# Planetary-scale streak structure reproduced in high-resolution simulations of the Venus atmosphere with a low-stability layer

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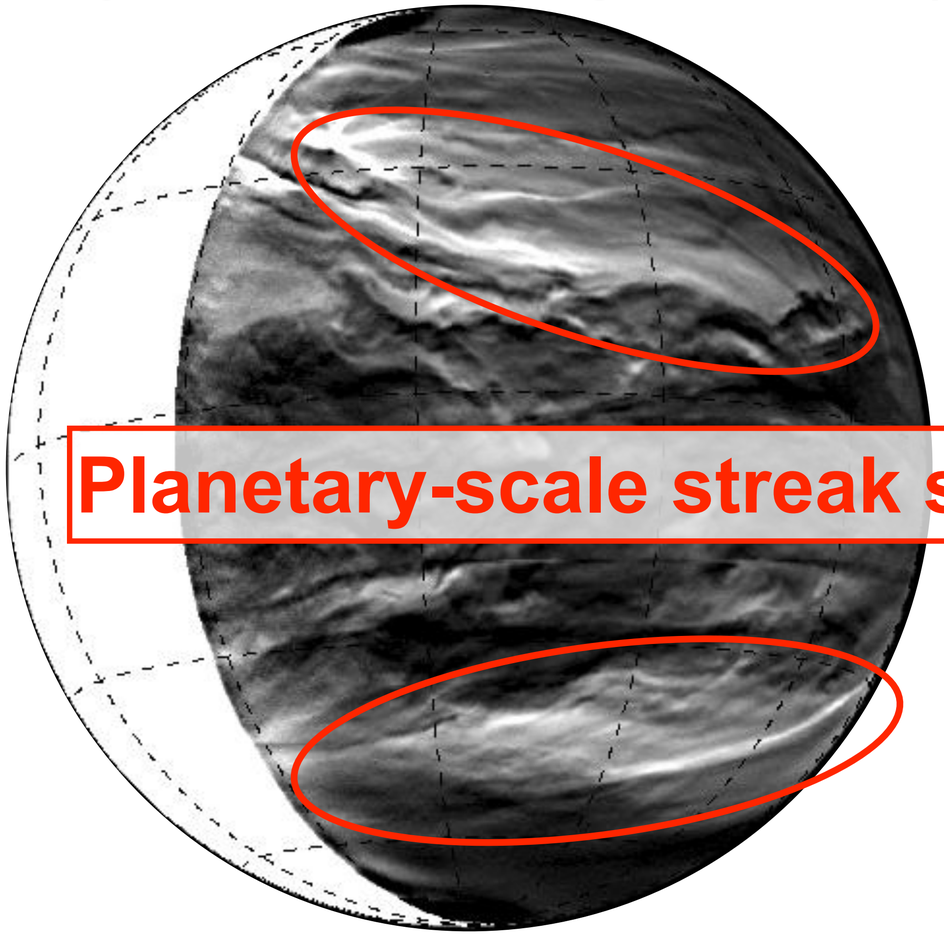
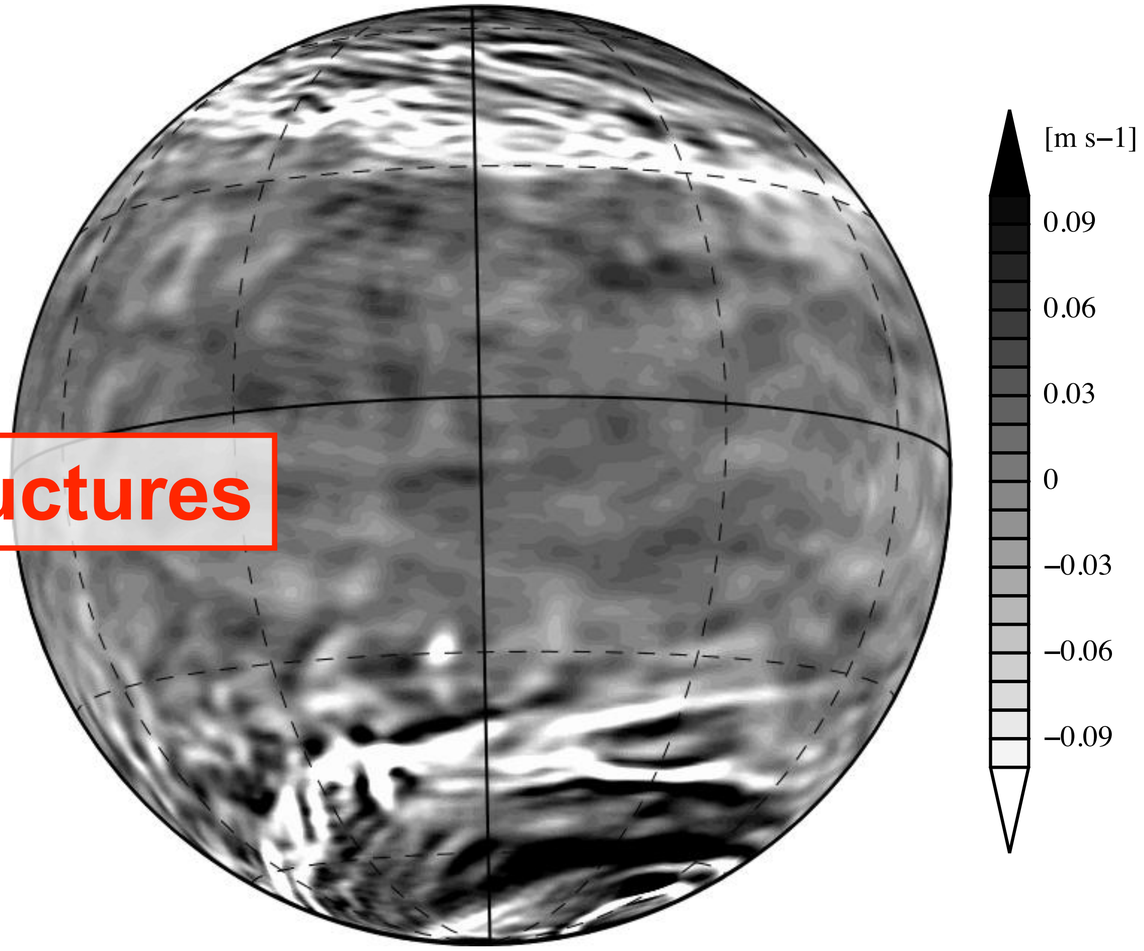
## Venus night-side image taken by Akatsuki IR2 (edge-enhanced)



## Vertical velocity field produced in our Venus GCM



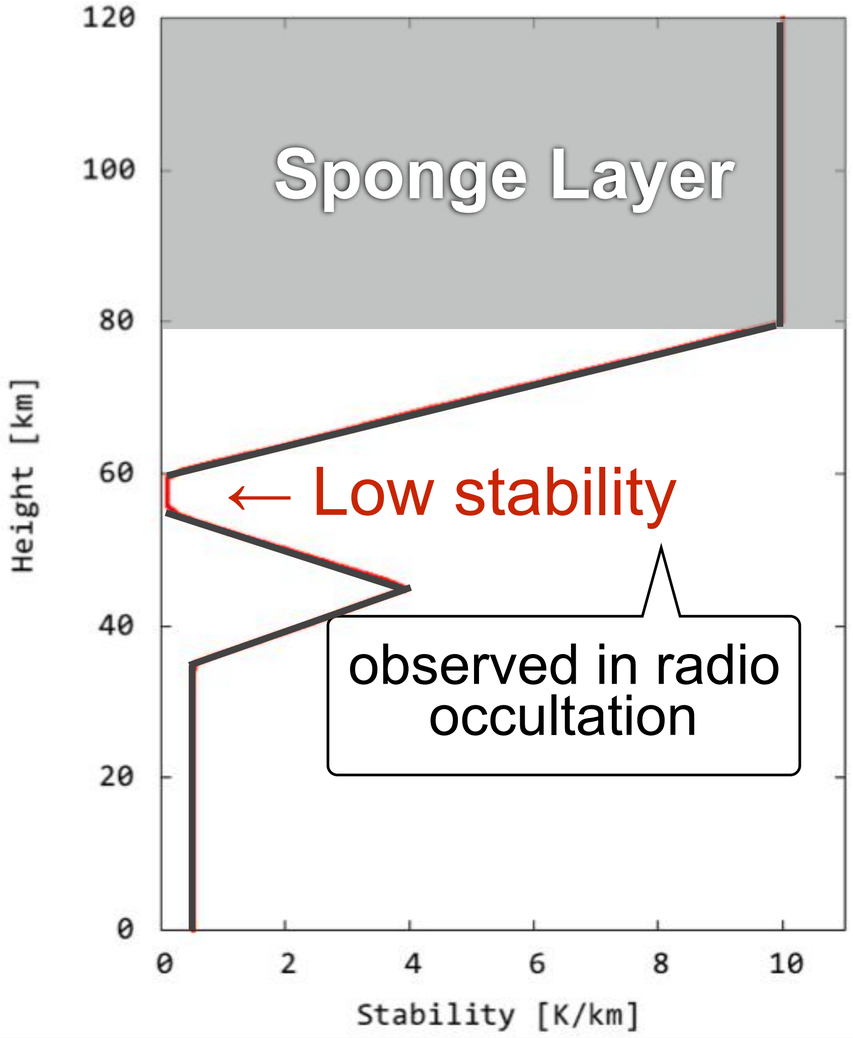

**Planetary-scale streak structures**

- IR radiated from near-surface atmosphere. Thick clouds blocks it.
  - White = thin clouds = downward flow?
  - Black = thick clouds = upward flow?
- Snapshot of simulated vertical velocity at z = 60 km.
  - White = downward flow
  - Black = upward flow

