EPSC 2015
Oral Program TP3: Venus
Convener: C. F. Wilson
11:30-11:45, 1 Oct, 2015

Simulation of Venusian atmosphere by AFES

(Atmospheric general circulation model For the Earth Simulator)

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This study is conducted under the joint research project of the Earth Simulator Center with title "Simulations of Atmospheric General Circulations of Earth-like Planets by AFES."

Today's focus

Introduction of AFES simulation for Venus

We have currently three main scientific results

1. Baroclinic instability & Waves
   - Main collaborator: M. Takagi (Kyoto Sangyo Univ.,)
     Y. Matsuda (Tokyo Gakugei Univ.)

   cf. Sugimoto et al., JGR (2014), GRL (2014)

2. Energy spectra (Venus vs. Earth)
   - Main collaborator: H. Kashimura (ISAS/JAXA)

   cf. Kashimura et al. (in preparation)

3. Polar vortex & Cold collar (Model vs. Obs.)
   - Main collaborator: H. Ando (ISAS/JAXA)
     T. Imamura (ISAS/JAXA)

   cf. Ando et al., (under revision); see also P14, Oct 01 (Today), 17:45-19:30

I have performed all numerical simulations on the Earth Simulator and data analysis of 1.

Outline

1. Introduction
   - **AFES** project (Atmospheric GCM For the Earth Simulator)
   - Strategy and Targets of Venus simulation
2. Model description
   - Experimental settings; radiative process, initial condition…
3. Results (in briefly)
   - *Runs without solar heating*
     - *Baroclinic instability (T42L60)*
   - Runs with solar heating
     - Baroclinic & Neutral waves (T63L120)
     - Energy spectra (T159L120)
     - Polar vortex & Cold collar (T42L60)
4. Summary

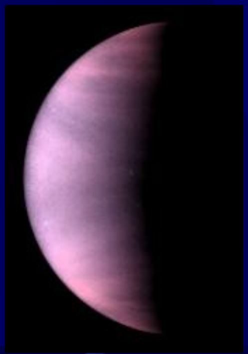
T; trancation wavenumbers
L; vertical layers

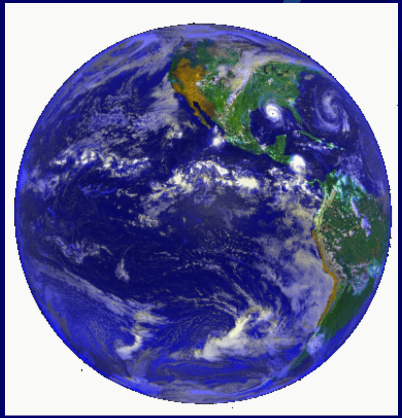
1. Introduction

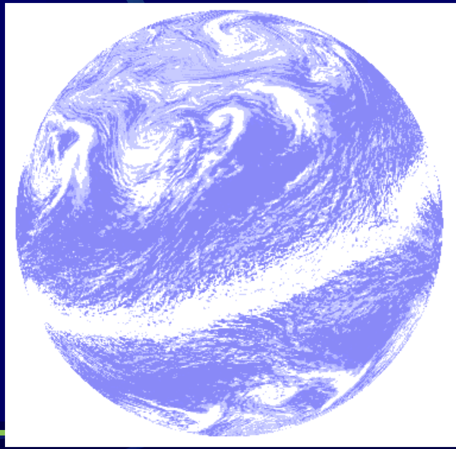
AFES project

(Y.-Y. Hayashi, Y. O. Takahashi, W. Ohfuchi, T. Enomoto, etc)

- To understand the varieties of global circulation in planetary atmospheres
  - ✓ Mars, Venus, Jupiter, Aqua-planet…
    - Common framework of Atmospheric GCM (AFES)







I am a member of Venus group and will report the results of Venus

Computational Efficiency

- **AFES** (AGCM For the Earth Simulator)
  - ✓ Optimized for parallel vector super computer
  - ✓ T639L96 simulation for Mars (Takahashi et al.)

Node number	64 node
Vector efficiency	99.4%
Parallel efficiency	99.8%
CPU time	1 martian days / ~4 hours

Mars simulation; grid intervals ~**11 km**, Nx=1920 grids, Ny=960 grids, Nz=96 layers

Venus GCM studies

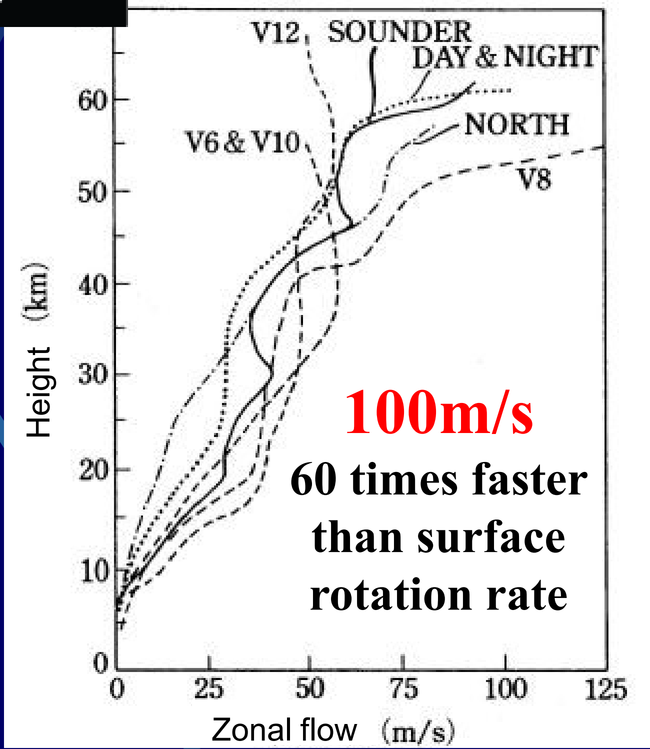
- **Super-rotation is driven by**
  - ✓ Mean meridional circulation

    Gierasch 1975; Yamamoto & Takahashi(YT)2003
  - ✓ Thermal tides

    Fels & Lindzen 1986; Takagi & Matsuda (2007)

Basically, starting from motionless state, long time integration, low resolution, not realistic solar heating and static stability

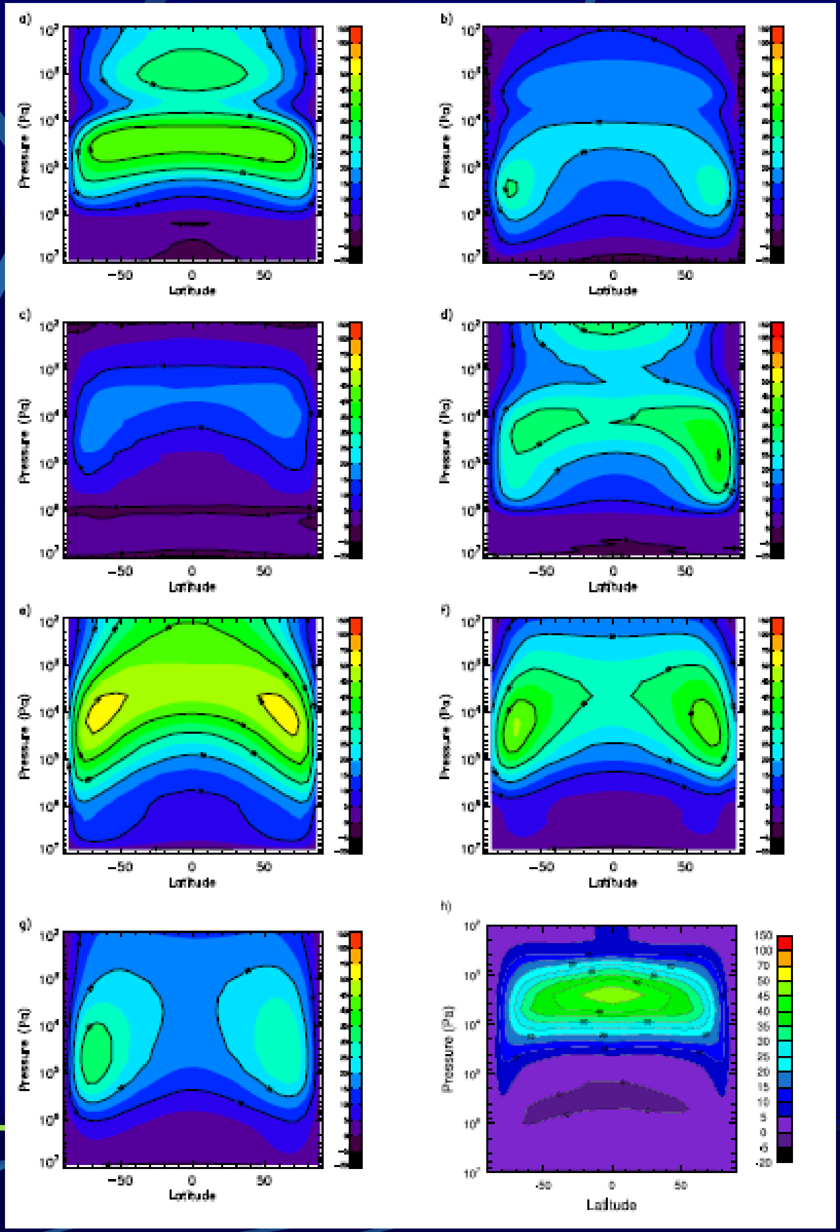
Schubert et al.(1980)



References	Horizontal resolution		Vertical grid
Yamamoto & Takahashi (2003)	T10 (~ 11° × 11°)	32×16 grids	50 levels
Lee et al. (2005)	5° × 5°	72×36 grids	32 levels
Kido & Wakata (2008)	T21 (~ 5.6° × 5.6°)	64×32 grids	60 levels
Takagi & Matsuda (2007)	≦T21 (~ 5.6° × 5.6°)	64×32 grids	60 levels
Lebonnois et al. (2010)	7.5° × 5.6°	48×32 grids	50 levels
Parish et al. (2011)	1.2° × 0.9°	300×200 grids	50 levels

Further Venus GCM studies

Lebonnois et al. (2013)



Inter comparison project

- ✓ Super-rotations are quite different among the models

Multiple equilibrium?
Waves or Missing process?

