Chapman conference: Venus

Feb. 14, 2006

Recent Development of CCSR/NIES AGCM for Venus Atmospheric Sciences

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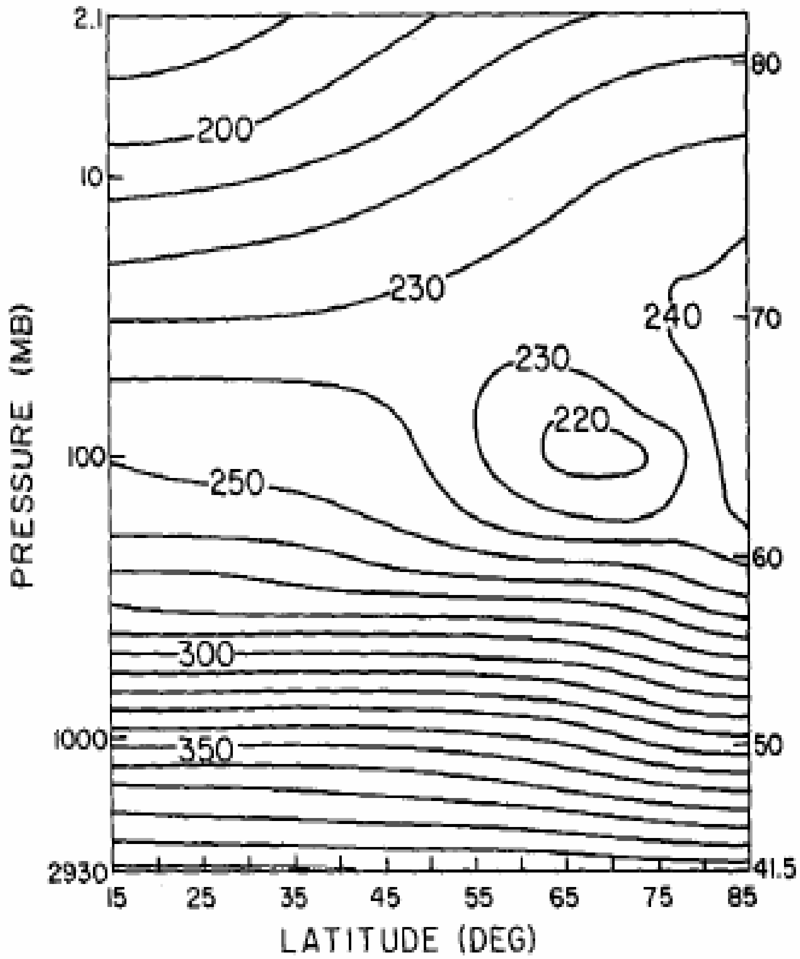
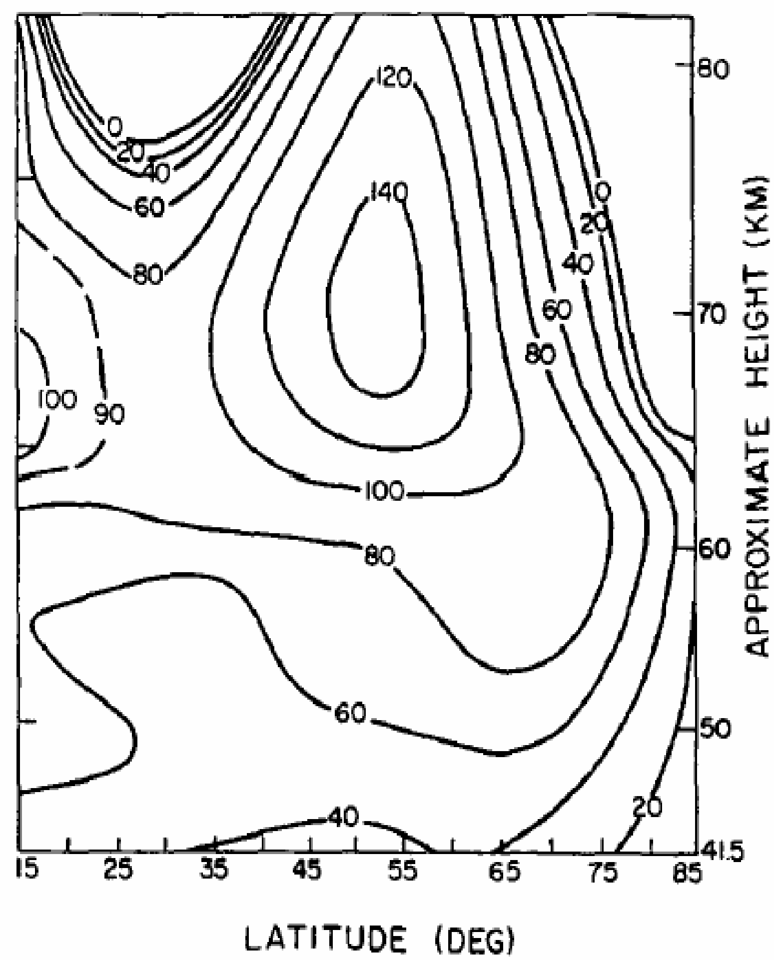
Observations

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

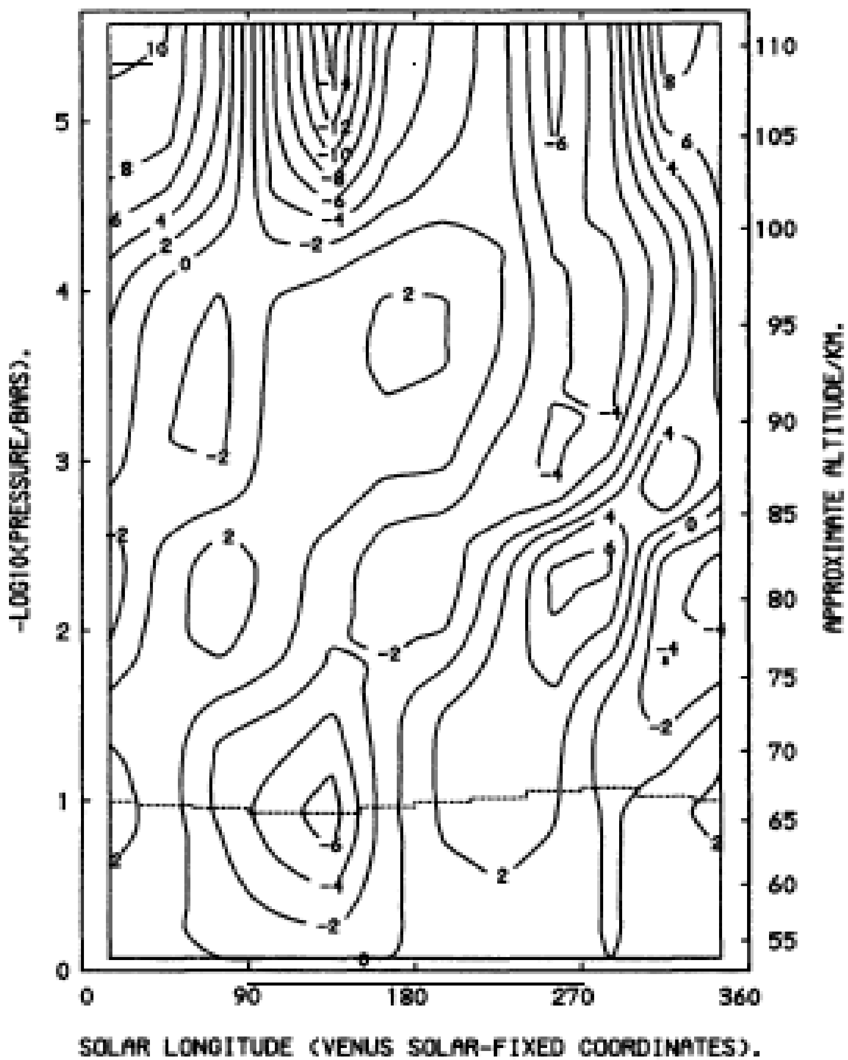
temperature $\Rightarrow$ zonal wind

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

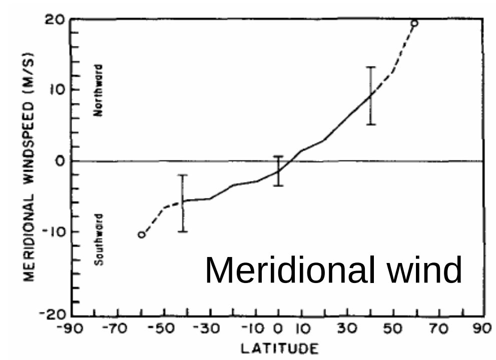
1. Dynamics in the stratosphere

(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 (*Rossow 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 Ps = 92 atm.

