Modeling of streak structure observed by Akastuski

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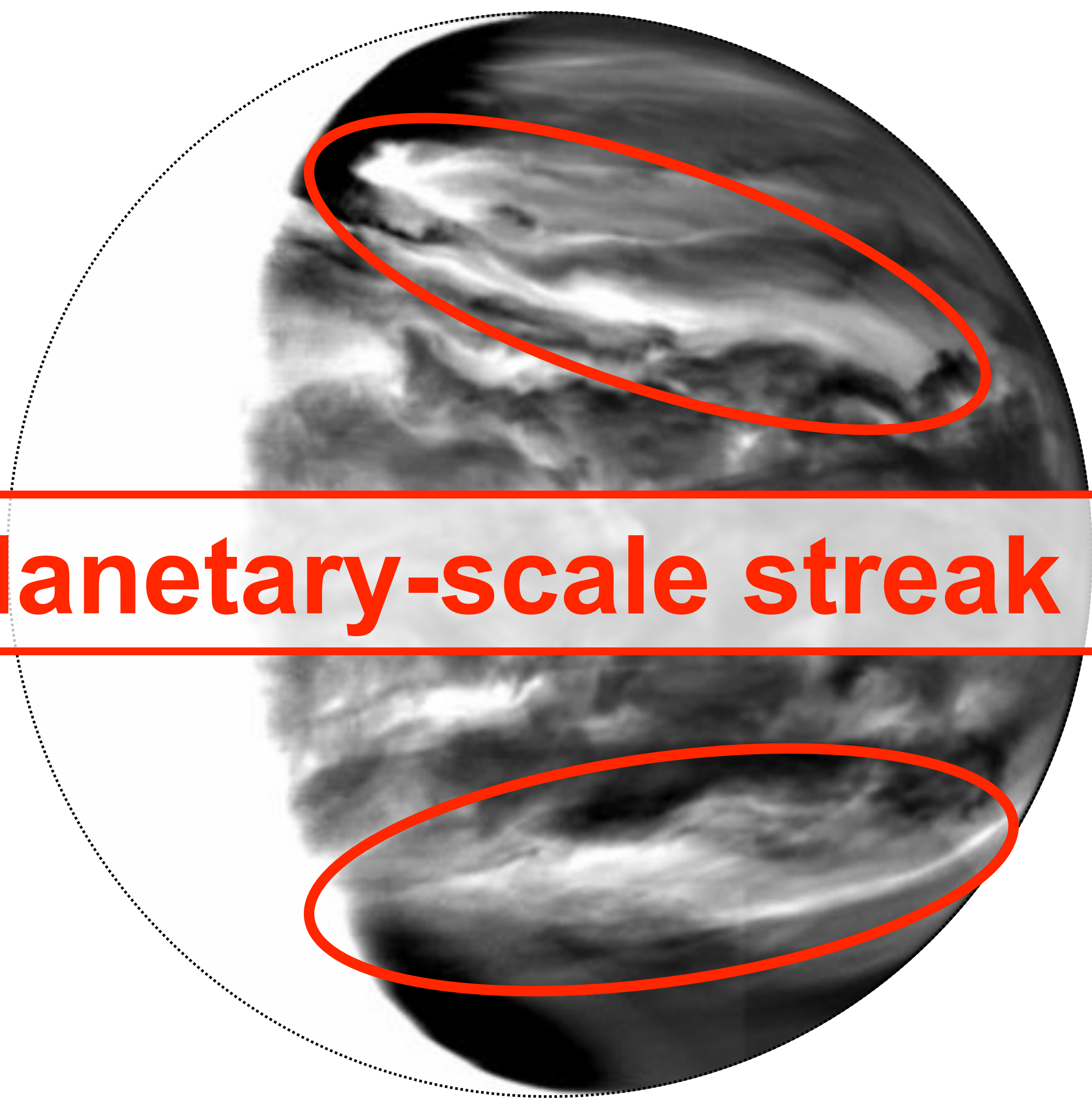
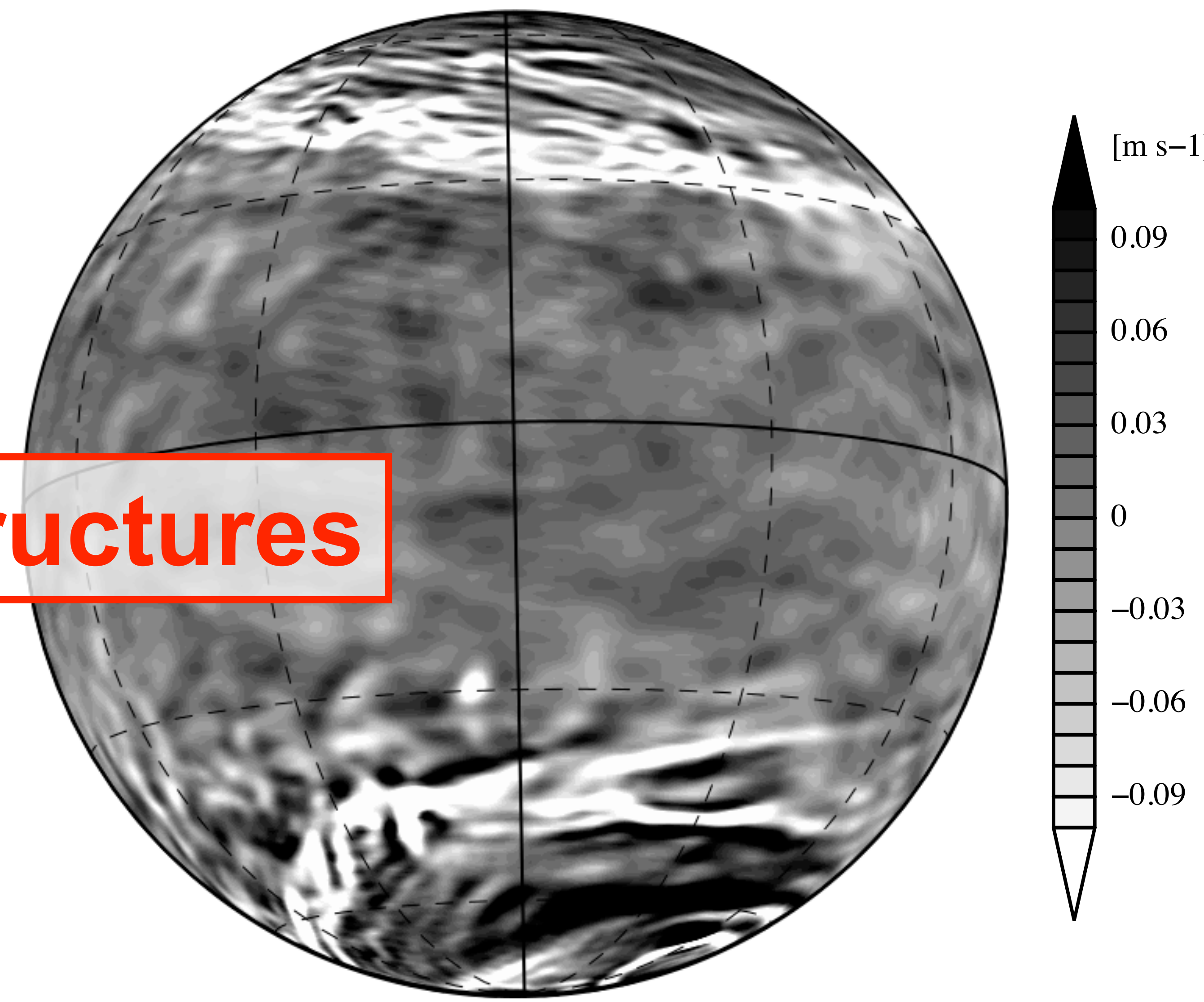
Venus night-side image taken by Akatsuki IR2 camera



Planetary-scale streak structures

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

Vertical velocity field produced in our Venus GCM

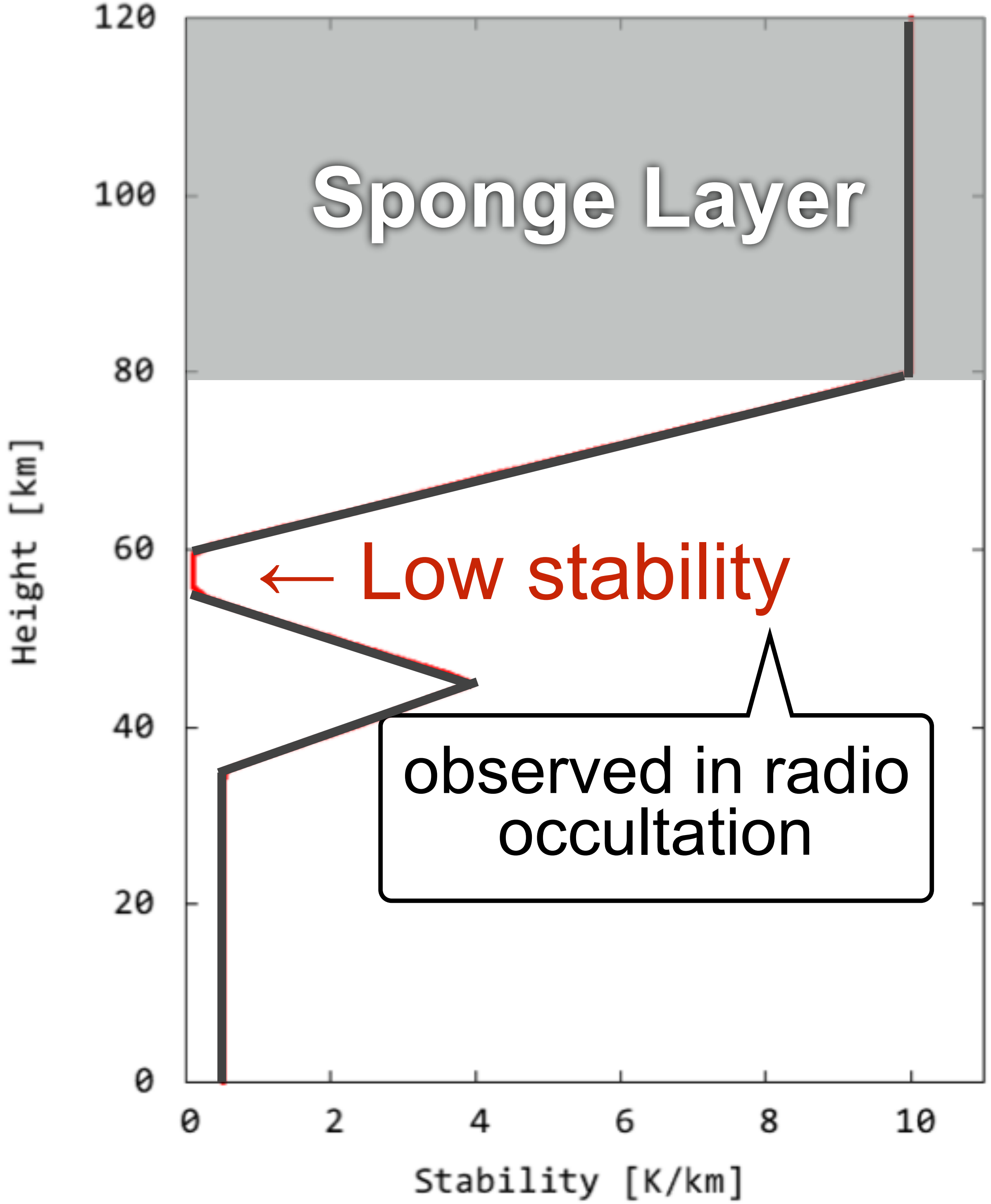


- Snapshot of vertical velocity at z = 60 km.
  - White = downward flow
  - Black = upward flow

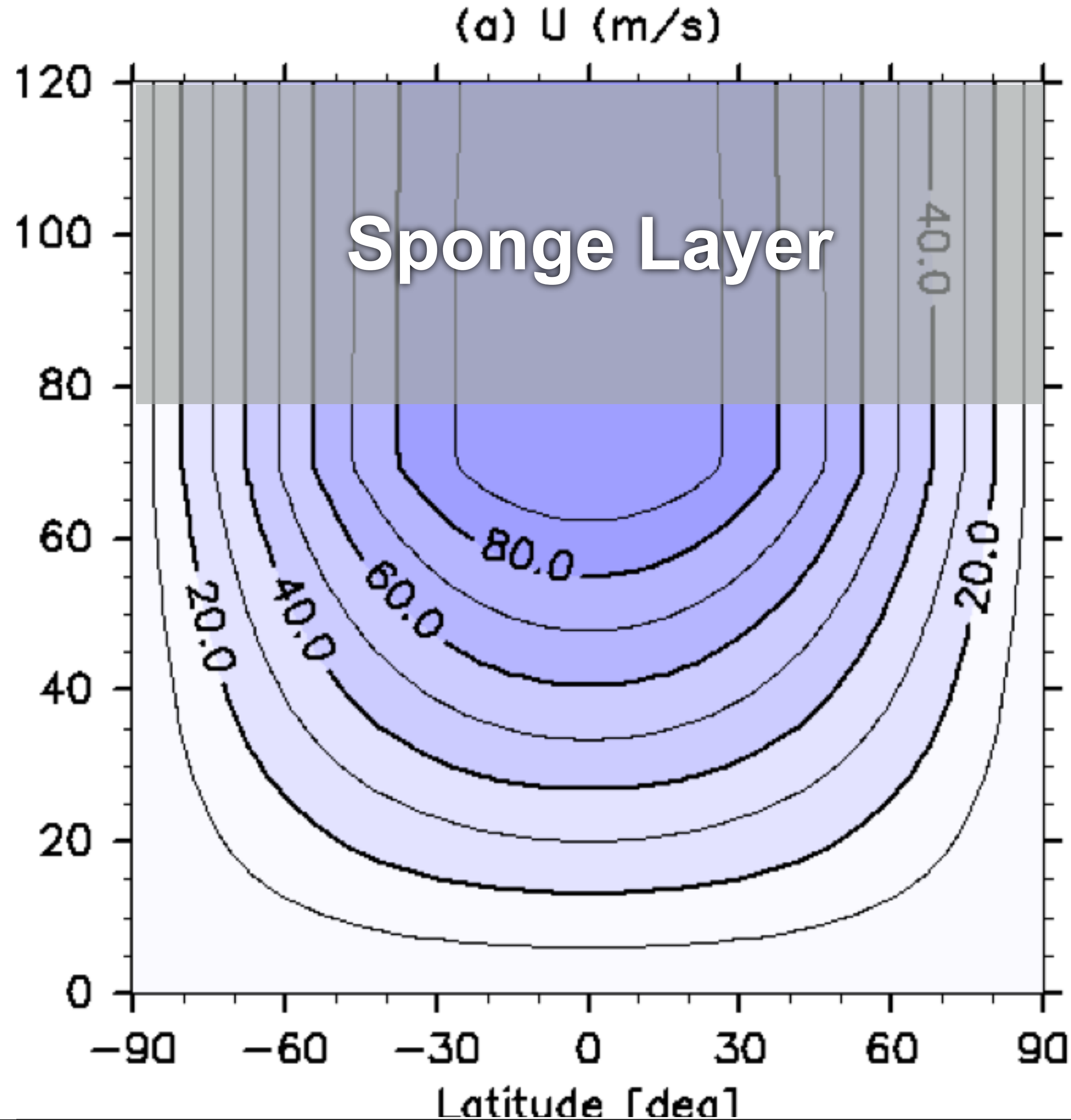
Our simplified Venus GCM

- 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 (Δz ~ 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 (∇^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)

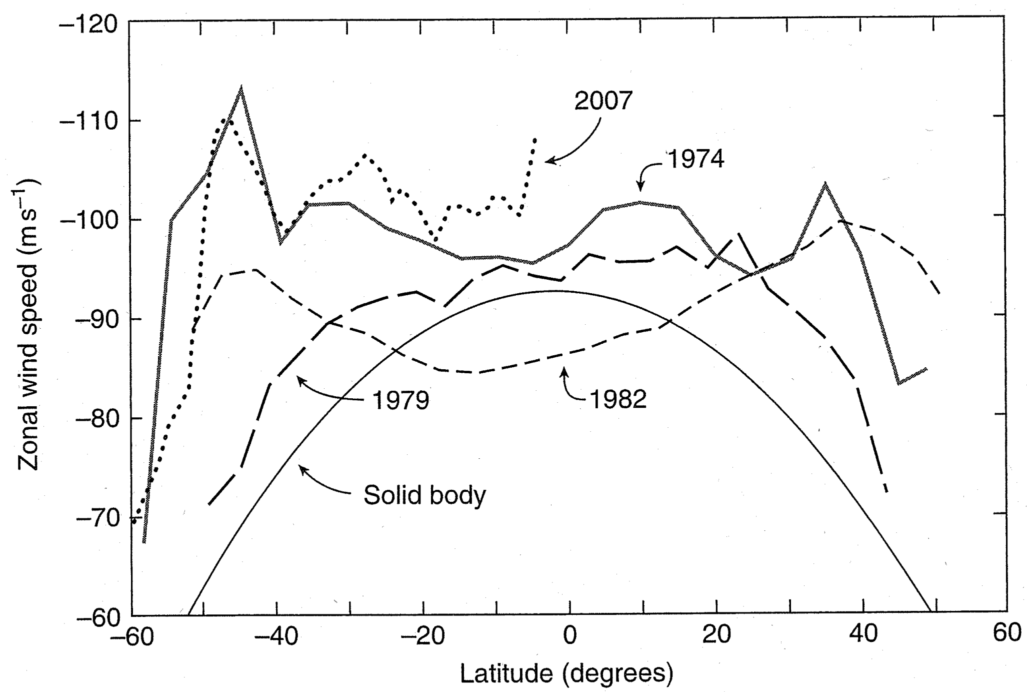


Initial state: superrotation

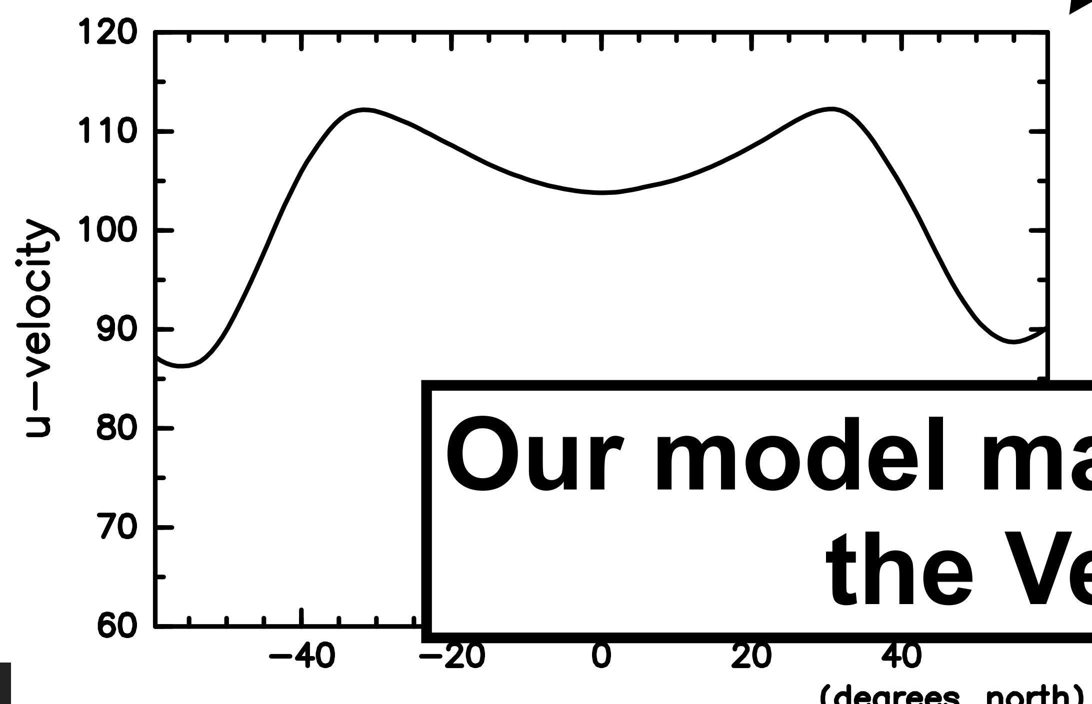


Results | zonal mean zonal wind

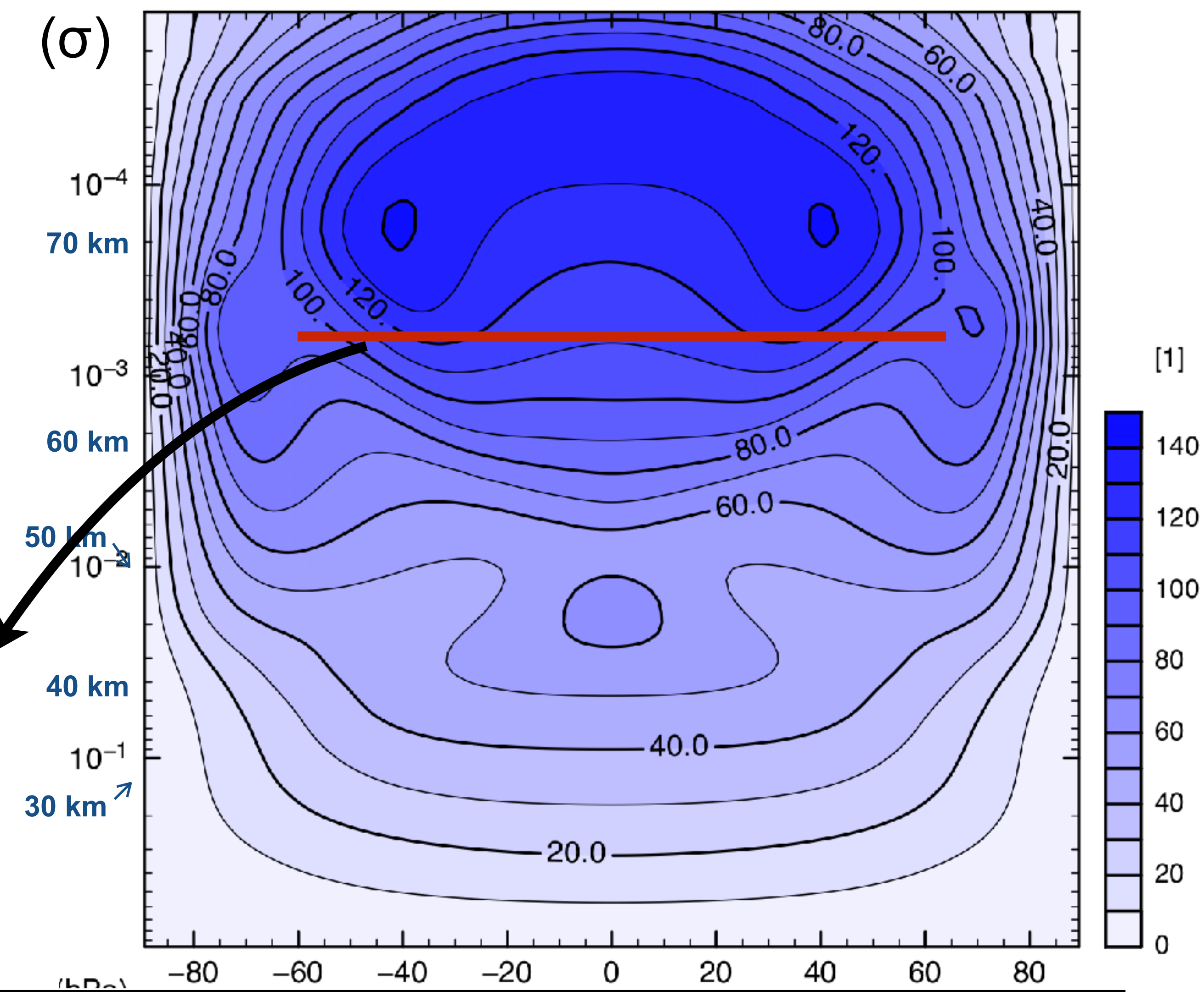
Observation: cloud tracked wind



(Taylor 2010)