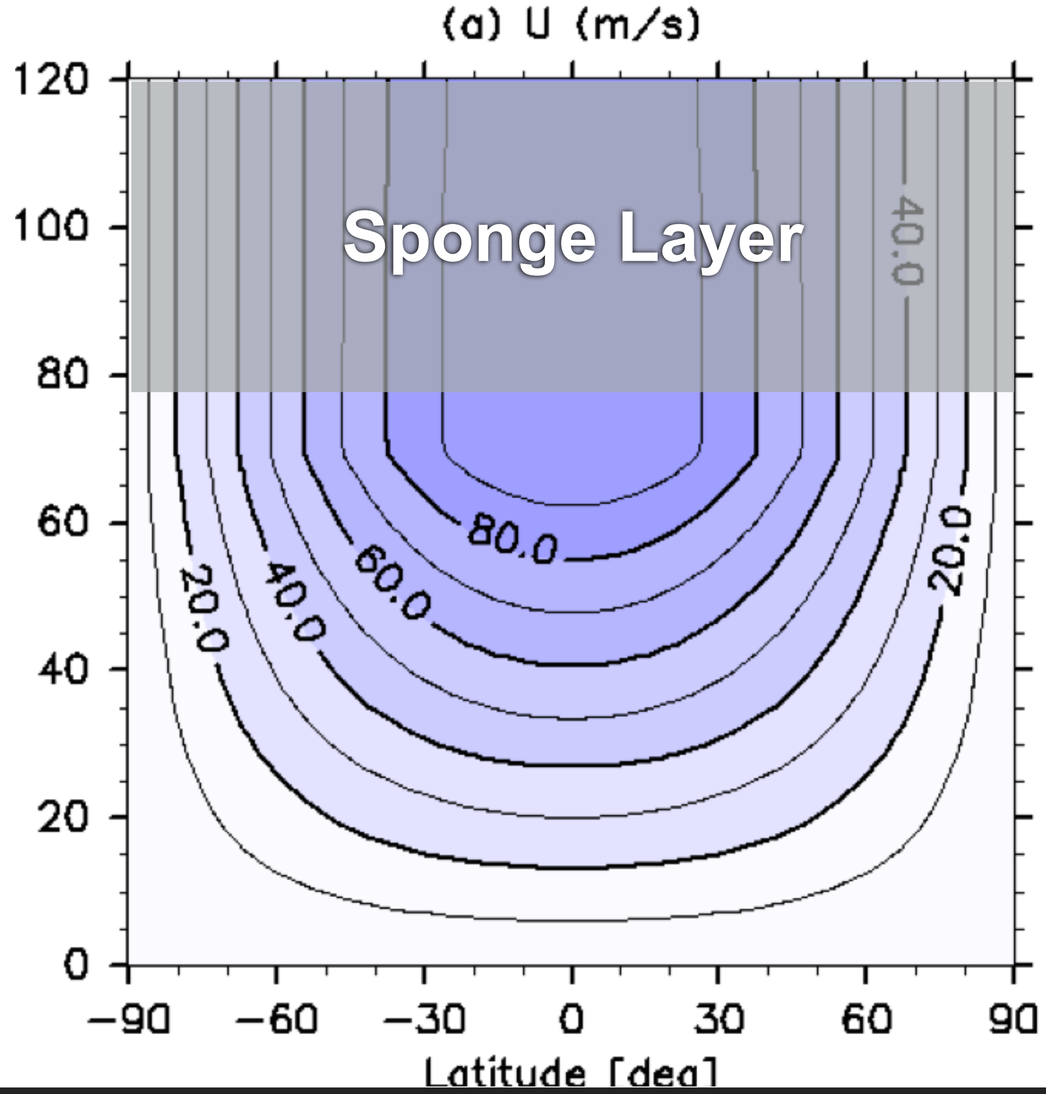
# Our simplified Venus GCM

- Based on AFES = Atmospheric GCM for the Earth Simulator (Ohfuchi *et al*. 2004; Enomoto *et al*. 2008)
  - The Earth Simulator is a vector type super computer.
- Basic equation: primitive equations
- Resolution:
  - T159 (~0.75°× 0.75°; 480×240 grids) - L120 ($\Delta z$ ~ 1 km; sigma coord.)
- Simplified Radiative forcing
  - Horizontally uniform Newtonian cooling (Crisp, 1989)
  - Solar heating with a diurnal variation (Tomasko *et al*., 1980).
- No topography • No moist processes
- Sponge layers located above 80 km
- Biharmonic horizontal diffusion ($\nabla^4$) with a damping time of 0.01 Earth days for the highest wave number.
- Vertical eddy diffusion with coefficient of 0.15 $m^2s^{-1}$
- **<u>Note that planetary-rotation direction is same as the Earth</u>** (some figures are rotated to match the real Venus and some are not.)

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

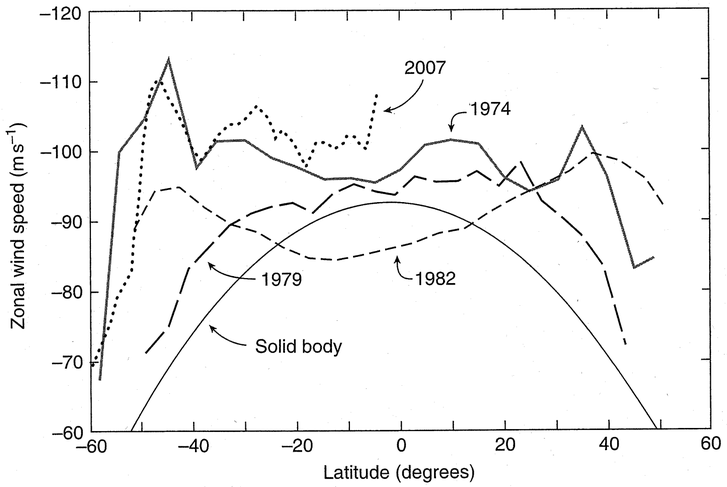



Initial state: superrotation



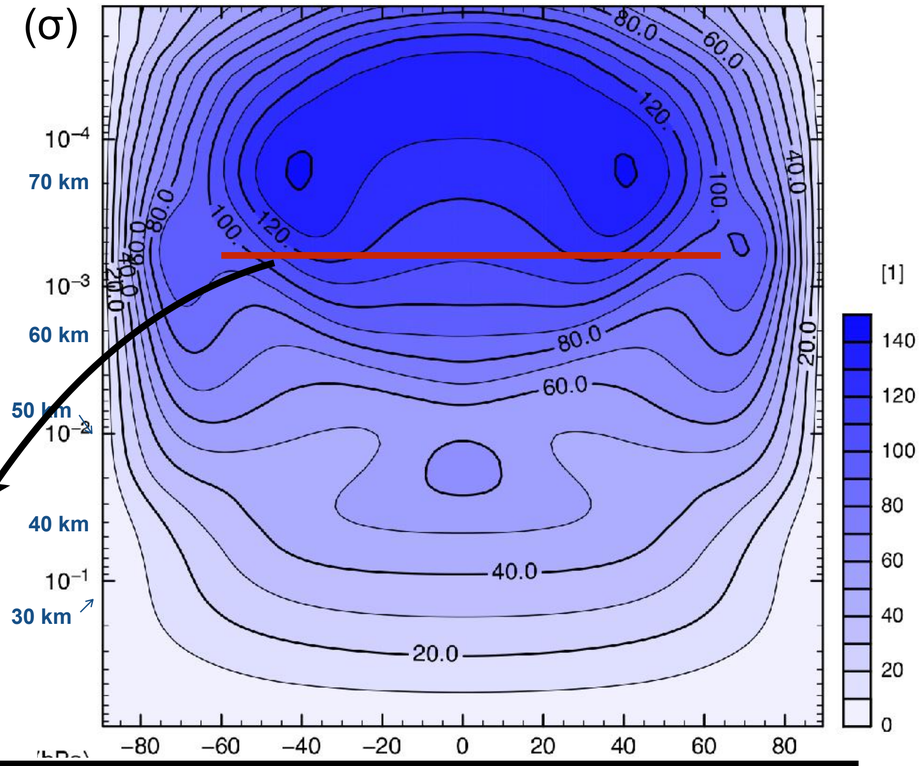
# Results | zonal mean zonal wind

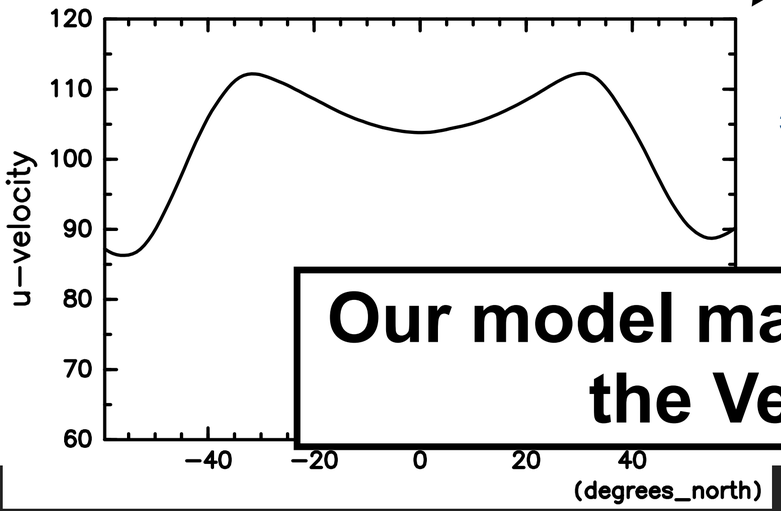
**Observation: cloud tracked wind**




(Taylor 2010)

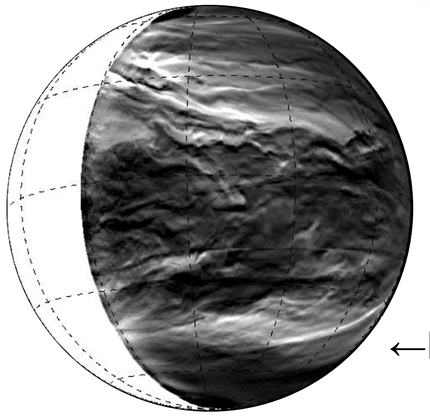
Time mean for
last 1 Earth year




**Our model may simulate circulation of the Venus atmosphere**

# Vertical velocity | movie (dt = 1h)



←IR2-nightside image

z = 60 km

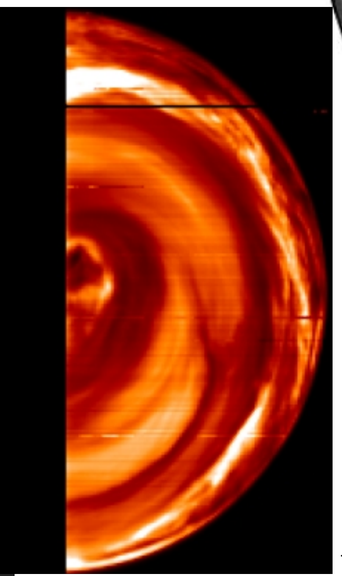
–0.08 –0.04 0 0.04 0.08 [m s–1]

