

Recent Development of CCSR/NIES AGCM for Venus Atmospheric Sciences

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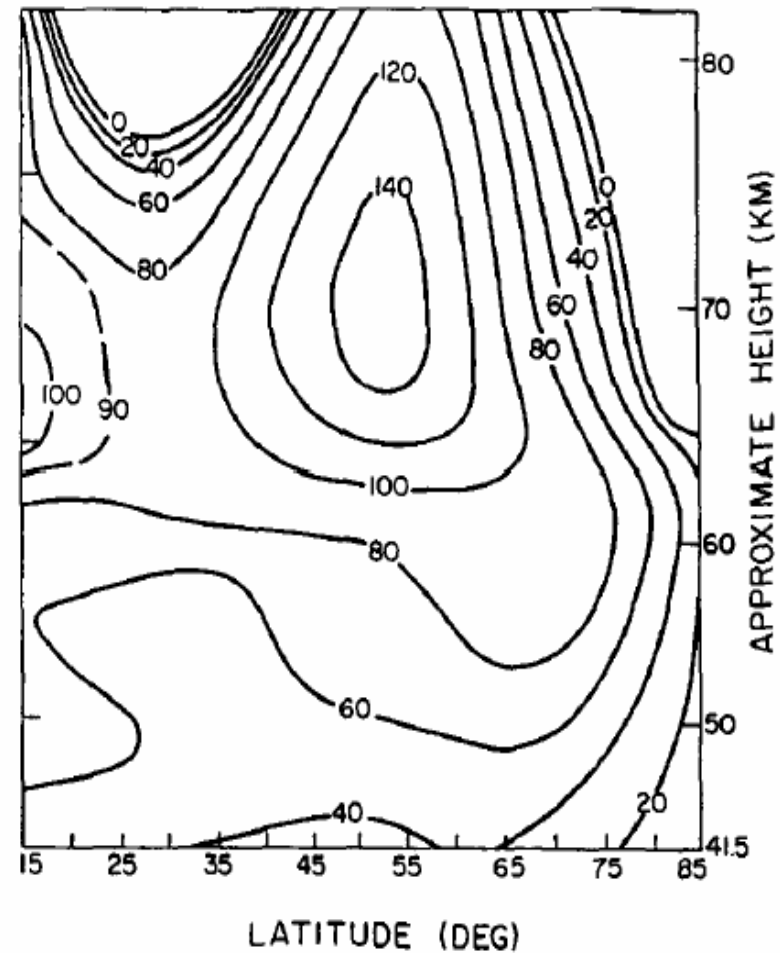
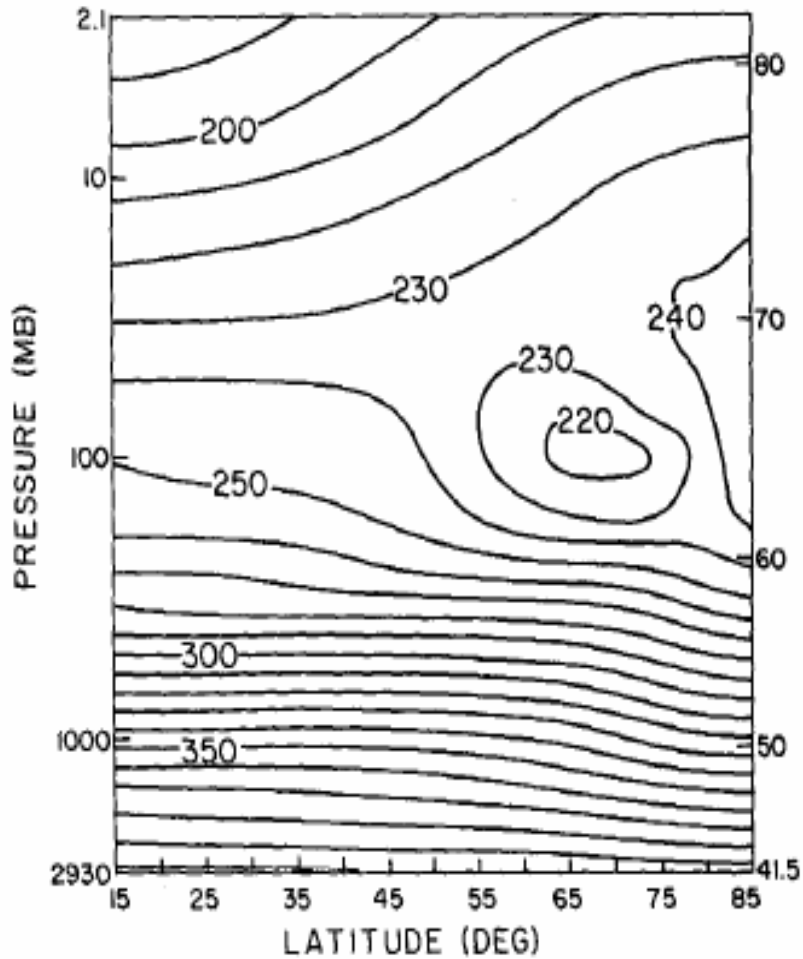
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Observations

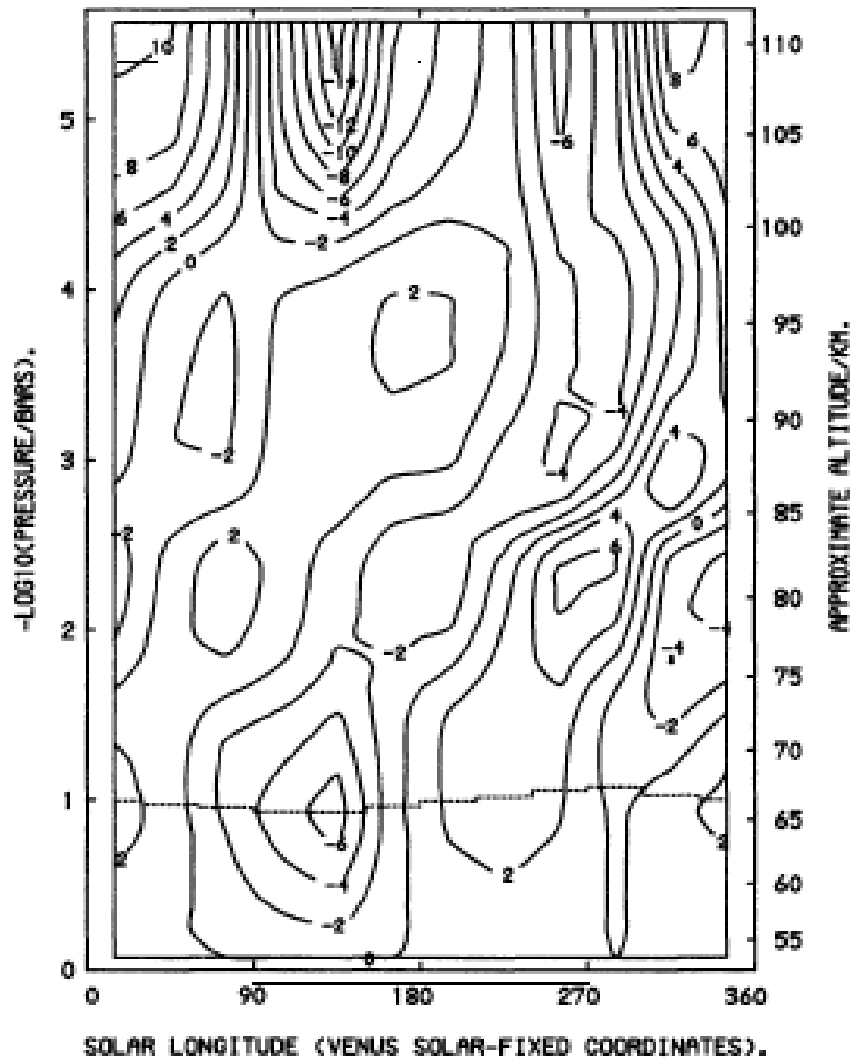
An observationally estimated latitude-height section of strong zonal mean flow in the Venus stratosphere (from Newman et al. 1984, JAS)

temperature \Rightarrow zonal wind

Cyclostrophic wind balance is used



An example of disturbances: thermal tides in the middle atmosphere



Longitude-height distribution of deviations from zonal mean temperatures (0-30N) obtained from the Orbiter infrared radiometer in the solar fixed coordinate



Thermal tides are important for dynamics of the middle atmosphere.

(from Schofield and Taylor, 1983, QJRMS)

Dynamical Backgrounds

1. Dynamics in the stratosphere

(e.g., *Schubert et al.* 1980; *Gierasch et al.* 1997)

- **Superrotation**

Fully-developed superrotation is observed in the Venus middle atmosphere

⇒ **Why is the superrotation 60-times faster than the planetary rotation (243 day)?**

- **Meridional circulation**

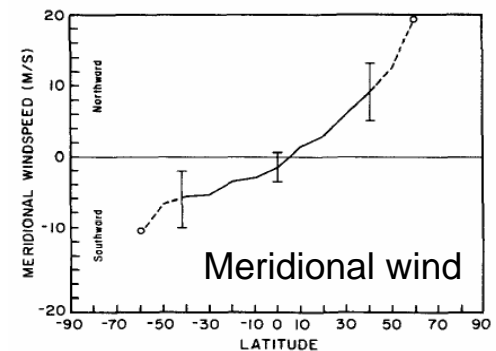
Poleward flow of 1–10 m/s

(e.g., *Rossow et al.* 1990; *Smith and Gierasch* 1996)

- **Many observational waves**

Thermal tides (e.g., *Schofield and Taylor* 1983),
planetary-scale Kelvin and Rossby waves
(e.g., *Del Genio and Rossow* 1990),

...



