Simulation of Venus atmosphere

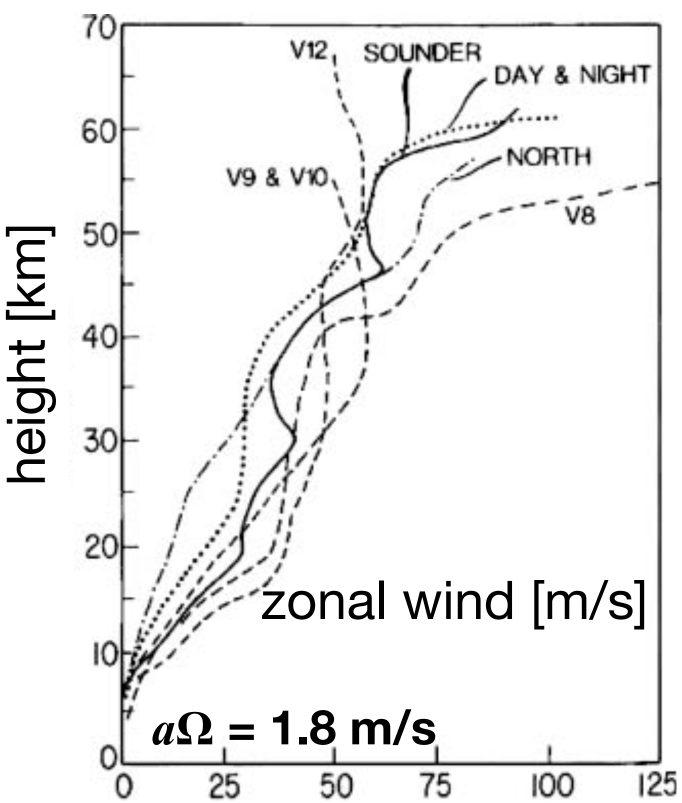
Results of a simple Venus GCM

Hiroki Kashimura (Kobe Univ./CPS)
collaborated with
N. Sugimoto, M. Takagi, H. Ando, Y. Matsuda,
W. Ohfuchi, T. Enomoto, K. Nakajima, Y. O. Takahashi, and Y.-Y. Hayashi

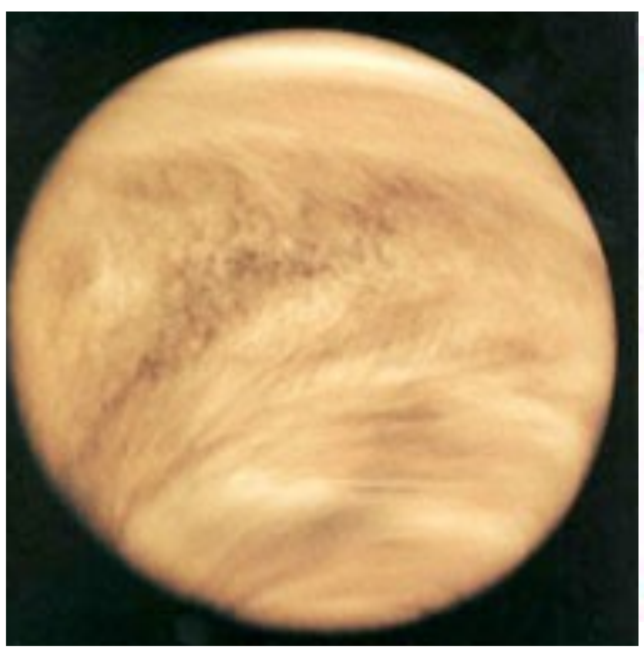
Acknowledgment: This study is conducted under the joint research project of the Earth Simulator Center with title "Simulations of Atmospheric General Circulations of Earth-like Planets by AFES."

Venus Atmosphere

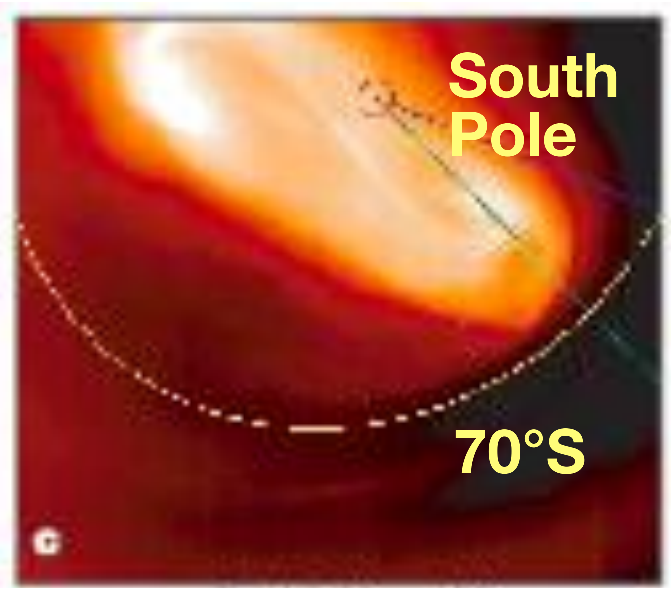
- Many notable phenomena have been observed in Venus Atmosphere. For example,
  - **Superrotation**: one of the biggest mystery of planetary atmospheres.
    - The atmosphere is rotating 60 times faster than the solid planet.
  - **Y-shaped structure** of a planetary-scale cloud pattern observed by ultra-violet.
  - **S-shaped polar vortex and cold collar** observed by infra-red.
  - **Planetary-scale streak structure**, recently revealed by night-side image of IR2 camera onboard Venus Climate Orbiter/Akatsuki.



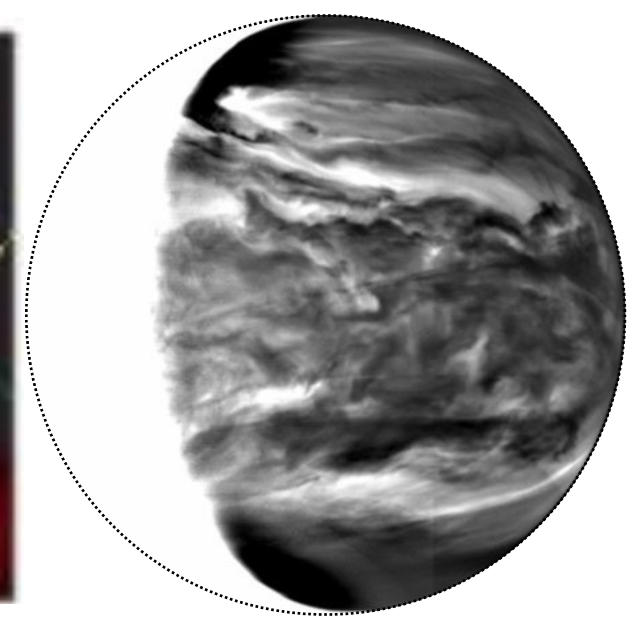
Schubert (1983)



Observed by Mariner 10 / NASA



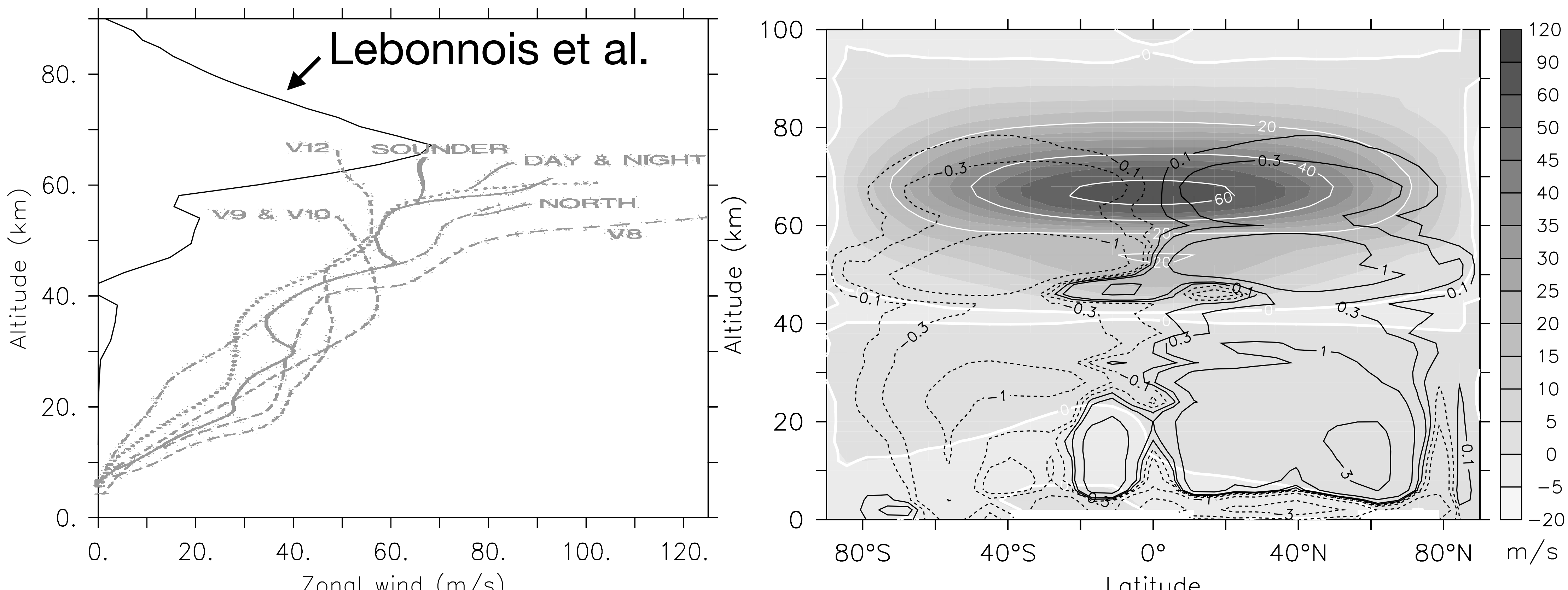
Piccioni et al. (2007)



IR2 on Akatsuki / JAXA

Simulations of Venus Atmosphere

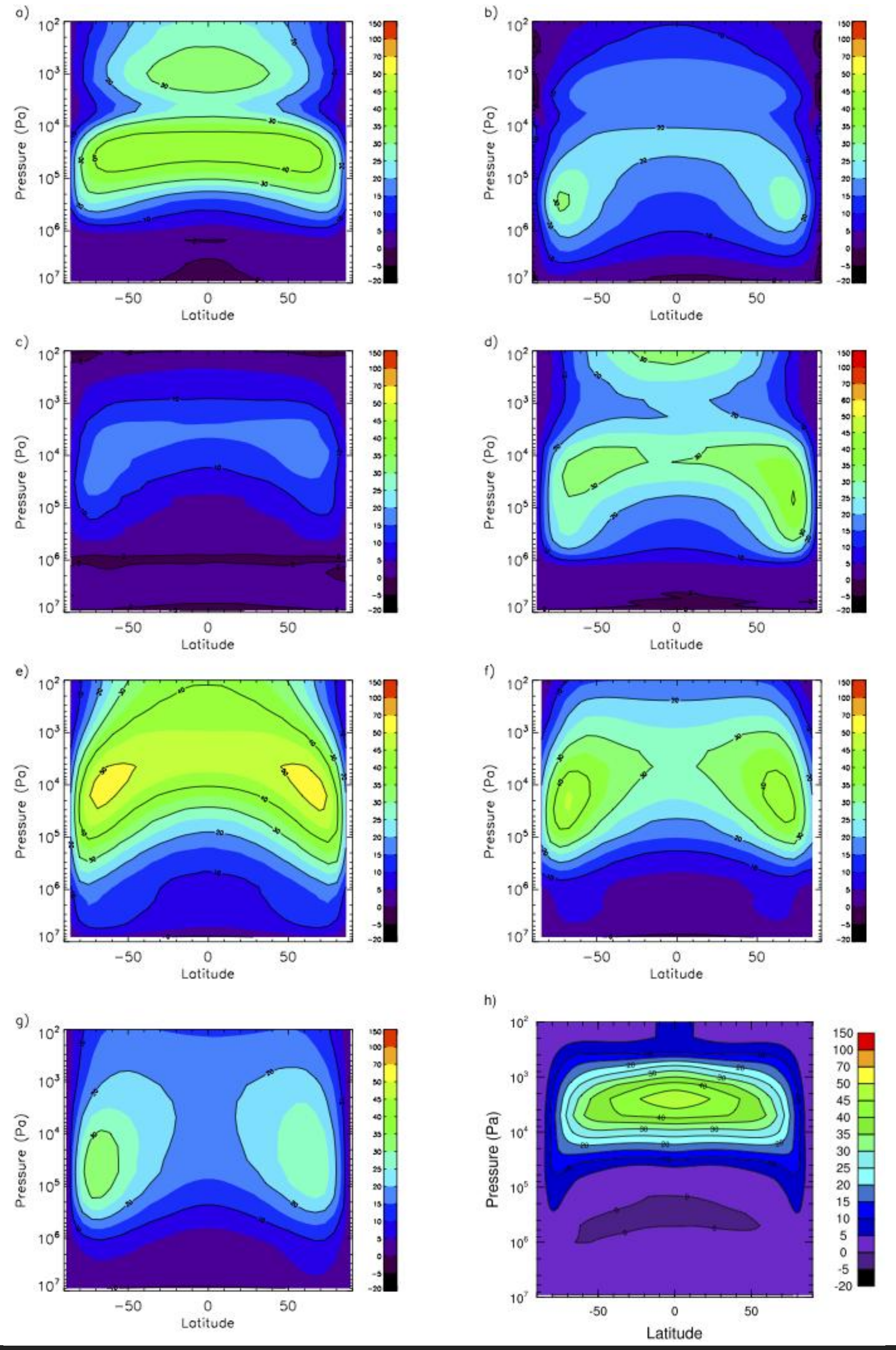
- **Many studies have tried to simulate the generation of the superrotation from a motionless initial state.**
  - Young and Pollack (1970), Del Genie and Zhou (1996)
  - Yamamoto & Takahashi (2003), Hollingsworth et al. (2007), Lee et al. (2007)
    - obtained a superrotation state but with unrealistic strong heating.
  - Lebonnois et al. (2010, 2015, 2016)
    - obtained a superrotation with sophisticated radiative code, but the zonal wind under the cloud layer was very slow.