# vertical velocity at 60 km height in STD (5th year)

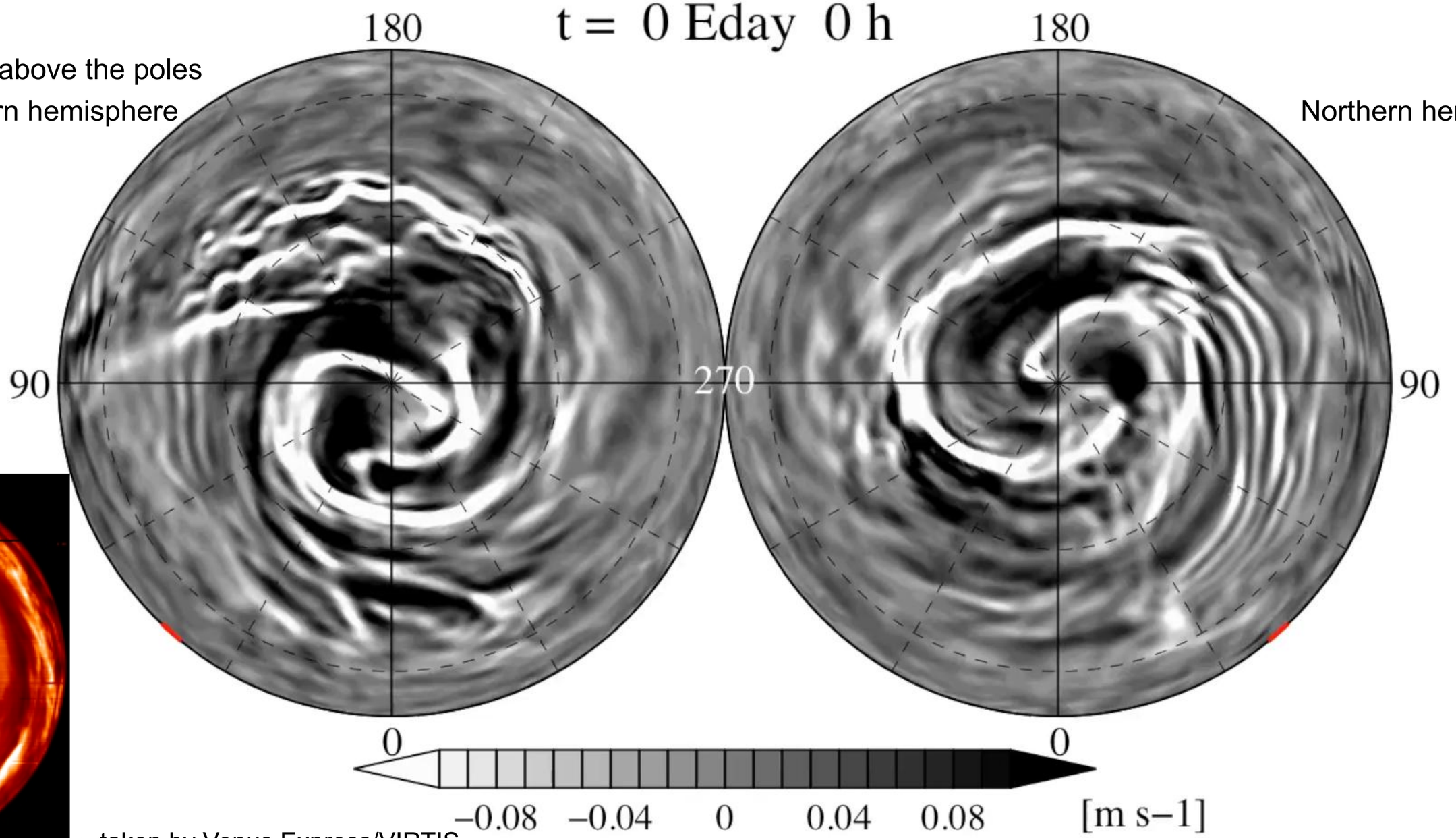
Seen from above the poles

Southern hemisphere

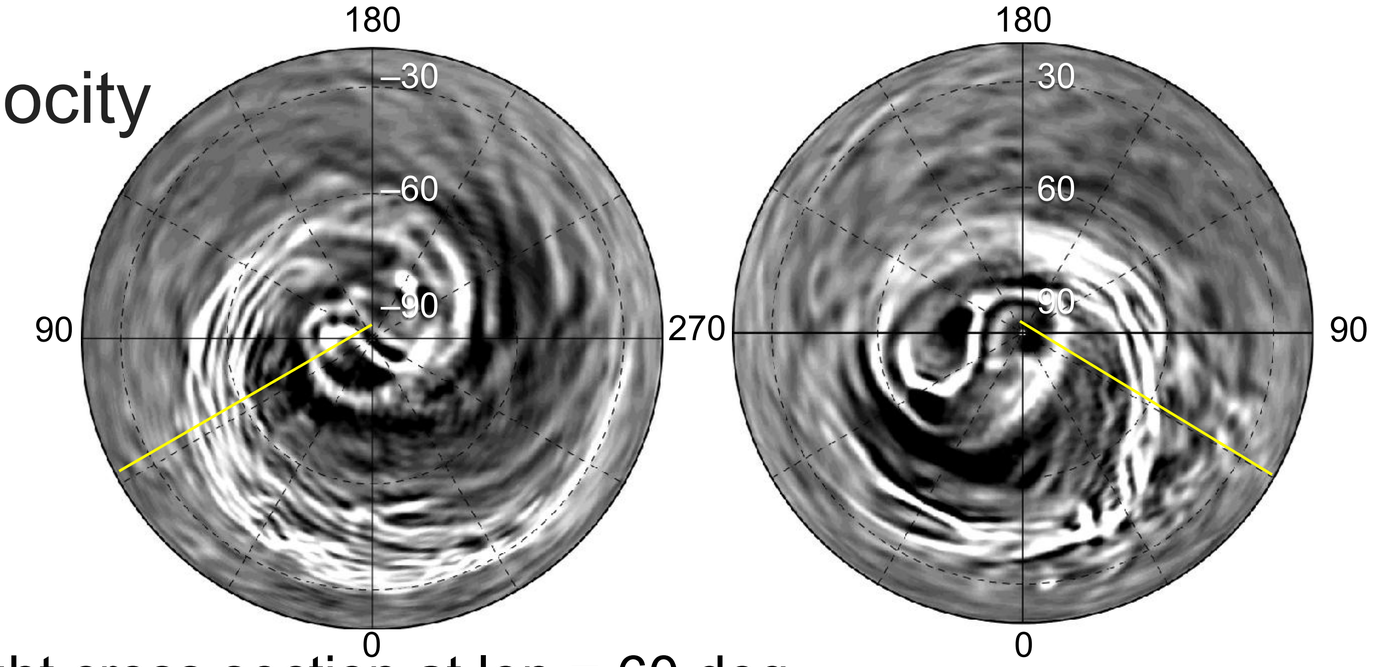
Northern hemisphere



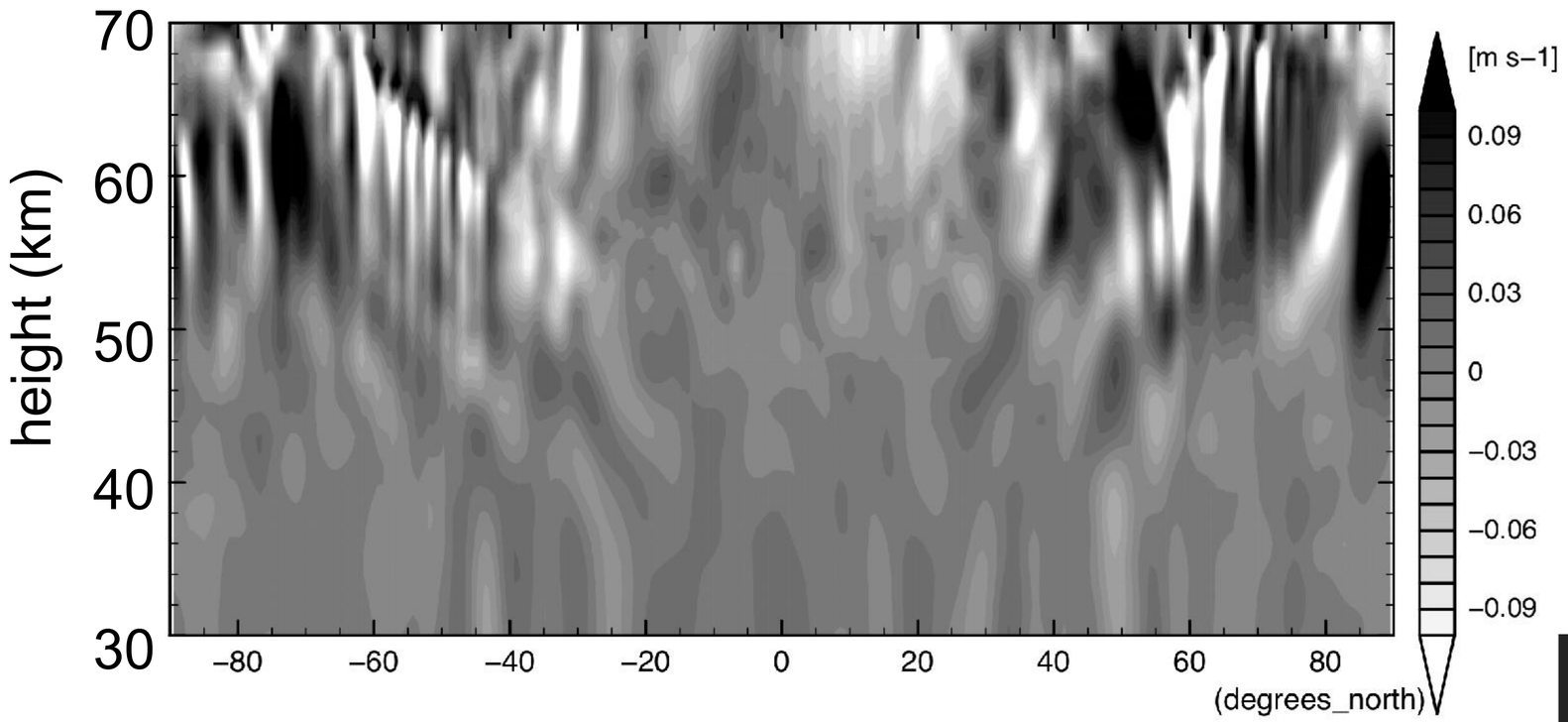
←taken by Venus Express/VIRTIS



# Vertical velocity

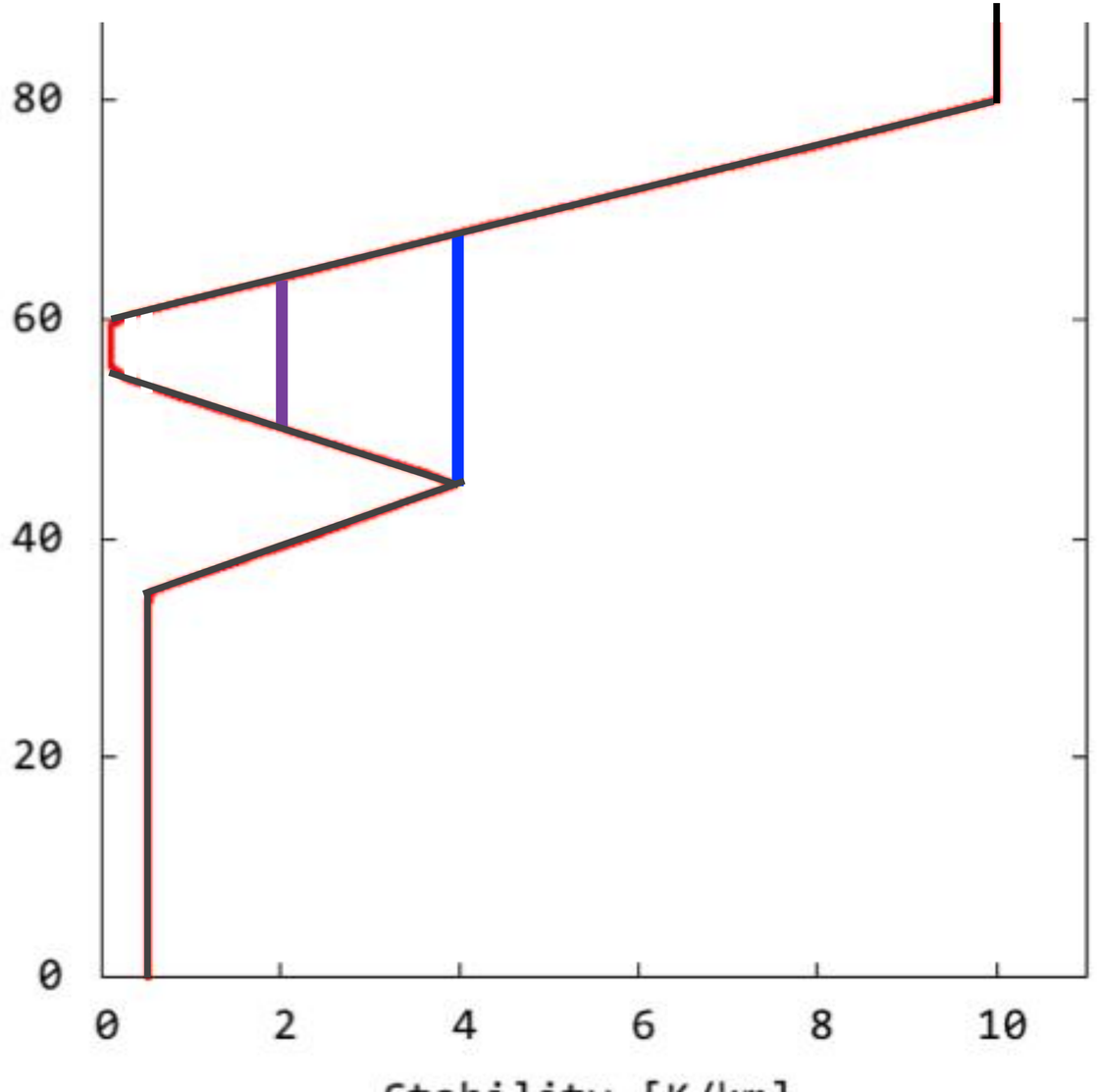



latitude-height cross section at lon = 60 deg



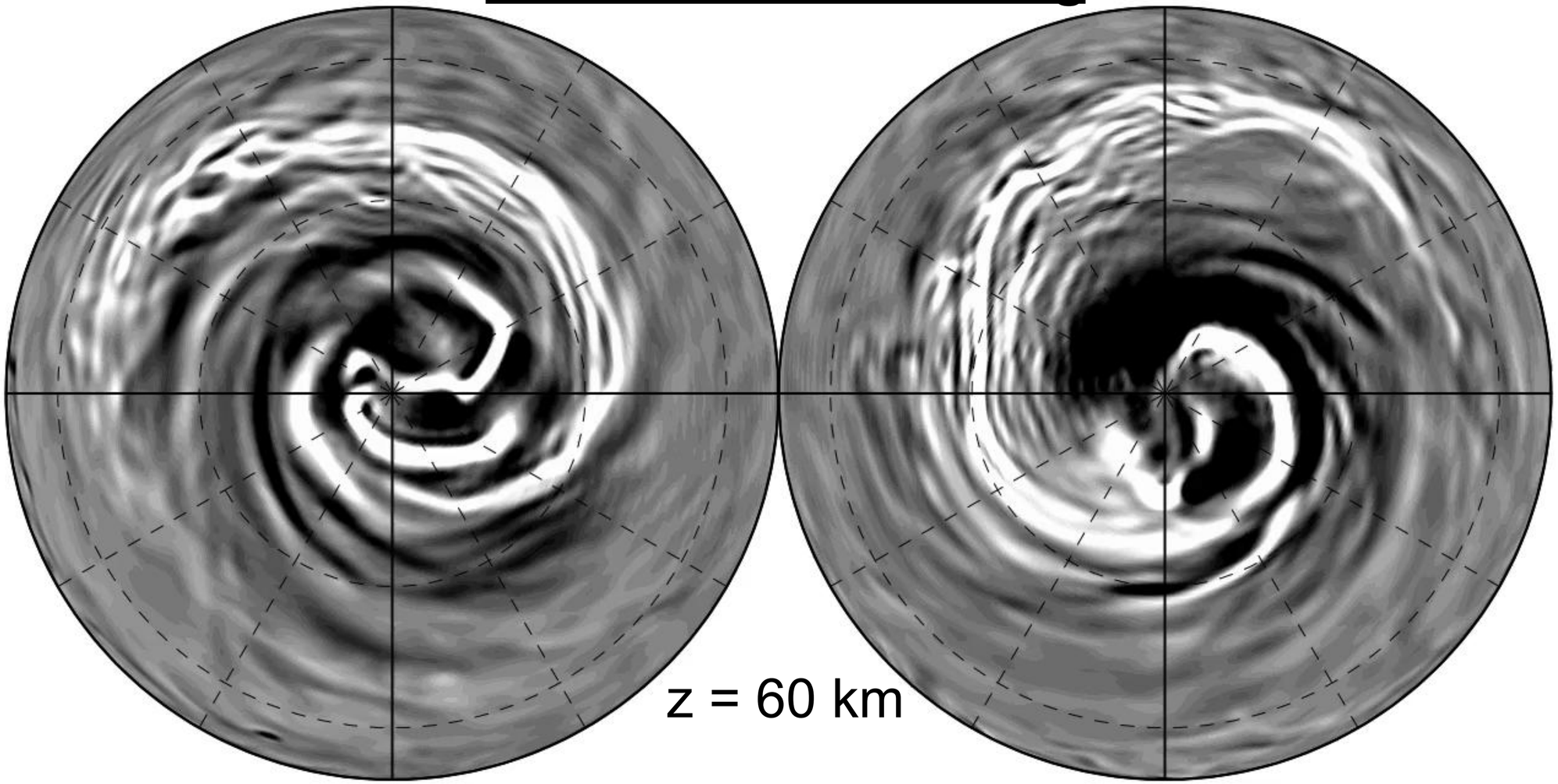
