	Venus	Earth
Radius	6050 km	6380 km
Gravity	8.9 m/s^2	9.8 m/s^2
Period of revolution	224 days	365 days
Period of rotation	–243 days	1 day
Solar day	117 days	1 day
Solar flux	2617 W/m^2	1370 W/m^2
Albedo	0.78	0.30
Effective equil. temp.	224K	255K
Composition of atm.	CO_2(97%), N_2(3%)	N_2, 0_2
Surface pressure	92 bar	1 bar

Vertical structure of Venus atmosphere

temperature distribution and cloud layer

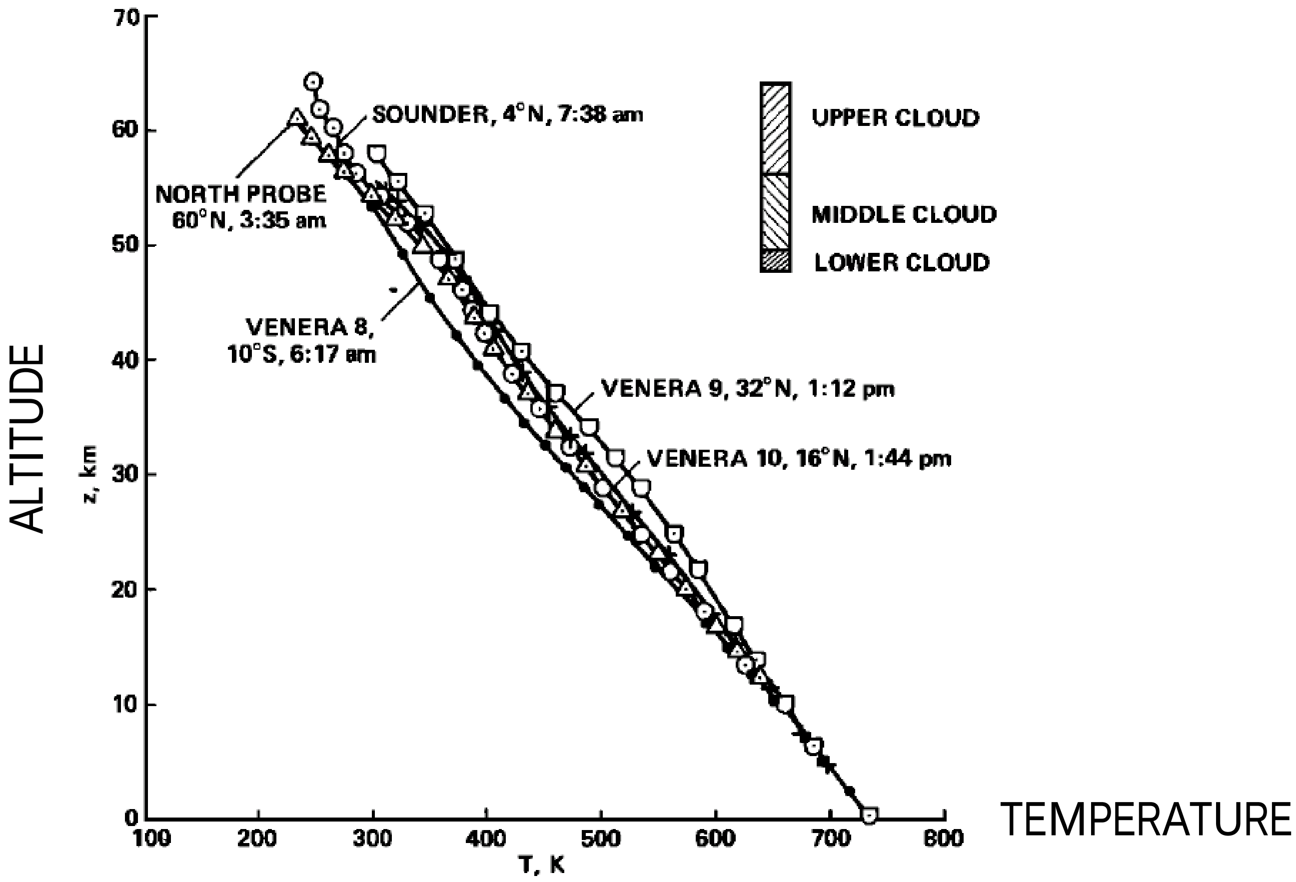
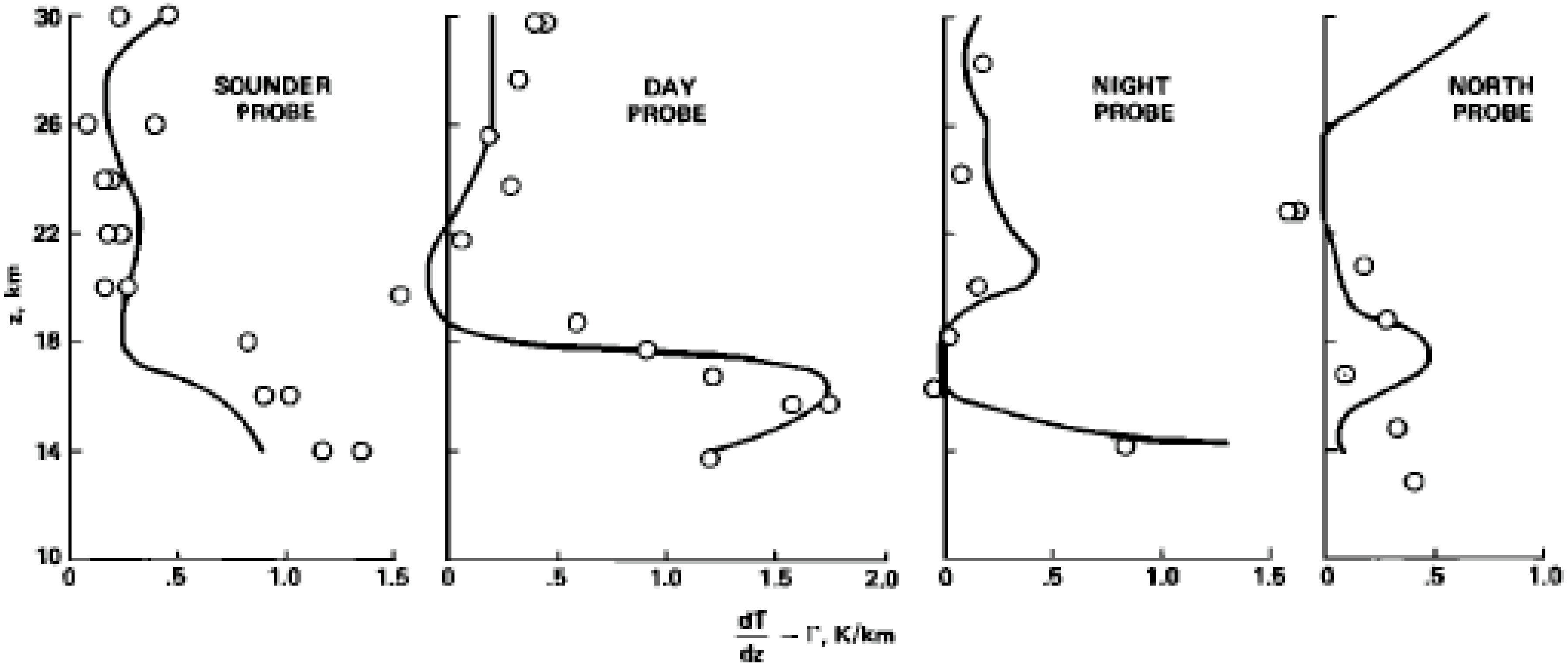


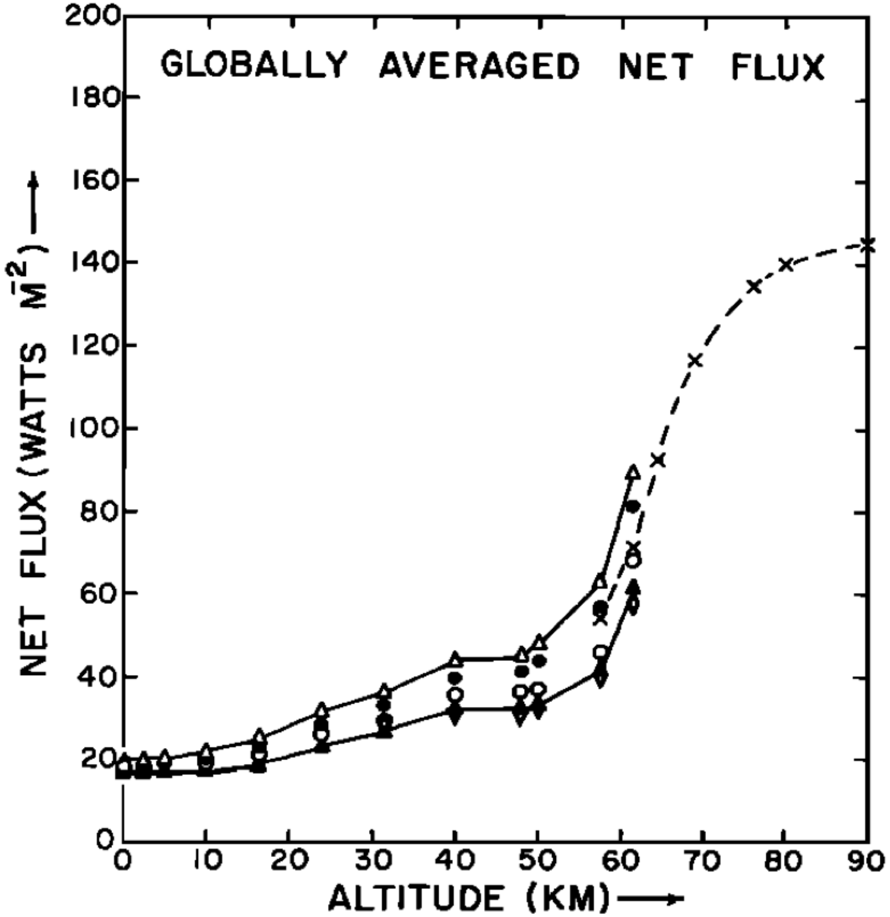
Fig. 2. Comparison of Venera 8, 9, and 10 temperatures with those of the Pioneer Venus sounder and north probes.

Atmospheric stability observed by probes of Pioneer Venus



The lower atmosphere of Venus is weakly stable?

Distribution of solar net flux

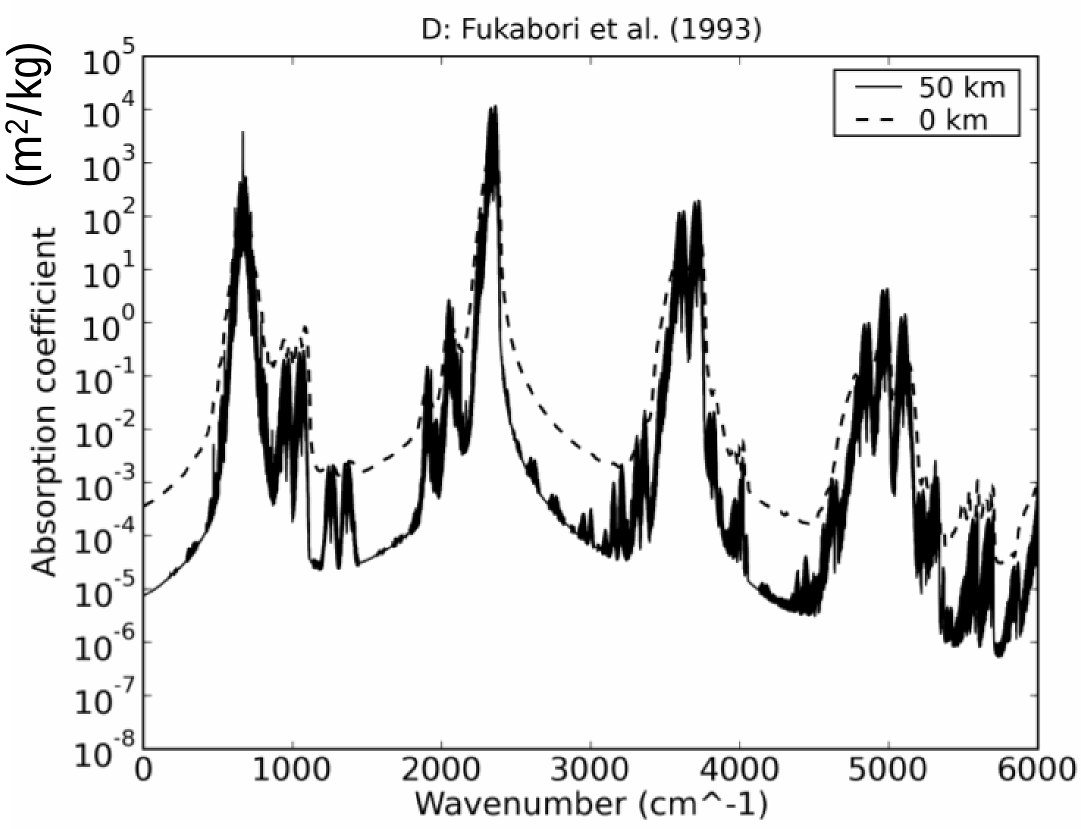


Tomasko et al. (1980)

- Most of solar energy is absorbed in the cloud.
- Its small amount reaches at the ground (10% of absorbed energy is absorbed at the ground).