Lebonnois et al. (2010)

Simulations of Venus Atmosphere

- **And, many Venus GCM studies used low-resolution models.**
  - A comparative study of Venus GCMs were conducted with low-resolution (~ T21) by Lebonnois et al. (2013)
    - The inter-model difference would be due to the difference in horizontal eddy diffusion.



- **Simulations should be performed in higher-resolution.**
  - Much more computational costs are required.

Our strategy

- We have attempted to simulate a superrotational state of Venus atmosphere with:
  - high-resolution up to T319 and L240.
  - an idealized superrotational initial state.
  - realistic strength of solar heating and static stability.
    - though the radiation process is a simple Newtonian cooling.

- To perform high-resolution simulation as above, we developed a simplified Venus GCM based on AFES.
  - AFES
    - stands for the Atmospheric GCM For the Earth Simulator.
    - was developed by Ohfuchi et al. (2004) and Enomoto et al. (2008).
    - achieves a very high computational efficiency in a vector-type super computer such as the Earth Simulator.

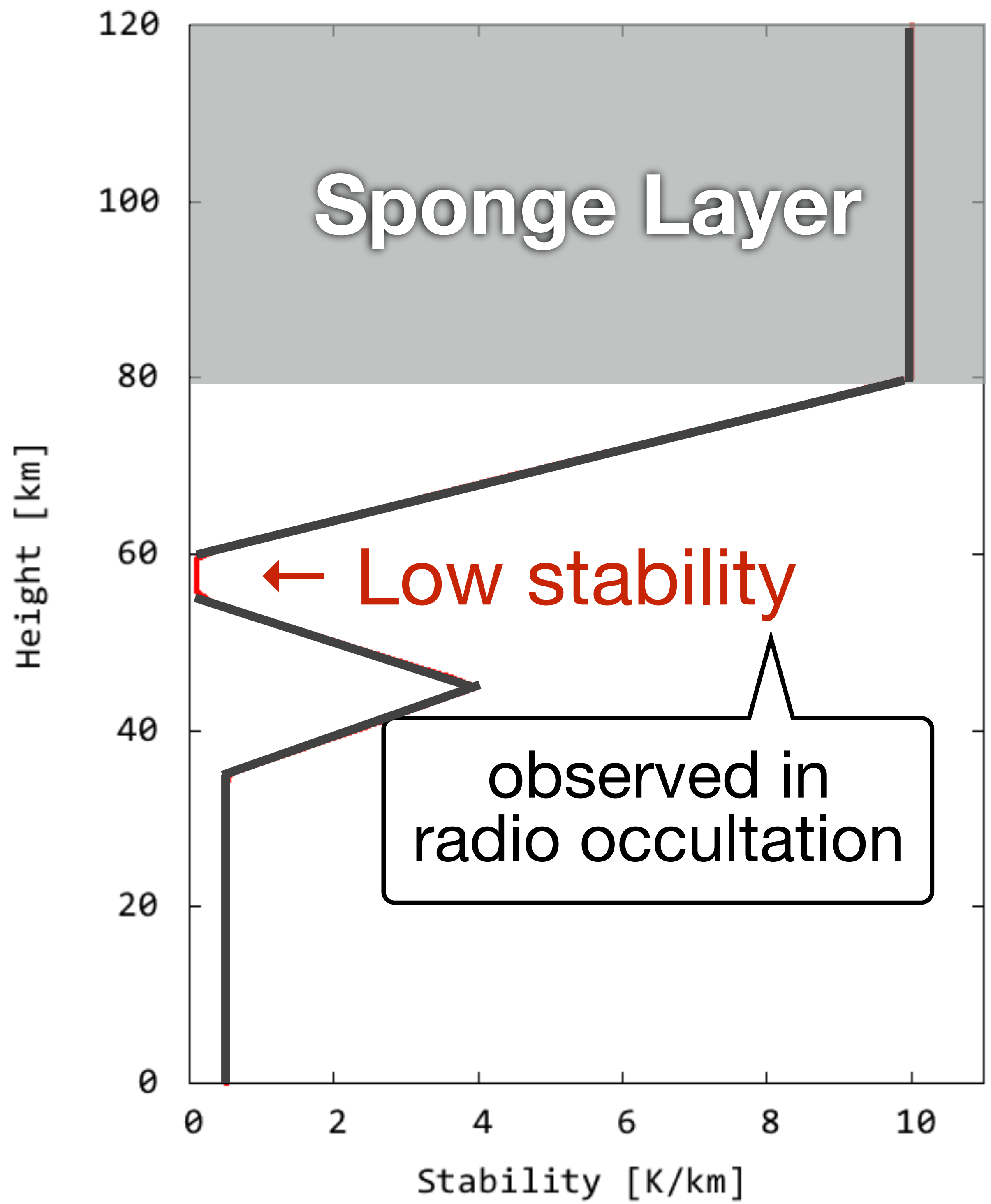
Our simplified Venus GCM

- Resolutions:
  - T42 (~2.8°× 2.8°; 128×64 grids) - L60 (Δz~2km)
  - T63 (~1.9°× 1.9°; 192×96 grids) - L120 (Δz~1km)
  - T159 (~0.75°× 0.75°; 480×240 grids) - L120 (Δz~1km)
  - T319 (~0.375°× 0.375°; 960×480 grids) - L240 (Δz~0.5km)
- Simplified Radiative forcing
  - Newtonian cooling and solar heating w/ or w/o a diurnal variation.
- No topography
- No moist processes
- No convective adjustments
- Sponge layers located above 80km
- Biharmonic horizontal diffusion (∇^4) with a damping time of 0.01 Earth days for the highest wave number.
- Vertical eddy diffusion with coefficient of 0.15 m^2s^{-1}

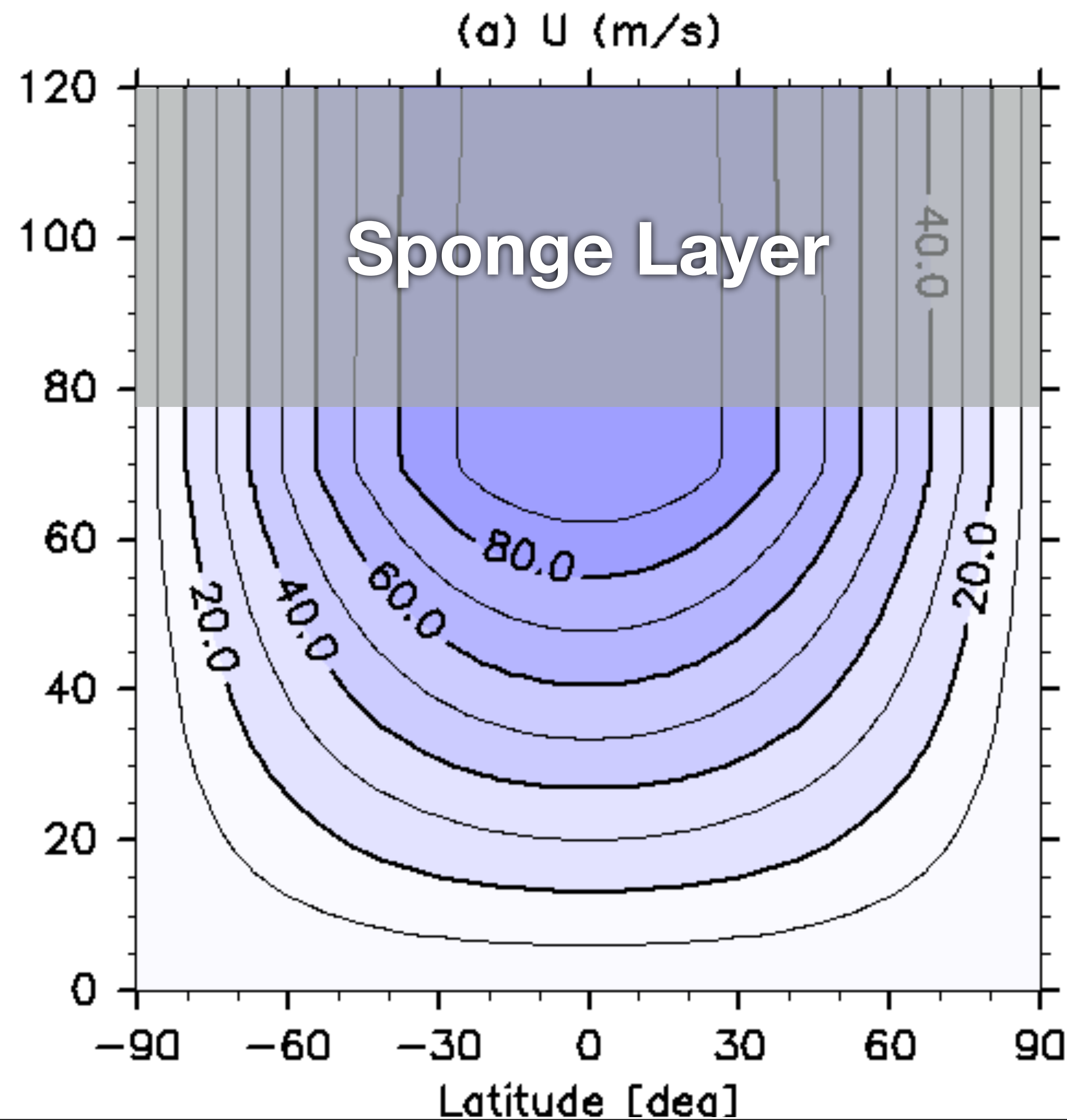
- **Note that planetary-rotation direction is same as the Earth**

Crisp (1986) for N. Coef.; Tomasko et al. (1980) for Solar heating

Stability in the “basic state” for Newtonian cooling (Sugimoto et al. 2013)



Initial state: superrotation



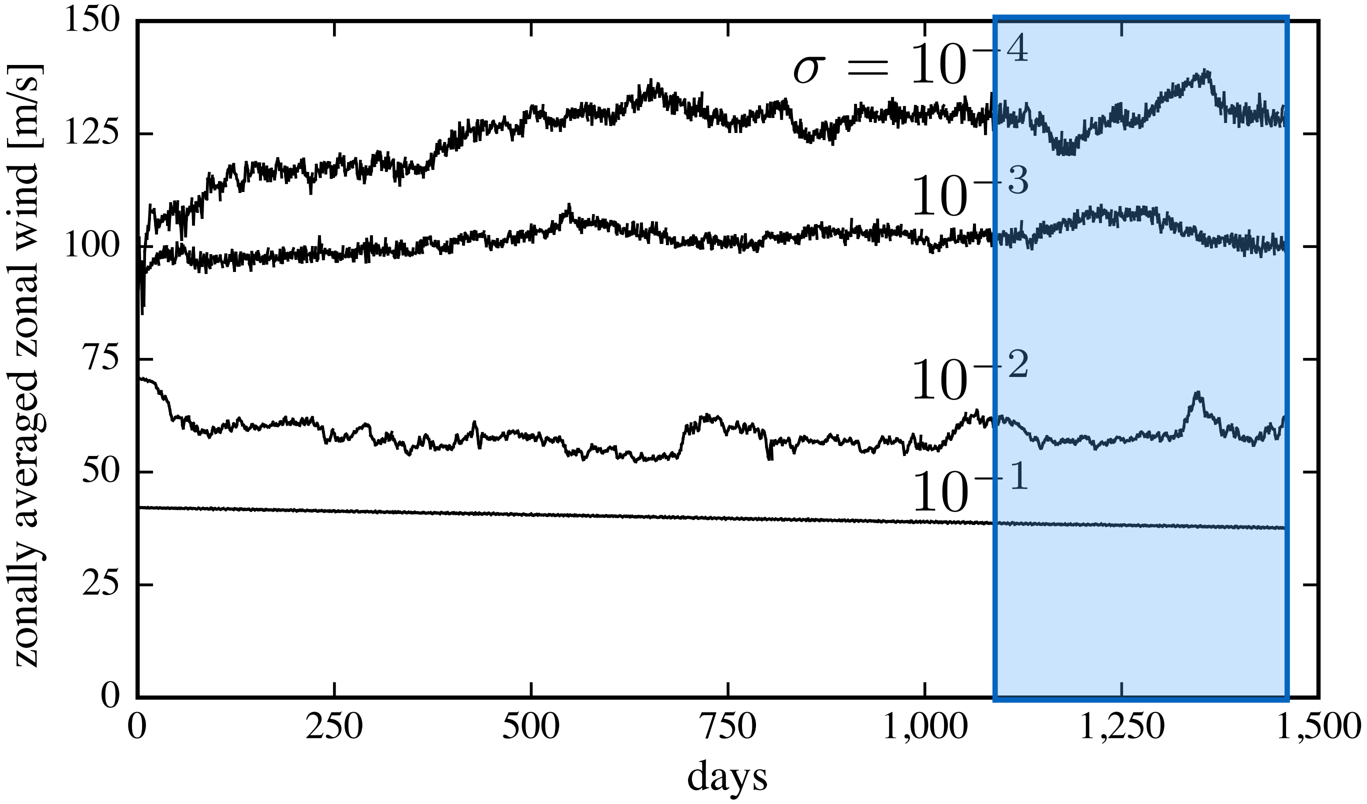
Targets

- Our members have done many works each focusing on specific features such as:
  - Baroclinic instability (Sugimoto et al. 2014, JGR)
  - Neutral waves (Sugimoto et al. 2014, GRL)
  - Thermal tides (Takagi et al. in preparation)
  - Planetary-scale streak structure (Kashimura et al. in preparation)
  - Cold collar/warm polar region (Ando et al. 2016, Nature Com.)
  - Energy spectra (Kashimura et al. in preparation)
  - Polar dipole (S-shape) (Ando et al. under revision)