# Experiments

- To explore the effects of
  - **the diurnal heating** ☀️ and
  - **the introduced low stability layer (55–60 km, 0.1 K/km),**
- we conducted experiments
  - **without the diurnal heating (i.e., using zonally averaged heating)** and
  - in which **the stability is changed to 2.0 K/km and 4.0 K/km**



# Vertical velocity | movie (dt = 6h)

**without diurnal heating**

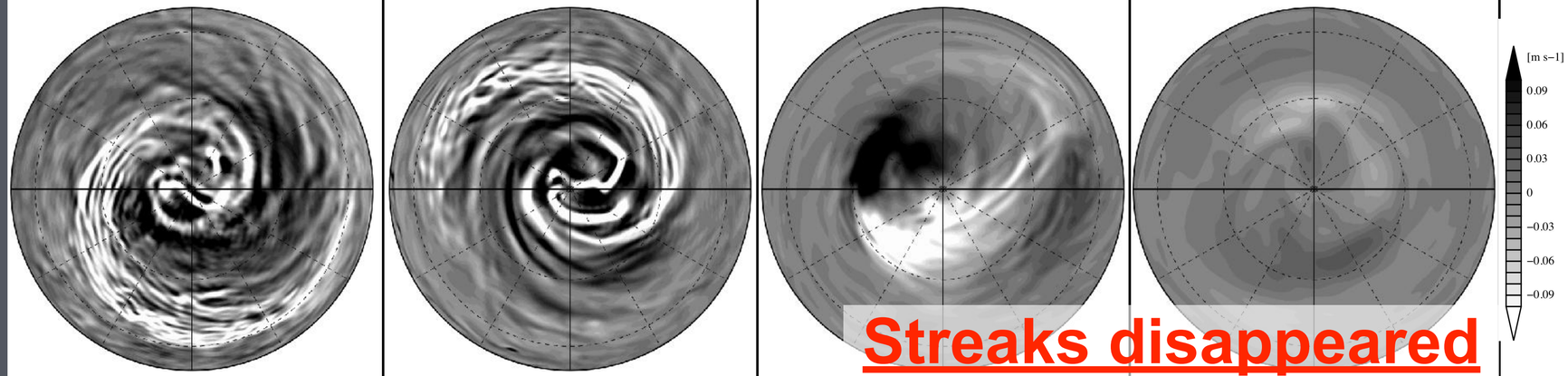



- Synchronized even without the diurnal heating.