Waves near the cloud top

2. Maintenance mechanism of Venus' superrotation

(1) Meridional circulation: **Gierasch mechanism**

- with large horizontal eddy diffusion (*Gierasch 1975*)
 - Barotropic instability (*Rosow and Williams 1979*)
- ⇒ 2D mechanistic model (*Matsuda 1982, Iga and Matsuda 1999*)

(2) Vertically propagating wave (*Fels and Lindzen 1974*)

- ⇒ 2D mechanistic model including meridional circulation
- Thermal tide (*Baker and Leovy 1987, Newman and Leovy 1991*)
 - 4-day wave (*Yamamoto and Tanaka 1997*)

(3) Vertically tilting convection (*Thompson 1970*)

- ⇒ 3D dynamics (*Takagi and Matsuda 1999*)

Which mechanism is dominated in the real atmosphere?
⇒ **Further observations & GCM experiments are needed**

3. Studies using Venus-like GCM (General Circulation Model)

Young and Pollack (1977)

⇒ Superrotation of 100 m/s

However, some problems are indicated by *Rossow et al. (1980)*.

Rossow (1983), Del Genio et al. (1993), ...

⇒ the Gierasch-Rossow-Williams scenario.

Meridional circulation + Barotropical waves

However, the superrotation of > 100 m/s is NOT simulated under Venus' condition.



The maintenance mechanism of the fully developed superrotation is still unknown.

Recent simulations

- A simplified GCM (*Utsunomiya and Matsuda 1998*)
- A simplified 2D model (*Joshi and Young 2002*)
to study Dynamics of Venus' lower atmosphere.
⇒ Dynamics of superrotation in the stratosphere had not been elucidated.

- *Yamamoto and Takahashi (2003)*
Venus-like GCM using ***a zonal-mean heating***
⇒ A fully developed superrotation was reproduced.

- ***Yamamoto and Takahashi (2004, 2006)***
Venus-like GCM using ***a 3-dimensional heating with a Venus day of 117 days***
⇒ **this presentation**

Objectives of present talk

- (1) To reproduce the fully-developed superrotation under the realistic condition of $2\pi/\Omega = 243$ days and $P_s = 92$ atm.
- (2) To understand the maintenance mechanism of the superrotation, based on the detailed wave analysis.
⇒ **Here, some results obtained from the wave analysis are shown.**

We are developing Venus GCM as a tool for theoretical and observational studies

Model (*Yamamoto & Takahashi 2004*)

- T21L52 CCSR/NIES AGCM ver.5.6 (cf., *Numaguti et al. 1995*)
- Simplified physical processes (using Newtonian cooling) are used

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

equator-pole contrast of 10 K for surface temperature

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

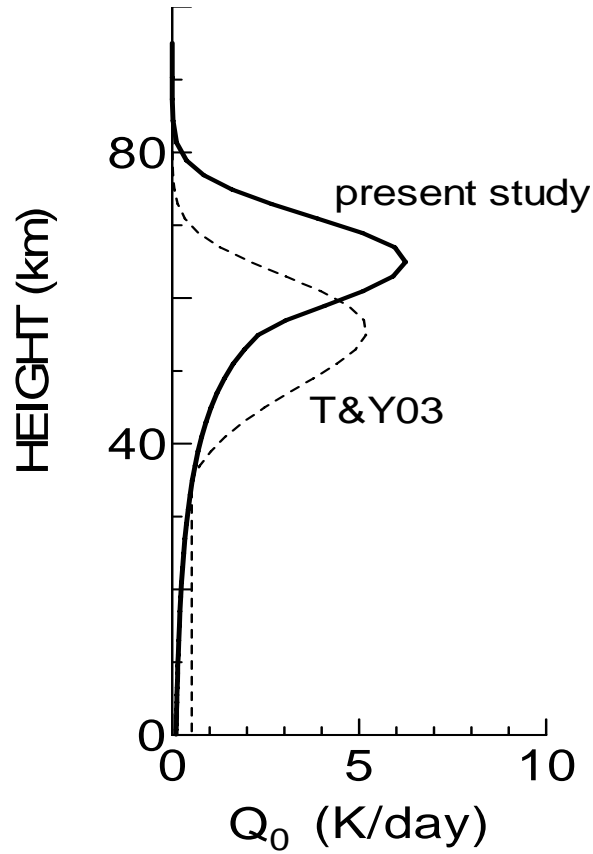
Rayleigh friction of 30 days near the top boundary

Rayleigh friction for eddy (with the Newtonian cooling rate)

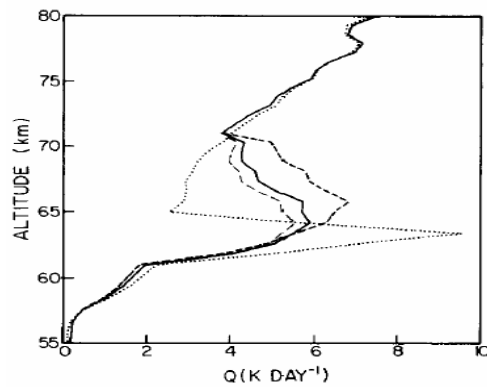
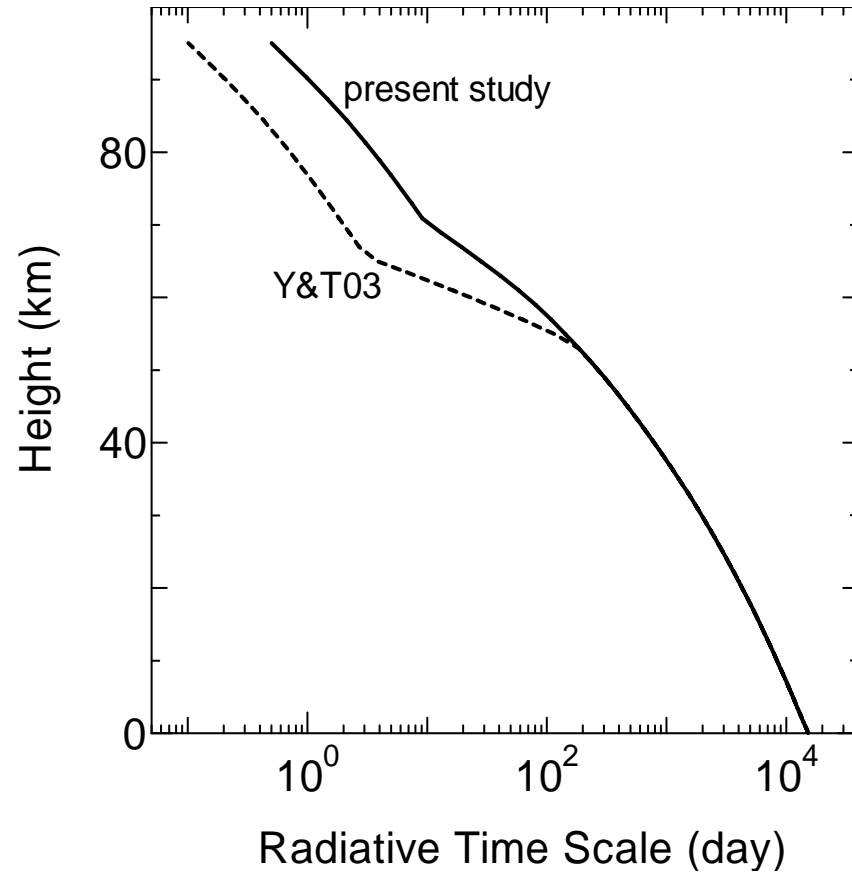
⇒ prevention of artificial effects near the top boundary

Constant vertical eddy diffusion with $K_v = 0.15\text{m}^2/\text{s}$ is set

Heating Rate (K/day)



Newtonian Cooling (day)



cf., solar heating rate in Crisp(1986)

Analysis is based on Transformed Eulerian Mean equation (e.g., Andrews et al. 1987)

Sampling period: 3072 hours (3-hour sampling) on Day 51480

Residual mean meridional circulation is shown

$$V^* = \bar{v} - (\rho_0 \overline{v'\theta'} / \bar{\theta}_z)_z / \rho_0$$

$$W^* = \bar{w} + (\cos \phi \overline{v'\theta'} / \bar{\theta}_z)_\phi / a \cos \phi$$

over-bar is zonal mean, ' is deviation from zonal mean

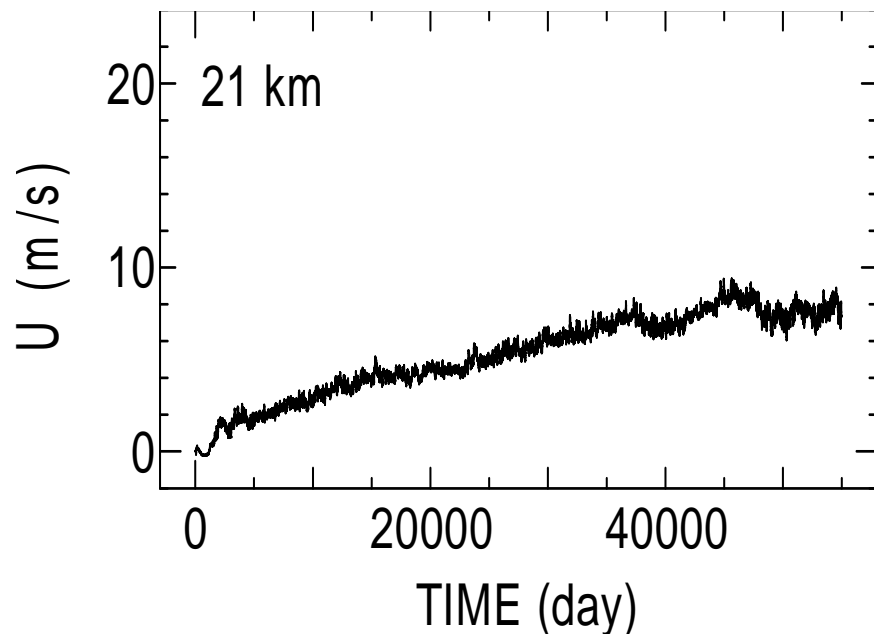
The Eliassen-Palm flux for eddy momentum flux is used

$$F_{EP}^z = \rho_0 a \cos \phi \{ \overline{u'w'} - [f - (\bar{u} \cos \phi)_\phi / a \cos \phi] \overline{v'\theta'} / \bar{\theta}_z \}$$