More realistic GCM

- ✓ New radiation code (Ikeda, 2011)
- ✓ Gravity wave parameterization
- ✓ Microphysics (YT2006)
- ✓ Topography (Lebonnois et al., 2010)
- ✓ Middle atmosphere (YT2011, Gilli2015)
- ✓ Non-hydrostatic (Mingalev et al., 2012)

Strategy

- Start from idealized super-rotation
  - ✓ Saving computational cost with high resolution run
- Maintain super-rotation with realistic solar heating
  - ✓ under the realistic static stability
  - ✓ not including artificial forcing

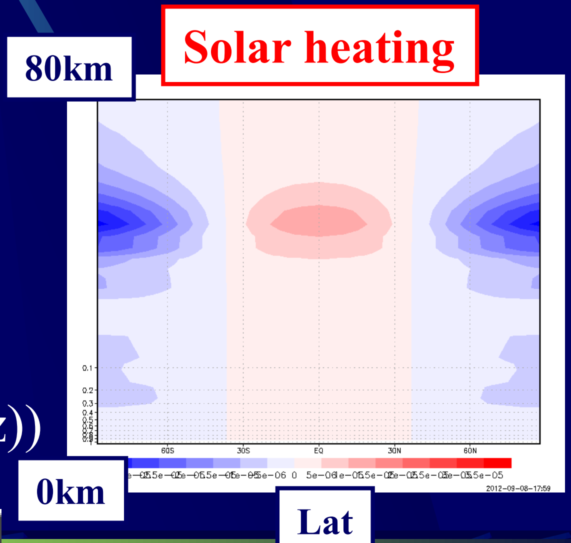
Targets

- Focus on atmospheric motions near the cloud
  - ✓ Baroclinic instability; No observations but predicted in the theoretical studies
  - ✓ Waves; Space-time variation of super-rotation, source, transport…
  - ✓ Energy spectra; Traditional analysis on Earth but no Venus study so far
  - ✓ Polar vortex; “S-shaped” structure frequently observed in VIRTIS
  - ✓ Cold collar; Puzzling cold latitudinal band which is not reproduced in GCM

Final goal: To understand fundamental mechanism of super-rotation

2. Model description <u>see Sugimoto et al. (JGR2014)</u>

- Venus AFES
  - ✓ 3-D Primitive equation on sphere (hydro static balance) without moist processes
  - ✓ Resolution: T42L60, T63L120, T159L120 (Δx & Δy～79km Δz～1km)
  - ✓ Specific heat: Cp is constant (1000 $Jkg^{-1}k^{-1}$)
  - ✓ Horizontal hyper-viscosity: 0.1(T42), 0.03(T63), 0.01(T159) Earth days for 1/e
  - ✓ Vertical eddy viscosity: 0.15m^2s^{-1}
  - ✓ Rayleigh friction: lowest and above 80km(sponge layer except for zonal flow)
  - ✓ No topography and planetary boundary layer
- Solar heating
  - ✓ Zonal and diurnal component of realistic heating
  - ✓ Based on Tomasko et al. (1980) and Crisp (1986)

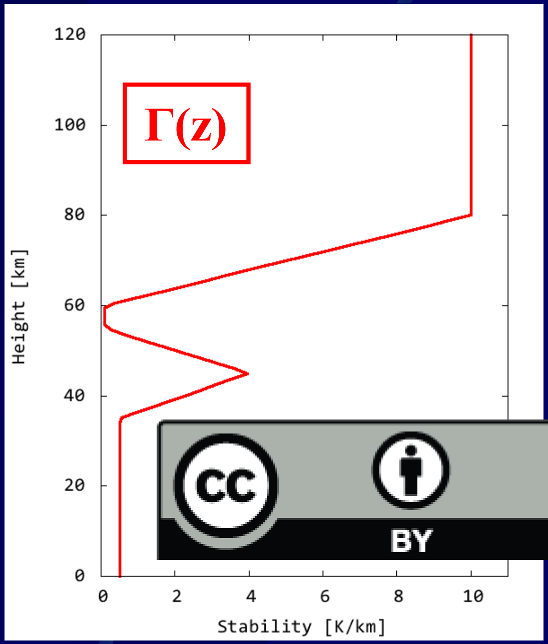


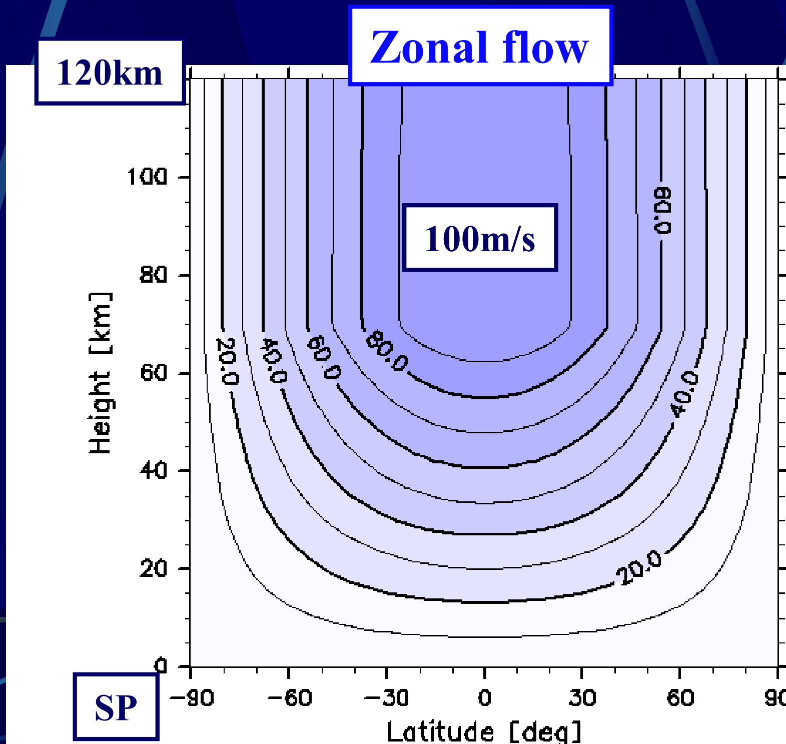
- Infrared radiative process
  - ✓ Simplified by <u>Newtonian cooling</u>: $dT/dt = -\kappa\,(T - T_{ref}(z))$

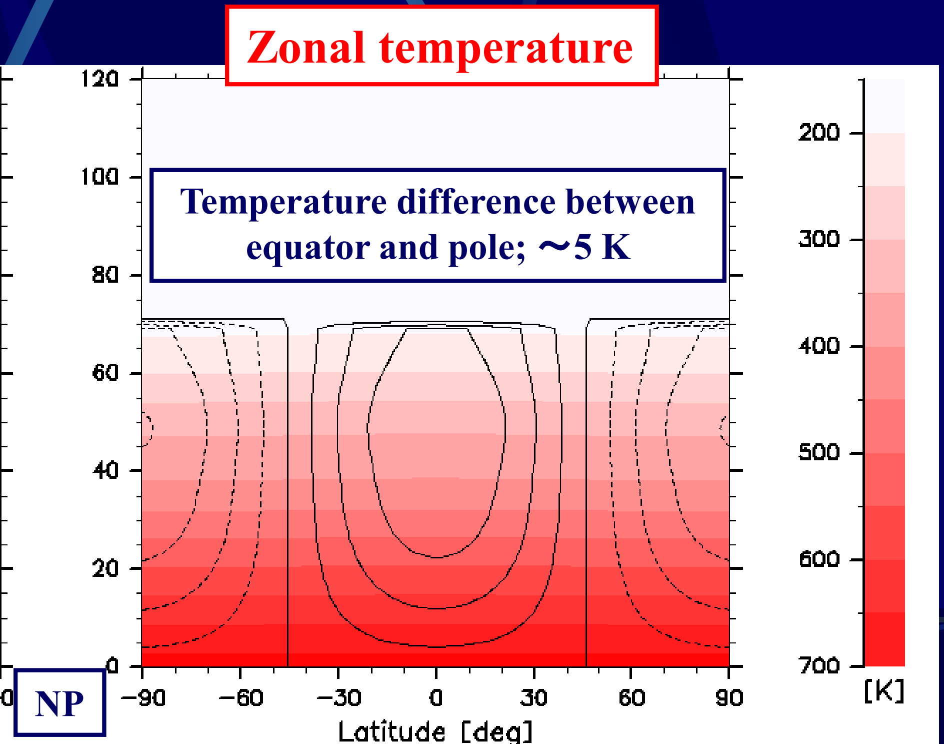
    κ: based on Crisp (1986)

    $T_{ref}(z)$: horizontally uniform field

- Initial condition: Super-rotation
  - ✓ Zonal flow increases with height linearly from ground to 70 km. 100 m/s above 70 km (const.).
  - ✓ Meridional distribution: solid-body rotation.
  - ✓ Temperature field is in balance with zonal flow field (gradient wind balance).
- Static stability: $\Gamma(z) = dT/dz + g/Cp$
  - ✓ Mimic observed realistic static stability.

