Japanese-French model studies of planetary atmospheres on 13 May 2015 at Kobe

# General circulation and high-latitude atmospheric dynamics of a cloud-covered planet

M. Yamamoto (RIAM, Kyushu Univ)*
M. Takahashi (AORI, Univ Tokyo)

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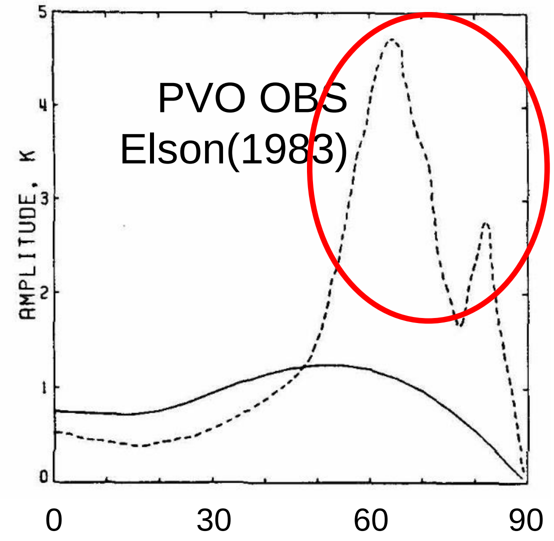
**1. Dynamics of Venus' polar vortex in the presence of strong diurnal thermal tide**
*using Venus middle atmosphere GCM (see detail in Yamamoto & Takahashi 2012 Icarus; 2015, PSS)*

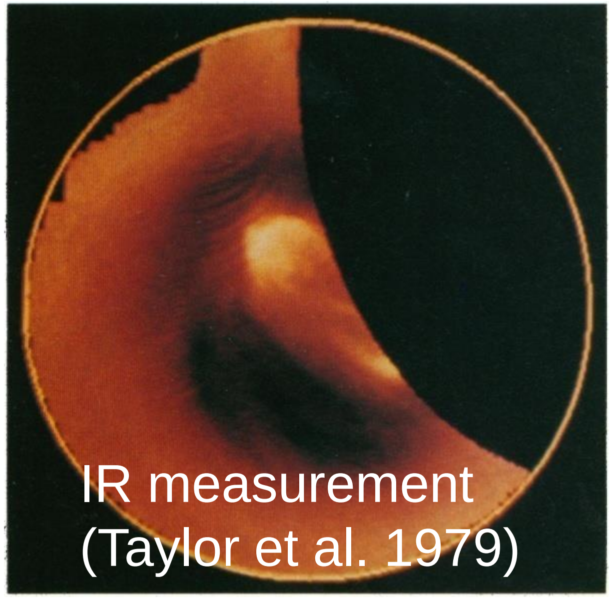
**2. Atmospheric superrotation of cloud-covered planets: significance of planetary rotation and polar eddy heat transport**
*using a simple model setting of the ISSI VGCM intercomparison project (Lebonnois et al.* 2013*).*

# 1. Dynamics of Venus' polar vortex in the presence of strong diurnal thermal tide

PVO OBS

Pechmann & Ingersoll (1984)



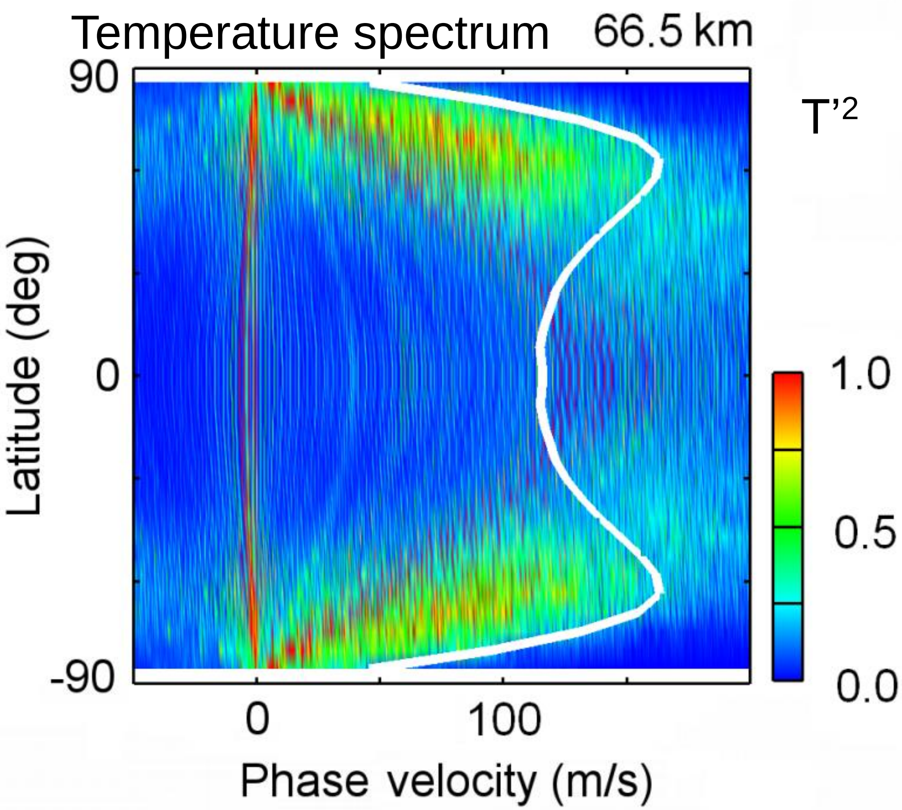




## Objective

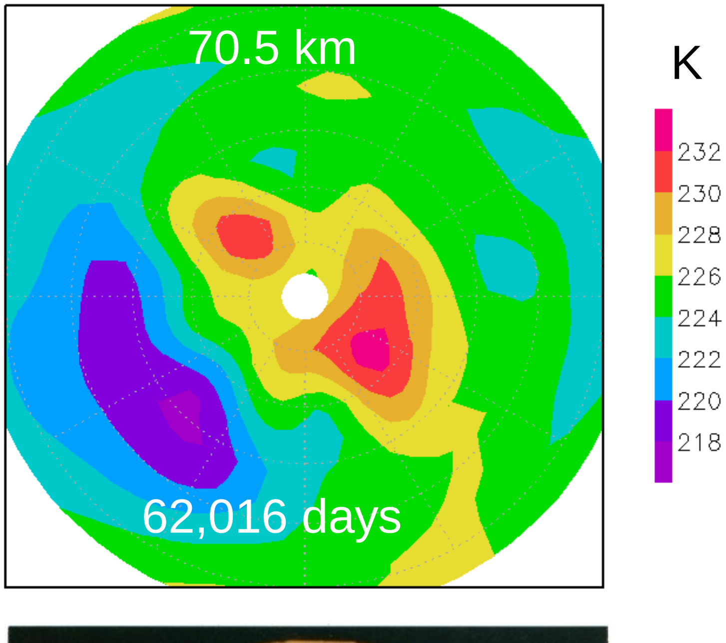
To elucidate dynamics of polar vortex under the condition of strong polar tide

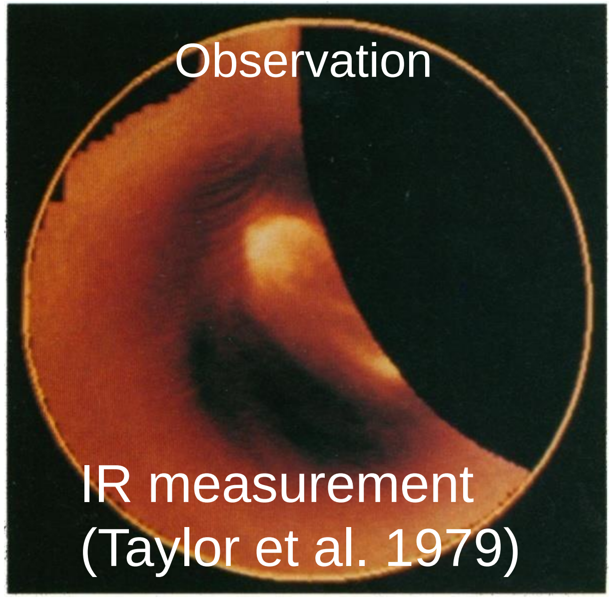
# Model results of VMAGCM (Yamamoto & Takahashi 2012)

(T21L72, 5.5-day Kelvin wave forcing exper.)




Temperature



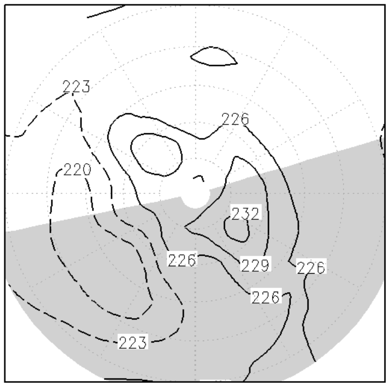




**Slowly traveling diurnal tide**

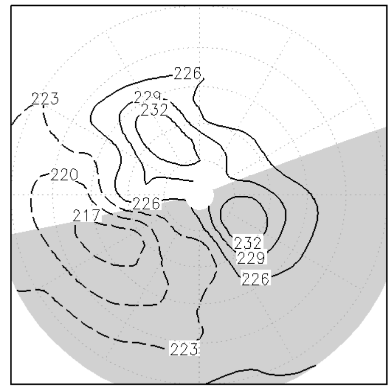
**Transient fast waves**

# Vortexes in VMAGCM (gray shading is night hemisphere)

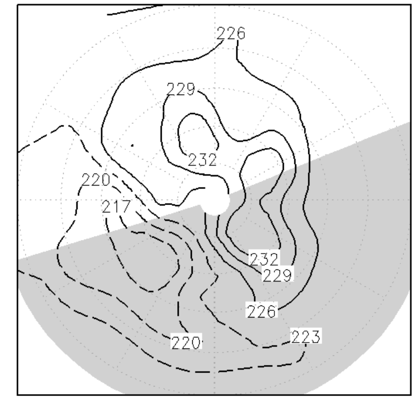
62016 days, T at 70.5 km



+9 hr

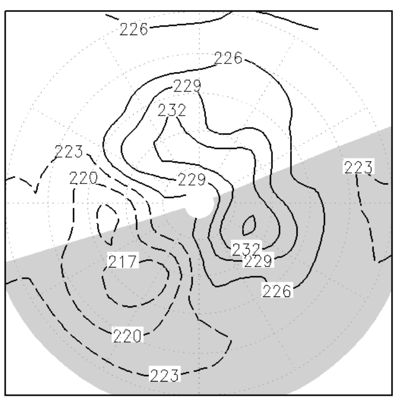


+18 hr

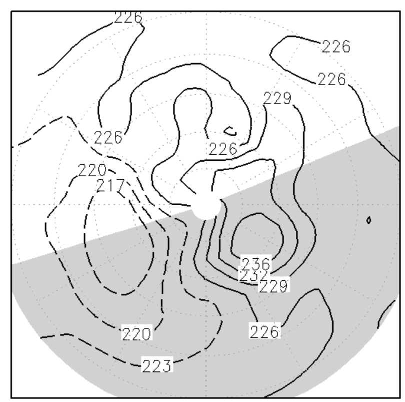


Polar dipole grows with time, and changes to tripole.