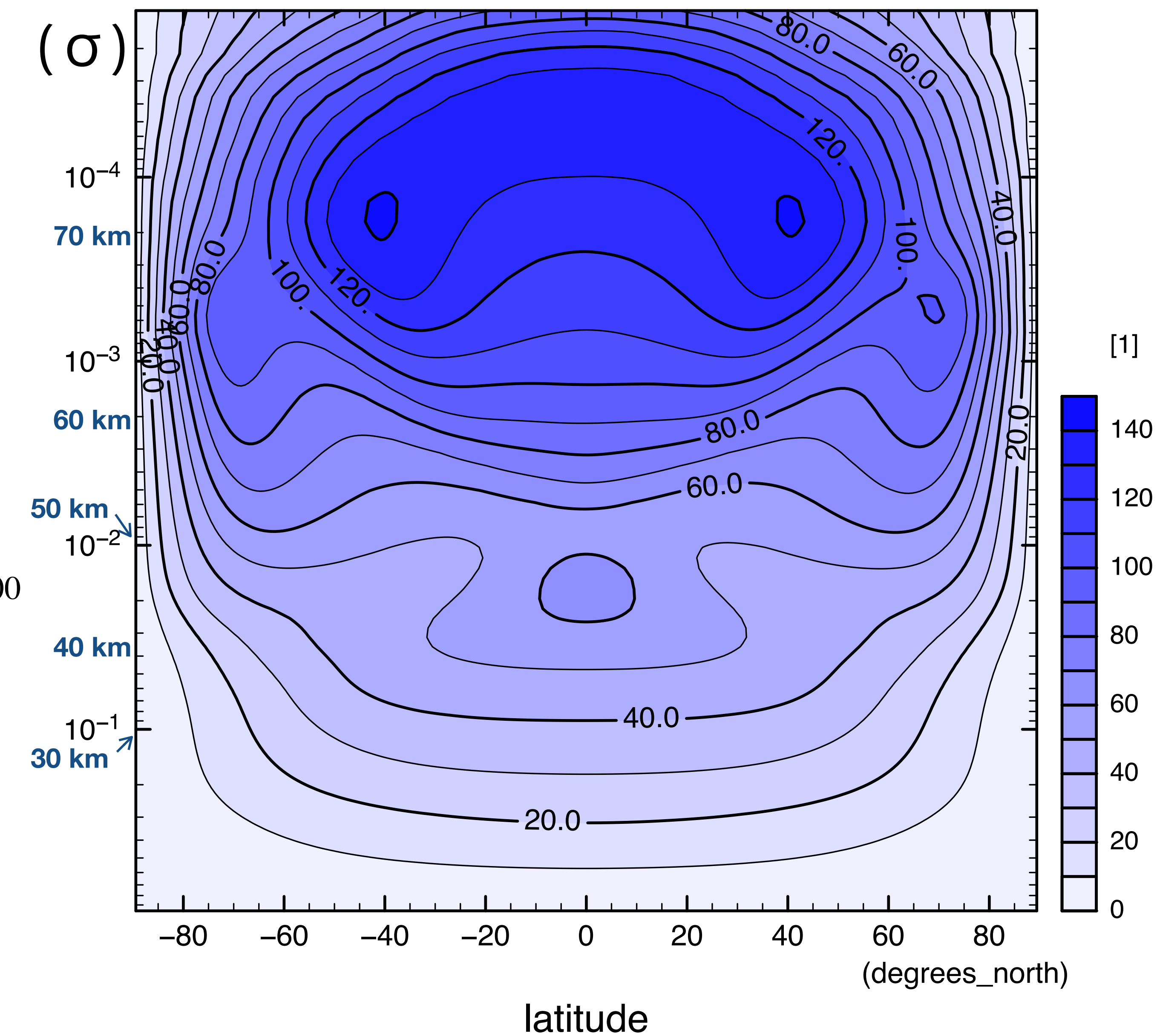
- In this talk, I focus on these 3 topics.

Results | zonal mean zonal wind

Time series of mean zonal wind above the equator

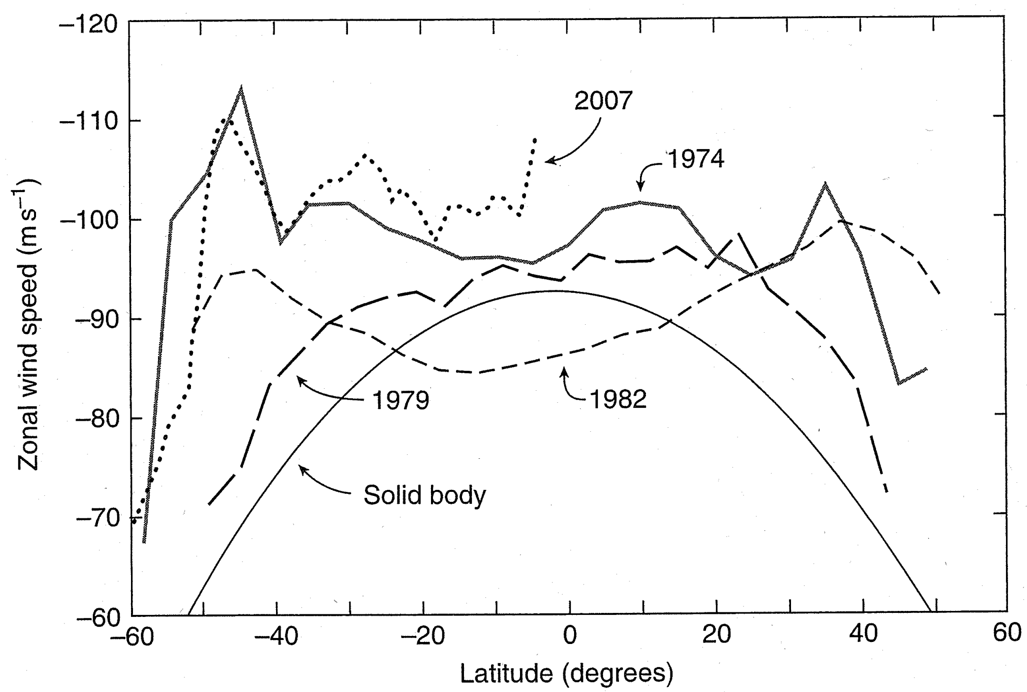


Time mean for last 1 Earth year

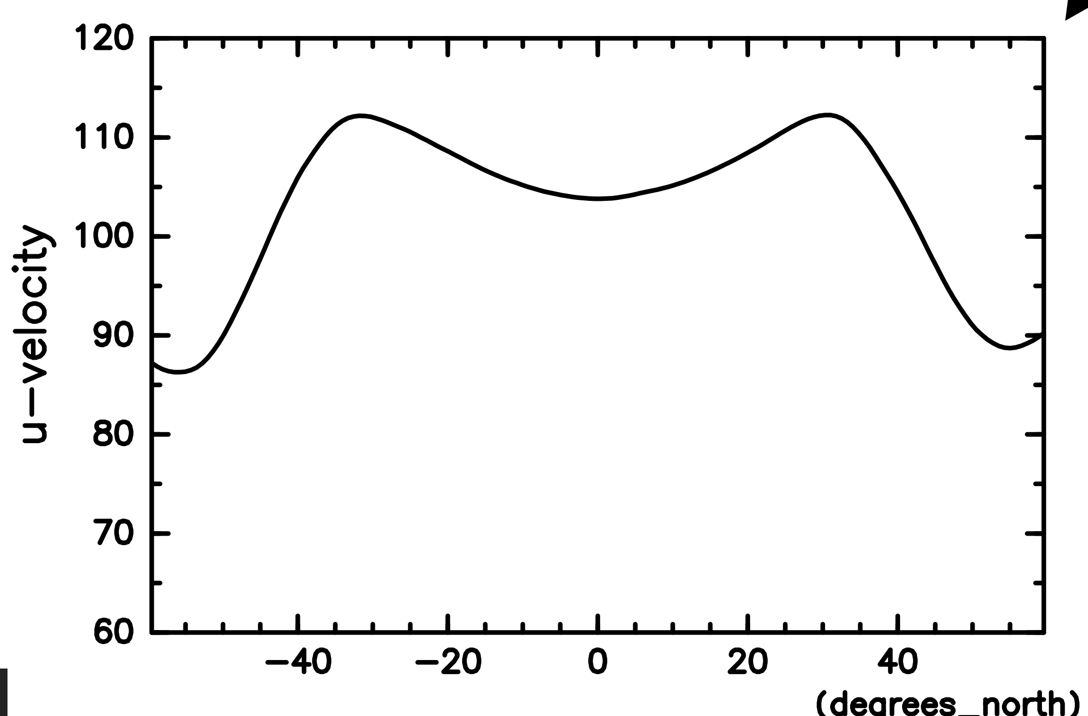


Results | zonal mean zonal wind

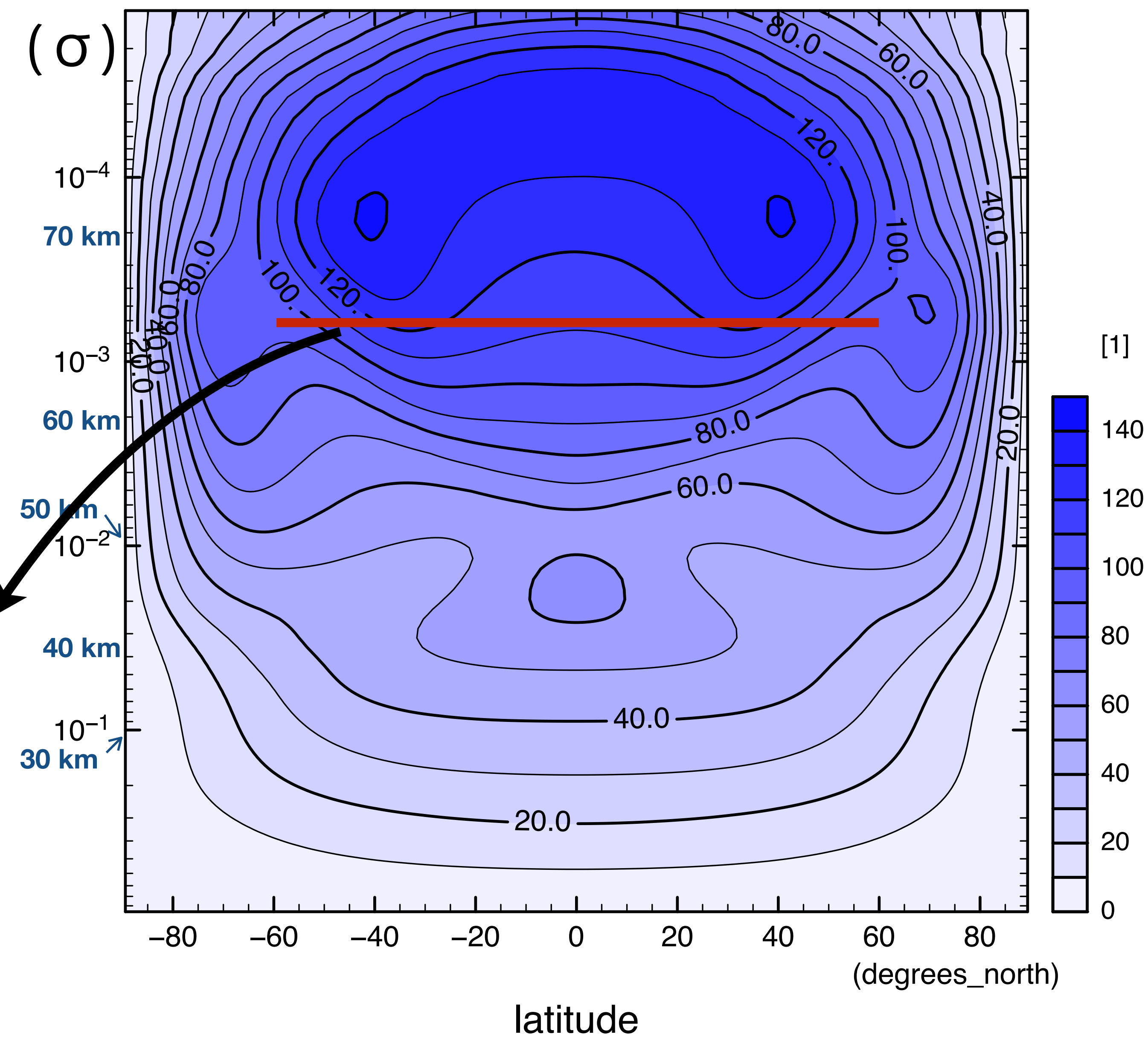
Observation: cloud tracked wind



(Taylor 2010)