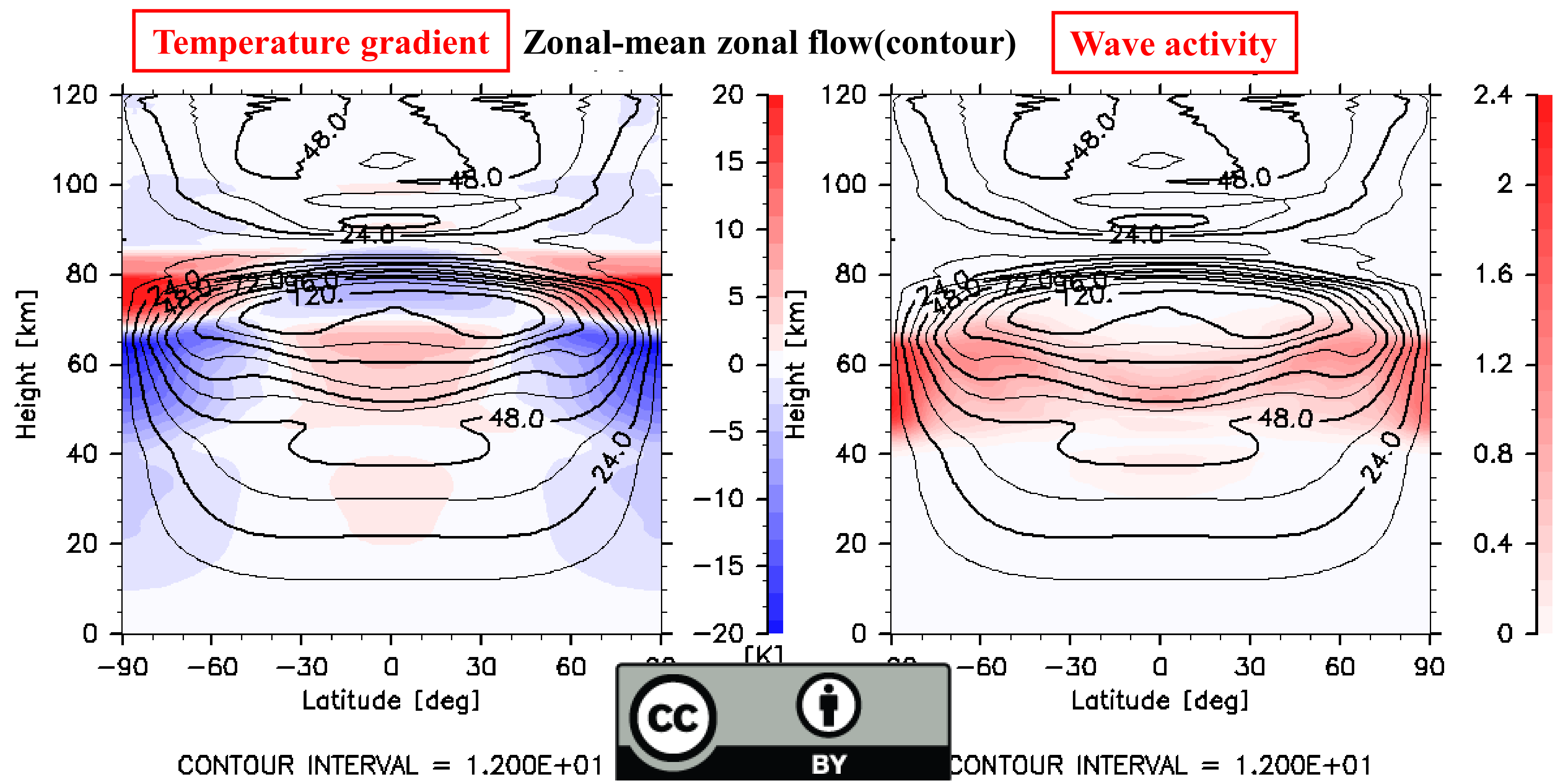






3. Results (T63L120 run) see Sugimoto et al. (GRL2014)

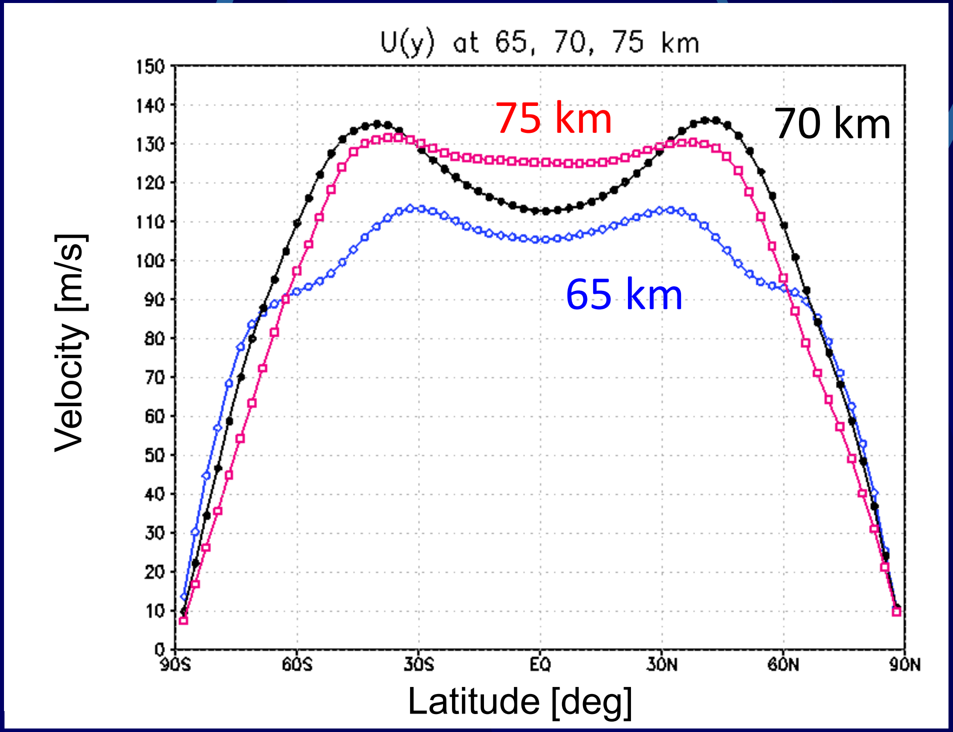
- Realistic super-rotation is reproduced (more than 10 Earth years).
  - ✓ Acceleration in equatorial region by thermal tides (120m/s).
  - ✓ Temperature difference between equator and pole; more than 25 K.



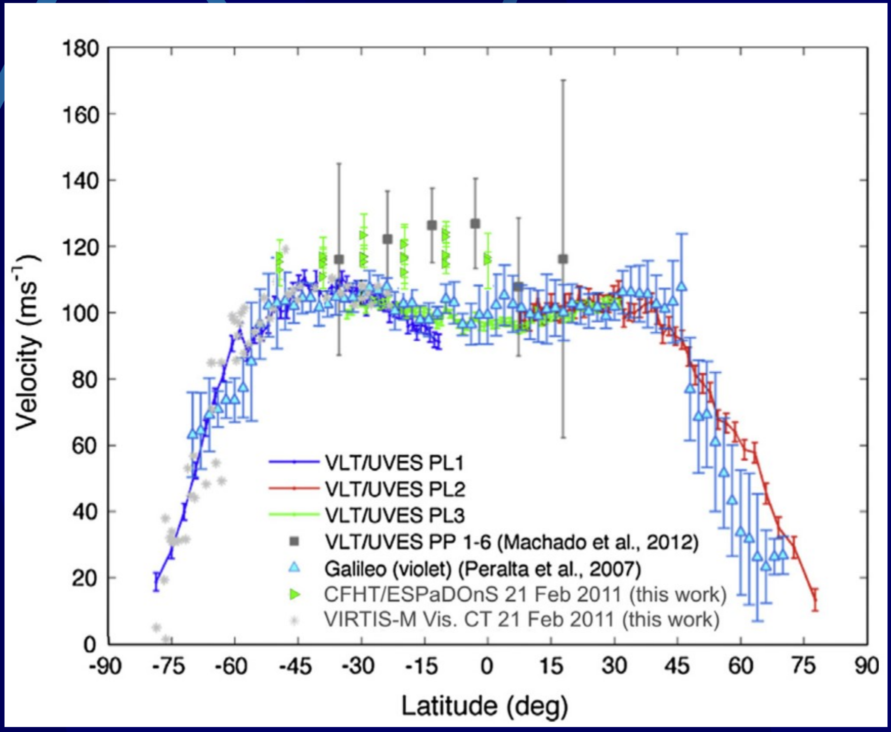
Super-rotation near the cloud

- ✓ Constant velocity at equatorial region with weakly mid-latitude jets .
- ✓ Close agreement with observations.