Greenhouse effect of CO_2 atmosphere

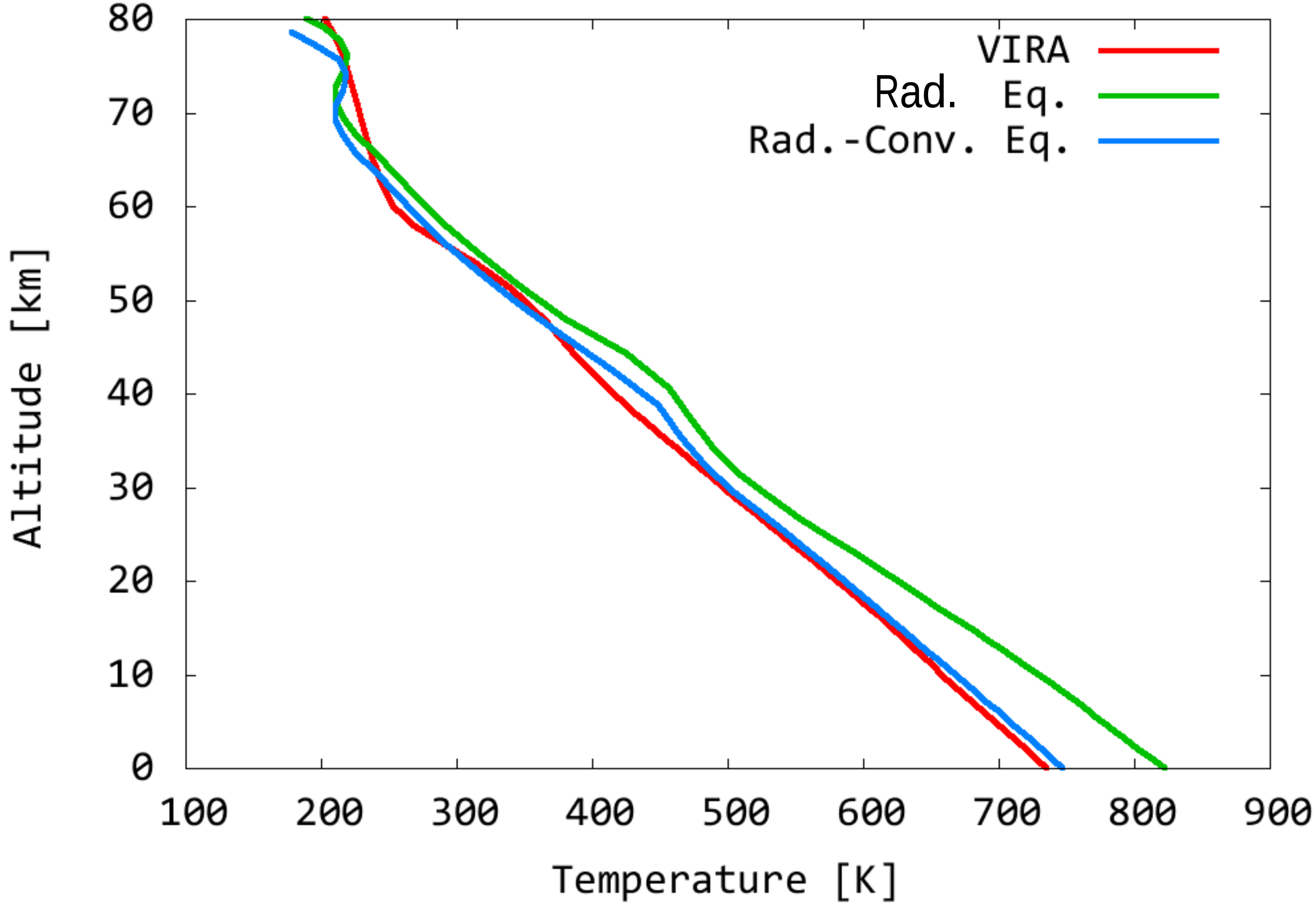
Cause of the high surface temperature: Greenhouse effect



Distribution of absorption coefficient

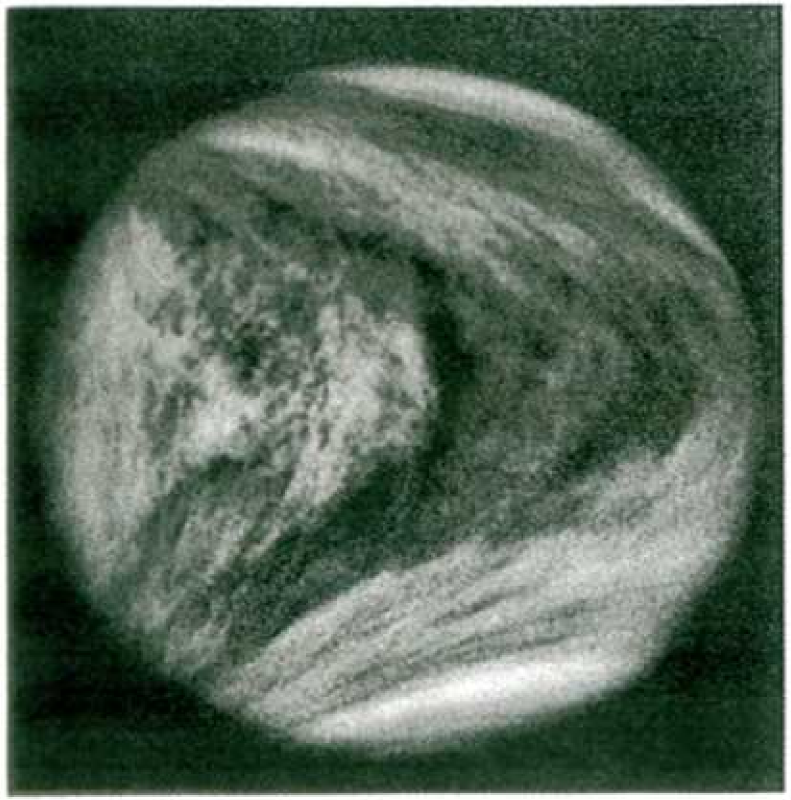
Radiative-convective equilibrium temperature

Takagi and Matsuda(in preparation) using Fukabori's line profile



(B) Observation of Super-rotation

(1) Image of Venus by ultraviolet



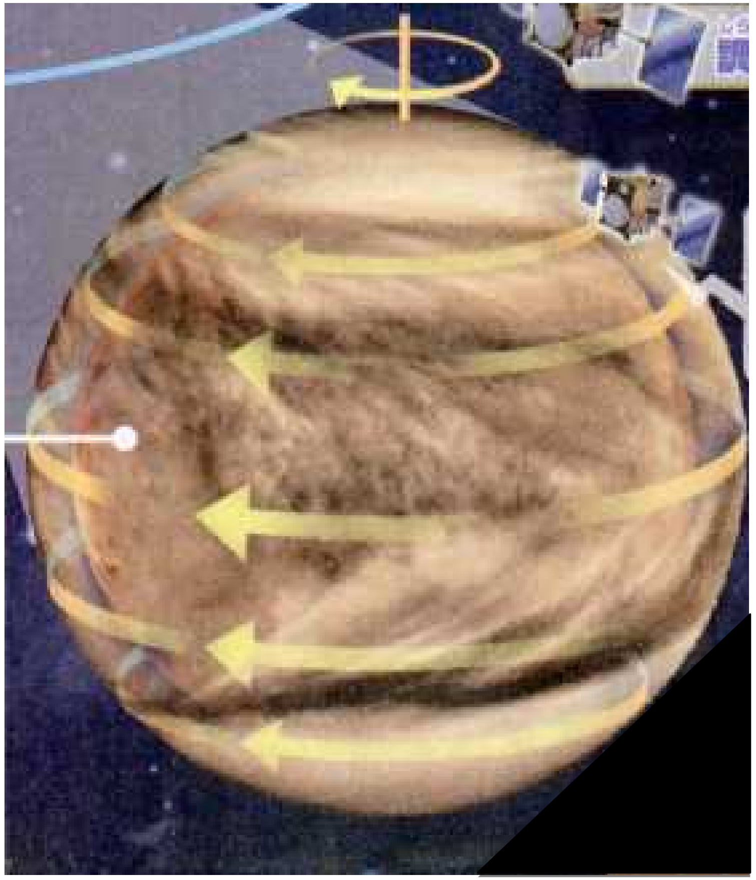
This pattern rotates around Venus by 4 days.

Planetary rotation and Super-rotation

Rotation period
of the pattern:
4 days

Rotation period
of the solid part:

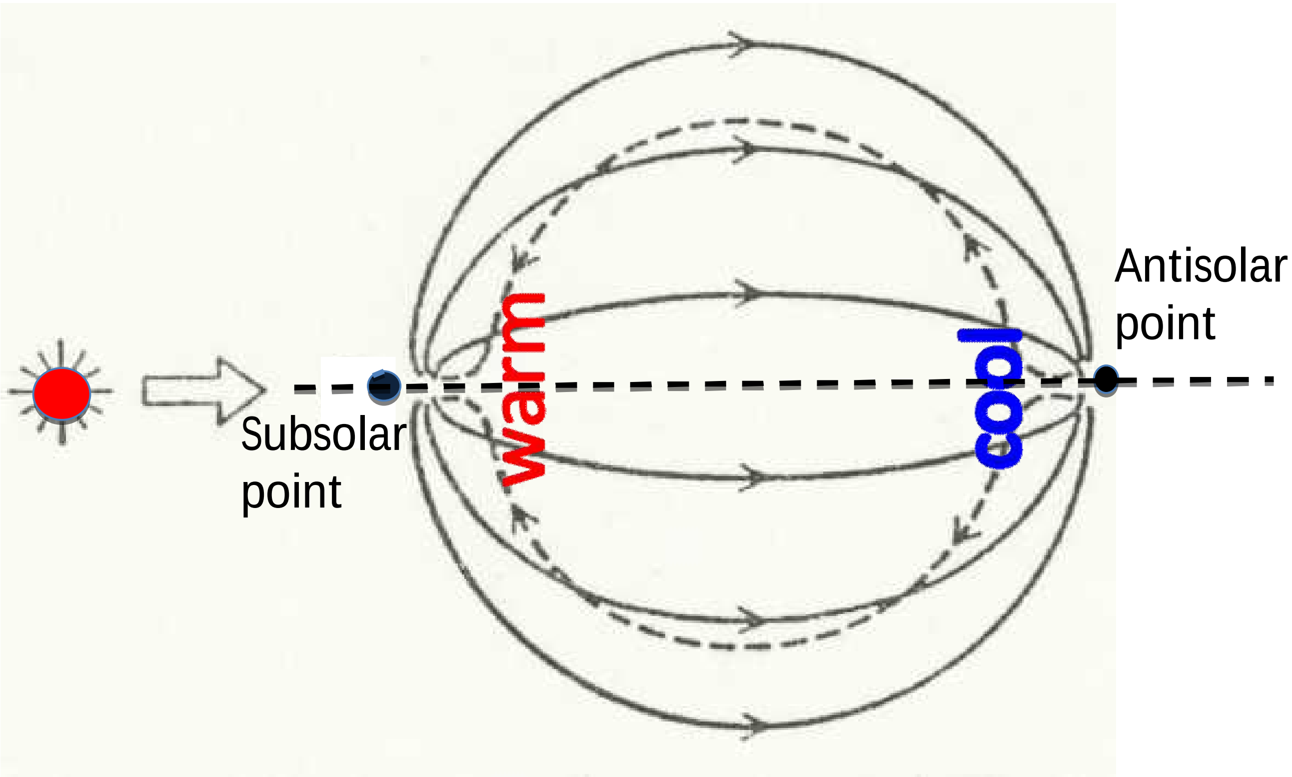
243 days



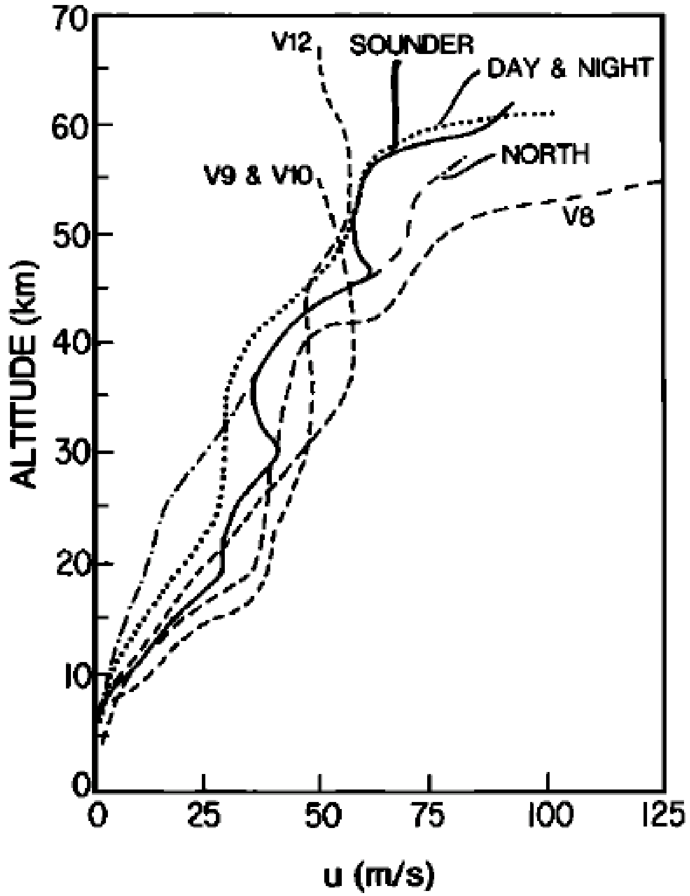
Convection between day and night sides

- One solar day of Venus is so long (117 (Earth) days).

→ It is natural to predict the predominance of convection between day and night sides (diurnal circulation).



(2) Vertical distribution of easterly winds observed by various probes



A comparison of zonal wind velocity profiles from Pioneer Venus and Venera probes.

No westerly wind is observed.

(3) Meridional distribution of easterly winds observed by some probes

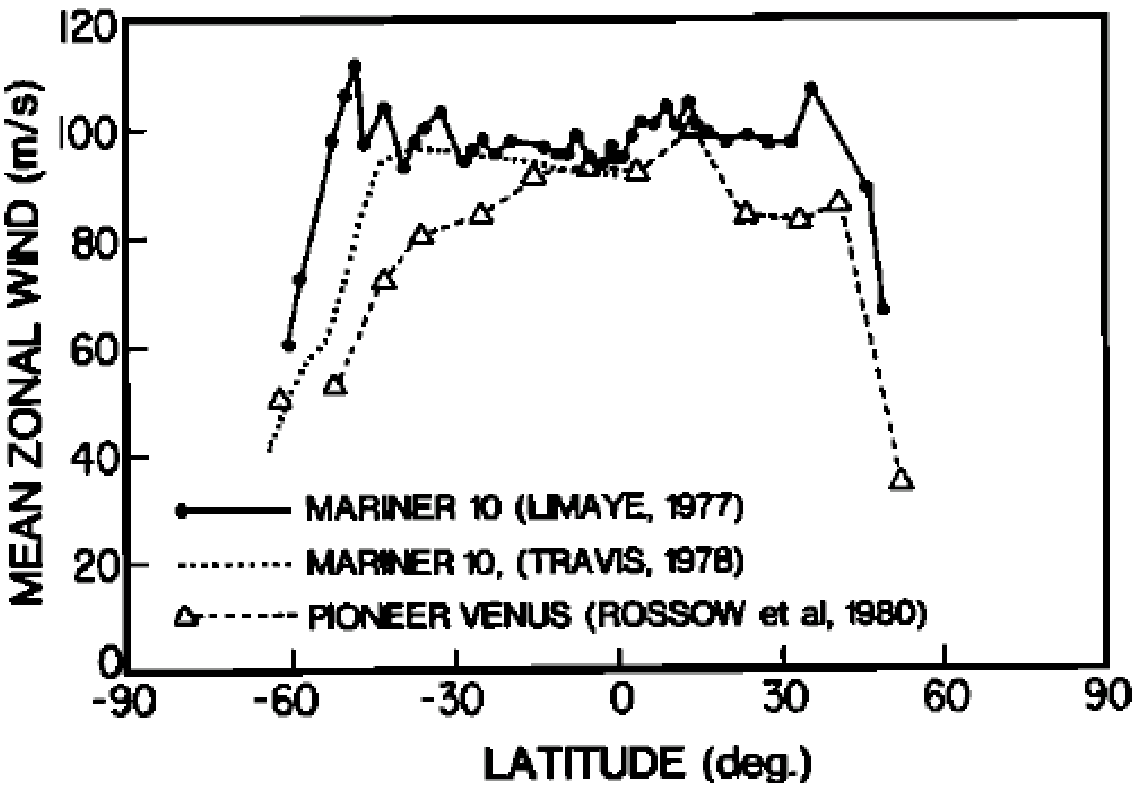
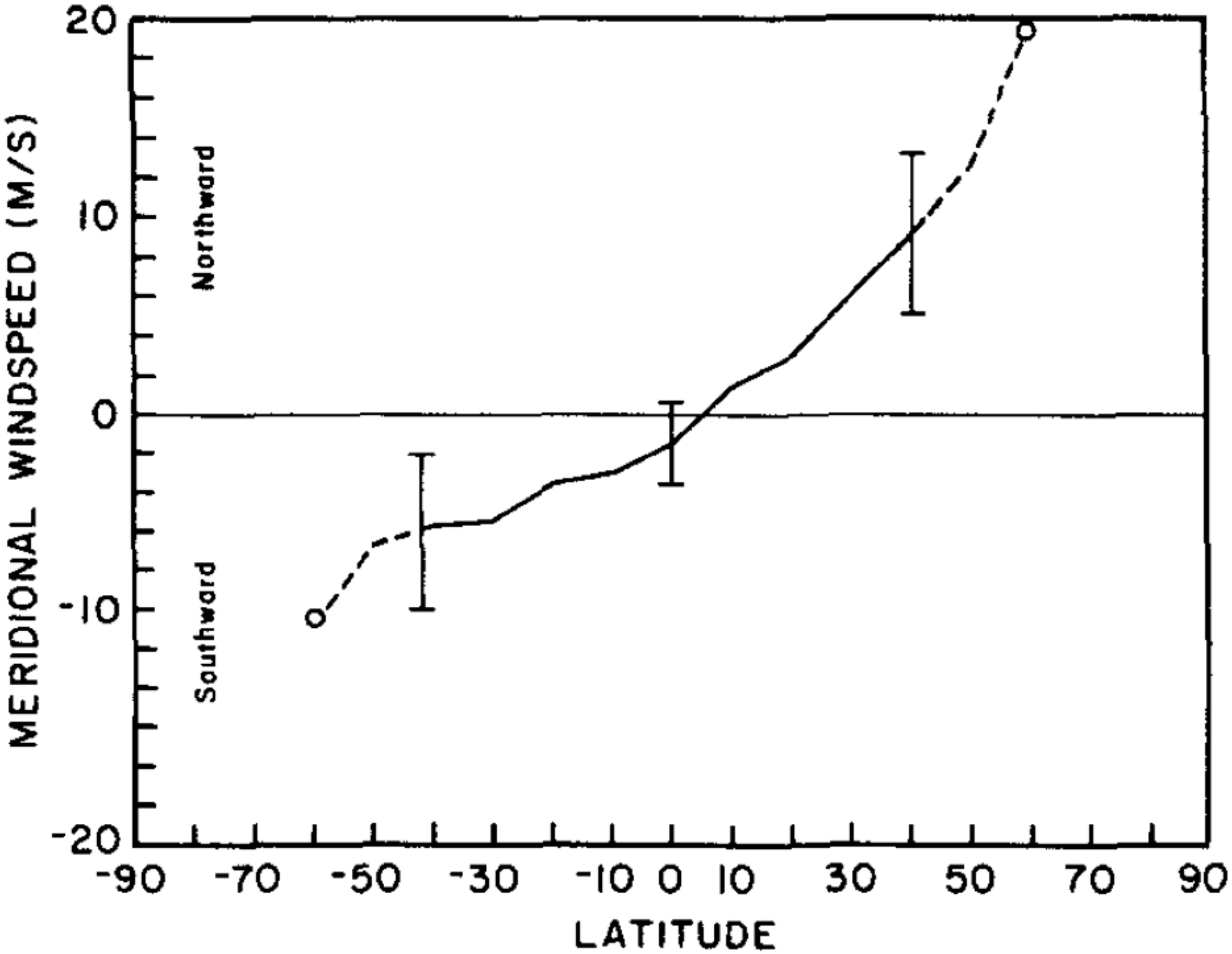