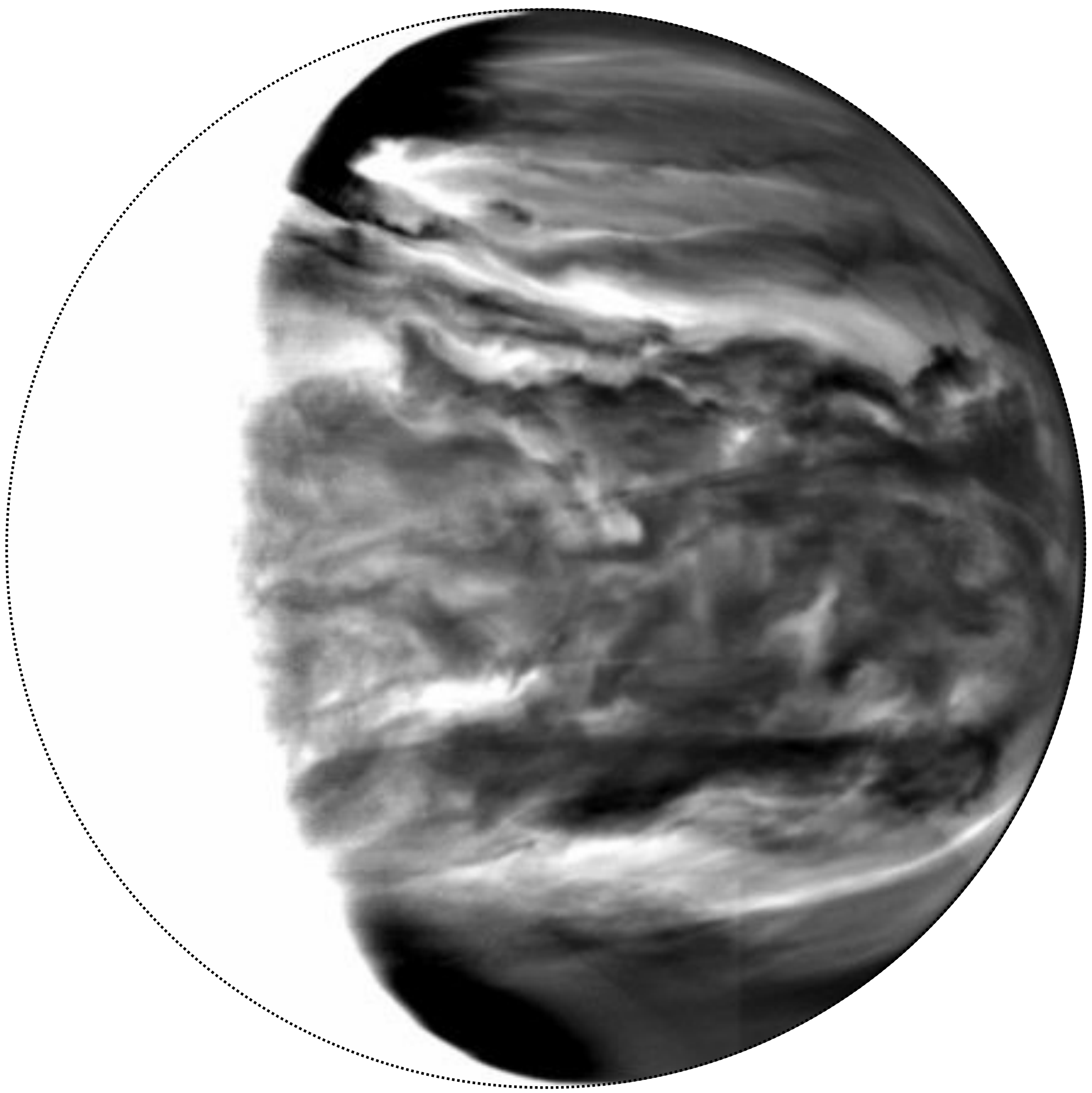
Time mean for last 1 Earth year



Planetary-scale streak structures

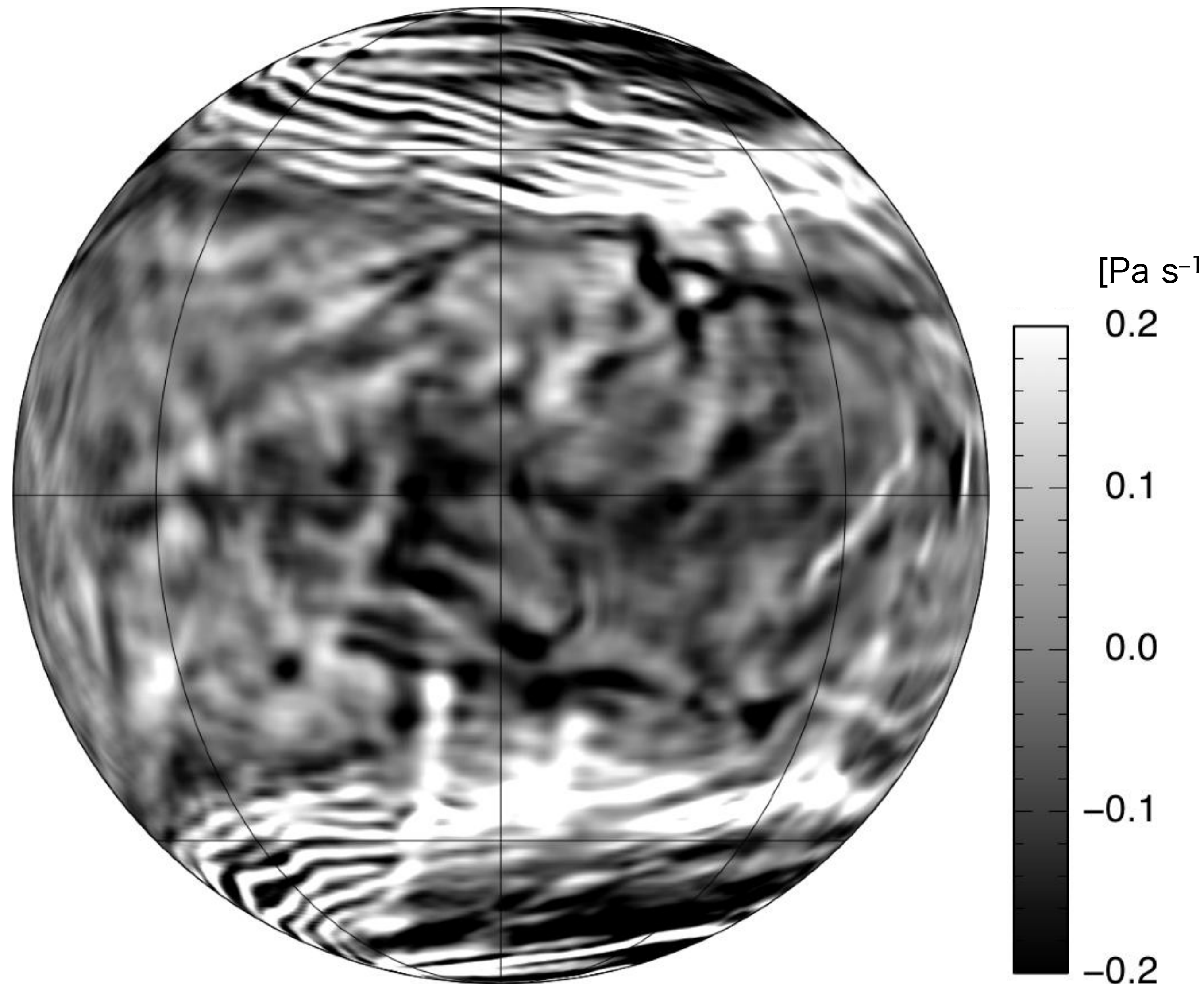
Planetary-scale streak structures

Observed in IR2 night-side



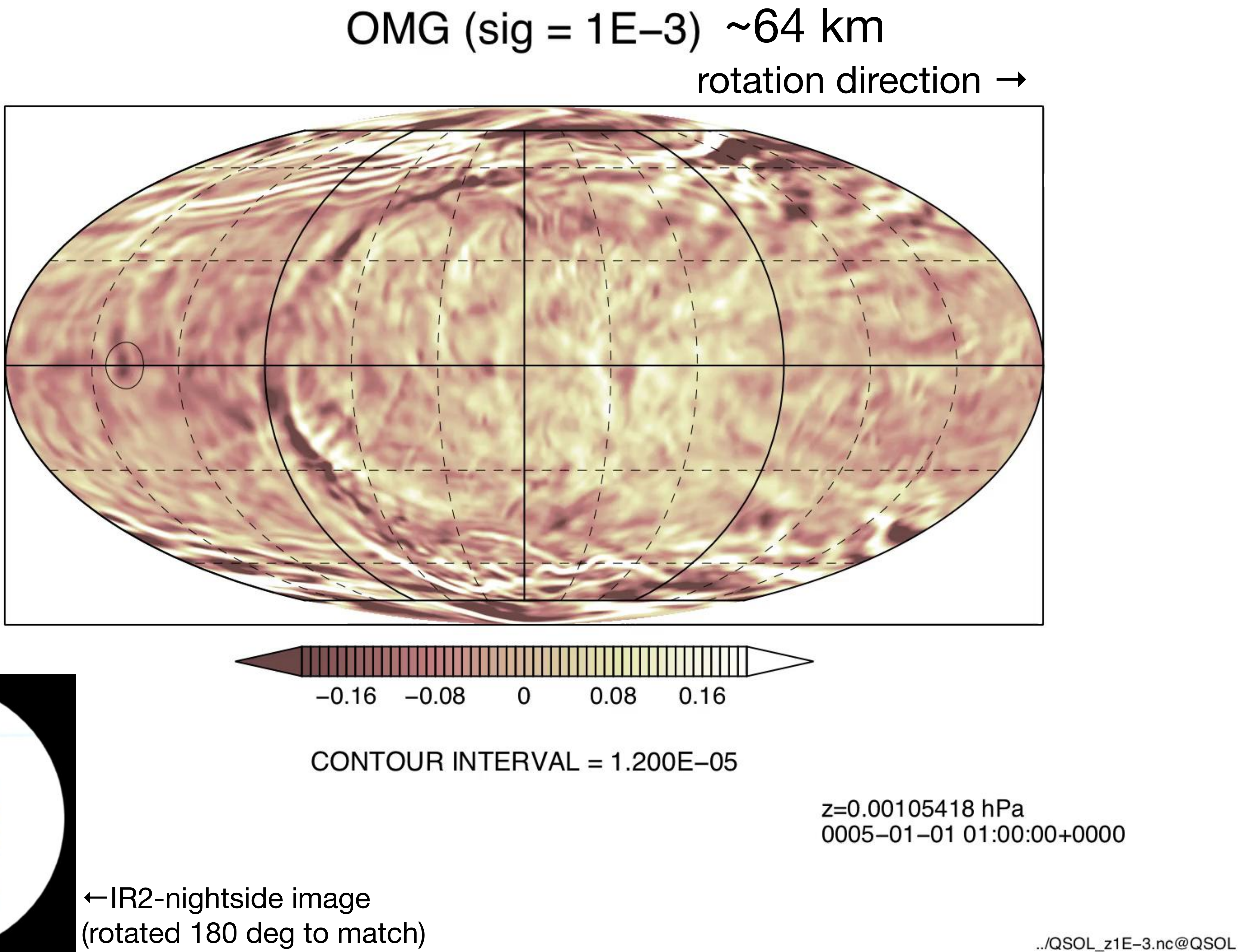
- IR radiated from near-surface atmosphere. Thick clouds blocks it.
  - White = thin clouds = downward flow?
  - Black = thick clouds = upward flow?