AFES results



Observations: Doppler measurements



Machado et al. (2014)

3. Results (T63L120 run) see Sugimoto et al. (GRL2014)

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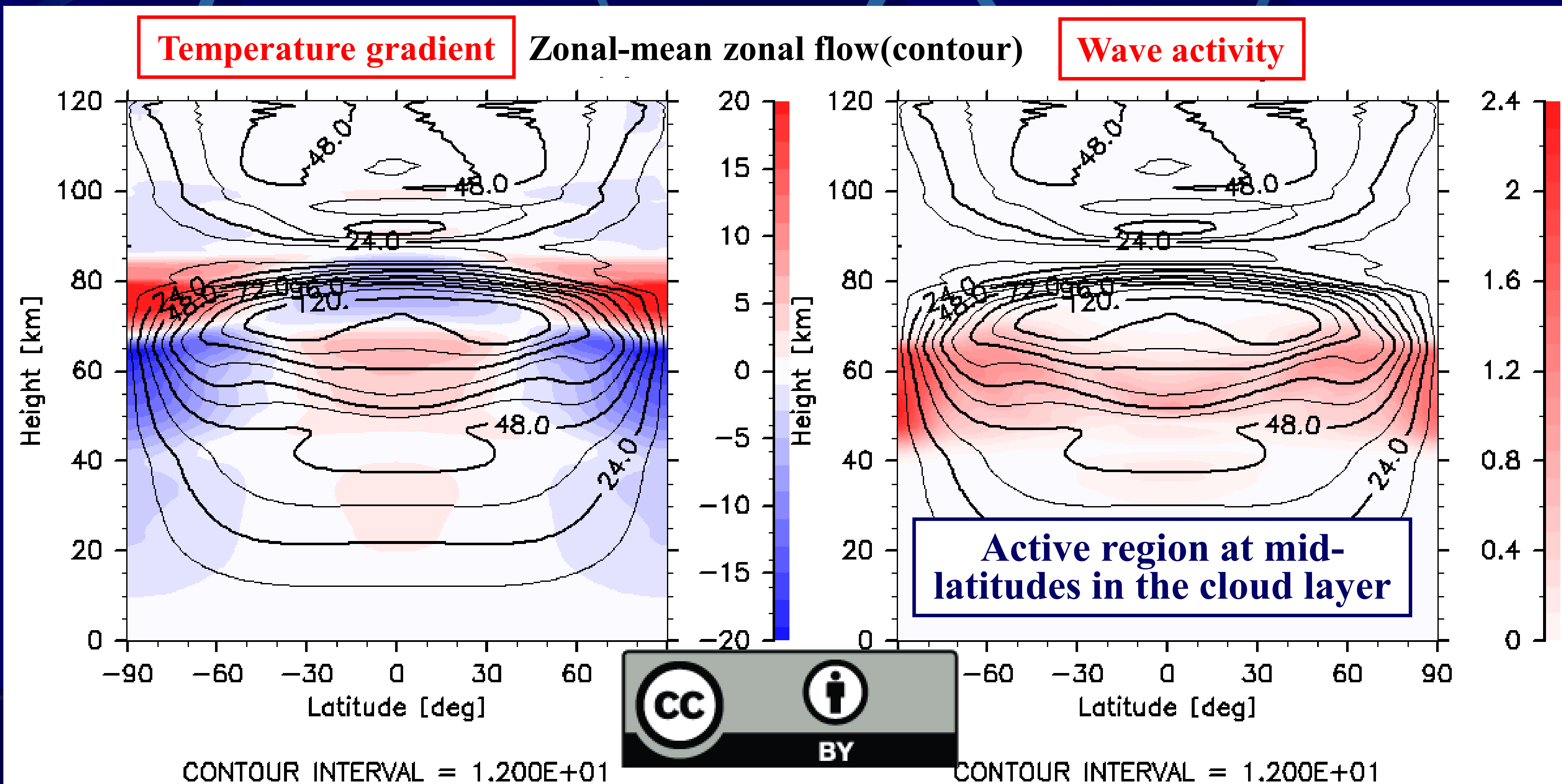
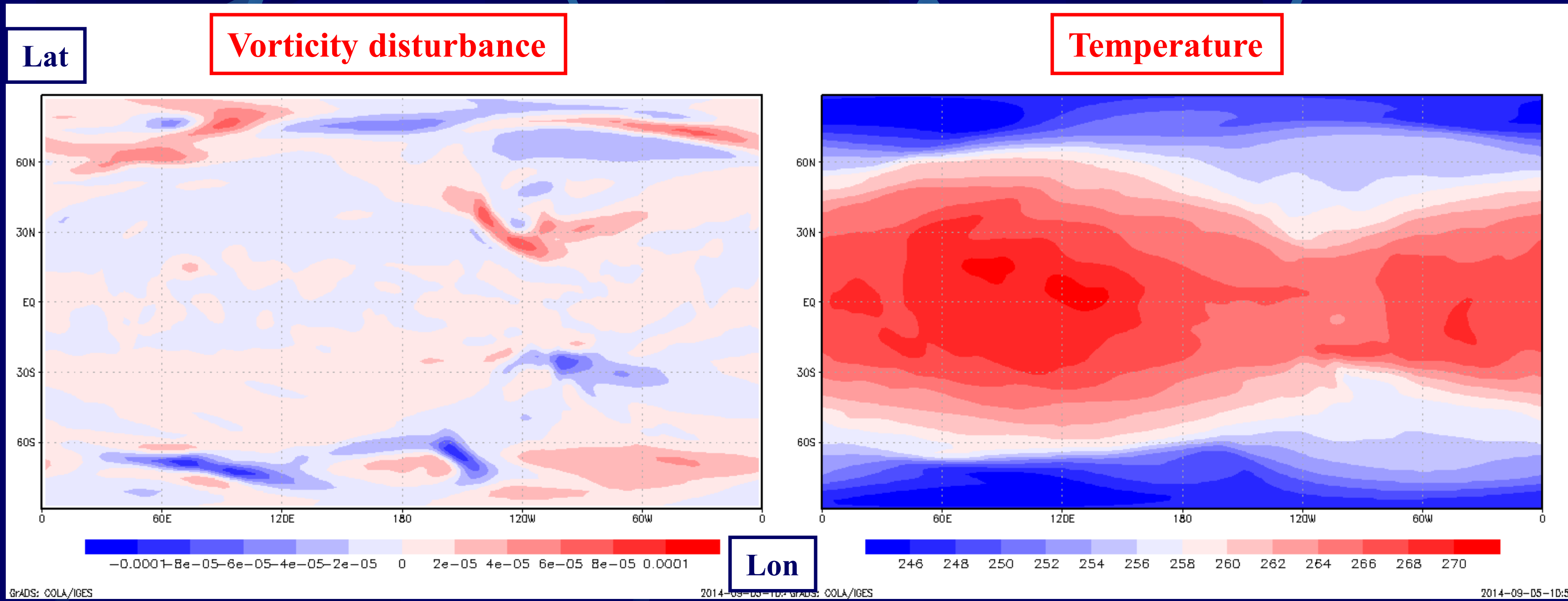


Life cycle of baroclinic waves (at mid-latitudes, 60 km)

- ✓ Large temperature gradient maintains baroclinic basic state continuously.
- ✓ Baroclinic waves appear intermittently (zonal wave number 1).
- ✓ Barotropic waves are also significant in the polar region.

