How do waves and turbulence maintain the super-rotation of Venus' atmosphere – results from Akatsuki

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Background

- Hide's theorem: Inviscid pure axial flow cannot **create** the maximum of angular momentum (AM) per unit mass inside the atmosphere. → It requires eddy AM transport.

- Also, AM transport is needed to **maintain** the AM maximum, if the meridional circulation passes through it (to wash it away).

→ AM budget is a key to approach the super-rotation (**SR**)

Past observational study of AM transport

- From PVO: Rossow et al (1990), Limaye (2007): did not provide effective constraint.
- From VEx: no paper so far.

- **Problem**: AM flux is second order ($\overline{u'v'}$): **requires accuracy and good sampling**.

Our strategy

- Improve automated cloud tracking
  (Ikegawa & Horinouchi 2016; Horinouchi et al 2017)
  - Better method; better error correction; sophisticated quality control (screening).
    - better than manual tracking not only in sampling density but also in accuracy
  - Actual error evaluation: see Horinouchi et al (2020; **H20**) **online supplement**

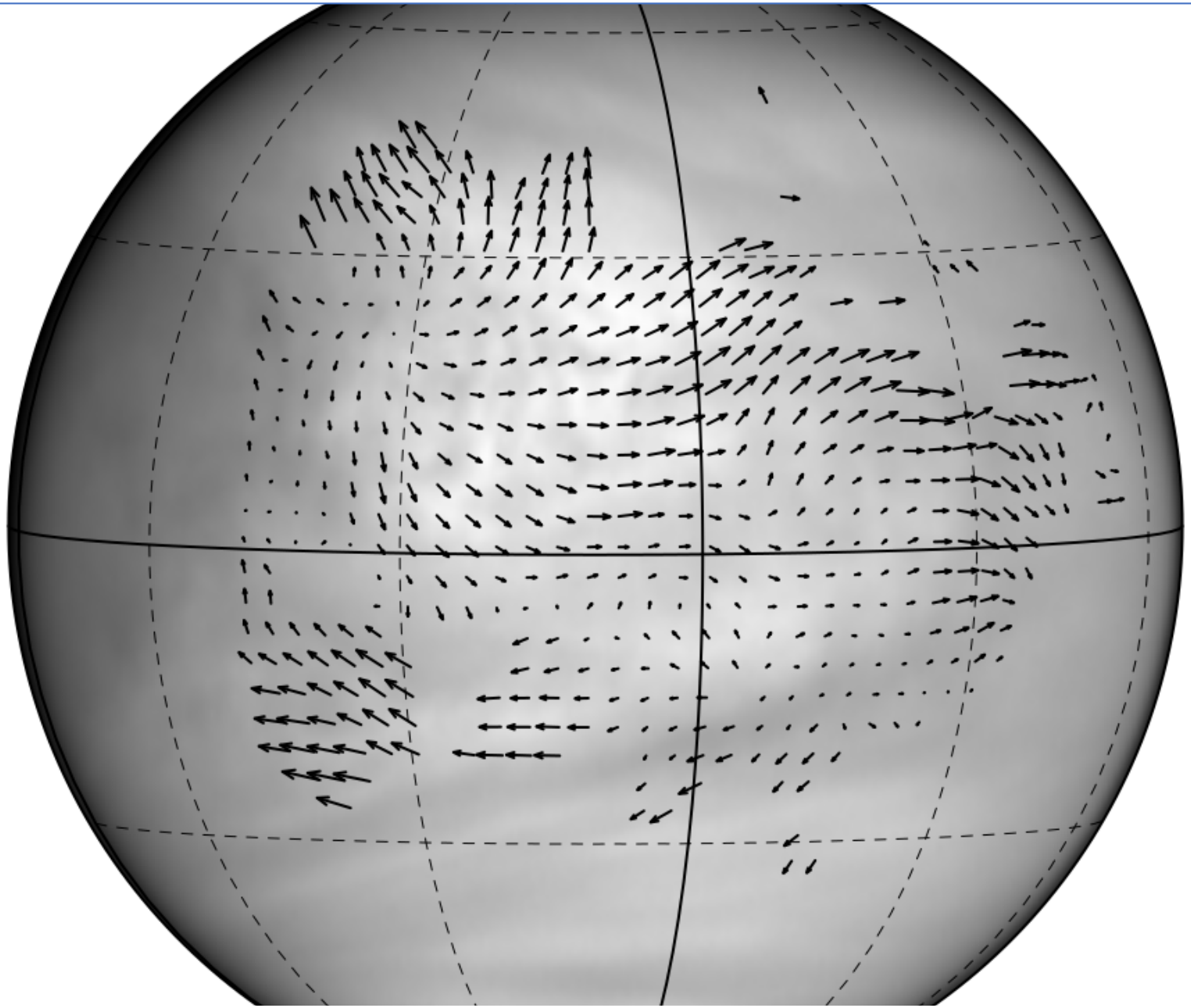
✓ Ikegawa and Horinouchi (2016) *Icarus*. https://doi.org/10.1016/j.icarus.2016.01.018
✓ Horinouchi et al (2017) *Meas. Sci. Tech*. https://doi.org/10.1088/1361-6501/aa695c
✓ Horinouchi et al (2020) *Science*. https://science.sciencemag.org/content/368/6489/405/
(DOI link is incorrect so far)

Data

- Period: Dec 2015 – Dec 2018
- Near cloud-top images from Akatsuki UVI (365 nm, 283 nm)
  - Used for cloud tracking
  - See Horinouchi et al (2018) for mean winds
- Thermal-infrared temperature from Akatsuki LIR
  - Limited to high-emission angles → near cloud-top

✓ Horinouchi et al (2018) *Earth, Planets, Space*. https://doi.org/10.1186/s40623-017-0775-3

Example: deviation from a rigid-body rotation (100 m/s at EQ; Derived from 3 images: 2017-01-01 12,14,16 UTC)



Introducing H20

Horinouchi et al (2020) *Science*. https://science.sciencemag.org/content/368/6489/405/
(DOI link is incorrect so far)

Evaluation basis: Transformed Eulerian Mean (TEM) equation at steady state (TEM is a kind of zonal mean)

$$\boldsymbol{v}^r \cdot \boldsymbol{\nabla} M = \rho_0^{-1} \boldsymbol{\nabla} \cdot \boldsymbol{F}$$

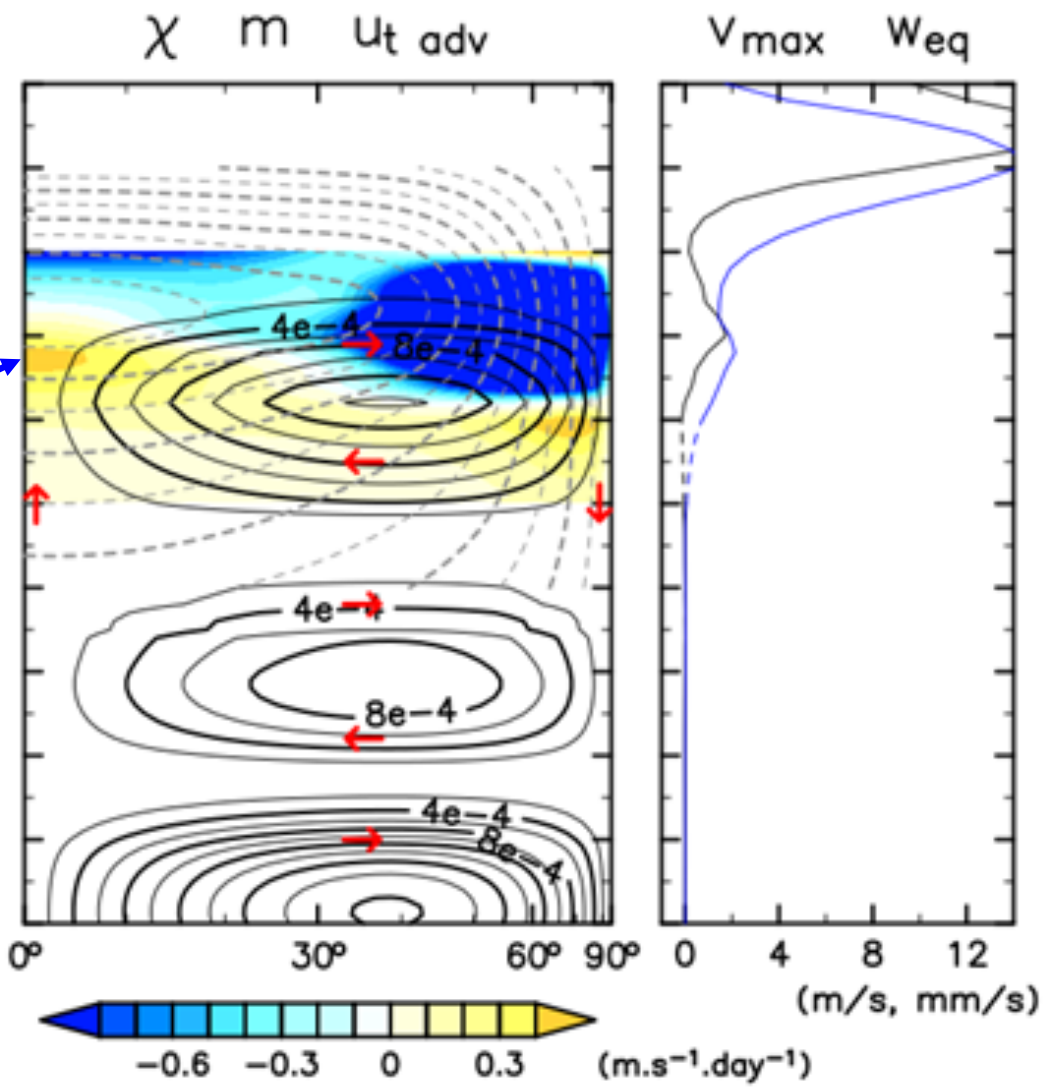
- $M \equiv a\bar{u}\cos\varphi + a^2\Omega\cos^2\varphi$ (AM per unit mass)
- $\boldsymbol{v}^r \equiv (0, v^r, w^r)$: zonal mean **meridional circulation** velocity ("residual"; incl. Stokes drift)
- $\boldsymbol{F} \equiv (0, F_y, F_z)$: Eliassen-Palm (EP) flux: **"eddy" AM flux (by waves and turbulence)**

- **Required eddy AM flux convergence (rhs) depends on the meridional circulation (lhs)**

Crudely estimated the mean meridional circulation from old data (VIRA shortwave heating) with a simplest assumption → Order-estimation of required eddy acceleration

Here we used $N^2 w^r \propto Q$ to get $\boldsymbol{v}^r$.
Introduced an idealized M distribution to get $-(a\cos\varphi)^{-1}\boldsymbol{v}^r \cdot \nabla M$.