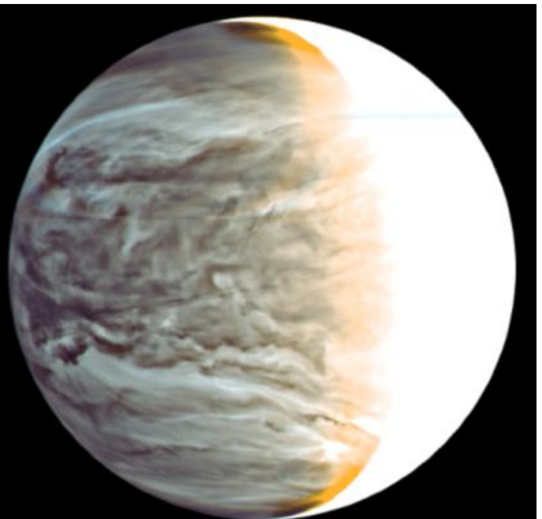
Produced in our Venus GCM



- Snapshot of vertical p-velocity.
  - White = downward flow
  - Black = upward flow

p-velocity | **movie** (1h interval)

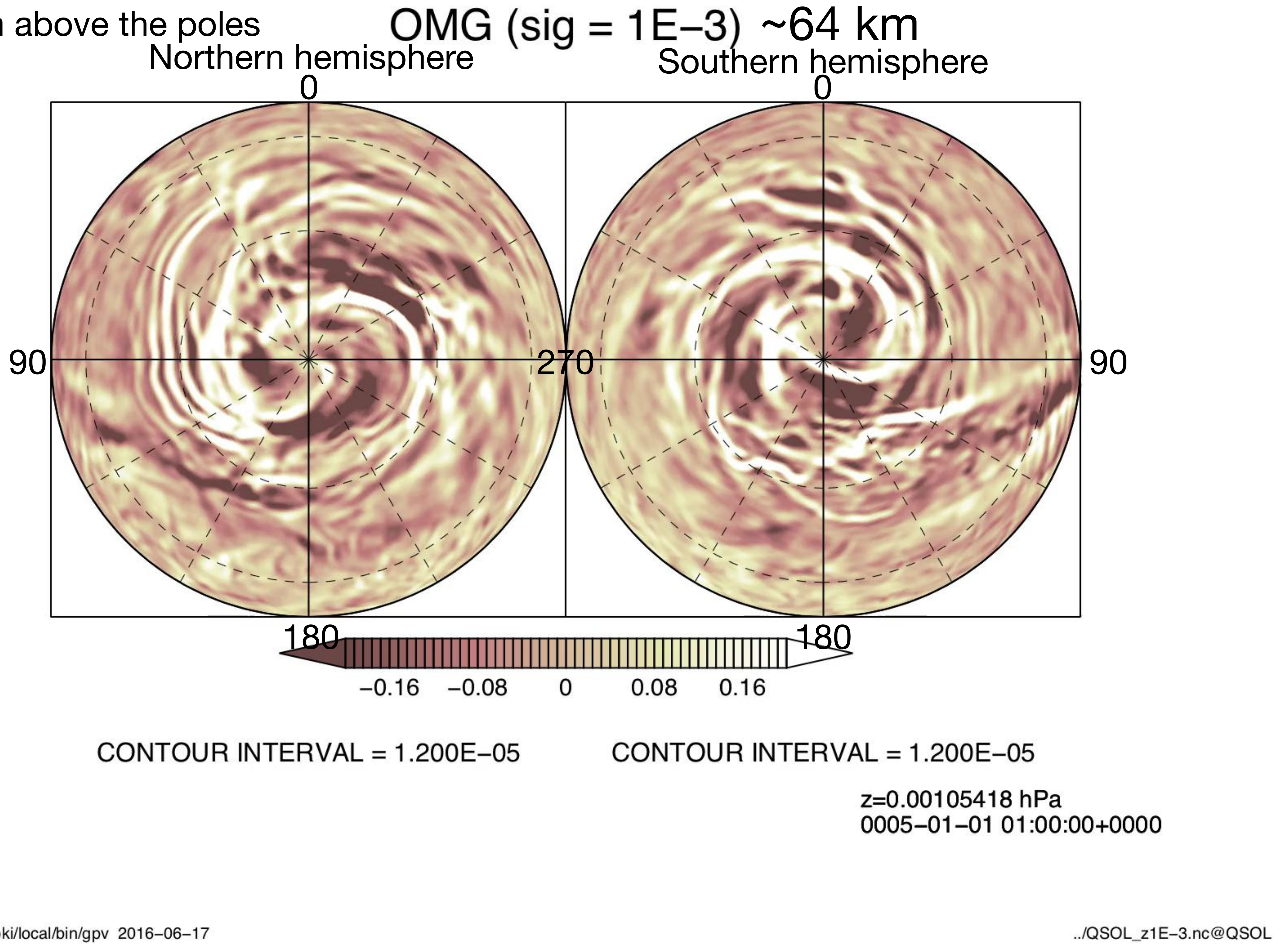




←IR2-nightside image
(rotated 180 deg to match)

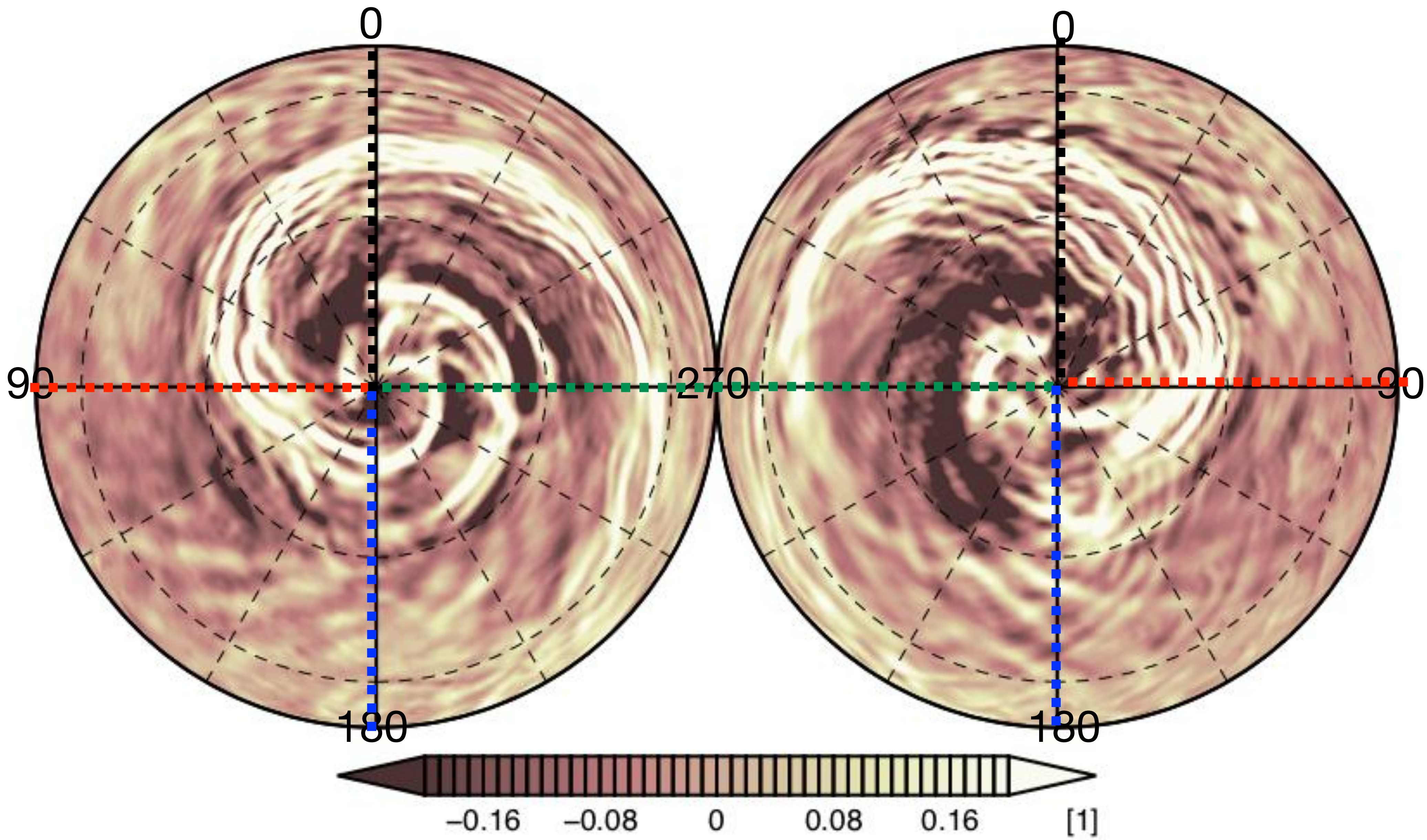
p-velocity | **movie** (1h interval)