Fig. 13. Latitude dependence of retrograde zonal wind speeds inferred from cloud tracking in Mariner 10 and Pioneer Venus ultraviolet images.

(4) Meridional distribution of meridional winds observed by Pioneer Venus



Rossow et al. (1990)

(5) Distribution of easterly winds on the meridional section

Walterscheid et al. (1985)

- Observation by occultation

Temperature

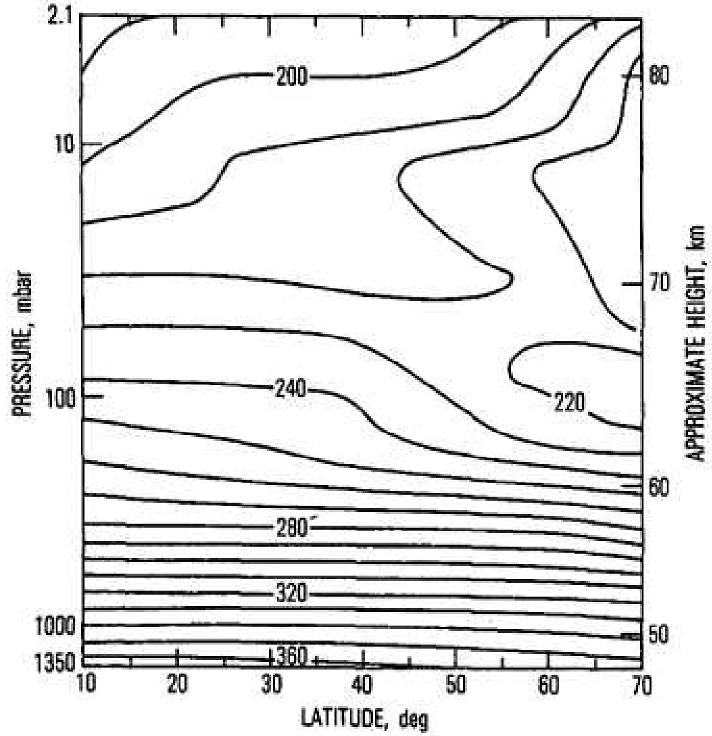


FIG. 3. Contours of Northern Hemisphere temperature data; SZA independence is assumed. The contour interval is 10 K. Approximate heights for this and subsequent figures are from Seiff *et al.* (1980). Contours have been smoothed.

Easterly wind velocity

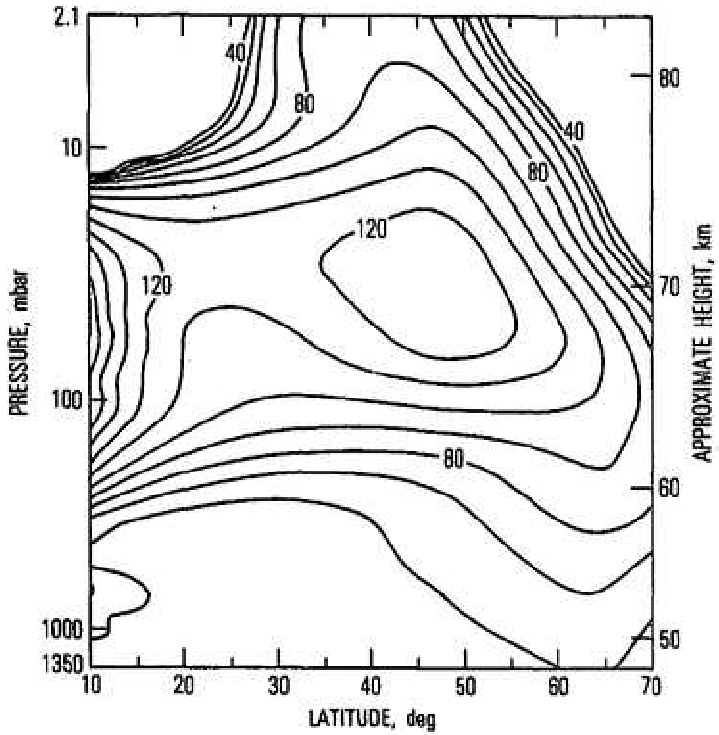
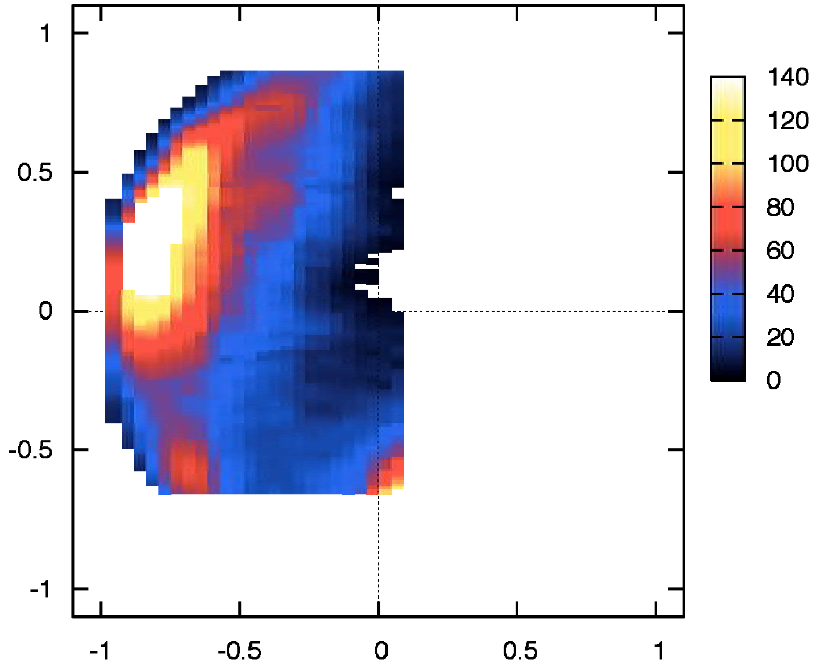


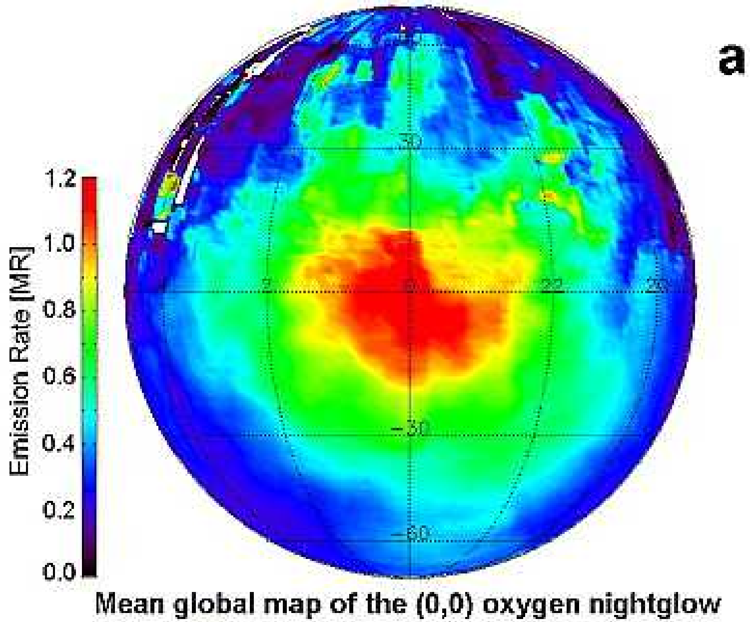
FIG. 4. Contours of westward zonal wind speed (m s^{-1}) for the Northern Hemisphere derived from temperature data assuming cyclostrophic balance. Contour interval is 10 m s^{-1}. Contours have been smoothed.

(6) Circulation in the thermosphere

- Circulation between day and night sides is suggested by observations



Ohtsuki et al. (2008)



[Piccioni et al., 2009]

Strangeness of the super-rotation

(i) U (zonal velocity)/aΩ (planetary rotation)=60

: very fast

→ origin of vast angular momentum ?

mechanism maintaining vertical shear against vertical viscosity ?

(ii) Why does the circulation between day and night sides predominate?

(The circulation of this type predominates in the thermosphere.)

(D) Basic mechanisms proposed for the super-rotation

(i) Mechanism based on the circulation between day and night sides

: Schubert and Whitehead(1969), Thompson(1970)

(ii) Mechanism based on the thermal tides

: Fels and Lindzen(1974)

(iii) Mechanism based on the meridional circulation

: Gierasch(1975), Matsuda(1980,82)

(2) Mechanism based on the circulation between day and night sides

1. “Moving flame” mechanism
2. Thompson mechanism
3. Reexamination of these mechanism

1. “Moving flame” mechanism

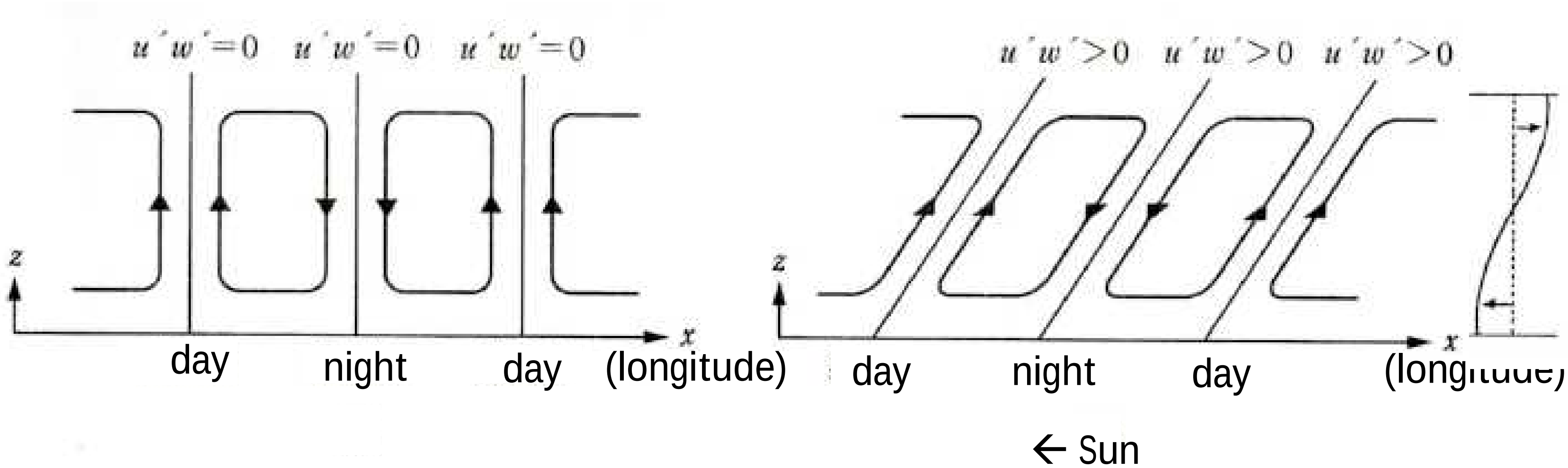
Basic idea: tilting of convection cell by motion of heat source

1. “Moving flame” mechanism(2)

2-dimensional model on the equator

(a) No motion of heat source

(b) Motion of heat source



$\overline{u'w'}$ >0 : upward transport of zonal momentum

“Moving flame” mechanism(3)

- Balance of momentum

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial \overline{u'w'}}{\partial z} + \nu \frac{\partial^2 \overline{u}}{\partial z^2}$$

- Results of laboratory experiments:

  fast zonal flow can appear by this mechanism

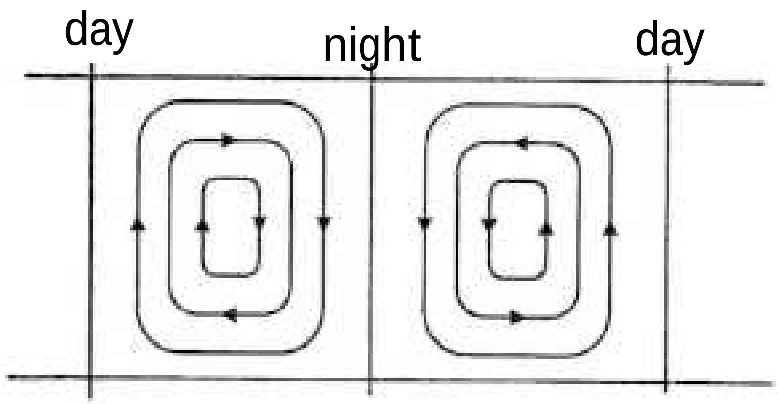
  (4-times super-rotation appears for mercury)

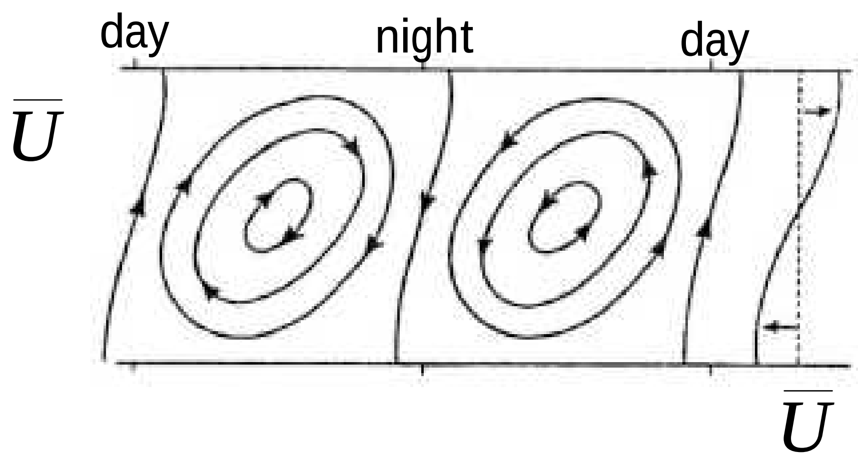
This mechanism contains some problems:

  The layer is heated from above in the cloud.