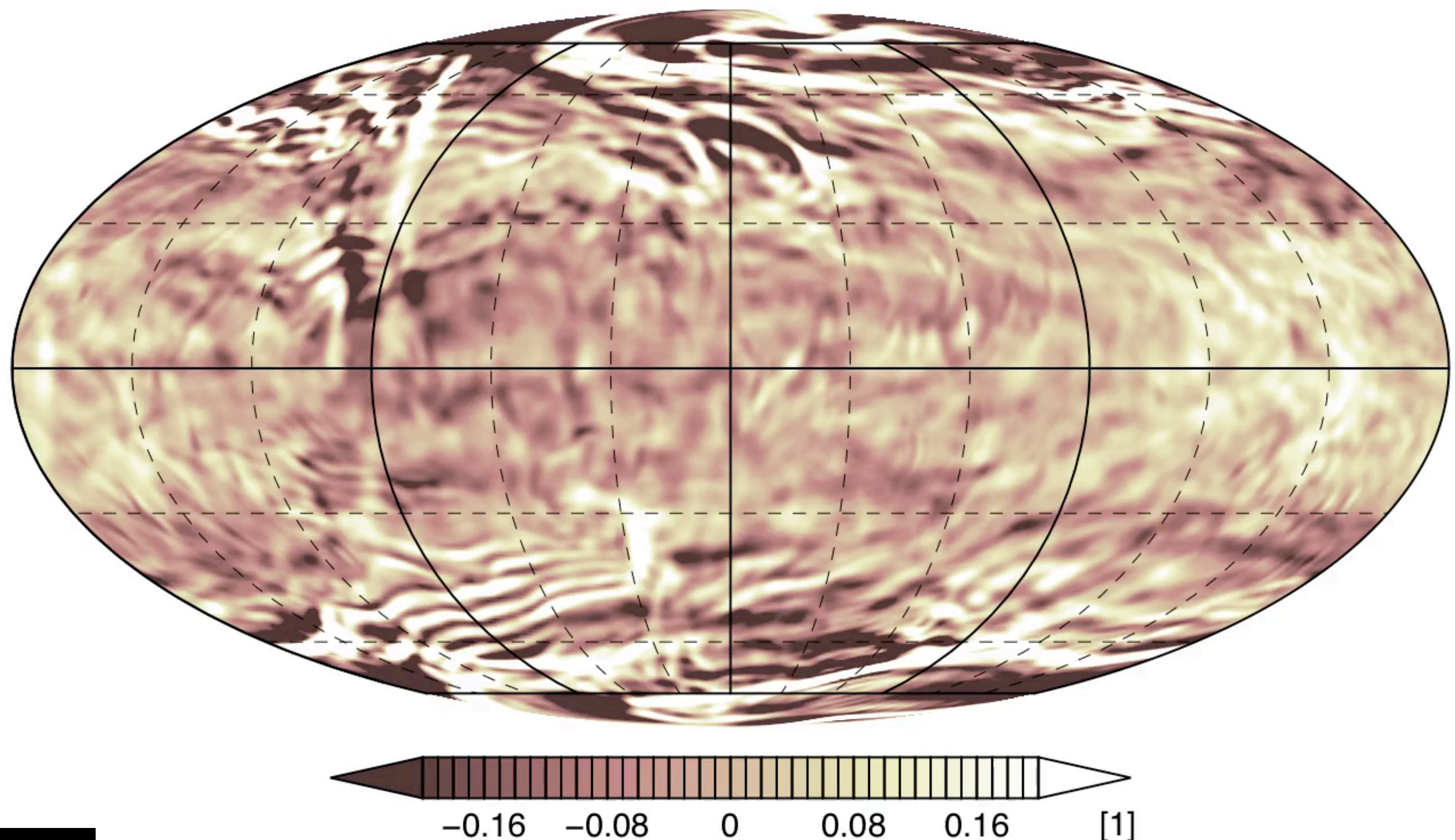


Time mean for last 1 Earth year



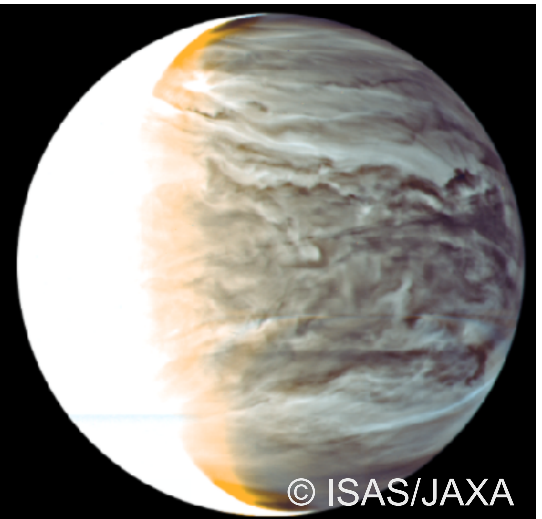
Our model may simulate circulation of the Venus atmosphere

Vertical p-velocity | movie (dt = 1h)



z ~ 60 km

z=0.0018708 hPa
0005−01−01 01:00:00+0000



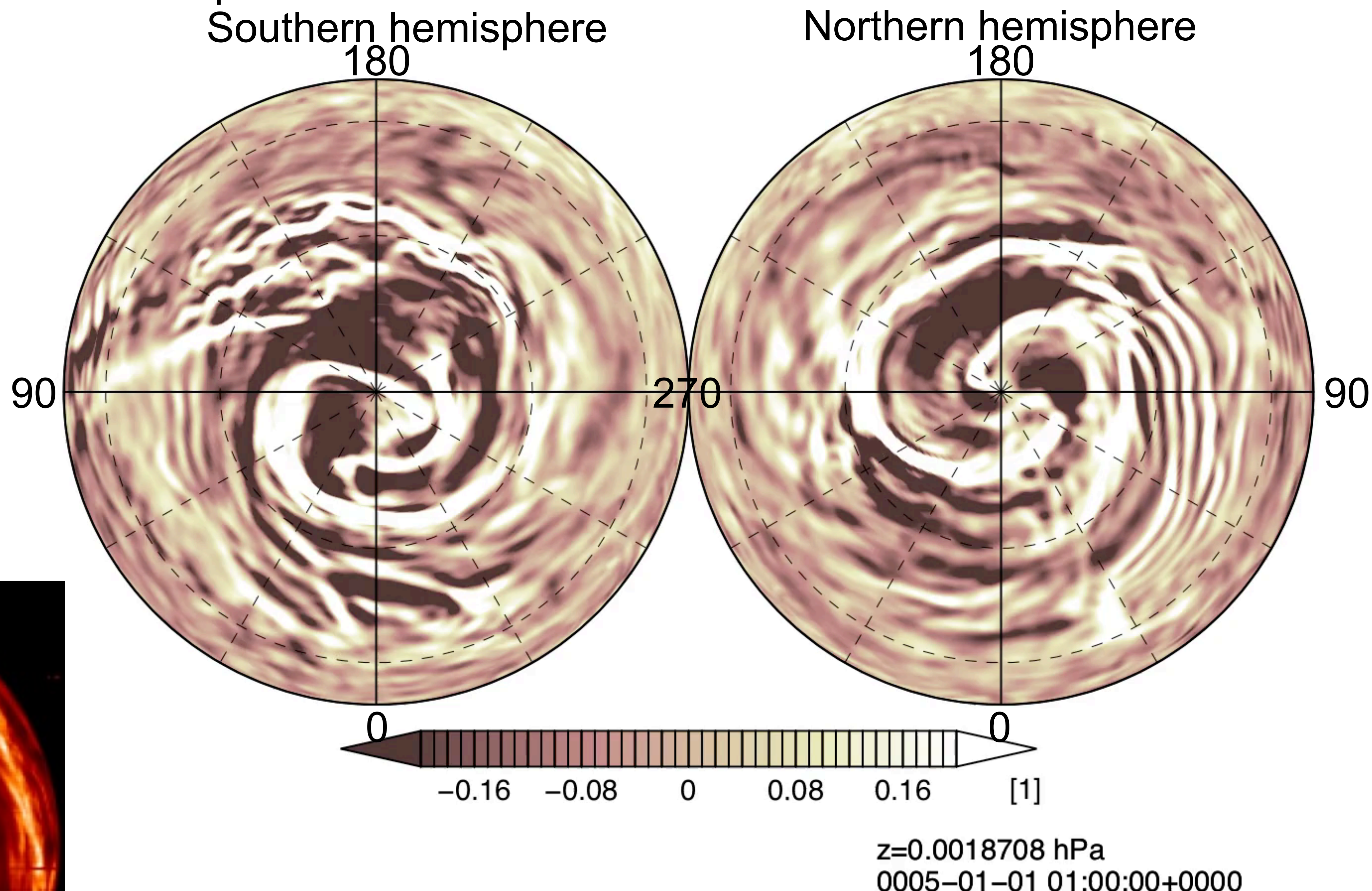
←IR2-nightside image

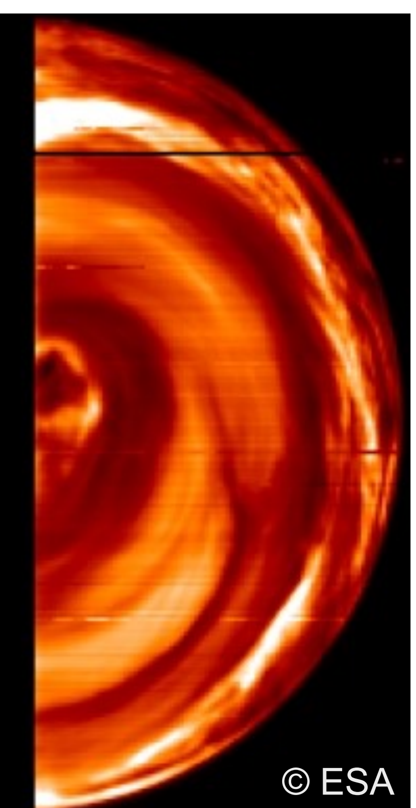
OMG.ctl@OMG,z=2E−3

Vertical p-velocity | movie (dt = 1h)

z ~ 60 km

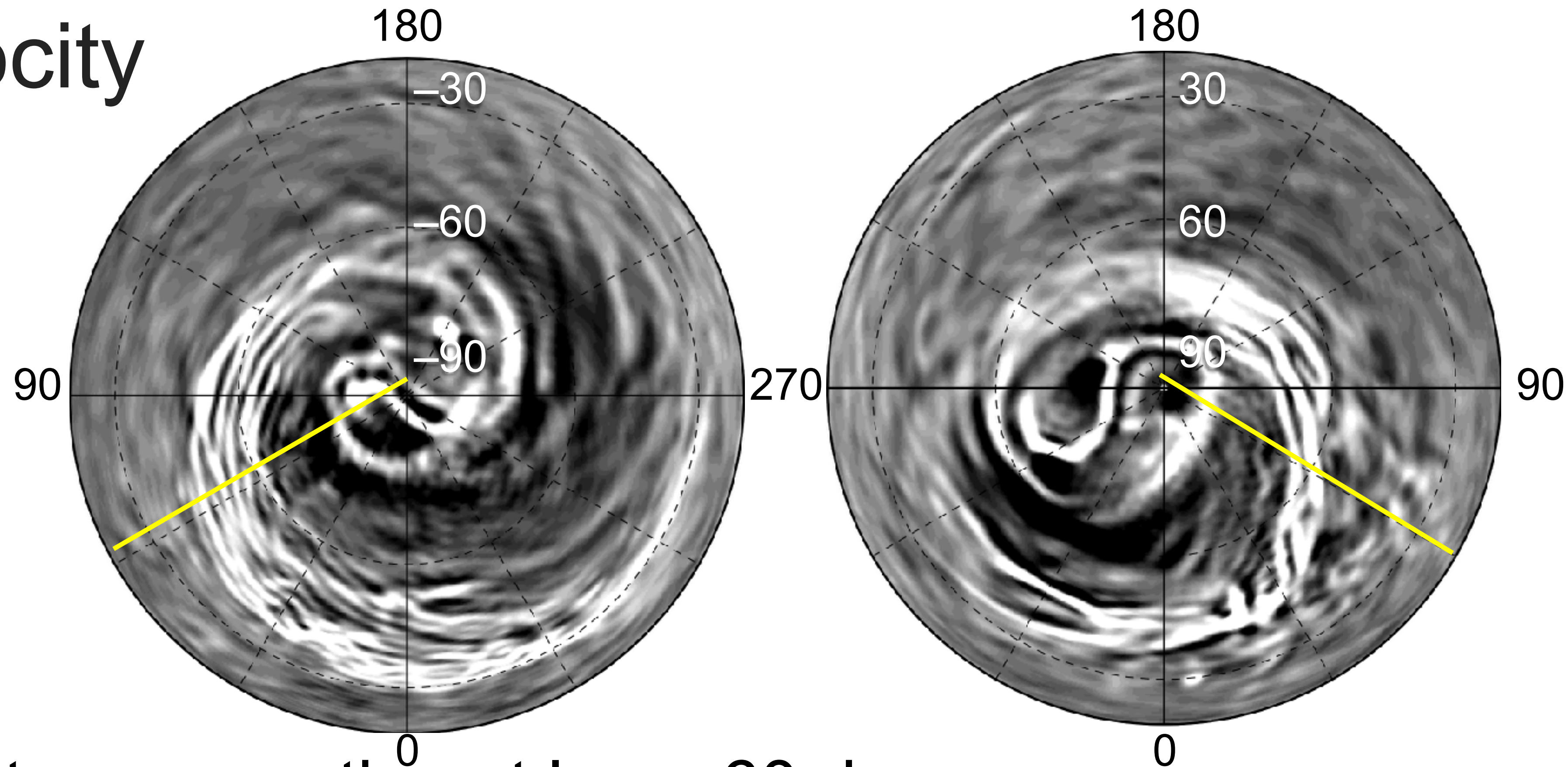
Seen from above the poles



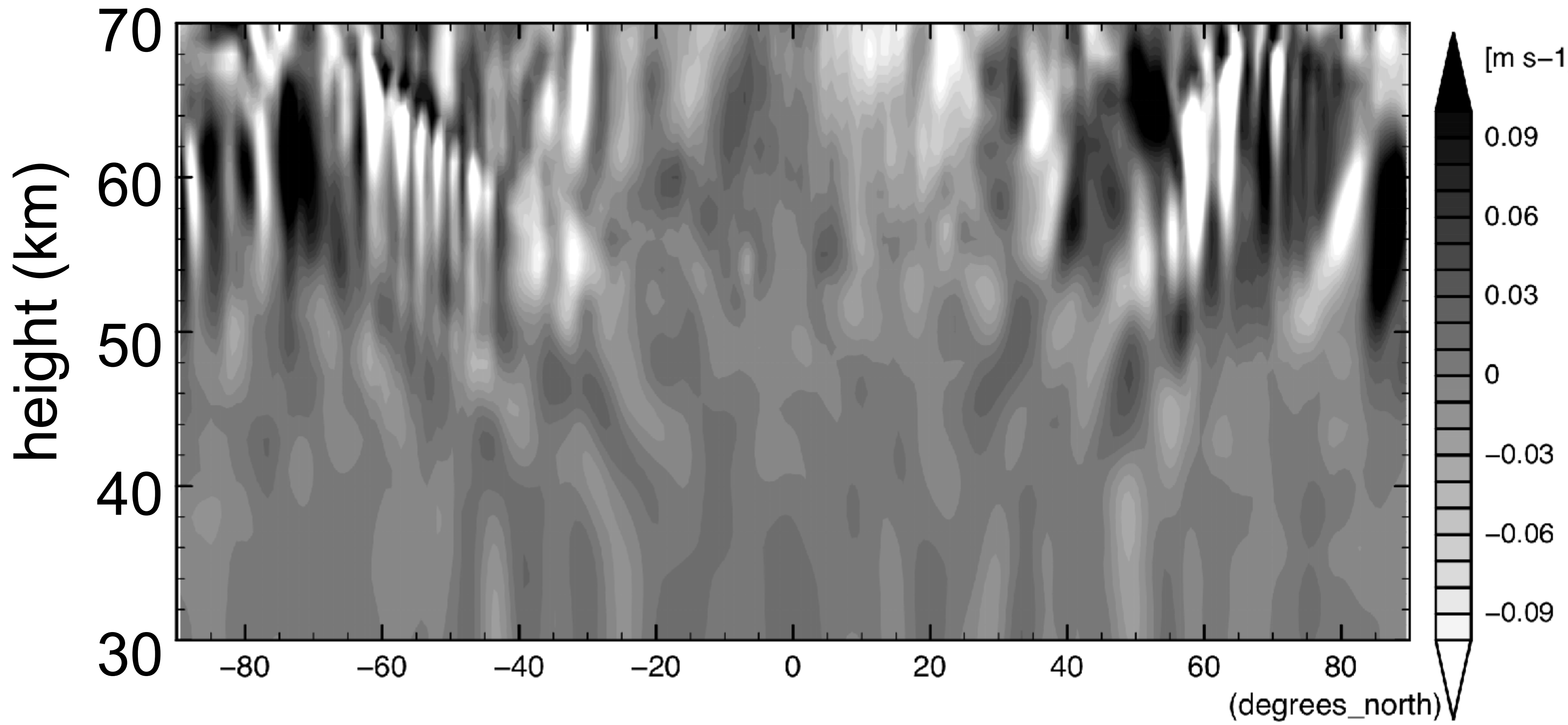


←taken by Venus Express/VIRTIS

Vertical velocity

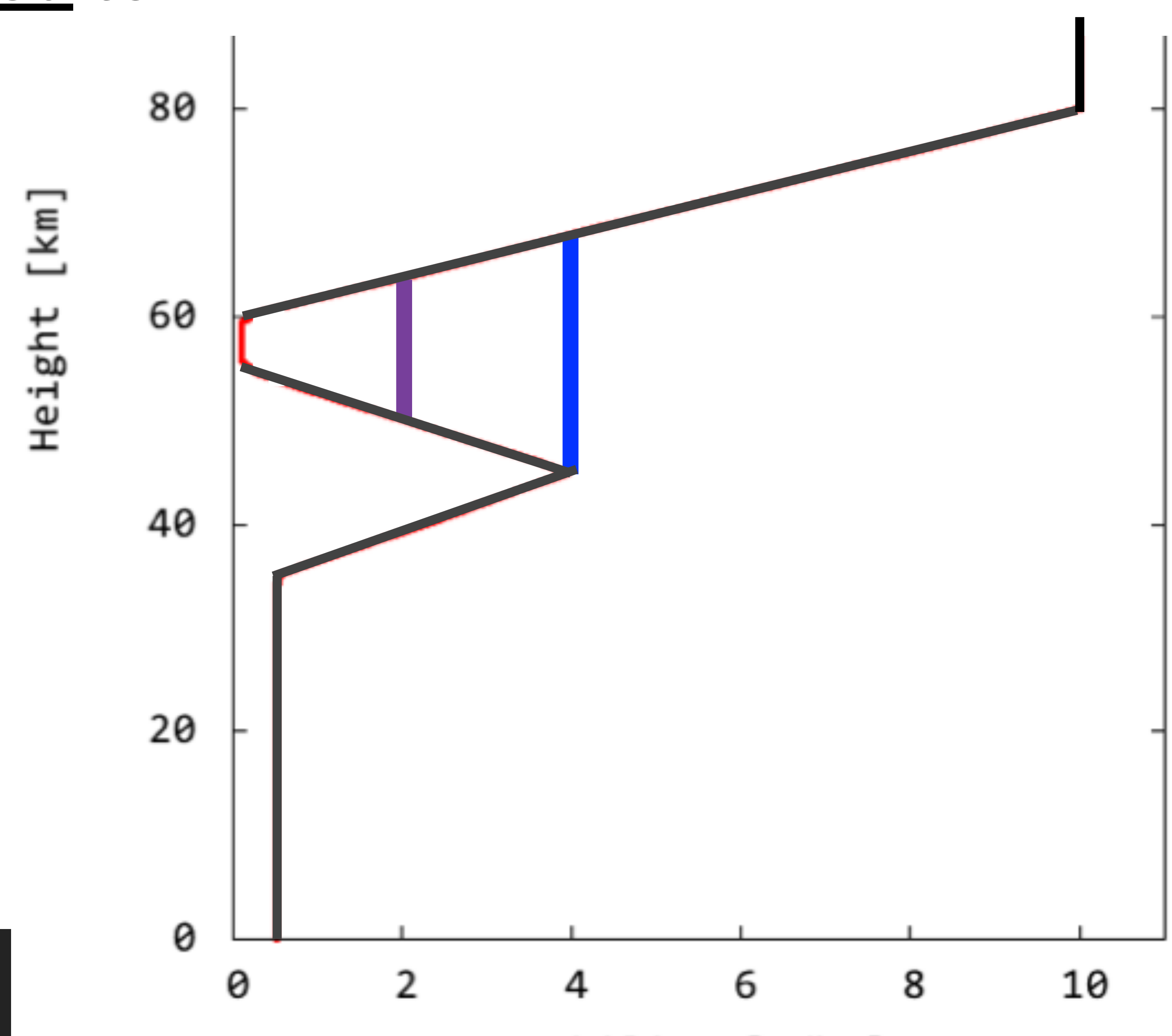


latitude-height cross section at lon = 60 deg



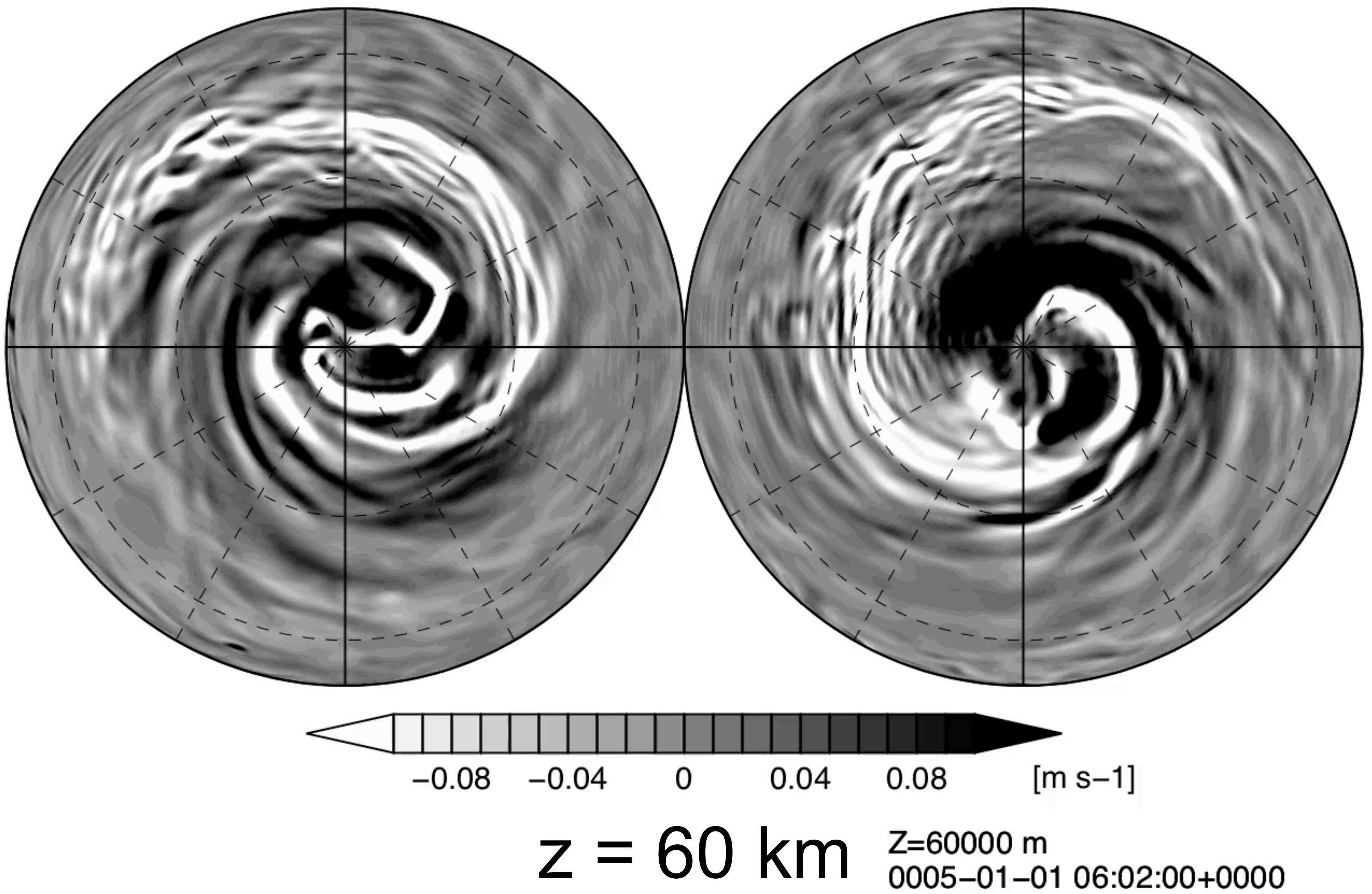
Experiments

- 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**



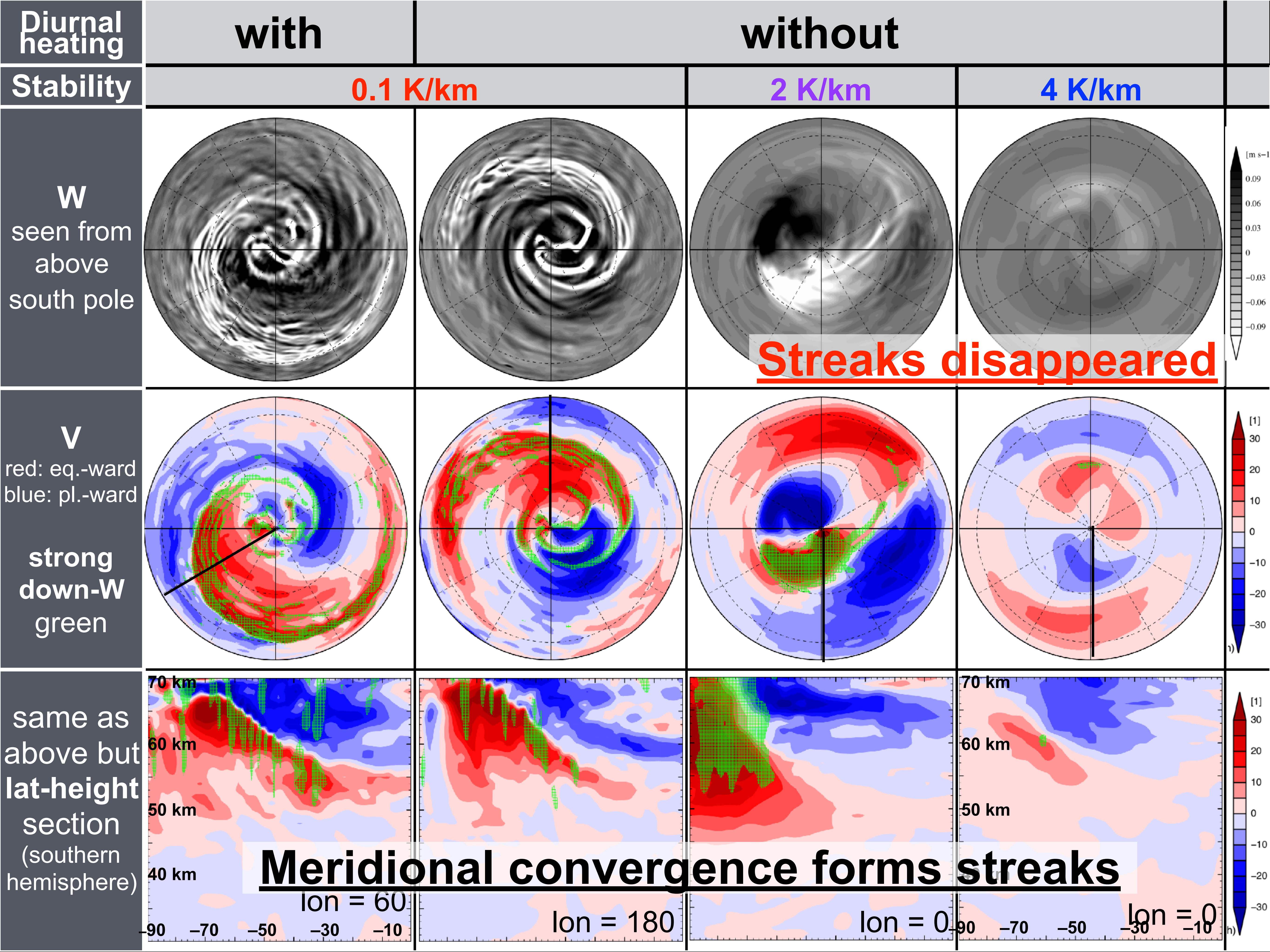
Vertical velocity | movie (dt = 6h)

<u>without diurnal heating</u>



- Synchronized even without the diurnal heating.