(2) To understand the maintenance mechanism of the superrotation, based on the detailed wave analysis.
$\Rightarrow$ **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

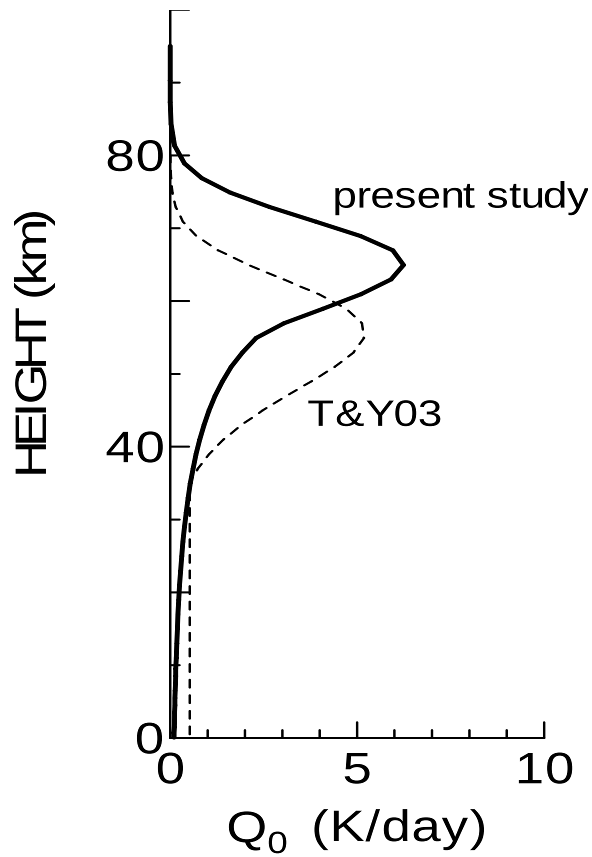
Frictional drag of 3 days in the thin undermost layer ($\Delta\sigma = 0.01$)

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

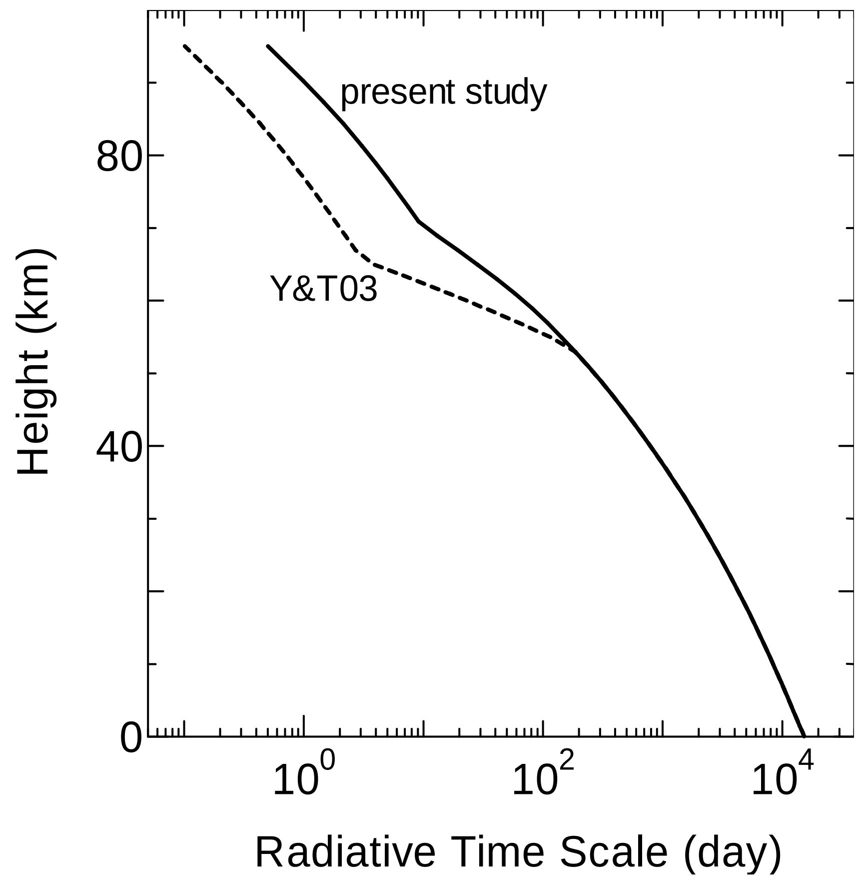
Rayleigh friction of 30 days near the top boundary
Rayleigh friction for eddy (with the Newtonian cooling rate)
$\Rightarrow$ prevention of artificial effects near the top boundary

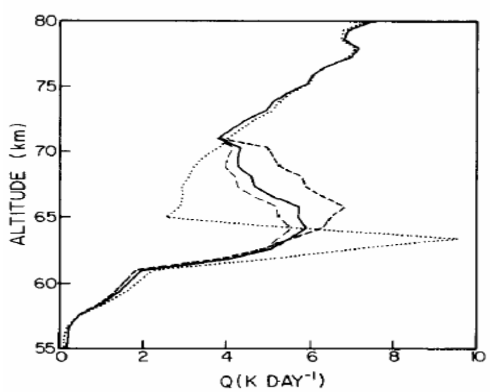
Constant vertical eddy diffusion with Kv = 0.15m^2/s is set

Heating Rate (K/day)



Newtonian Cooling (day)





cf., solar heating rate in Crisp(1986)

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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

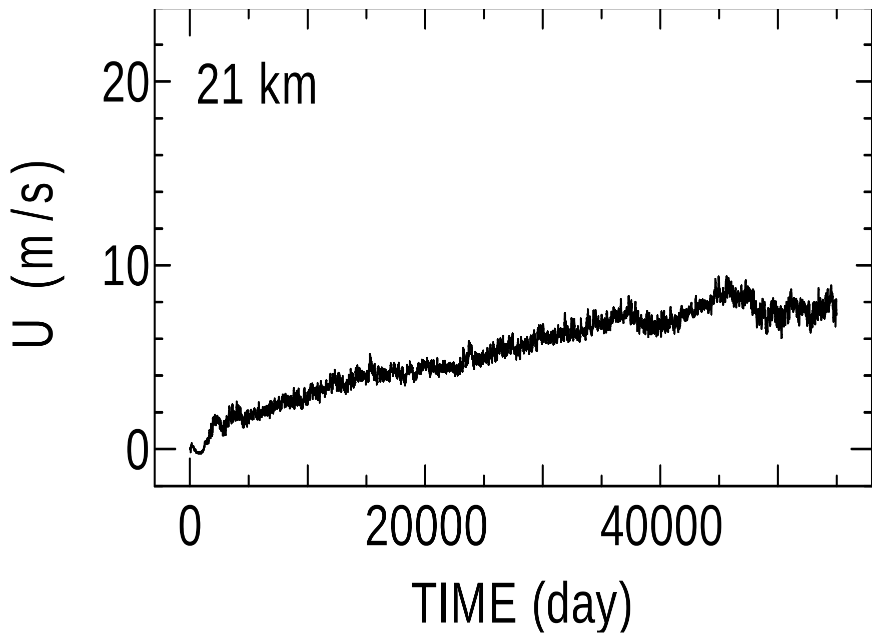
The Eliassen-Palm flux for eddy momentum flux is used

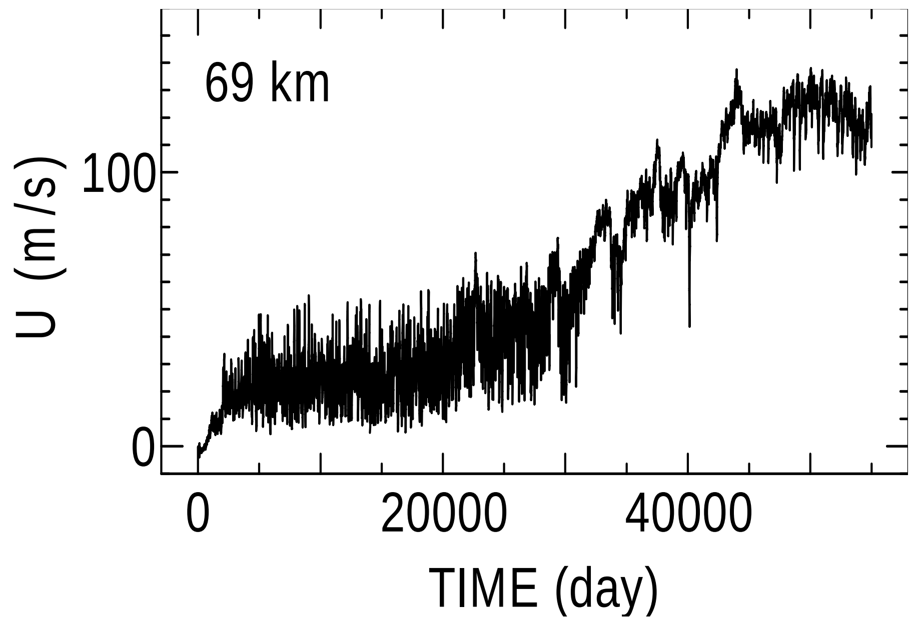
$$F_{EP}{}^{z} = \rho_0 a \cos\phi \{\overline{u'w'} - [f - (\bar{u}\cos\phi)_\phi / a\cos\phi] \overline{v'\theta'} / \bar{\theta}_z\}$$