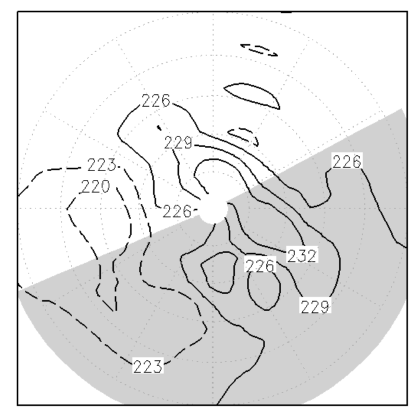
+24 hr



+48 hr



+72 hr



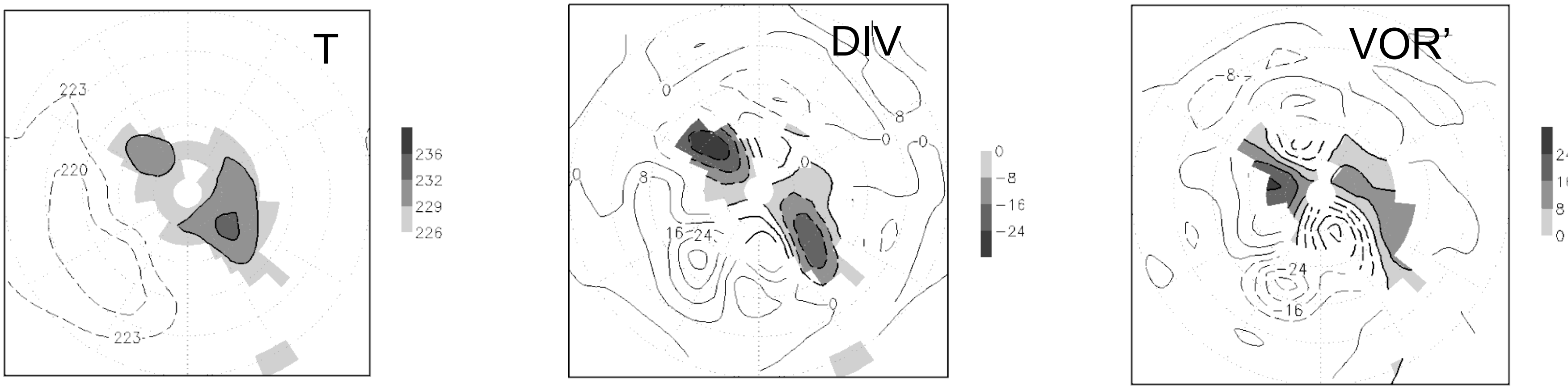
The dipole rotates, and mergers into monopole.

The monopole breaks up, and becomes dipole.

(Yamamoto & Takahashi 2012; 2015)

# Relationship with DIV and VOR

62016 days **(gray shading is warm areas of > 226 K at 70.5 km)**




Warm & convergence area are in phase.

⬇

DIV induces temperature anomaly in the vortex

⬇

Baroclinic wave (Young et al. 1984)

⬅

Both DIV & VOR' have large amplitudes.

DIV & VOR' are out of phase by a 1/4 cycle

⬇

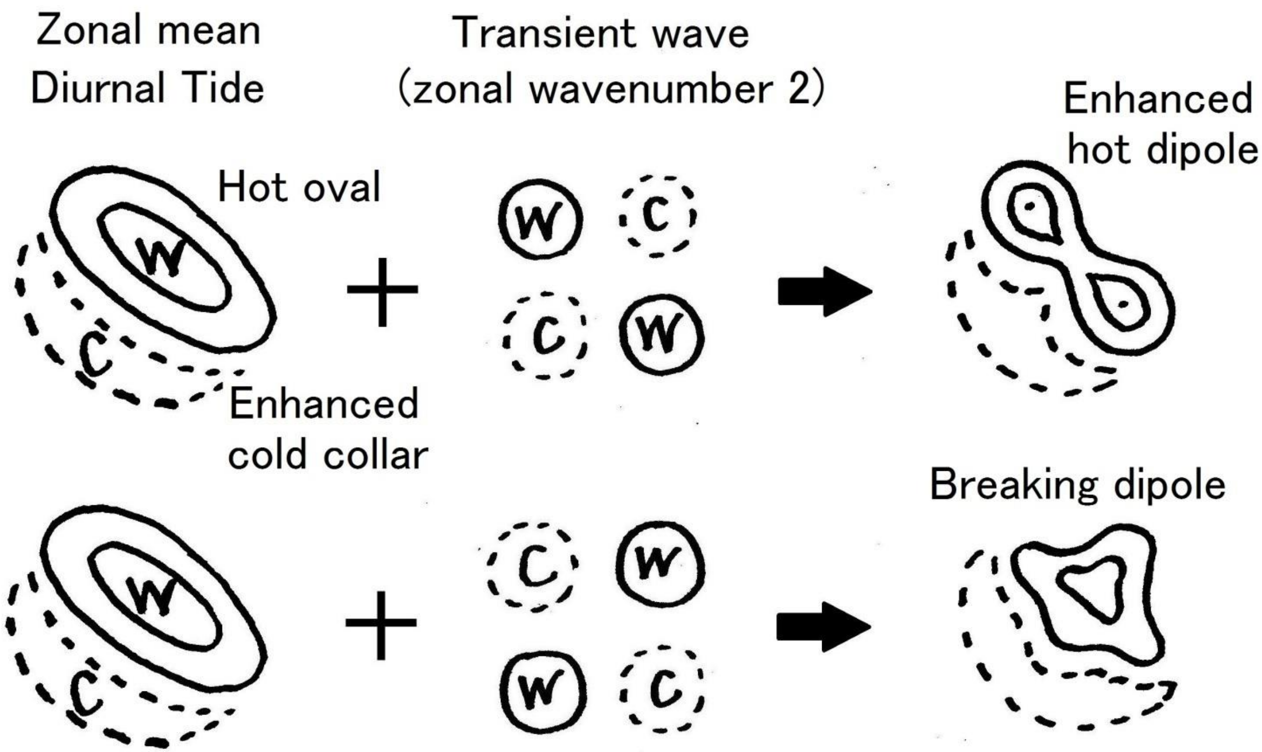
Vortical flow transport heat from the warm polar region to cold outside

(Yamamoto & Takahashi 2015)

# Summary (1)

Under the condition of strong polar tide,

1. Superposition of diurnal tide and transient waves could produce complex vortex patterns.




After the transient
wave rotates by ½ cycle

(Yamamoto & Takahashi 2015)

# Summary (2)

2. Horizontal divergence is strong, and induces temperature anomaly pattern.

3. Vortical flow transports heat from the hot polar region to cold outside.

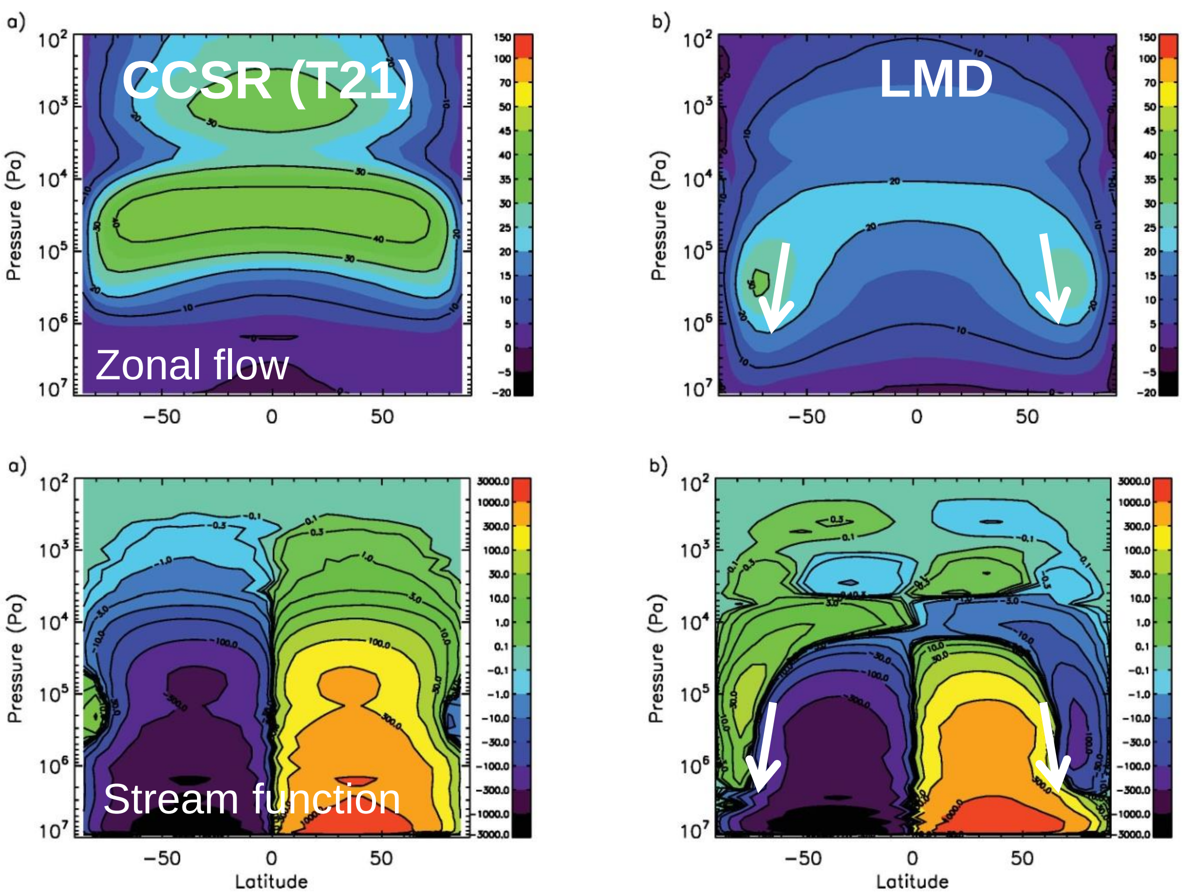
$\Rightarrow$*Transient baroclinic wave contributes to the vortex pattern.*

# Future work

Maintenance mechanism of hot dipole is still unknown under the condition of weak polar tide (VEX).
We need to further investigate them.

# 2. Atmospheric superrotation of cloud-covered planets: significance of planetary rotation and polar eddy heat transport

*using an idealized VGCM (baseline model setting of the ISSI intercomparison project, Lebonnois et al. 2013).*




Large differences of super-rotation strength and polar indirect cells among GCMs

The polar circulation affects the high-latitude superrotation.

We needs high-resolution GCM experiments to fully resolve polar indirect circulation.

# 2. Atmospheric superrotation of cloud-covered planets: significance of planetary rotation and polar eddy heat transport

*using <u>an idealized VGCM</u>* (*baseline model setting of the ISSI intercomparison project, Lebonnois et al. 2013*).

- Easy to compare among different VGCMs

⇒ *Lee and Rechardson* (2010), *Lebonnois et al.* (2013)

- Easy to conduct long-term and high-resolution simulation

⇒We can examine the dynamical effect of polar indirect cell in superrotation using a long-term and high-resolution GCM.

- Easy to apply cloud-covered planet with different rotation rate

For <u>**cloud-covered planet**</u>, the sensitivity of superrotation to the planetary rotation rate is **not** fully understood.

⇒We will examine superrotation structure of cloud-covered planet with arbitrary planetary rotation rate ?

# Objective

- To elucidate dynamical effect of polar indirect cell in superrotation
- To elucidate superrotation structure of cloud-covered planet with arbitrary planetary rotation rate

⇒We investigate sensitivities of superrotation and polar circulation to the planetary rotation rate of a cloud-covered planet.