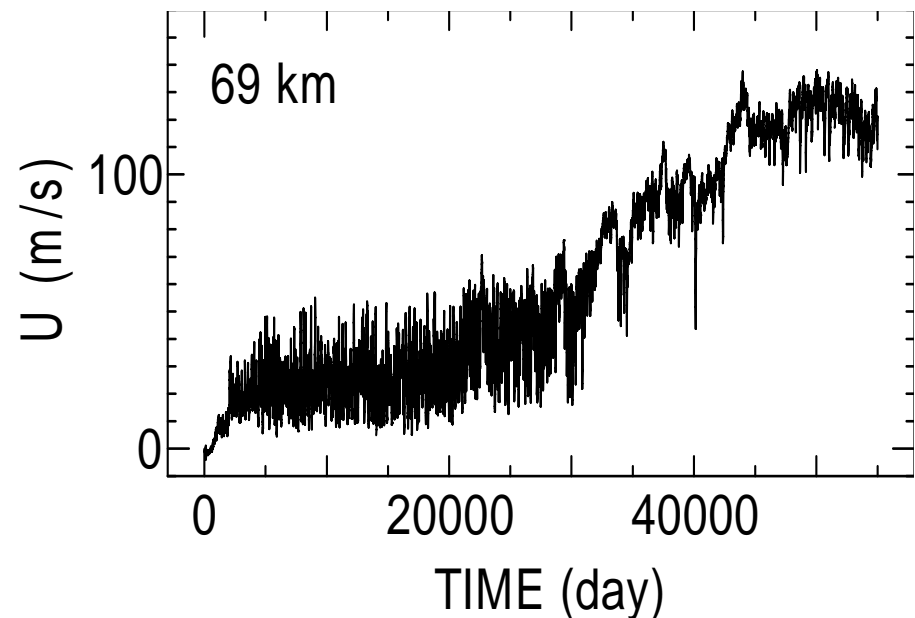
$$F_{EP}^\phi = \rho_0 a \cos \phi (\overline{u'v'} - \bar{u}_z \overline{v'\theta'} / \bar{\theta}_z)$$

Numerical Results:

Time histories of equatorial mean zonal flows



in the lower atmosphere

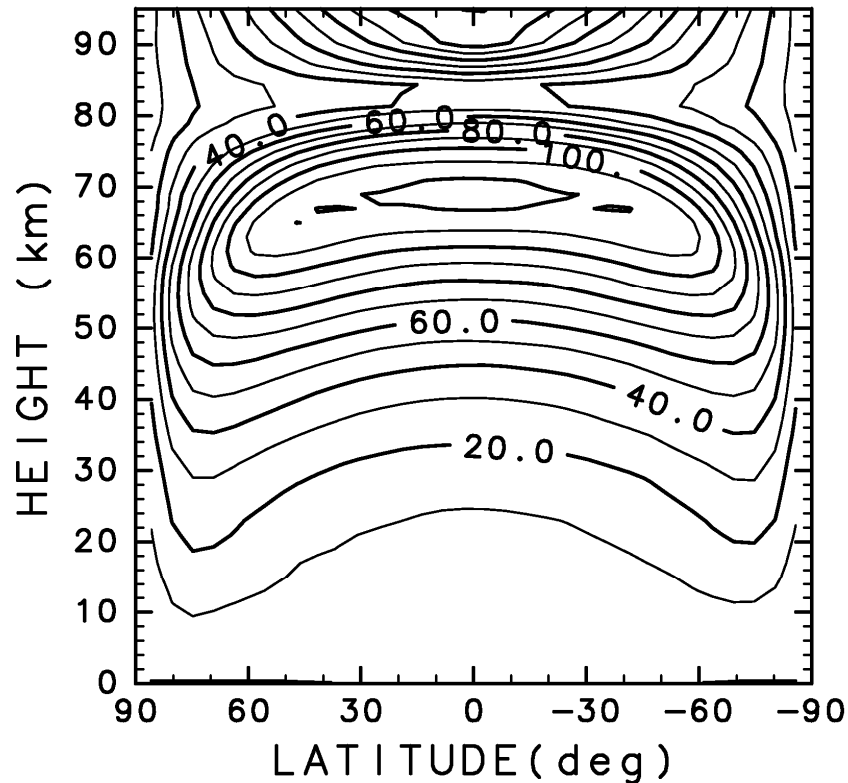


in the middle atmosphere

⇒ get to an equilibrium state at 45000 days

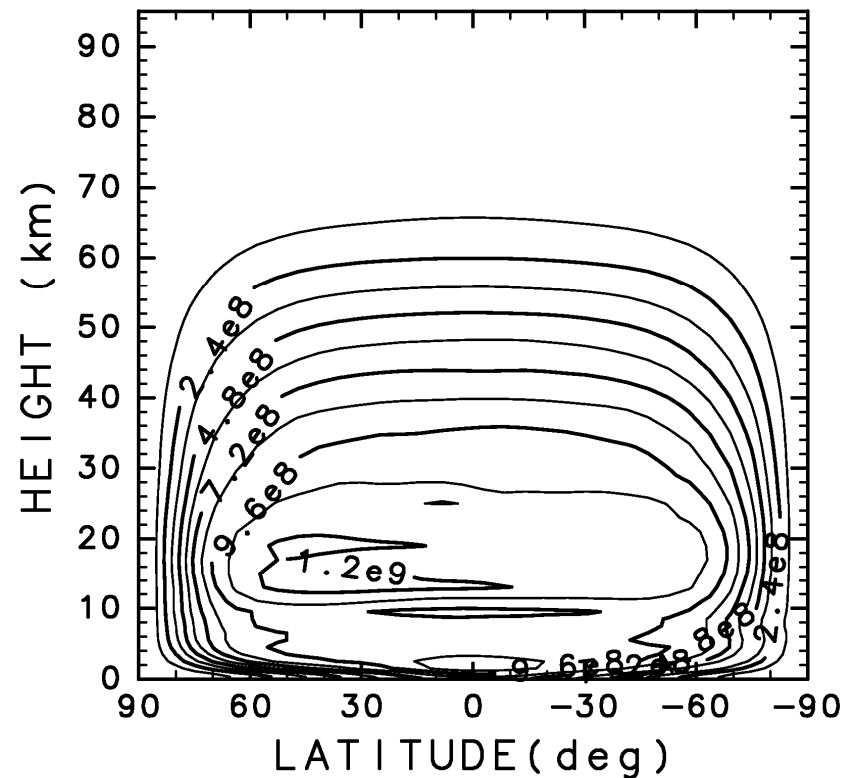
Latitude-Height distributions of mean fields

Mean Zonal Flow (m/s)



CONTOUR INTERVAL = 1.000E+01

Abs. Ang. Momen. (kg/m/s)