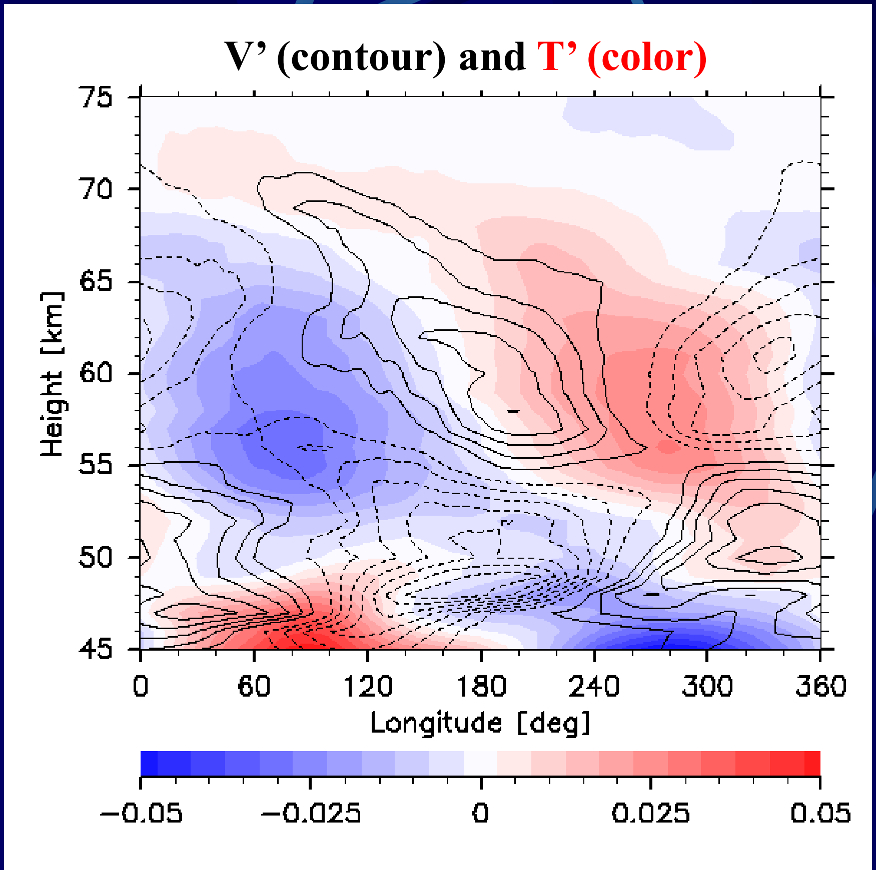


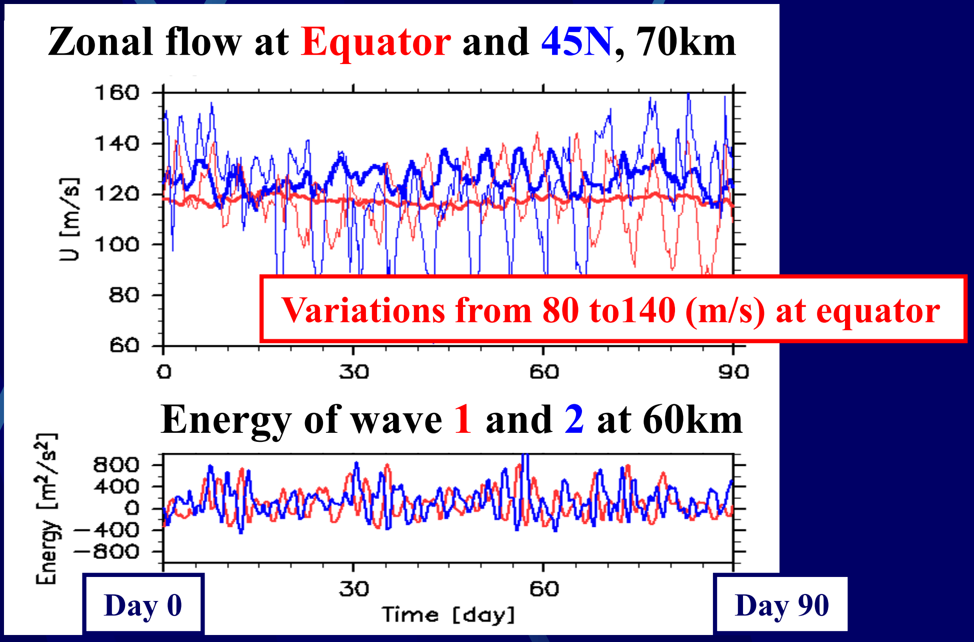
Rotation

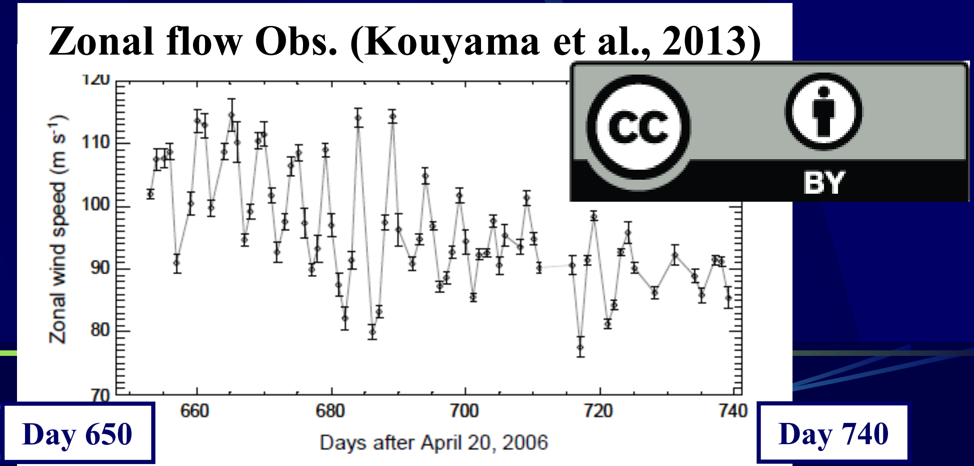
(Each interval is 6 hour)

Vertical structure and time variations of zonal flow.

- ✓ Typical vertical structure of baroclinic waves.
- ✓ Baroclinic waves cause spatio-temporal variations of super-rotation.



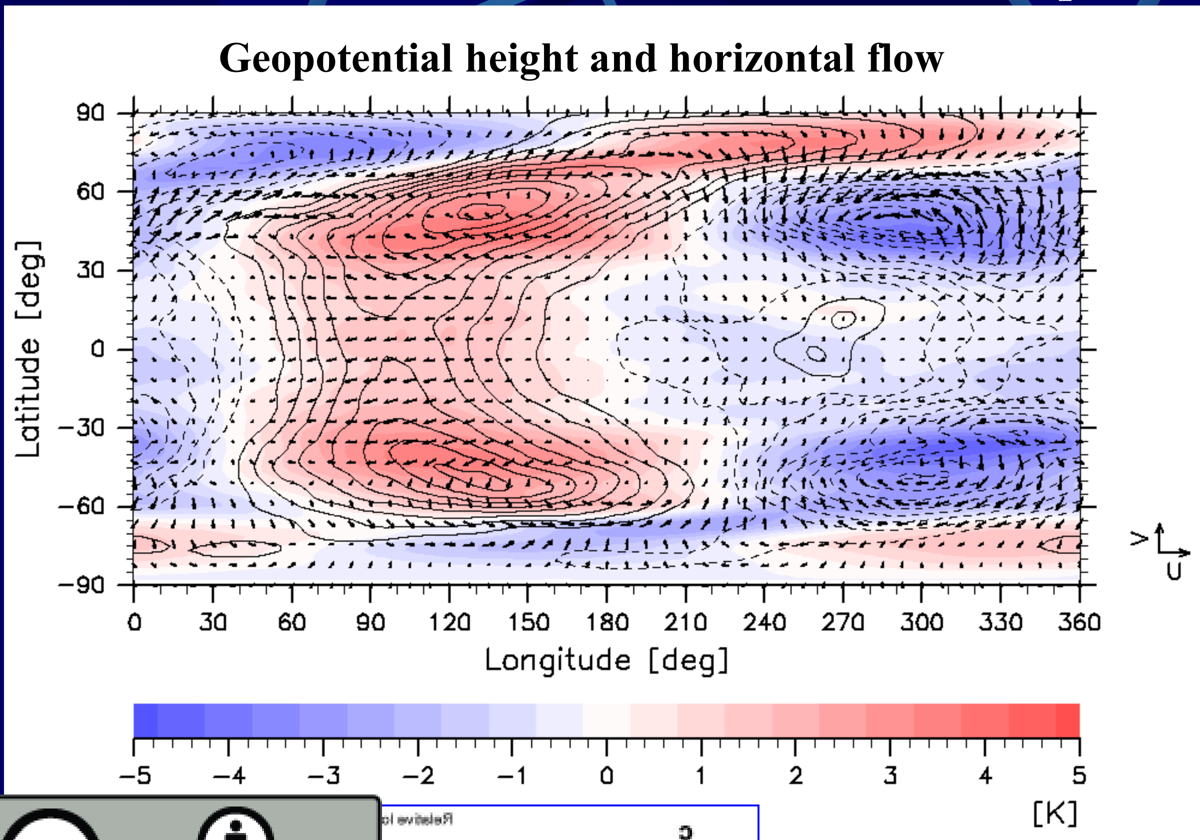


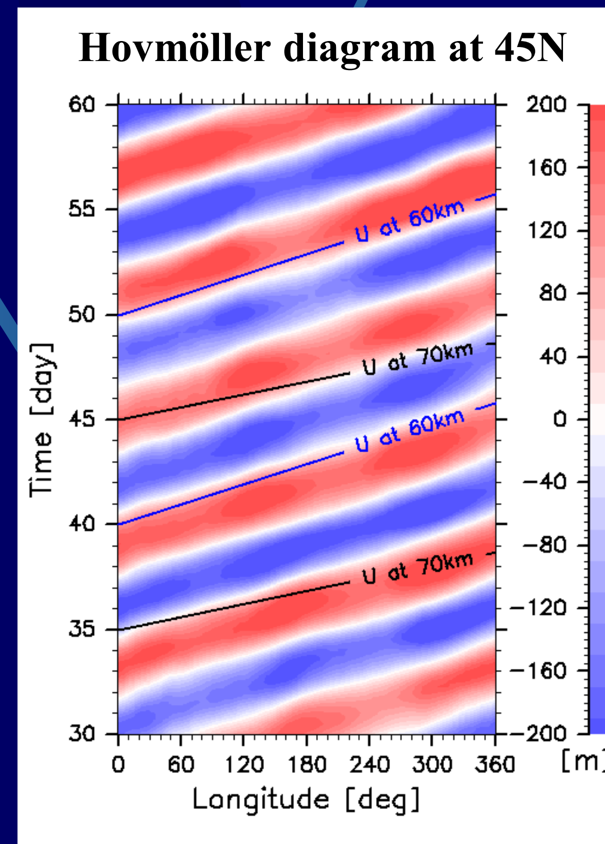


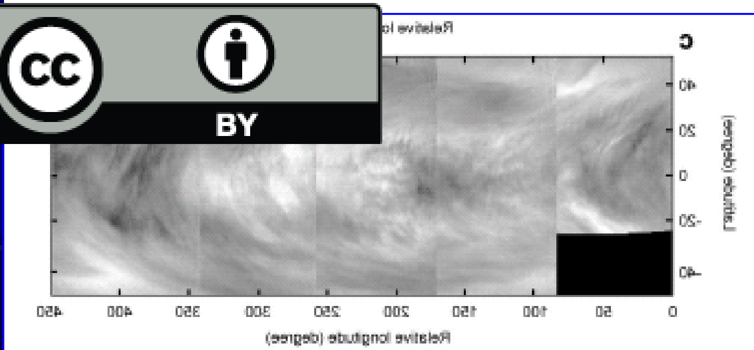
Time variations are qualitatively similar to observational study

Rossby-type waves at the cloud top level (70km).

- ✓ Propagating against zonal-mean zonal flow (periods of 5.8 days).
- ✓ Z’ ~200 m, V’ ~20 m s^{-1} at 70 km. In phase of T’ ~3 K at 60 km.