➡ **Diurnal heating is NOT a reason for the synchronization.**

| Diurnal heating | with | without | |
|---|---|---|---|
| Stability | 0.1 K/km | 2 K/km | 4 K/km |

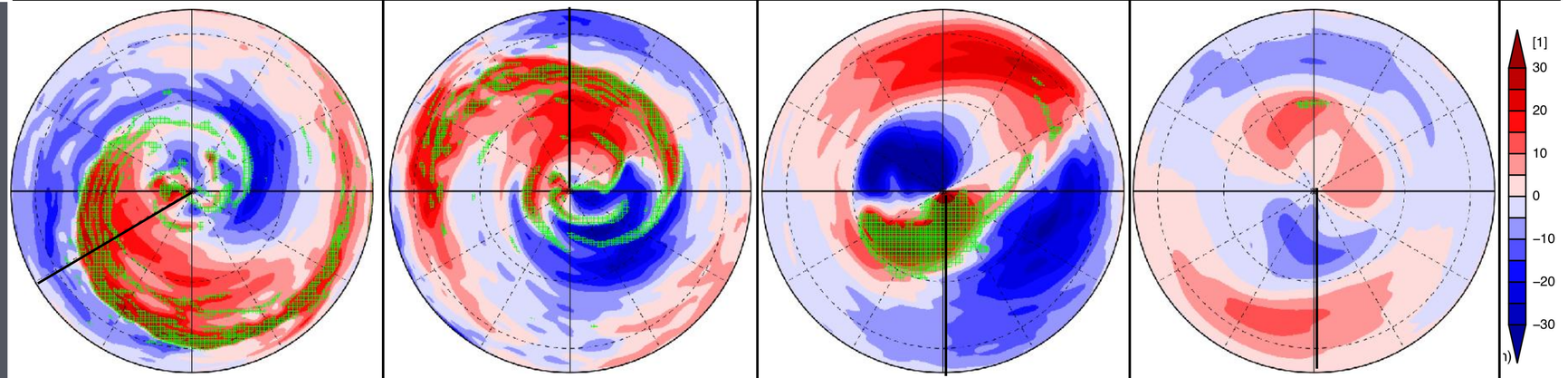
**W**
seen from above south pole



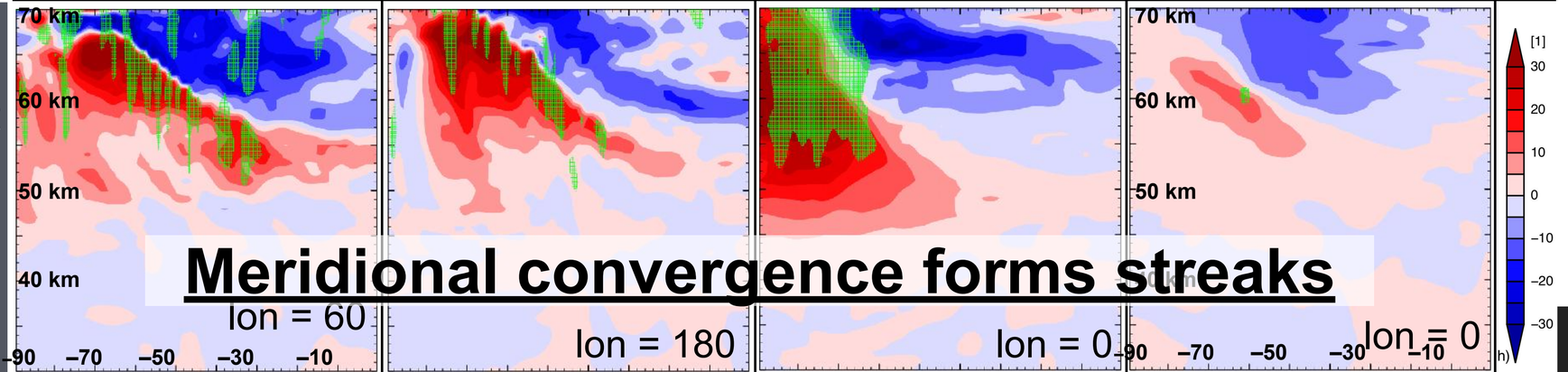

**Streaks disappeared**

**V**
red: eq.-ward
blue: pl.-ward

**strong down-W**
green




same as above but **lat-height** section (southern hemisphere)



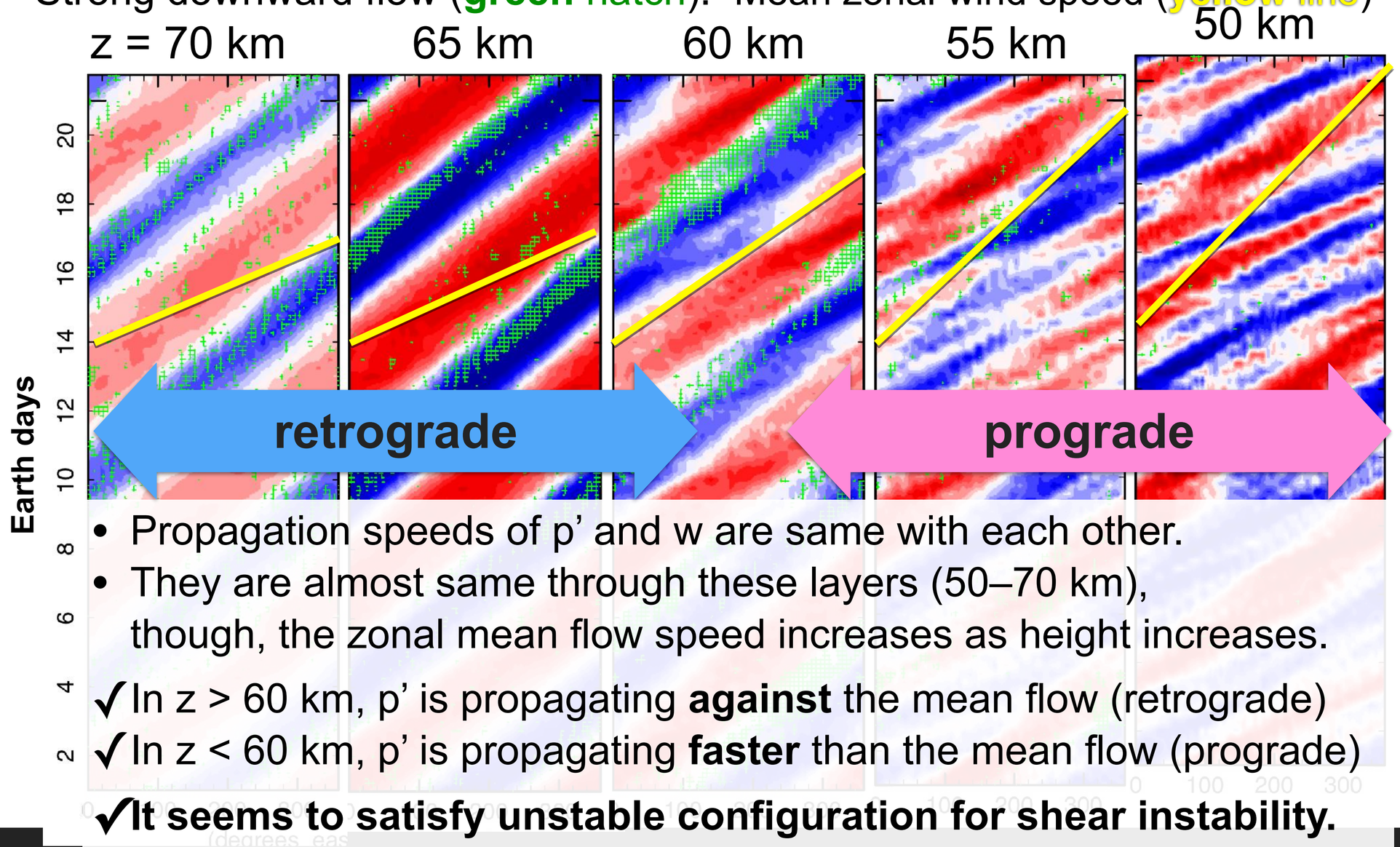

**Meridional convergence forms streaks**

# Three Questions arose:

- **Q1. How are the convergence zone formed?**
- **Q2. How are the streak structures synchronized?**
- **Q3. Why do they disappear in a high-stability case?**

# Longitude-time cross-section at lat = –35 **(No diurnal heating 0.1K/km)**

- Pressure deviation from the zonal mean (**red**-**blue**)
- Strong downward flow (**green** hatch). Mean zonal wind speed (**yellow line**)




- Propagation speeds of p' and w are same with each other.
- They are almost same through these layers (50–70 km), though, the zonal mean flow speed increases as height increases.

✓In z > 60 km, p' is propagating **against** the mean flow (retrograde)

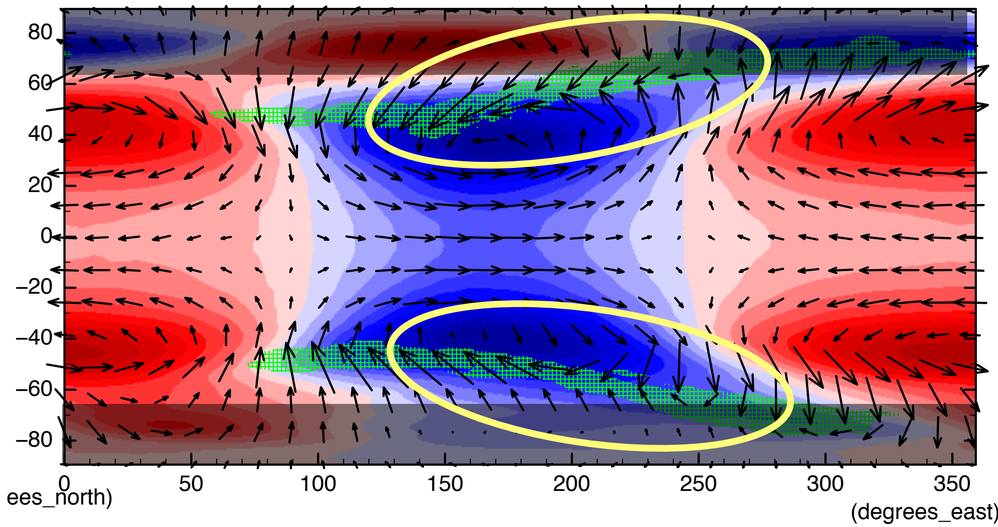
✓In z < 60 km, p' is propagating **faster** than the mean flow (prograde)