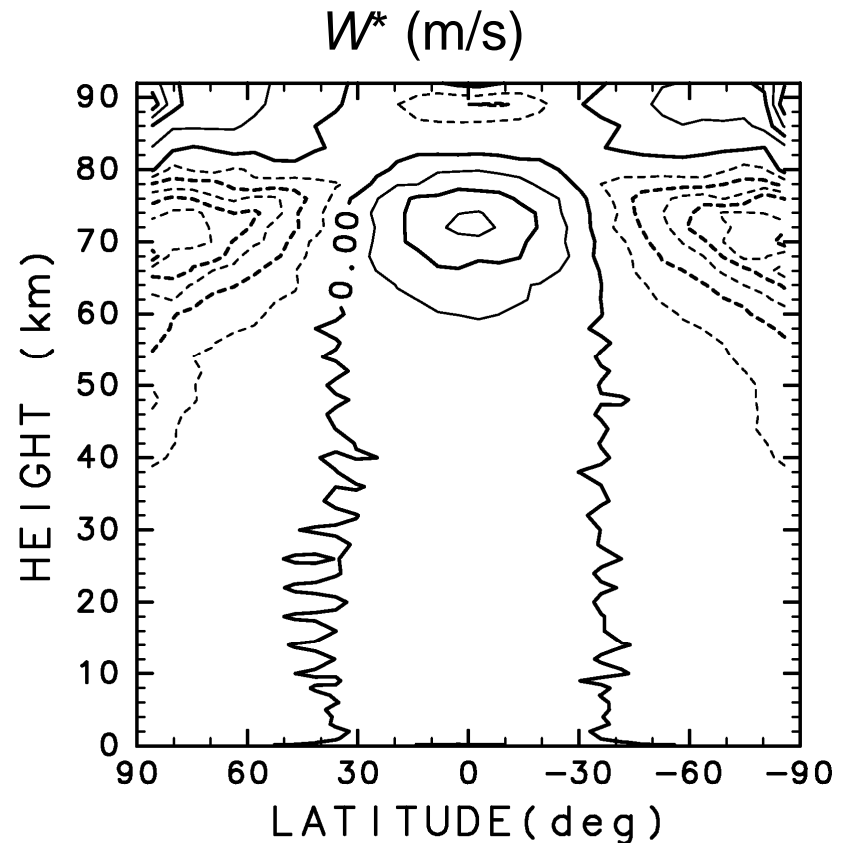
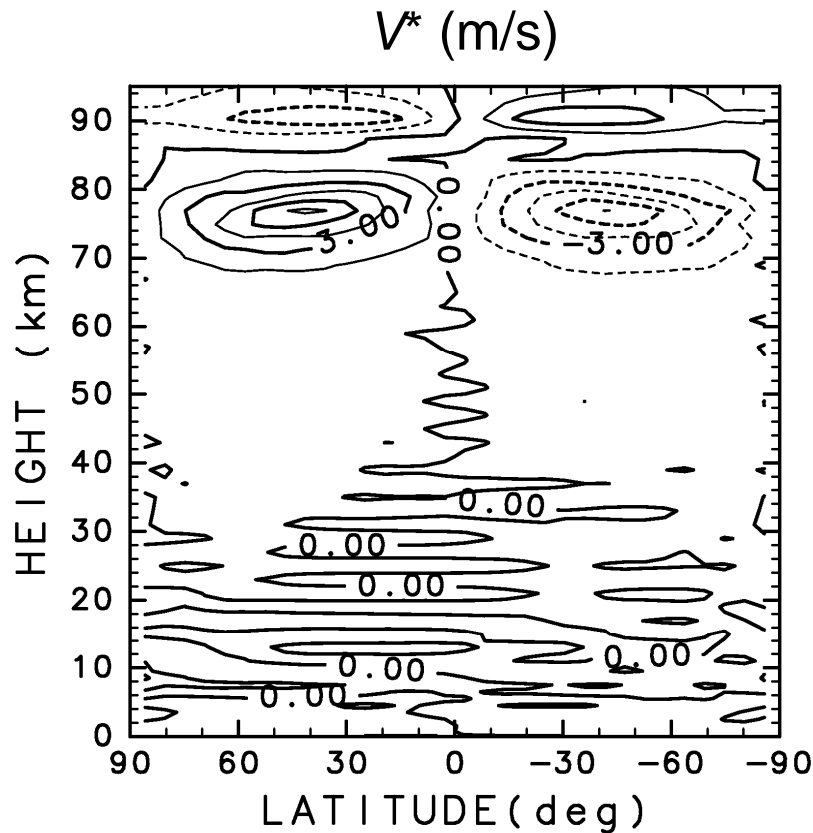


CONTOUR INTERVAL = 1.200E+08

Superrotational flow of more than 100m/s is reproduced near the cloud top in the model.

A maximum of angular momentum is located near 20 km.

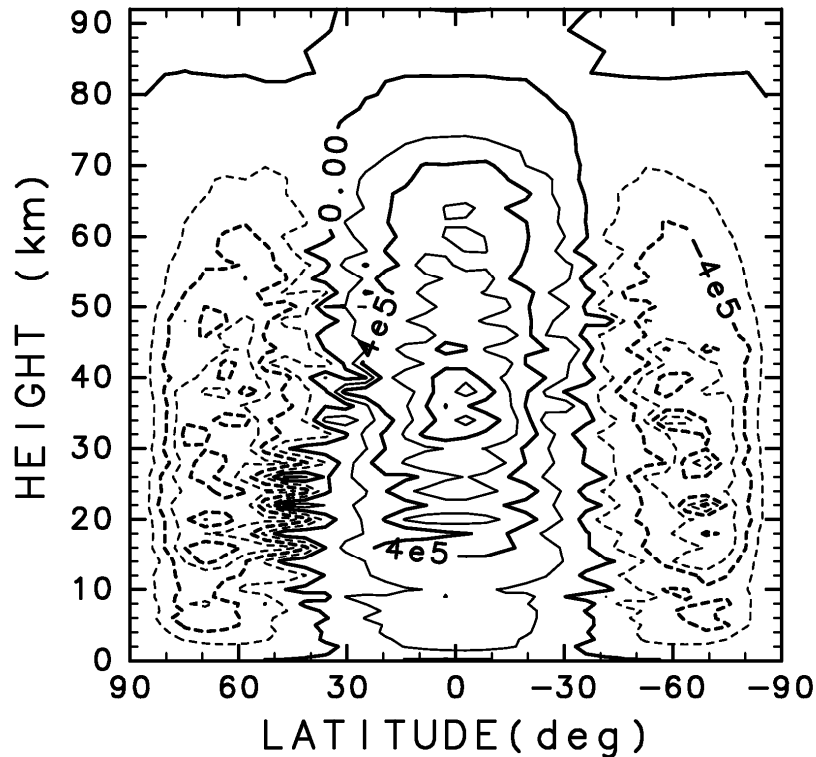
Residual Mean Meridional Circulation



Strong poleward flows are seen near 75 km.
A single-cell with upward motion over the equator is dominated in a latitude-height section between 0 and 80 km.

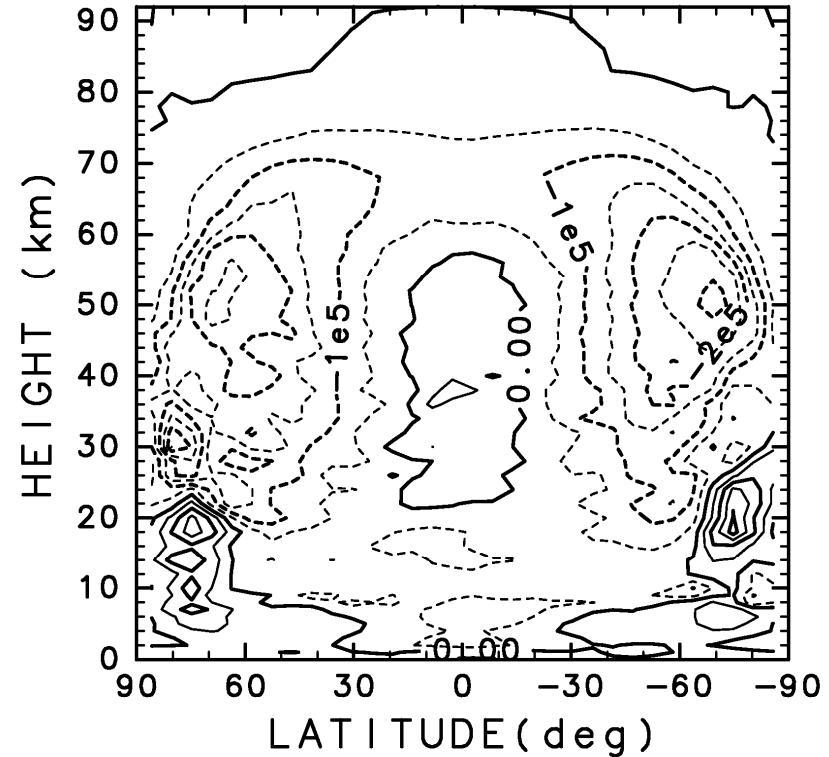
Vertical Angular Momentum Transport

by mean vertical flow (W^*)



CONTOUR INTERVAL = 2.000E+05

by eddy (F_{EP^2})



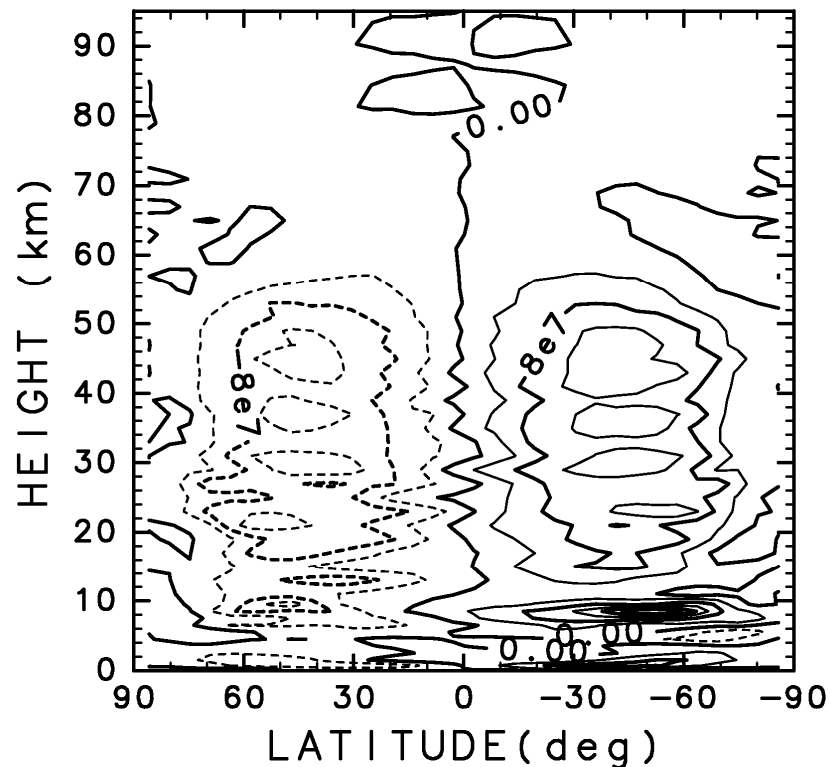
CONTOUR INTERVAL = 5.000E+04

Mean vertical flow transports angular momentum upward at low latitudes.