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

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

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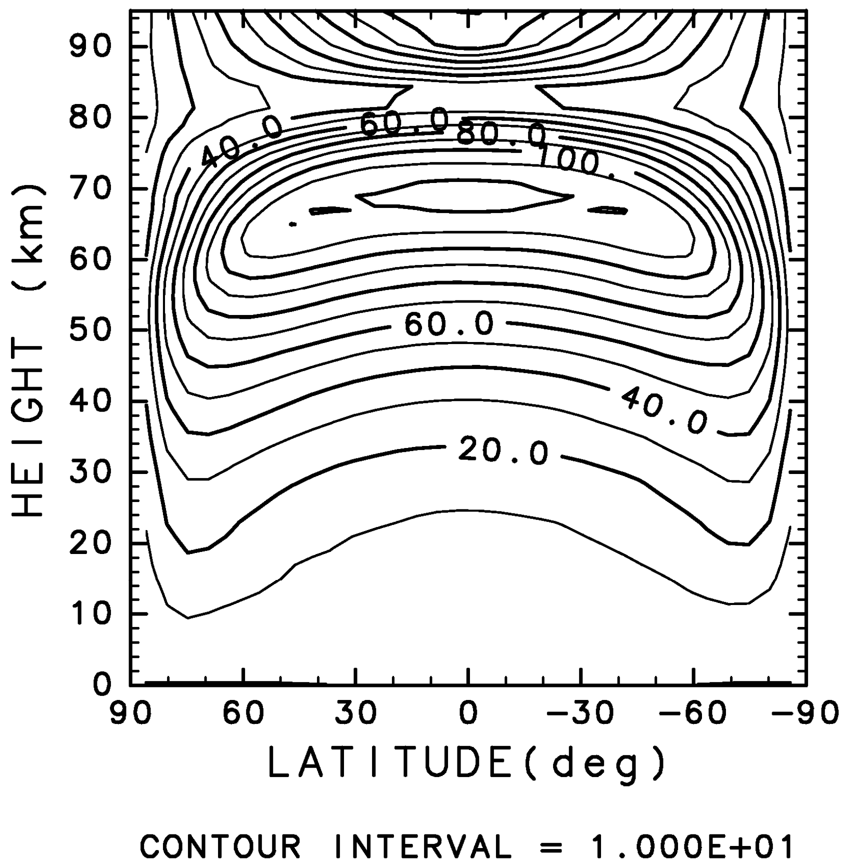
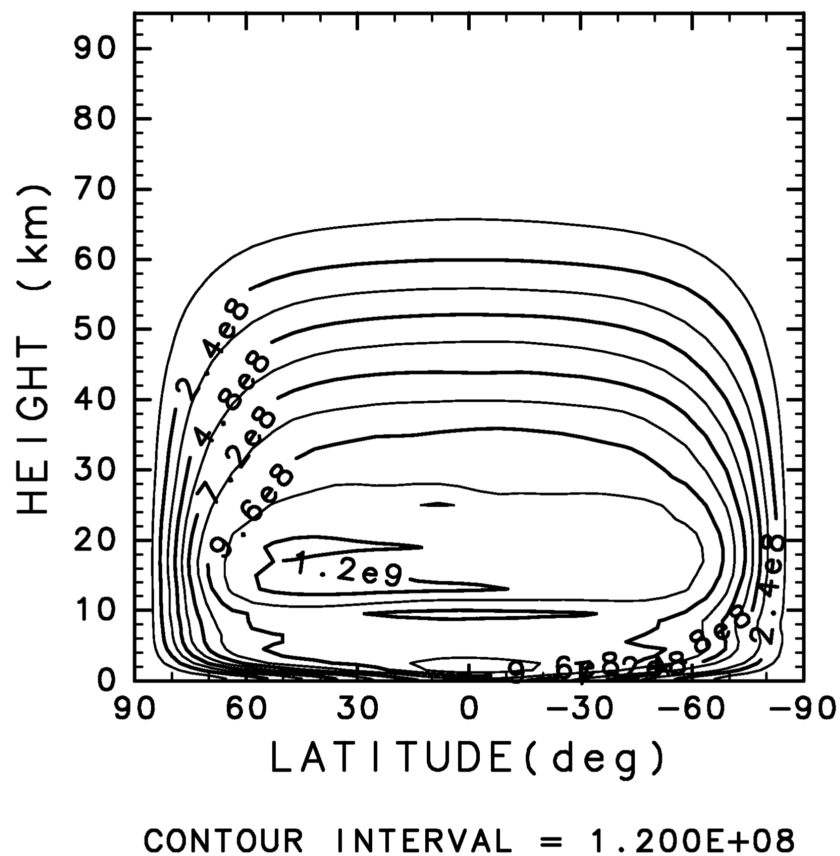
Latitude-Height distributions of mean fields

Mean Zonal Flow (m/s)



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

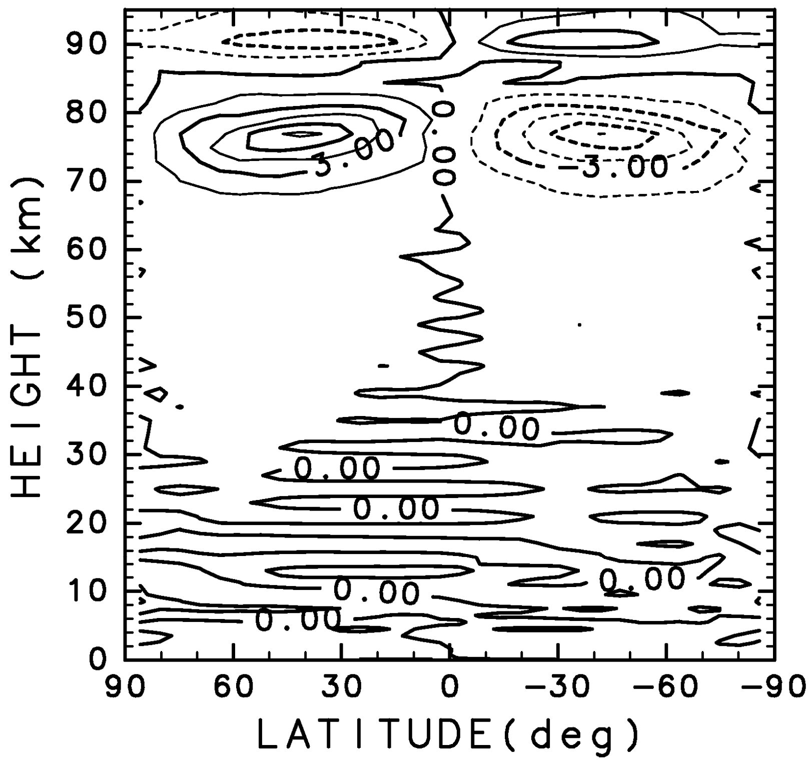


Superrotaional flow of more than 100m/s is reproduced near the cloud top in the model.

A maximum of angular momentum is located near 20 km.

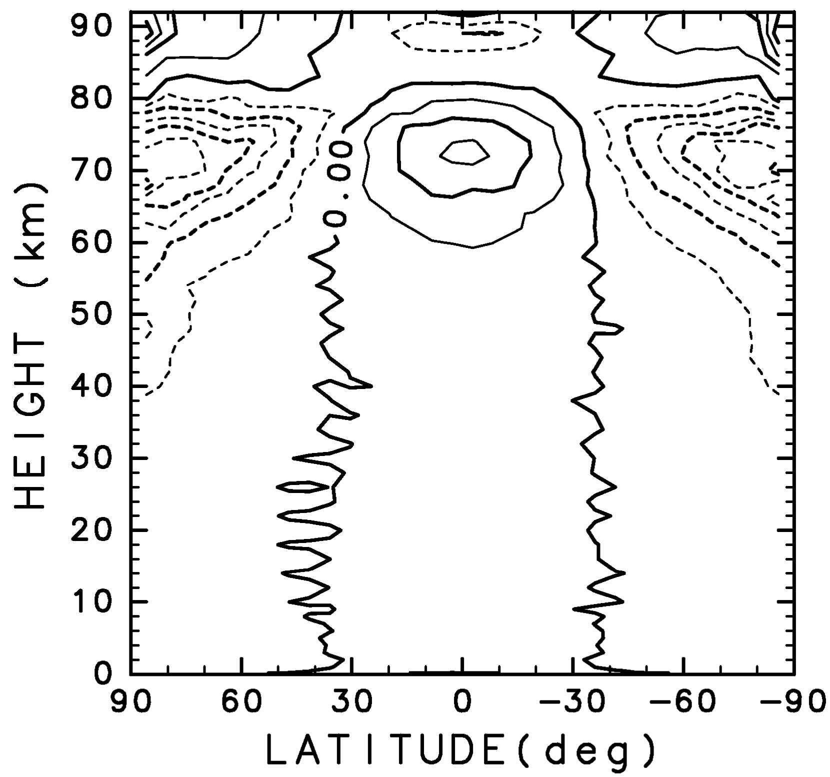
Residual Mean Meridional Circulation

*V** (m/s)



CONTOUR INTERVAL = 1.500E+00

*W** (m/s)

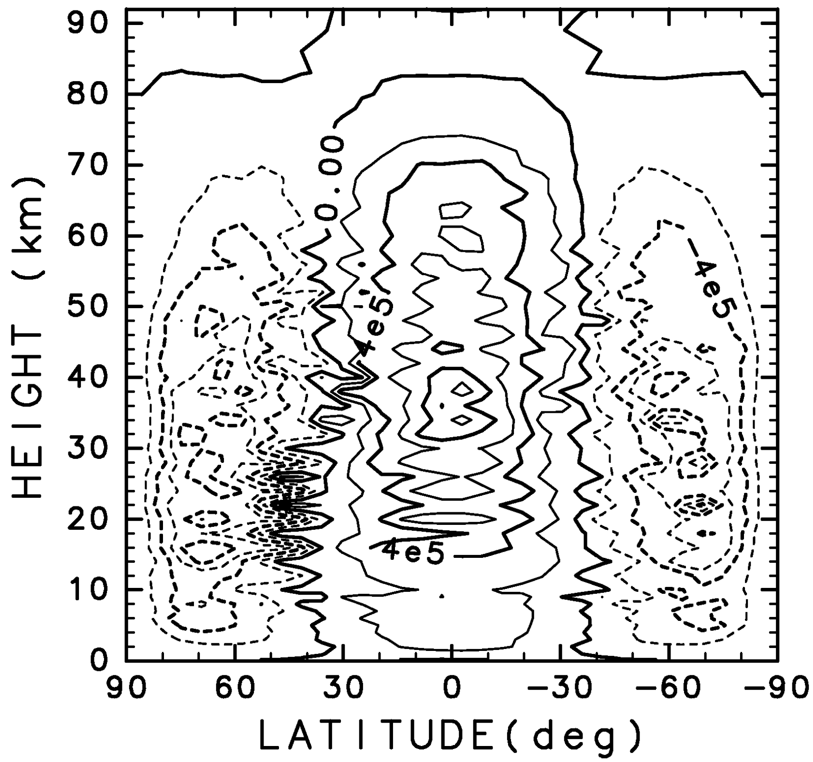


CONTOUR INTERVAL = 2.500E−03

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.