## Previous studies

- *Earth-like GCMs*

⇒*Many* (Williams & Holloway1982, *Mitchell & Vallis* 2010, …)

- *Cloud-covered GCMs*

⇒*A few* (*Del Genio et al.* 1993, Yamamoto & Takahashi 2008 *AA* **490,** L11)⇒<u>however, low-resolution</u>

## Present study

*Model setting*

⇒Baseline run of ISSI (Lebonnois et al. 2013)

**T21 ⇒ T106**

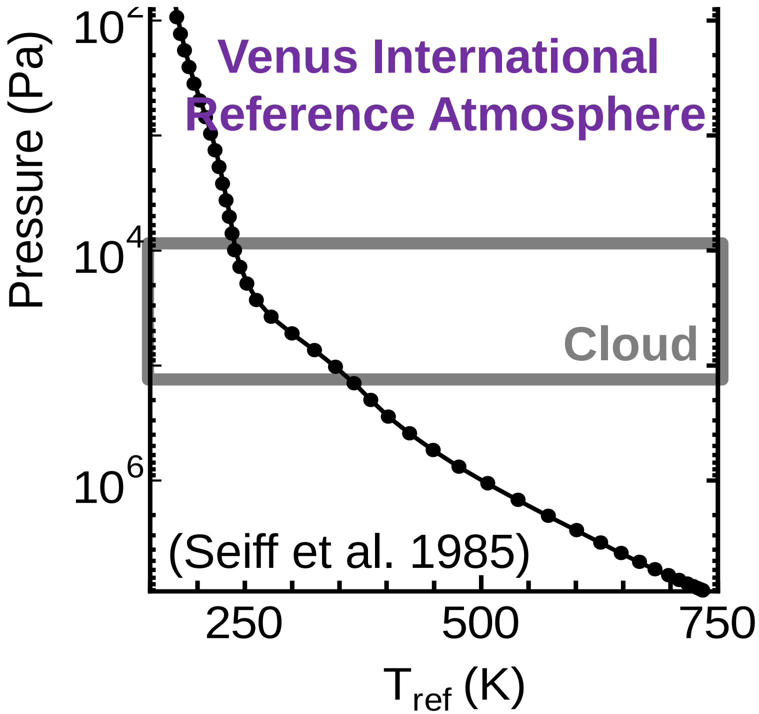
- Exp V $2\pi/\Omega$ = 243 Edays
- Exp T $2\pi/\Omega$ = 16 Edays
- Exp E $2\pi/\Omega$ = 1 Edays

# Held & Suarez (1994)

⇒simplified by Newtonian cooling relaxing temperature $T$ to *the Earth's tropospheric temperature*. This is well used as an idealized Earth-like planet.

# Baseline run of ISSI VGCM intercomparison

⇒simplified by Newtonian cooling relaxing $T$ to *Venus' value*. This is used as an idealized cloud-covered planet.

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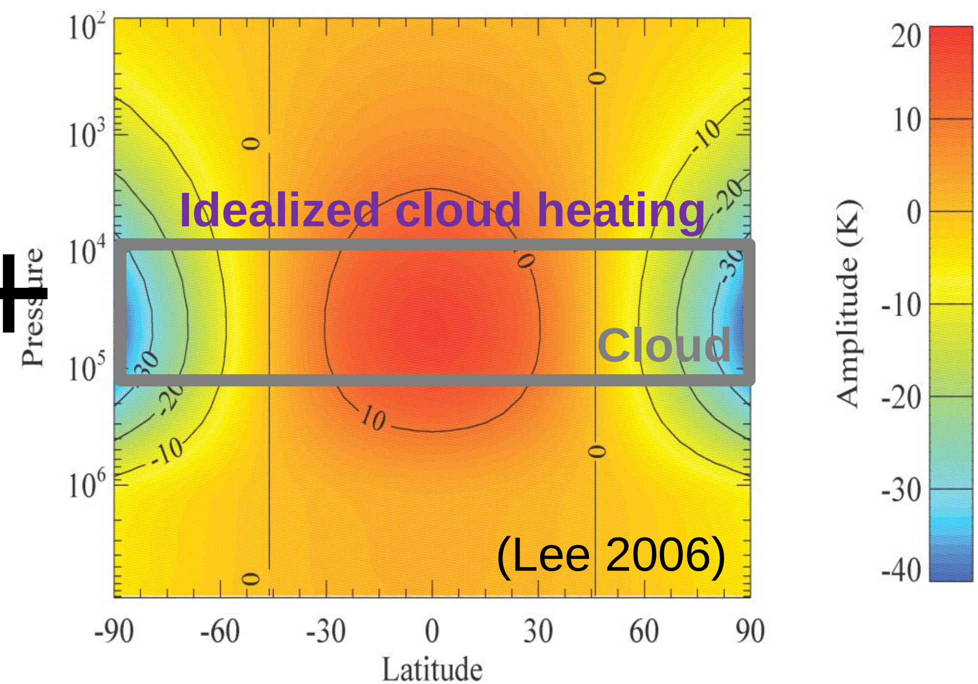


# Zonal mean wind speed

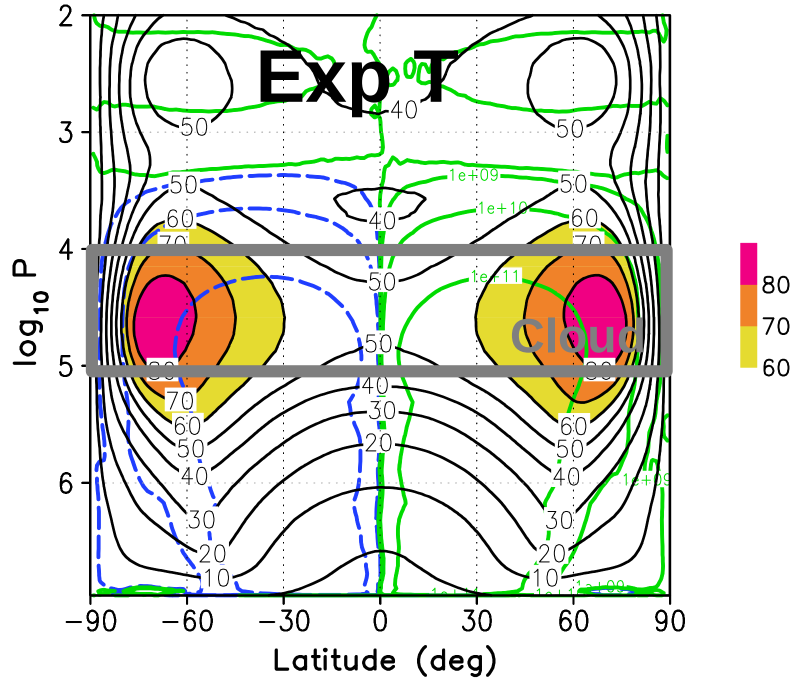
(Color shading is jet core)

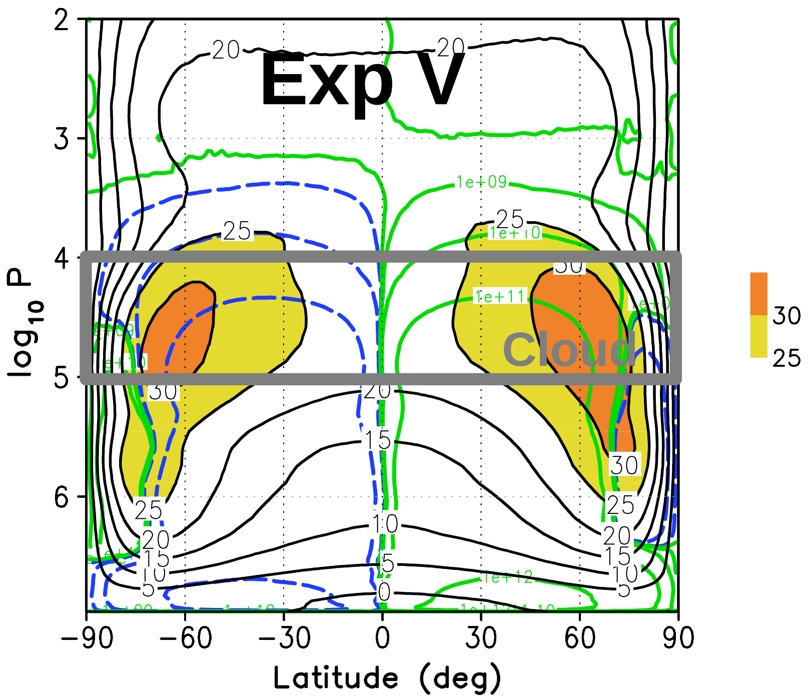
**Exp V:** Weak jets are extended to lower atmos. **below the cloud layer**.

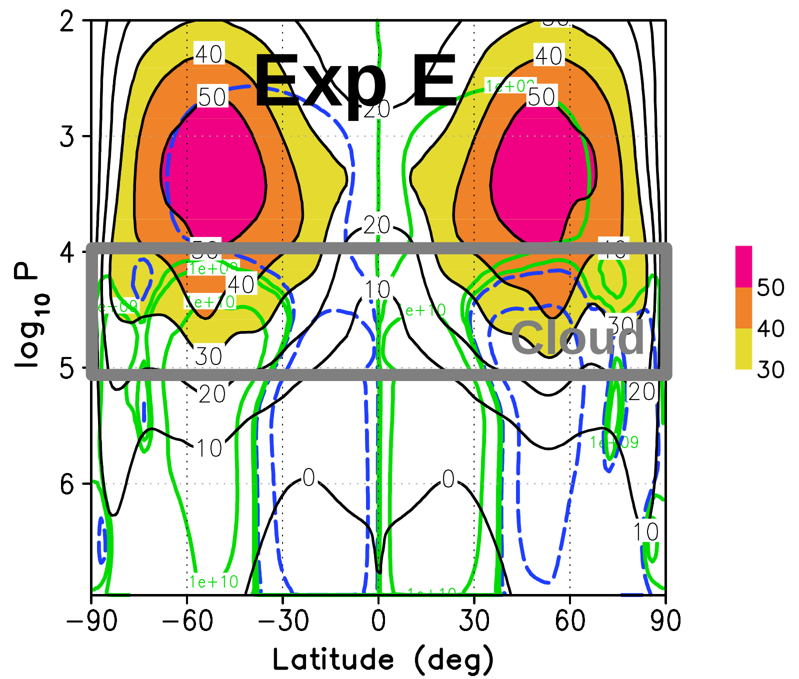
**Exp T:** Strong jets are located **in the cloud layer**.

**Exp E:** Moderate jets are located **above the cloud layer**.

***⇒The strength and location of the jet core depend on the planetary rot. rate.***



# Mass stream func.

(Green contour is clockwise flow)

(Blue contour is anticlockwise flow)

**Exp V:** Equator-pole Hadley cells
+ **Polar indirect cells**

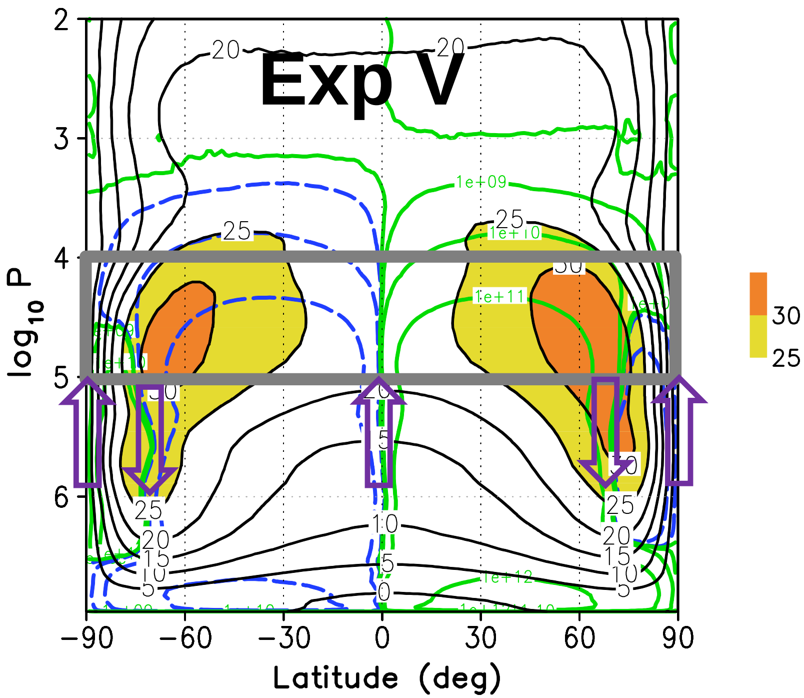
⇒ Jets extend to **the lower atmos**.