Vertical transport of eddy angular momentum is predominantly downward at high latitudes in the stratosphere.

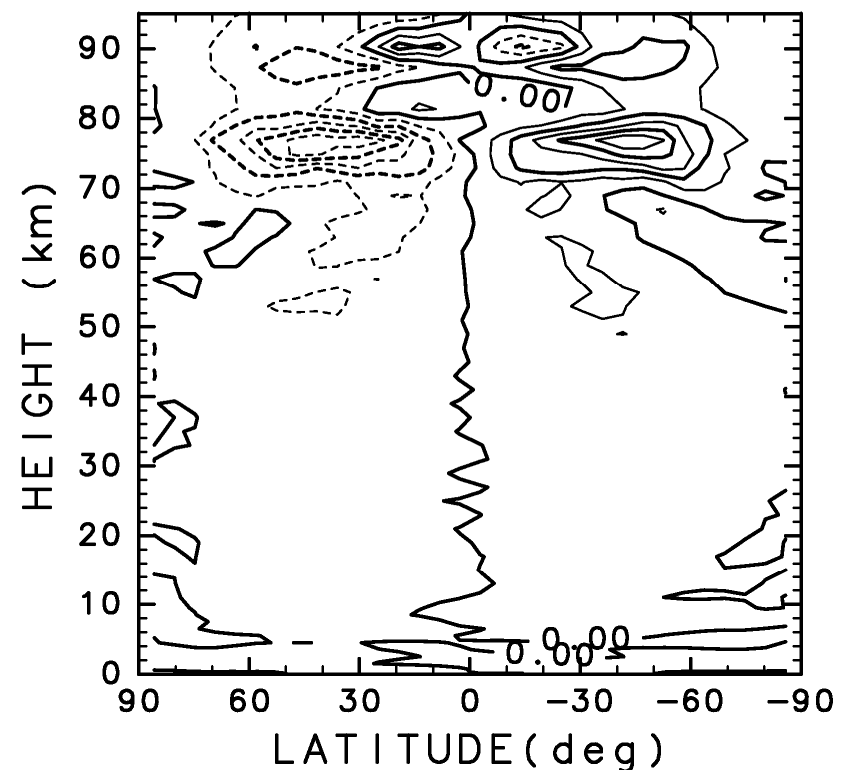
Horizontal Eddy Momentum Transport

$$F_{EP}^{\phi} = \rho_0 a \cos \phi (\overline{u'v'} - \overline{u'_z v' \theta'} / \overline{\theta'_z})$$



CONTOUR INTERVAL = $4.000E+07$

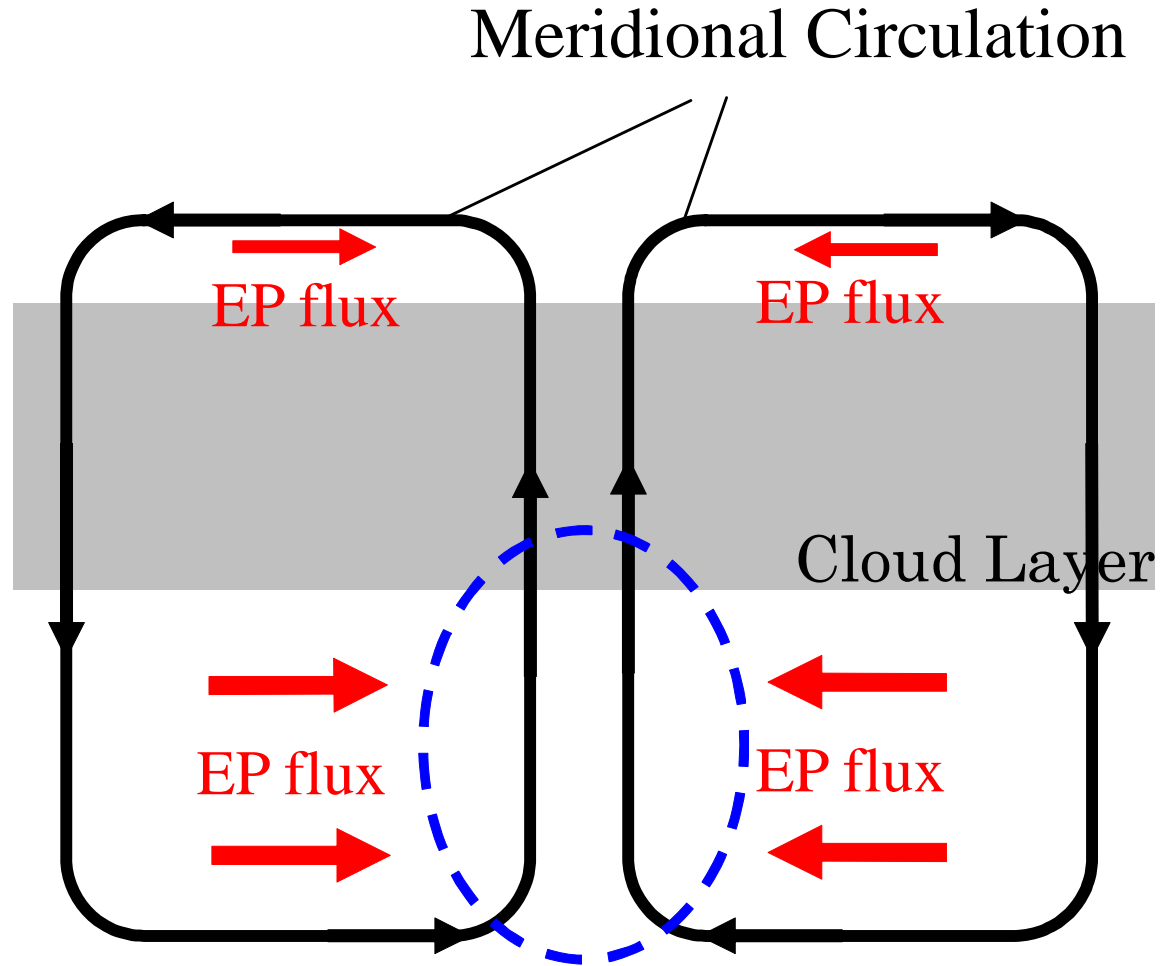
$$F_{EP}^{\phi} / \sigma$$



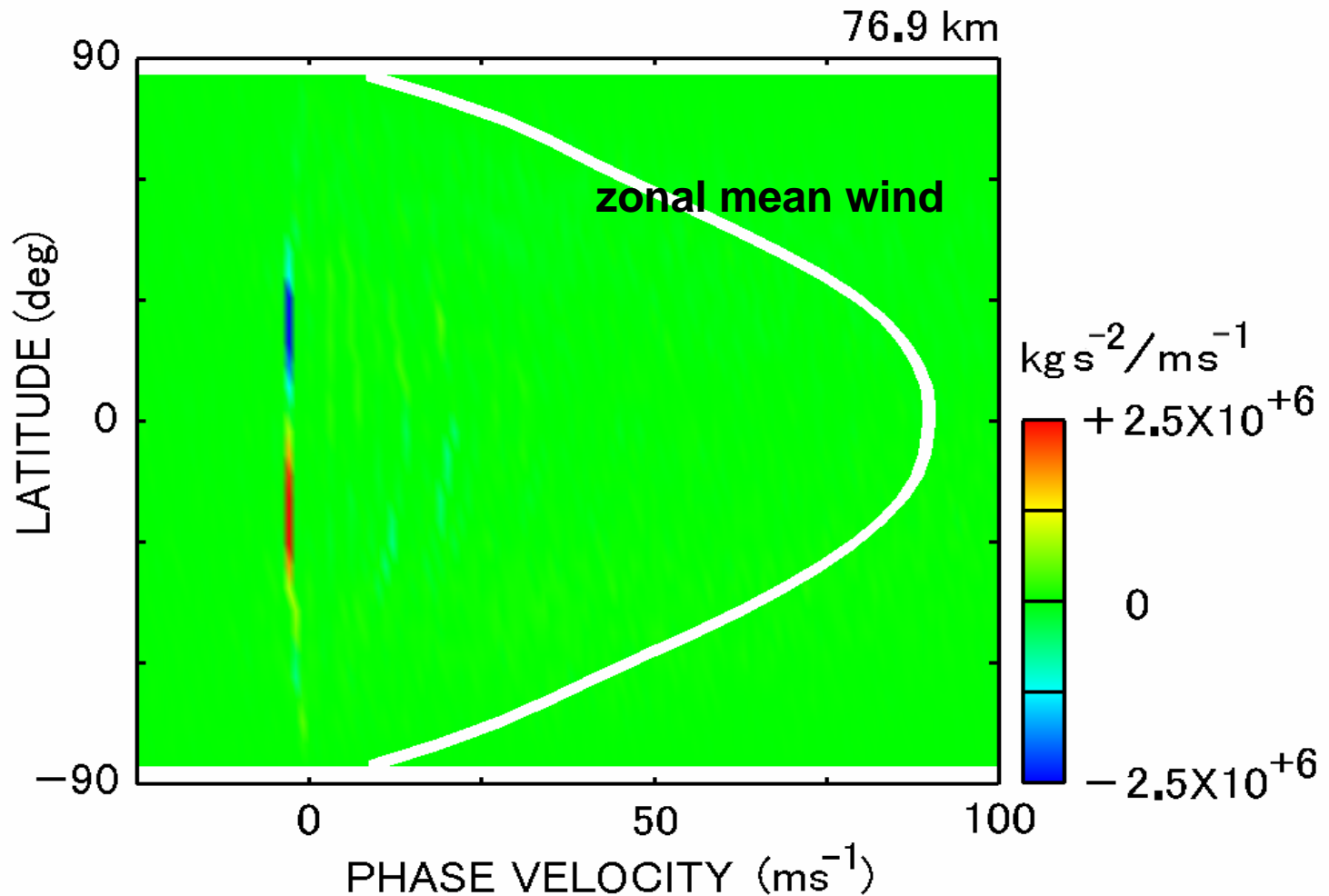
CONTOUR INTERVAL = $1.000E+10$

Horizontal EP fluxes are predominantly equatorward. The angular momentum is deposited into the low-latitude regions by eddies.