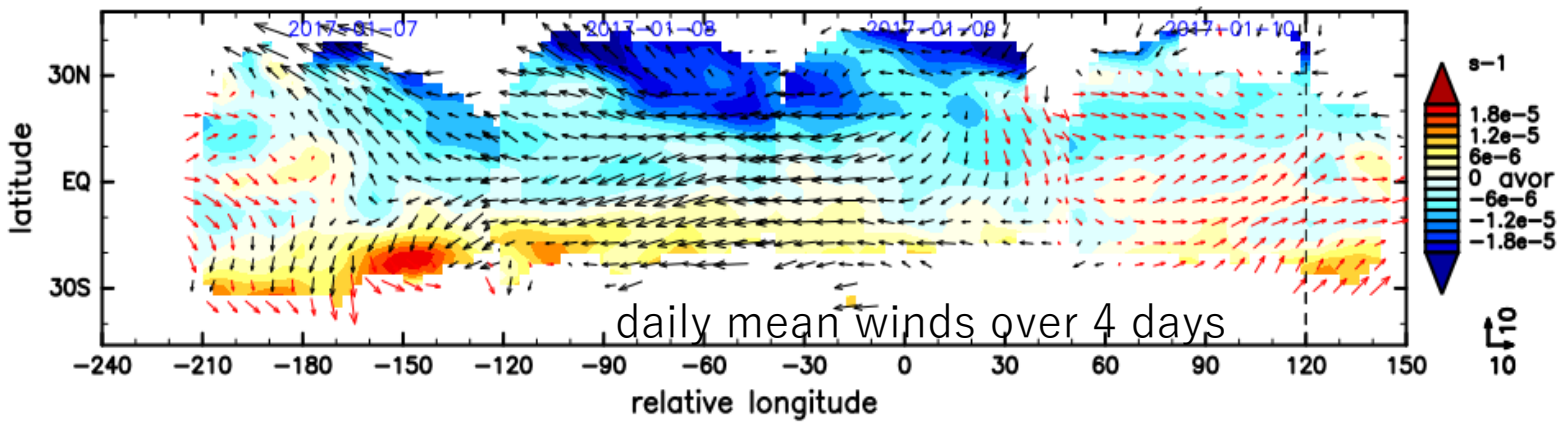
Acceleration needed to maintain M's peak at ~equatorial cloud top (< ~1 m/s/day)



part of Fig. 1 of **H20**

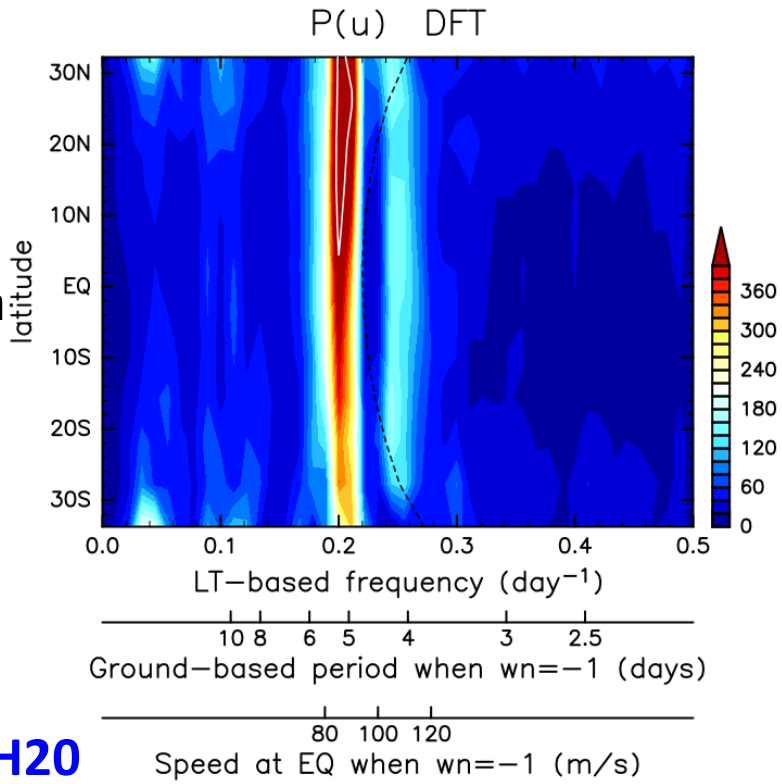
The mean meridional circulation we obtained is consistent with the satellite derived shortwave – longwave differences
(**supplement of H20**)

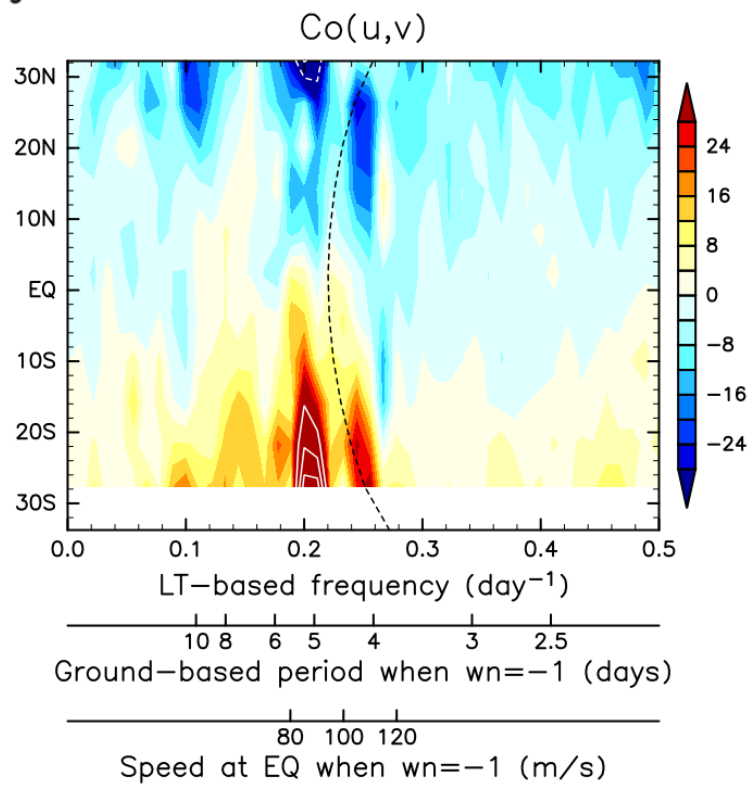
Example and spectra of wind disturbances (other than thermal tide)



absolute vorticity

power spectrum (u')



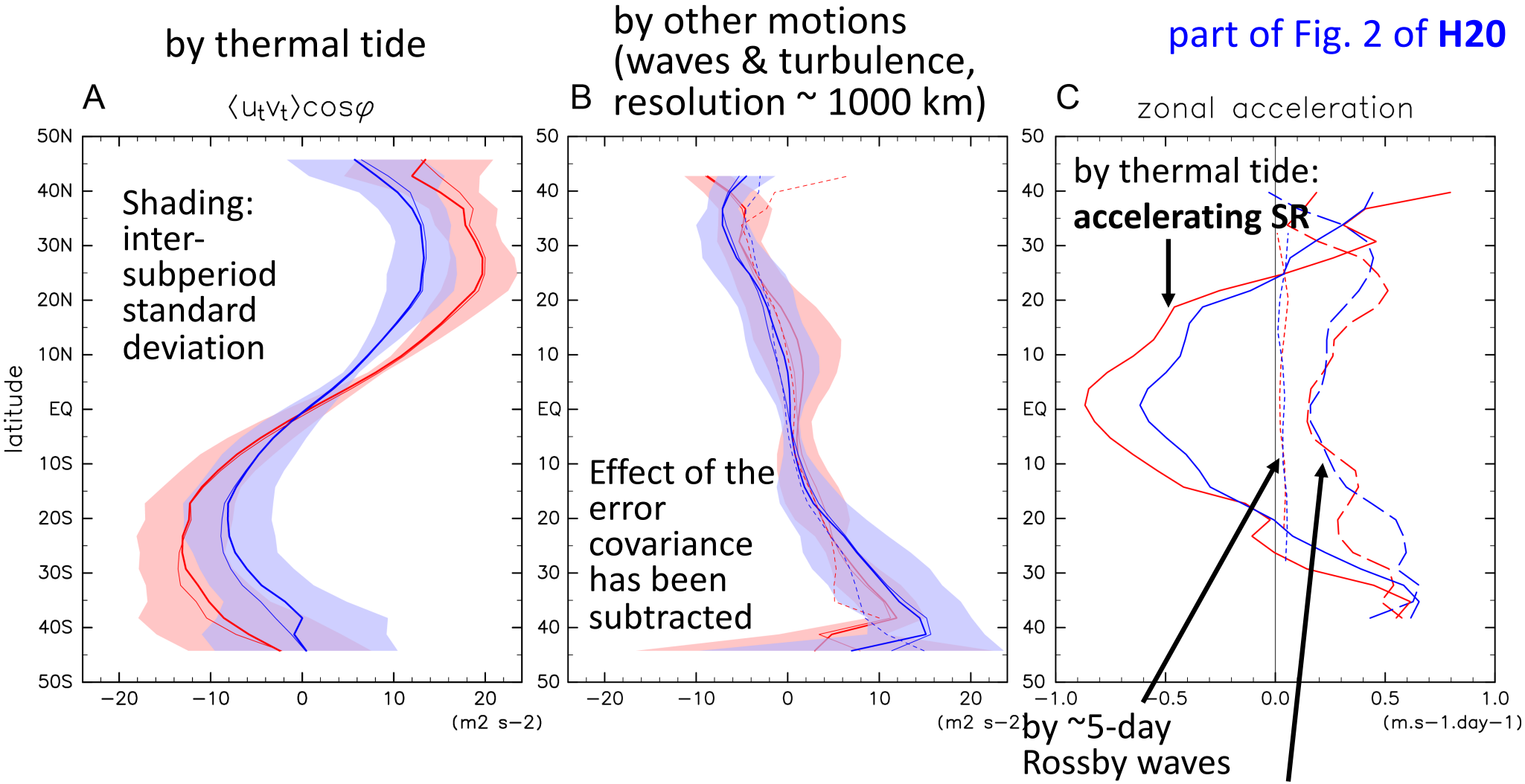


co-spectrum (u',v')