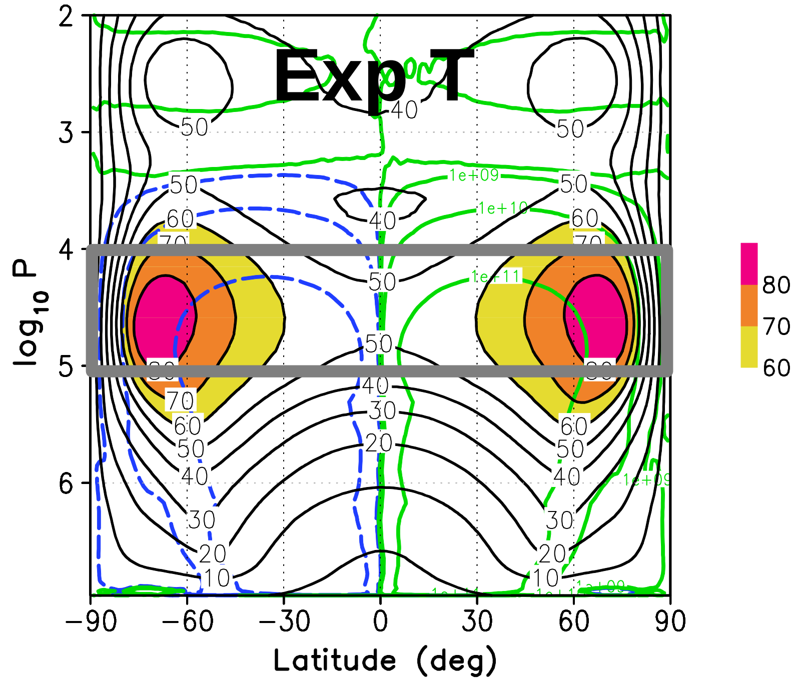
**Exp T:** Equator-pole Hadley cells

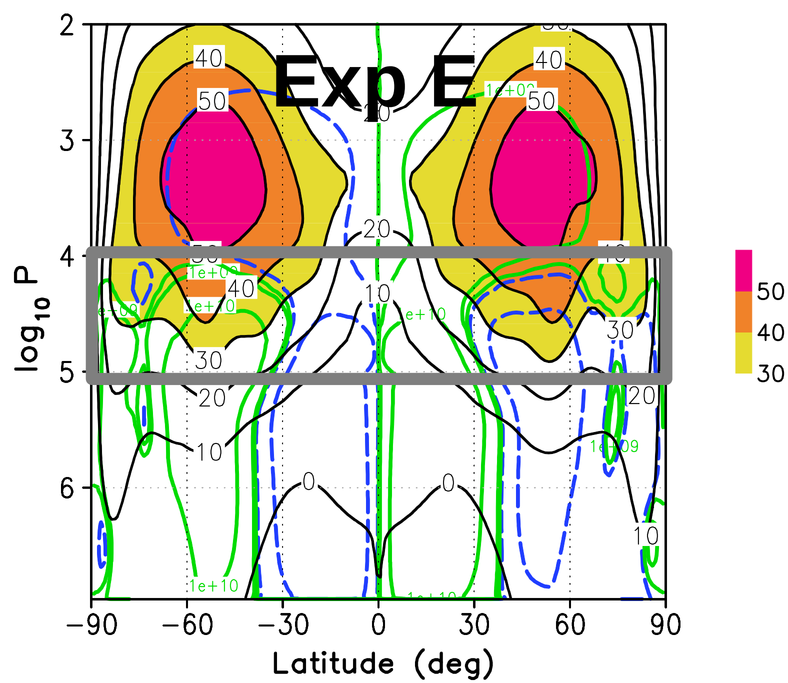
⇒ Jets effectively develop **in the cloud**.

**Exp E:** Equator-pole **multiple** cells

⇒ Jets do not develop **in and below the cloud**.



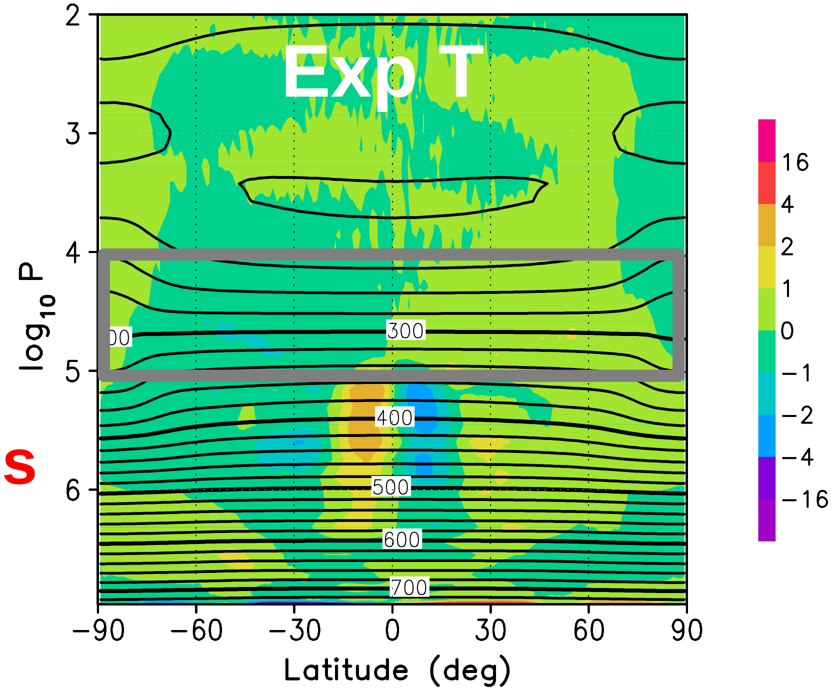
# Horizontal eddy heat flux

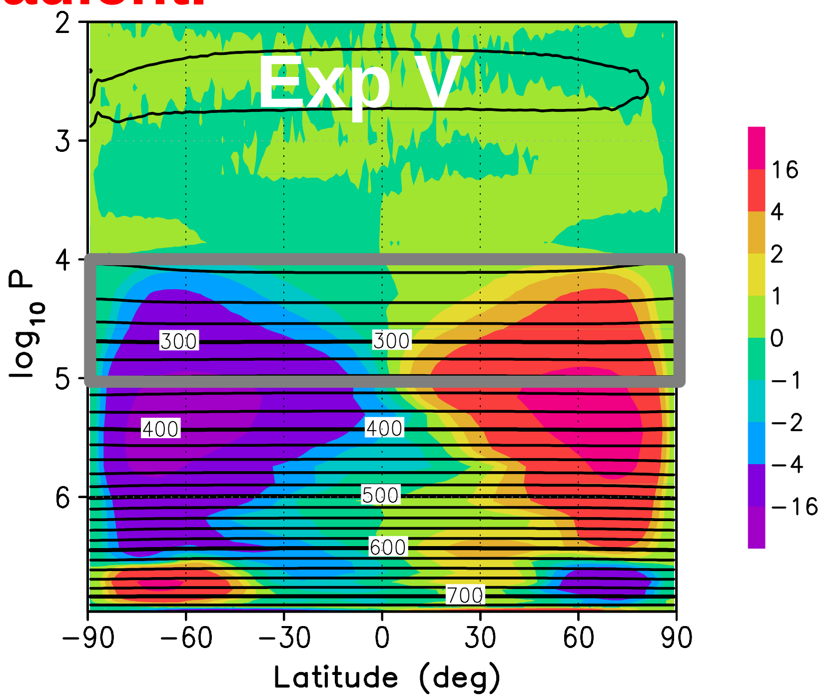
(color shading is $\rho_0 \cos\phi \theta' v'$)

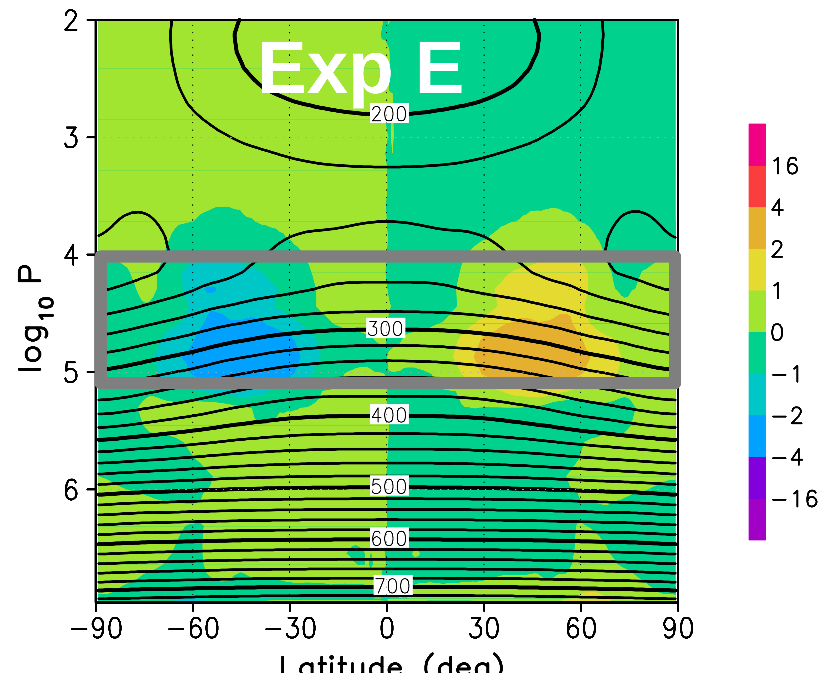
(Contour is zonal-mean temperature)

**Poleward heat flux is strong in Exp V.**

**The strong eddy heat flux induces polar indirect circulation, and reduces meridional temperature gradient.**

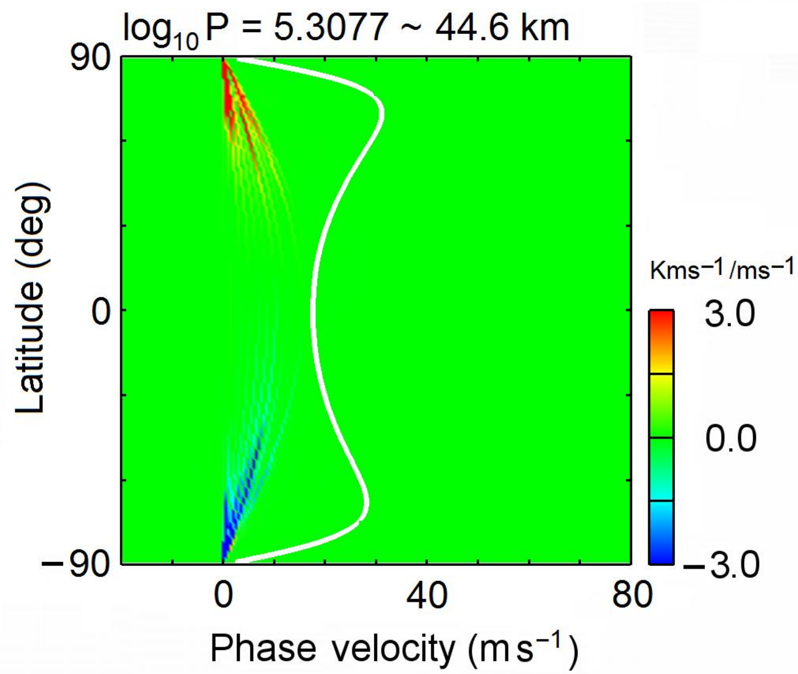


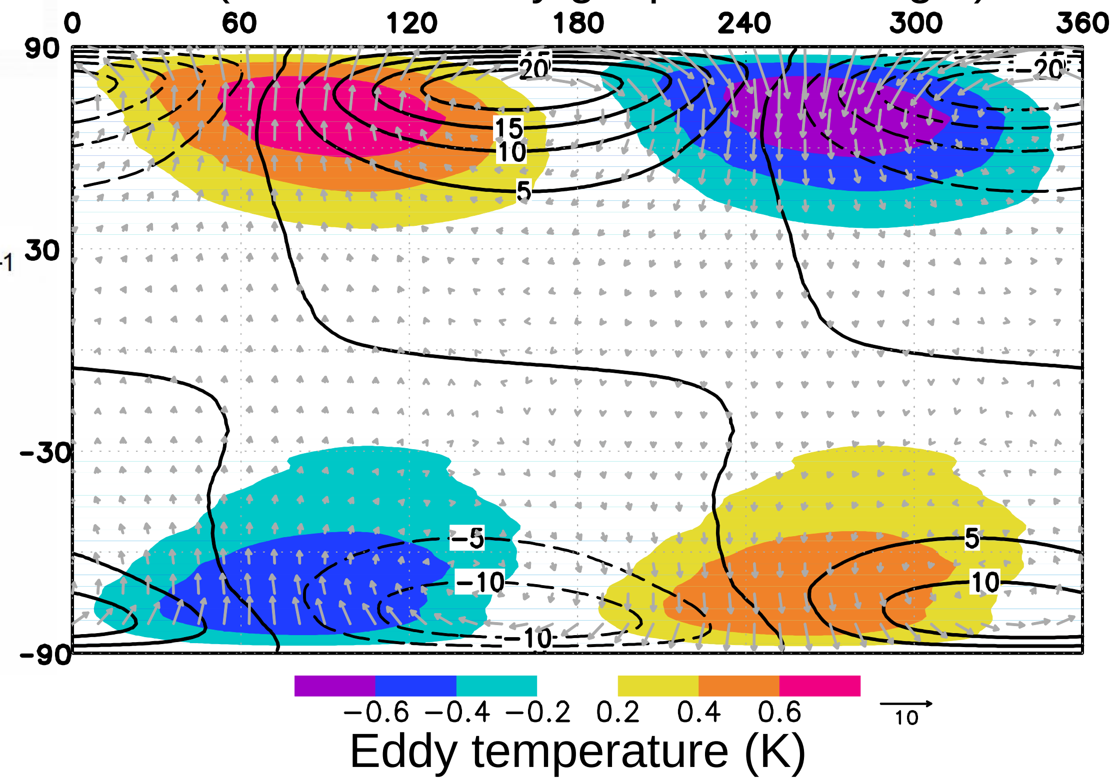
# Spectrum of horizontal eddy heat flux at $2.03 \times 10^5$ Pa
# The most predominant modes in the flux spectrum in Exp. V