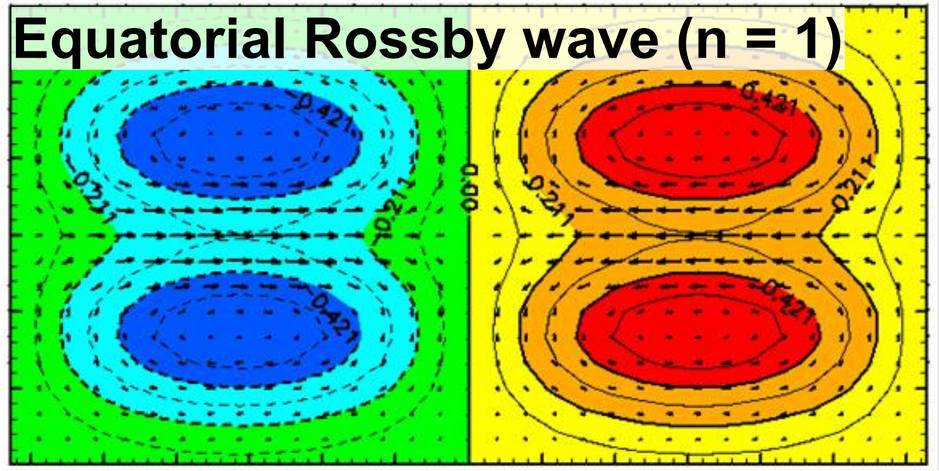
✓**It seems to satisfy unstable configuration for shear instability.**

# Composite mean along the wave propagation (6.25 days)

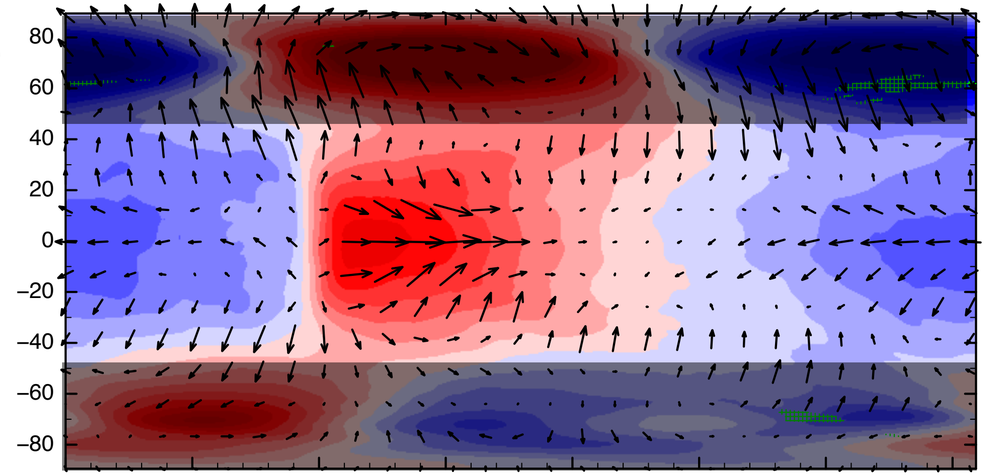
## p' [red-blue], (u', v') [vectors], & w [green hatch] (No diurnal heating 0.1K/km)

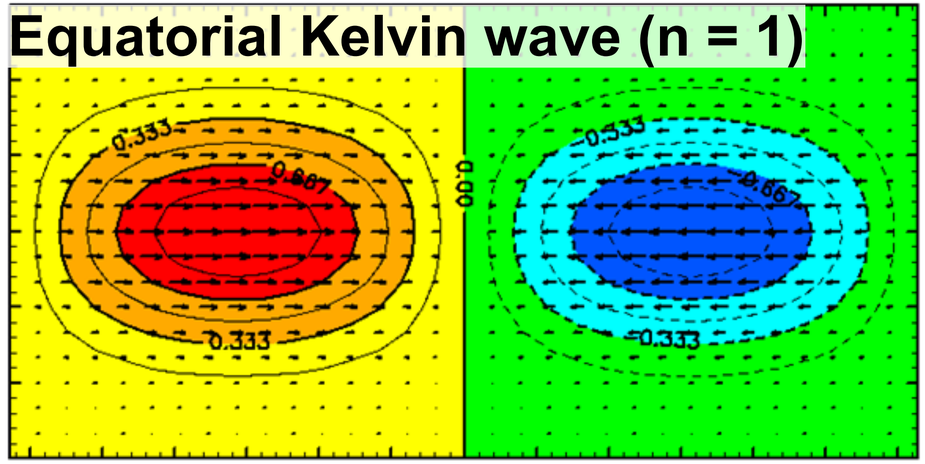
**65 km height**




**55 km height**




(1) k = 0.5, omg = 0.500

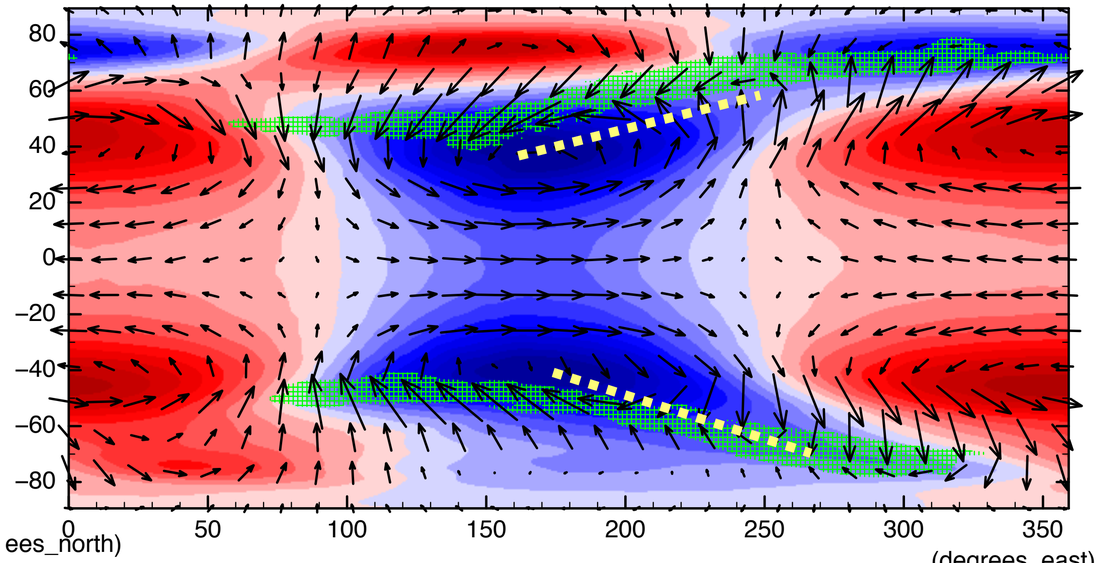
- In mid- and low-latitudes, there are equatorial Rossby-like wave in the upper layer and equatorial Kelvin-like wave in the lower layer, which are seems to be connected by shear instability.
  ✓**And these waves regulate the north-south symmetry. (Answer to Q2)**
- The convergence zone is associated with the equatorial Rossby-like wave.

Fig: Nakajima et al. (2012)

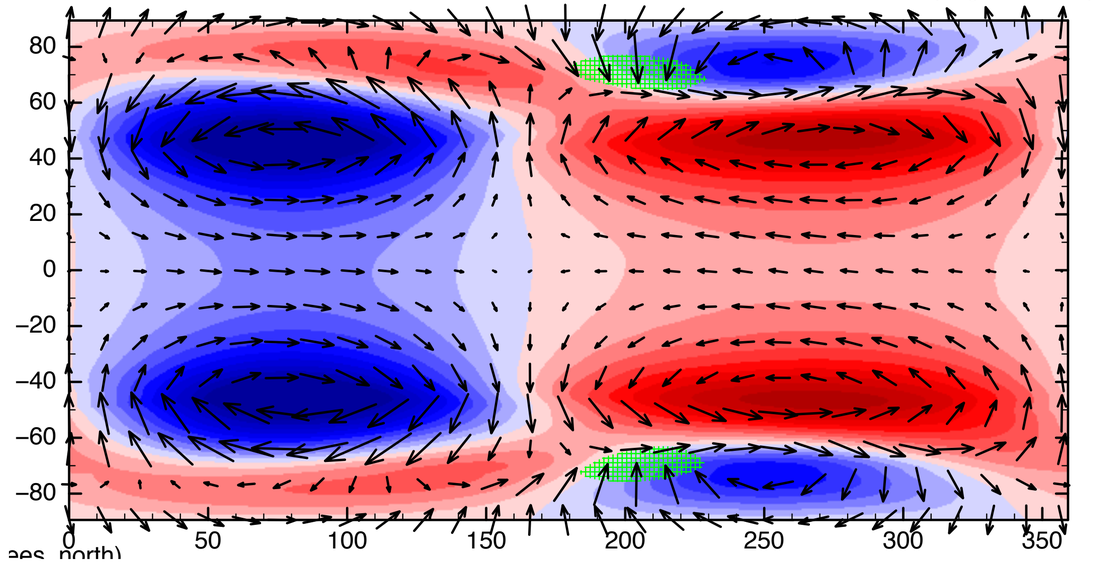
Composite mean along the wave propagation:

p’ [red-blue], (u’, v’) [vectors], & w [green hatch]

**Low-stability case (0.1 K/km)**




**High-stability case (4.0 K/km)**




- The Equatorial Rossby-like wave appears both in the Low-stability case and in the High-stability case.
- In the Low-stability case, **the phase line** of the Rossby-like wave is **meridionally tilted**; however, such tilting cannot be seen in the High stability case.