Fig. 3 of **H20**

Latitudinal AM transport (A,B) and its convergence (C; acceleration at low lat) estimated from UVI images (dayside, near cloud-top). Red: 283 nm; Blue: 365 nm

part of Fig. 2 of **H20**



Caution: observations are available only on dayside

Caution: results are limited to low lat

Vertical AM transport

- Thermal tide (estimated from UVI+LIR results & theoretical/observational vertical structure: Kouyama et al 2019) : accelerates SR at magnitude comparable to its horizontal AM transport (previous page)
- Other sources: could not be estimated

AM balance suggested from observation by Akatsuki

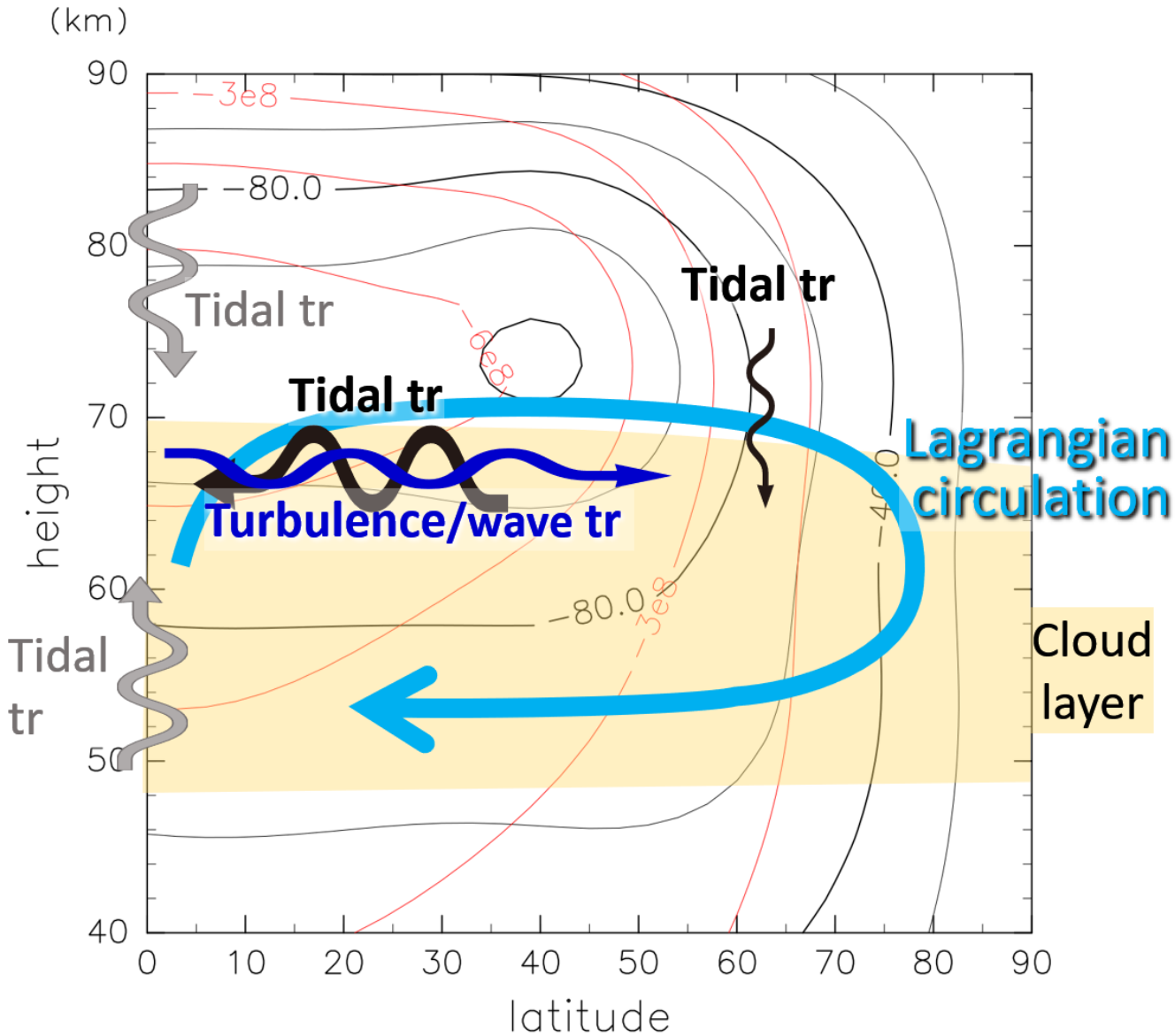


Fig. 4A of **H20**

Schematic illustration of suggested AM balance in the cloud layer of Venus. A: those quantified or order-estimated in this study; Wavy arrows indicate eddy transports of SR's negative AM; items with "tr" represent transports quantified (black, blue) or order-estimated (gray) in this study