➡ **<u>Diurnal heating is NOT a reason for the synchronization.</u>**



Diurnal heating
with
without
Stability
0.1 K/km
2 K/km
4 K/km
W
seen from above south pole
V
red: eq.-ward
blue: pl.-ward
strong down-W
green
same as above but
lat-height section
(southern hemisphere)
Streaks disappeared
Meridional convergence forms streaks
[m s-1]
0.09
0.06
0.03
0
−0.03
−0.06
−0.09
[1]
30
20
10
0
−10
−20
−30
70 km
60 km
50 km
40 km
lon = 60
lon = 180
lon = 0
lon = 0
−90
−70
−50
−30
−10

Two Questions arose:

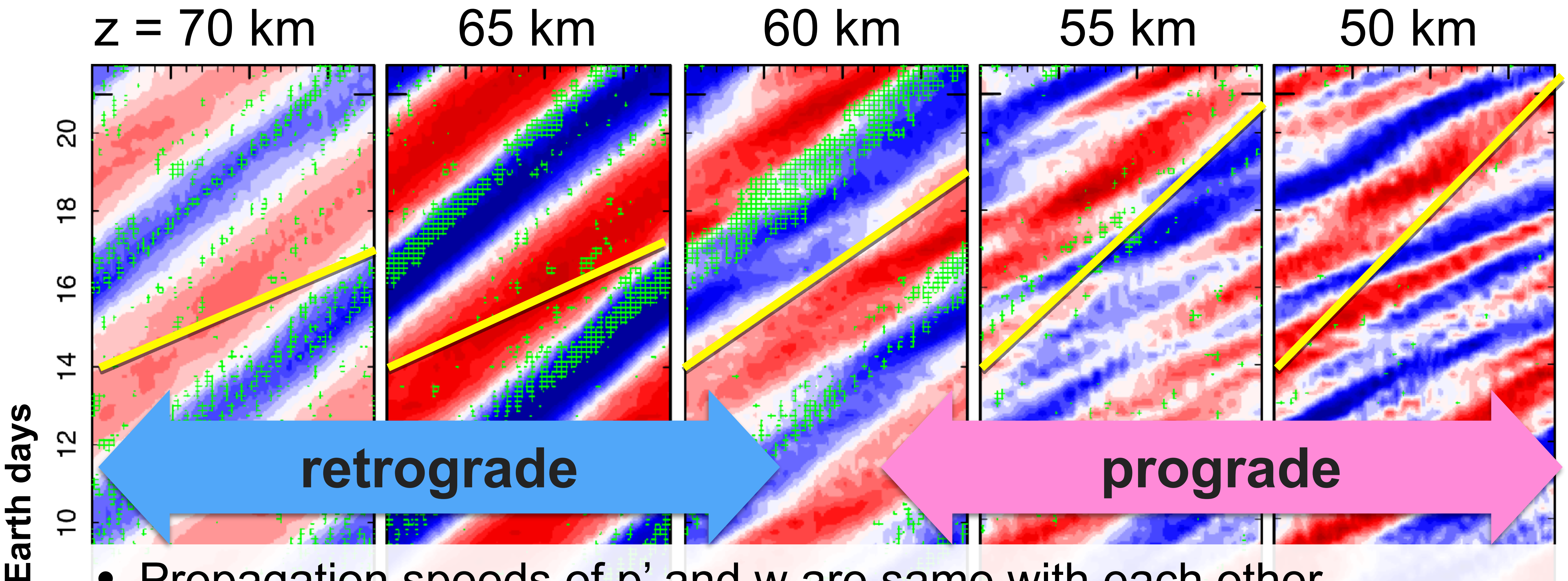
Q1. How are the streak structures synchronized?

Q2. How are the convergence zone formed?

- 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)

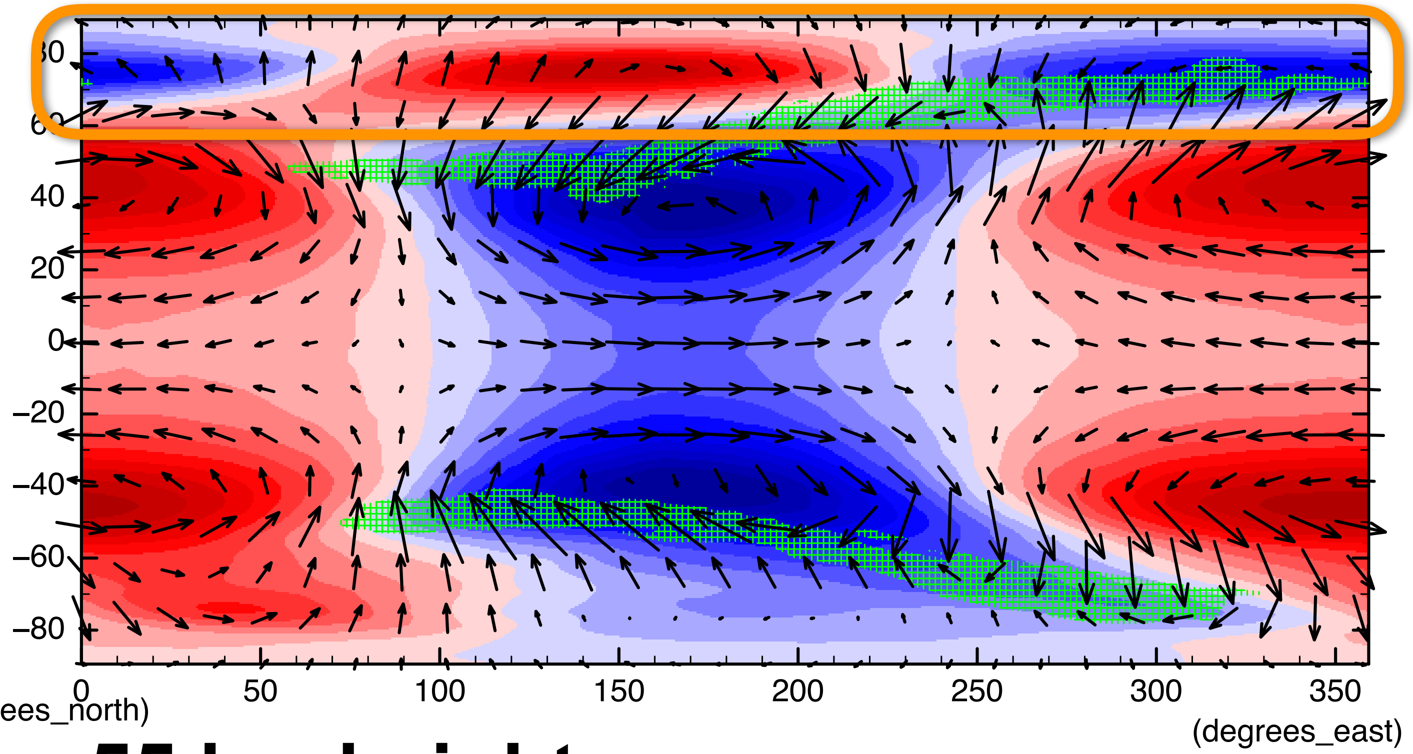
✓In z < 60 km, p' is propagating **faster** than the mean flow (prograde)

✓It seems to satisfy unstable configuration for shear instability.

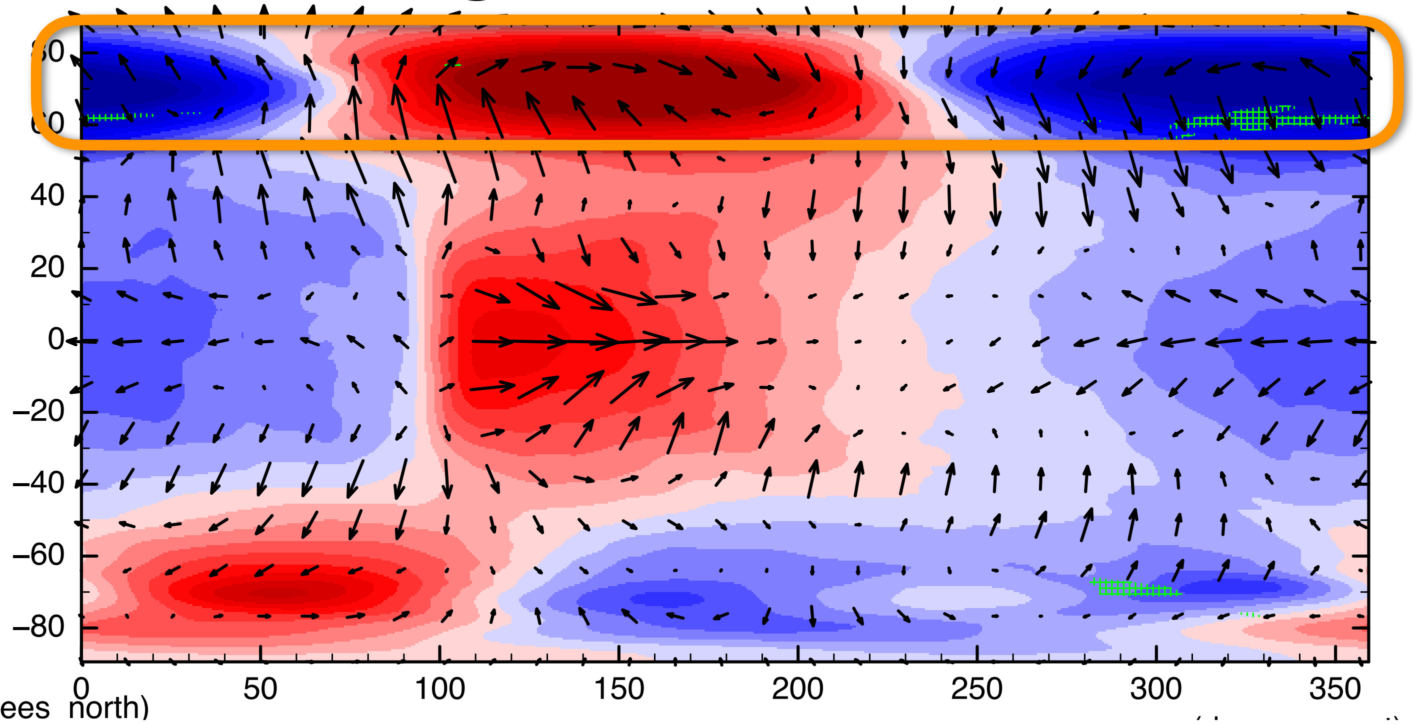
Composite mean along the wave propagation (6.25 days)

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

65 km height



55 km height

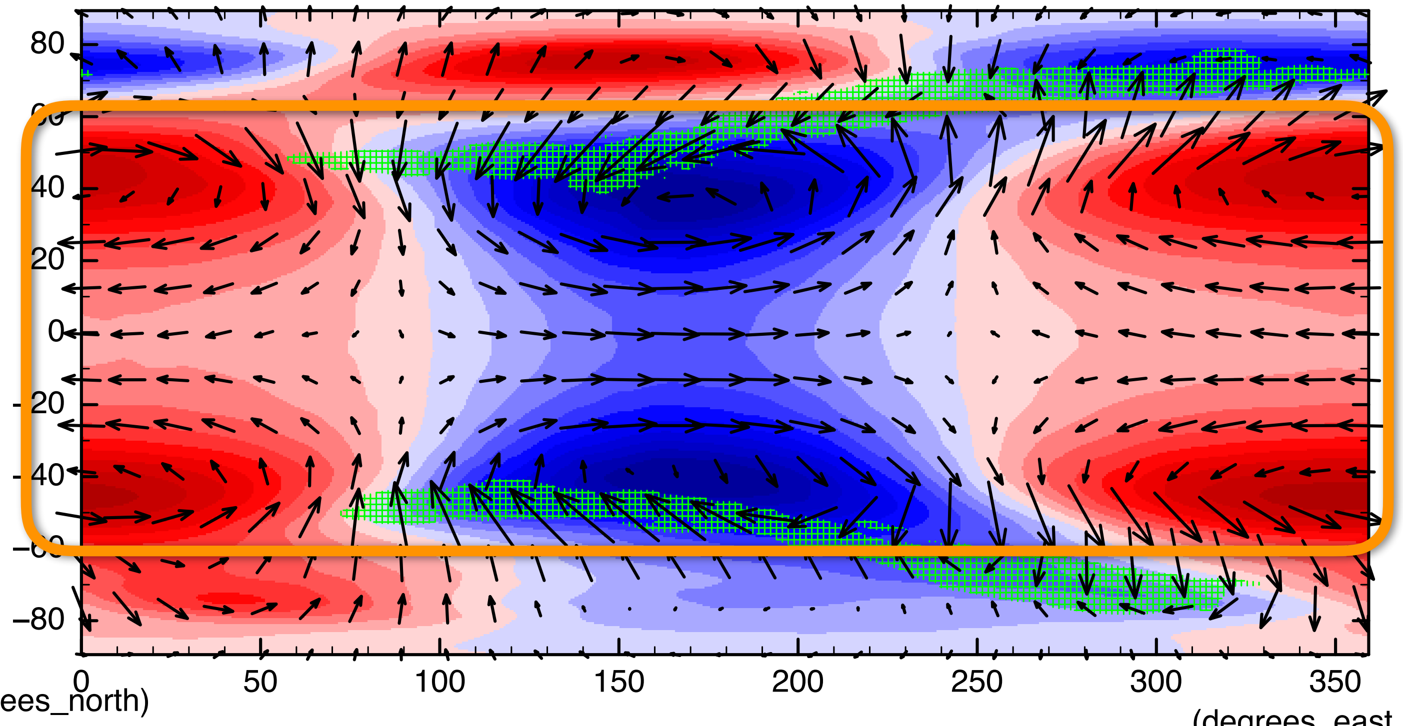


- **Pairs of p' in polar-region is due to the barotropic instability. (Sugimoto et al. 2014)**

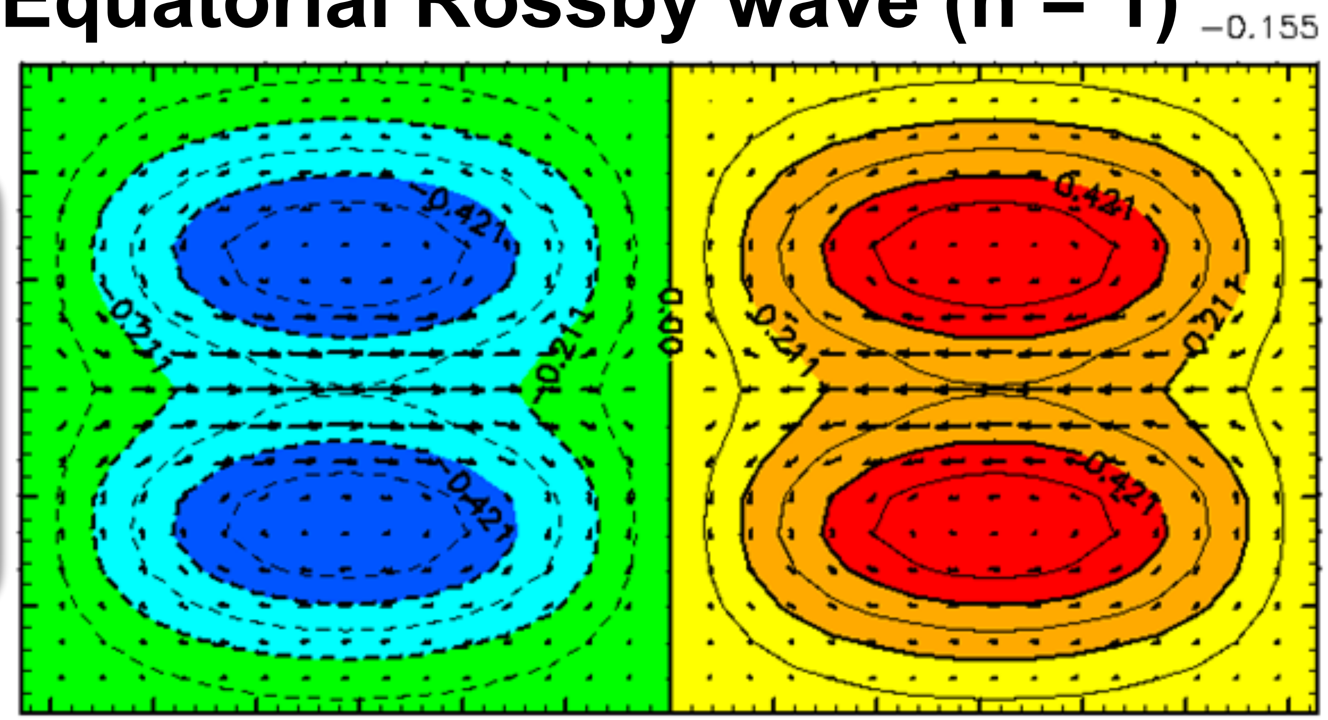
Composite mean along the wave propagation (6.25 days)

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

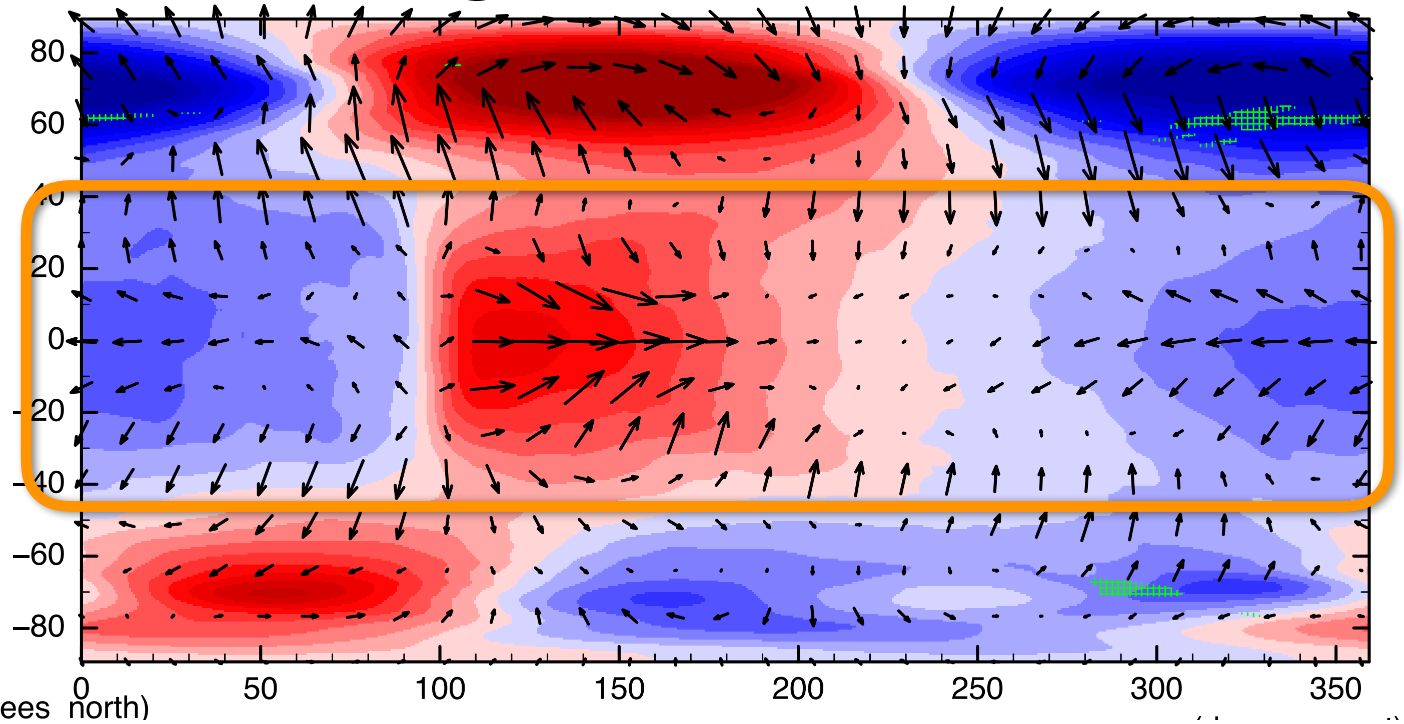
65 km height



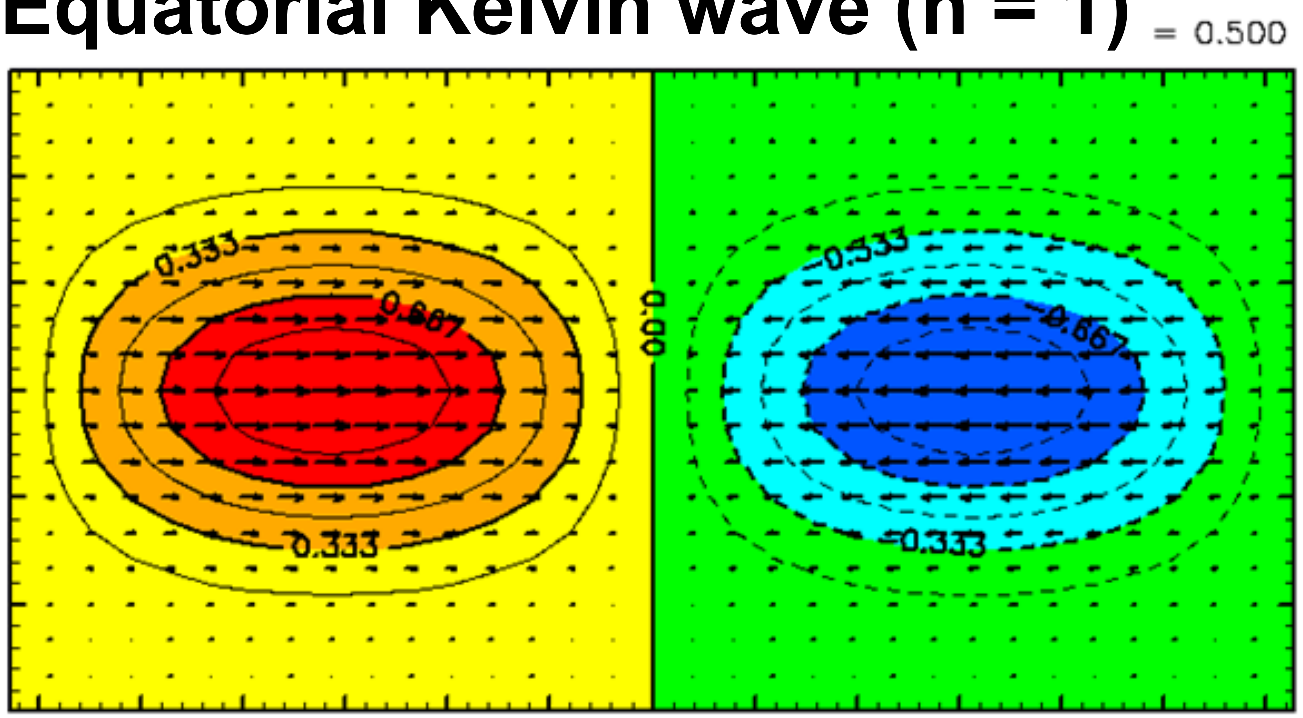
Equatorial Rossby wave (n = 1)



55 km height



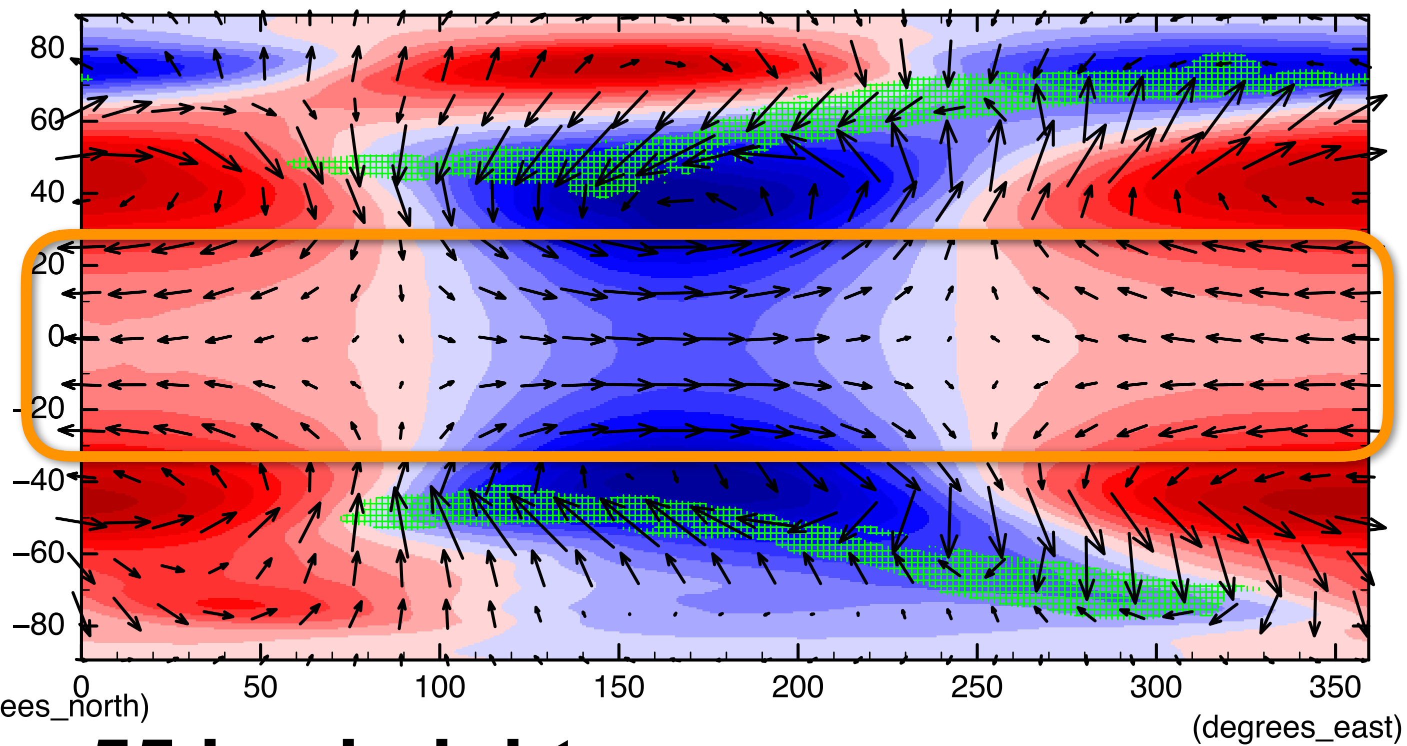
Equatorial Kelvin wave (n = 1)