$\overline{T'v'}$




**128-day Rossby wave**

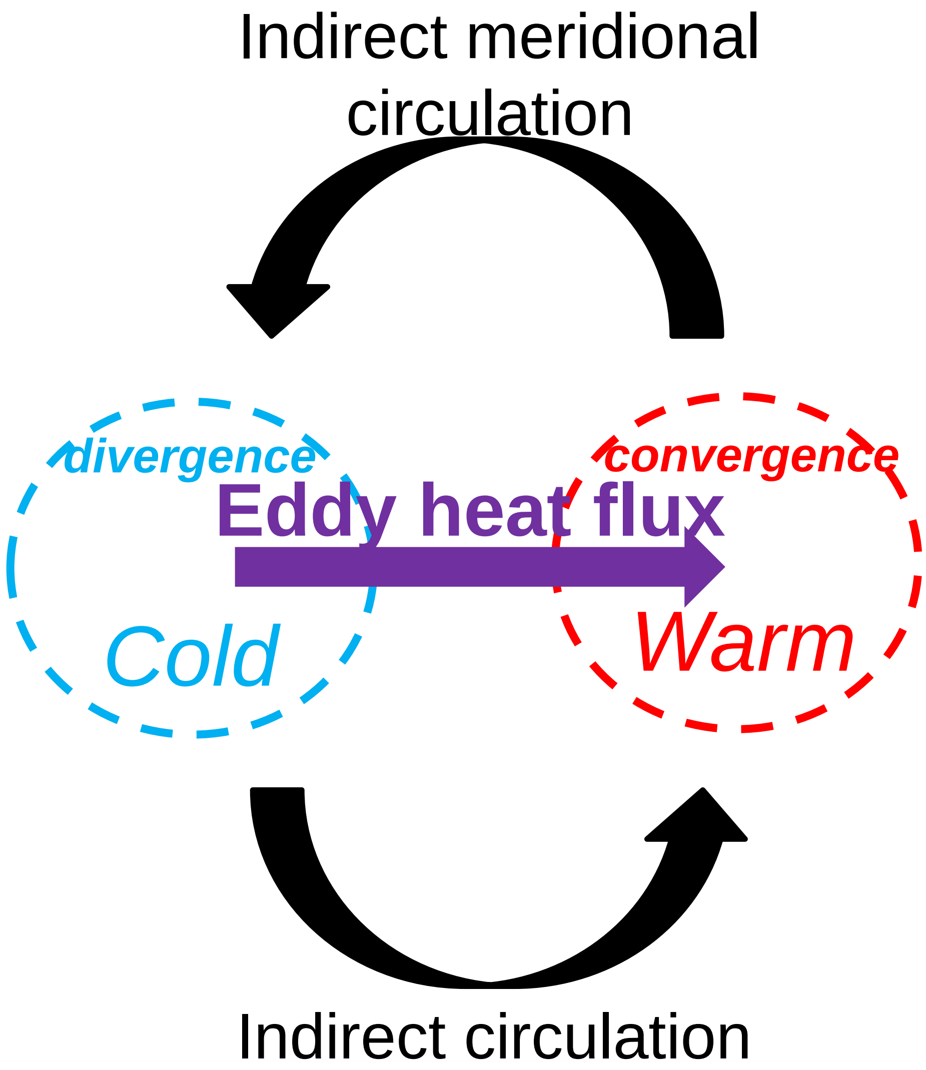
(contour is eddy geopotential height)




- **The strong poleward eddy heat flux is produced by slowly traveling planetary-scale <u>*polar Rossby waves with meridional winds across the poles*</u>.**

- **The poleward (equatorward) eddy flows are in phase with respect to the eddy temperature, and advect warm (cold) air masses.**

# Horizontal eddy heat flux & indirect circulation




**"Strong" eddy heat flux**
modifies atmospheric heating via the eddy heat flux convergence.

⇩

**Indirect meridional circulation**
is induced by **strong eddy heat flux,** and largely modifies angular momentum.

⇩

**Transformed Eulerian-Mean (TEM)** equation system is used.

# **Transformed Eulerian-Mean (TEM)** equation system (Andrews and McIntyre 1976)

## Residual-mean Meridional Circulation (RMC)

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

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

Eulerian zonal-mean meridional circulation

**RMC is *"direct circulation"*, in which *eddy-driving indirect circulations* are removed.**

## Eliassen-Palm (E-P) flux

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

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

Eulerian zonal-mean eddy momentum flux

**E-P flux is "effective eddy angular momentum flux", in which *eddy-driving indirect circulations* are added.**

# Horizontal E-P fluxes

**(Color shading is E-P flux)**

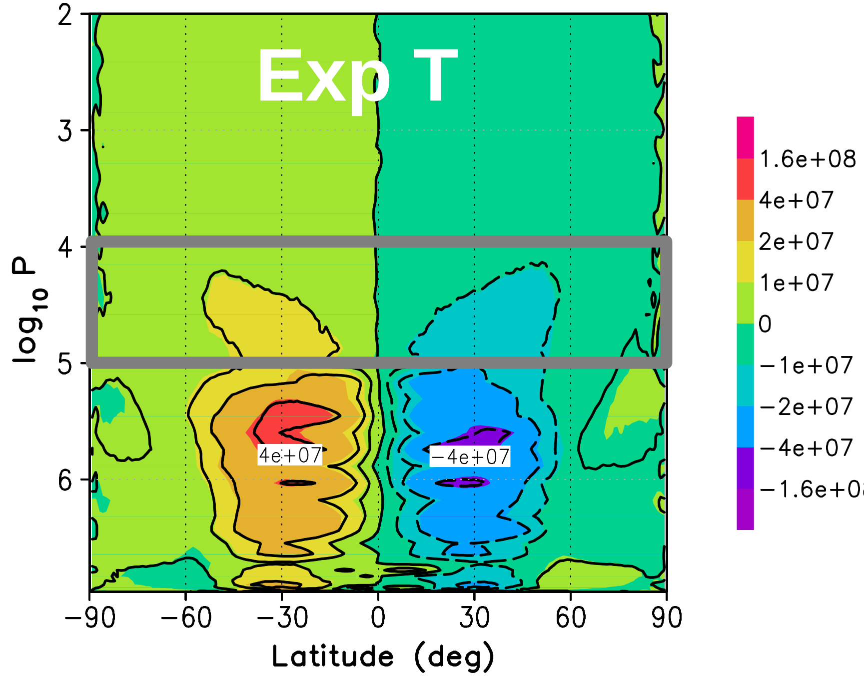
**(Contour is $\rho_0 a \cos\phi u'v'$ )**

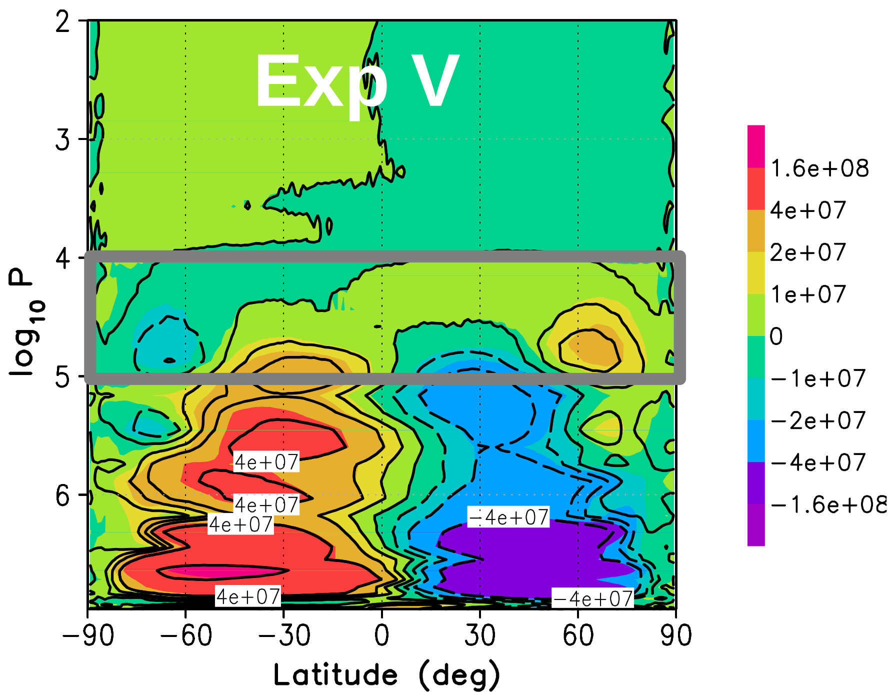
**Exp V:** equatorward near the surface

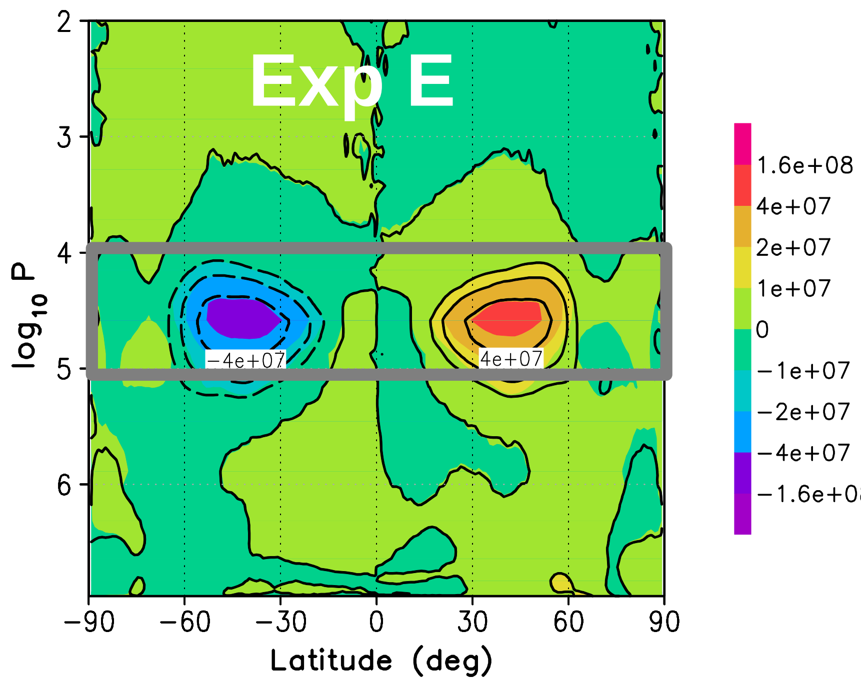
**Exp T:** equatorward near the cloud base

**Exp E:** poleward in the cloud layer

$\Rightarrow$ As planetary rotation rate is faster, the level of the strongest E-P flux is located at the higher level.