AM balance suggested from observation plus physical considerations

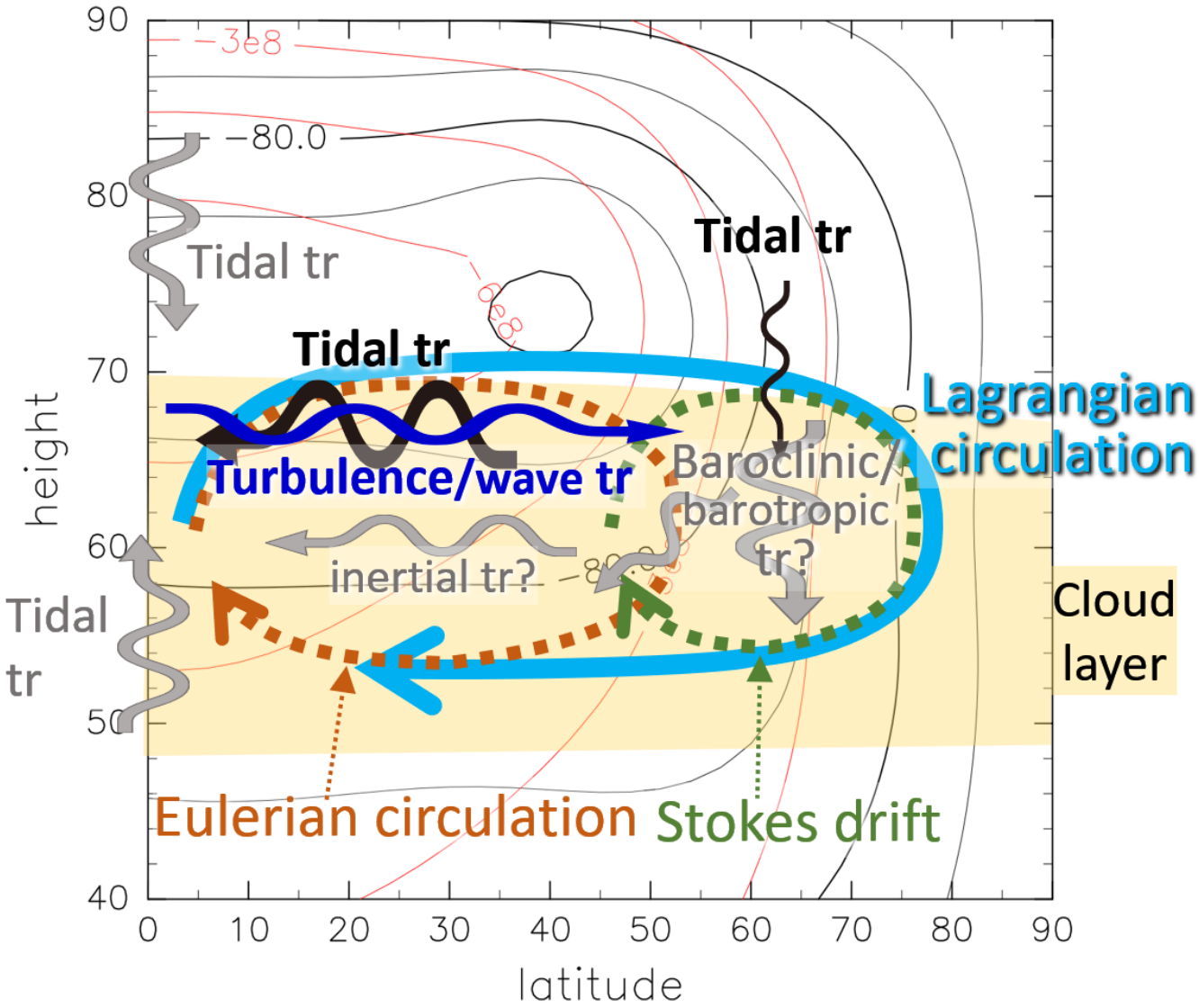


Fig. 4B of **H20**

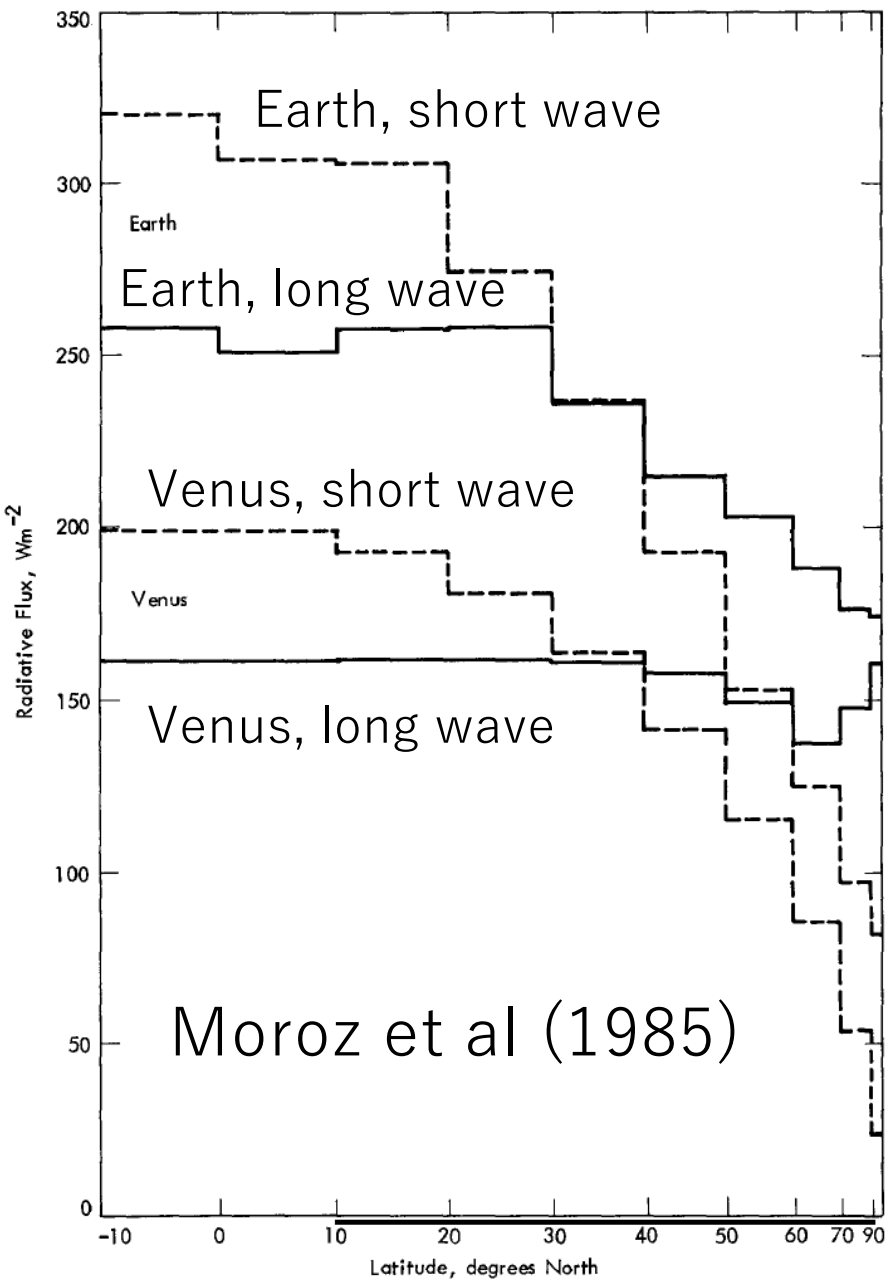
Schematic illustration of suggested AM balance in the cloud layer of Venus. B: **A** plus speculation. Wavy arrows indicate eddy transports of SR's negative AM; items with "tr" represent transports quantified (black, blue) or order-estimated (gray) in this study, and those with "tr?" (in B) represent suggested ones.

Discussion: super-rotation as a day-night heat transporter

- Radiative time scale in the upper cloud layer: ~10 days < solar day ⇒ day-night heat transport needed
- Zonal flow such as super-rotation does that, but it alone cannot transport heat poleward (**problem**).
- **Solution: to allow both super-rotation & meridional circulation by having AM transport by thermal tide** (and other kinds of eddy motion)
- Remark: pure axi-symmetric framework (like Gieracsh 1975) is inadequate in the sense that it does not require day-night heat transport (but it's OK for near surface where radiative time scale is ~10^4 days)

Conclusions

- We have successfully **quantified the AM transport** near the cloud top at low-to-mid latitude
  - Also quantified spectral features; found turbulent motions
- The AM peak around the equatorial cloud top is maintained by the AM transport by **thermal tide** (against run off by meridional circulation)
  - **Turbulence and other waves** act oppositely there, but they should be important for the AM redistribution at mid-latitude
- Proposed a thermo-dynamic view of the SR:
  - Heat transport system by SR and meridional circulation mediated by thermal tide and/or other kind waves & turbulence
    - Remark: **Atmospheric general circulation** should be told in terms of how the non-uniform absorbed solar energy is circulated.
  - Possible application to exo-planets: might be ubiquitous



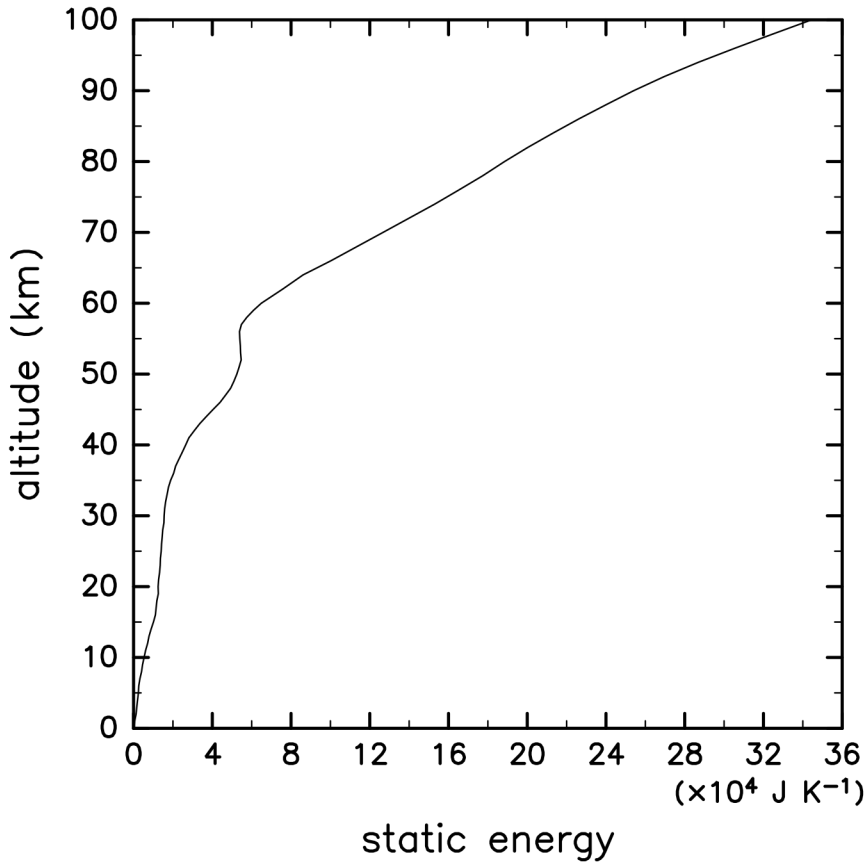
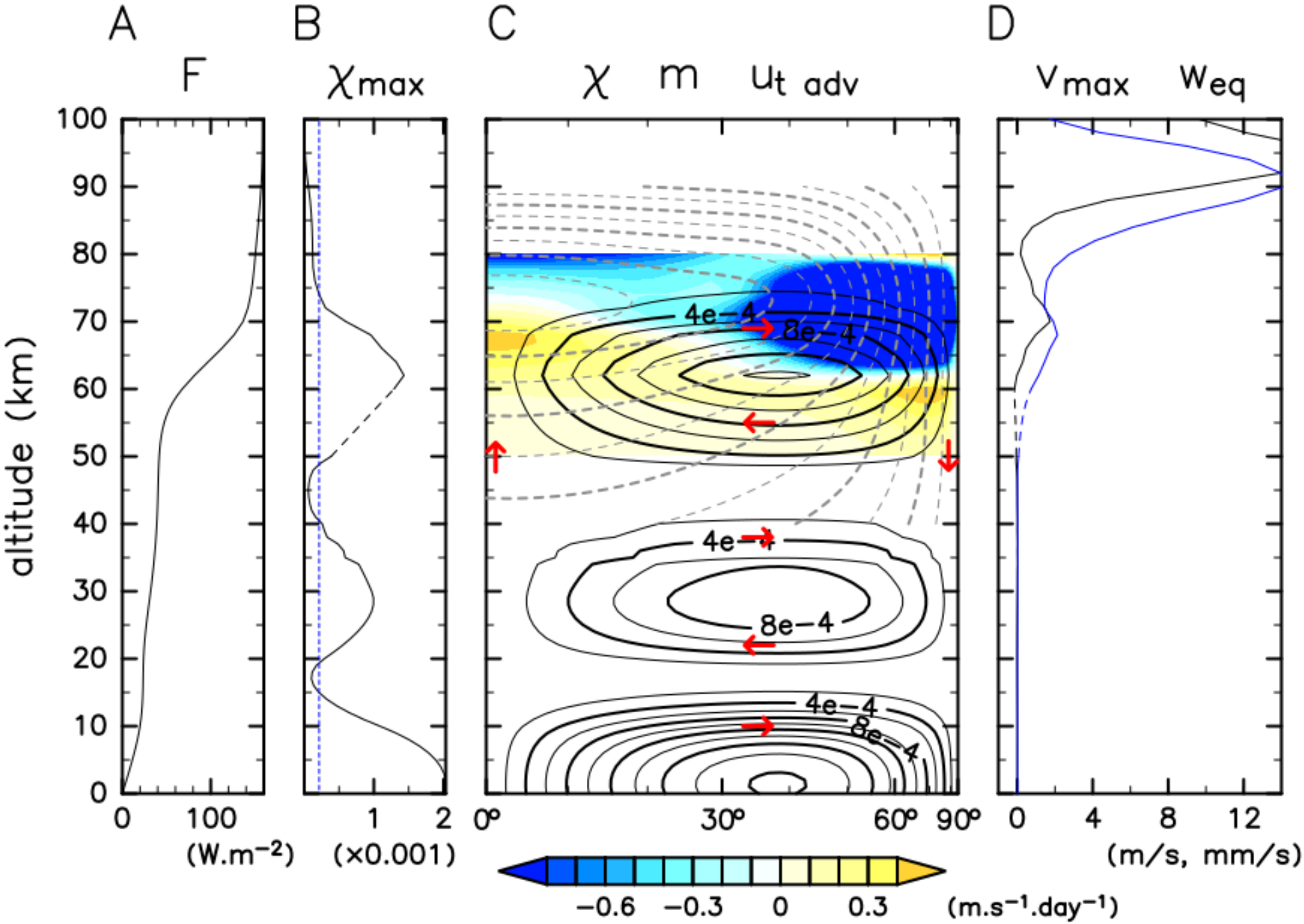