Seen from above the poles



Venus AFES | vertical p-velocity

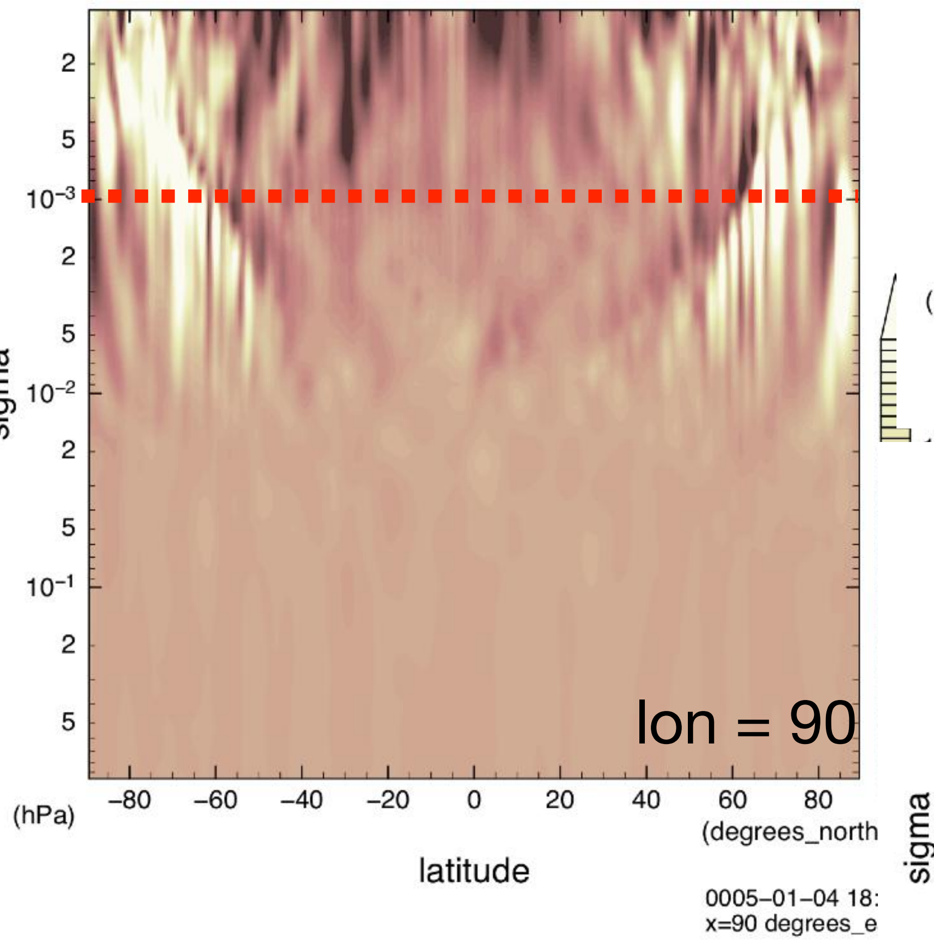
Seen from above the poles

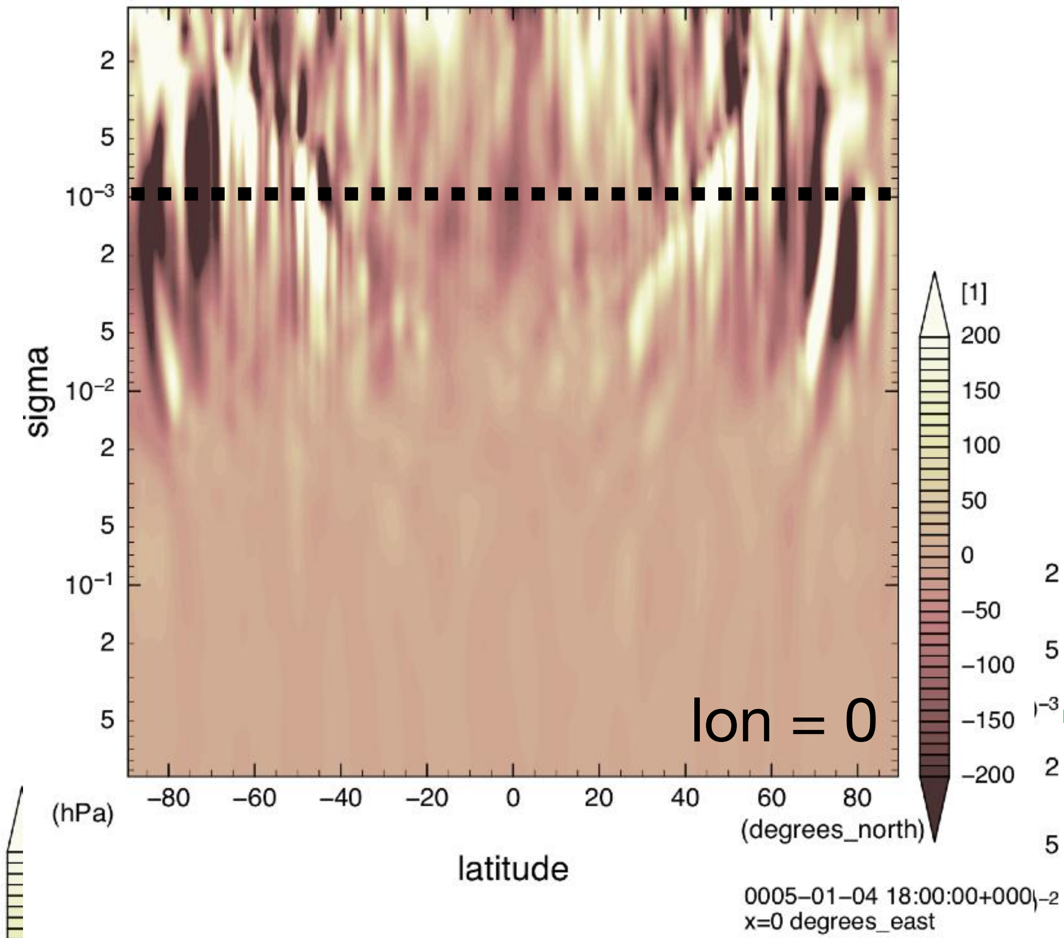


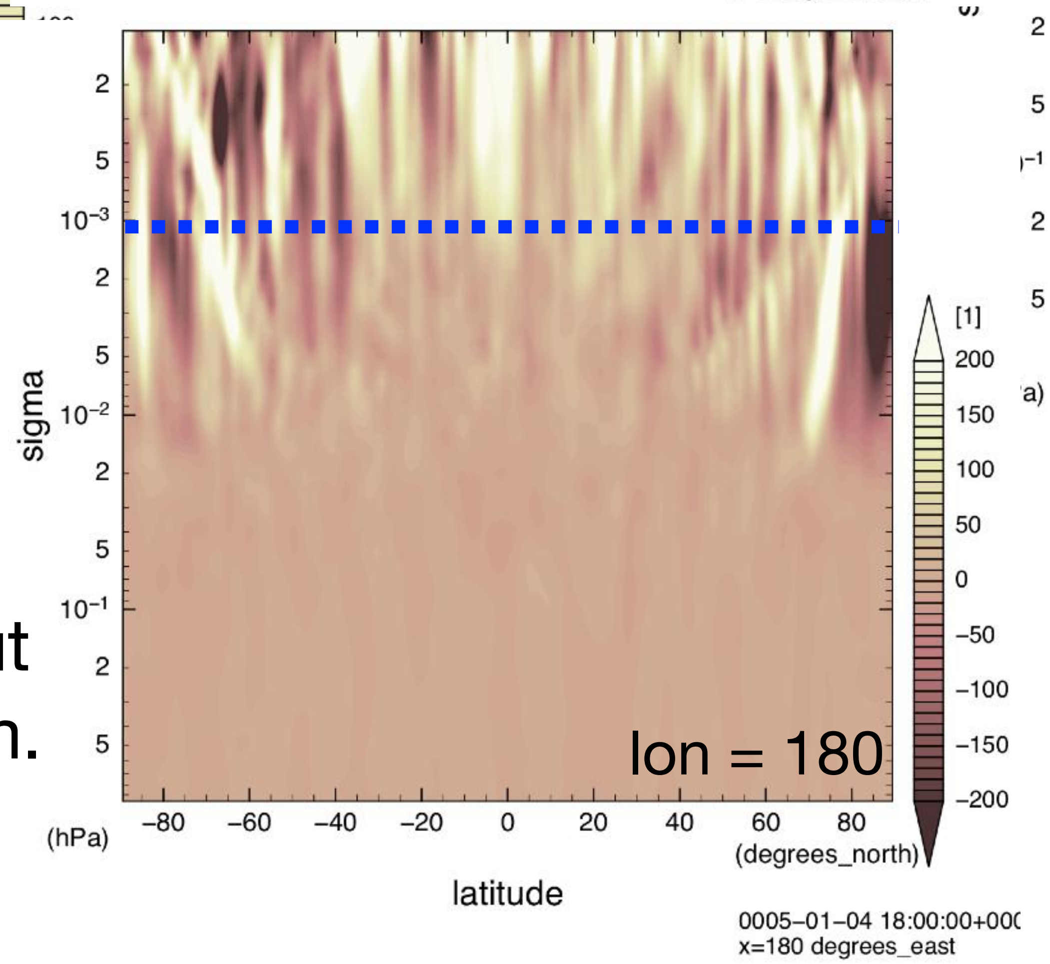
- The streak is a part of a huge spiral extending from the pole to about lat = 30 deg in each hemisphere.
- The spirals in both hemispheres are synchronized.