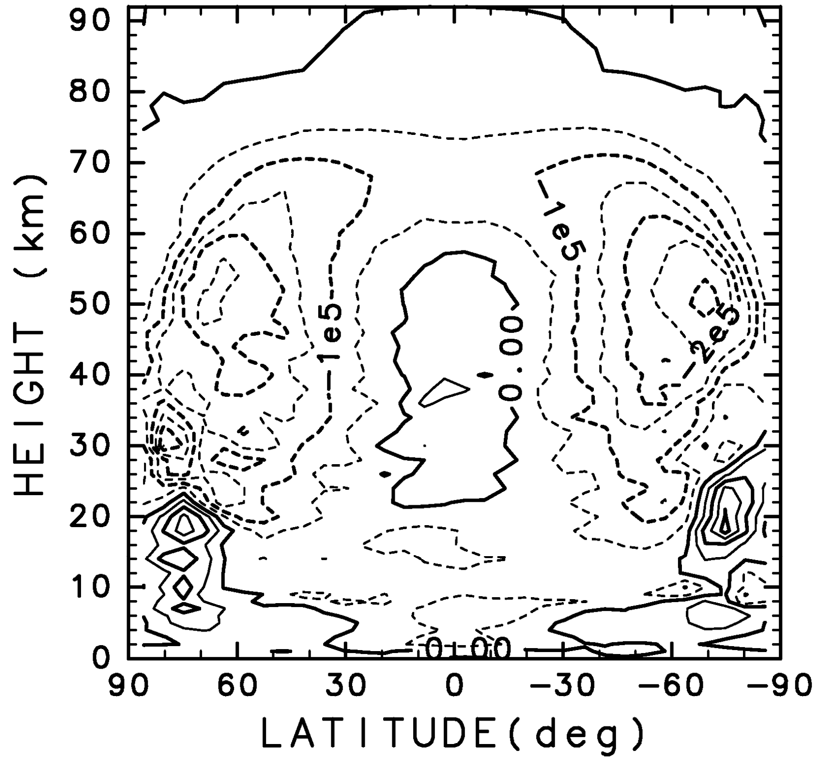
Vertical Angular Momentum Transport

by mean vertical flow (W^*)



CONTOUR INTERVAL = 2.000E+05

by eddy (F_{EP}^{z})



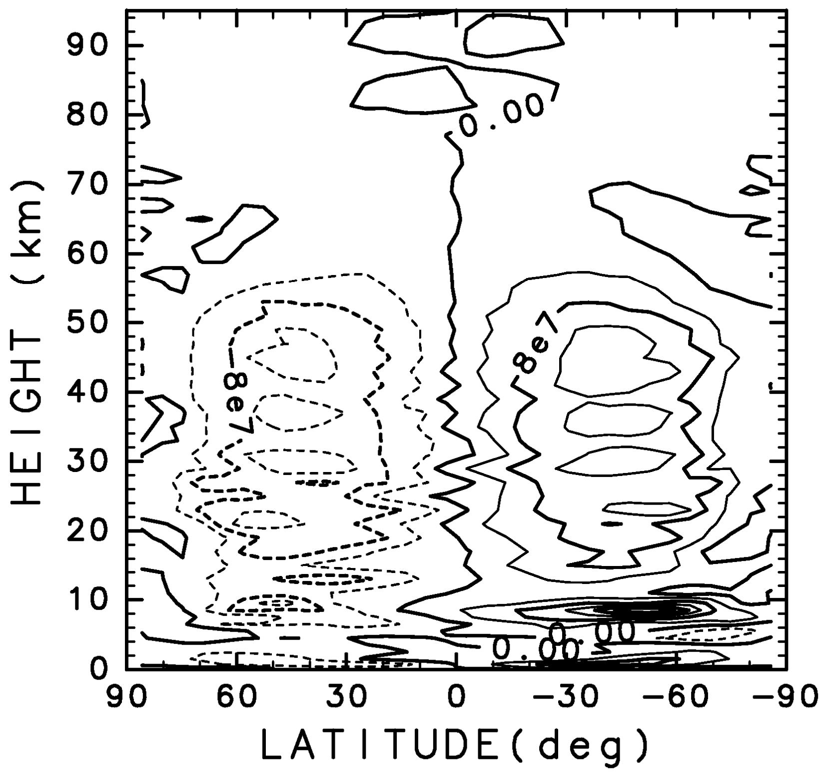
CONTOUR INTERVAL = 5.000E+04

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.