2. Thompson mechanism(1)

Basic idea : instability based on positive-feedback between tilt of convection cell and mean zonal flow

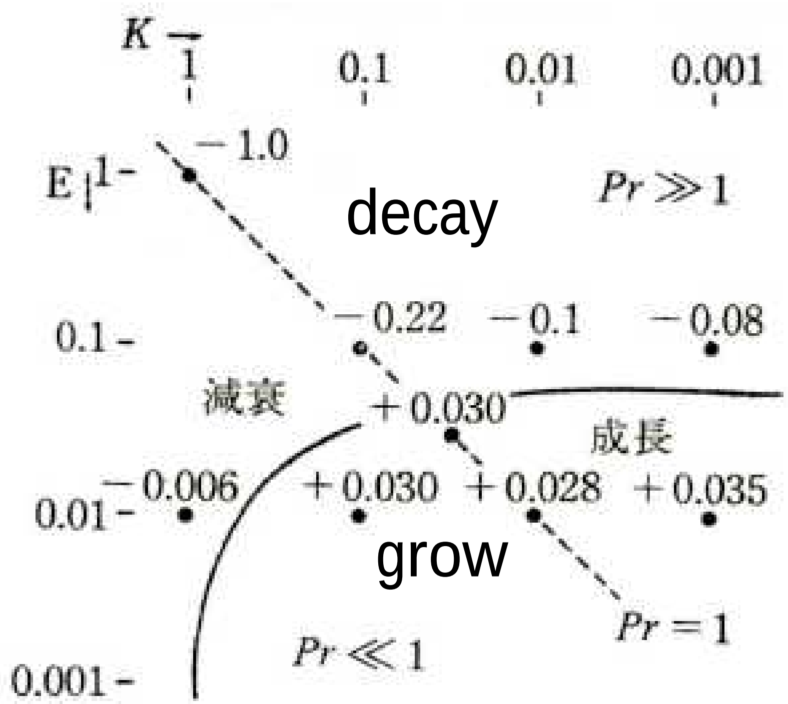




2. Thompson mechanism(2)

Results of numerical calculation:

stability/instability diagram



E: coefficient of viscosity

K: coefficient of heat conduction

3. Reexamination of Thompson mechanism

- Reexamination by 3-dimensional model on the sphere: Takagi and Matsuda (1999, 2000)

Instability does not take place in the parameter range where it does in the 2-dimensional model on the equator.

→ This mechanism cannot work in the real 3-dimensional atmosphere of Venus.

(3) Mechanism based on thermal tides

- Basic idea of Fels and Lindzen(1)

:interaction between wave and mean-zonal flow

(basic concept developed in the dynamic meteorology)

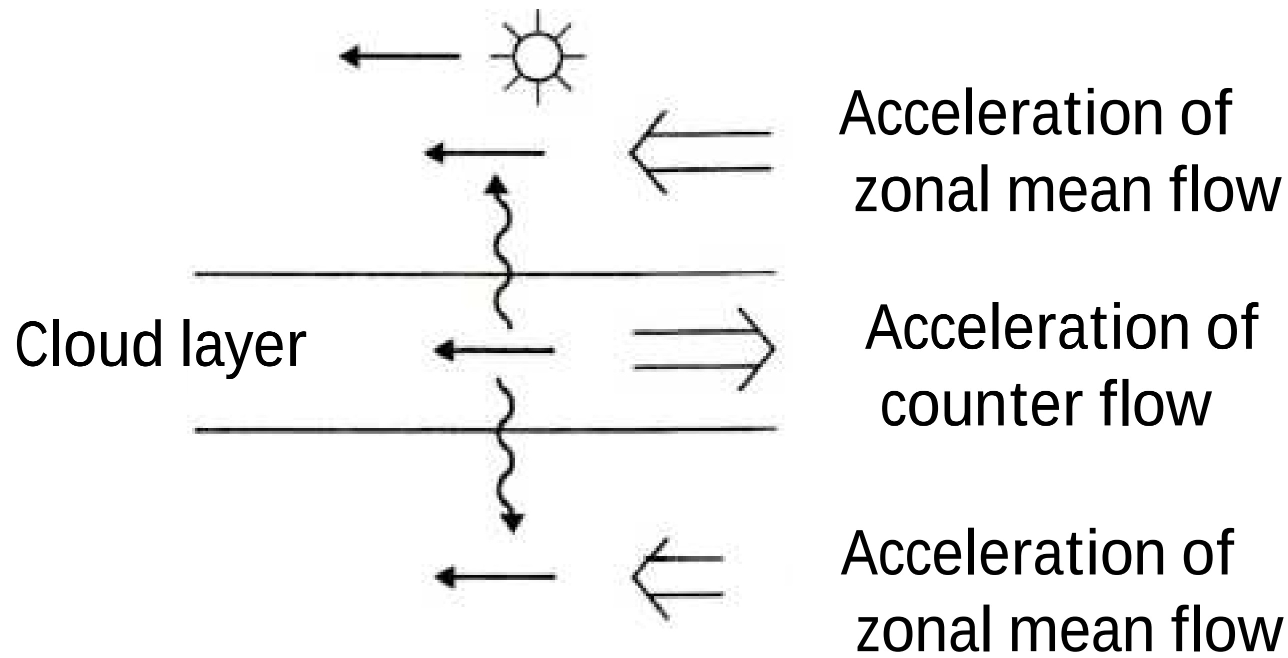
↓

Zonal momentum (U) is associated with vertically propagating wave

$U \propto c_x$ (phase velocity)

Uryu's relation : $U = E / c_x$ (E :wave energy)

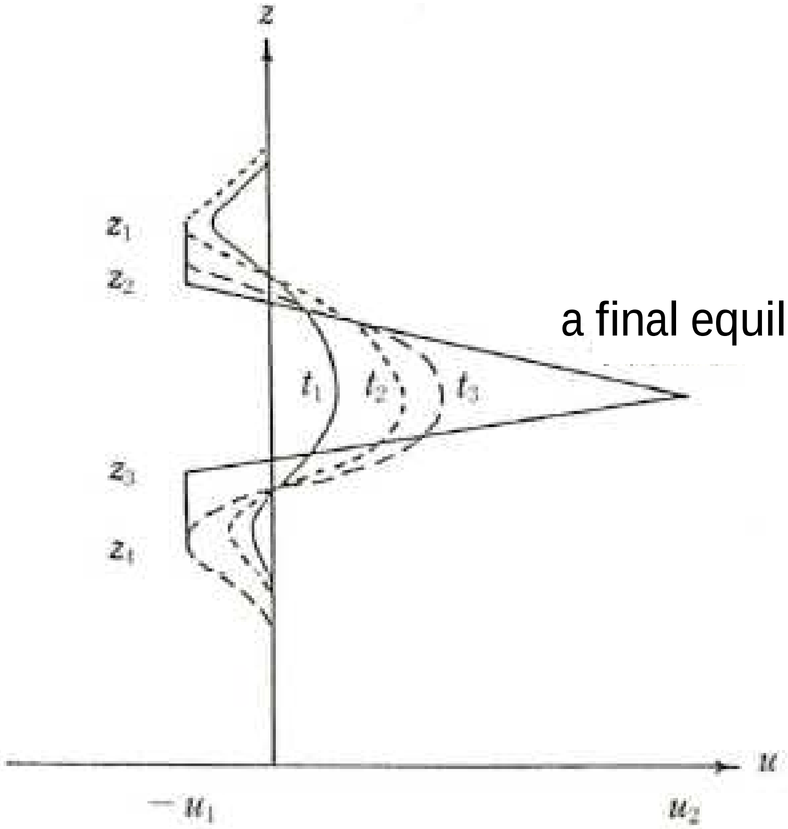
Basic idea of Fels and Lindzen(2)



- difficulty of this mechanism: formation of critical level (at which $U = c_x$)

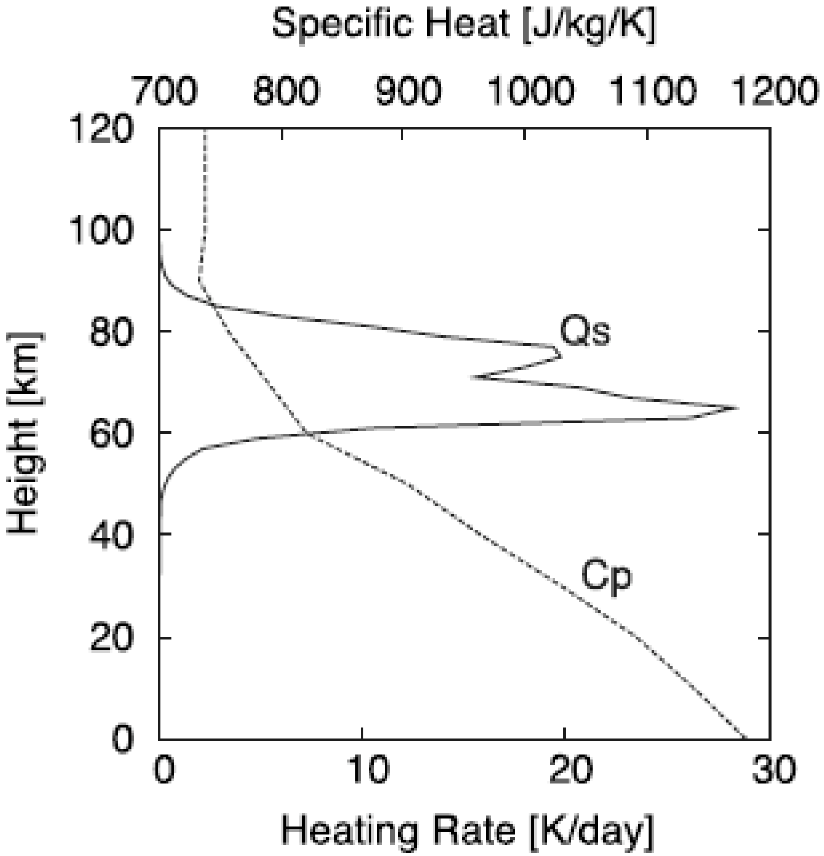
Formation of critical levels

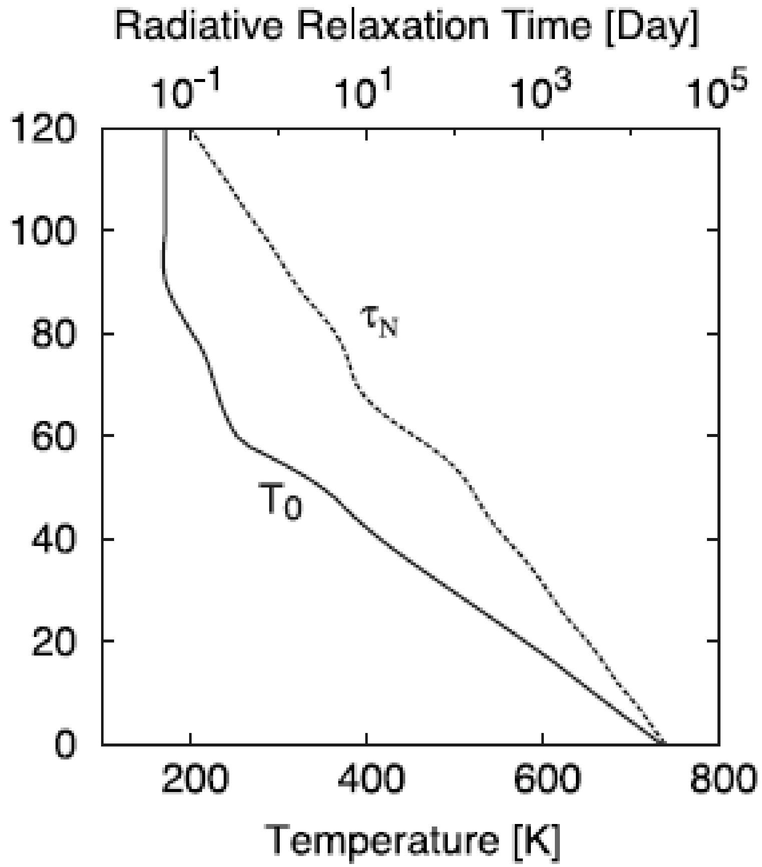
evolution of mean zonal flow



a final equilibrium state

Propagation of thermal tides in the realistic atmosphere: Takagi and Matsuda (2006)





Qs: solar heating rate

τ_N : relaxation time of Newtonian cooling

Propagation of thermal tides to the ground

Results of Takagi and Matsuda (2006)