✓**Meridional tilting of the phase line would form the meridional convergence zone, which causes the streak structure. (Answer to Q1)**

65 km height

Composite mean along the wave propagation:

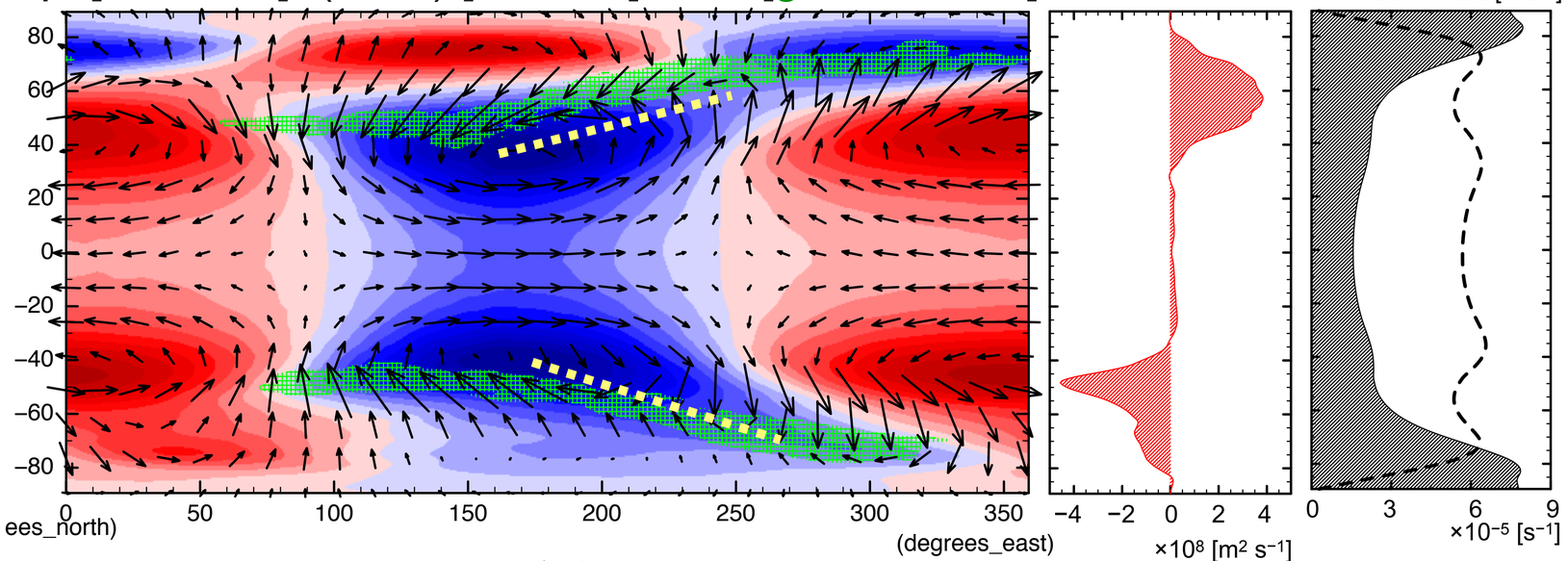
p’ [red-blue], (u’, v’) [vectors], & w [green hatch]

$\overline{v'M'}$

$\overline{\text{Ang. Vel.}}$ & $\overline{u}$

(shaded region) (dashed line)

**Low-stability case (0.1 K/km)**





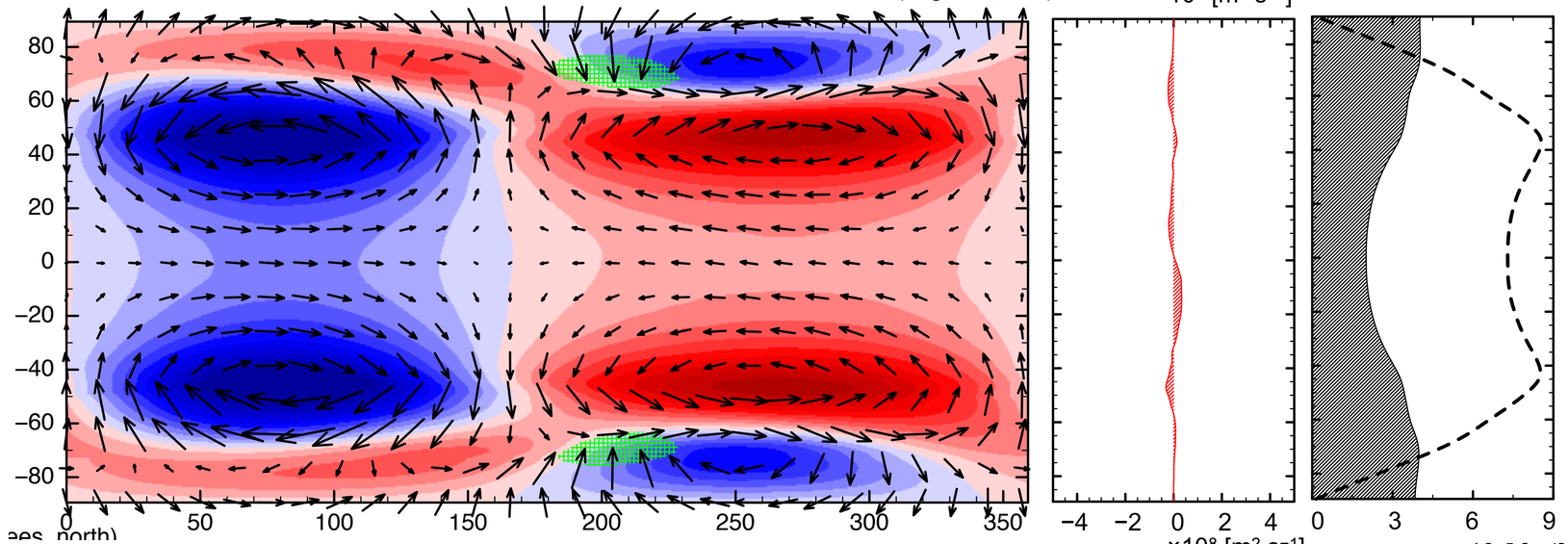





← **high-lat. jet**

← **mid-lat. jet**

**High-stability case (4.0 K/km)**










← **mid-lat. jet**

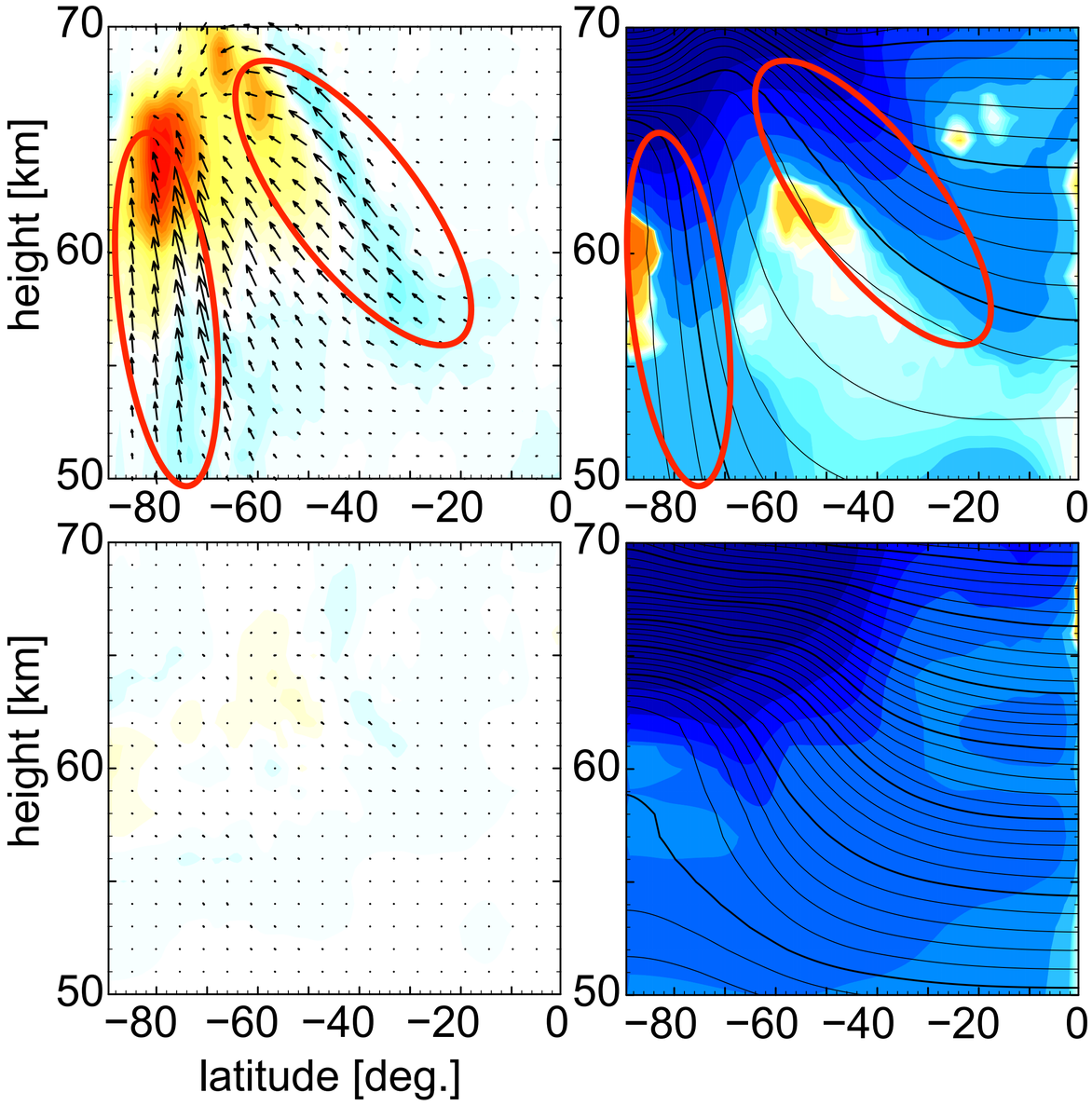
65 km height

**Low stability case (0.1 K/km)**

**High stability case (4.0 K/km)**

eddy heat transport (vectors) & convergence (color)

Potential Vorticity (color) & potential temperature (contour)