Schematic figure of Equatorward Eddy Momentum Transport

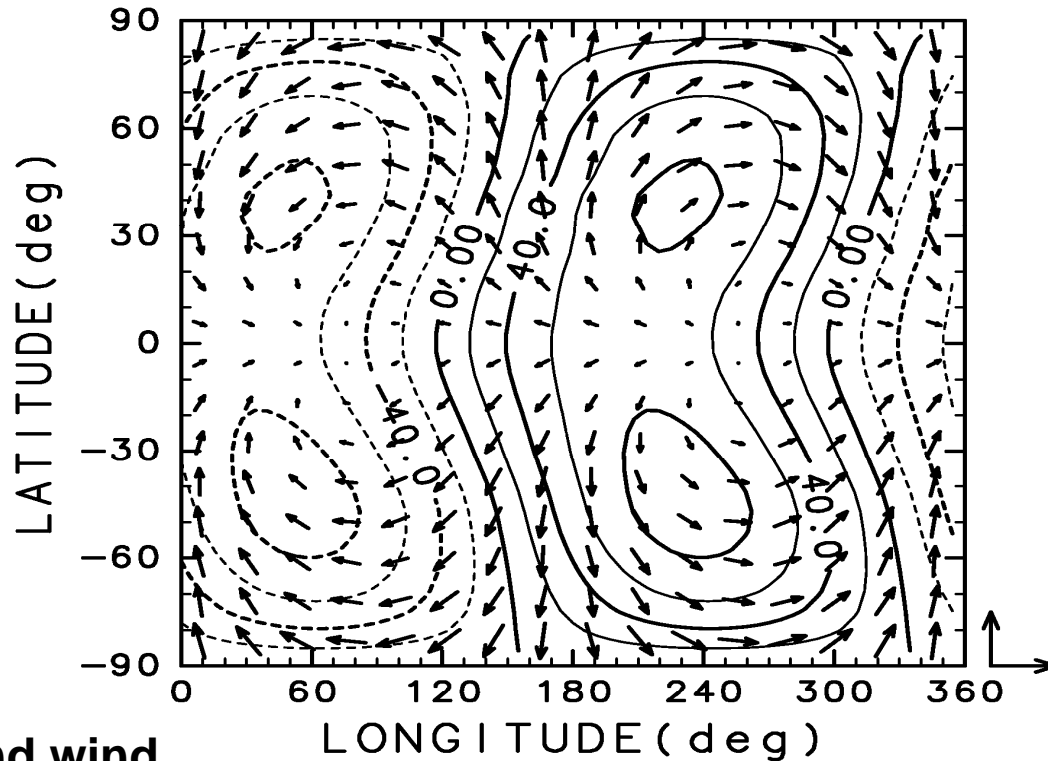


Spectrum of horizontal EP flux $F_{EP\phi}$ at 77 km



Thermally induced waves produce the equatorward EP flux near the cloud top.

Longitude-latitude structure of equatorward momentum transporter at 77 km



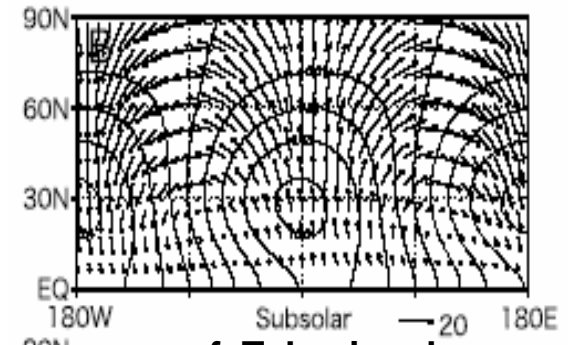
CONTOUR INTERVAL = 2.000E+01

XUNIT = 2.500E+01, YUNIT = 2.500E+01

Zonal wavenumber 1
thermally-induced wave



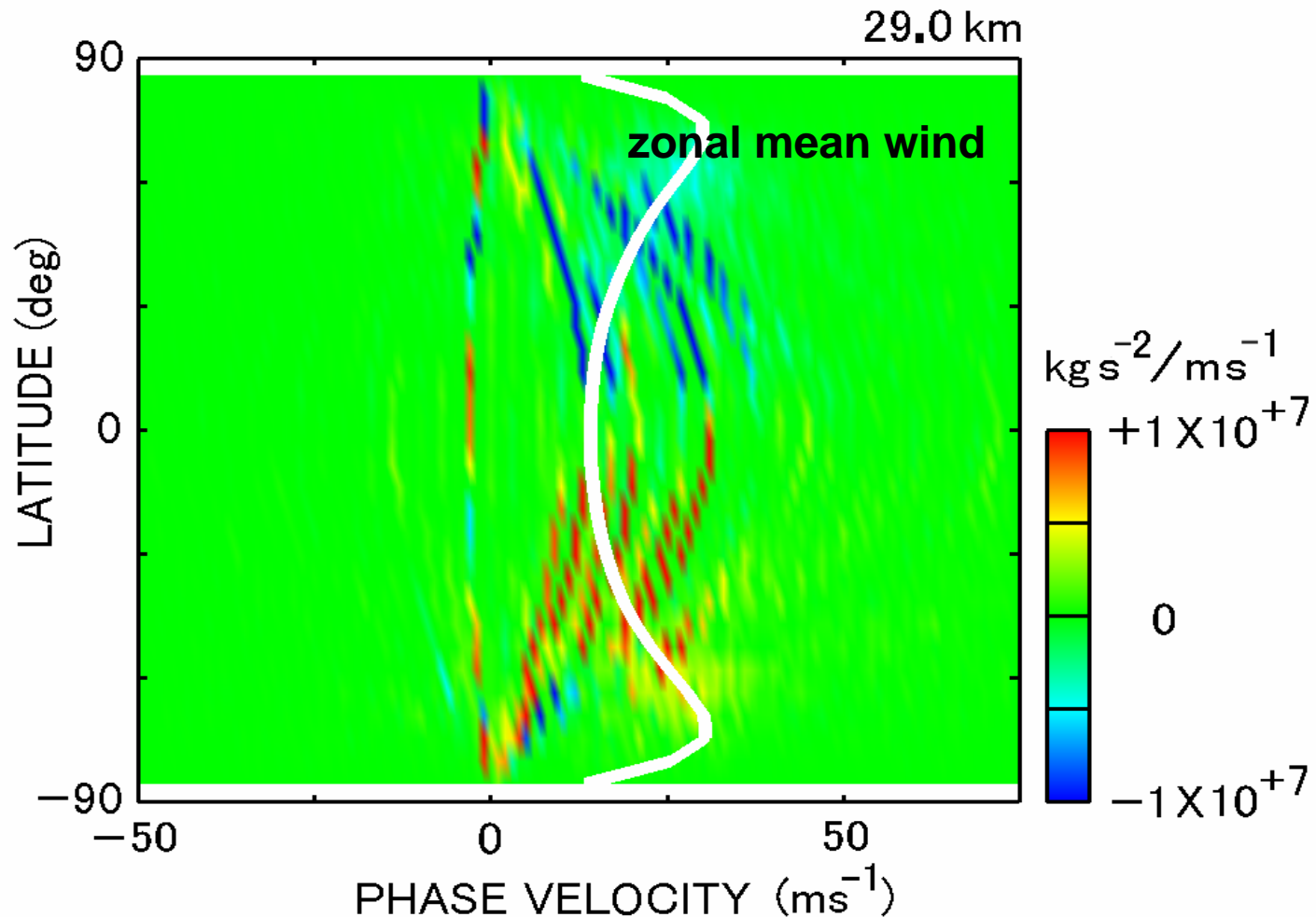
Diurnal tide



cf. Takagi and
Matsuda, 2005

Phase tilting of geopotential height and divergence of the horizontal flow are seen. The diurnal tide produces equatorward momentum flux in the stratosphere.