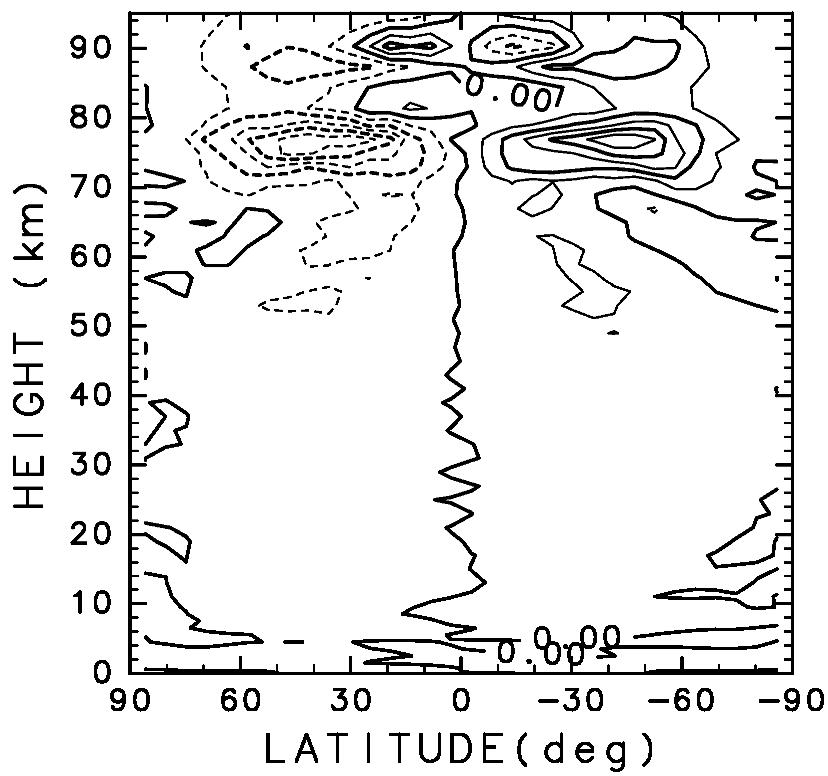
Horizontal Eddy Momentum Transport

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

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



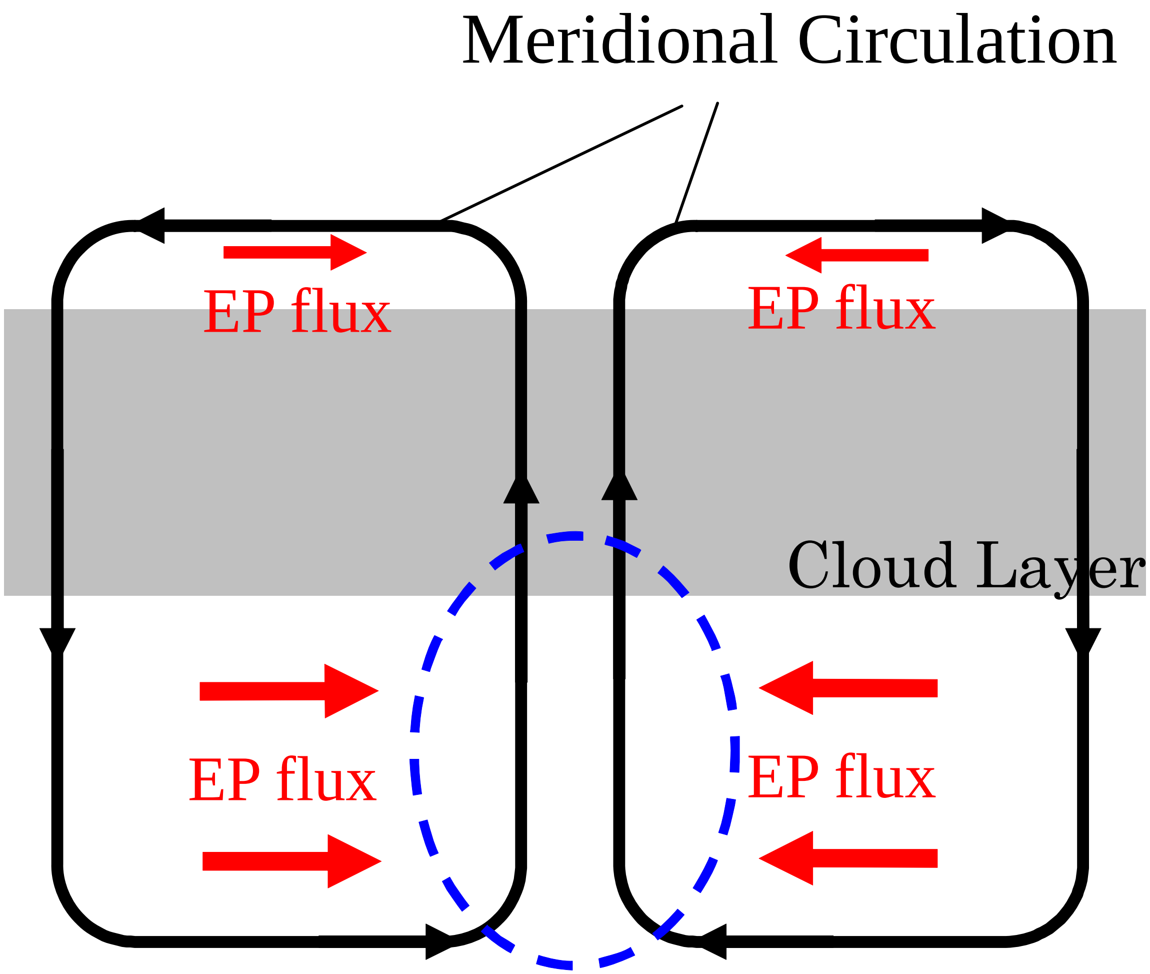
CONTOUR INTERVAL = 4.000E+07



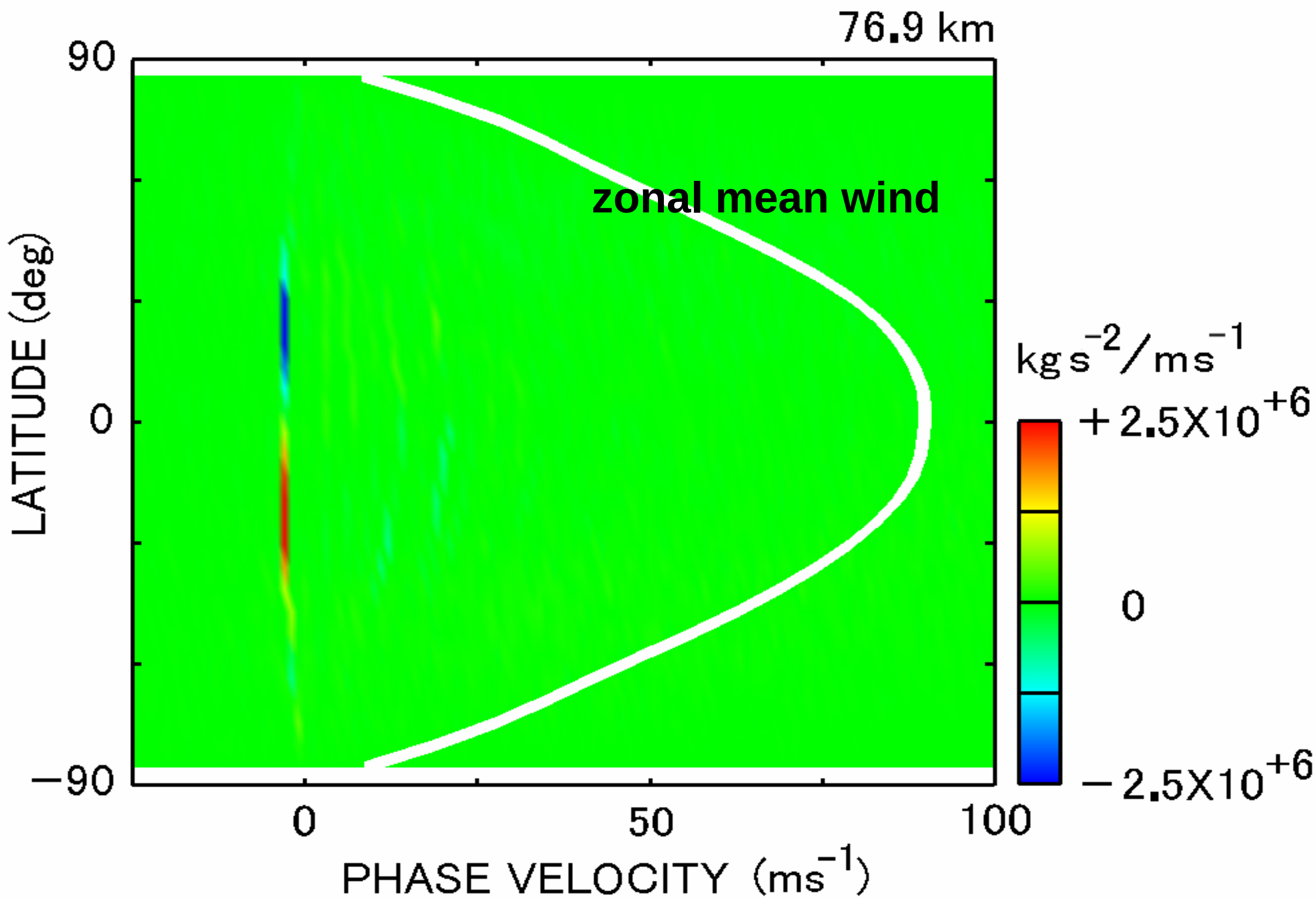
CONTOUR INTERVAL = 1.000E+10

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

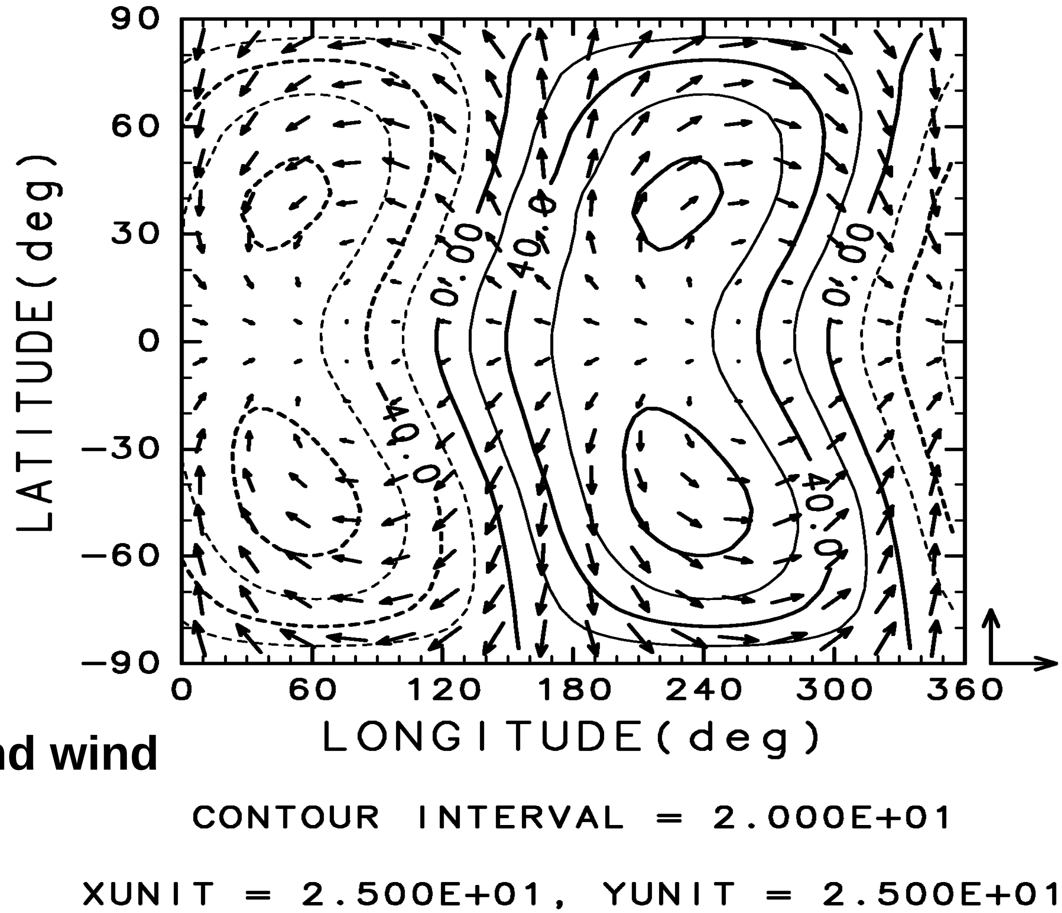


Spectrum of horizontal EP flux F_{EP}^{ϕ} at 77 km



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

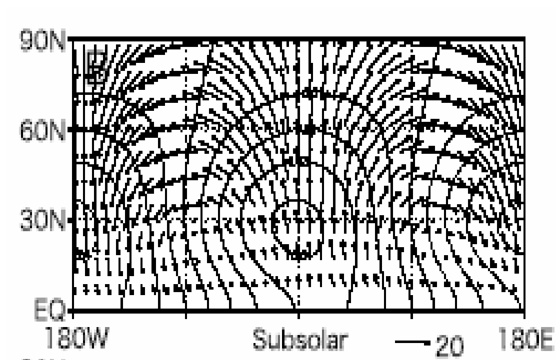
Longitude-latitude structure of equatorward momentum transporter at 77 km