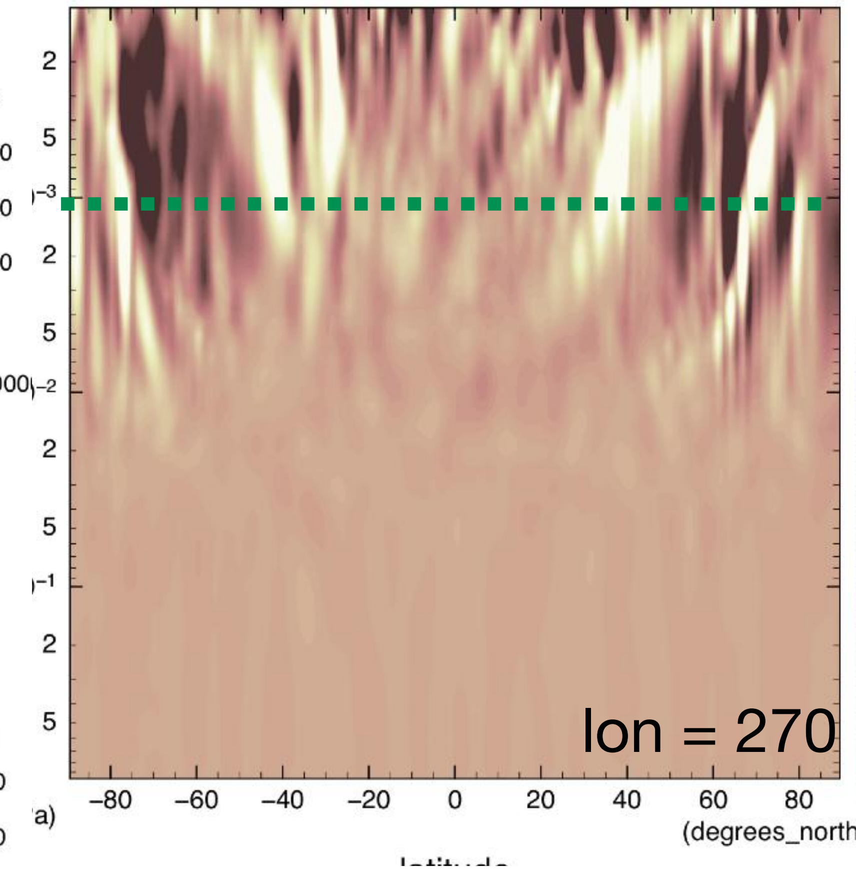
p-velocity/sigma

meridional cross section snapshot



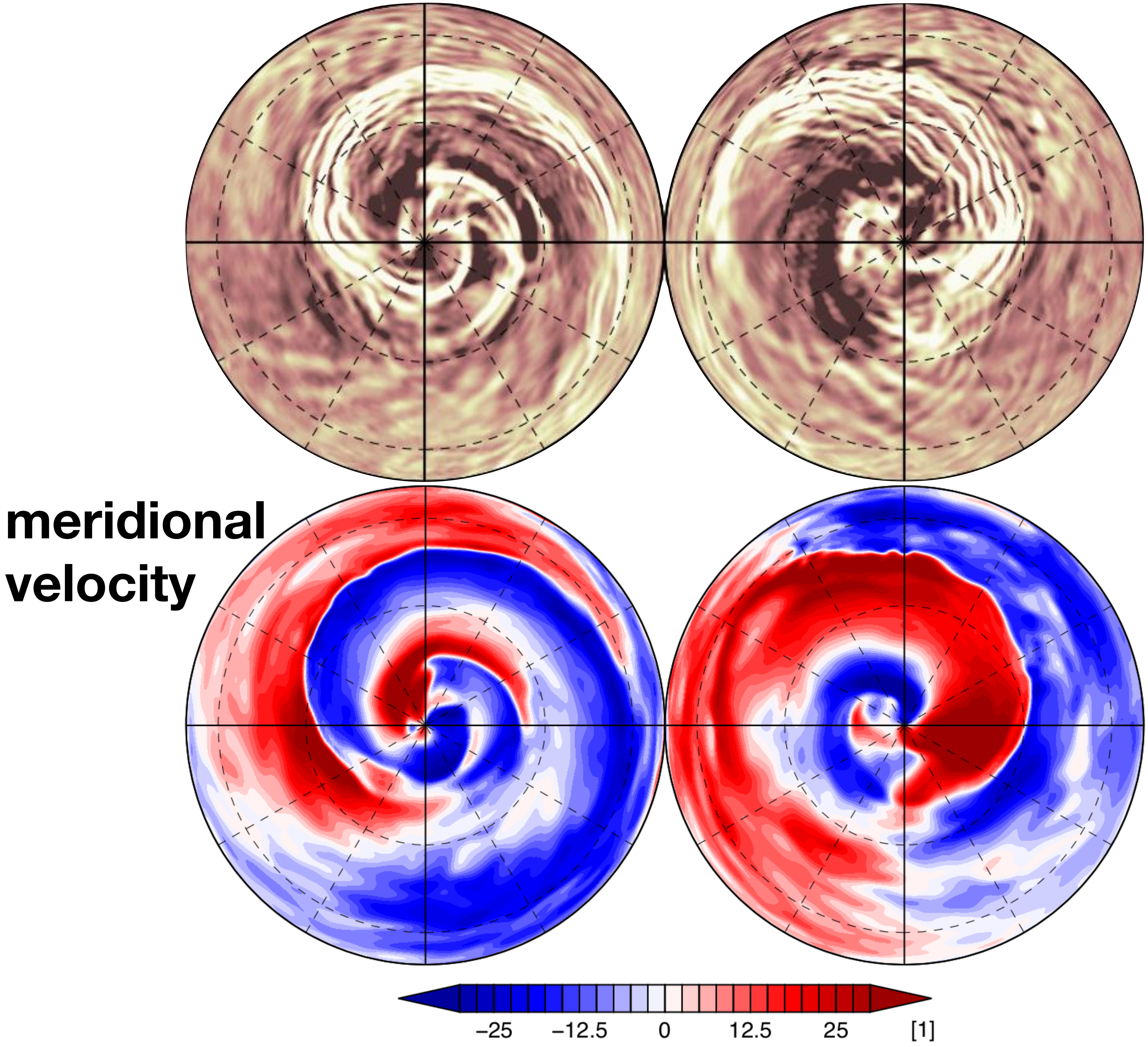


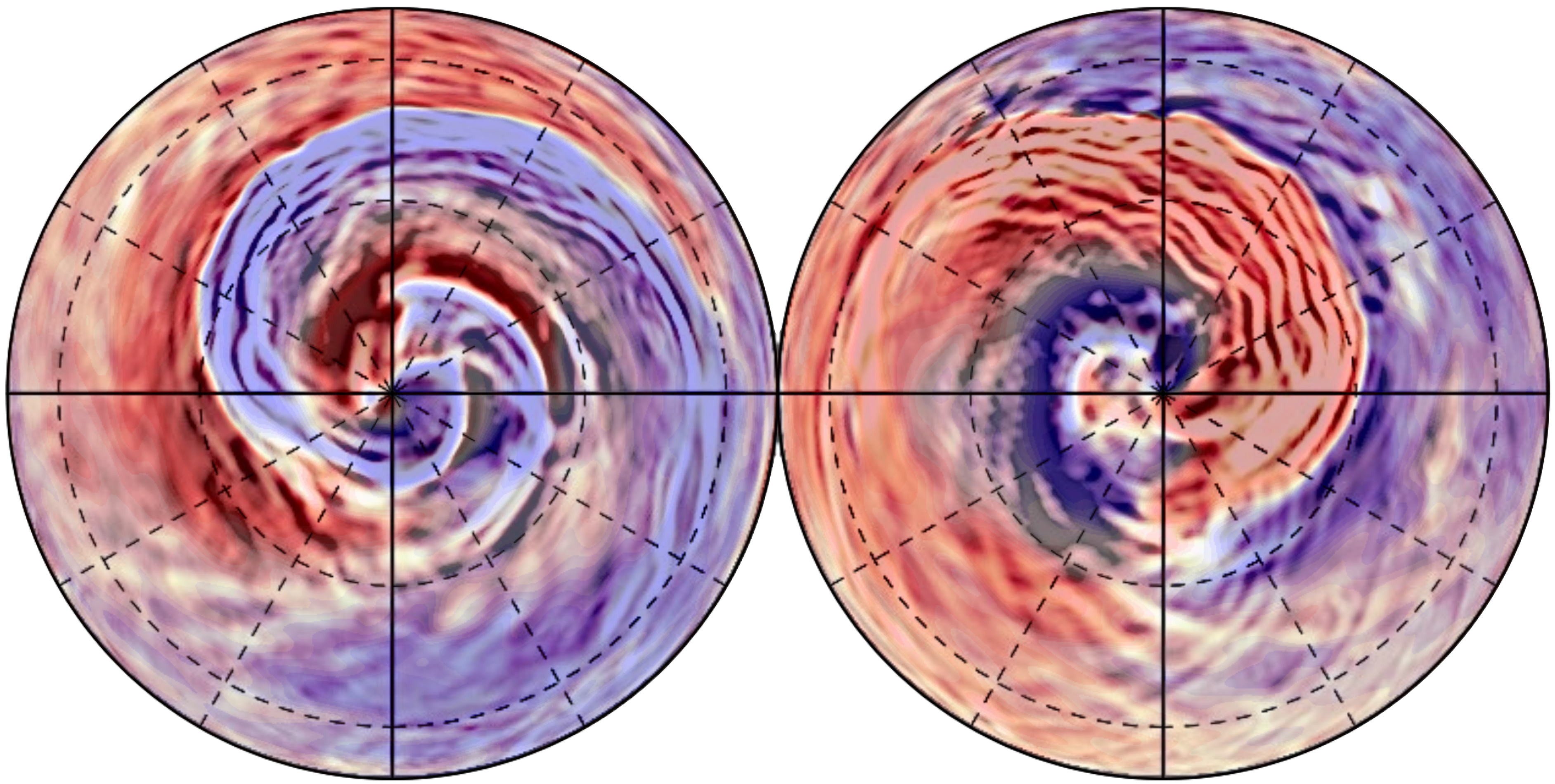




- Strong-downward-flow regions are located about sig=10^{-2}–10^{-4} ~ 50–70km.
- Inclined toward lower equatorial region.

sigma = p/p_s

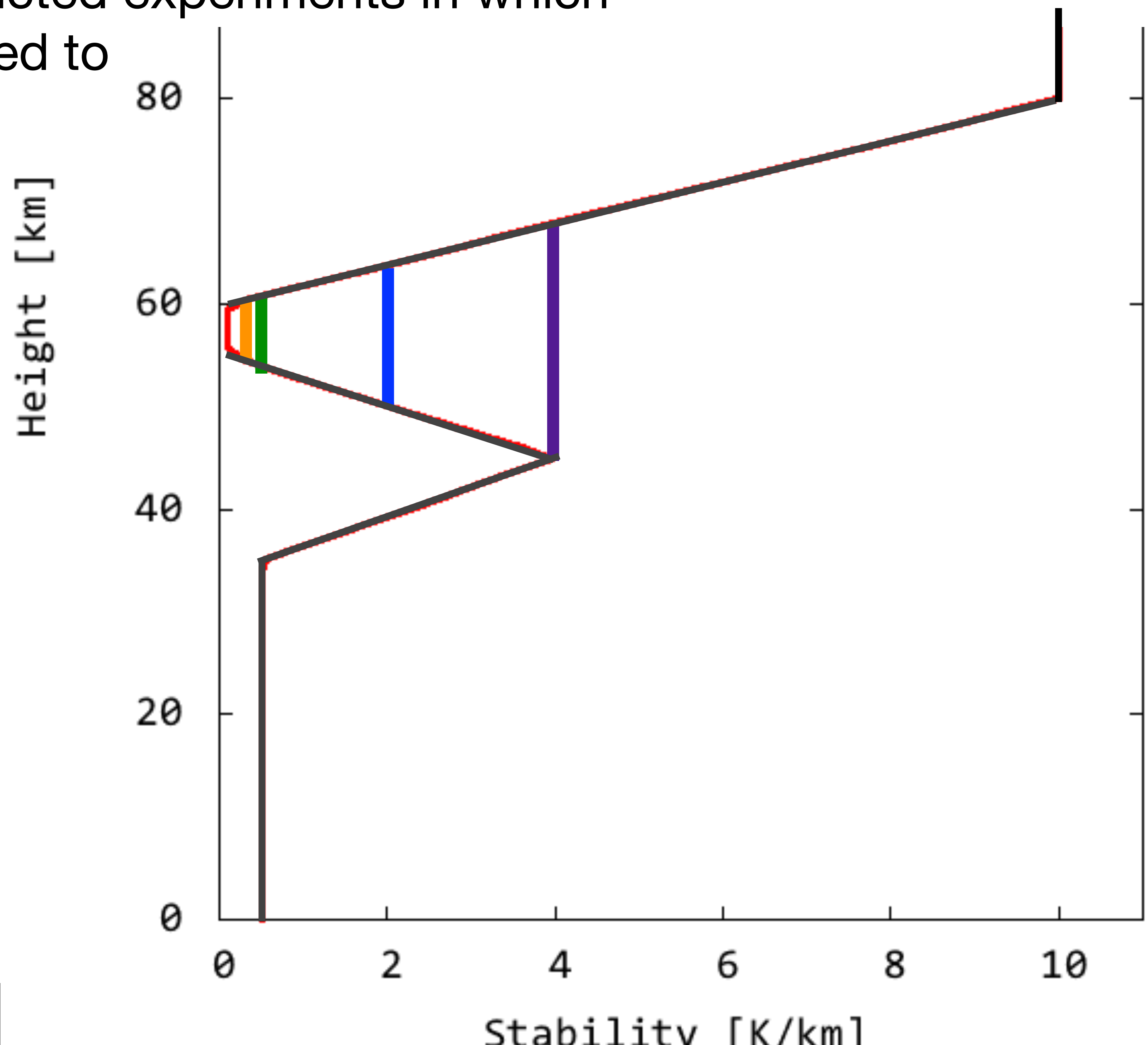

meridional
velocity
−25
−12.5
0
12.5
25
[1]



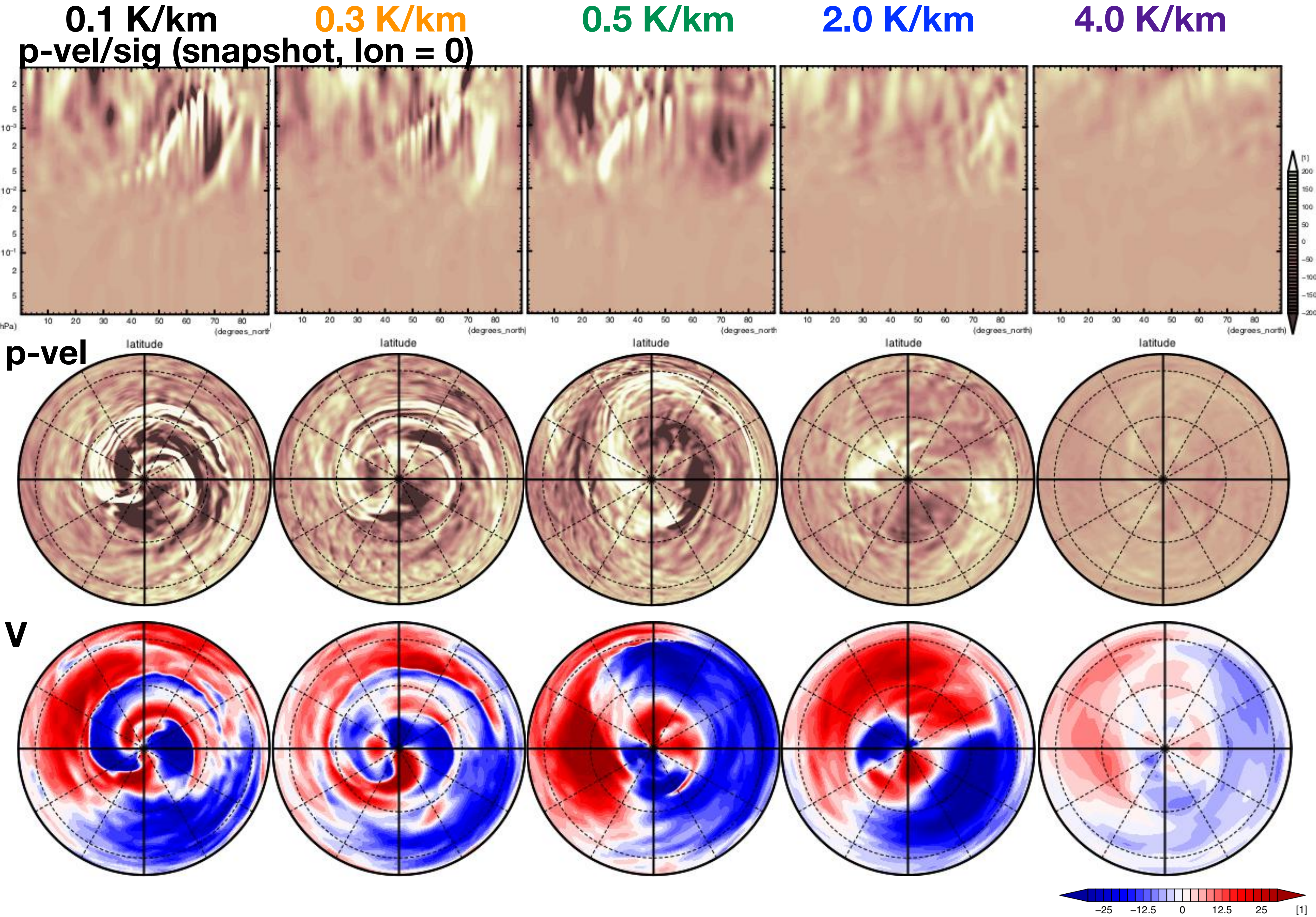
- Equatorial-side edge of the spiral corresponds to convergence of meridional flow.
- I suspect strong convergence induced by the meridional flow makes strong downward flow and also gravity waves are excited.

Experiments

- To explore the importance of the introduced low stability layer (55–60 km, **0.1 K/km**), we conducted experiments in which the stability is changed to
  - **0.3 K/km**
  - **0.5 K/km**
  - **2.0 K/km**
  - **4.0 K/km**

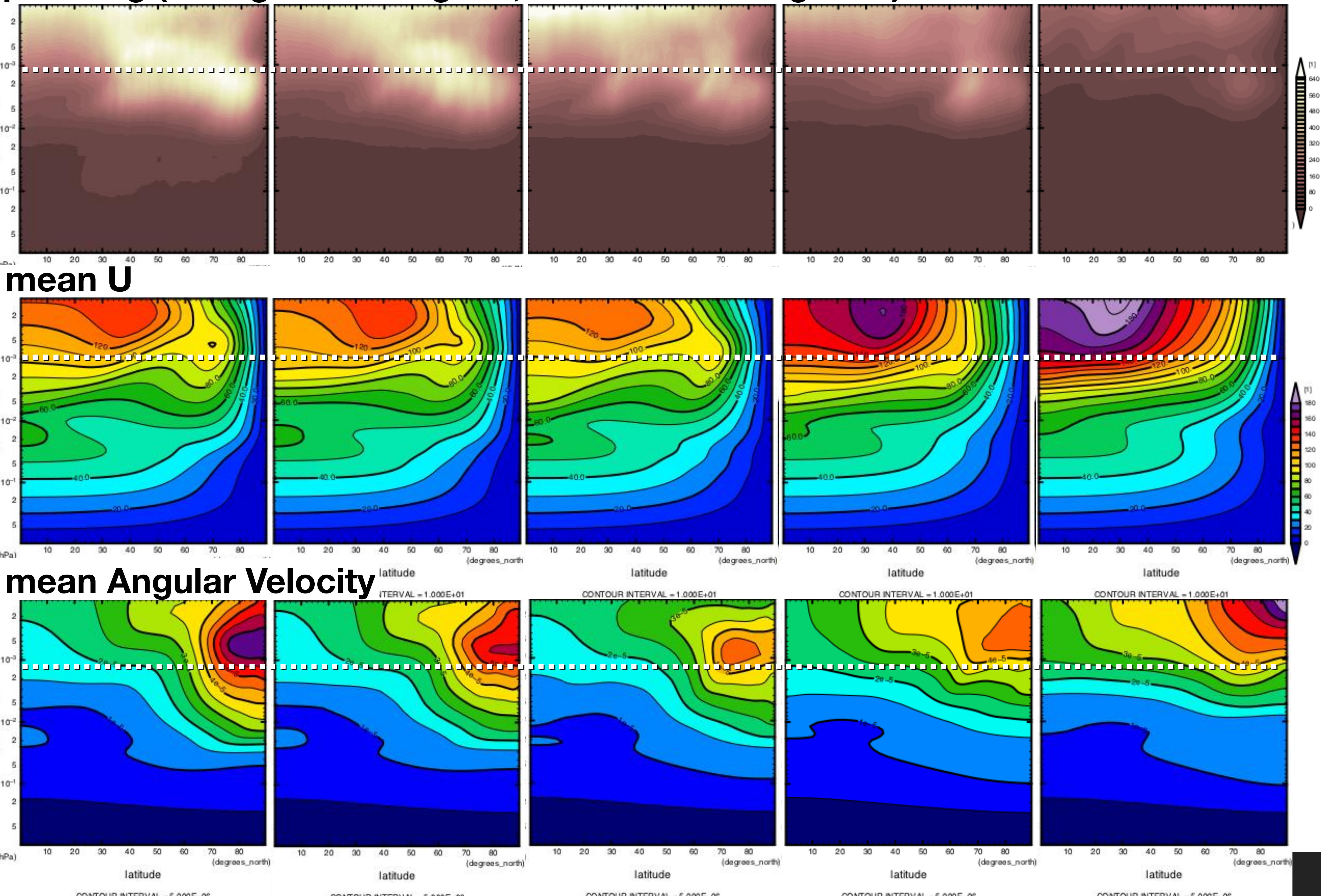


[redacted]