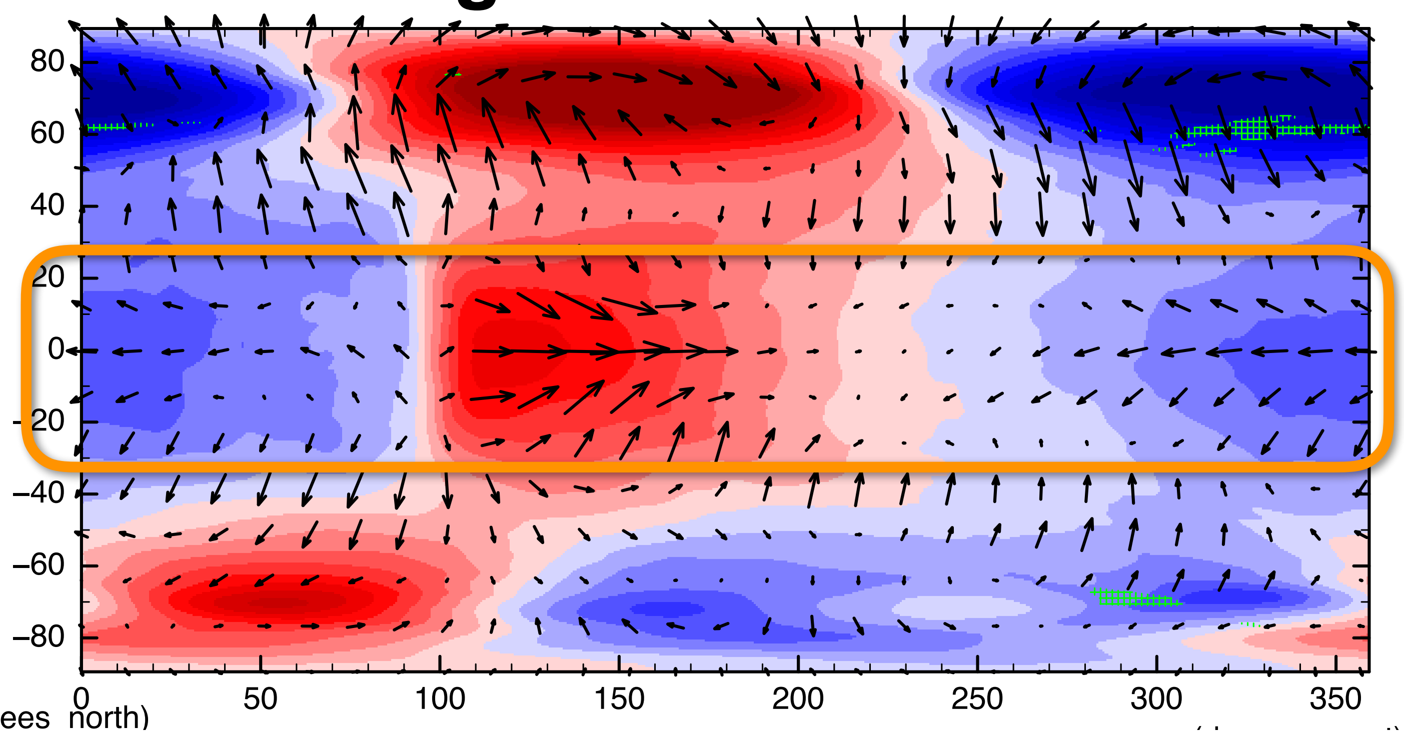
Composite mean along the wave propagation (6.25 days)

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

65 km height



55 km height

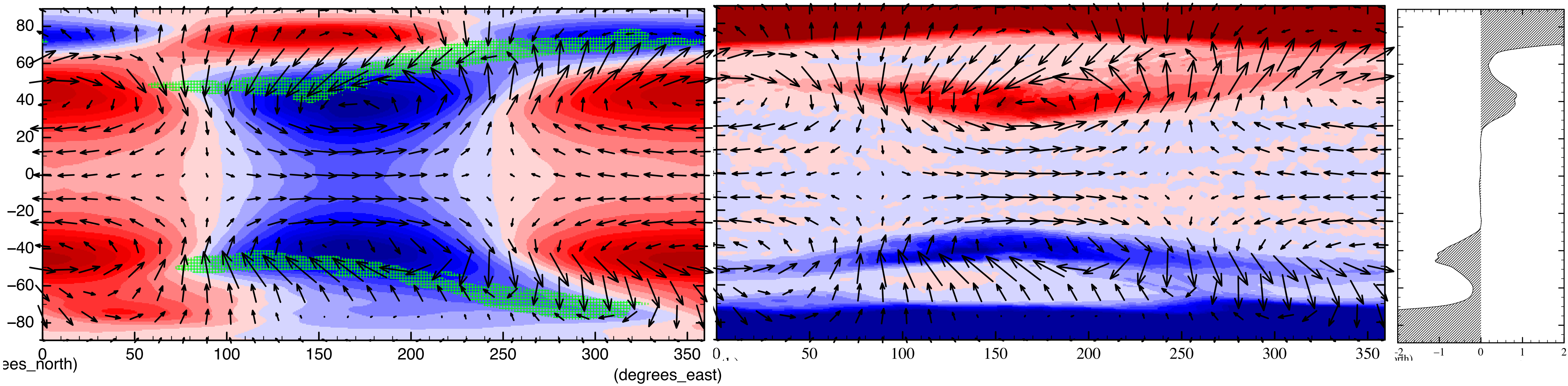


- Pairs of p’ in polar-region is due to the barotropic instability. (Sugimoto et al. 2014)
- **Equatorial waves in both heights are vertically coupled (have same u’ in equatorial region), and these waves would regulate the north-south symmetry of the streak structure. —Answer to Q1.**

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 — **Potential Vorticity $= (\boldsymbol{\omega}_a \cdot \nabla\theta)/\rho$** — **zonal mean**



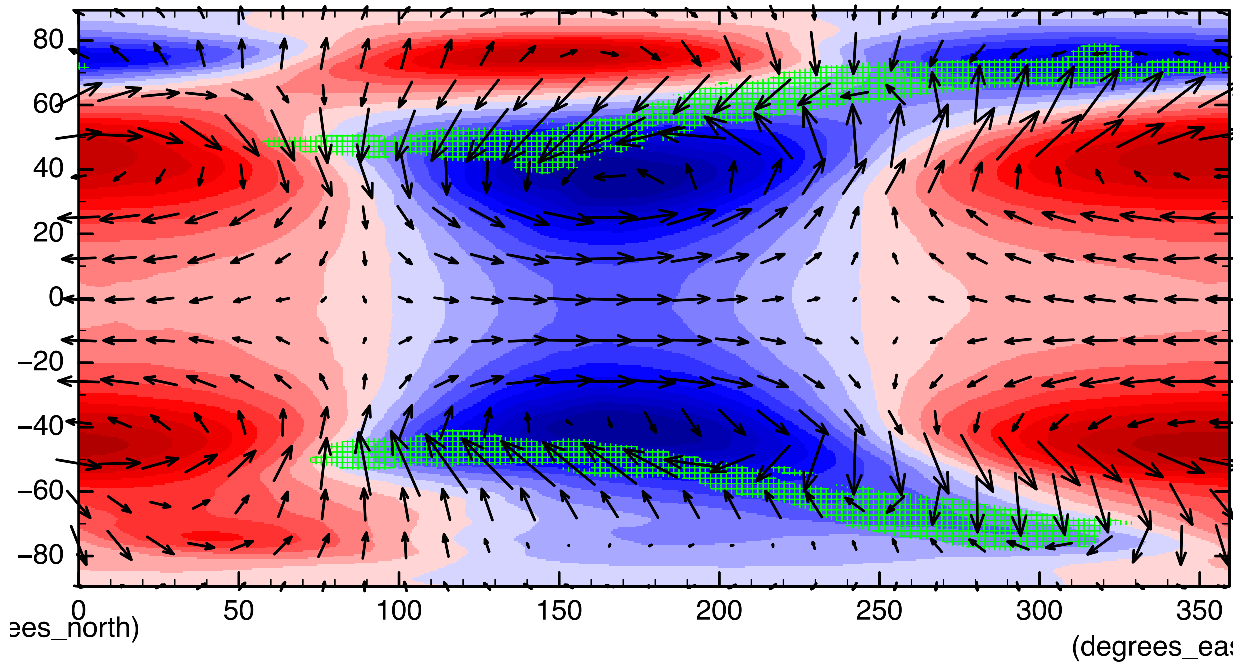
- The horizontal structure of the equatorial region is similar to that of the equatorial Rossby wave.
- **However, the horizontal distribution of the potential vorticity (PV) is NOT consistent with the Rossby wave.**
  - **That is, zonal mean PV should monotonically increase;**

✓**but it is not on 65 km height.**

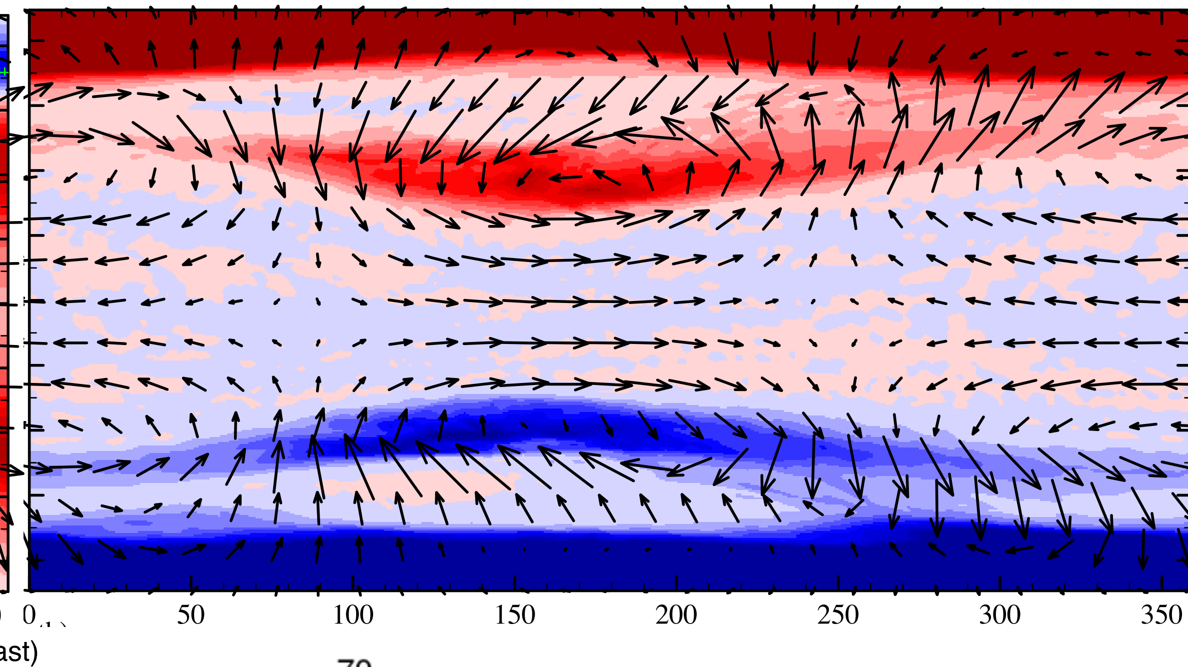
ω_a: Absolute vorticity, θ: potential temperature, ρ: density

Composite mean along the wave propagation (6.25 days) (No diurnal heating 0.1K/km)

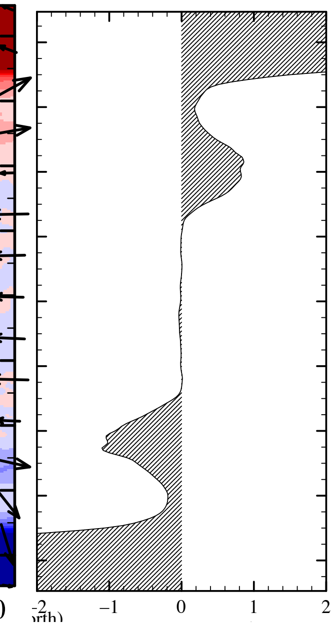
65 km height p’, (u’, v’), & w



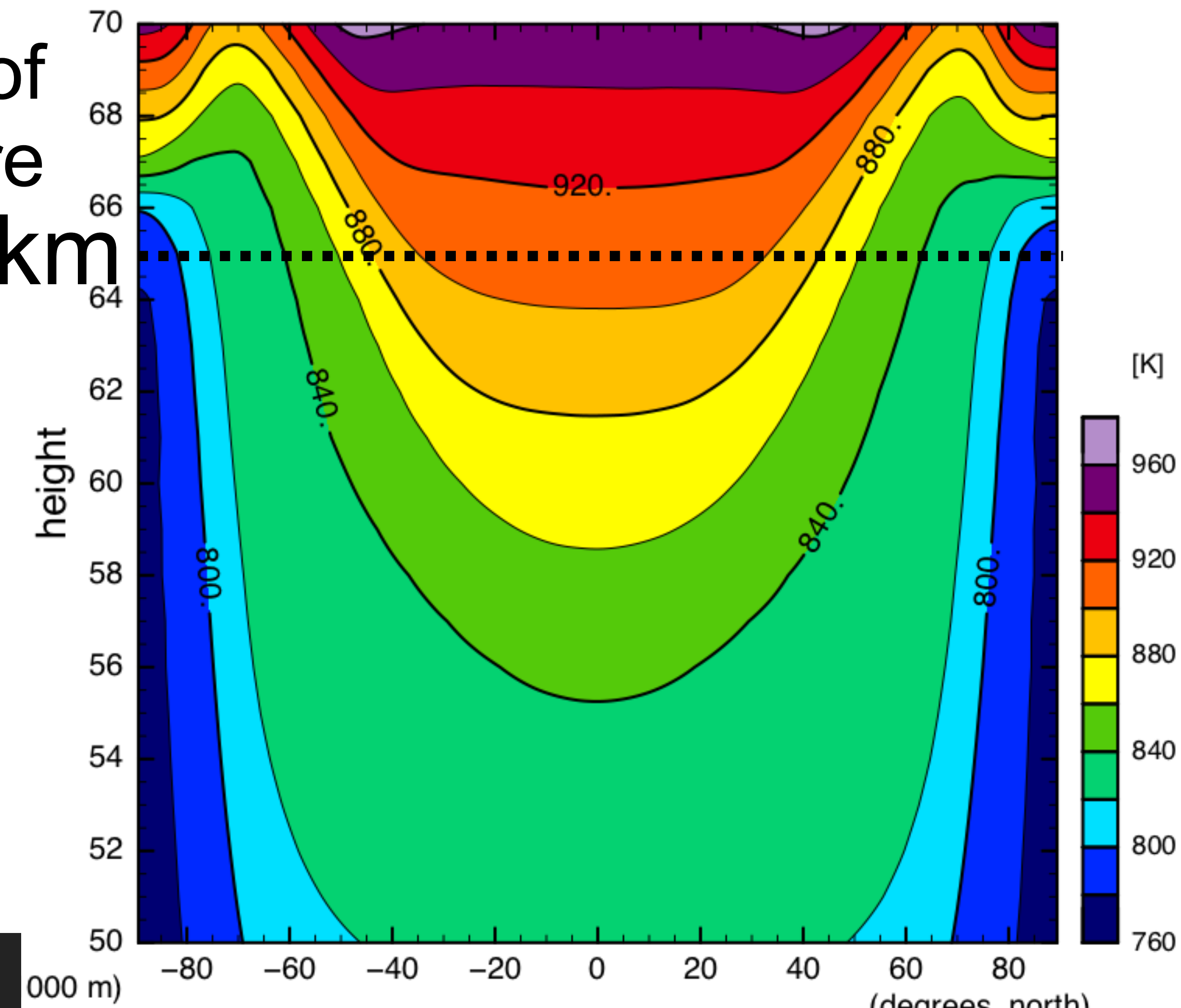
Potential Vorticity $= (\omega_a \cdot \nabla\theta)/\rho$



zonal mean



Mean meridional distribution of the potential temperature

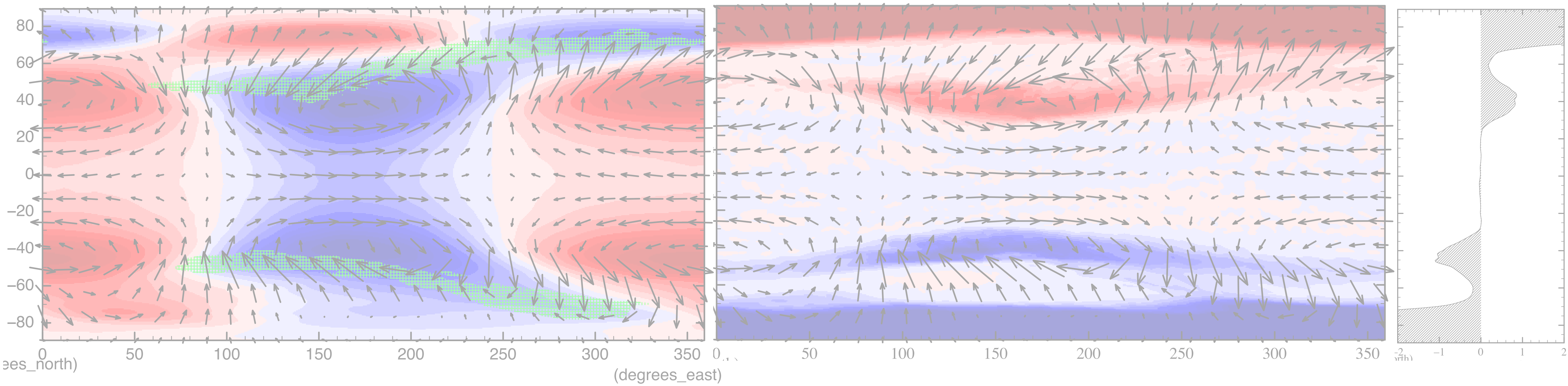


- **Isentropic surface is largely tilted with respect to the horizontal surface.**

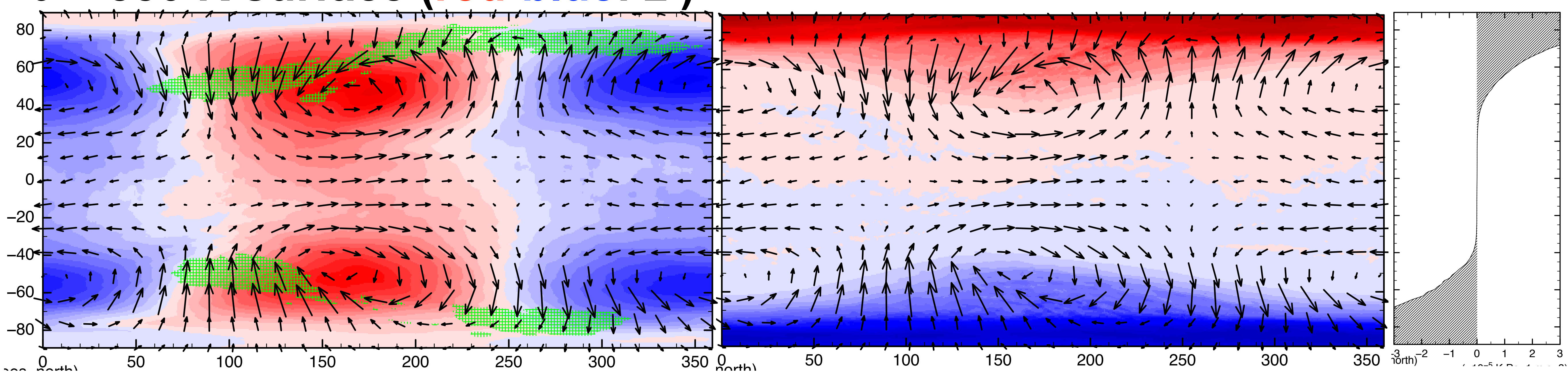
ω_a: Absolute vorticity, θ: potential temperature, ρ: density

Composite mean along the wave propagation (6.25 days) (No diurnal heating 0.1K/km)

65 km height p', (u', v'), & w Potential Vorticity = $(\omega_a \cdot \nabla\theta)/\rho$ zonal mean



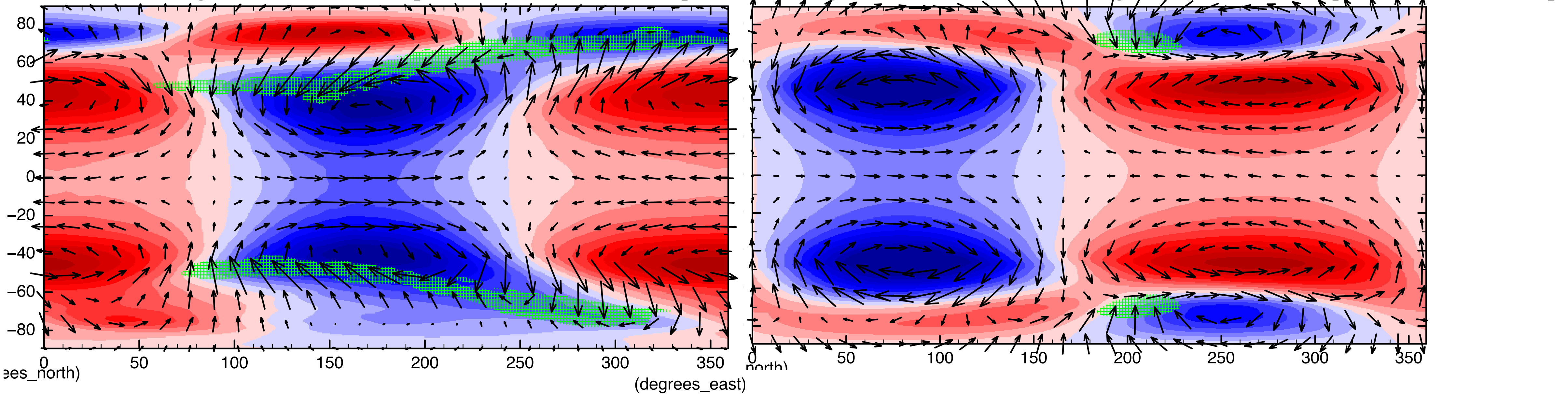
θ = 880 K surface (red-blue: z')



- PV on the isentropic surface is consistent with the Rossby wave theory.
  - **This wave might propagate along the tilted isentropic surface.**

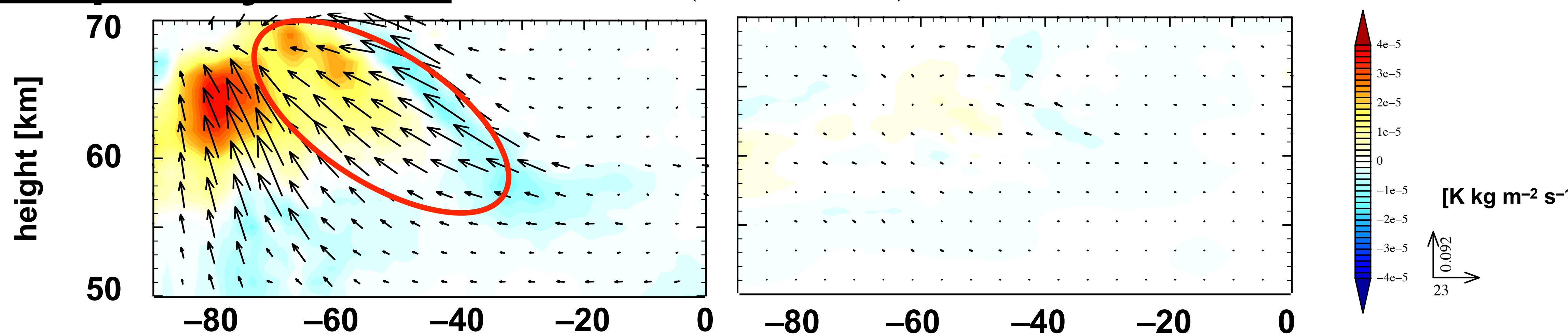
Low-stability case (0.1 K/km) High-stability case (4 K/km)