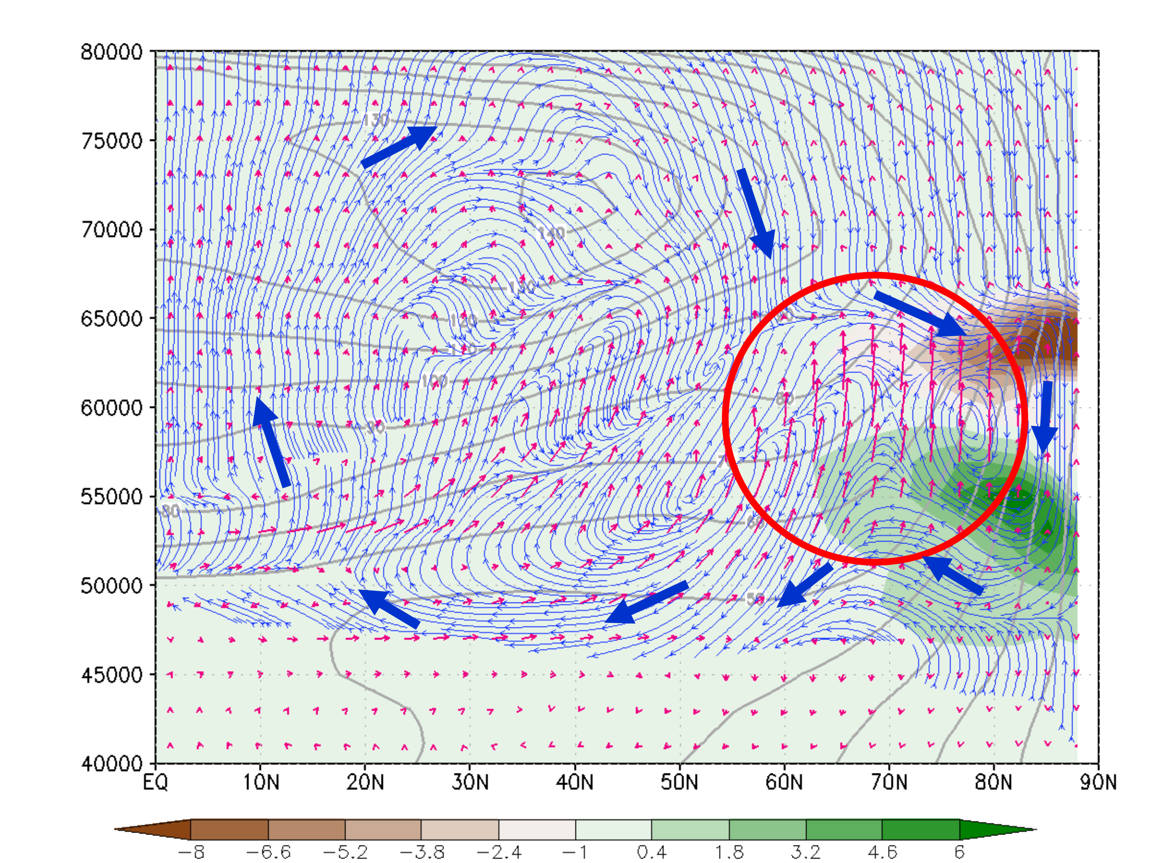


Rossby-type waves are generated from and/or a part of baroclinic waves

Reminiscent of Y-shape structure

Residual mean meridional circulation (RMMC) on NH

- ✓ Baroclinic waves make a local meridional circulation
- ✓ Acceleration/deceleration with north/south heat transport

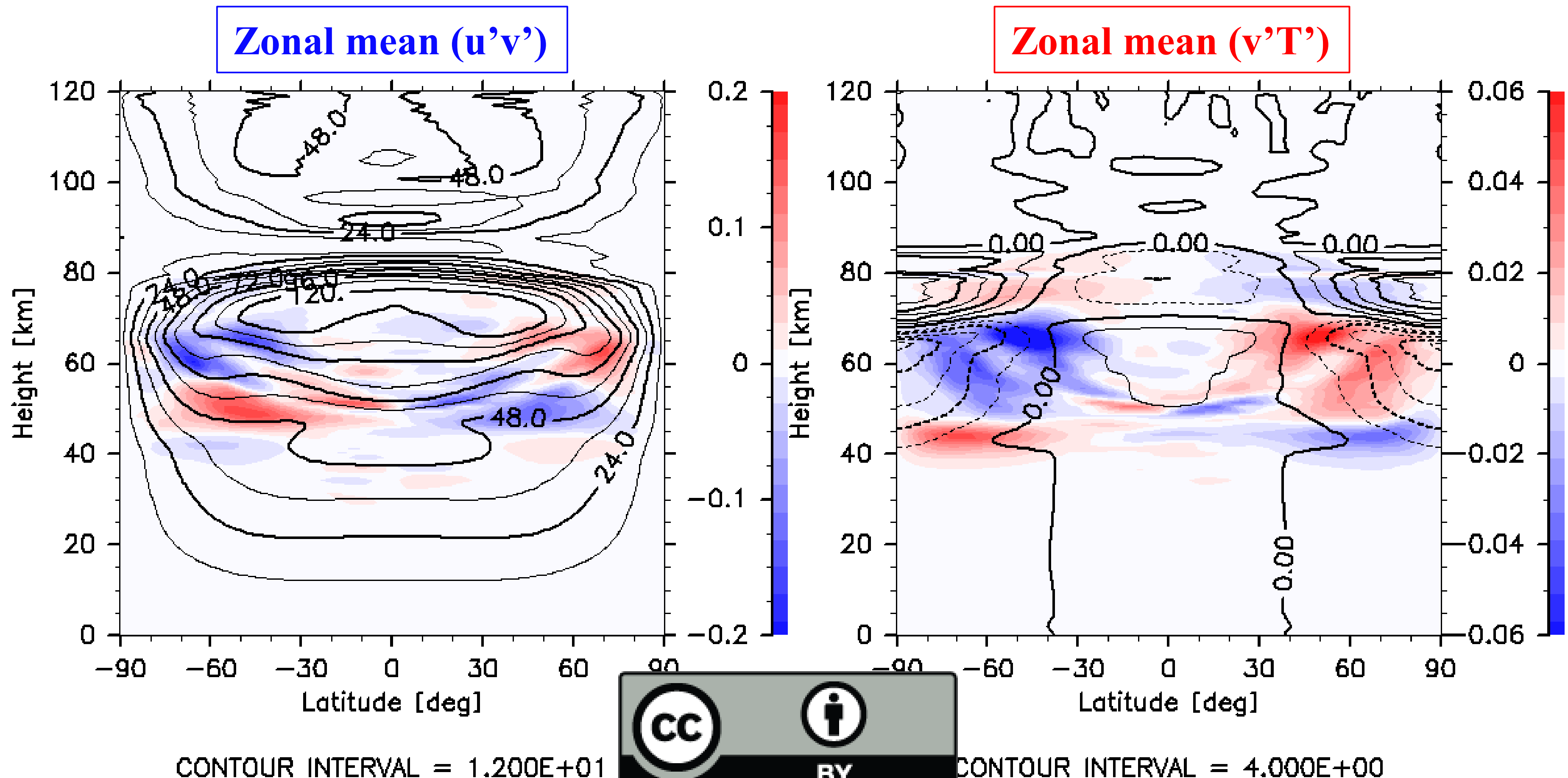


Red Vector: EP flux
Blue contours: RMMC (V*, W*)
Color tones: dU/dt [m/s/day]
Grey contours: Ubar

Baroclinic waves might contribute to material transport (cloud formation) in the polar region

Momentum and heat flux averaged over 90 Earth days.

- ✓ Accelerate where unstable modes grow using available potential energy.
- ✓ Typical heat transports (from equator to pole) of baroclinic instability.



Baroclinic waves contribute to momentum and heat transport significantly

Energy Spectra (T159L120 run)

$$E_n = \frac{1}{4}\frac{a^2}{n(n+1)}\sum_{m=-n}^{n}\left(|\tilde{\zeta}_m^n|^2 + |\tilde{D}_m^n|^2\right)$$

- ✓ Rotational & divergent component

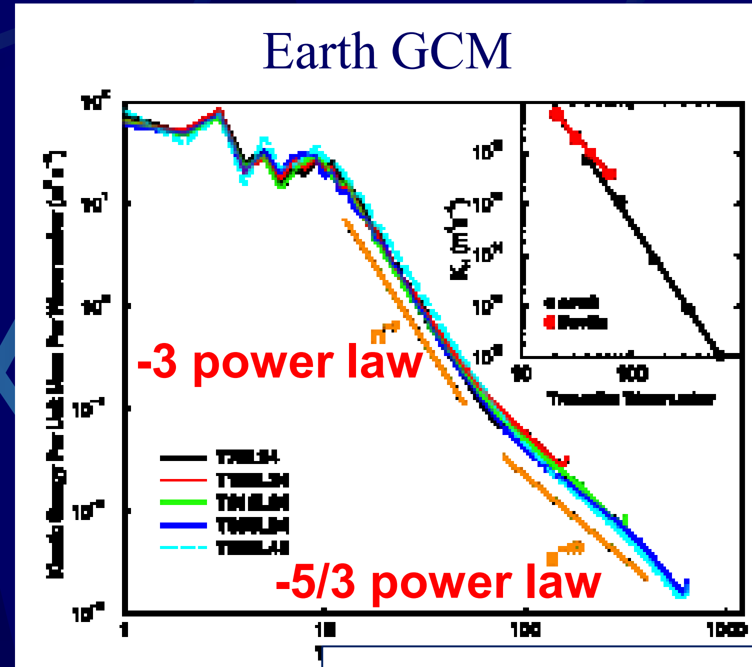
$$E_n^{\mathrm{R}} \equiv \frac{1}{4}\frac{a^2}{n(n+1)}\sum_{m=-n}^{n}|\tilde{\zeta}_m^n|^2$$