0.1 K/km
0.3 K/km
0.5 K/km
2.0 K/km
4.0 K/km
p-vel/sig (snapshot, lon = 0)
latitude
p-vel
V
−25
−12.5
0
12.5
25
[1]

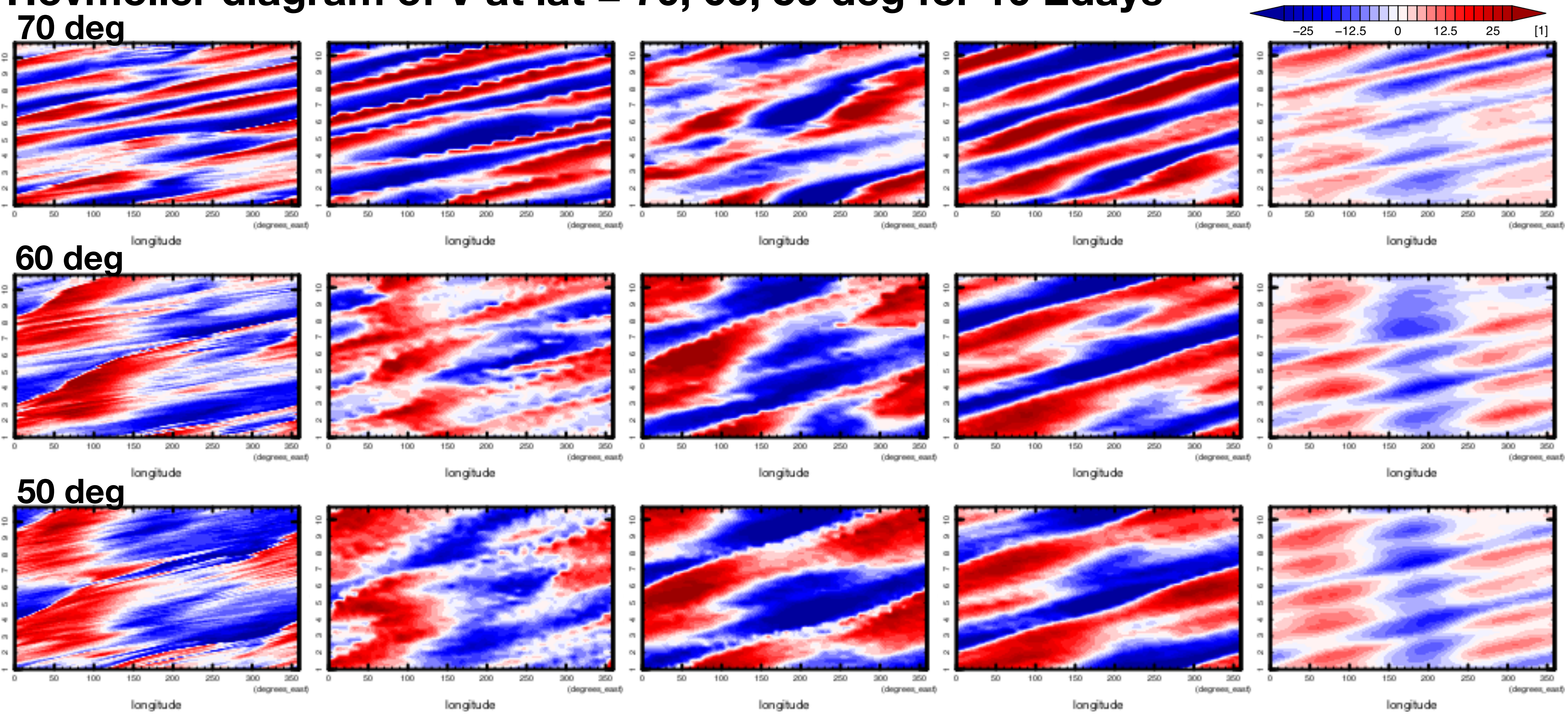
0.1 K/km **0.3 K/km** **0.5 K/km** **2.0 K/km** **4.0 K/km**

p-vel/sig (taking max along lon, then mean along time)

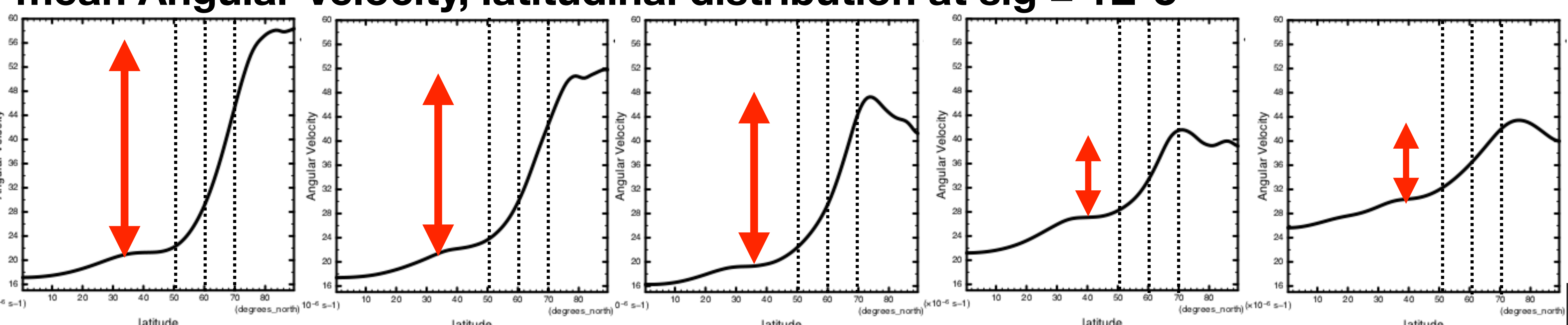


0.1 K/km **0.3 K/km** **0.5 K/km** **2.0 K/km** **4.0 K/km**

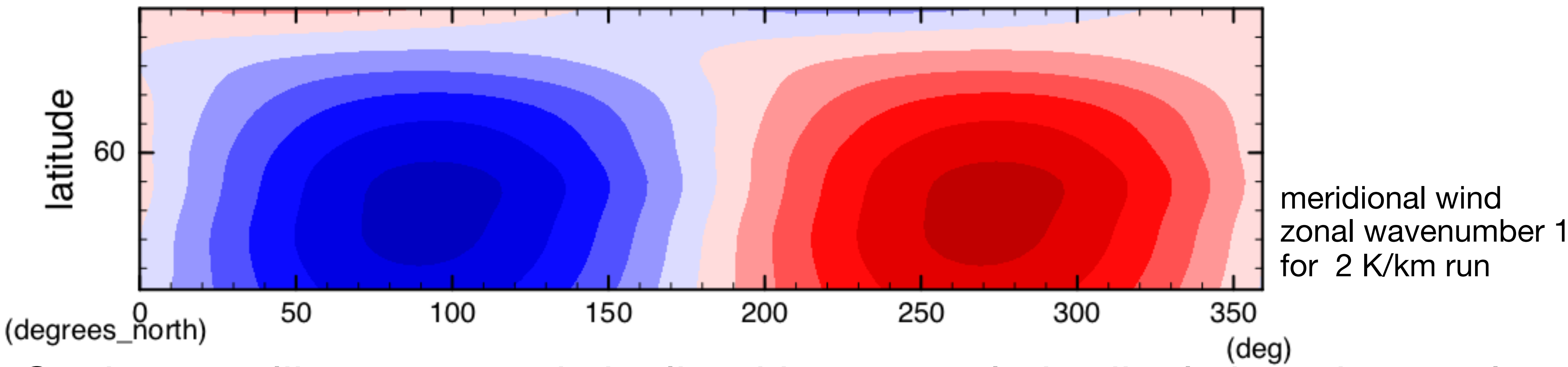
Hovmöller diagram of V at lat = 70, 60, 50 deg for 10 Edays



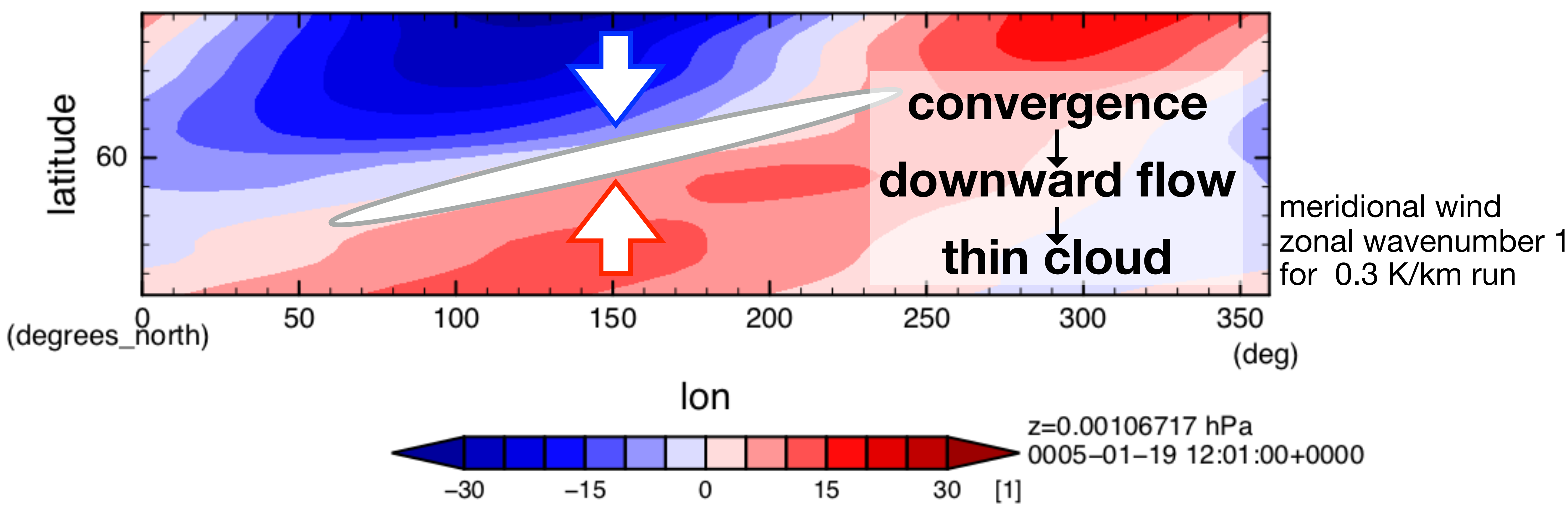
mean Angular Velocity, latitudinal distribution at sig = 1E-3



Mechanism?



- Such wave-like structure is inclined by strong latitudinal shear in angular velocity and may result in as below.



Summary for streak structures

- **Planetary-scale streak structures** *similar to those observed in a night side IR2 image* are reproduced in vertical velocity in our simple Venus GCM, which has dynamics only but has a “low stability layer” (55–60km).
  - **Planetary-scale streaks** are:
    - **strong downward flow**, possibly corresponds to thin cloud region.
    - a part of huge spirals extending from the pole to about lat = 30 deg.
    - synchronized in each hemisphere.
  - **Strong downward flow** seems to be caused by convergence of meridional wind.
  - Num. experiments with changing the static stability of the “low stability layer” are performed.
    - Experimental results suggest that **a large gap in mean angular velocity between mid- and high-latitudes inclines the meridional velocity field** (~ structure of some waves?) and produces strong convergence streak.
    - However, relation between the “low stability layer” and mean zonal wind field is not explored yet.