65 km



Thermal transport by eddies

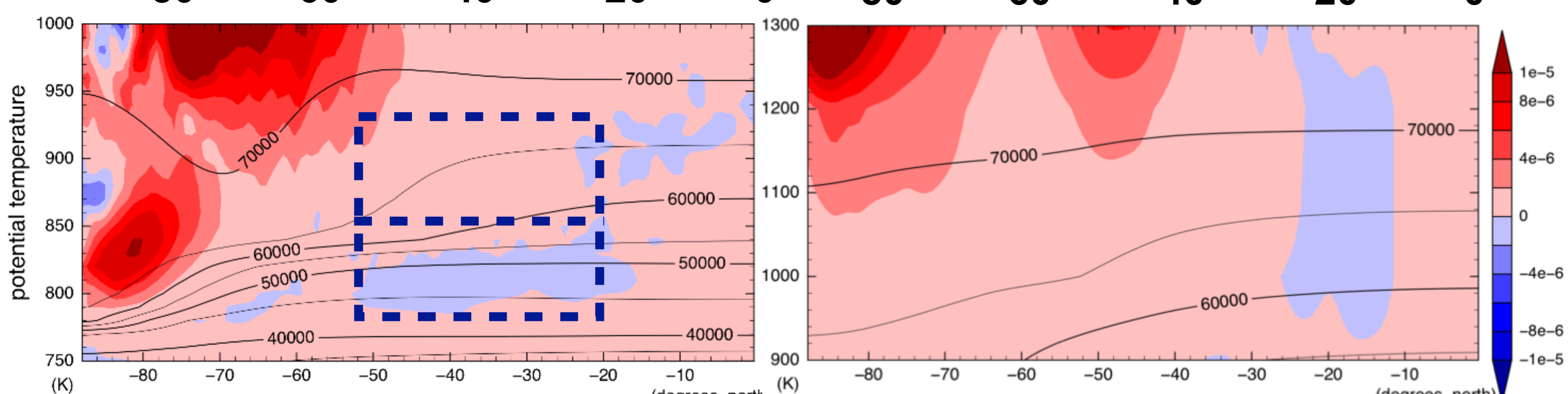
vectors: $(\overline{v'\theta'},\ \overline{w'\theta'})$ **colour: convergence**



dPV/dy on θ coordinate

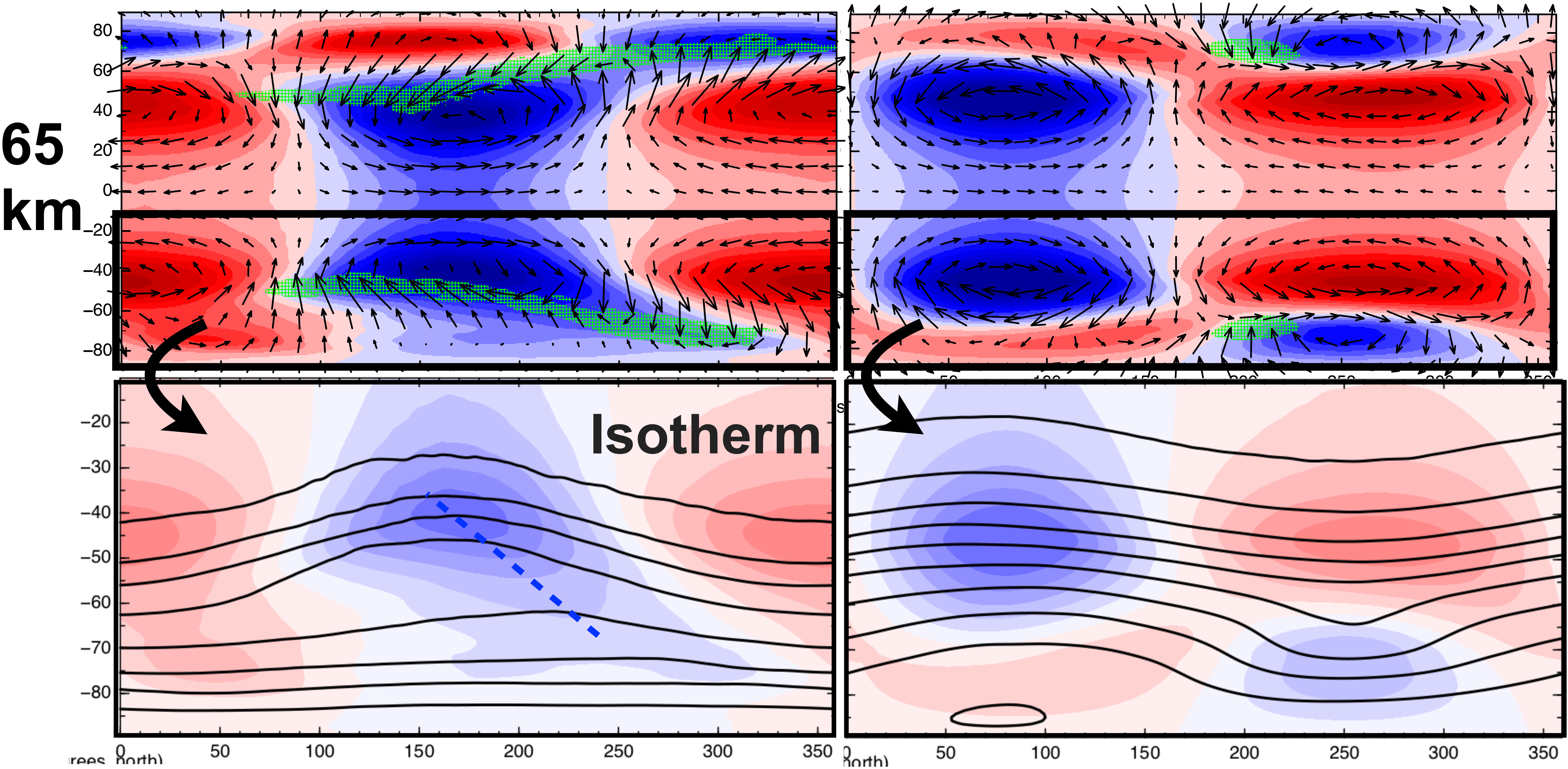
(colour)

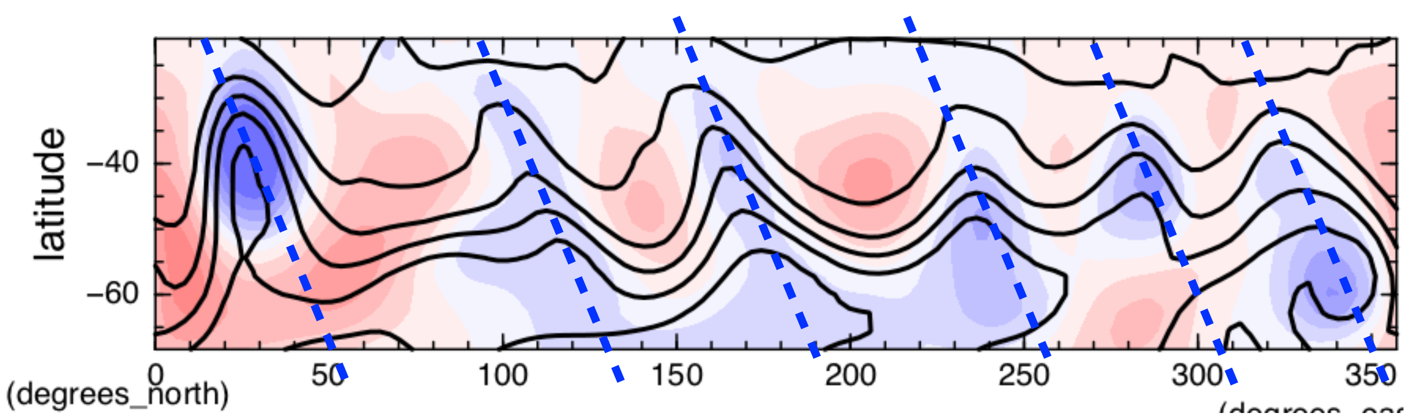
(contour: Z)



- **Distributions of thermal eddy-transport and dPV/dy suggest baroclinic instability in the low stability case**

Low-stability case (0.1 K/km) High-stability case (4 K/km)

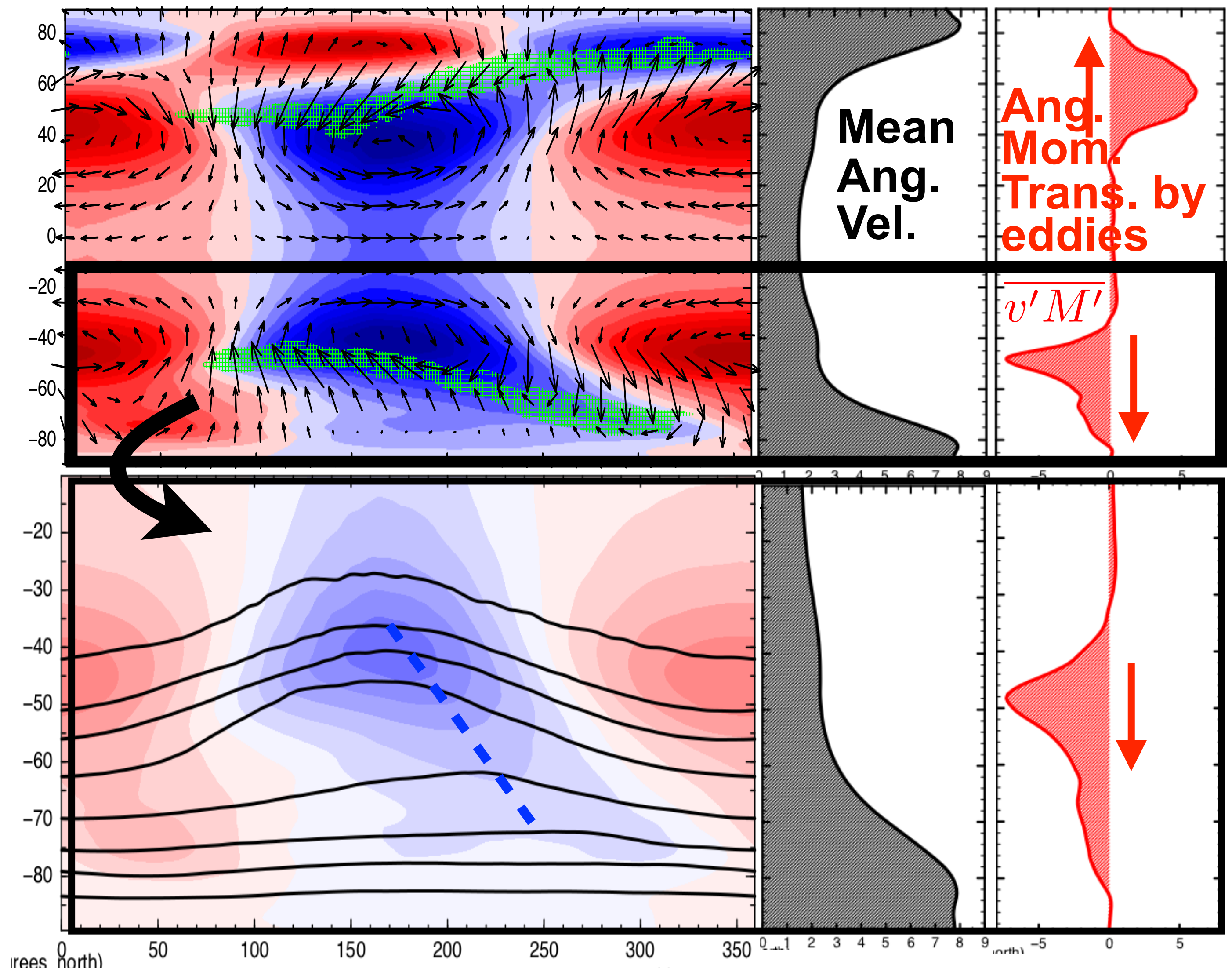


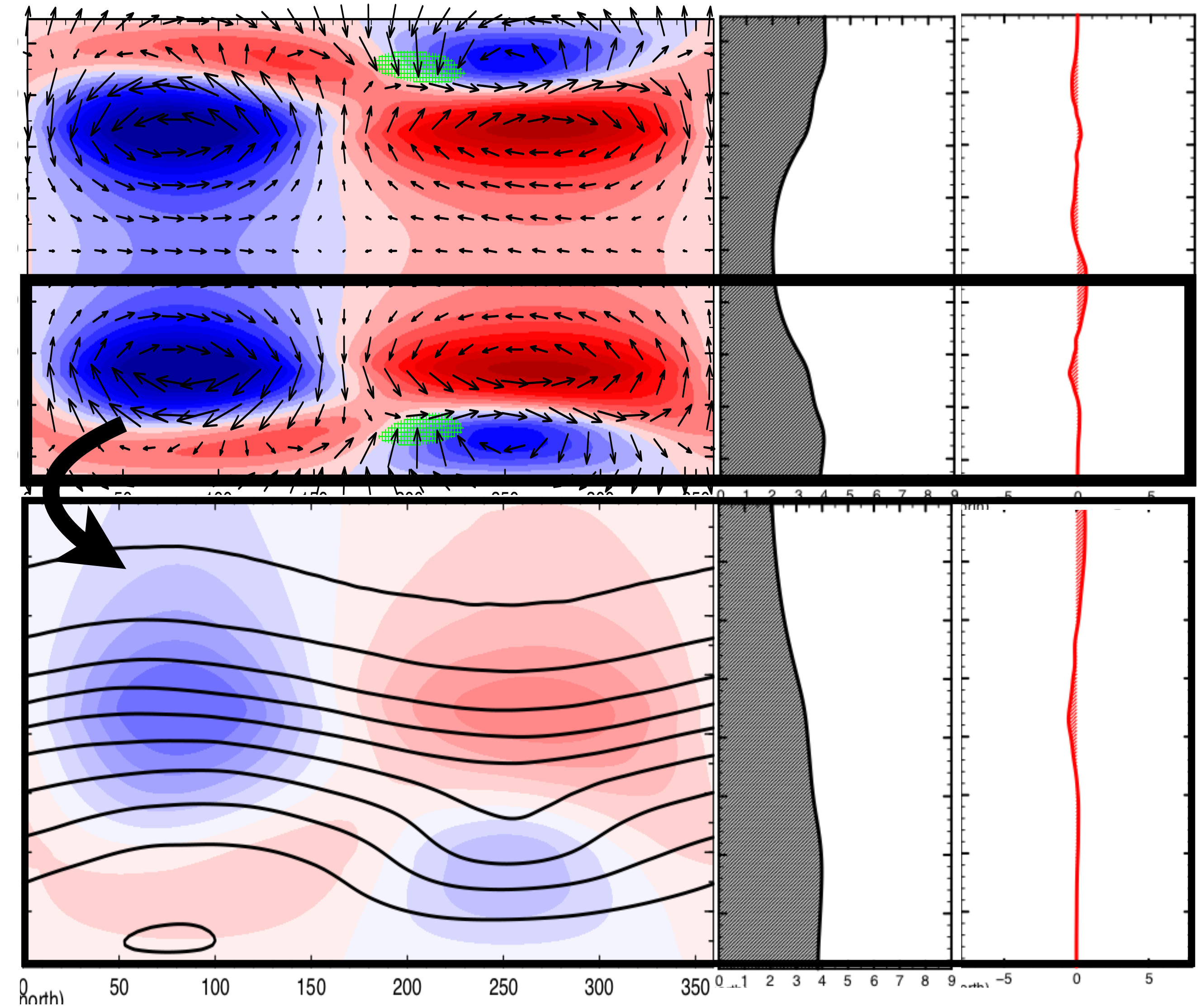


←Barocilinic Inst. in Earth-like case. (HS94)

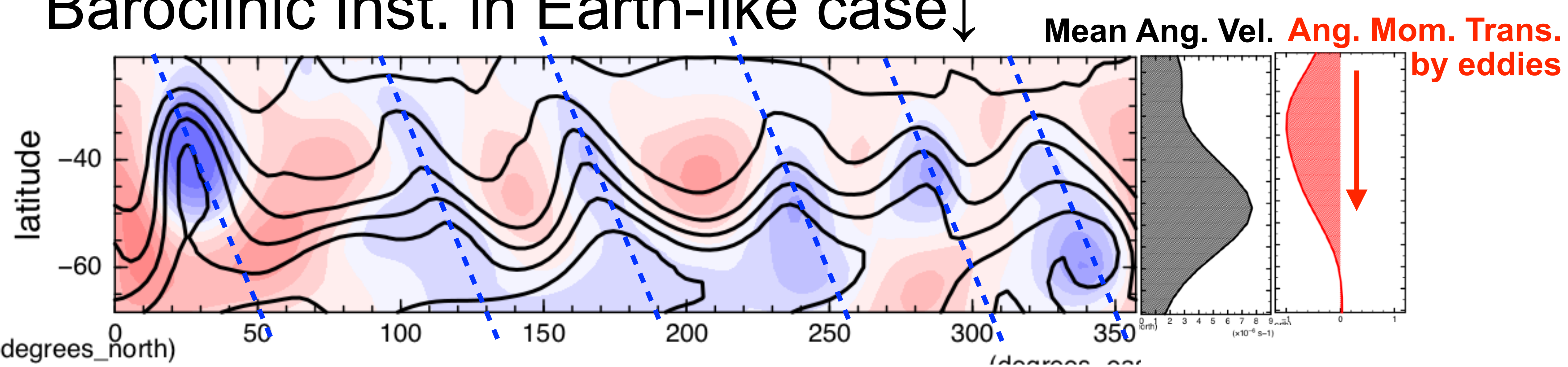
Low-stability case (0.1 K/km)

High-stability case (4 K/km)

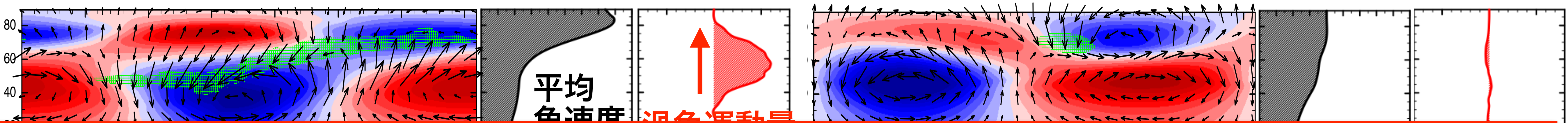




Baroclinic Inst. in Earth-like case↓

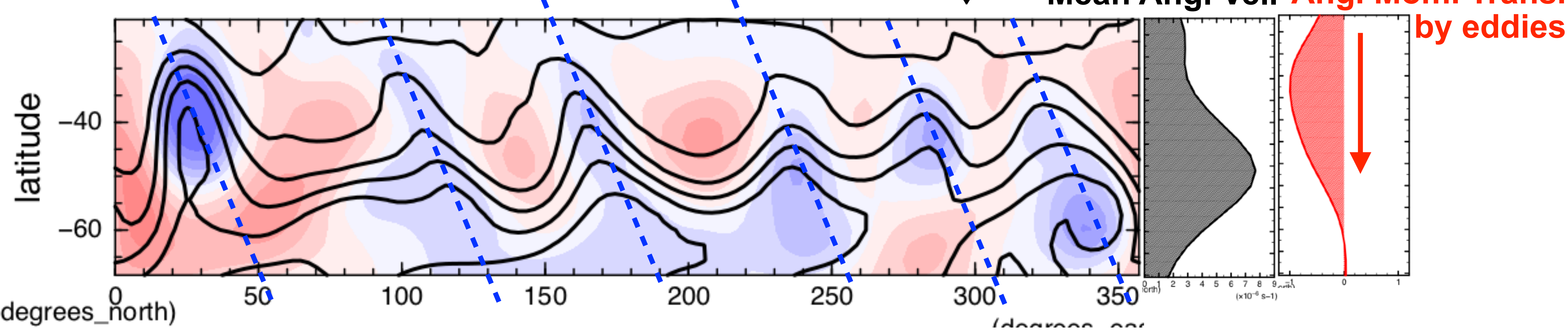


Low-stability case (0.1 K/km) High-stability case (4 K/km)



- **Self-maintained eddy-induced jet (strong angular velocity in high-latitudes) mechanism works;**
  - that would be similar to that in Earth atmosphere.
- **The inclined eddies (which are a part of Equatorial Rossby wave) induces convergence zone of the meridional wind, and then the the streak structure of the strong downward flow. —Answer to Q2.**

Baroclinic Inst. in Earth-like case↓



Summary

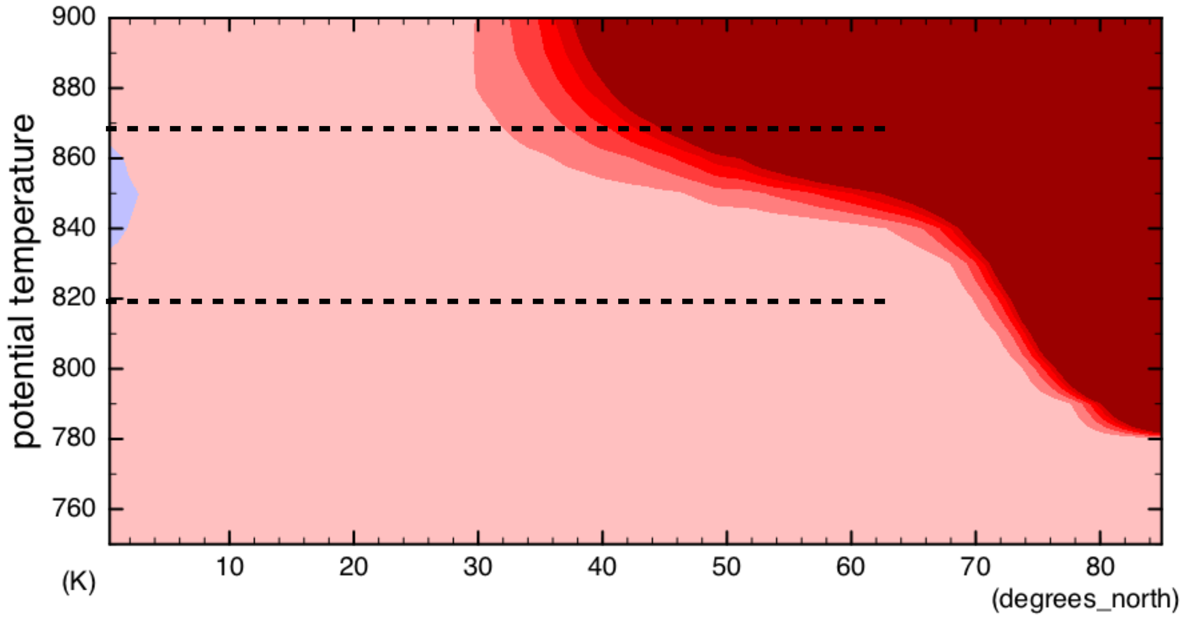
- **Planetary-scale streak structures** *similar to those observed in a night side IR2 image* are reproduced in vertical velocity in our simple Venus GCM, which has dynamics only but has a “low stability layer” (55–60km).
  - **Planetary-scale streaks** are:
    - **strong downward flow**, possibly corresponds to thin cloud region.
    - a part of huge spirals extending from the pole to about lat = 30 deg.
    - **synchronized** in the northern and southern hemisphere.
  - Num. exps. without diurnal heating and changing the static stability of the “low stability layer” are performed; and the results suggest that
    - ✓ **Synchronization seems to be caused by the vertically coupled Rossby wave and Kelvin wave in the equatorial region.**
    - ✓ **Baroclinic instability and inclination of the eddies induced by strong angular velocity, which occurs only in the low stability case, would cause the planetary-scale streak structure.**
- Our numerical results, which are obtained by dynamics-only simulation, suggest that *the dynamics/circulation is dominant for the planetary-scale streak structure observed in Venus*.