balanced flow; Rossby waves

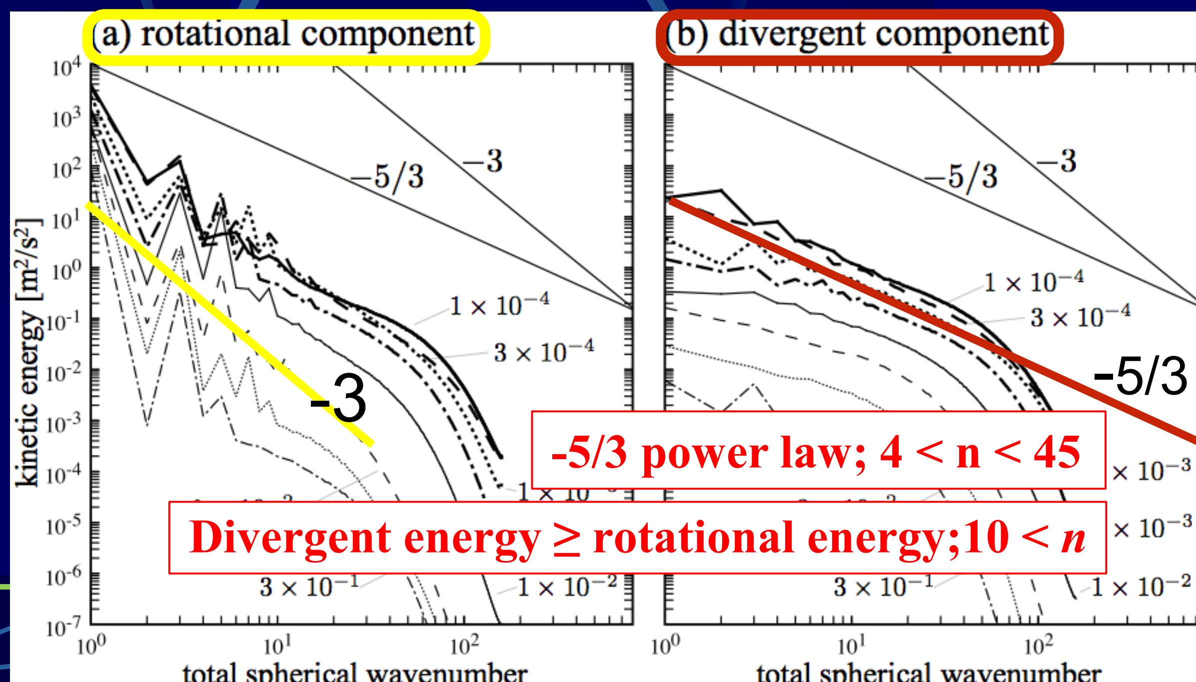
$$E_n^{\mathrm{D}} \equiv \frac{1}{4}\frac{a^2}{n(n+1)}\sum_{m=-n}^{n}|\tilde{D}_m^n|^2$$

unbalanced flow;
gravity waves

Gravity waves might be more important than those on Earth



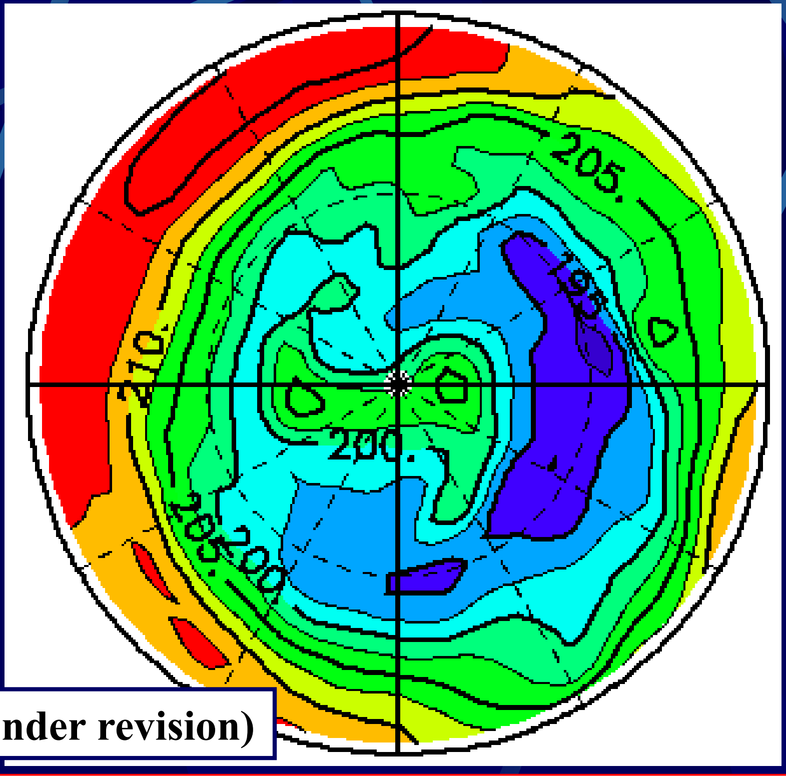
Takahashi et al.(2006)



Kashimura et al. (in preparation)

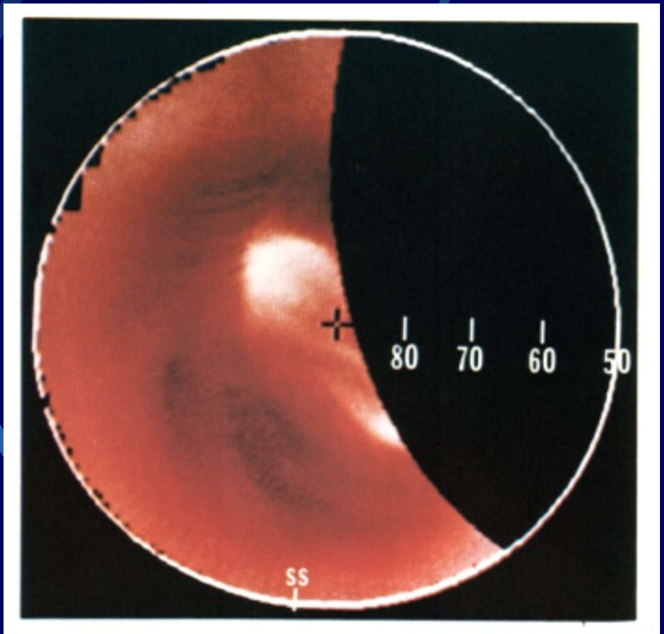
Polar vortex & Cold collar (T42L60 run)

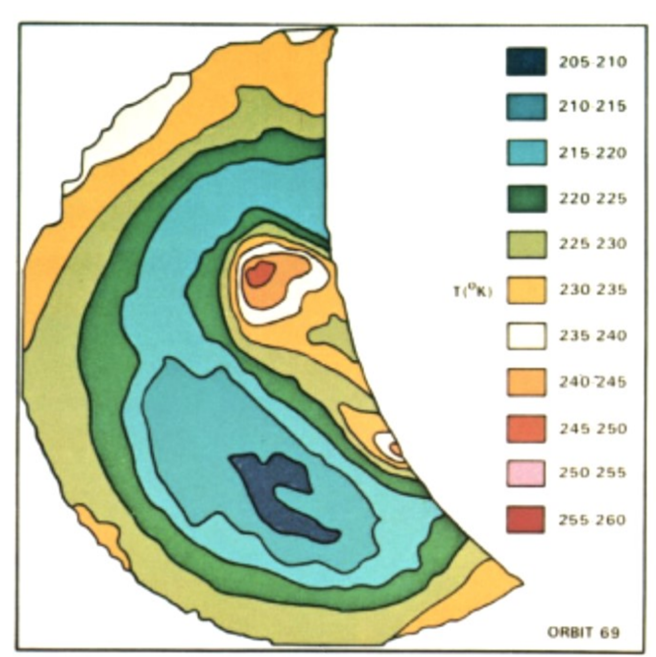
- ✓ "S-shaped" polar vortex with cold latitudinal band "cold collar"



Ando et al. (under revision)

Taylor et al.(1980)





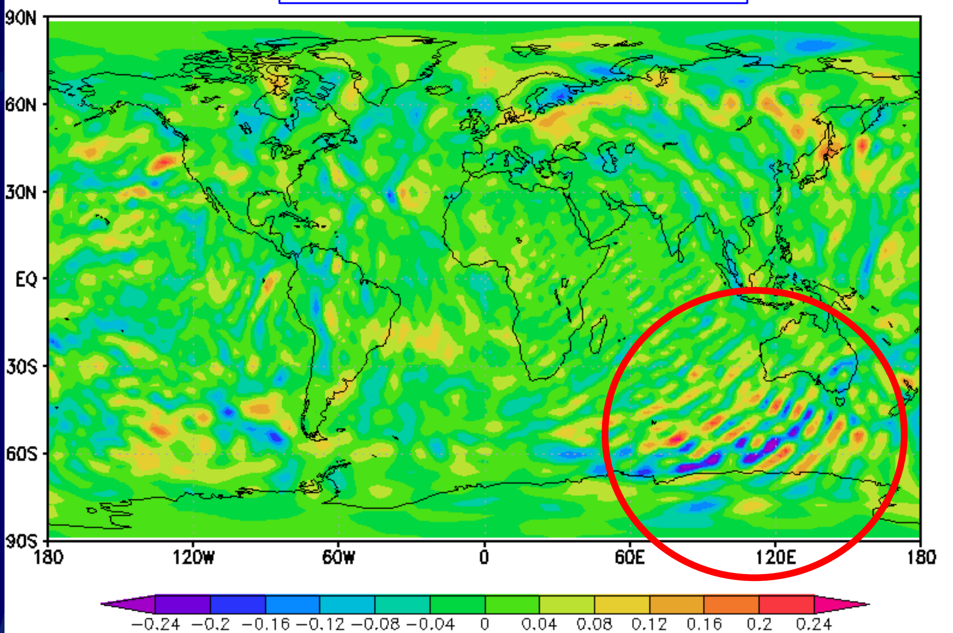
Puzzling structure is well reproduced in the Venus GCM for the first time

see Poster, **P14**, Oct 01 (Today), 17:45-19:30

Further topics

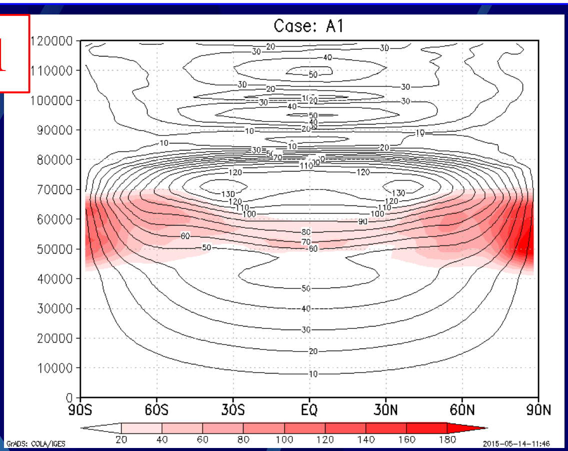
- ✓ Gravity waves observed at 75 km
- ✓ Parameter sweep experiments (solar heating)