height and wind

Zonal wavenumber 1
thermally-induced wave

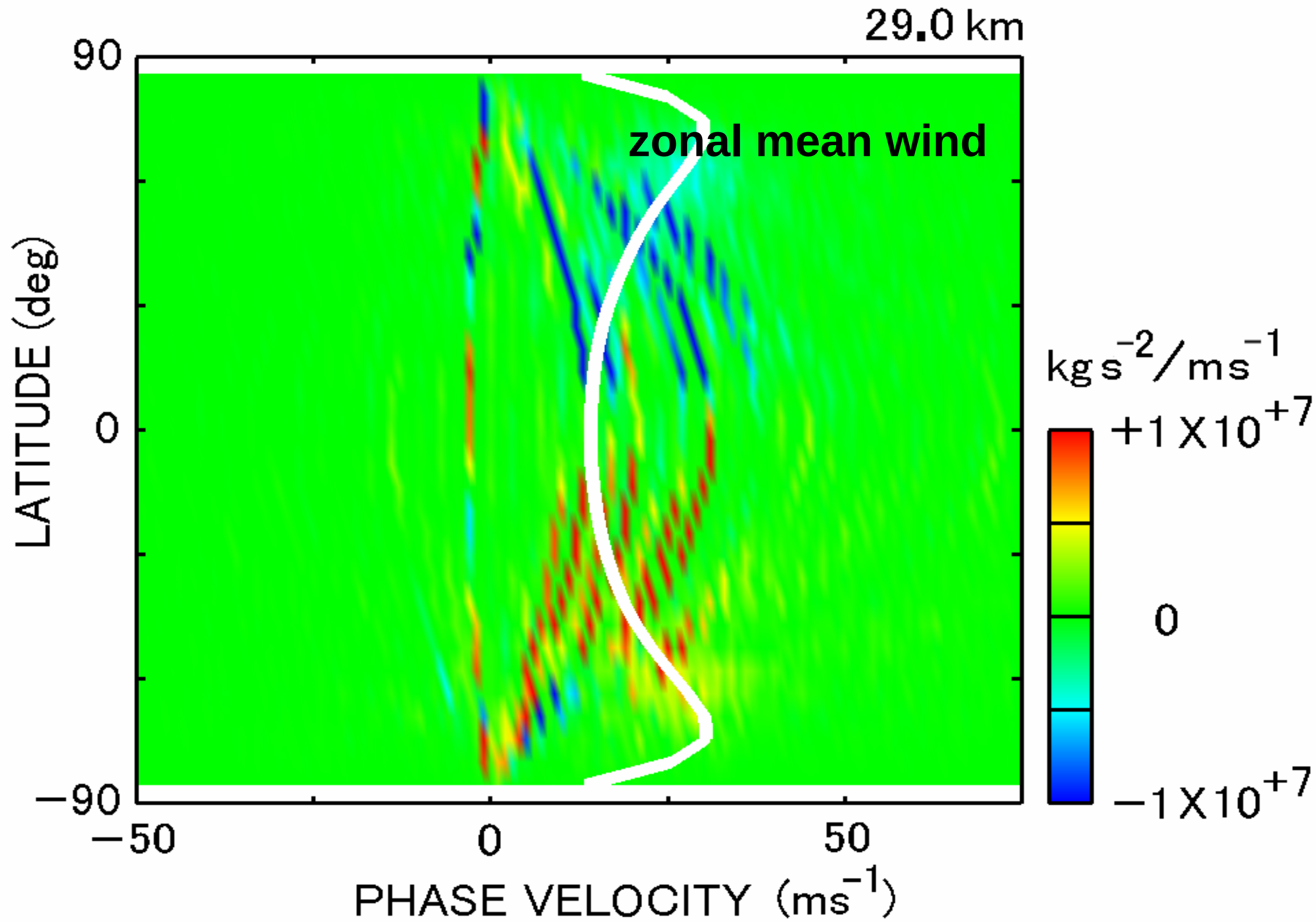
Diurnal tide



cf. Takagi and Matsuda, 2005

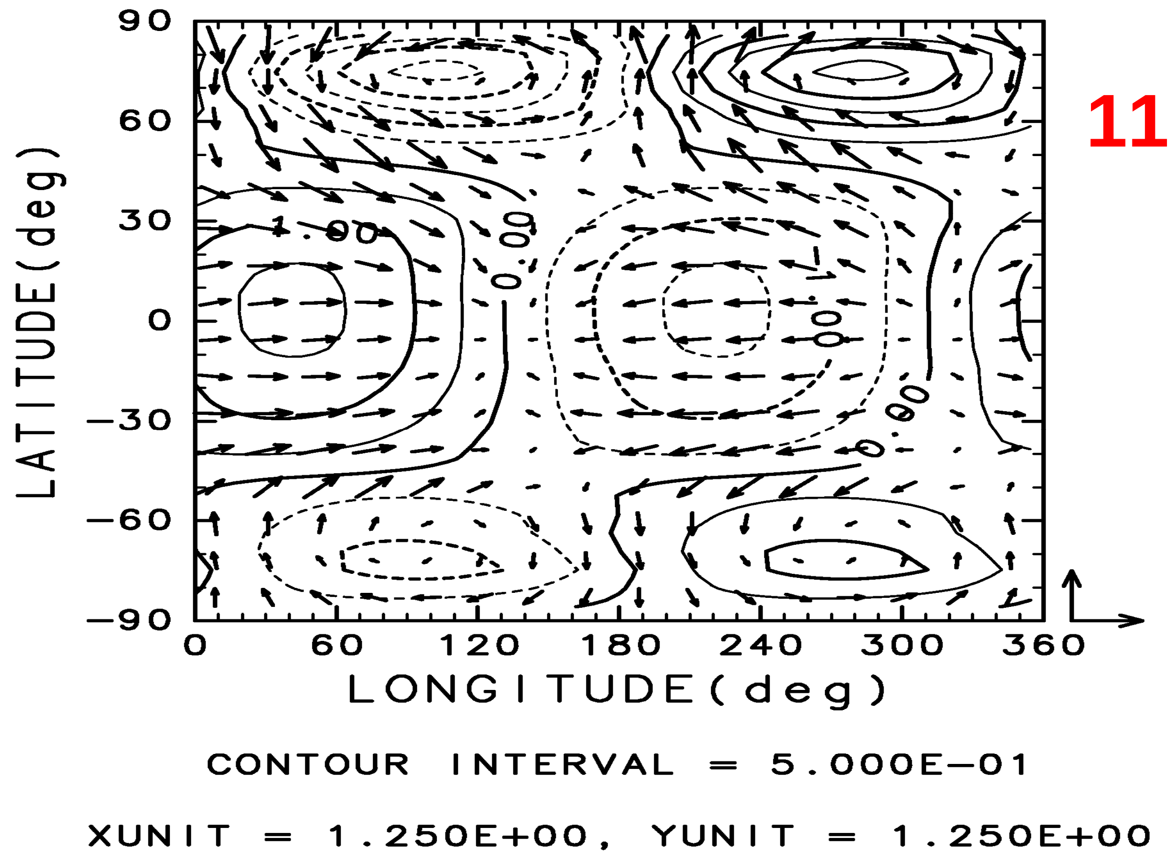
Phase tilting of geopotential height and divergence of the horizontal flow are seen. The diurnal tide produces equatorward momentum flux in the stratosphere.

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.

Structure of an equatorward Momentum Transporter at 29 km in the lower atmosphere



11-day waves

Coupled pattern of Rossby wave in high latitude and Kelvin wave in equatorial region is similar to unstable mode of shear instability by Iga and Matsuda(2005)