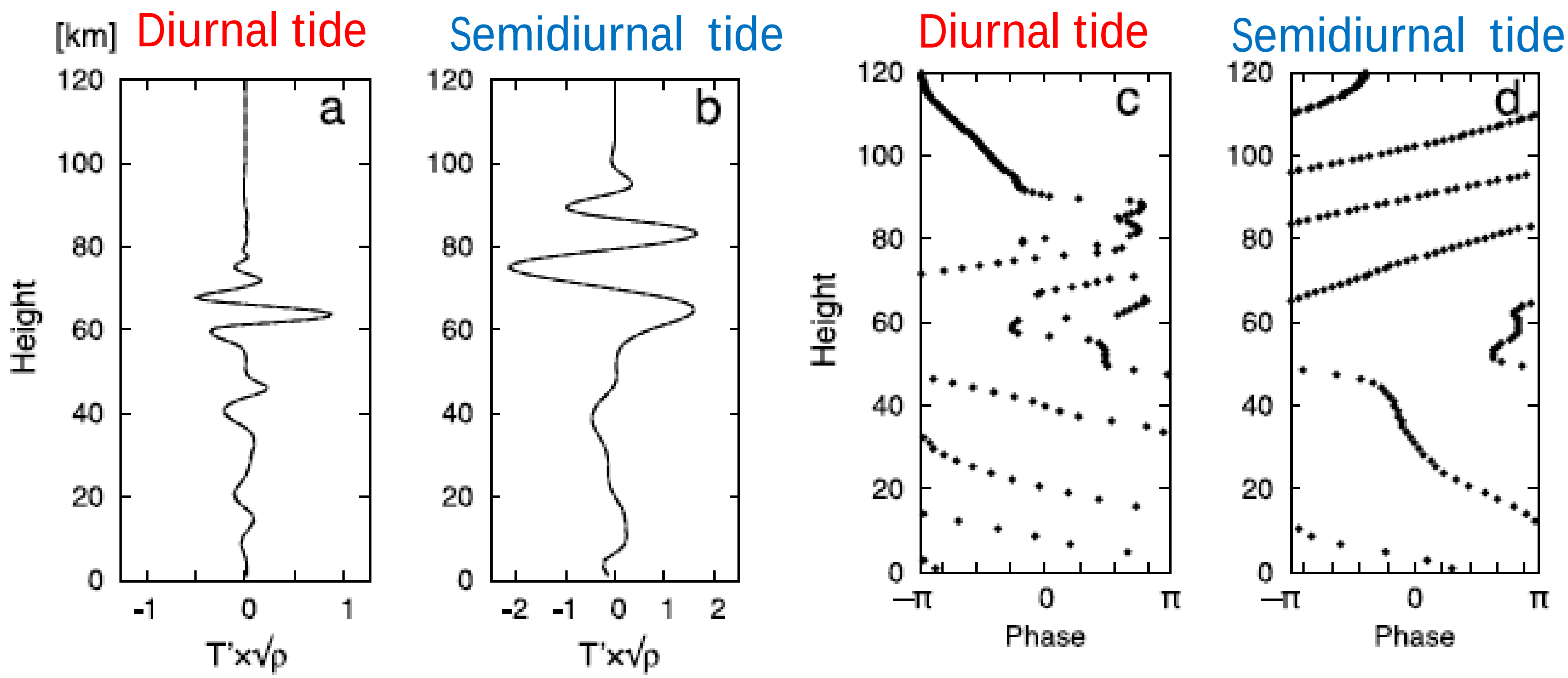


Figure 1. Vertical distributions of temperature deviations and their phase associated with (a and c) diurnal and (b and d) semidiurnal tides at the subsolar point multiplied by square root of the basic state density ($T' \times \sqrt{\rho}$), which are calculated for the heating profiles (a) and (b) and without ground heating. The two distributions are overlapped almost

Mechanism of production of net angular momentum in the atmosphere

Fels and Lindzen   Takagi and Matsuda

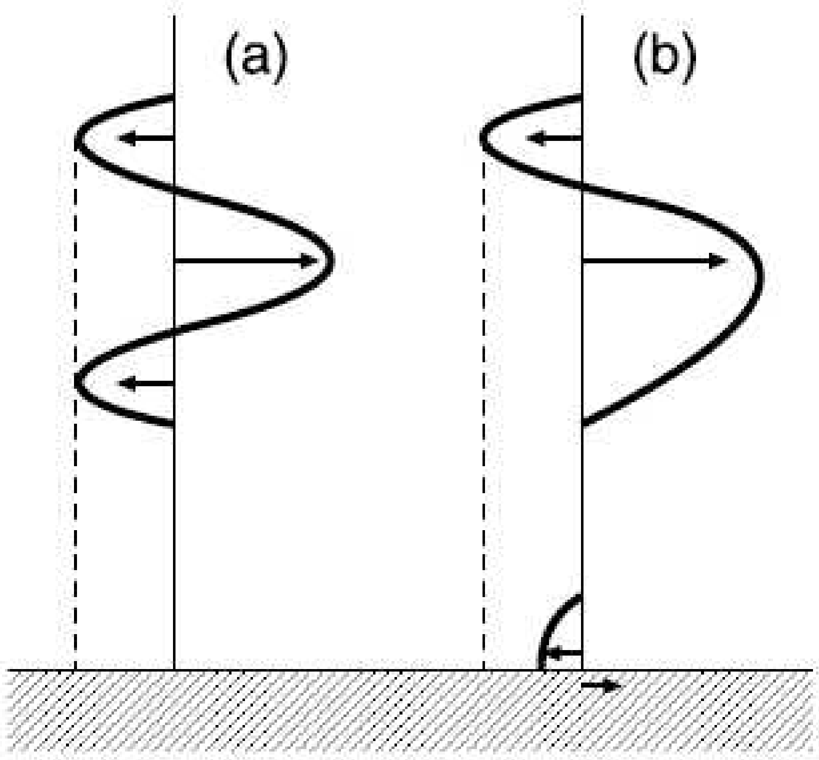
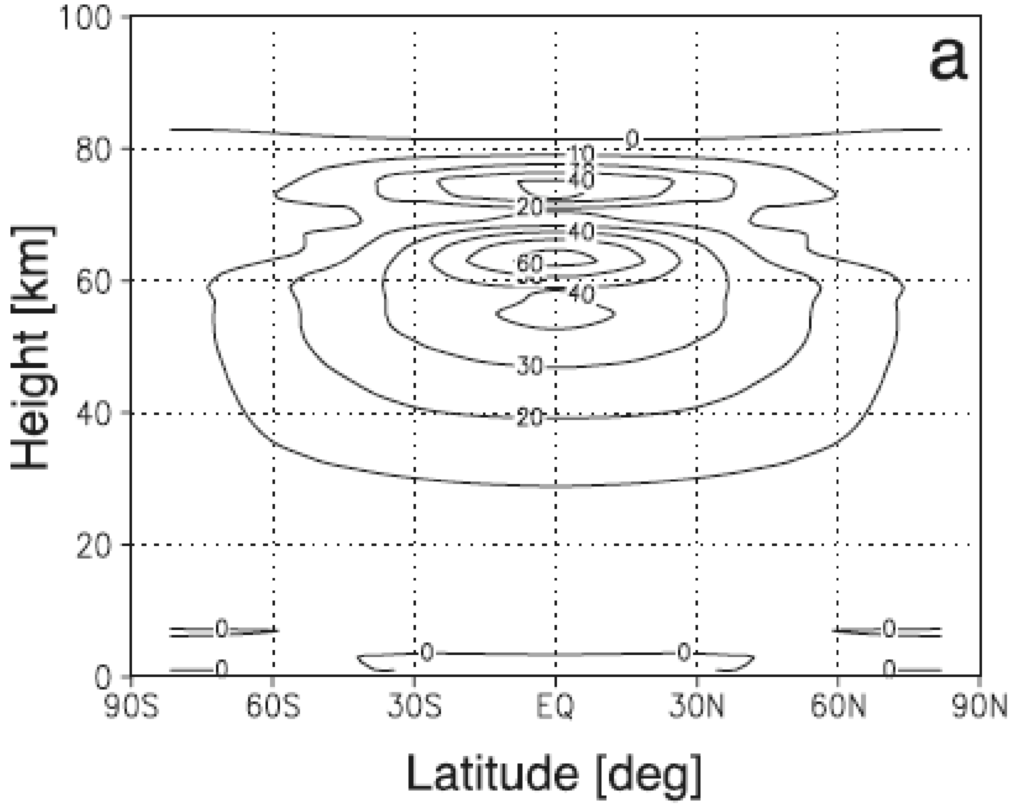


Figure 10. Schematic illustration of acceleration mechanism of mean zonal flow by the thermal tides (a) in the work of *Fels and Lindzen* [1974] and (b) in the present model.

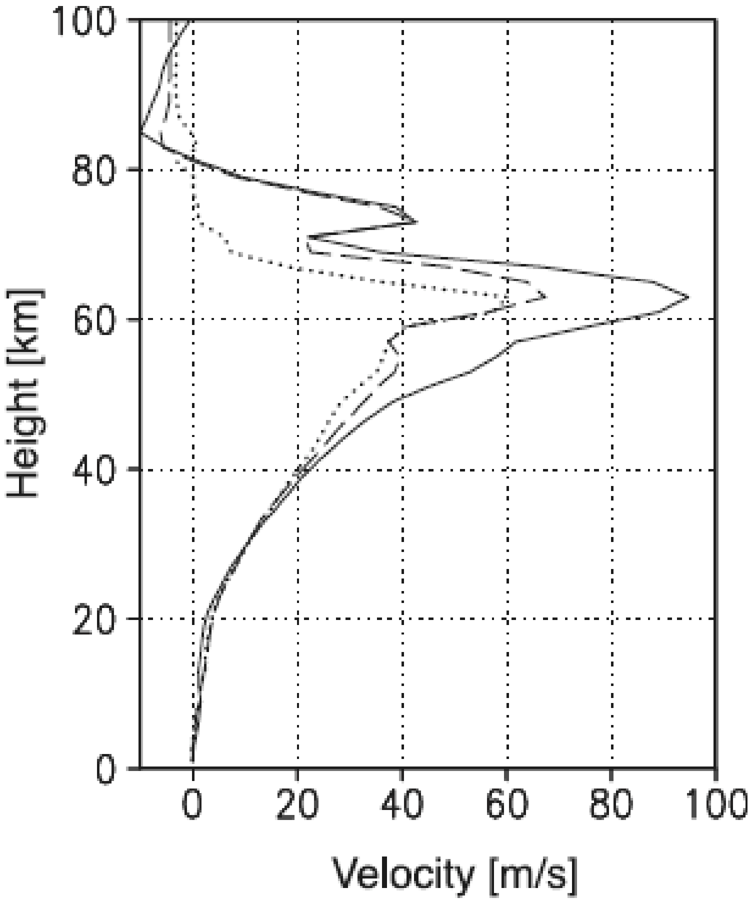
Simulation of super-rotation generated by thermal tides

- Reproduction of super-rotation by Takagi and Matsuda (2007)



Distribution of zonal velocity in the meridional section

Parameter dependency of super-rotation generated in Takagi and Matsuda (2007)



Zonal velocity at the equator

Solid: weak Newtonian cooling

Dashed: standard case

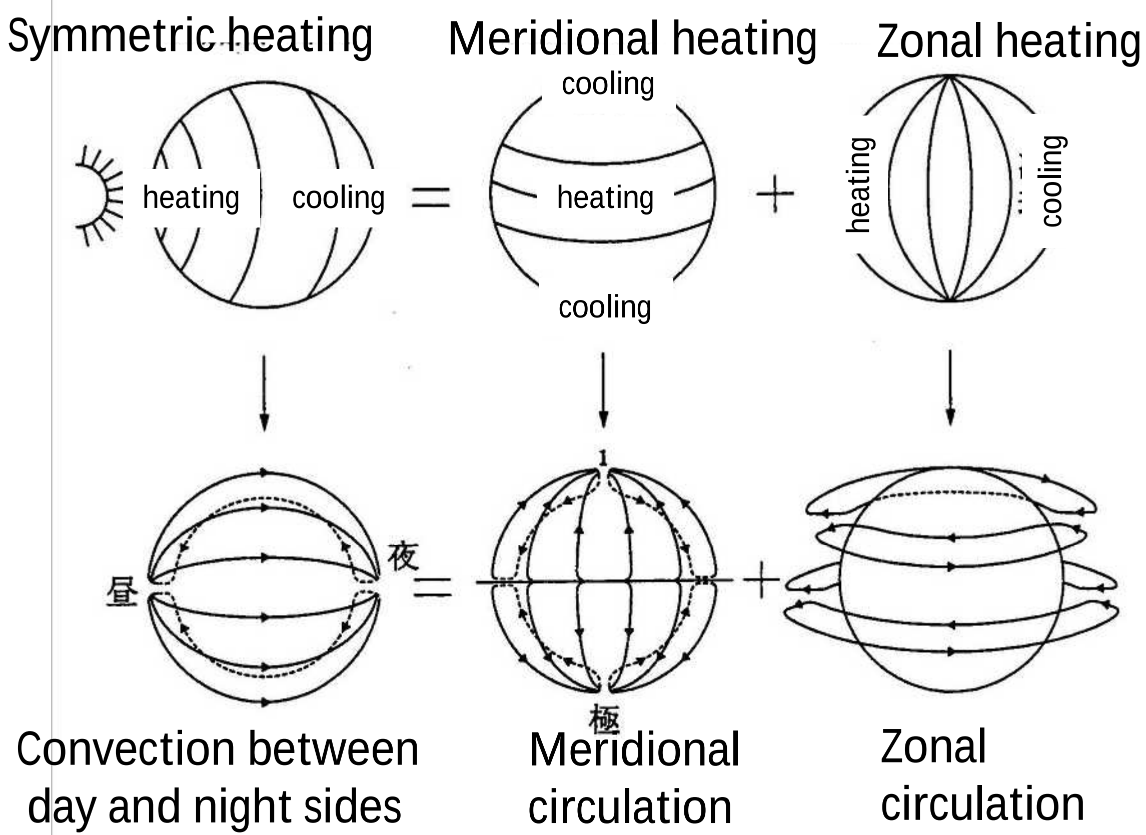
Dotted: strong Newtonian cooling

Note: meridional circulation is not involved in T and M (2007).

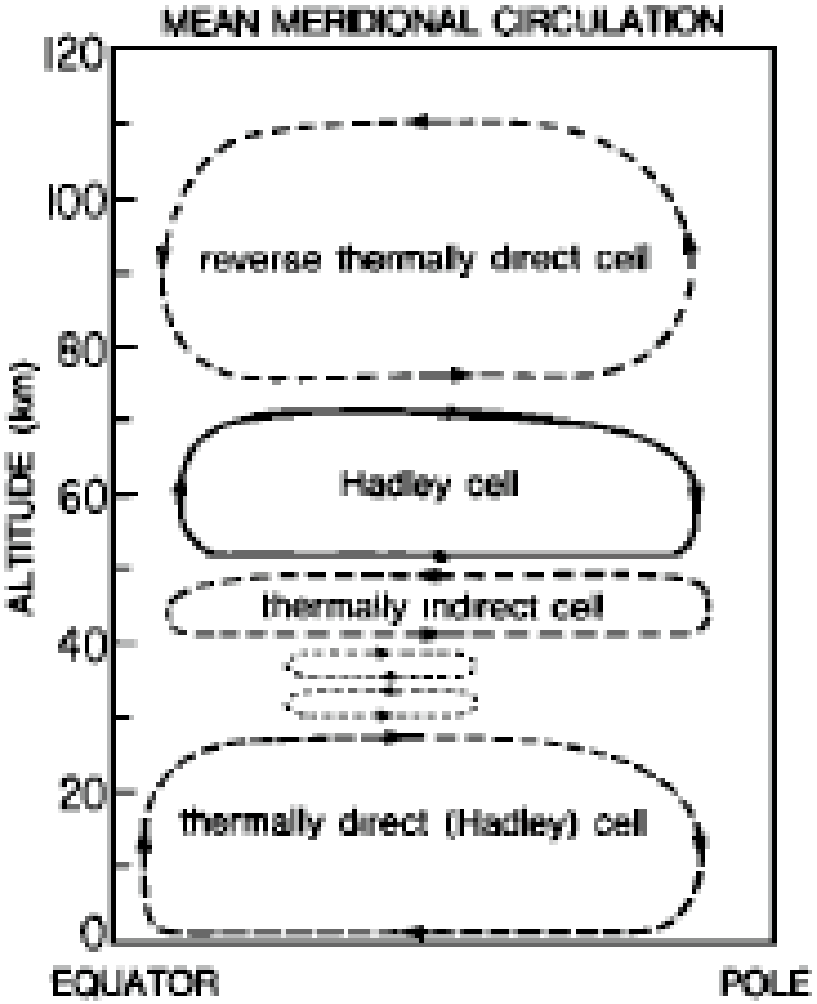
(4) Mechanism based on meridional circulation