Fig. S1. A vertical distribution of static energy. It is obtained from the VIRA data *(39)*, and is expressed as the difference from the surface value, $s' \equiv s - s(z=0\,\mathrm{km})$. This profile was used to compute the meridional heat transport shown in subsection **S13**. Its theoretical basis is found in *(54)*


A
B
C
D
F
χmax
χ m ut adv
vmax weq
altitude (km)
100
90
80
70
60
50
40
30
20
10
0
0 100
(W.m−2)
1 2
(×0.001)
0° 30° 60° 90°
4e−4
8e−4
4e−4
8e−4
4e−4
8e−4
0 4 8 12
(m/s, mm/s)
−0.6 −0.3 0 0.3
(m.s−1.day−1)

Thermal tide: T ~ cloud top from LIR (high emission angle observation)

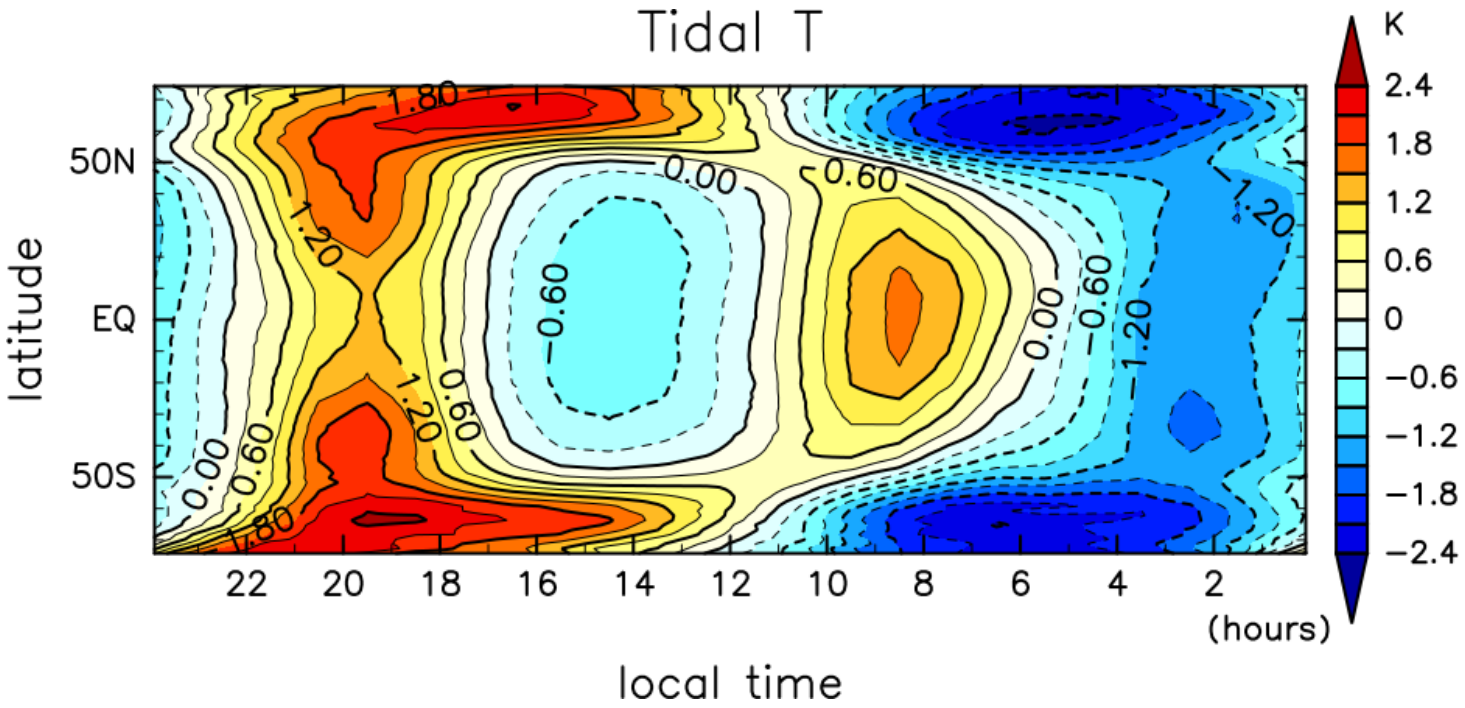


Fig. S11 of **H20** （あかつきの熱赤外カメラLIRによる雲頂付近の潮汐の温度場）

365 nm

Fig. S9 of **H20**

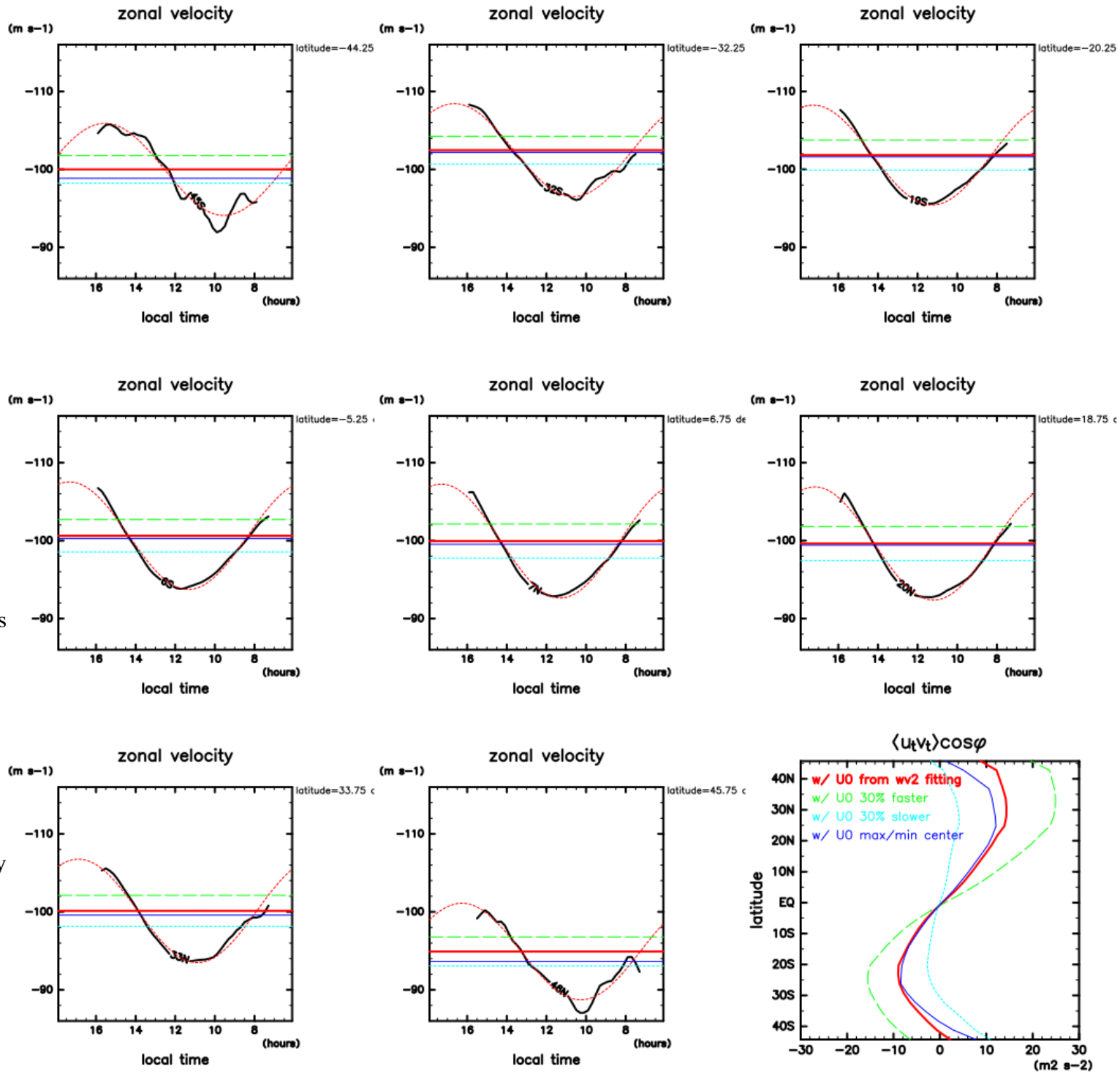
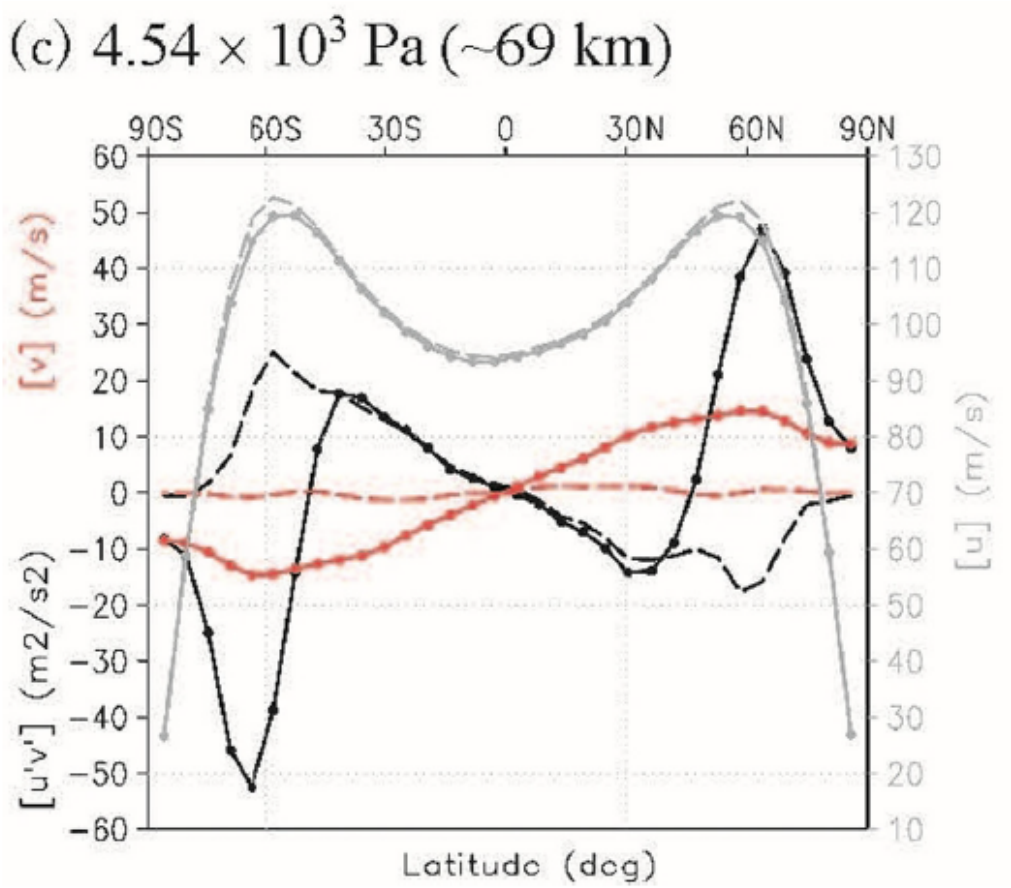
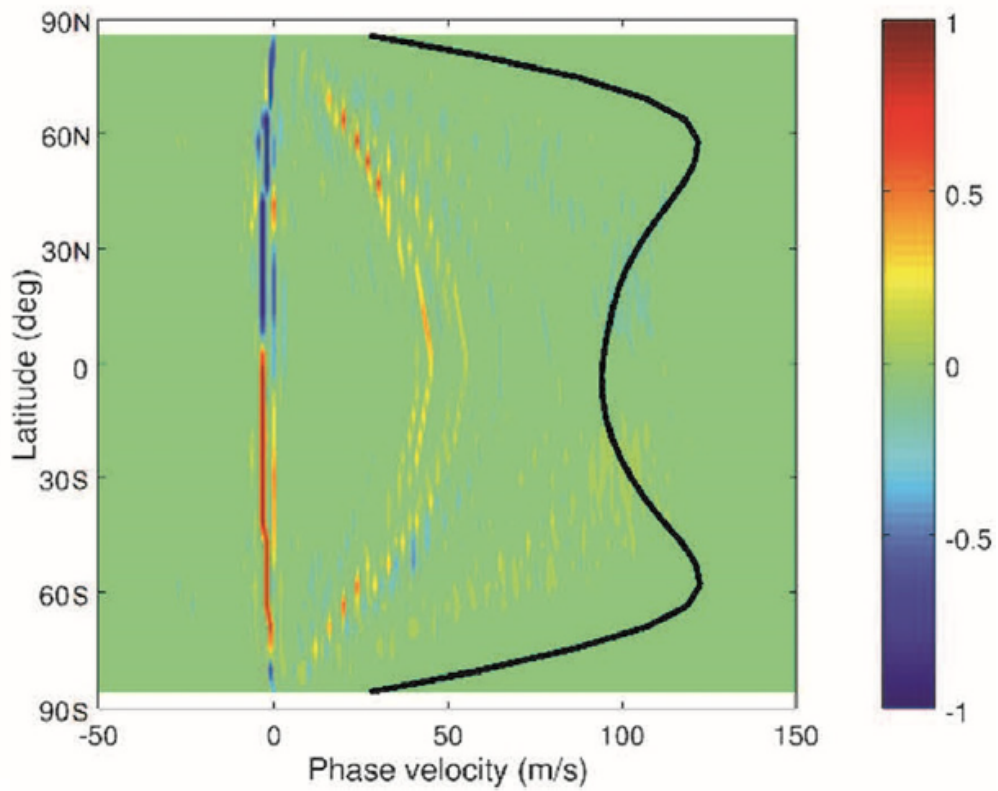