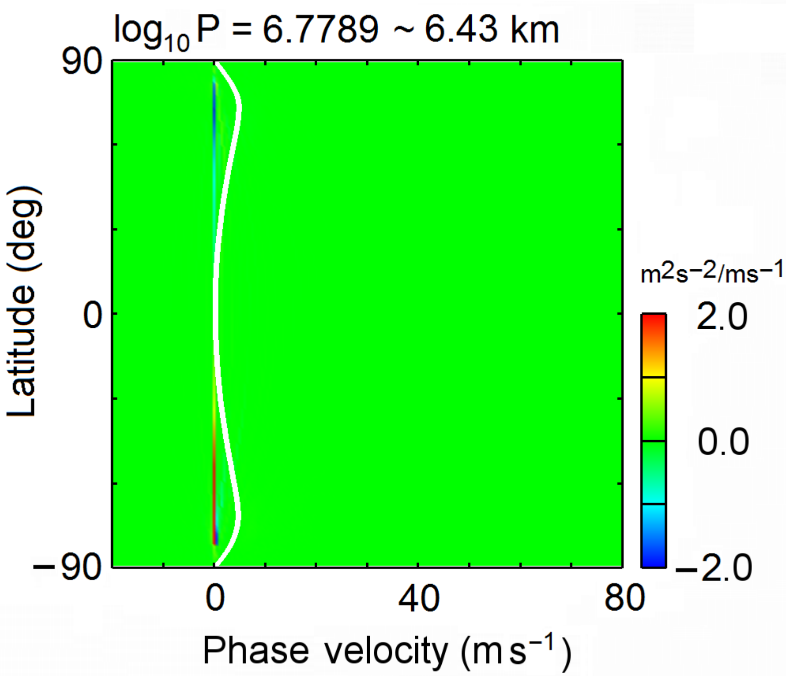


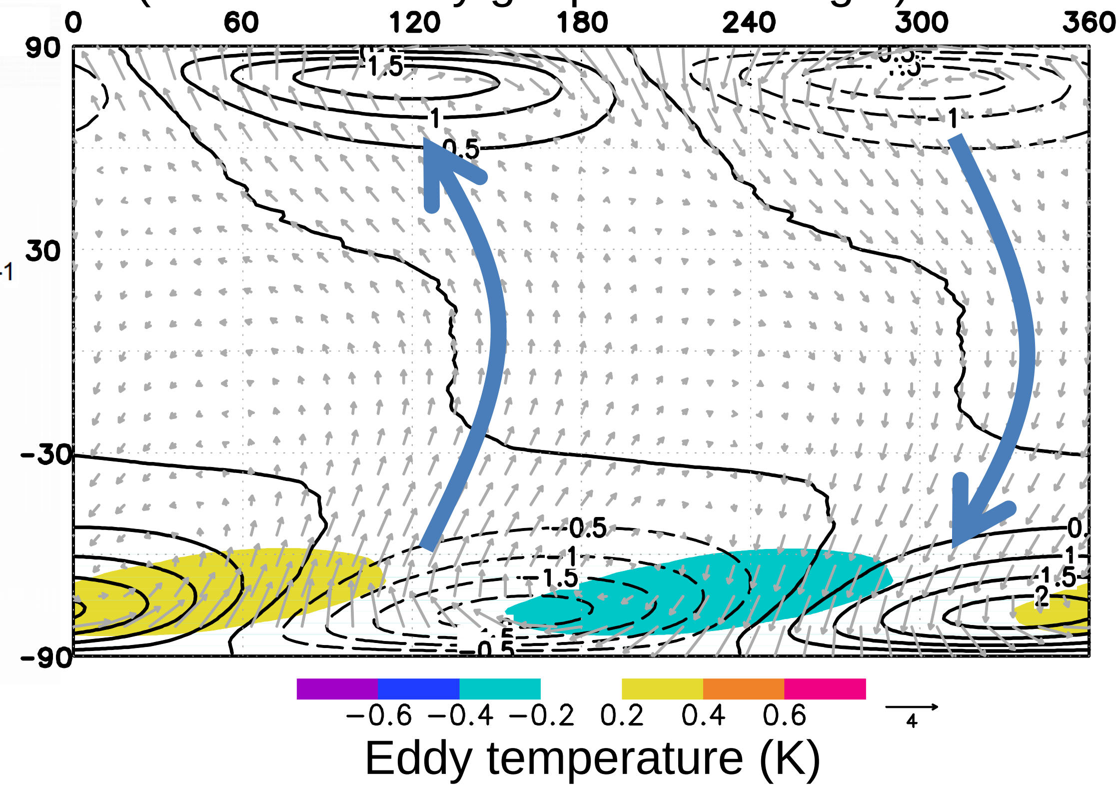



# Spectrum of horizontal eddy momentum fluxes at $6.0 \times 10^6$ Pa
# The most predominant modes in the flux spectrum in Exp. V

$\overline{u'v'}$




**Stationary mixed Rossby-gravity wave**
(contour is eddy geopotential height)

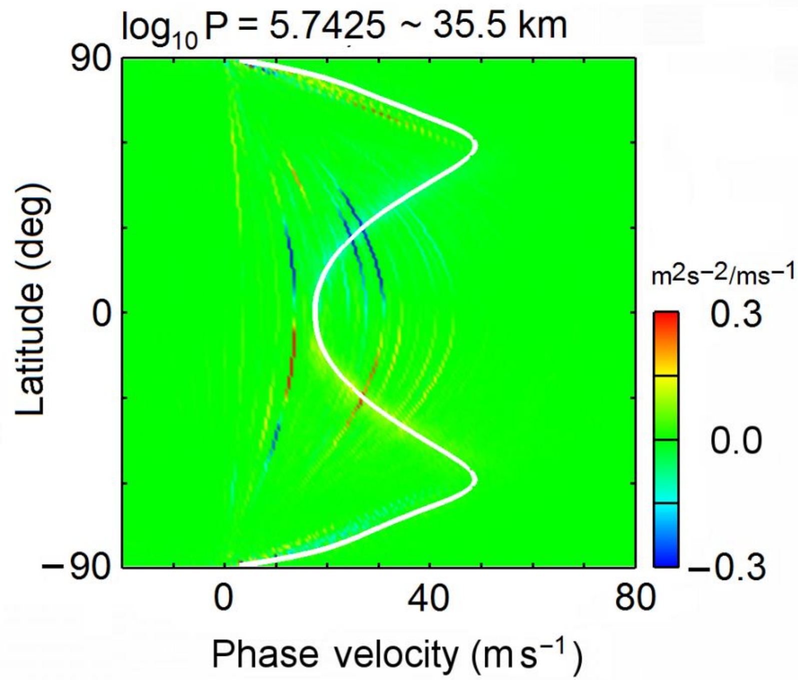



**Stationary mixed Rossby-gravity wave** contributes to horizontal momentum transport.

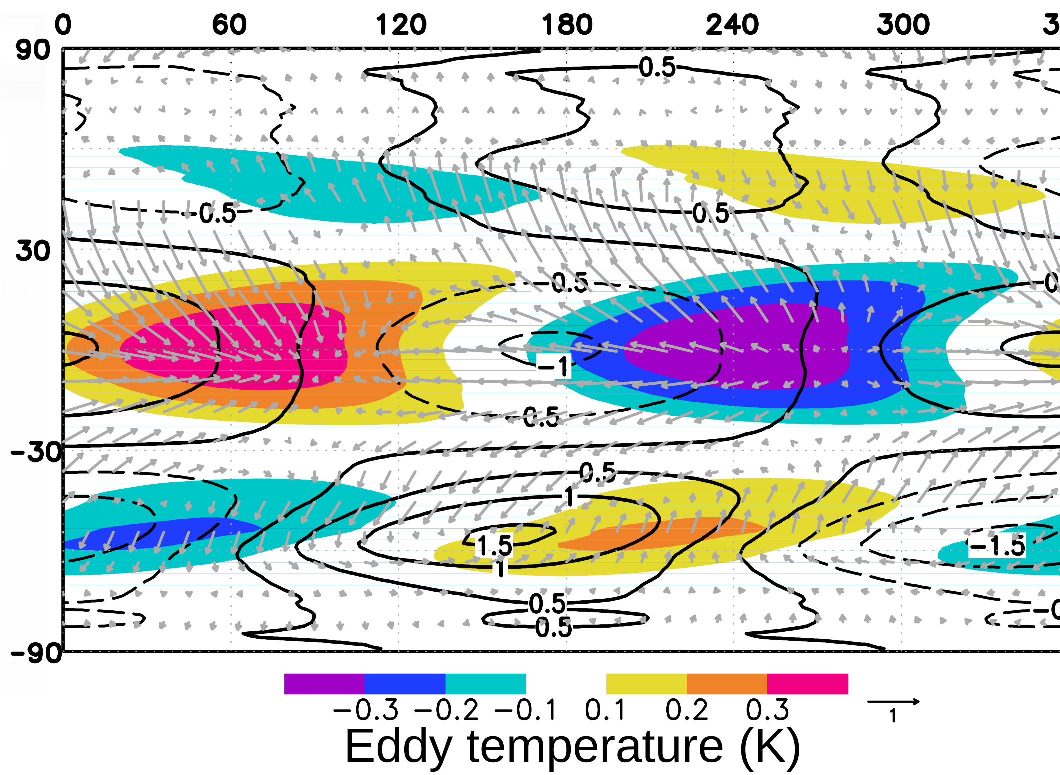
**The meridional flow across the equator tilts at mid- and high-latitudes. The wind tilt produces equatorward momentum flux (*Yamamoto &Takahashi*, 2003).**

# Spectrum of horizontal eddy momentum fluxes at $5.5 \times 10^5$ Pa
# The most predominant modes in the flux spectrum in <u>Exp. T</u>