Appendix

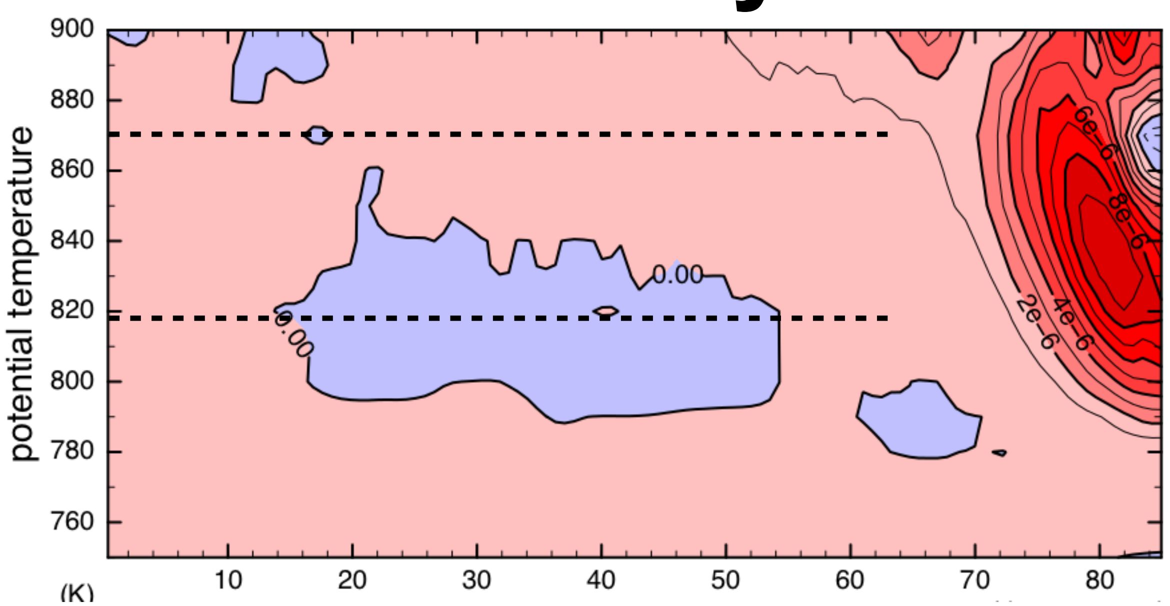
Low-static stability (0.1 K/km)

lat-θ cross section of PV

PV



dPV/dy

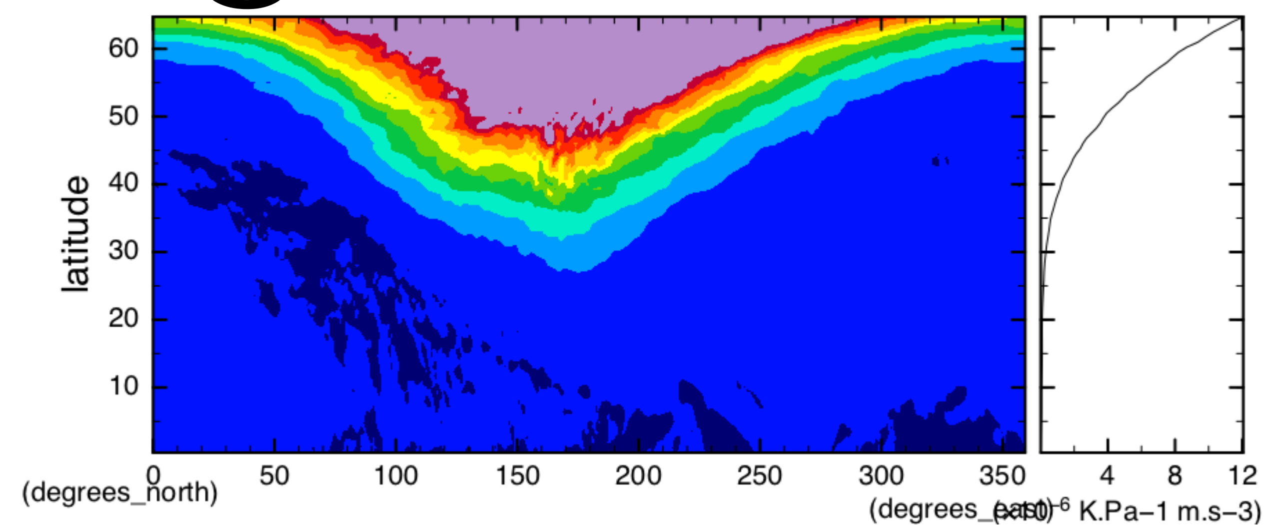


baroclinic insttability

composite mean

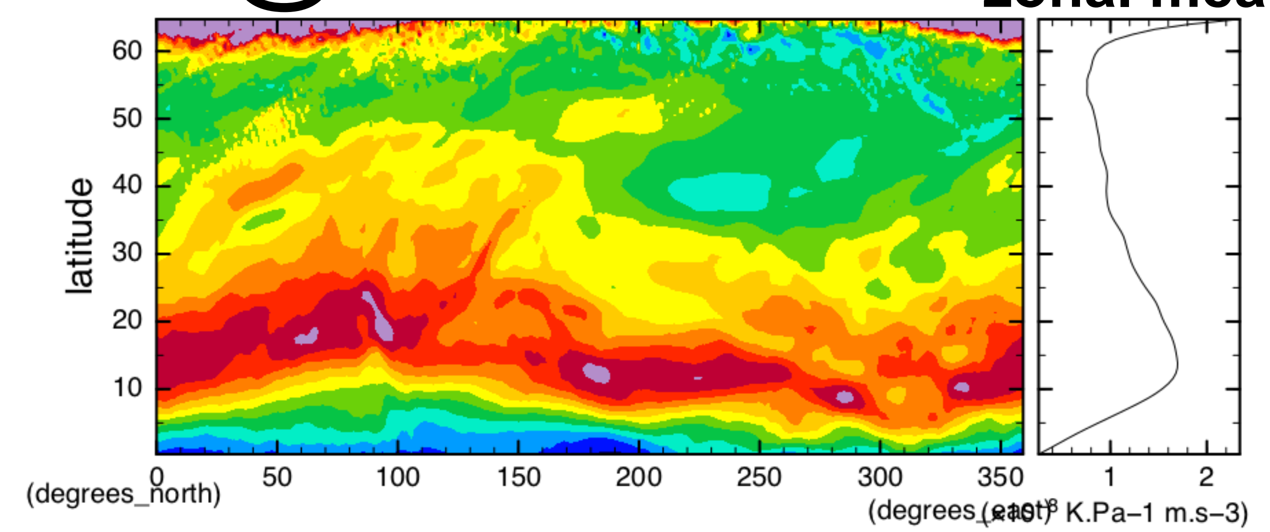
PV@Theta = 870 K

zonal mean



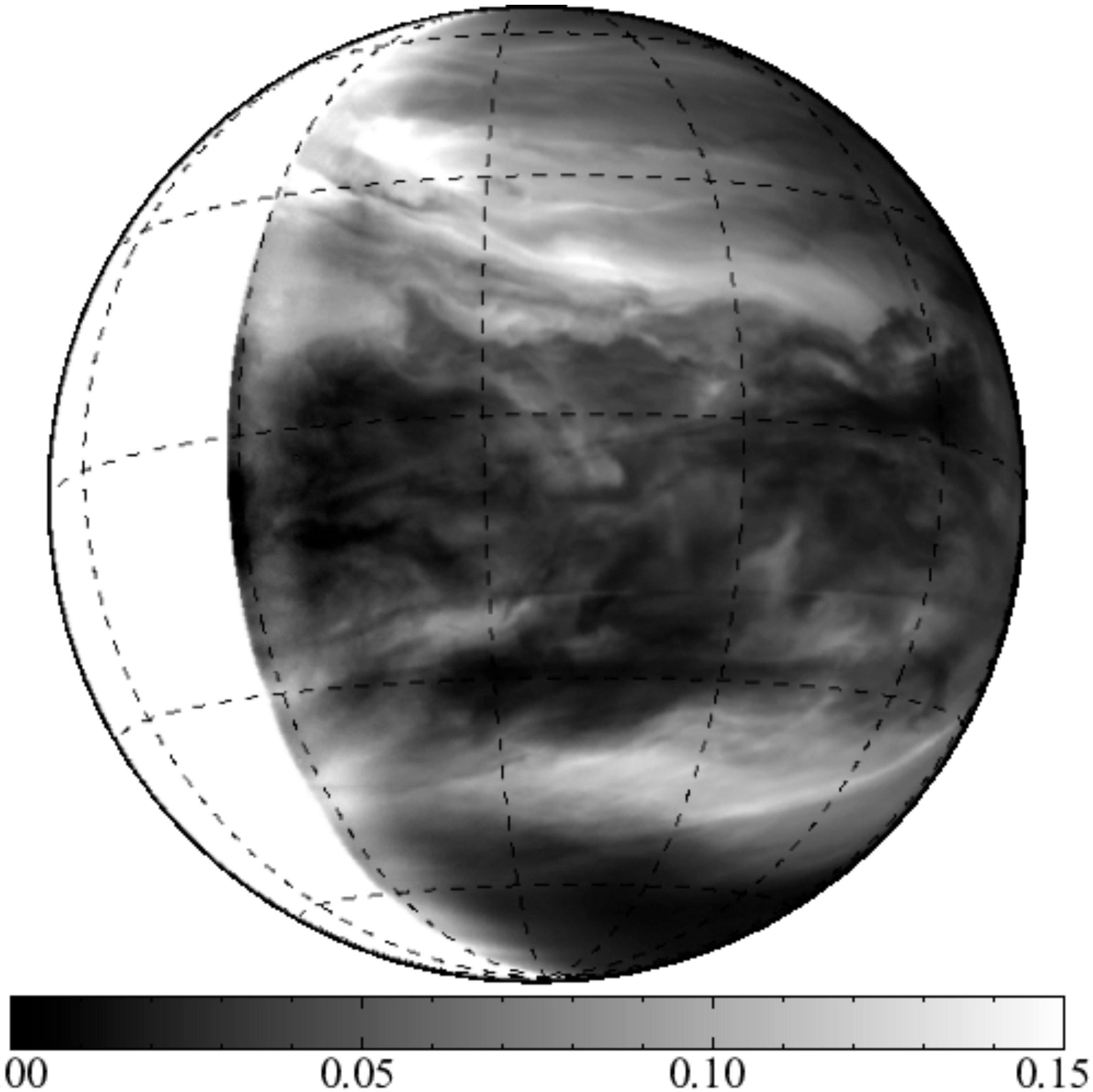
PV@Theta = 820 K

zonal mean



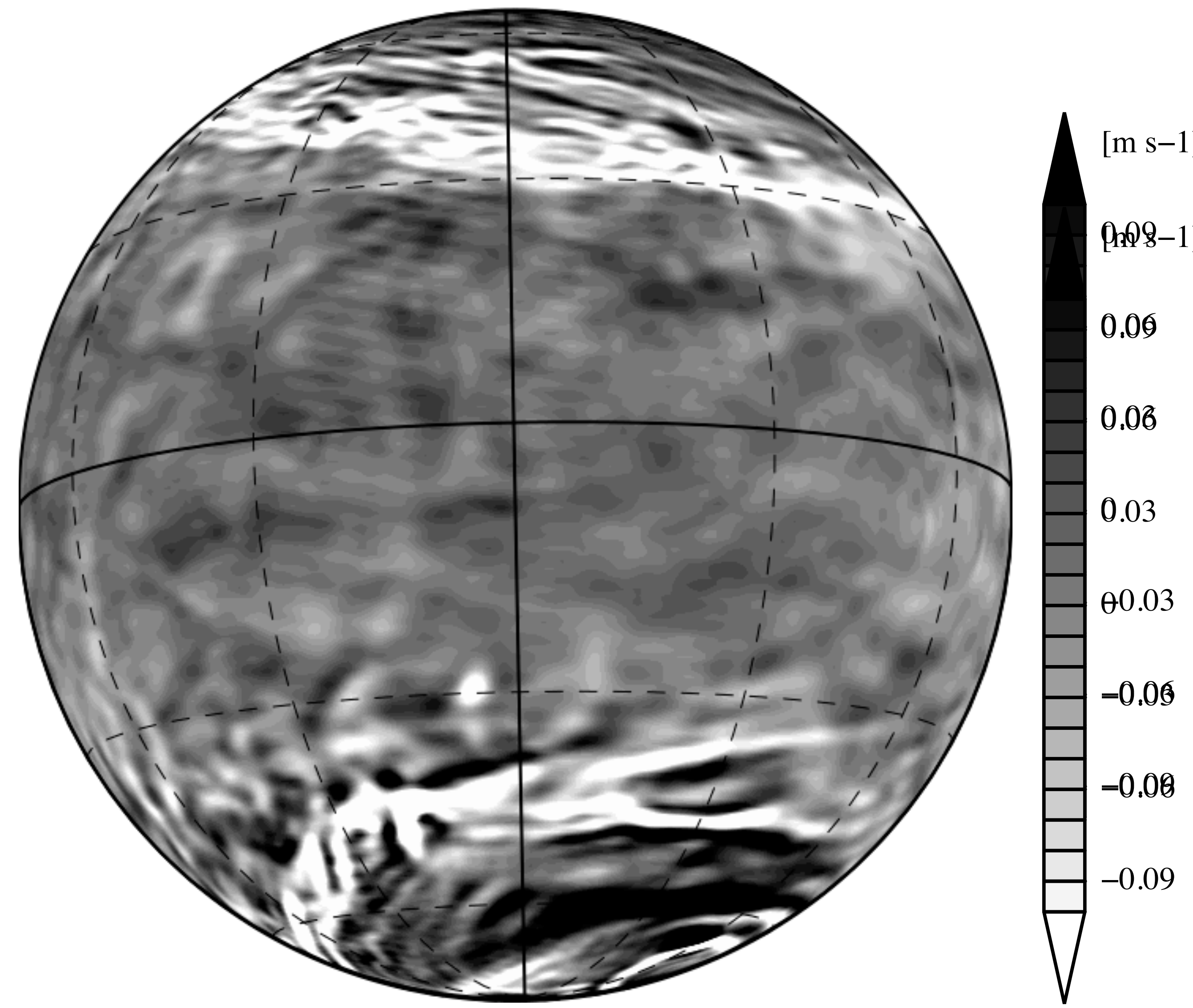
Planetary-scale streak structures

Observed in IR2 night-side (calibrated)



- 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

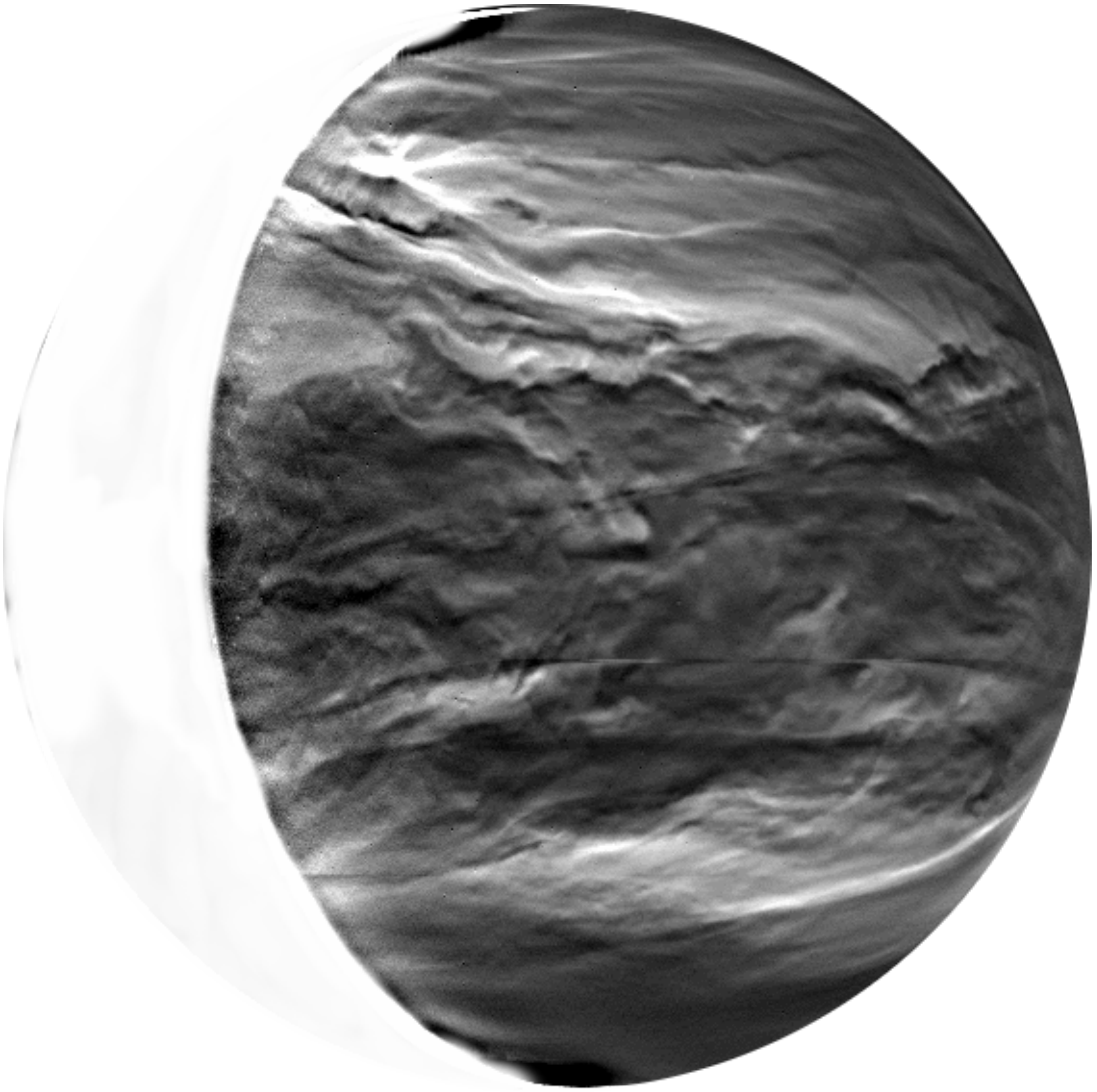


- Snapshot of vertical velocity at z = 60 km.
  - White = downward flow
  - Black = upward flow

Fig: © ISAS/JAXA

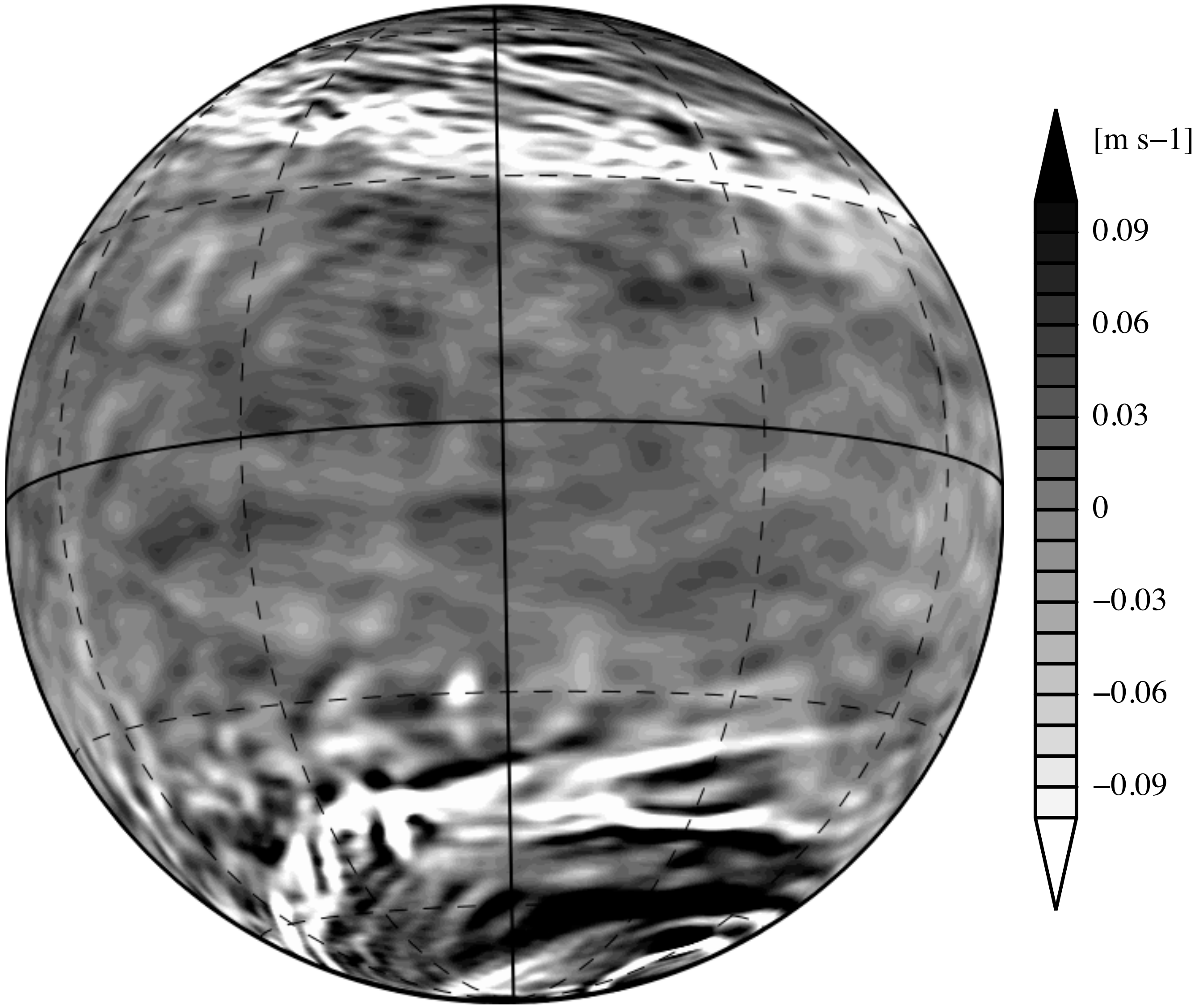
Planetary-scale streak structures

IR2 night-side (edge-enhancement)



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

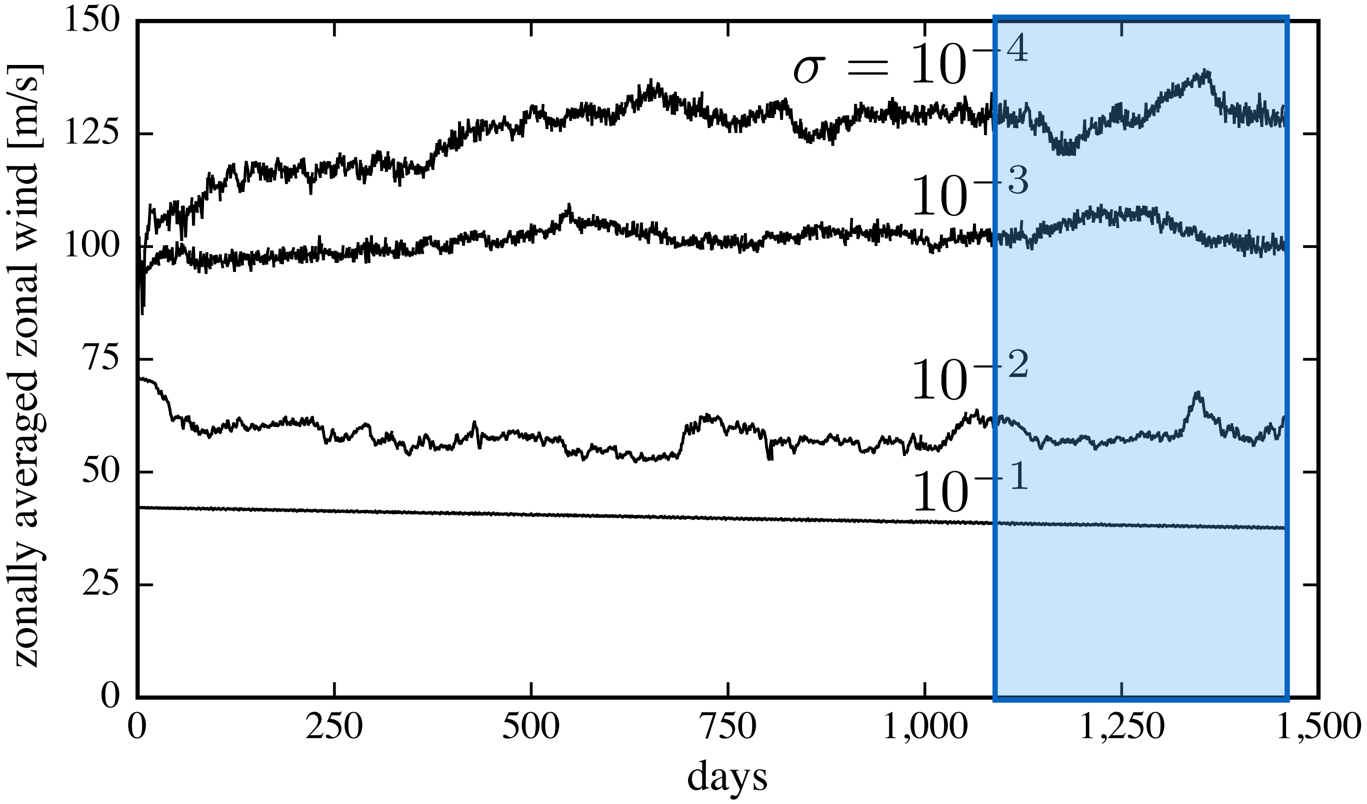
Produced in our Venus GCM



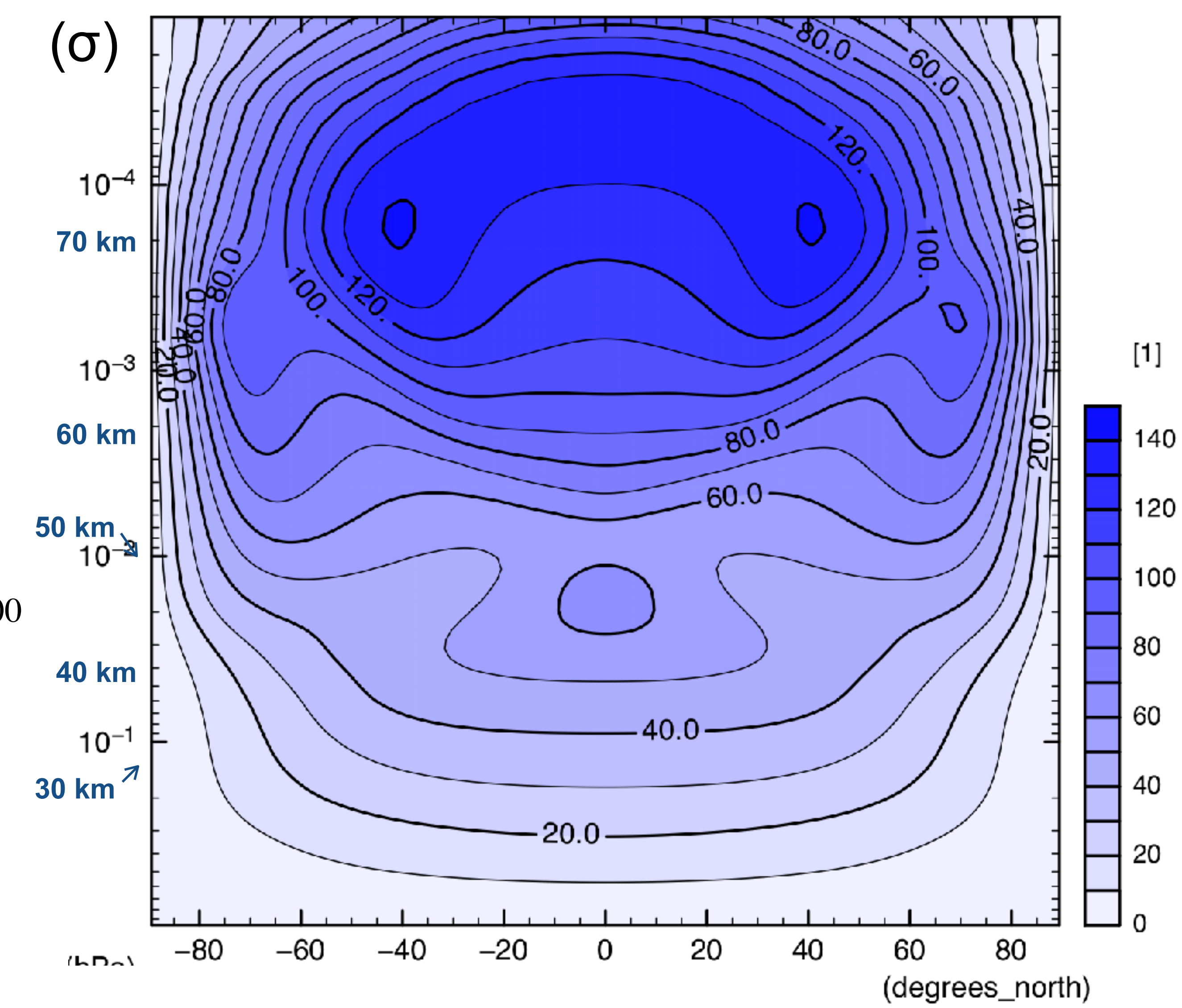
- Snapshot of vertical velocity at z = 60 km.
  - White = downward flow
  - Black = upward flow