Fig. S10. Illustration of the sensitivity test to investigate the dependence of tidal angular momentum flux on the assumption of u_0. A–H: mean zonal wind $\bar{u}$ obtained from the three-year period (black curves) at latitudes shown on their upper-right corners. The red lines indicate the values of u_0 obtained by the least-square fitting of the wavenumber-2 sinusoidal curve. **I**, $\langle u_t v_t \rangle \cos\varphi$ obtained from this assumption (red curve), which is the same as the thin solid blue curve in **Fig. 2A**. All panels: the green and cyan lines (**A-H**) and curves (**I**) show the cases in which u_0 defined this way is shifted by ±0.3 times the fitting-based tidal amplitude (green: the faster; cyan: the slower). The blue lines (**A-H**) and curve (**I**) show the case in which u_0 is defined as the center in between the maximum and the minimum of $\bar{u}$.

Yamamoto et al (2019) Venus GCM results

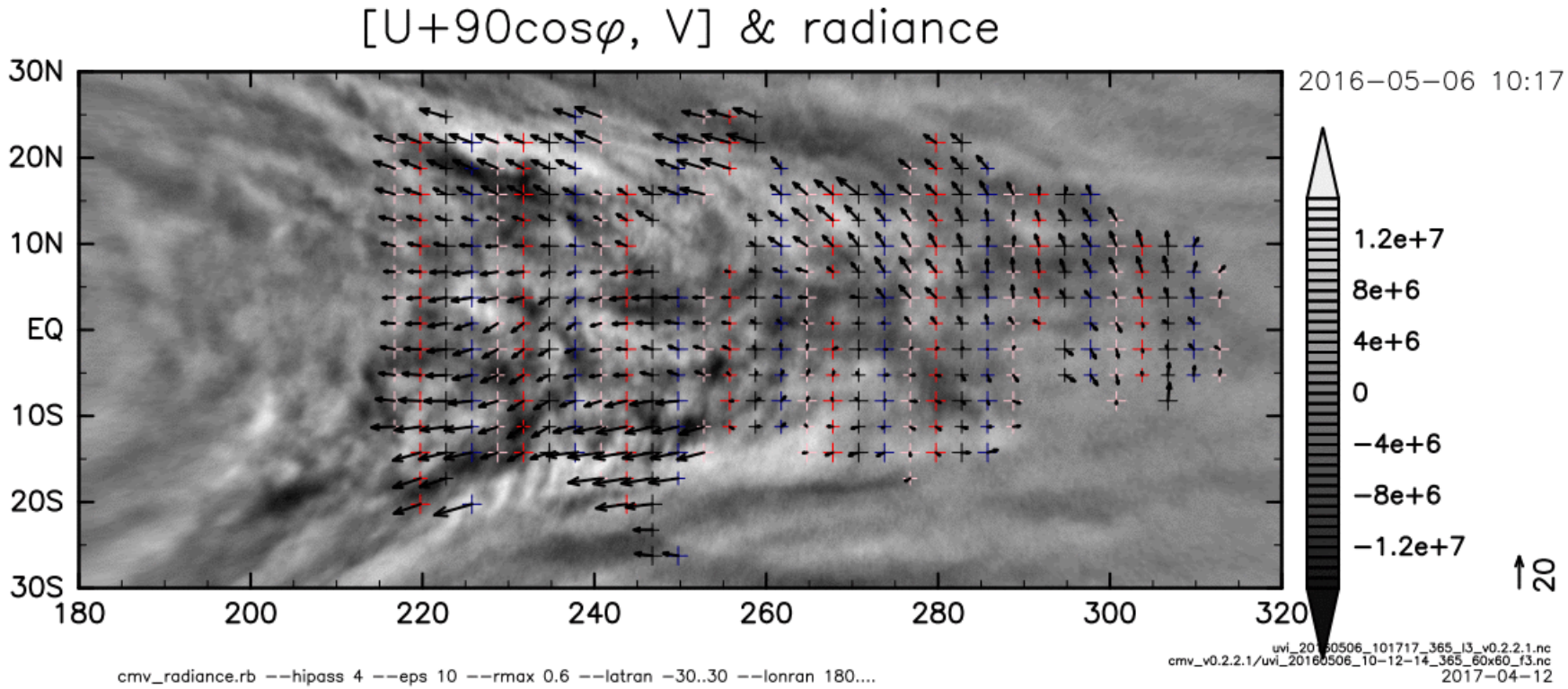




Dashed: true zonal mean
Solid: mean over dayside
u'v' : major contribution is from tides

Cloud top wind (traditional UV obs., but highly improved)