- Meridional circulation and zonal winds

contra circulation between day and night sides

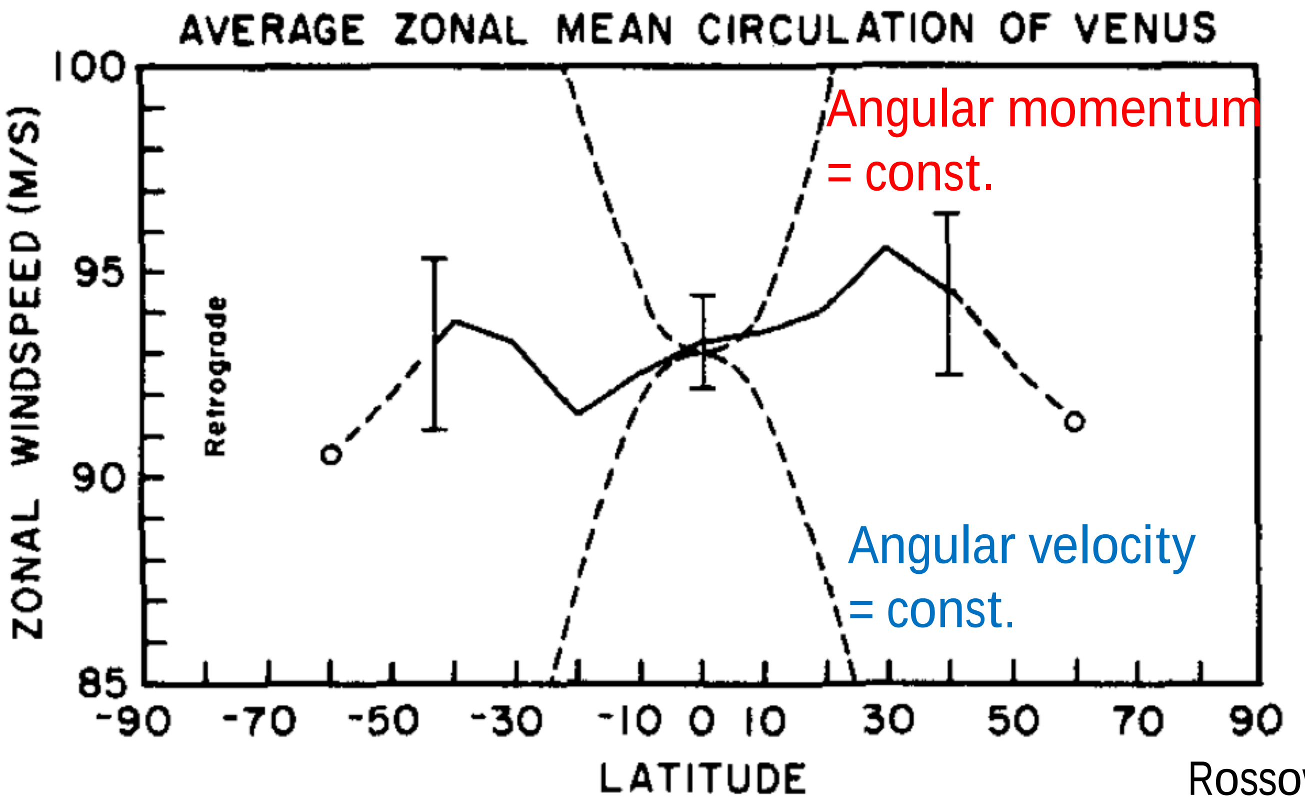


Prediction of meridional circulation



Sketch of Venus' mean meridional circulation by Schubert et al. (1980)

Meridional distribution of zonal wind or angular momentum in Venus atmosphere

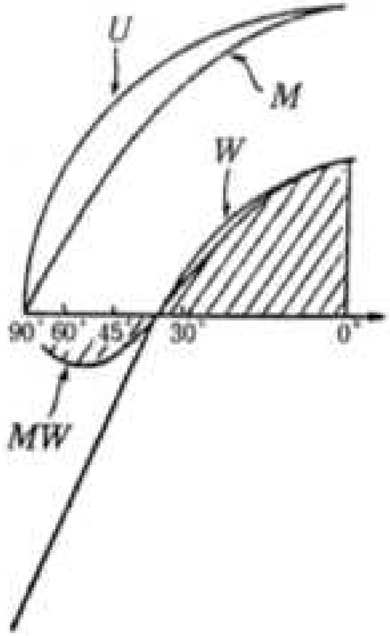


Rossow et al. (1990)

U decreases or slightly increases with latitude

→ Angular momentum = **ρ** U x (distance from axis)
decreases with latitudes

Upward transport of angular momentum by meridional circulation



U: velocity of zonal wind

M: angular momentum of zonal wind

W: vertical velocity of merid. circ.

MW: vertical transport of *M* by *W*

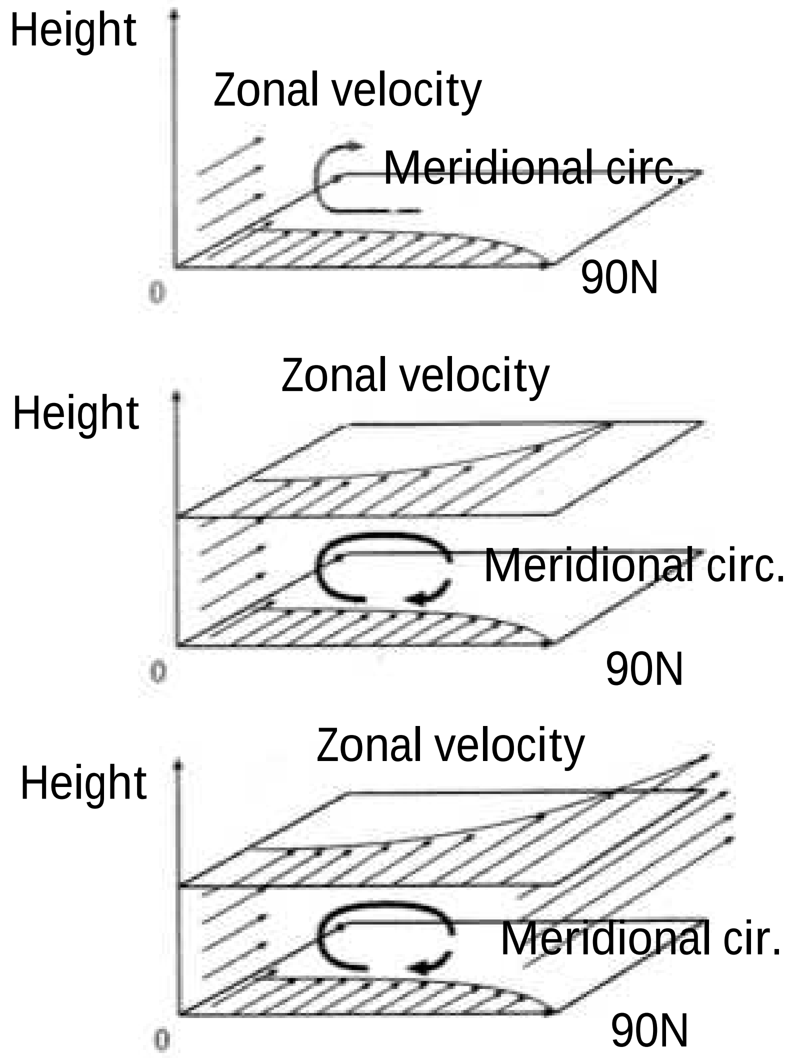
W>0 → *MW*>0: ang. mom. is upward in low latitudes

W<0 → *MW*<0: ang.mom.is downward in high latitudes

M is larger in lower latitudes

→ $\overline{MW} > 0$: upward transport of angular mom.

Horizontal advection of angular momentum by meridional circulation



In poleward advection by meridional circulation angular momentum is conserved. Zonal wind and angular momentum increase in higher latitudes.

Auxiliary mechanism for this mechanism to work

By horizontal advection angular momentum will increase in higher latitudes.

→Upward transport of angular momentum by meridional circulation cannot work.

→Auxiliary mechanism for transporting angular momentum equatorward is required:

→Gierasch(1975) parameterized this unknown mechanism by ν_H (“eddy” horizontal viscosity).

Conditions under which angular momentum can be transported upward

If ν_H is sufficiently large, distribution of zonal winds is close to a solid body rotation at each altitudes.

(1) The first condition is that distribution of zonal winds is not much deviated from solid body rotation:

a^2 / ν_H (relaxation time of eddy mixing)

< a / V (turnaround time of merid. circul.)

(2) The second condition is that, before super-rotation with vertical shear is destroyed by ν_V, momentum is effectively transported upward by merid. circ.:

H^2 / ν_V (relaxation time of vertical viscosity) > a / V

Analytic solution in the case of $\nu_H = \infty$

$\nu_H = \infty$ → angular velocity = const. i.e.

solid body rotation for each z:

$\bar{U}(\phi, z) = U(z)\cos\phi$ (ϕ : latitude)

Eq. of angular momentum conservation can be modified to be

$$\frac{\partial(U + a\Omega)}{\partial t} + \frac{\partial(U + a\Omega)W(z)}{\partial z} = \nu_V \frac{\partial^2(U + a\Omega)}{\partial z^2}$$

$W(z)$ = amplitude of vertical motion of merid. circ.

For stationary state, this eq. can be integrated for z

$$(U + a\Omega)W(z) - \nu_V \frac{\partial(U + a\Omega)}{\partial z} = \text{const.}$$

The solution of this eq. is

$$U + a\Omega = a\Omega \exp\left(\frac{1}{\nu_V}\int_0^z W(z')\,dz'\right)$$

for super-rotation: $U/a\Omega > 1$

$\frac{1}{\nu_V}\int_0^z W(z')\,dz' > 1$ is necessary

$$\frac{1}{\nu_V}\int_0^z W(z')\,dz' \sim \frac{WH}{\nu_V} = \frac{H^2/\nu_V}{H/W}$$

$$= \frac{\text{relaxation time of vertical viscosity}}{\text{turnaround time of merid. circ.}} > 1$$

Matsuda's study (1980)

- Three aspects of this study

(1) An extension of Gierasch(1975) to the case of $\nu_H \neq \infty$

(2) Classification of types of circulation system of planetary atmospheres

(3) Analysis of a nonlinear system in the light of multiple equilibrium solutions

Mathematical model used in this study

- A highly truncated system (spectrum model) : associated nonlinear equations of amplitudes of several modes
- The velocity field symmetric about the axis of planetary rotation is expressed by three modes:

T_1^0 (z,t) represents solid body rotation $\rightarrow \overline{U}$

T_3^0 (z,t) represents differential rotation $\rightarrow \Delta U$

S_2^0(z,t) represents meridional circulation $\rightarrow W$

Stationary solutions are treated in this study.

Relation between zonal wind and meridional circulation

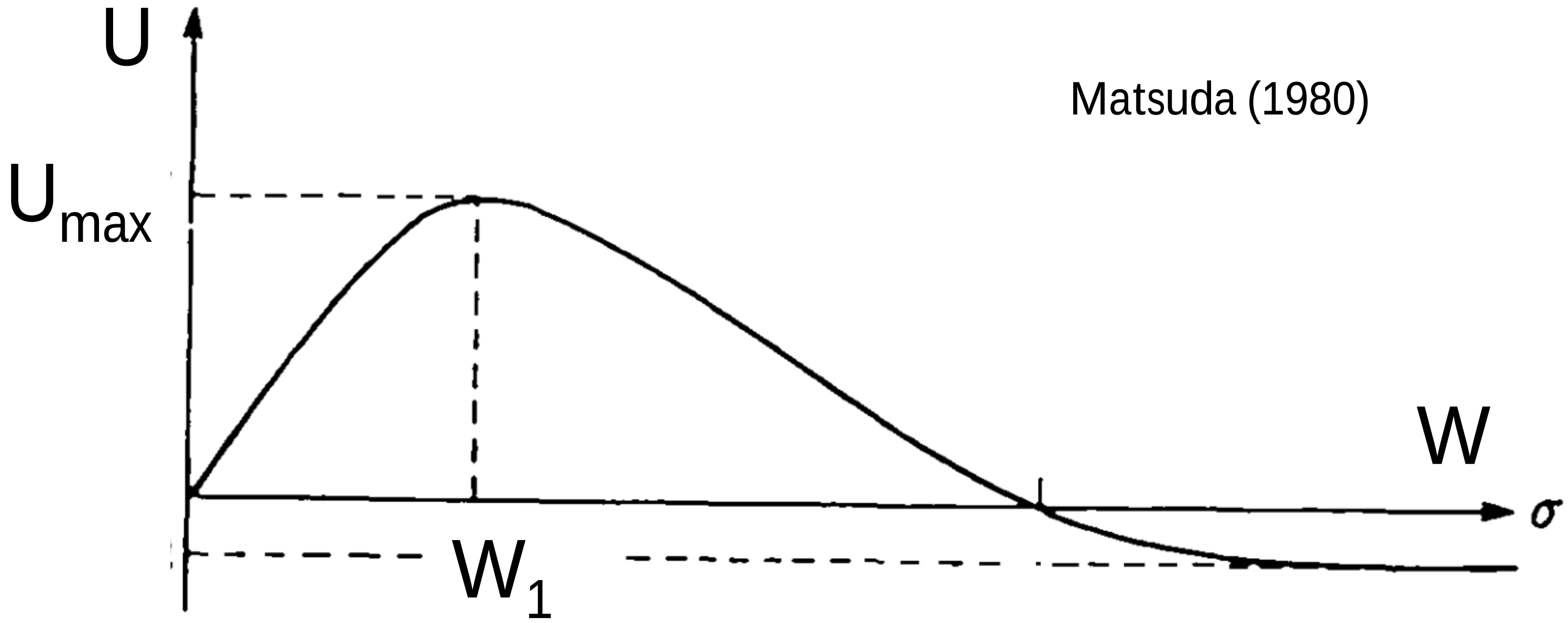
- From eq. of angular momentum, we can obtain zonal wind as a function of meridional circulation.
- In this relation, following processes are reflected:

(i) Upward transport of angular momentum by meridional circulation

(ii) Generation of differential rotation by horizontal advection of angular momentum by meridional circulation

(iii) Suppression of (i) by differential rotation

Zonal wind velocity *U* (amplitude of solid body rotation) as a function of *W* (amplitude of meridional circulation)



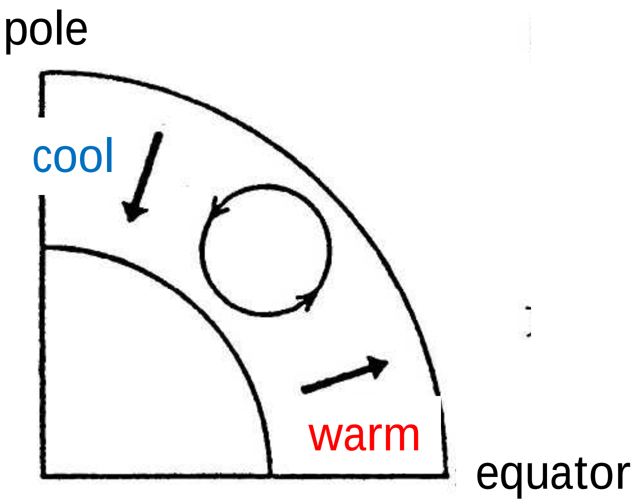
- *U* has a maximum value for $W = W_1$

Balance of moment (torque) in a meridional plane (a)

- Which effect can balance (0) moment of buoyancy due to meridional temperature difference ?