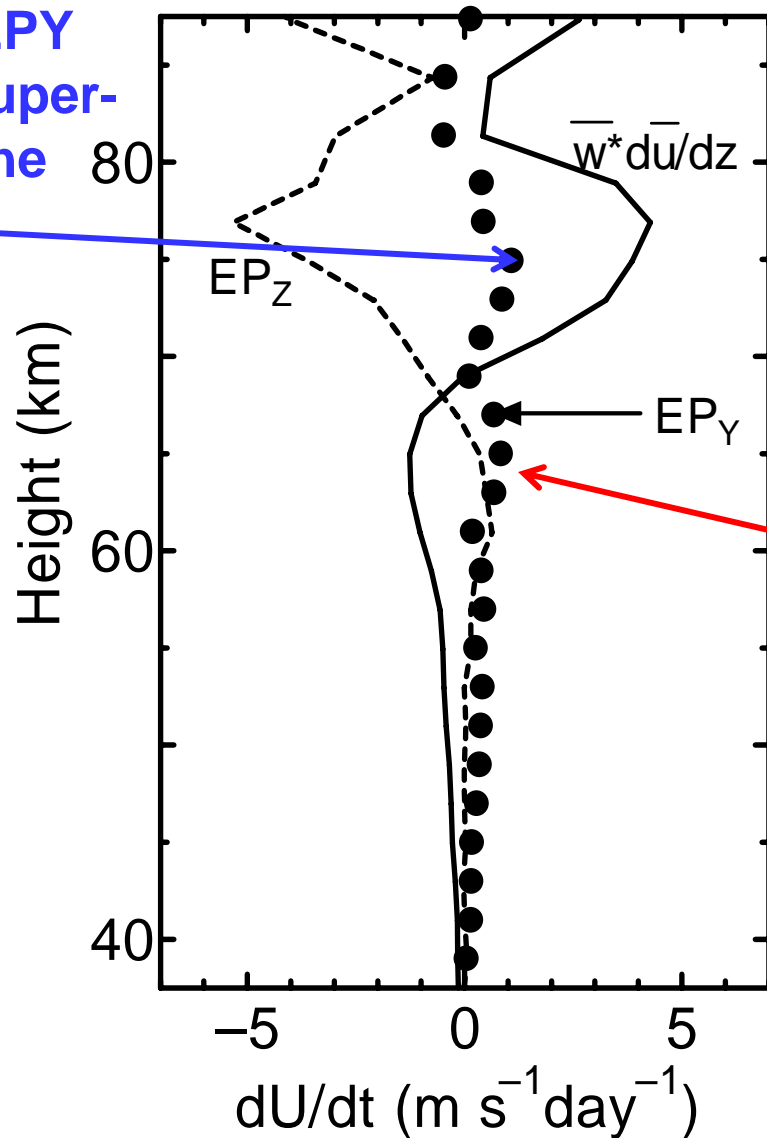
Spectrum of F_{EP}^ϕ at 29 km in the lower atmosphere



There are many wave signals of equatorward momentum flux with nearly zonal wind phase velocity.

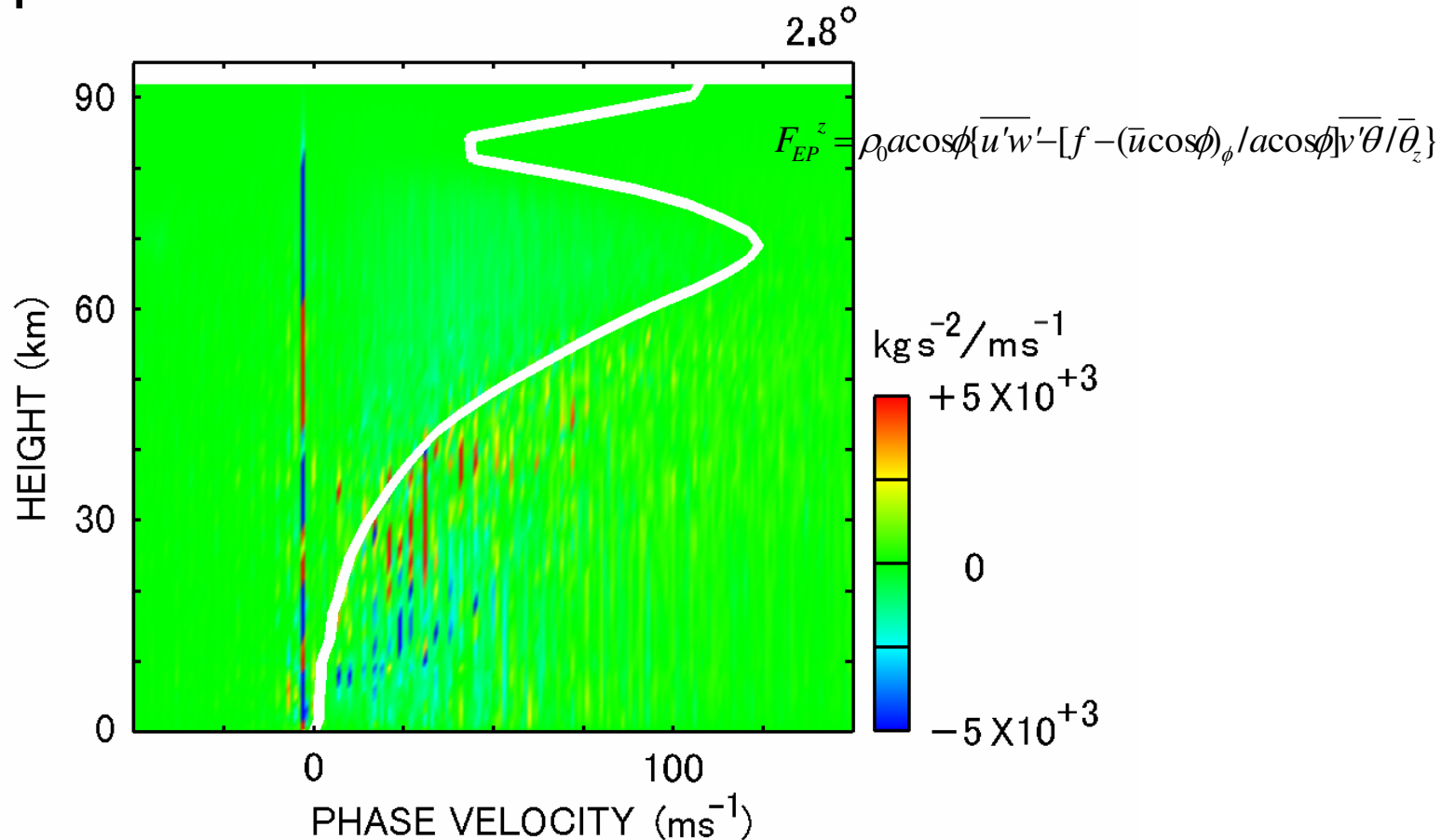
Maintenance of equatorial superrotation in the middle atmosphere

Advection and EPY accelerate the superrotation above the cloud top.



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

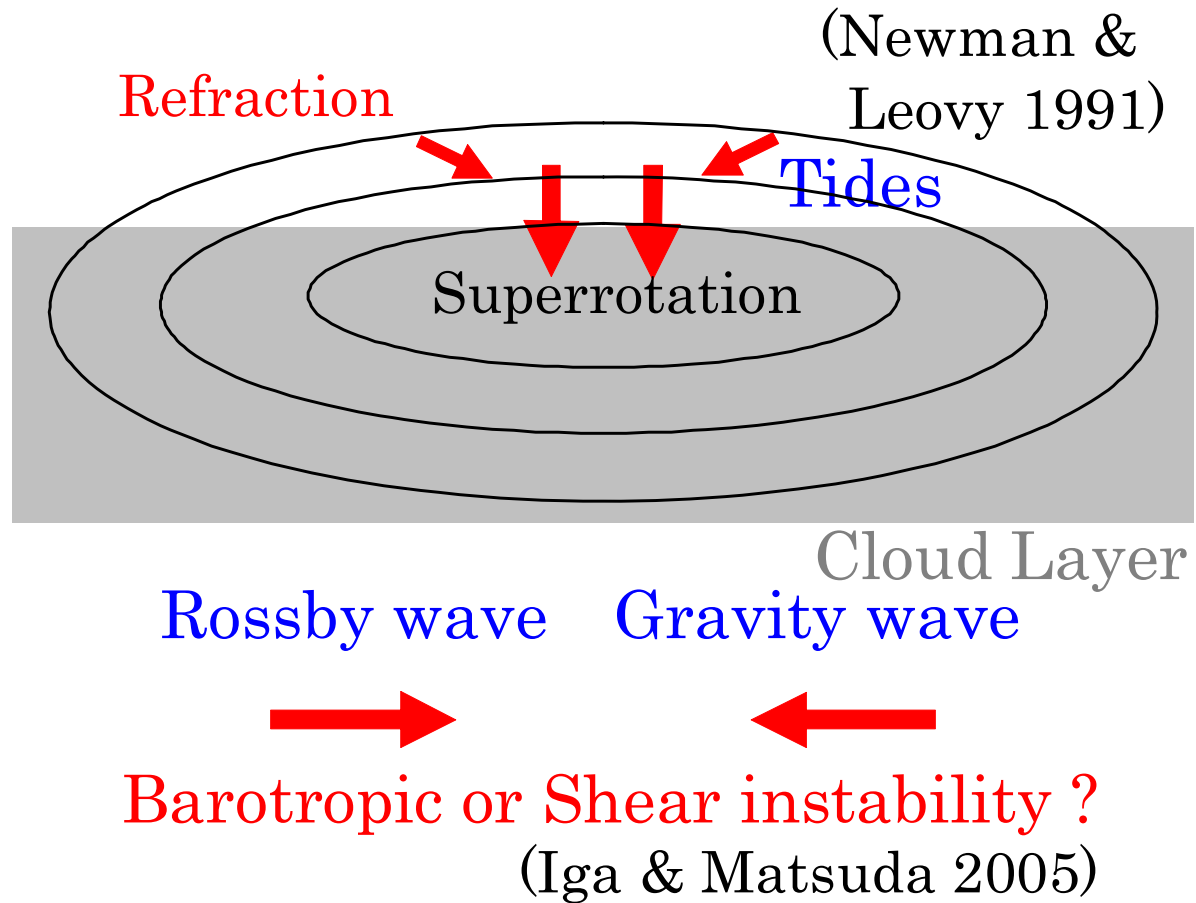
Spectrum of the vertical EP flux at 2.8°