Motion relative to a representative rotation

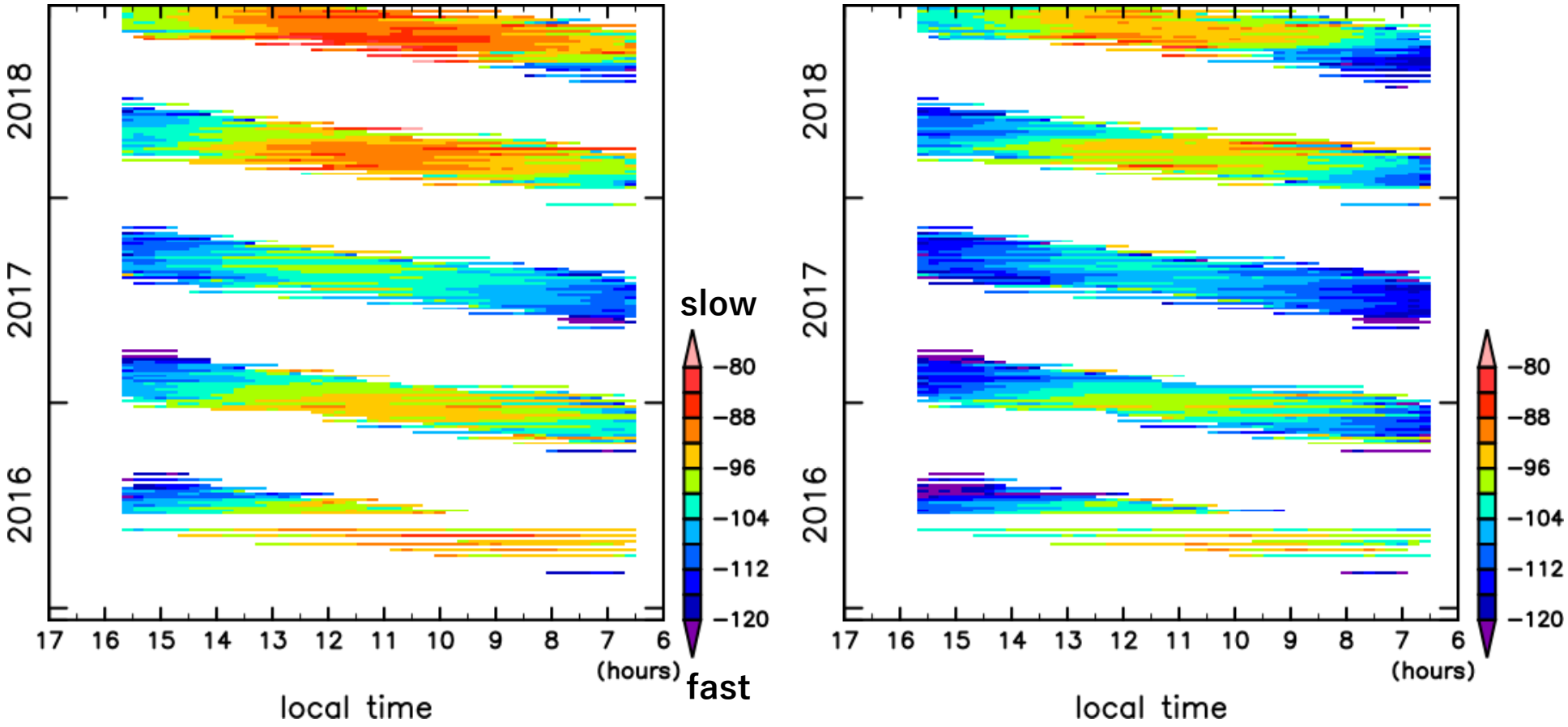


U averaged over 20°S-20 ° N

Super-rotation + tide

365 nm slower

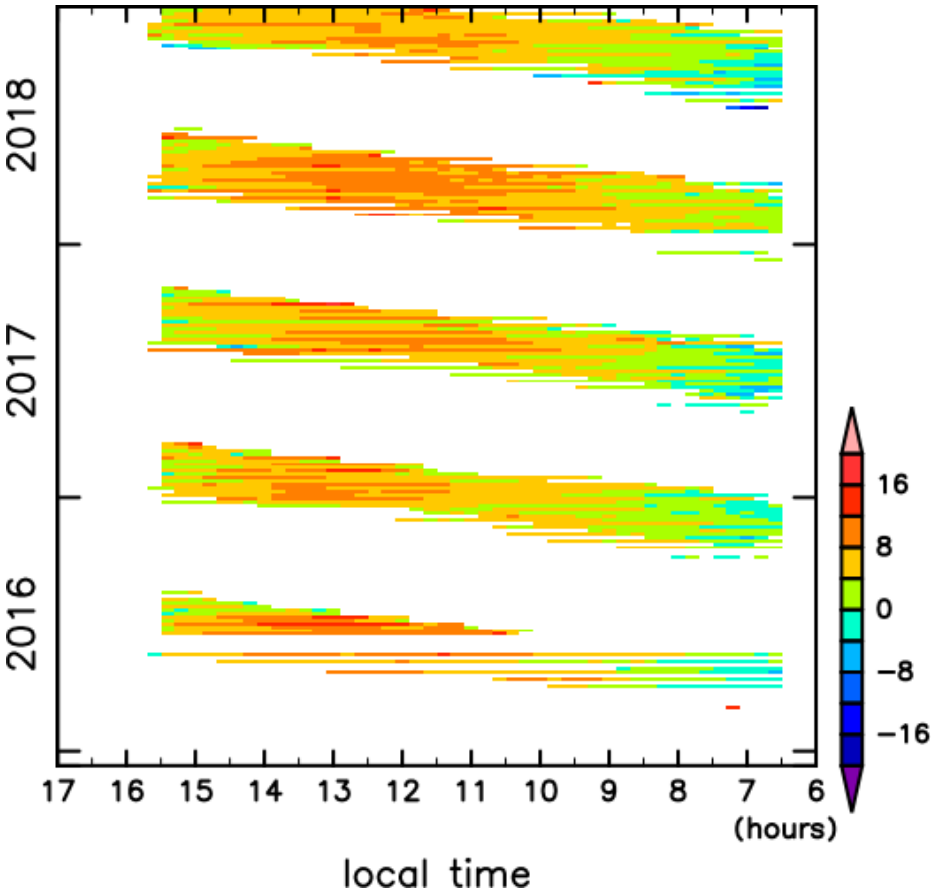
283 nm faster



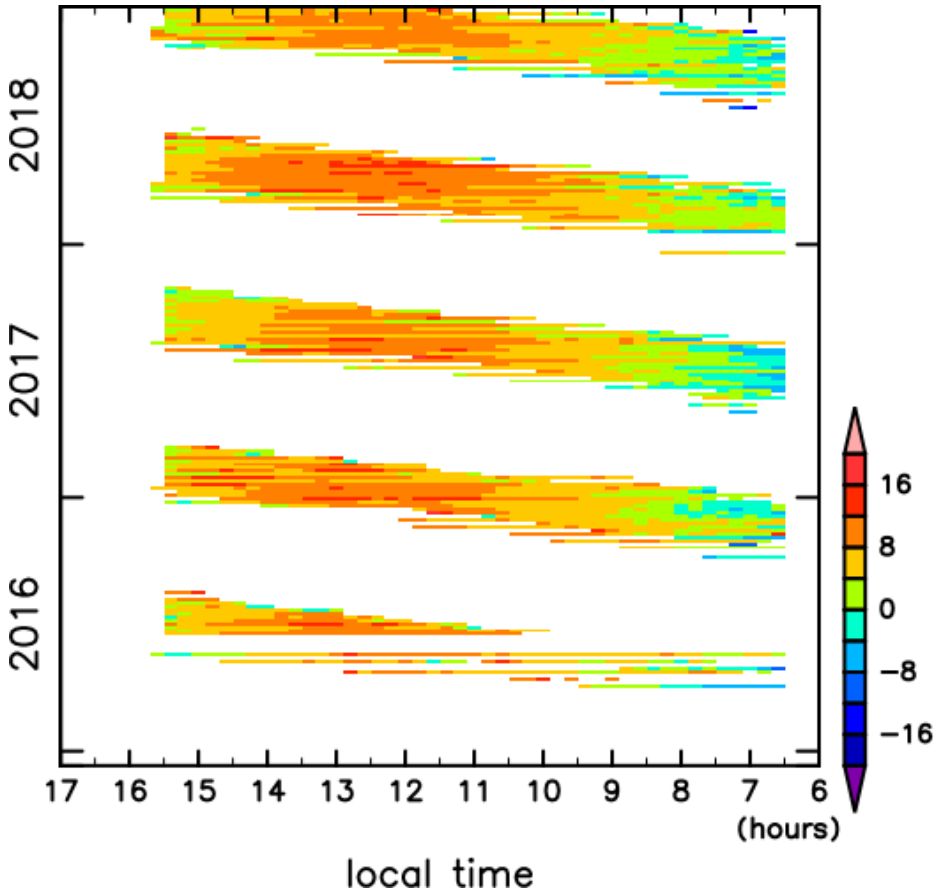
V averaged over 20°-35 ° N

Poleward dayside tidal wind

365 nm slightly slower

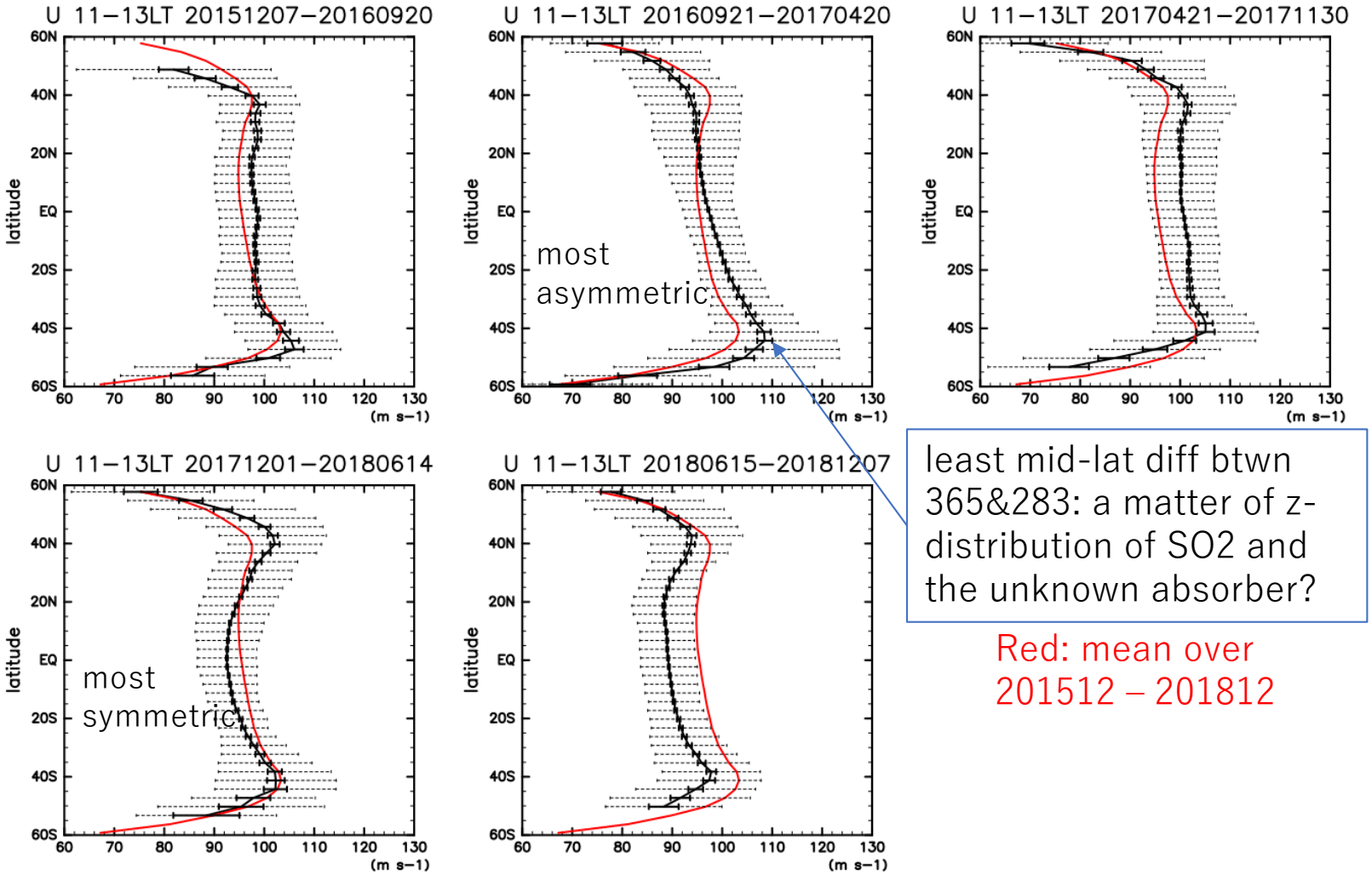


283 nm slightly faster



U 365nm 11-13LT

Dotted bars: standard deviation w/ t



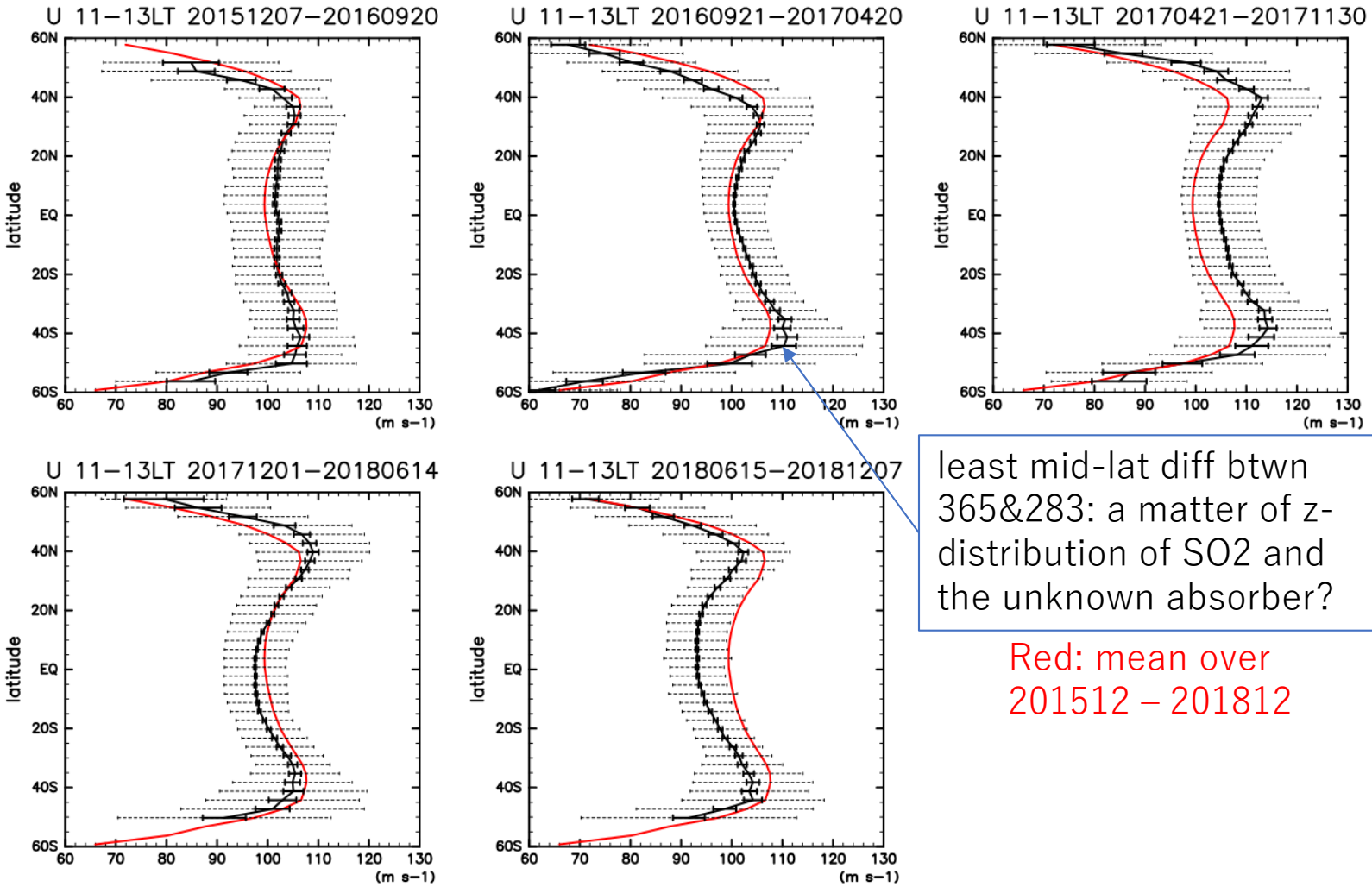
least mid-lat diff btwn 365&283: a matter of z-distribution of SO2 and the unknown absorber?

Red: mean over 201512 – 201812