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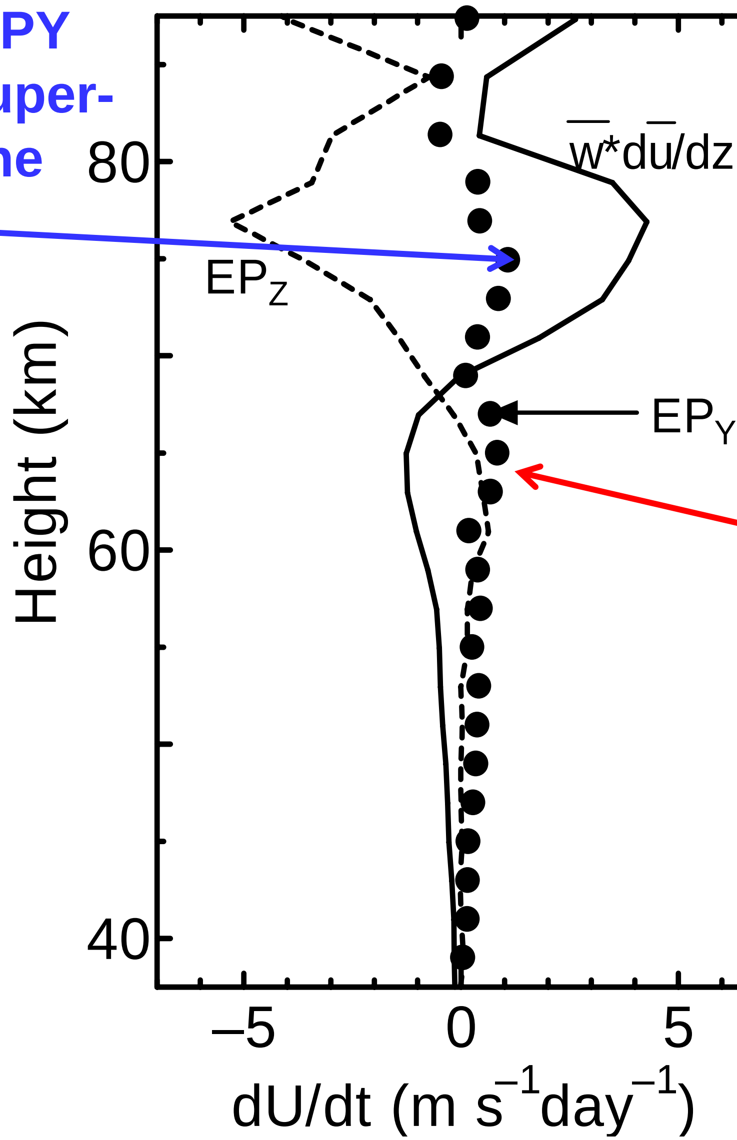
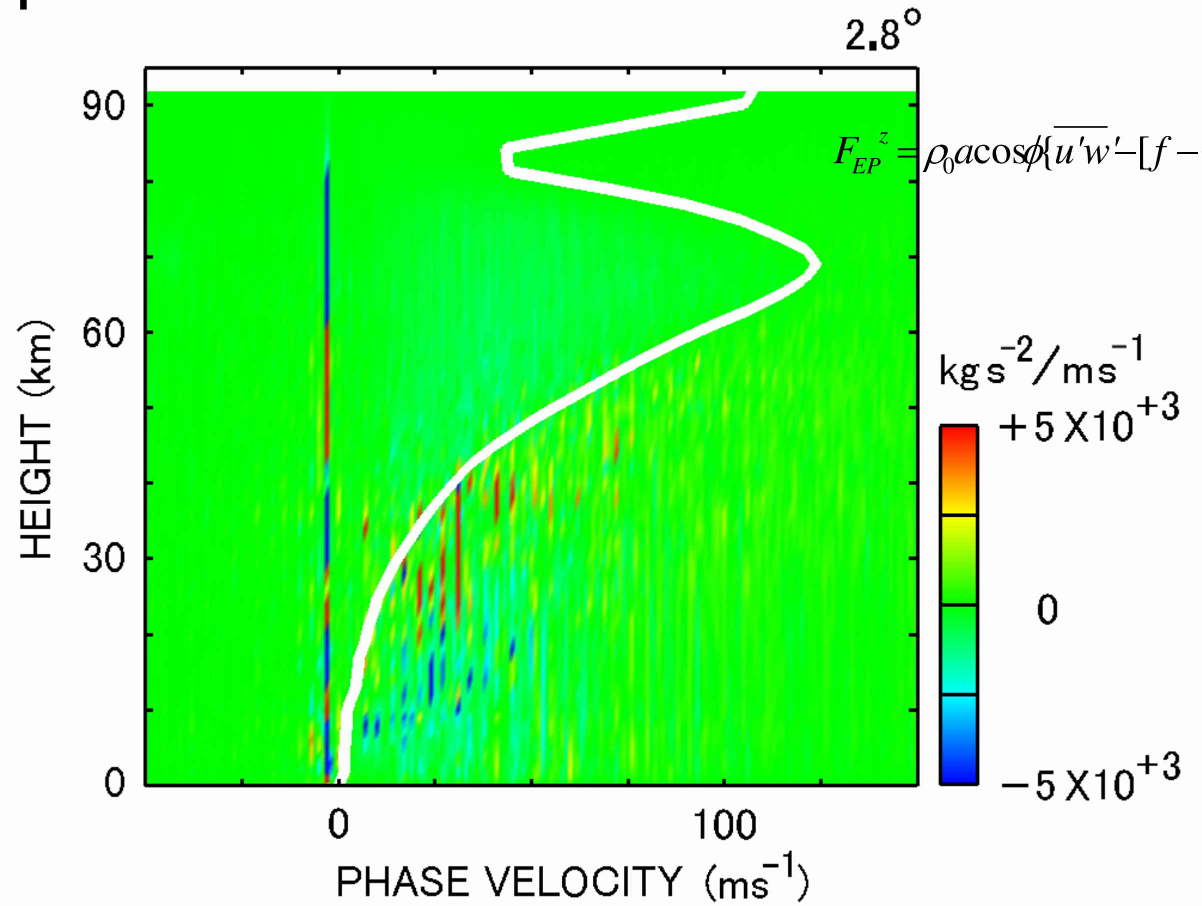
Maintenance of equatorial superrotation in the middle atmosphere

Advection and EPY accelerate the super-rotation above the cloud top.



EPY and EPZ of thermal tide maintain the super-rotation near the cloud top.

Spectrum of the vertical EP flux at 2.8°

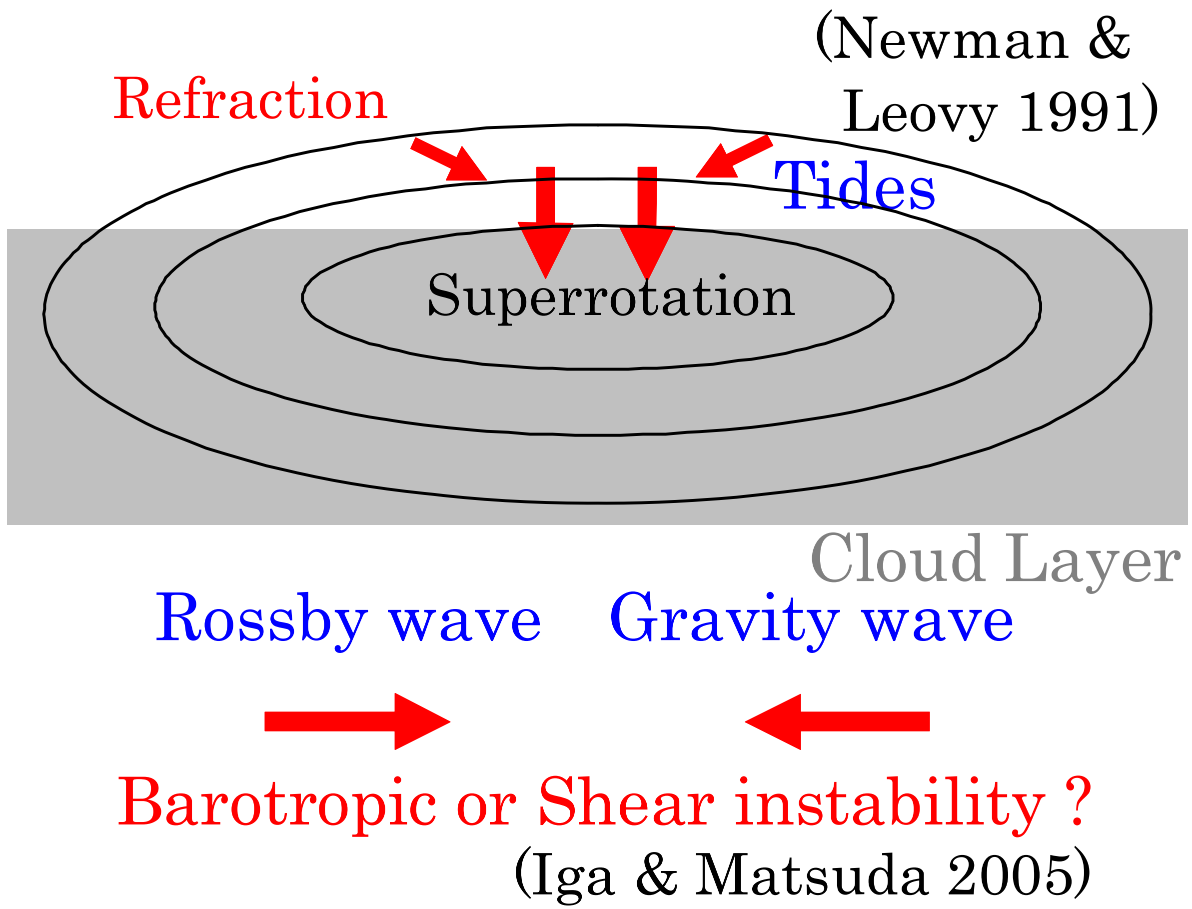


$$F_{EP}^{\ z} = \rho_0 a\cos\phi\{\overline{u'w'} - [f - (\bar{u}\cos\phi)_\phi / a\cos\phi]\overline{v'\theta'}/\bar{\theta}_z\}$$

Thermal tide is predominant.

Kelvin waves are seen below the critical levels.