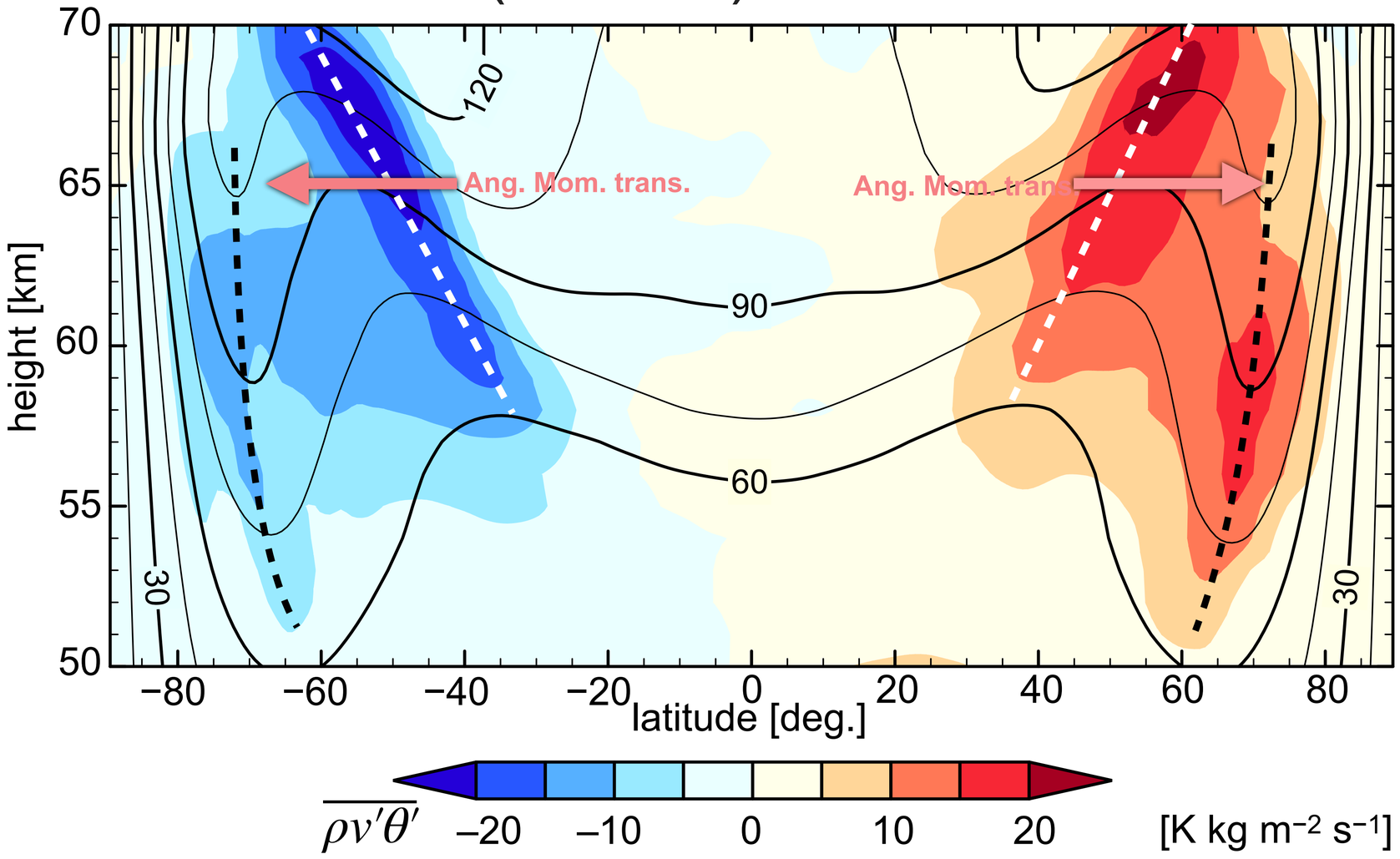



- Lager poleward and upward heat transport by eddies exists in Low-stability case, but not in Higher case.
- In Low-stability case,
  - heat fluxes can be grouped in two: one in mid-latitudes and the other in high-latitudes.
  - There are also pairs of layers with opposite PV-gradient (along with isentropic surface)

➡**Baroclinc instability** might appear both in mid-latitudes and in high-latitudes.

✓**Baroclonic instability does not occur in High-stability case (Answer to Q3.)**

# Zonal- & time-mean of **meridional heat transport by eddies** (red-blue) and **zonal wind** (contour)




**<u>In High-latitudes</u>**

- Locations of the jet axis and the peak of heat transport agrees.

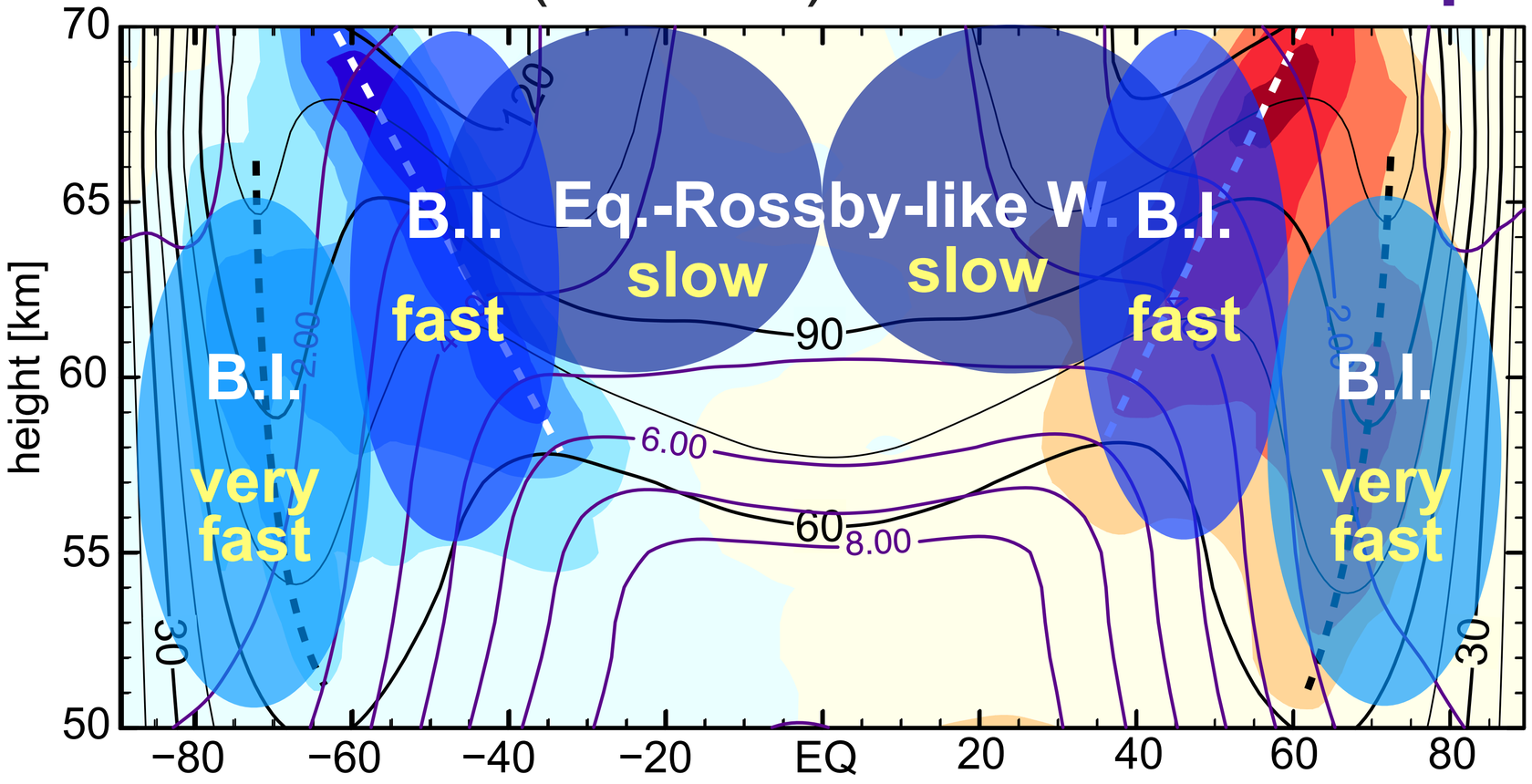
➡ The jet would be formed by “PV stirring”, the same manner as the mid-latitude jet in Earth.

**<u>In Mid-latitudes</u>**

- Locations of the jet axis and the peak of heat transport **do not** agree.

➡ This baroclinic instability may be unique to the Venus atmosphere…

# Zonal- & time-mean of meridional heat transport by eddies (red-blue) and zonal wind (contour) **+ mean rotation period (purple cont.)**

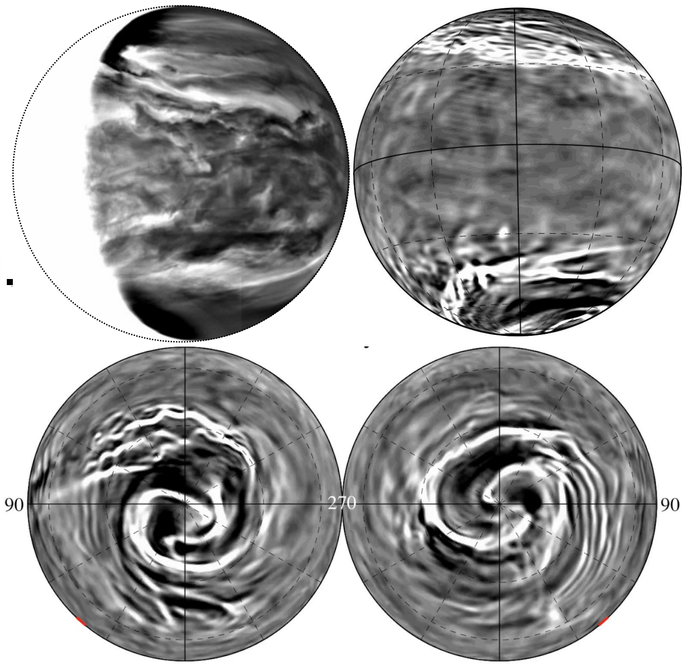


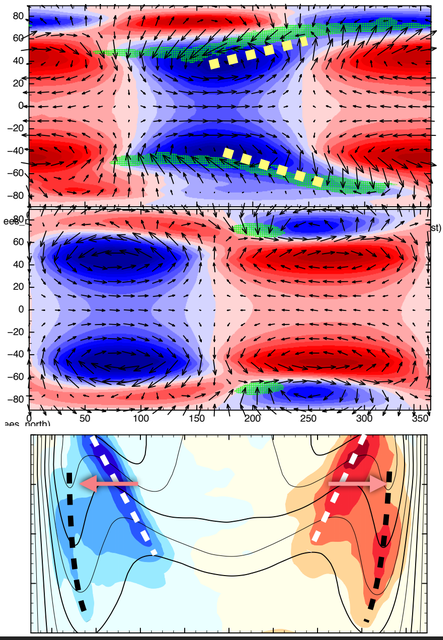

- Rotation period of the eq.-Rossby-like wave is about 6 days.
- However that of baroclinic perturbation in mid- and high-lat. seem to be shorter due to the distribution of the rotation period of the mean flow.

➡Slow eq.-Rossby-like wave is stretched and inclined by jets induced by fast baroclinic perturbations.

# Summary

- **Planetary-scale streak structures** *similar to those observed in a night side IR2 image* are reproduced in <u>vertical velocity</u> 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 edge of the poler region to about lat = 30 deg.
    - **synchronized** in the northern and southern hemisphere.
  - Num. exps. <u>without diurnal heating</u> and <u>changing the static stability</u> of the “low stability layer” are performed; and the results suggest that
    - ✓**Synchronization is caused by the vertically coupled Rossby-like and Kelvin-like waves in the equatorial region.**
    - ✓**Streak structure is formed by meridional tilting of the phase line of the Rossby-like wave.**
    - ✓**The tilting would be triggered by the Baroclinic instability in mid-latitudes and in high-latitudes, which is produced around the the low-stability layer.**



Please check Kashimura *et al*. (2019) in *Nature Communications* (open access) for more details.