ltm_winds_lines.rb --eps_errbar cmv_v20190201_nt3il/daily_uvi_365_eps20_pp0hvlen2.0_LT.nc --tstr 2015-12-07,2016-09-21,2017-04-21,2017-12-01,2018-06-15 --tend 2016-09-2... 2019-04-14

U 283nm 11-13LT

Dotted bars: standard deviation w/ t

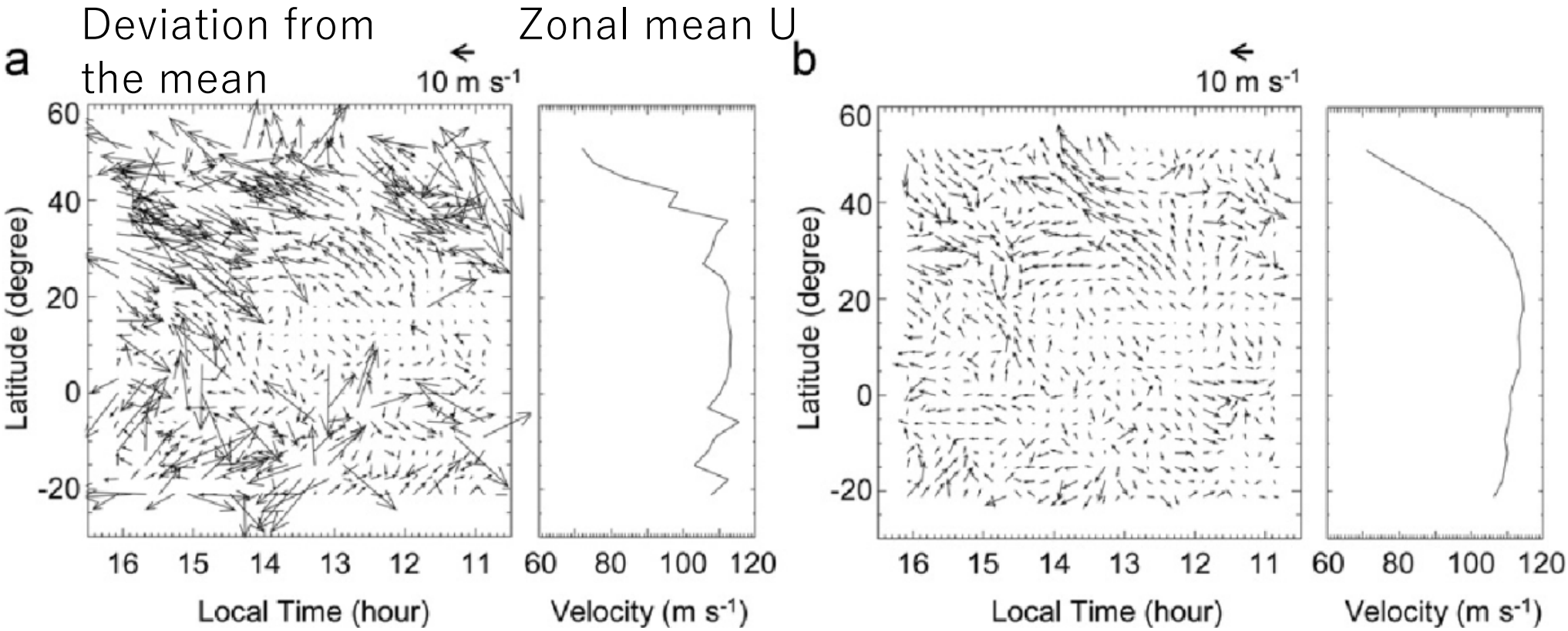


least mid-lat diff btwn 365&283: a matter of z-distribution of SO2 and the unknown absorber?

Red: mean over 201512 – 201812

ltm_winds_lines.rb --eps_errbar cmv_v20190201_nt3il/daily_uvi_283_eps20_pp0hvlen2.0_LT.nc --tstr 2015-12-07,2016-09-21,2017-04-21,2017-12-01,2018-06-15 --tend 2016-09-2... 2019-04-14

Ref: Kouyama et al (2012) from Galileo SSI



Simple CC

Corrected by relaxation labeling (w/ formulation having problems: see Horinouchi et al 2017)