Schematic figure: Yamamoto & Takahashi (2004,2006)



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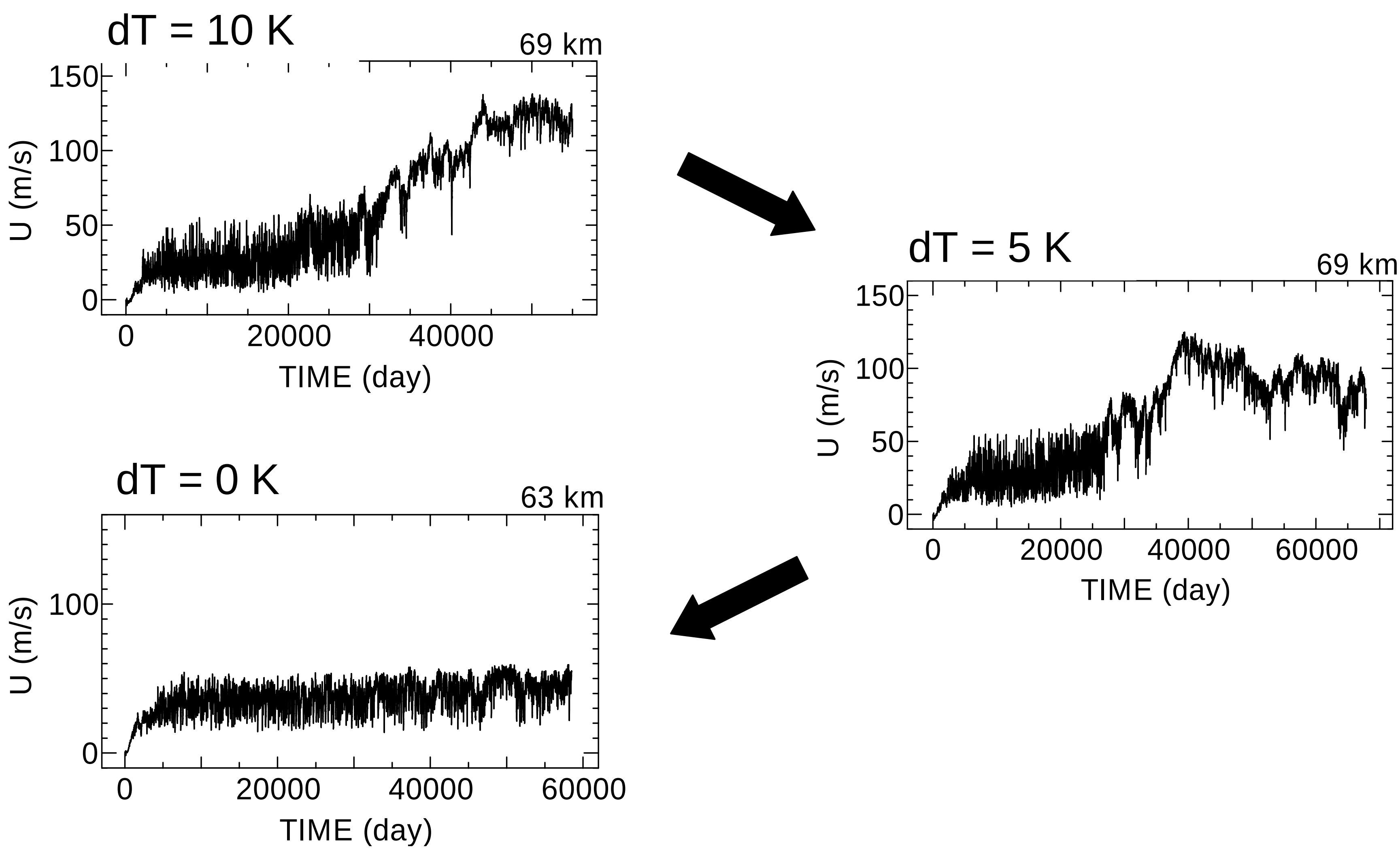
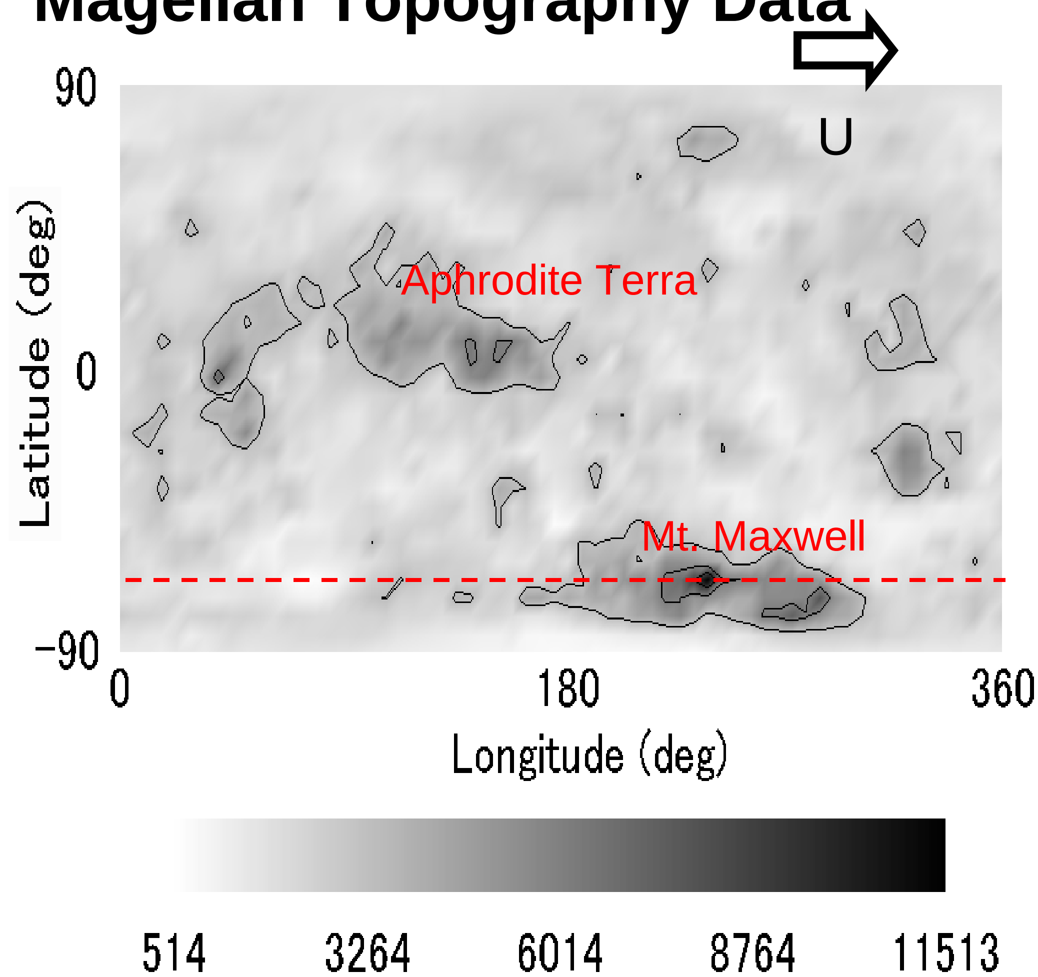
Sensitivities of equatorial superrotation to equator-pole contrast of surface temperature



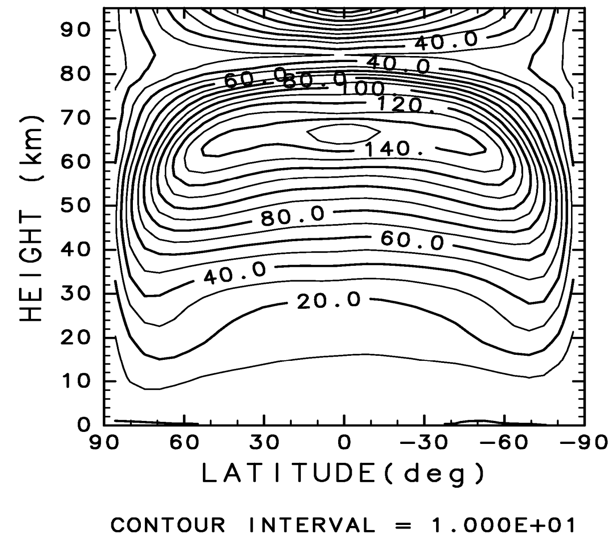
An additional experiment with surface topography

Magellan Topography Data

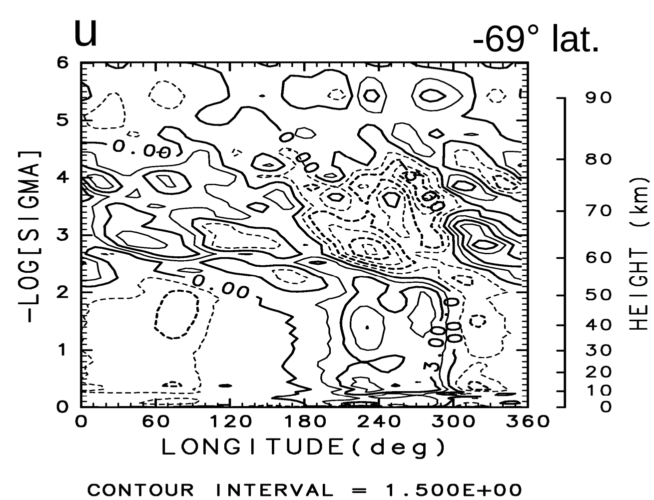


http://pds-geosciences.wustl.edu/geodata/mgn-v-rss-5-gravity-l2-v1/mg_5201/topo/

(Ford and Pettengill 1992)



Mean Zonal Flow (m/s)



Mt. Maxwell

Summary

Our simulation supports the Gierasch mechanism.

$\Downarrow$ 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

$\Downarrow$

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