Results | zonal mean zonal wind

Time series of mean zonal wind above the equator



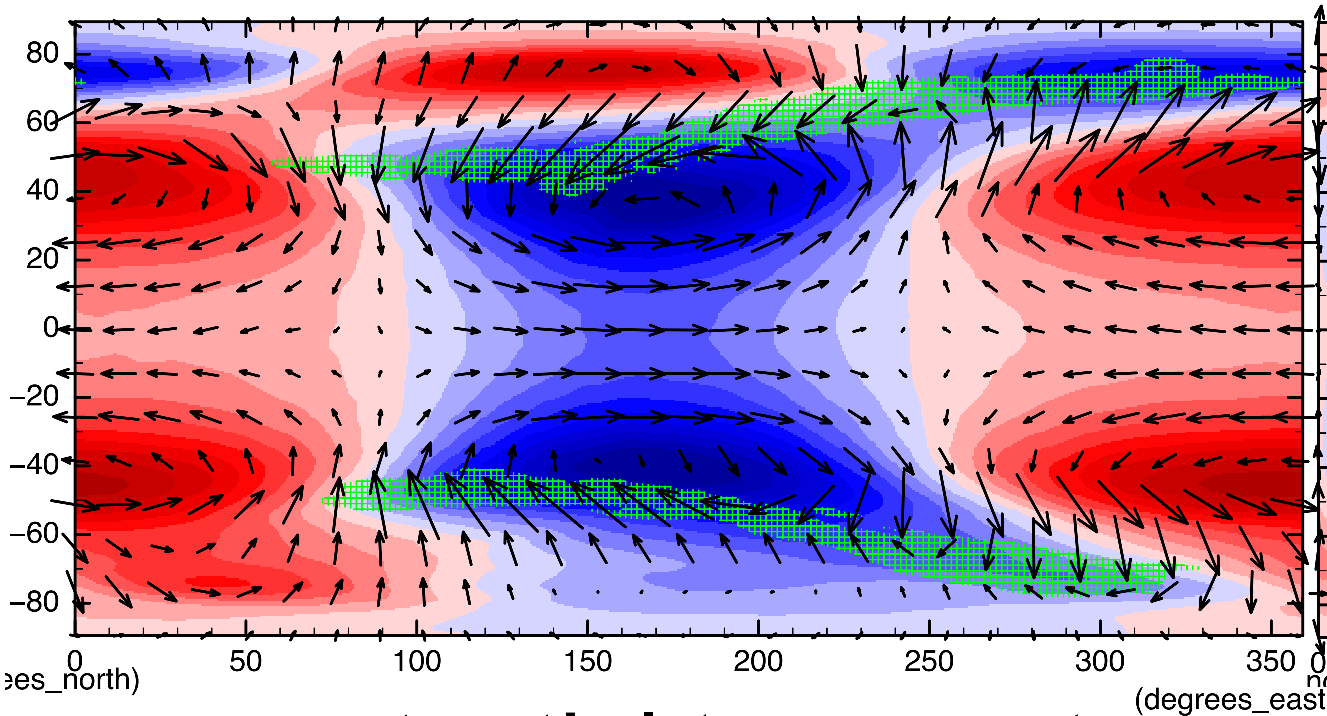
Time mean for last 1 Earth year

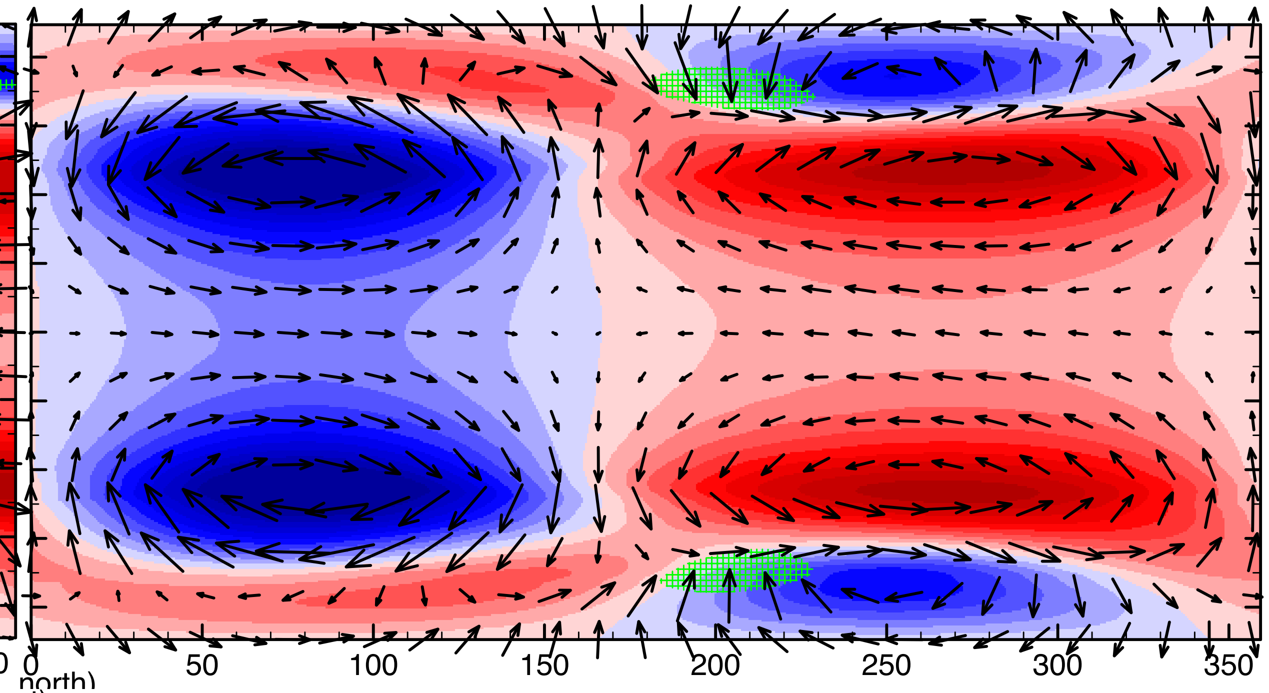


No-diurnal heating | 0.1 K/km

4 K/km

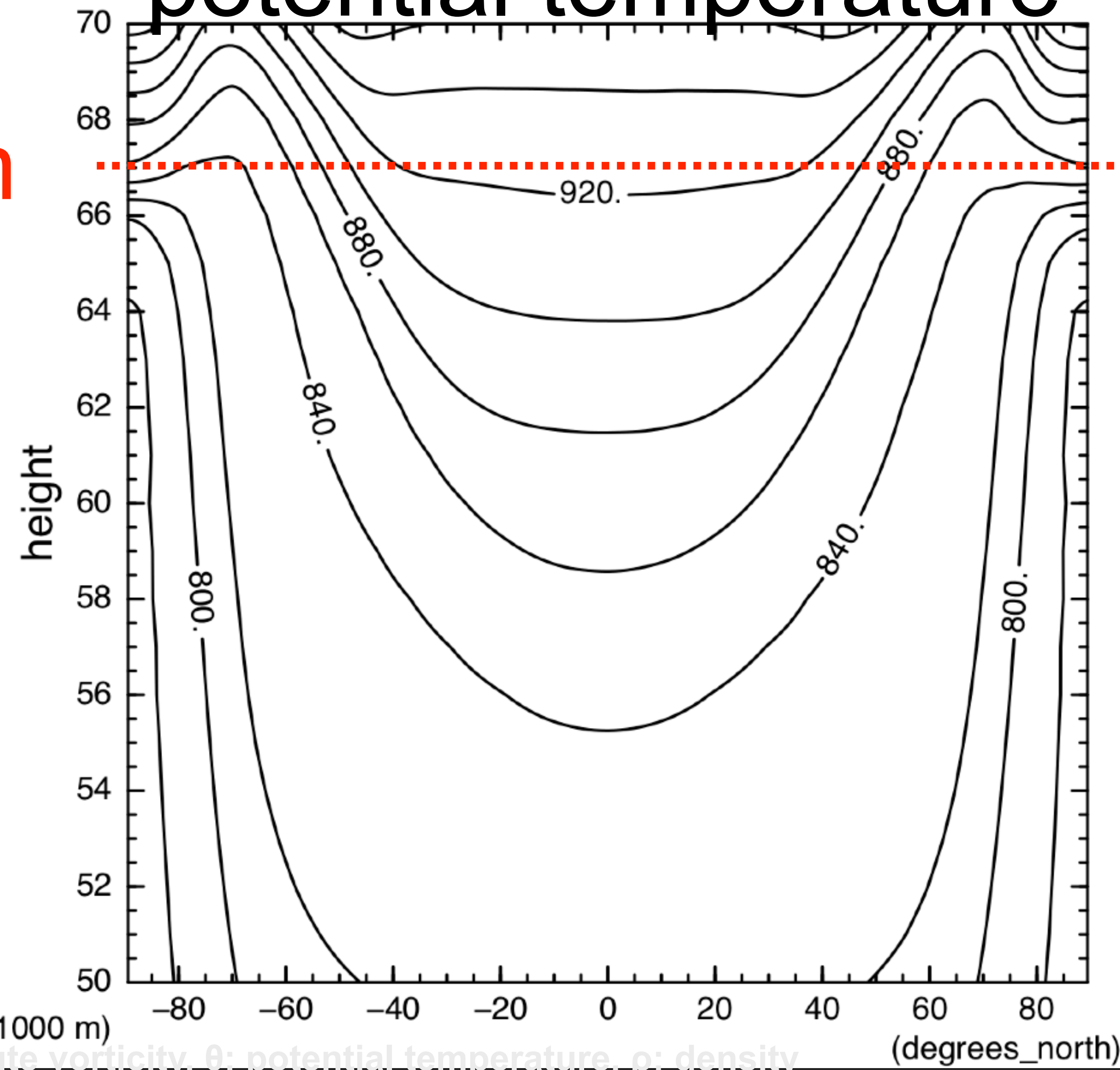
65 km

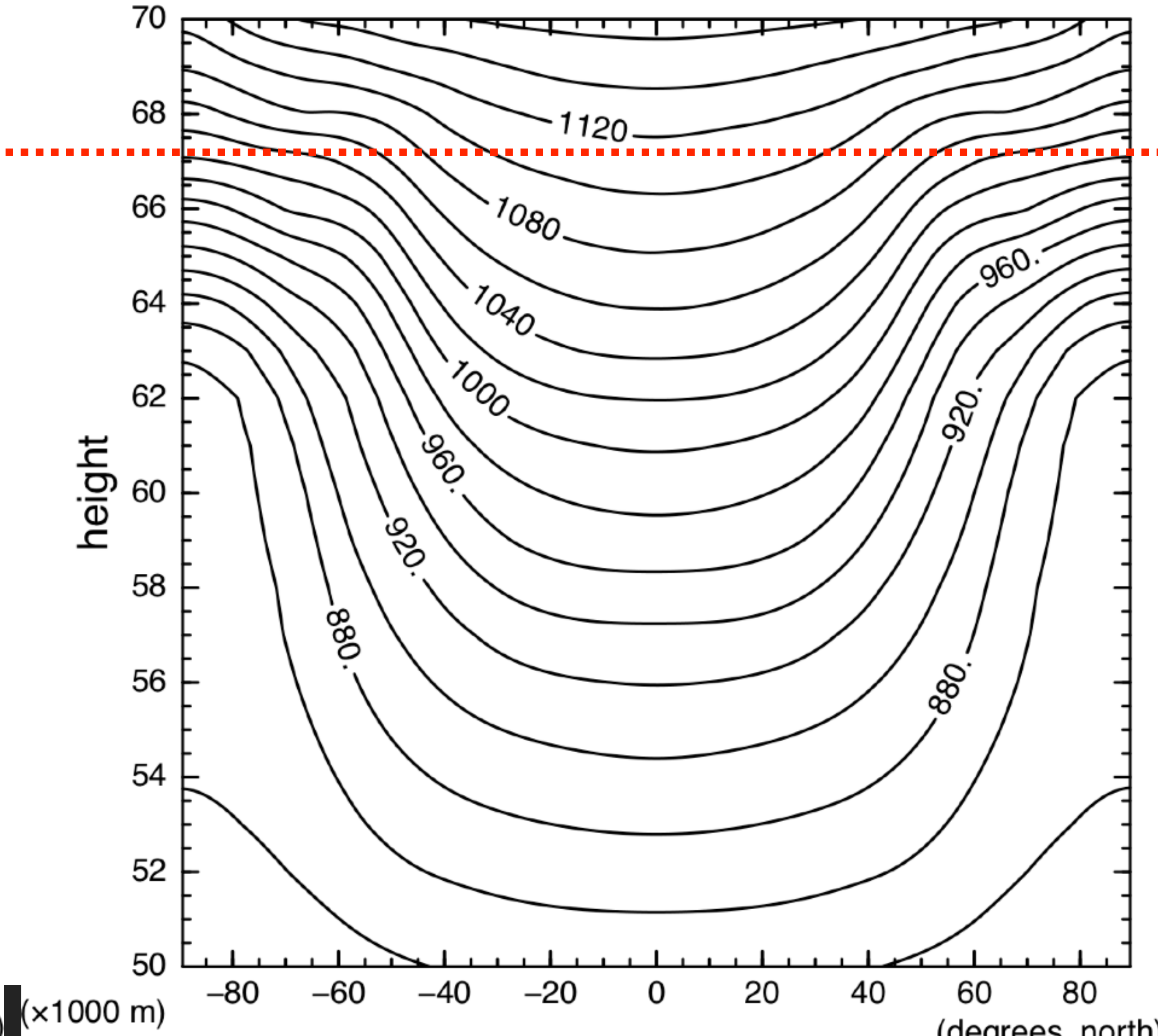




potential temperature

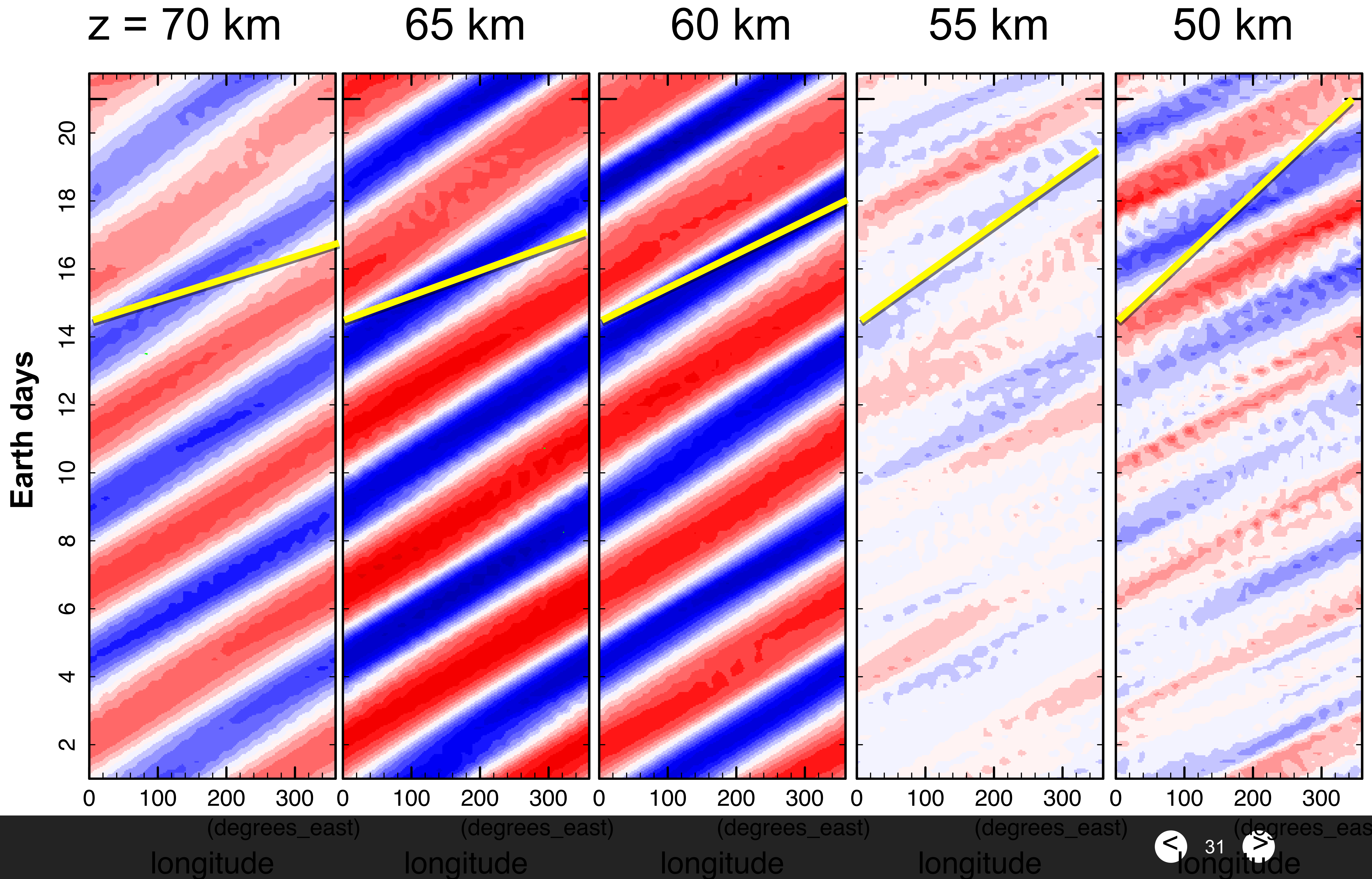
65 km





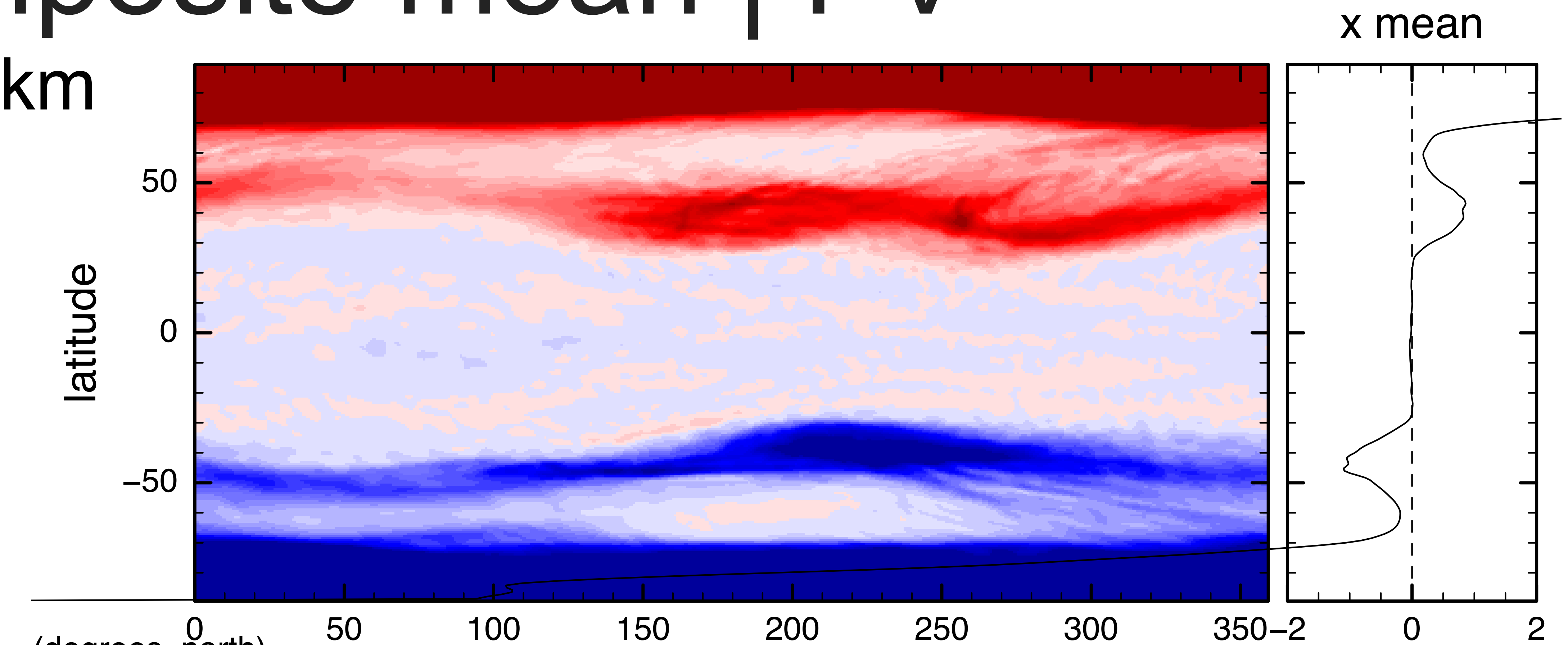
Longitude-time cross-section at lat = –35 **(No diurnal heating 4K/km)**