$\overline{u'v'}$



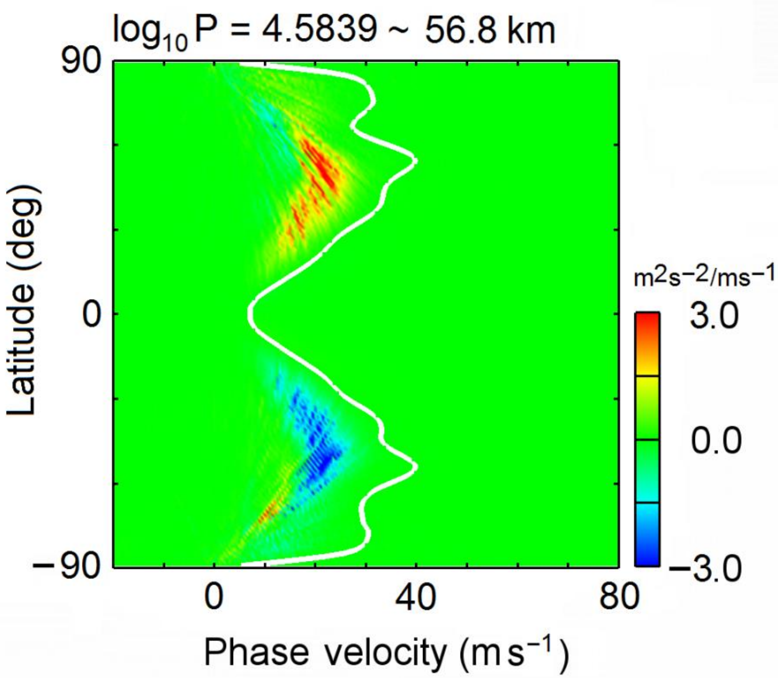

**14.2-day Kelvin-Rossby wave**
(contour is eddy geopotential height)



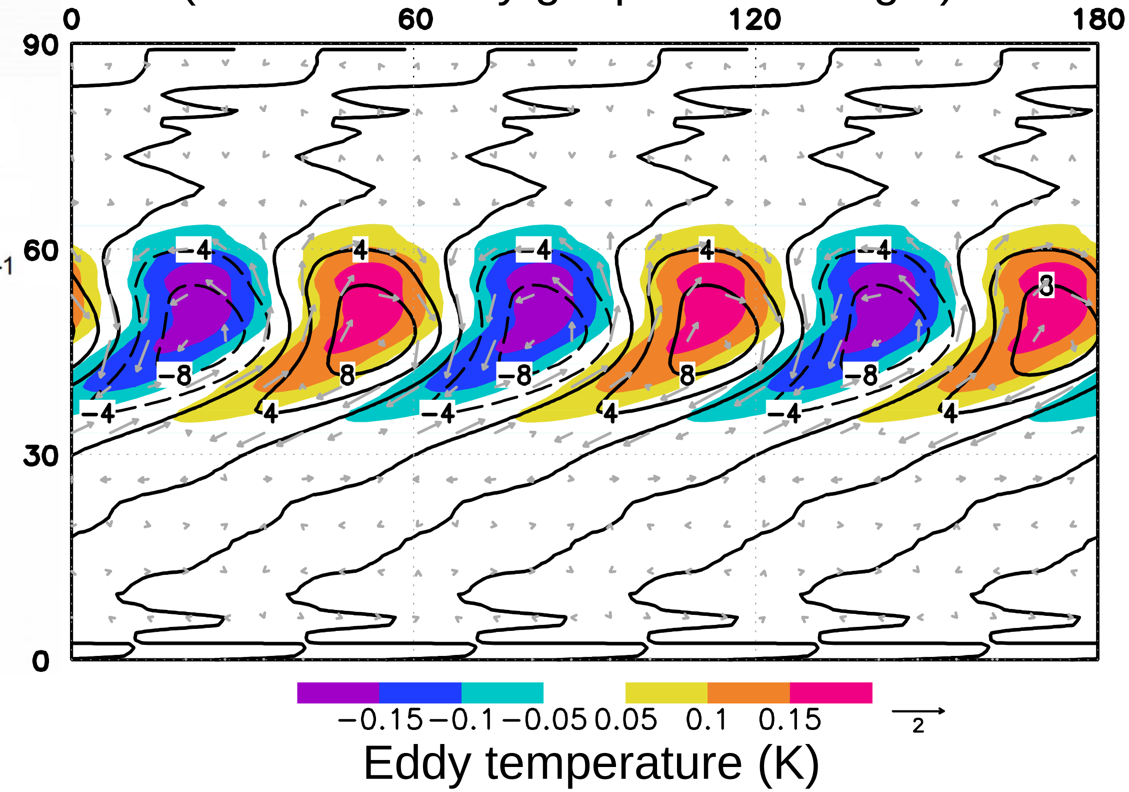

**High-latitude Rossby and low-latitude Kelvin wave structure across the critical latitude is similar to a Kelvin-Rossby mode (*Iga and Matsuda*, 2005) which was simulated in Venus GCMs (e.g., *Yamamoto and Takahashi,* 2004).**

# Spectrum of horizontal eddy momentum fluxes at $3.8 \times 10^4$ Pa
# The most predominant modes in the flux spectrum in <u>Exp. E</u>

$\overline{u'v'}$




**2.78-day Rossby wave**
(contour is eddy geopotential height)




**The strongest momentum flux is caused by a Rossby wave with a phase velocity slower than the zonal-mean wind velocity at midlatitudes**

**The eddy temperature component is small, and in phase with the eddy geopotential height at the central latitude of the wave.**

# Vertical E-P fluxes

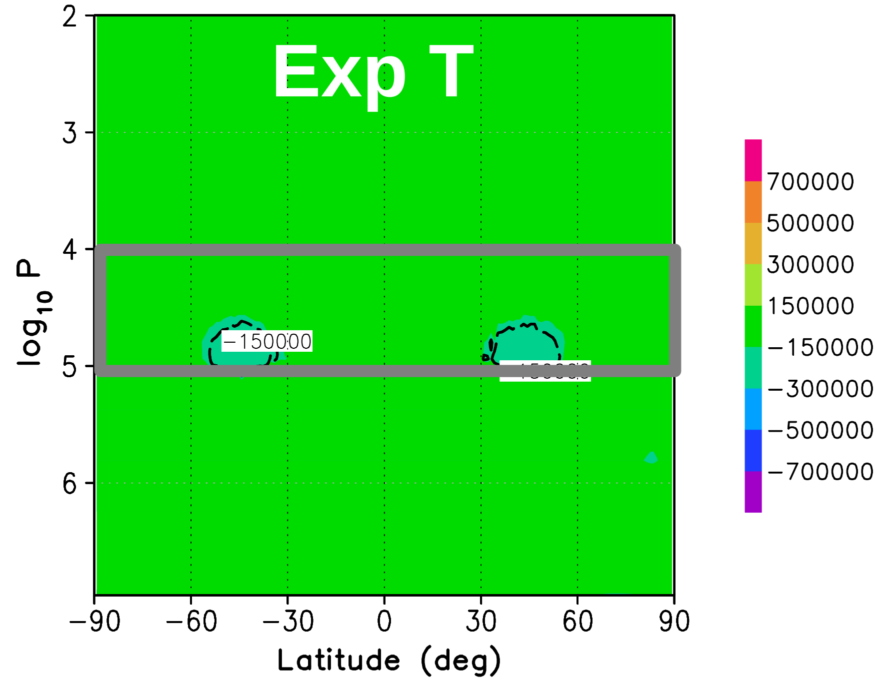
**(Color shading is E-P flux)**

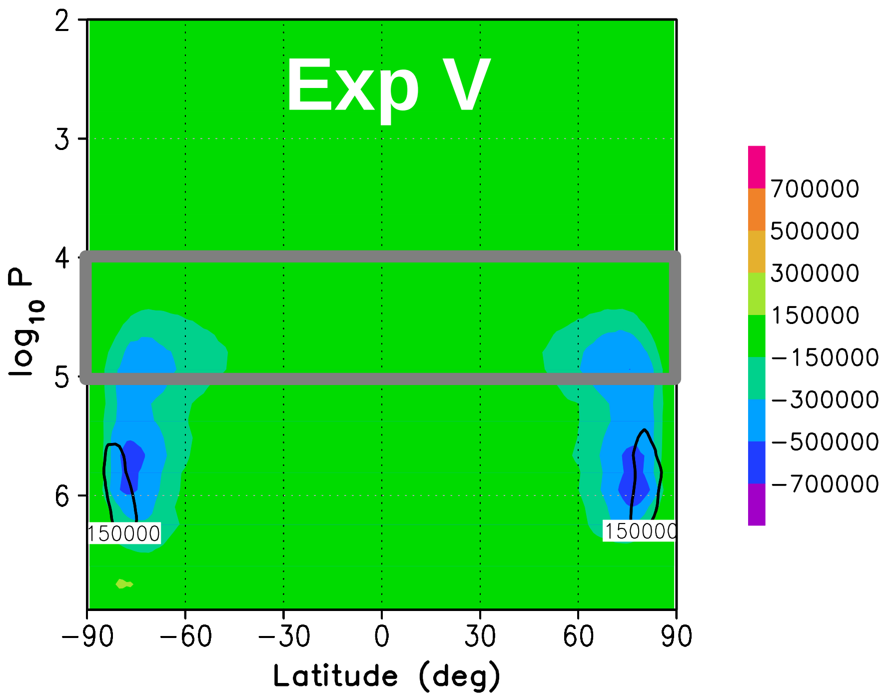
**(Contour is $\rho_0 a \cos\phi\,\overline{u'w'}$ )**

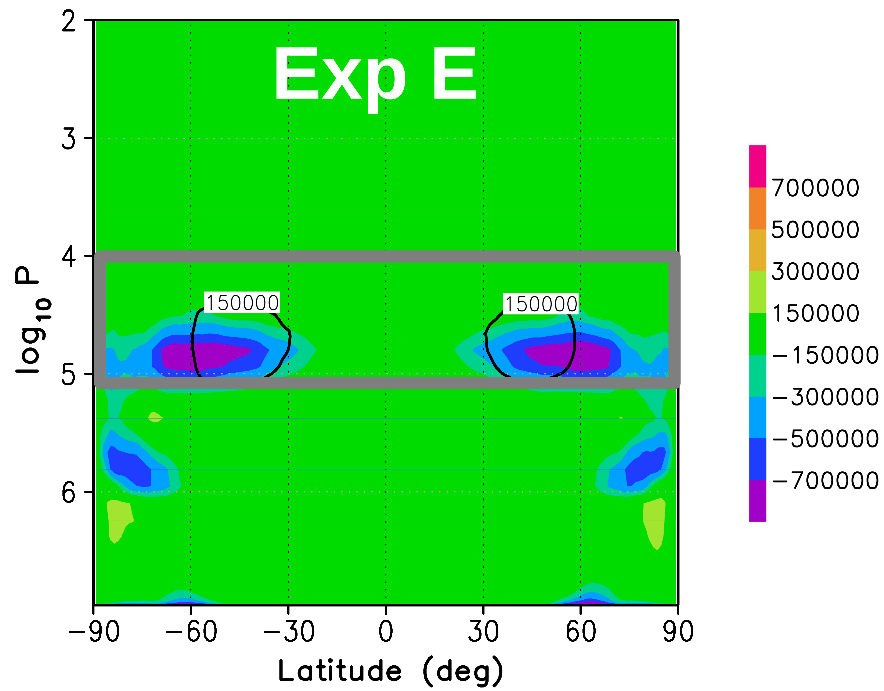
**Exp V:** Downward E-P flux is caused by strong poleward eddy heat flux.