Vertical velocity (w')

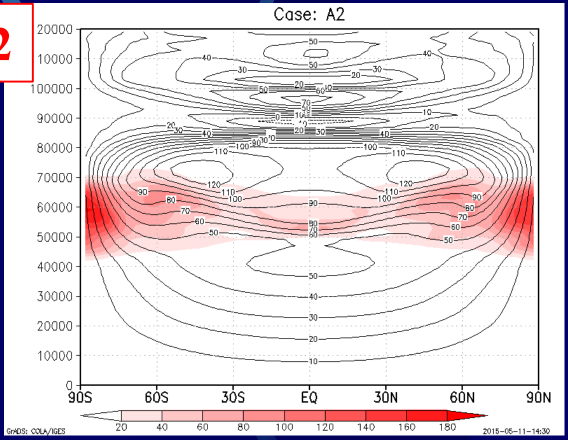


Zonal flow & wave activity

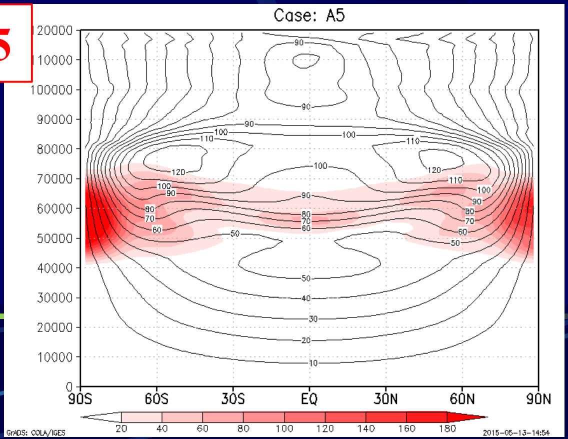
A1



A2



A5



	A1	A2	A5
Zonal solar heating	1.0	1.0	1.0
Diurnal Solar heating	1.0	0.5	0.0

(Analysis by Shimizu)

4. Summary

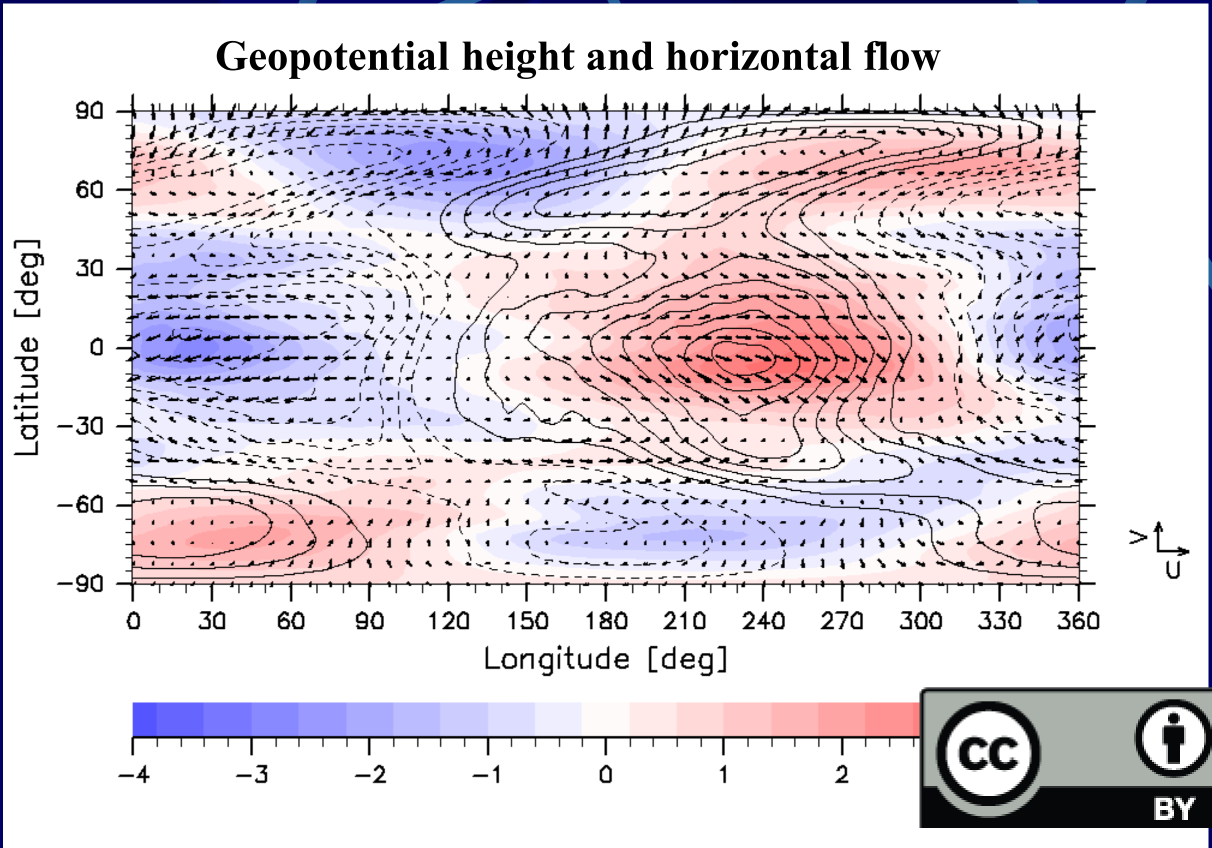
- **AFES (AGCM For ES) simulation for Venus.**
  - ✓ High resolution GCM optimized for parallel vector super computer.
  - ✓ Start from idealized super-roation with realistic solar heating
- Realistic super-rotation is reproduced and maintained (>10 years).
  - ✓ Super-rotation with a uniformly equatorial flow of 120 m/s at 70 km.
  - ✓ The latitudinal temperature difference is more than 25 K at 60 km.

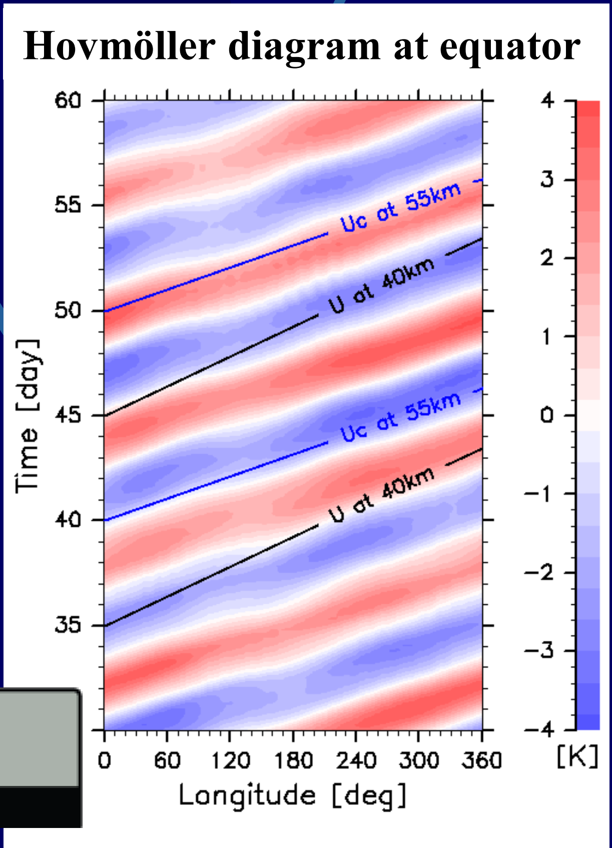
  ⇒ Life cycle of baroclinic waves appears using available potential energy derived from above baroclinic basic state.
- *Two* notable waves appear in good agreement with observations.
  - ✓ Rossby-type waves (~ 5.8 days) at the cloud top (~70 km) at mid-latitudes.
  - ✓ *Kelvin-type waves (~ 6.2 days) at the cloud bottom (~50 km) at low-latitudes.*

  ⇒ Baroclinic waves and generated neutral waves transport momentum and heat significantly and keep the structure of super-rotation.
- Energy spectra; gravity waves might be more important than Earth.
- Polar Vortex and Cold collar; well reproduced in our Venus GCM.

Kelvin-type waves at the cloud bottom level (50km)

- ✓ Propagating faster than zonal-mean zonal flow (periods of 6.2 days)
- ✓ Z' ~10 m, V' ~5 m s^{-1} at 40 km. In phase of T' ~3 K at 50 km.





Overall characteristics of waves are consistent with Hosouchi et al. (2012)

Similar to unstable modes developed by shear instability in spherical shallow water model (Iga and Matsuda, 2005)