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

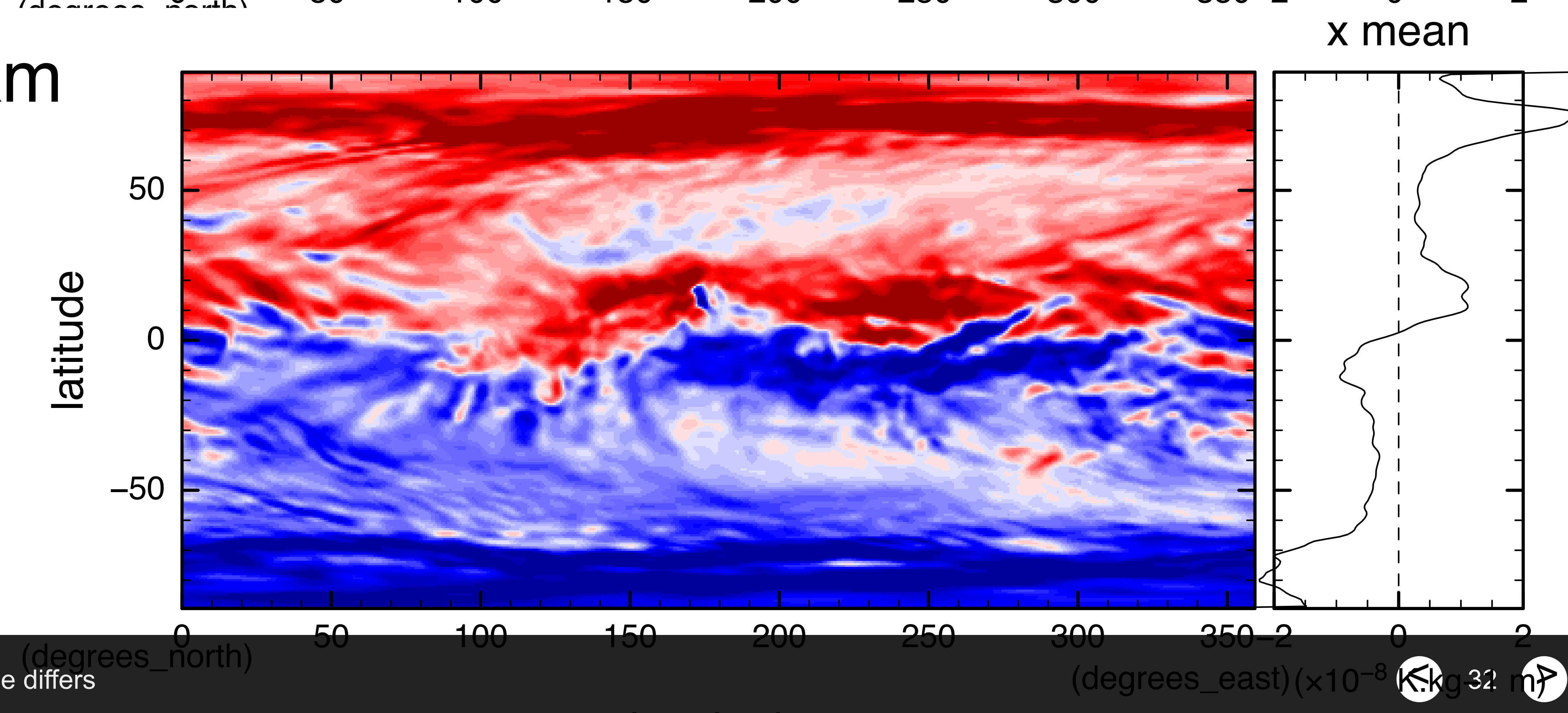


Composite mean | PV

z = 65 km



z = 55 km



*color scale differs

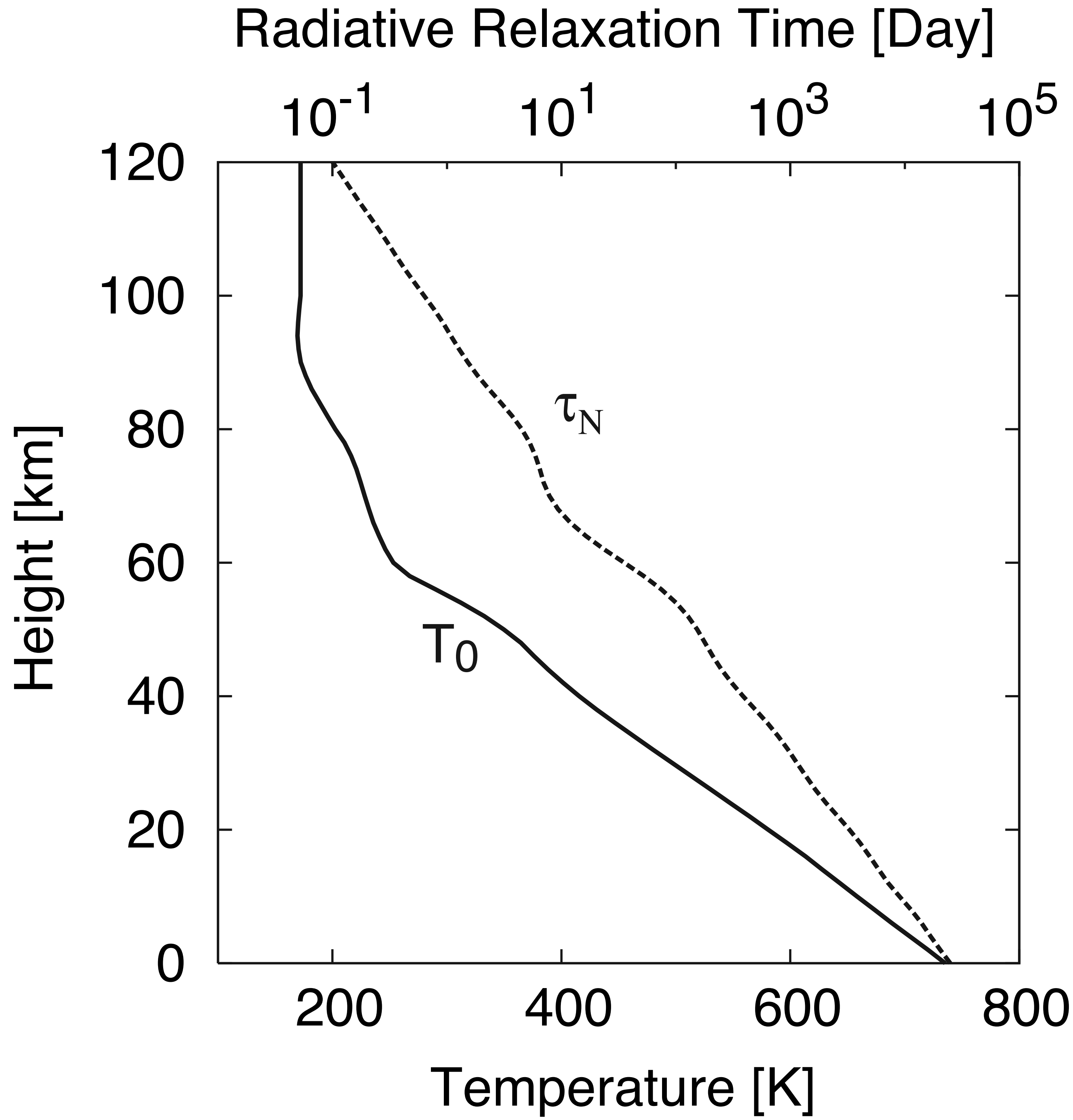
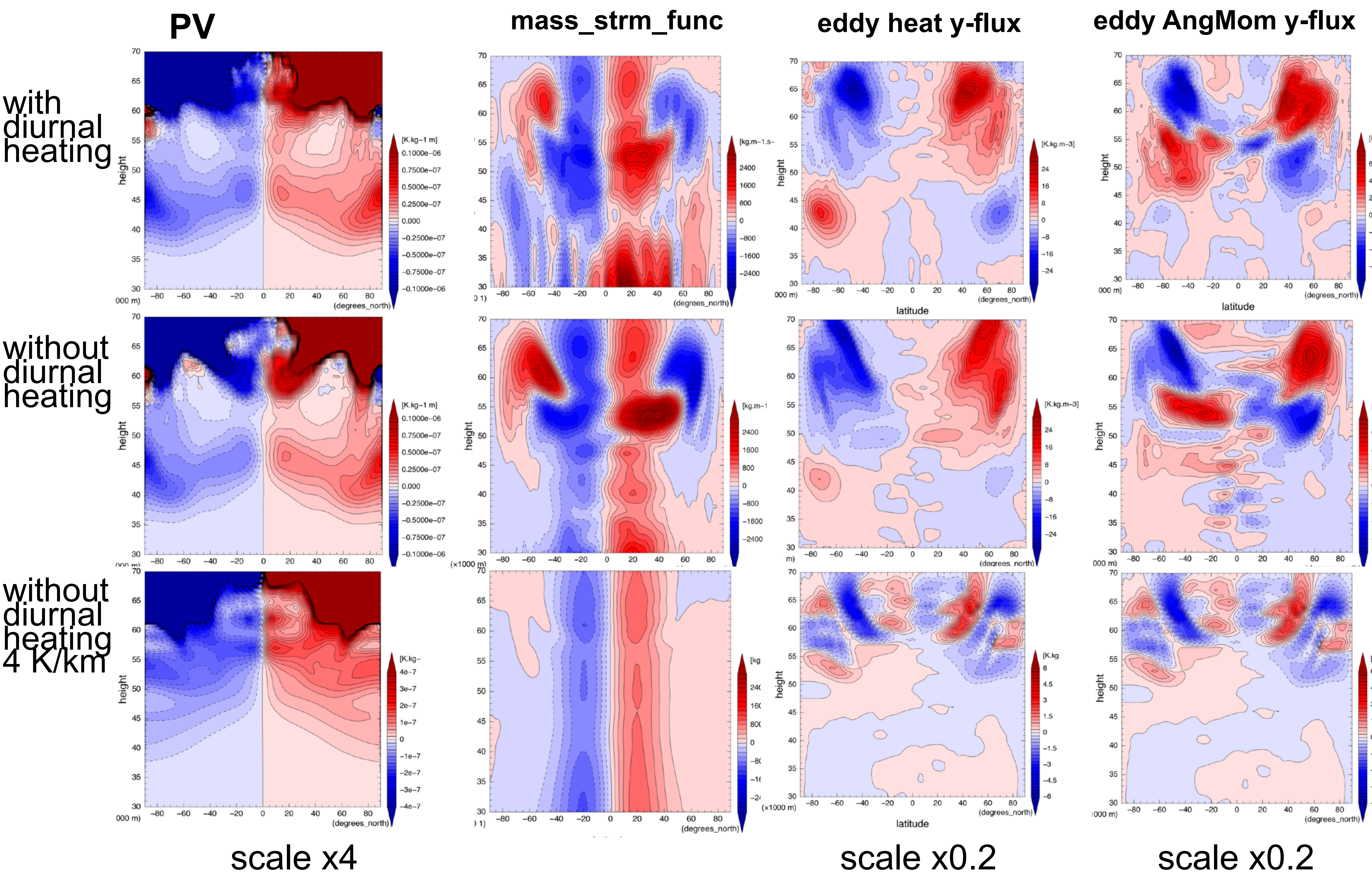


Figure 2. Vertical profiles of the prescribed temperature field, $T_0(z)$ (solid line), and the relaxation time of Newtonian cooling, $\tau_N(z)$ (dotted line).

time-zonal mean



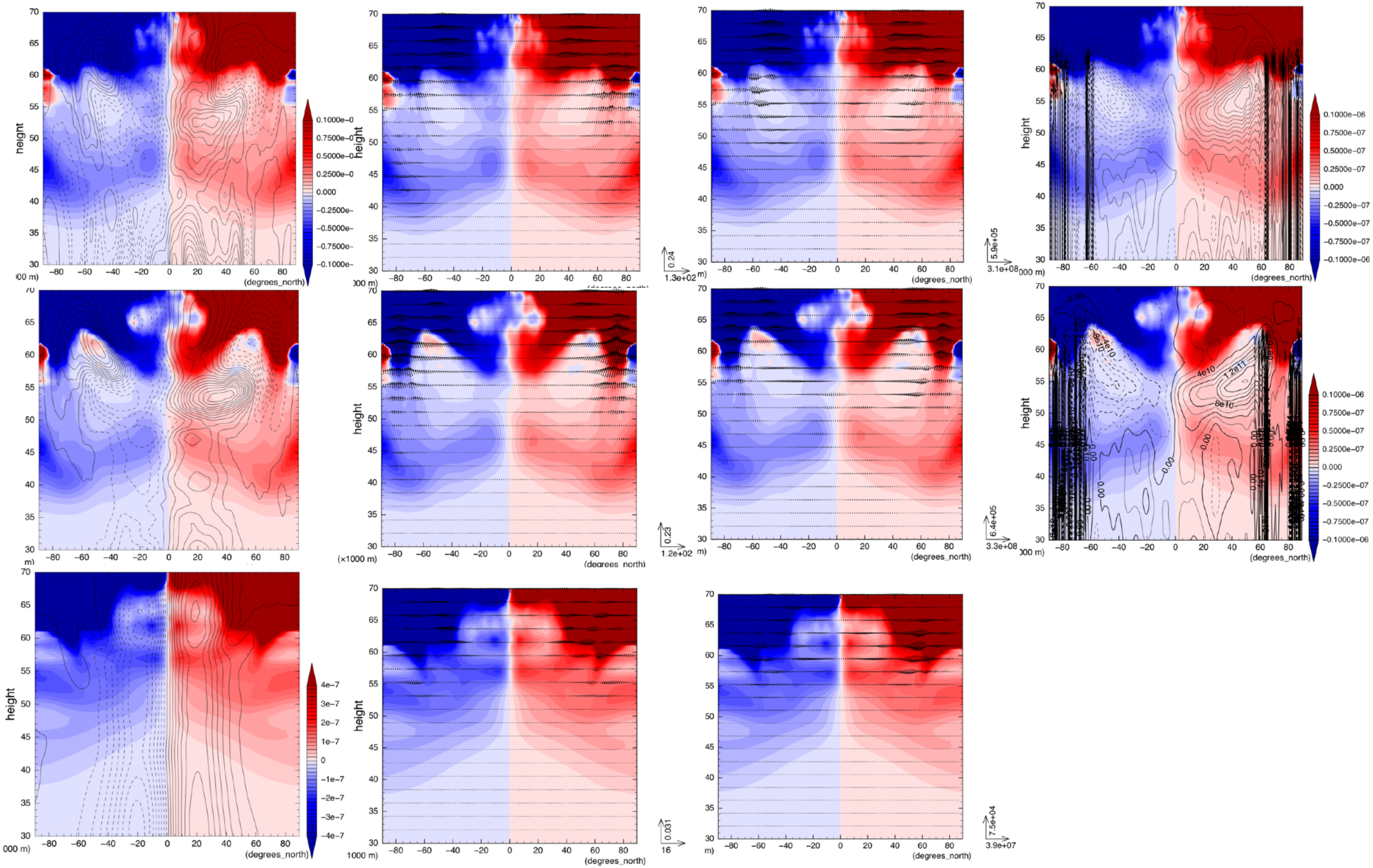
time-zonal mean

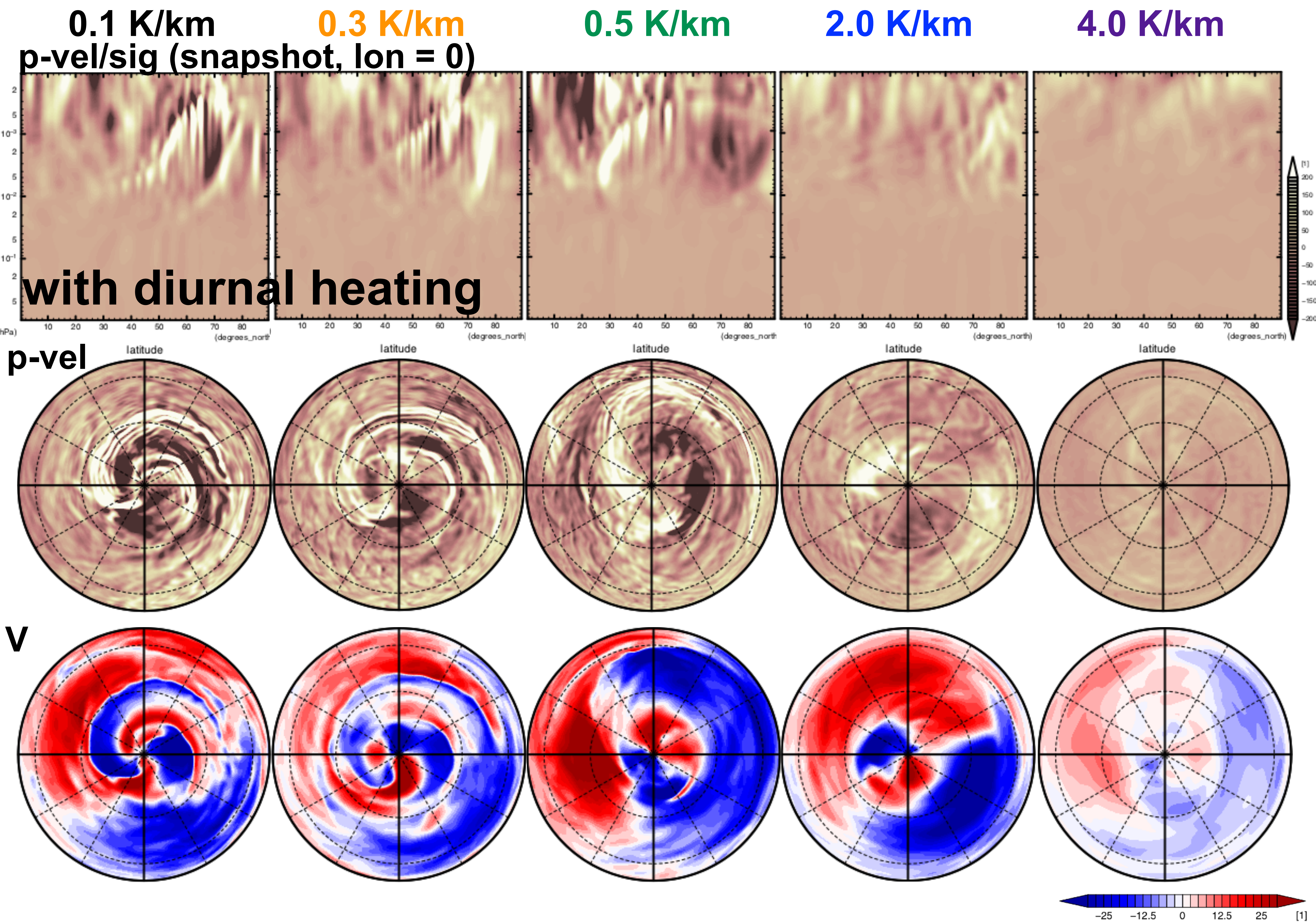
PV **& mass_strm** **& eddy heat flux** **& eddy AngMom flux** **& residual_strm (calc. in p-coord)**

with diurnal heating

without diurnal heating

without diurnal heating 4 K/km

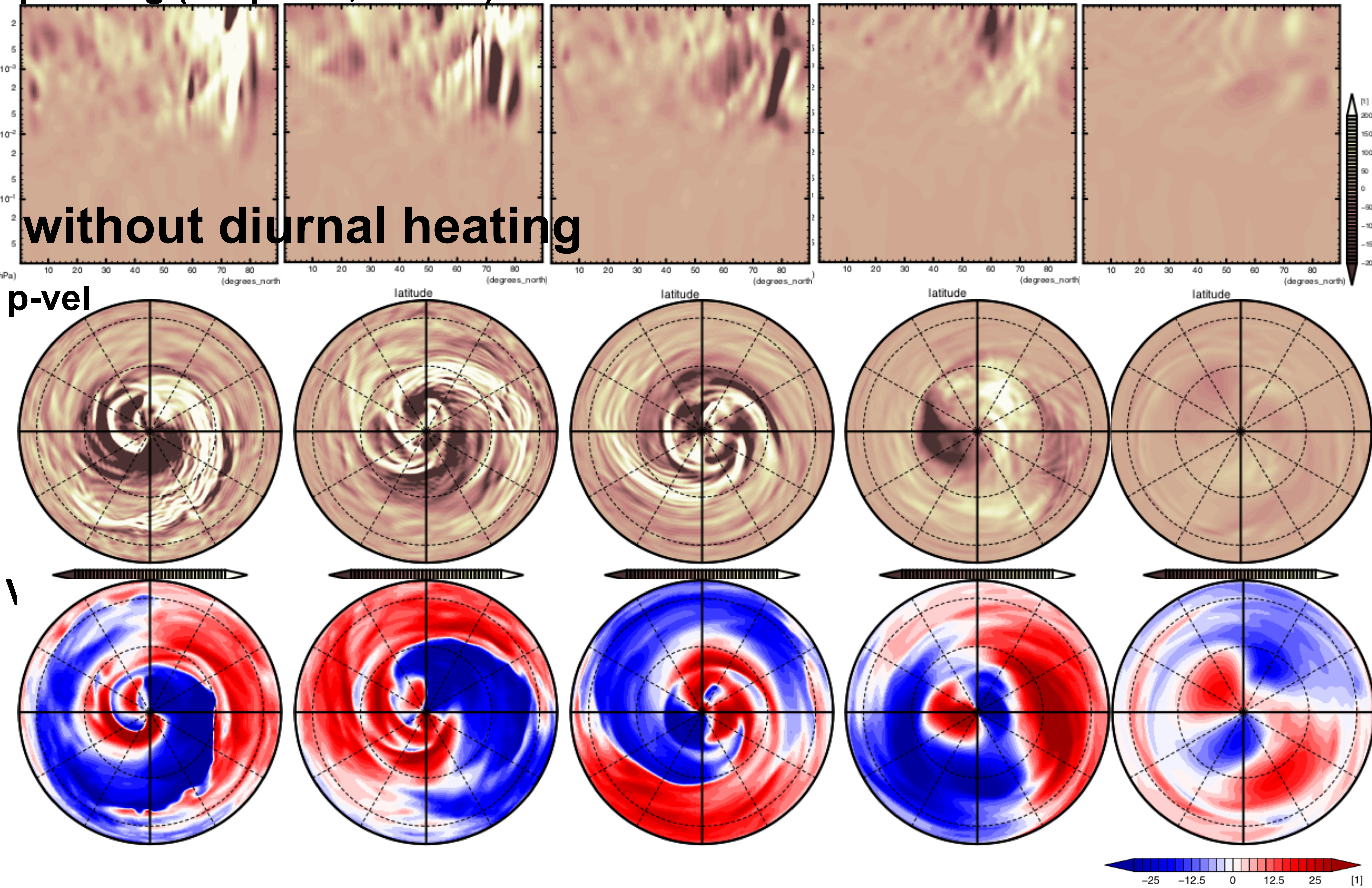



0.1 K/km
0.3 K/km
0.5 K/km
2.0 K/km
4.0 K/km
p-vel/sig (snapshot, lon = 0)
with diurnal heating
latitude
(degrees_north)
p-vel
V
−25
−12.5
0
12.5
25
[1]

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

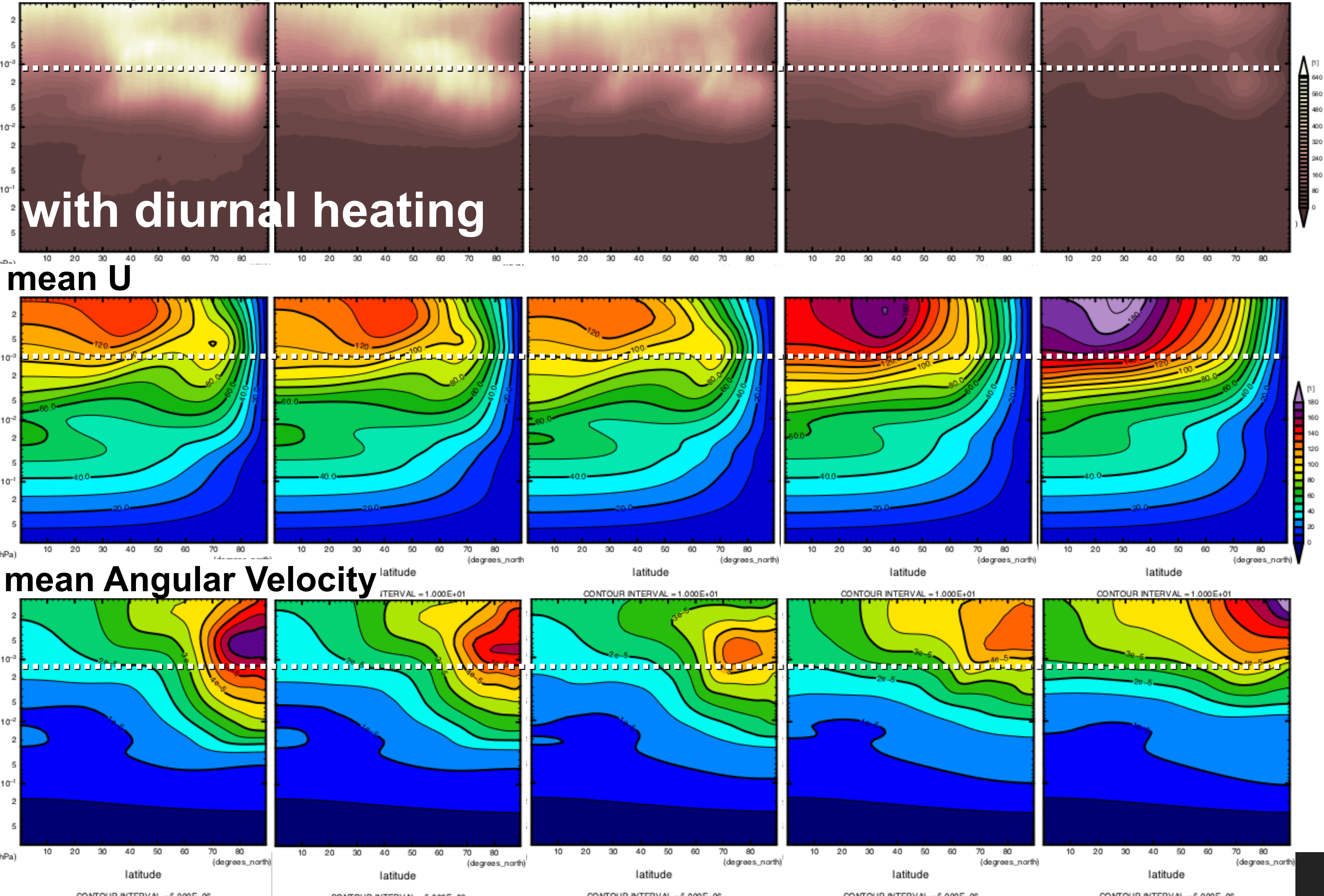
p-vel/sig (snapshot, lon = 0)

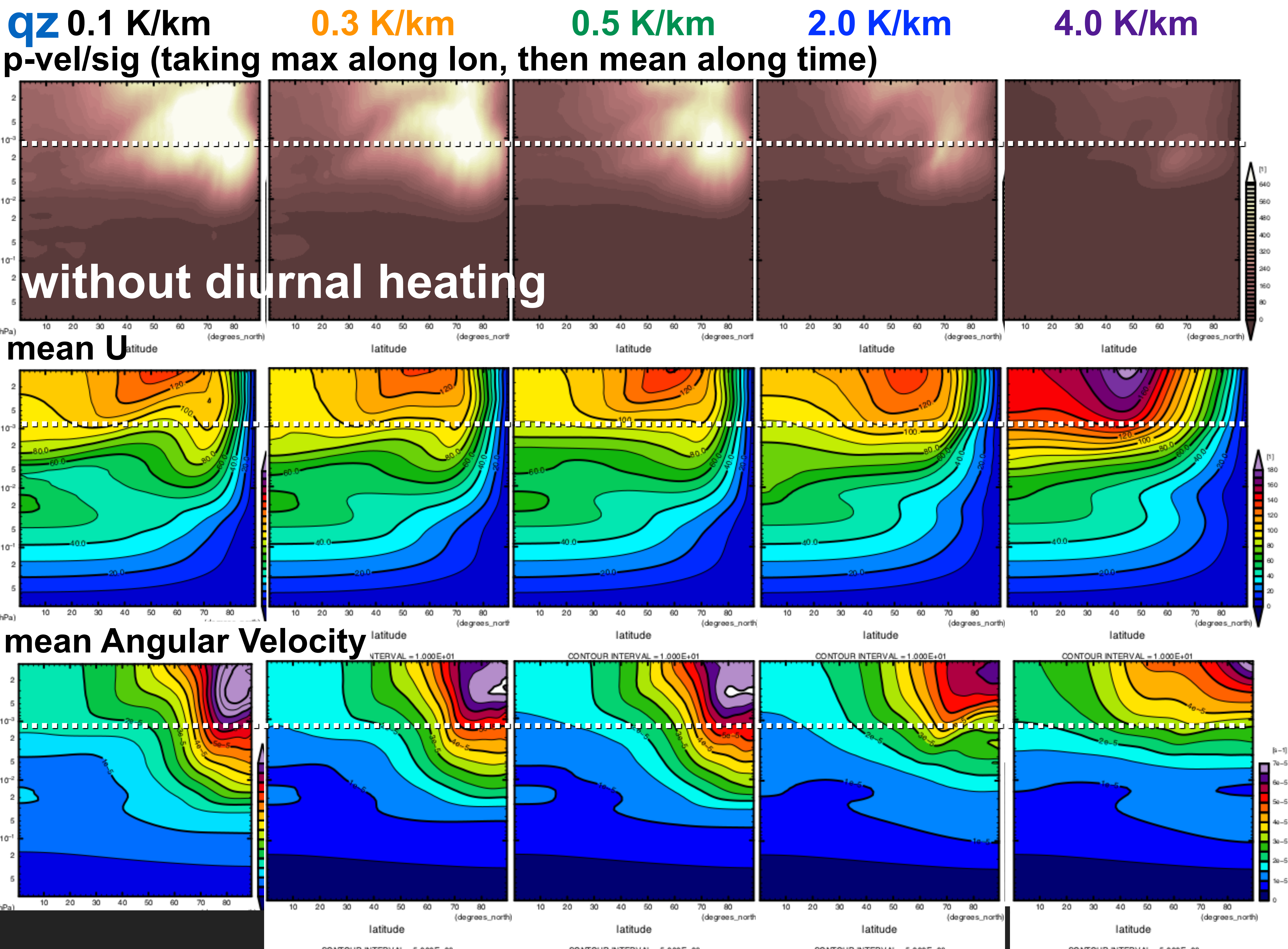
without diurnal heating



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)





qz 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)
without diurnal heating
mean U
mean Angular Velocity
latitude
(degrees_north)
CONTOUR INTERVAL = 1.000E+01
CONTOUR INTERVAL = 5.000E-06