**Exp T:** Downward E-P flux is caused by downward momentum flux.

**Exp E:** Downward E-P flux is caused by weak eddy heat flux and strong Coriolis parameter.



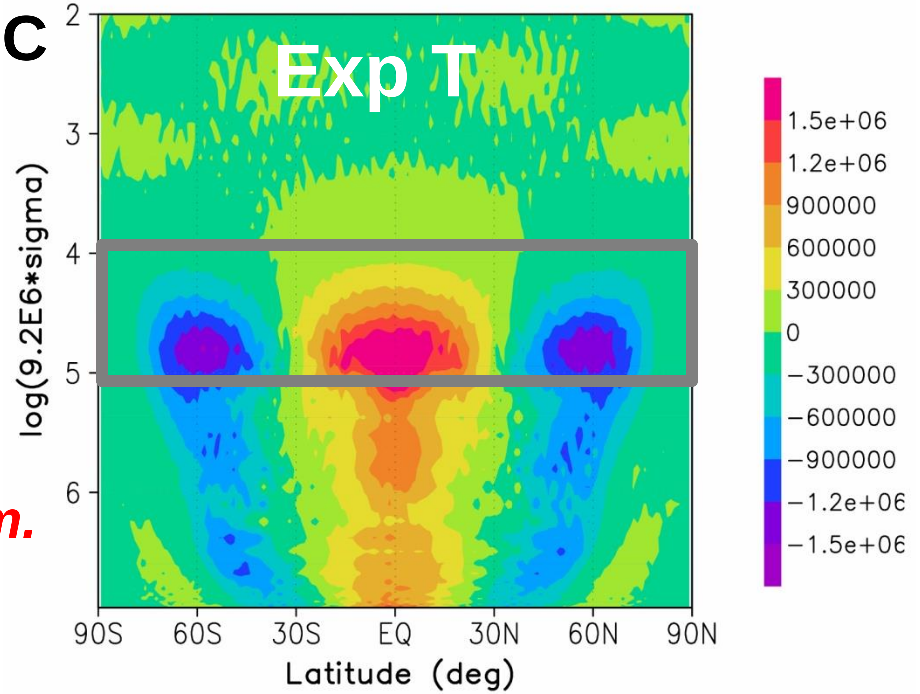



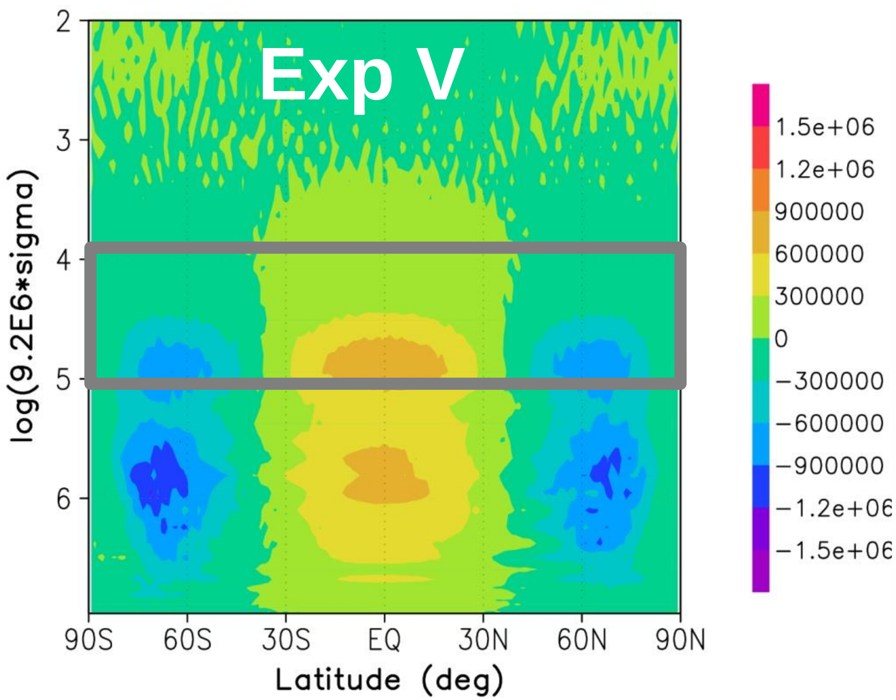
# Vertical ang. mom. fluxes by RMC

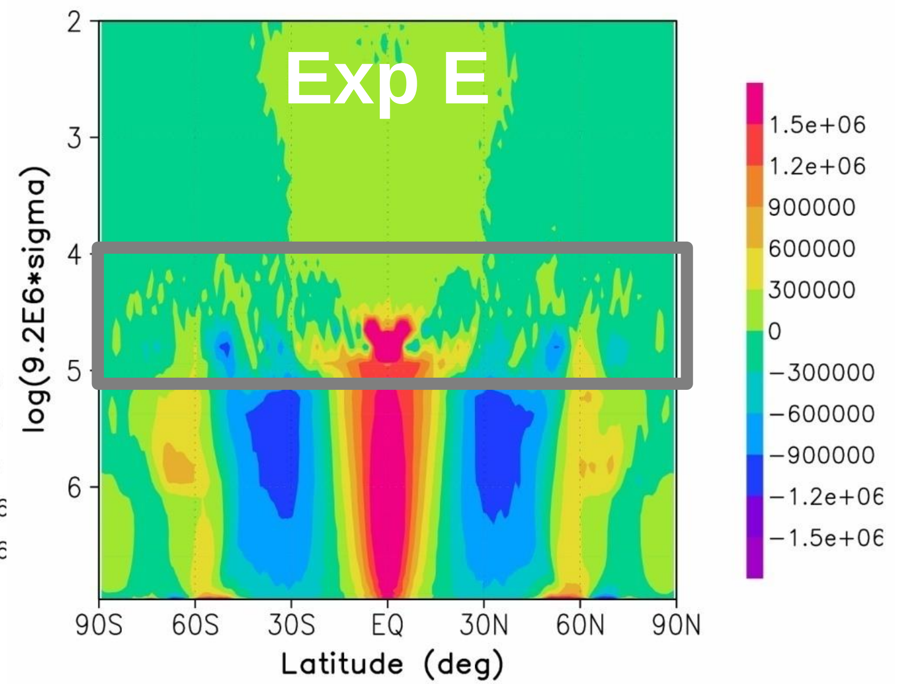
The global-mean angular momentum flux is upward.
⇒ ***RMC pumps up angular mom.***

**Exp V and T:** The Hadley cells are extended to the poles.
⇒ ***RMC efficiently pumps up ang. mom.***

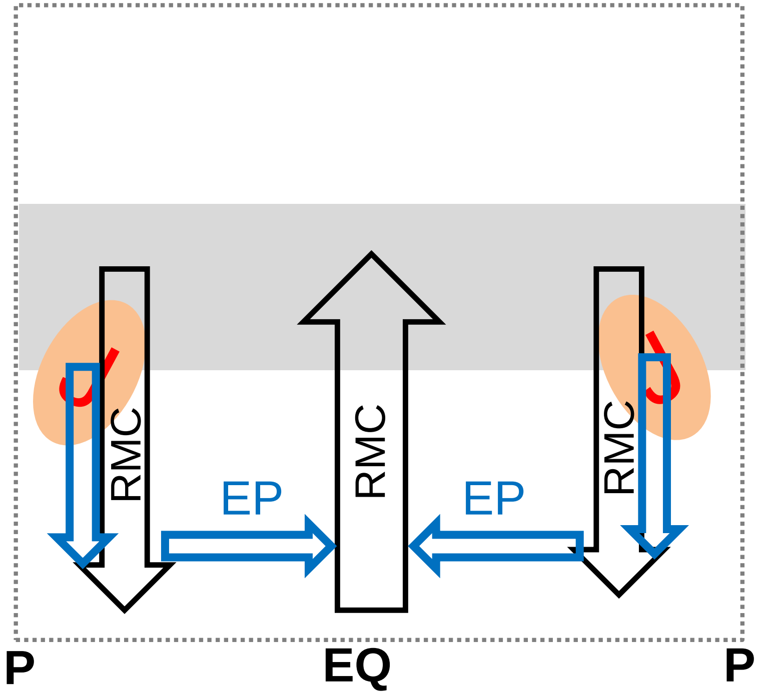
**Exp E:** The Hadley cell is confined within *tropical region*.



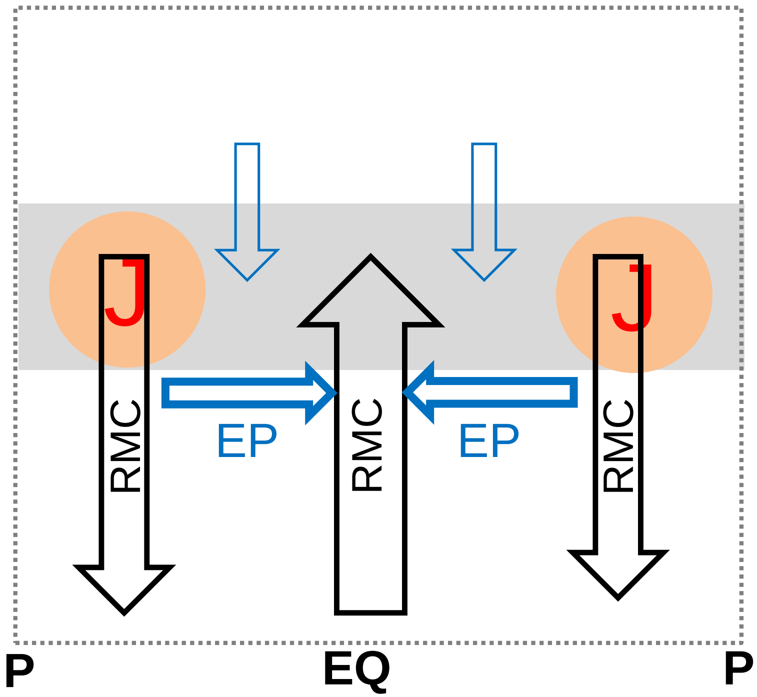
# Summary (Exp V, $2\pi/\Omega$ = 243 Edays)




- ***Strong equatorward angular momentum flux*** is produced by stationary mixed-RG wave ***near the surface***.
- ***Strong poleward heat flux due to polar wave*** produces the ***strong downward E-P flux*** and its related ***polar indirect circulation***, which ***weaken the superrotation*** in the cloud layer.
- ***Strong poleward heat flux*** also reduces the meridional temperature gradient and vertical shear of high-latitude jets in accordance with the thermal-wind relation.

- ***Weak high-latitude jets*** are extended to ***'the lower atmosphere'*** in the presence of polar indirect circulation.

# Summary (Exp T, $2\pi/\Omega$ = 16 Edays)



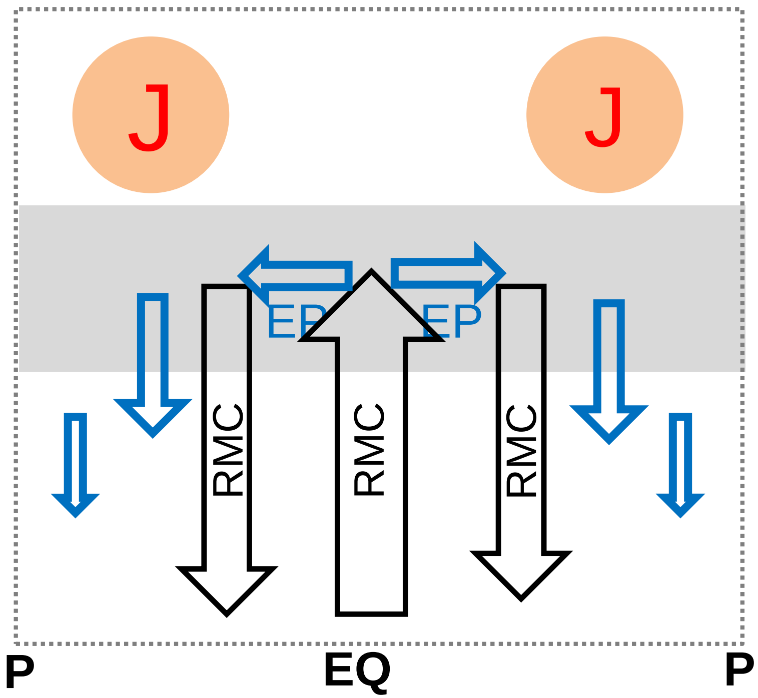

- ***Strong horizontal angular momentum flux*** is produced by *fast traveling Kelvin-Rossby waves*, and is located ***near the cloud base***.

- ***Polar indirect circulation is absent***, while ***horizontal heat flux is weak***. Only the equator-pole Hadley cell is predominant.

- ***Meridional temperature gradient is strong*** below the strong jets in accordance with the thermal-wind relation.

- ***Strong mid-latitude jets and meridional temperature gradient*** are maintained ***"in the cloud layer"*** in the absence of polar indirect circulation.

# Summary (Exp E, $2\pi/\Omega$ = 1 Eday)




- ***Strong poleward angular momentum flux*** is produced by fast traveling midlatitude Rossby waves ***in the cloud layer***.
- Although ***poleward heat flux is weak, large Coriolis parameter*** contributes to ***strong downward E-P flux within the cloud layer***.
- Strong RMC is confined within low latitudes in and below the cloud layer. The multiple meridional circulation reduces upward angular momentum transport.

- ***Weak midlatitude jets*** are formed ***'above the cloud layer'*** by weak global-scale Hadley circulation of the low-density upper atmosphere, whereas superrotation is not formed in and below the cloud layer in the presence of equator-pole multiple circulation.

# *Conclusion*

- Three different types of middle-atmospheric jet structures depend on the planetary-rotation rate of cloud-covered planets.
- Poleward eddy heat transport induces polar indirect circulation and weakens cloud-level superrotation via vertical E-P flux and thermal wind relation in Exp. V.
- Poleward eddy heat transport is driven by planetary-scale eddy meridional winds across the poles, which is unique to the slow superrotation seen in Exp. V.

*The presence or absence of strong poleward eddy heat flux is one of the important factors determining the slow or fast superrotation state in the cloud layer through the E–P flux and the thermal-wind relation.*

# *Future works*

- **Sensitivity experiments for model resolution (T21, 42, 63, and 106) were done, based on the ISSI protocol (baseline, Exp. V). We are analyzing sensitivity of wave activity.**

$\Rightarrow$*We can compare with dynamical cores of different GCMs. If the resolution is increased, the differences among GCMs are expected to become smaller.*

- **The simplified modeling is changed to realistic Venusian cloud-covered condition towards understanding of the atmospheric dynamics.**