(1)Moment of friction acting on meridional circulation

This moment is proportional to W

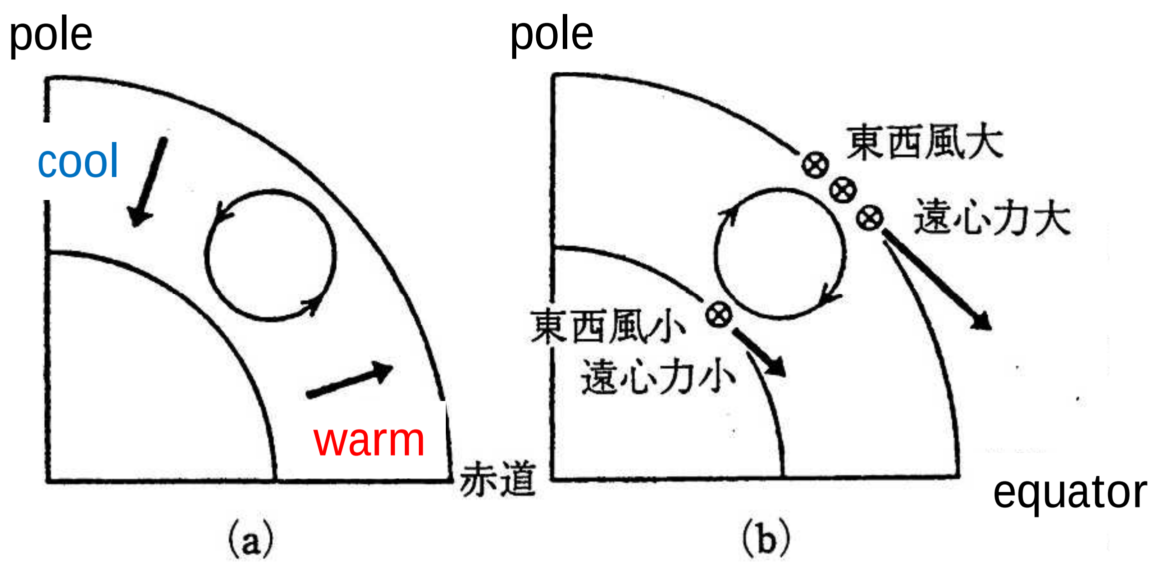


(a)

Balance of moment (torque) in a meridional plane (b)

(2) Coriolis force acting on zonal winds with vertical shear : this moment is proportional to $\frac{d(fU)}{dz}$

(3) Centrifugal force acting on zonal winds with vertical shear: this moment is proportional to $\frac{d(U^2/a)}{dz}$



Balance of moment (torque) in a meridional plane (c)

moment of (1) + (2) + (3) = (0)(moment of buoyancy
due to temp. diff.)

$$kW + f\frac{dU}{dz} + \frac{U}{a}\frac{dU}{dz} \propto \Delta T$$

if (2), (3) << (1) → (1) = (0): predominance of meridional circul. →(D)

if (1), (3) << (2) → (2) = (0): thermal wind balance by
Coriolis force → (E)

if (1), (2) << (3) → (3) = (0): thermal wind balance by
centrifugal force → (V)

Comparison of atmospheric balance between Earth and Venus

	Earth	Venus
$a\Omega$	460m/s	1.5m/s
U	30m/s	100m/s

$a\Omega \frac{dU}{dz} >> U \frac{dU}{dz}$ → (2)>>(3) →(2)=(0): (E) for Earth

(troposphere in extratropics)

$a\Omega \frac{dU}{dz} << U \frac{dU}{dz}$ → (2)<<(3) →(3)=(0): (V) for Venus

$$kW + f\frac{dU}{dz} + \frac{U}{a}\frac{dU}{dz} = (0)$$

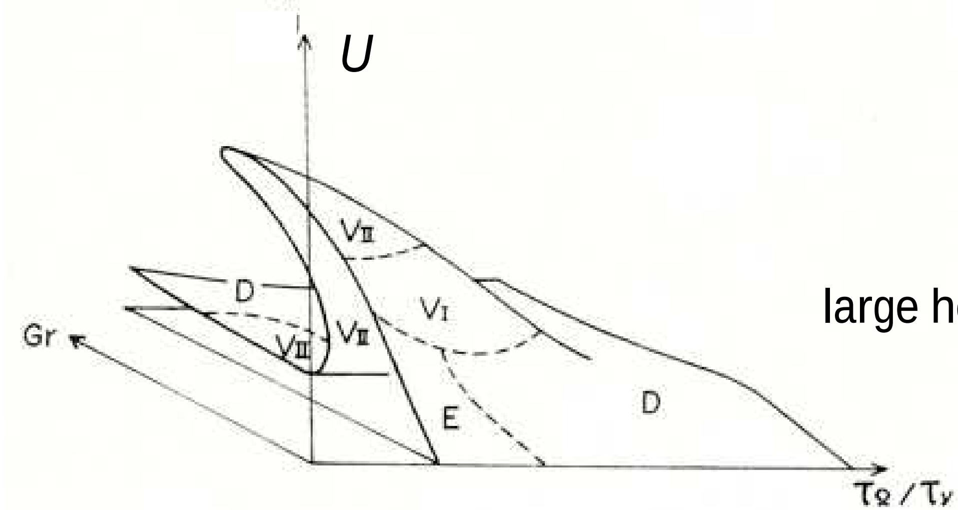
(1) (2) (3)

Stationary solutions of this system

- To obtain final solutions, eq. of momentum is associated with the relation between U (zonal wind) and W (meridional circulation).
- For simplicity, the parameters involved in this system are summarized into (1) period of planetary rotation $\tau_\Omega = 2\pi/\Omega$ (divided by diffusion time τ_ν) and (2) (non-dimensional) differential heating Gr

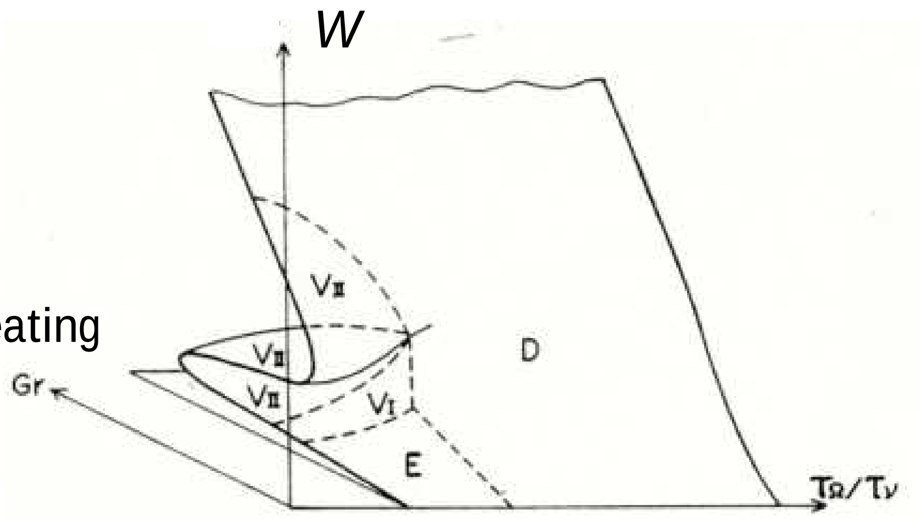
Zonal wind and meridional circulation of stationary solutions of this system

U (zonal wind) and W (magnitude of meridional circulation) are represented as functions of the two parameters.



fast ←planetary rotation → slow

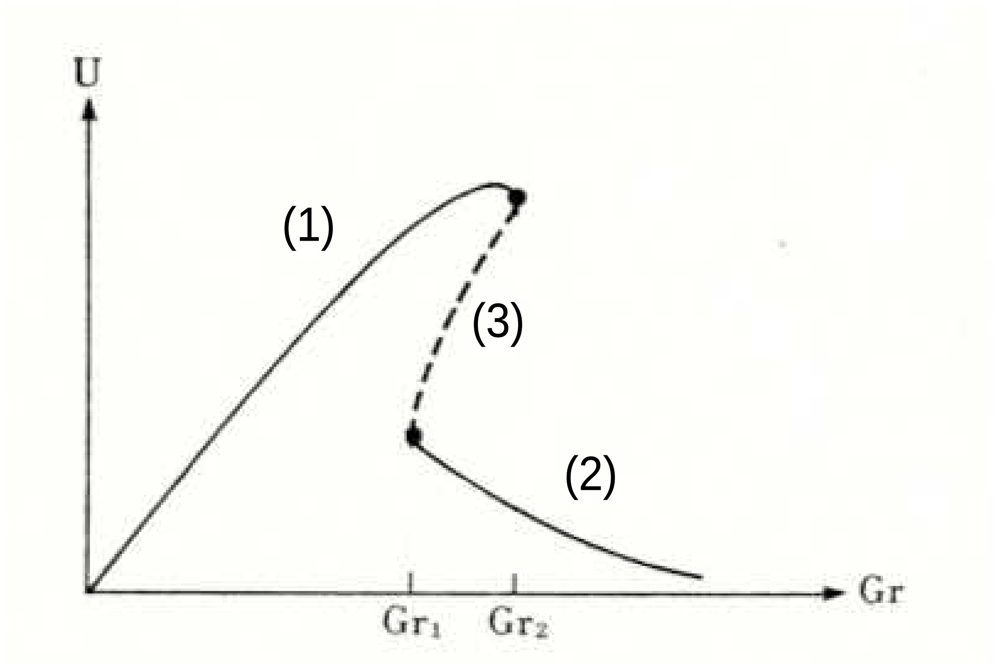
large heating



fast ←planetary rotation → slow

Multiple solutions in this nonlinear system

(1) Stable solution with fast zonal flow (super-rotation)
(2) Stable solution representing circulation between day and night sides
(3) Unstable solution representing a state intermediate between the two solutions



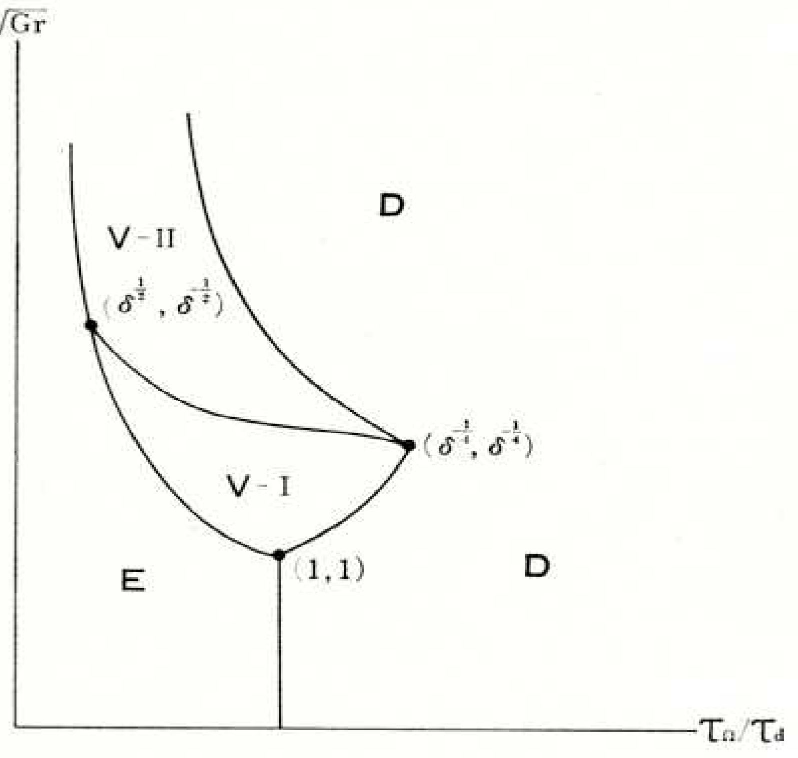
Classification of types of circulation system of planetary atmosphere

(D) U:small, W∝Gr:large → Predom. of meridional circulation

(E) U:small, W:very small → Thermal wind balance (geostophic)

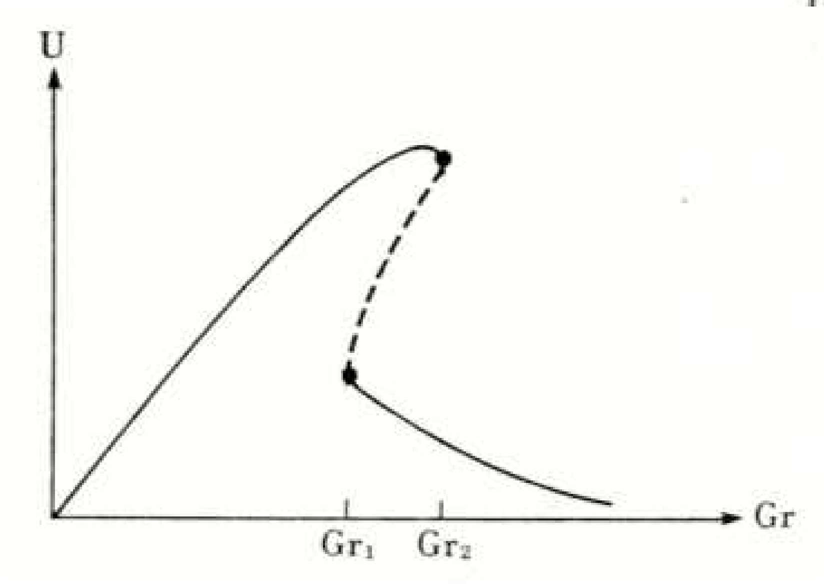
(V) U:large, W:small → Thermal wind balance (cyclostrophic)