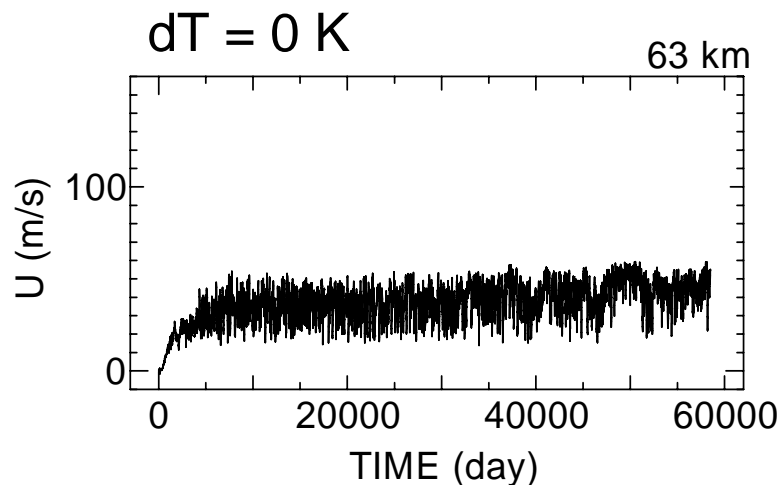
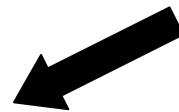
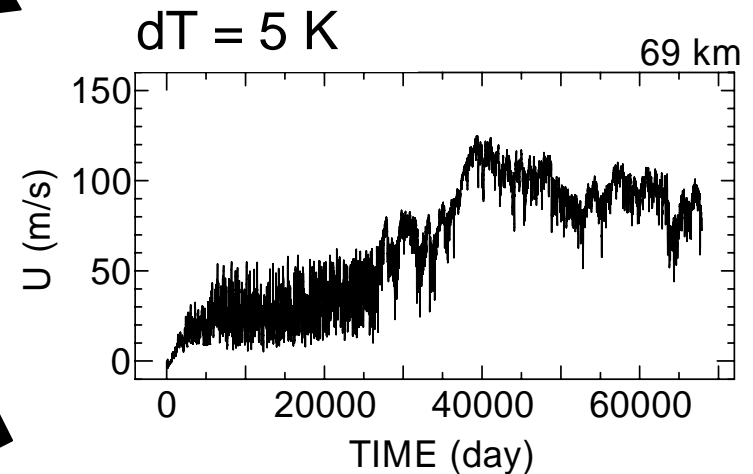
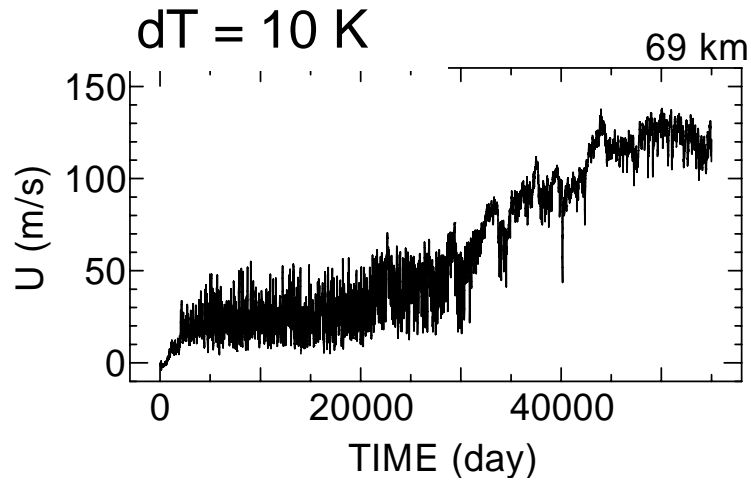
Thermal tide is predominant.

Kelvin waves are seen below the critical levels.

Schematic figure: Yamamoto & Takahashi (2004,2006)

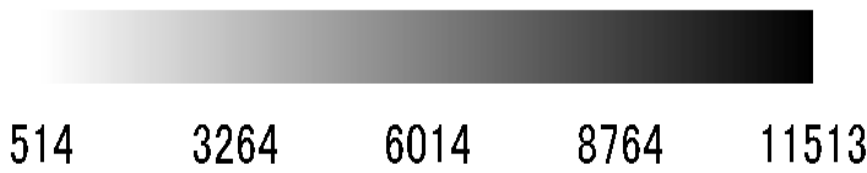
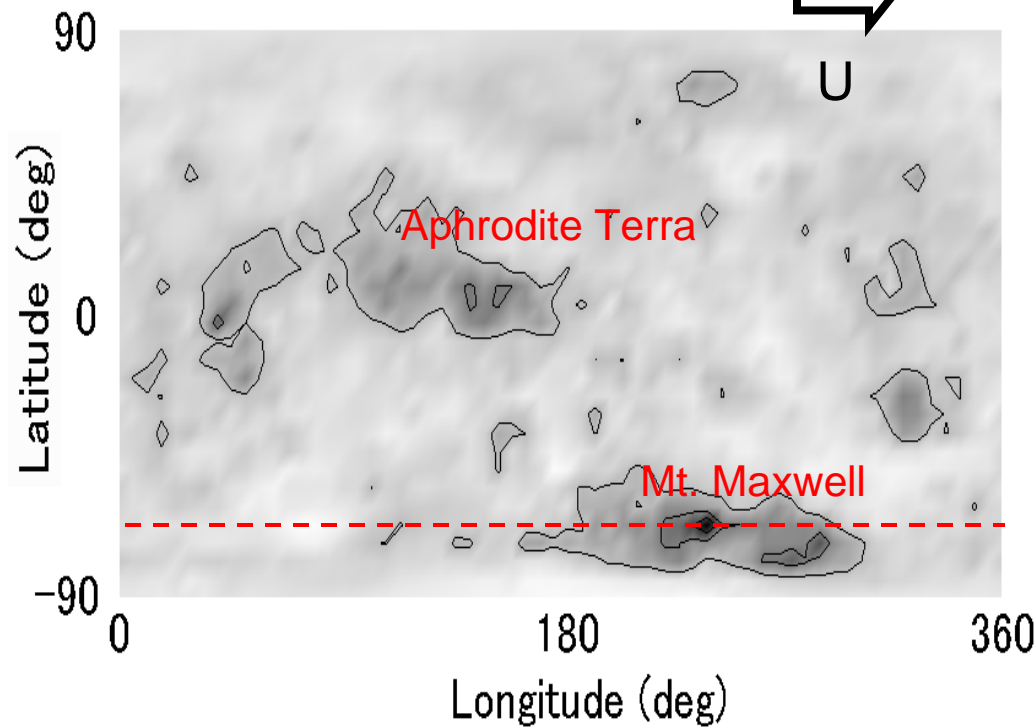


Sensitivities of equatorial superrotation to equator-pole contrast of surface temperature



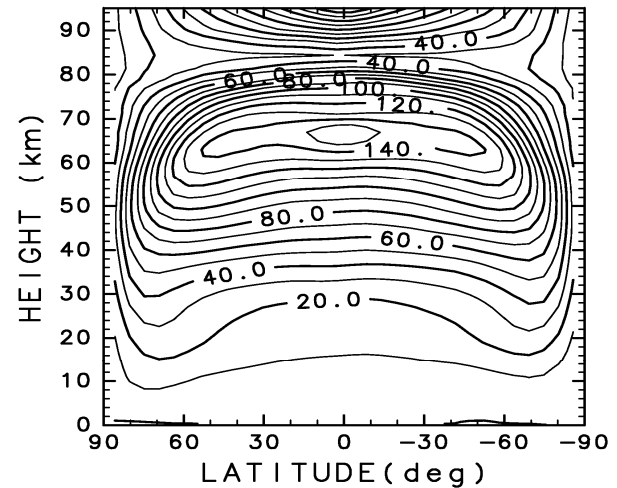
An additional experiment with surface topography

Magellan Topography Data



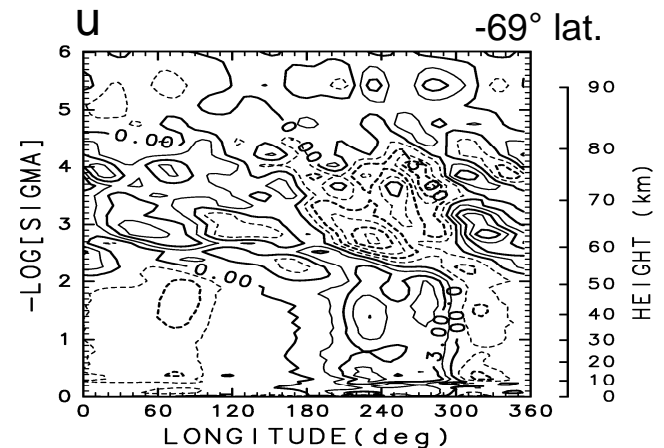
http://pds-geosciences.wustl.edu/geodata/mgn-v-rss-5-gravity-l2-v1/mg_5201/topo/

(Ford and Pettengill 1992)



CONTOUR INTERVAL = 1.000E+01

Mean Zonal Flow (m/s)



CONTOUR INTERVAL = 1.500E+00

Mt. Maxwell

Summary

Our simulation supports the Gierasch mechanism.

↓ detailed wave analysis

Thermal tide in the middle atmosphere

Slowly propagating waves, such as high-latitude Rossby wave & low-latitude gravity wave, in the lower atmosphere



Slowly propagating planetary-scale waves ($c < 50$ m/s) should be also treated as primary targets of explorations for Venus' atmospheric dynamics.