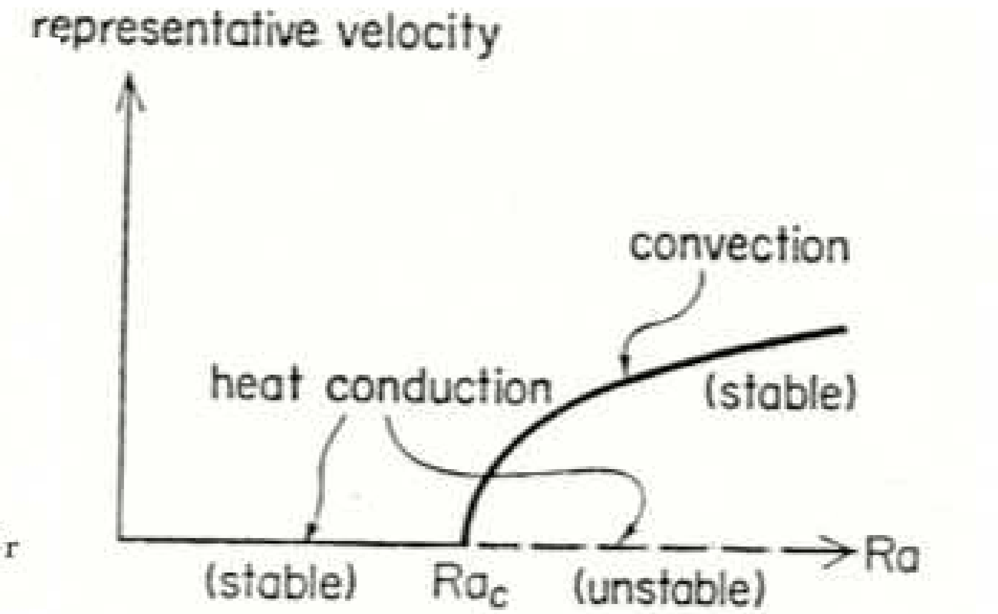
--> large heating



--> slow planetary rotation

Structure of critical points in nonlinear systems





Snap point

Bifurcation point

→ Matsuda's study(1983) on classification of critical points

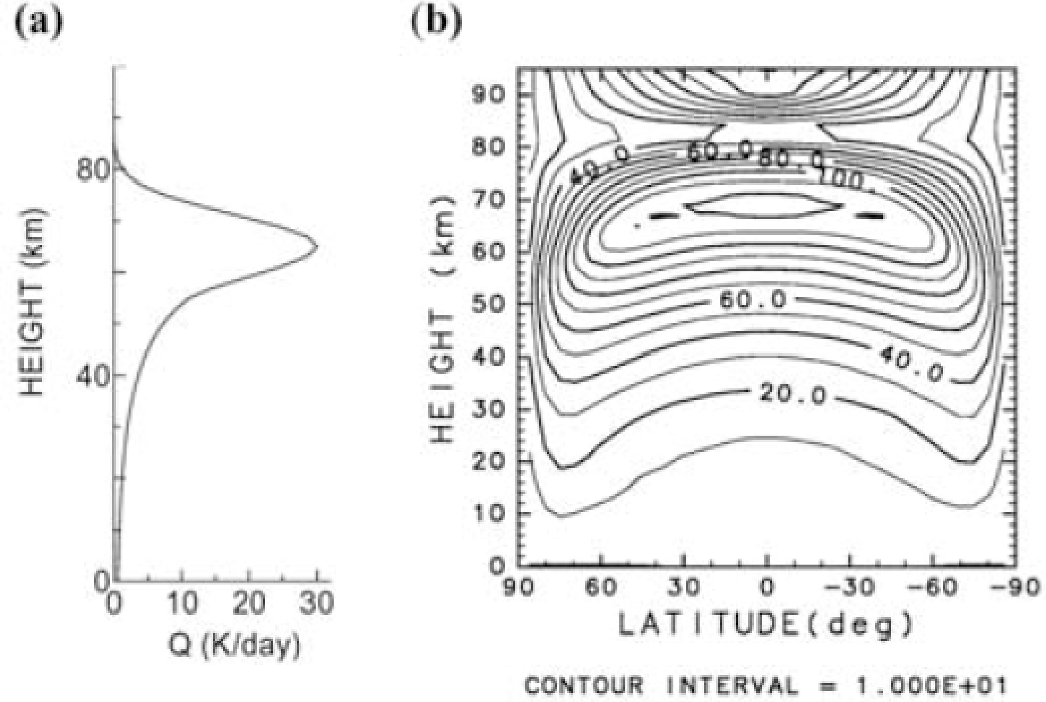
Numerical simulations of super-rotation by GCM (mechanism due to meridional circulation)

(a) Yamamoto reproduces super-rotation :

mechanism due to meridional circulation is working in his model (Yamamoto and Takahashi (2003a,b,04))

(a): Heating distribution

(b): Zonal velocity in Y and T(2004)



Numerical simulations of super-rotation by GCM (mechanism due to meridional circulation)

(b) Lee et al. (2005, 2007)

(c) Hollingsworth et al.(2007)

(Lebonnois et al. (?))

(a)-(c) adopt Newtonian cooling and extremely large diabatic heating.

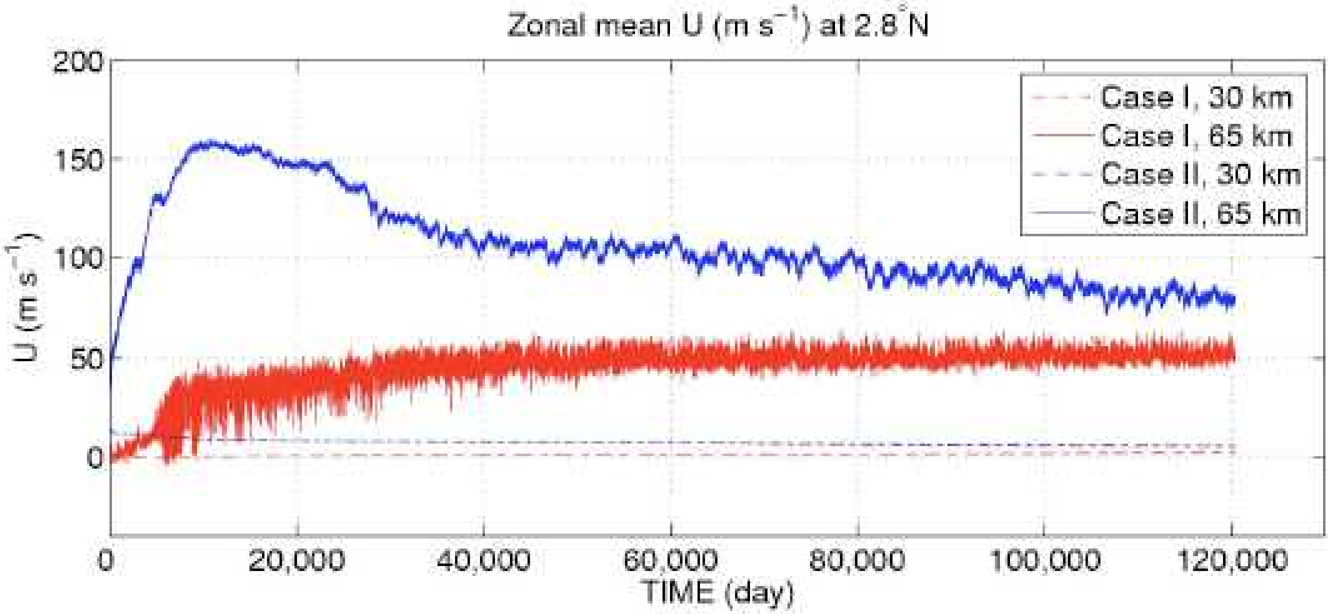
(c) described "when realistic diabatic heating is imposed in the lowest scale height, only extremely weak atmospheric superrotation results."

(b) Kido's study on multiple equilibiria in the Venus circulation

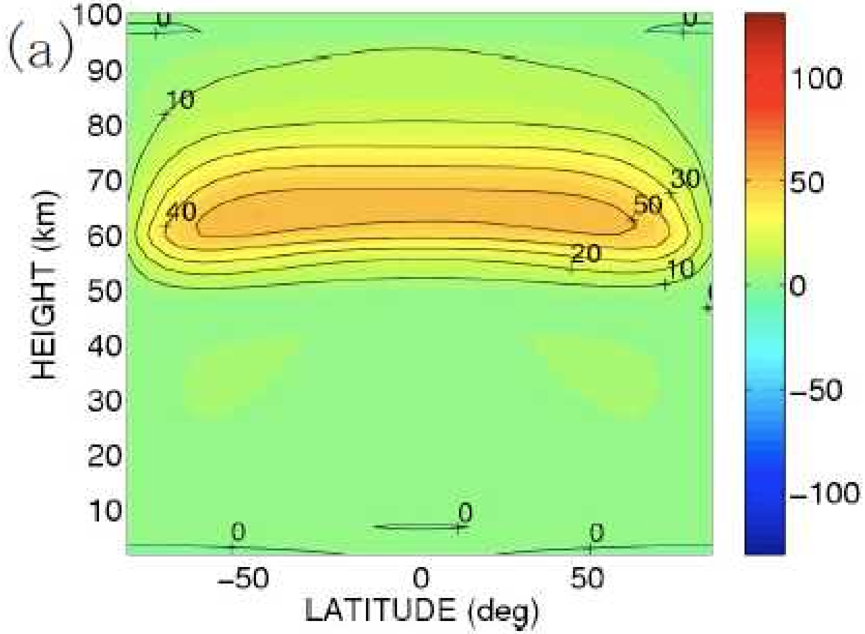
- Kido reproduces multiple equilibria predicted by Matsuda in his GCM (Kido and Wakata(2007,09)).

Case I starts with motionless initial condition

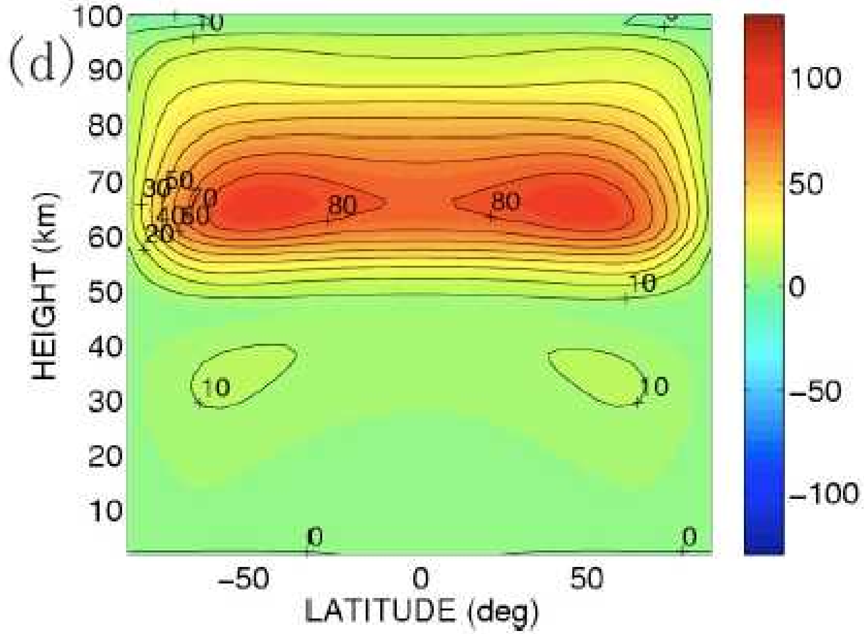
Case II starts with fast zonal winds



Two different distributions of zonal wind in Kido and Wakata (2009)



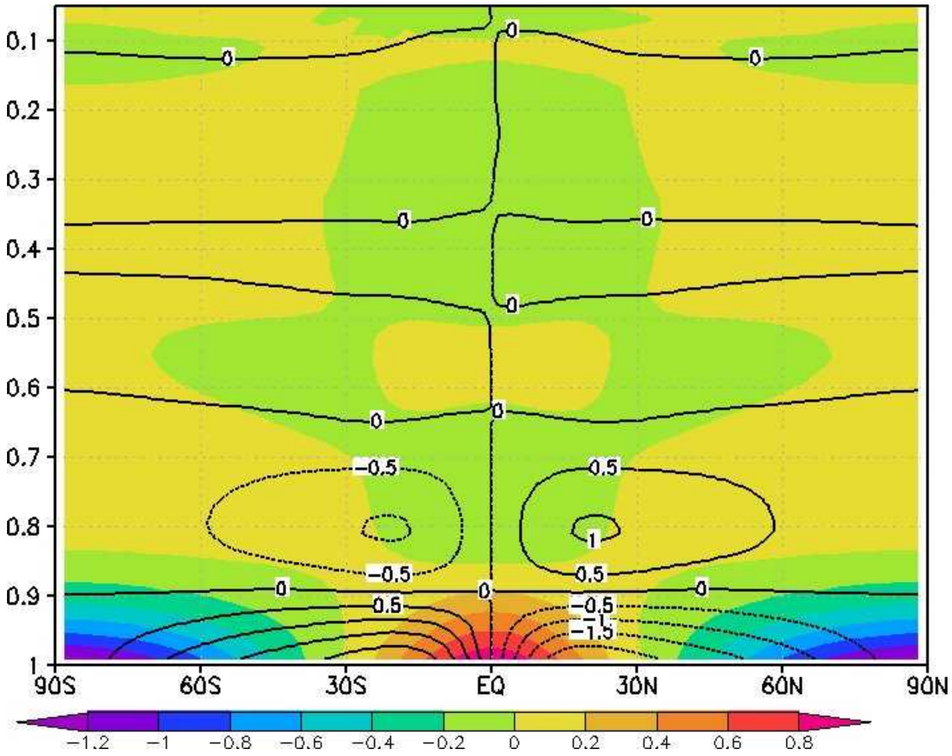
case I



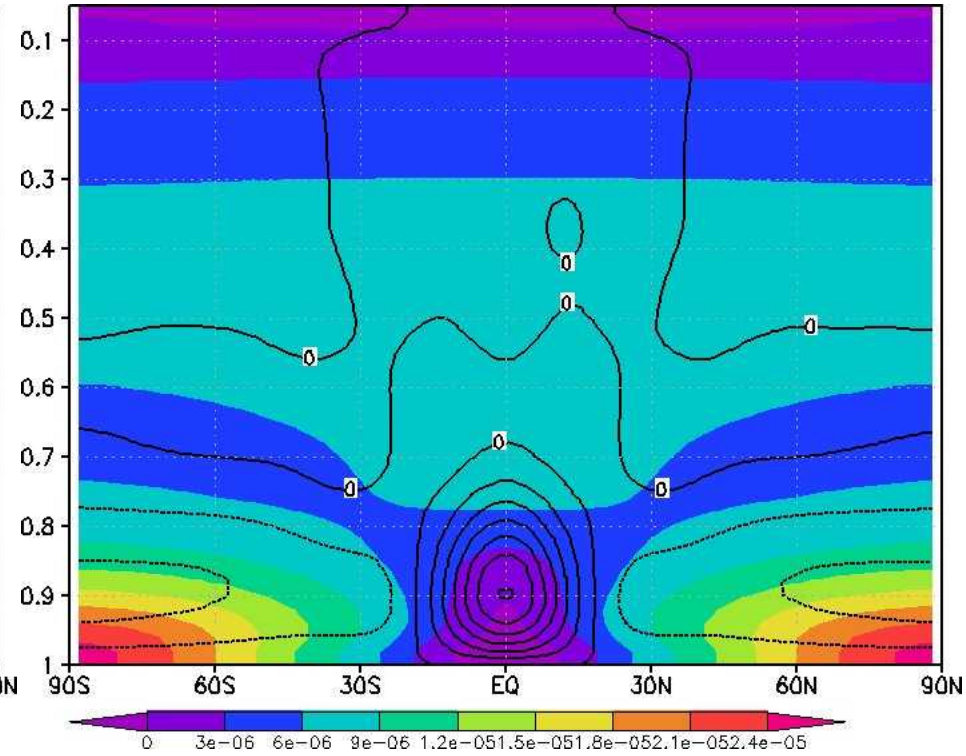
case II

Results of Takagi's GCM with an exact radiation model

V (contour) and T' (color)



-sigma velocity (contour) and N^2 (color)



(5) Conclusion

1. Promising mechanisms explaining the super-rotation:

(a) mechanism based on the thermal tides

(b) mechanism based on the meridional circulation

2. Observations required for specifying the mechanism working in the Venus atmosphere

(1) Thermal tides

Does it propagate to the ground ?

Wind velocity of thermal tides in the cloud layer

(2) Meridional circulation :

Does it exist really ?

Its meridional wind velocity?

(3) Meridional transport of zonal momentum by eddies:

$$\overline{u'v'} = ?$$

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