Venus atmosphere dynamics revealed by cloud tracking using images from Akatsuki

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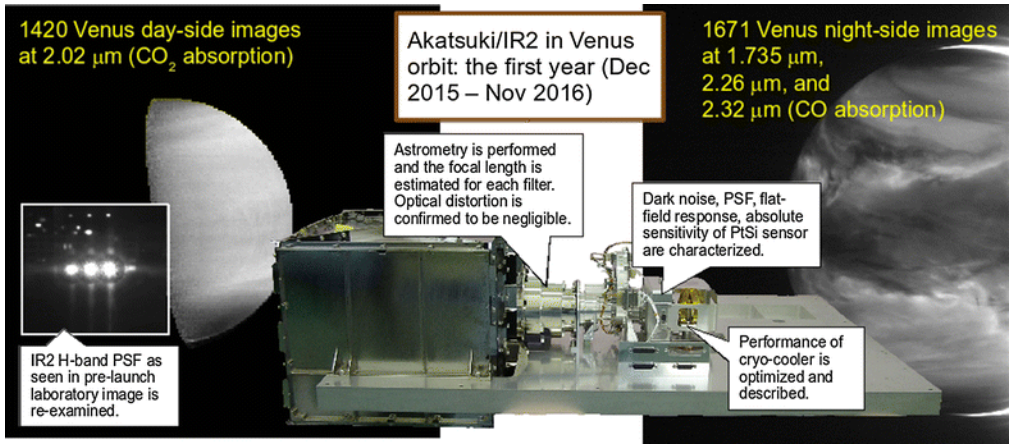
Cloud tracking method → poster P39

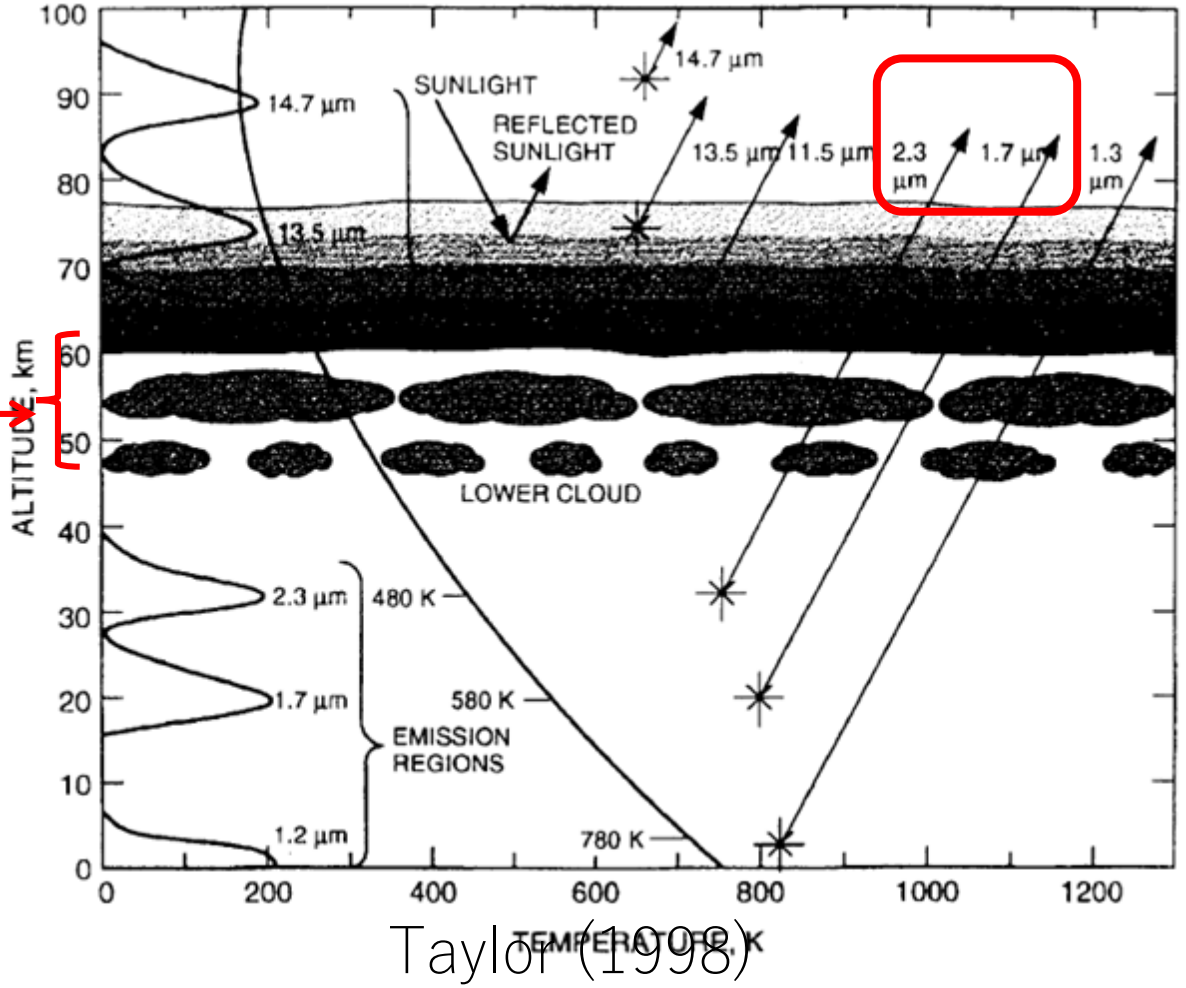
- A novel automated method: a key point
  - Based on the cross-correlation method but using 3 or more images (Ikegawa and Horinouchi 2016: IH16)
  - Sophisticated **error correction** and **quality control** (Horinouchi et al., 2017a, IH16)

→ high-quality gridded horizontal wind dataset
(much greater # of wind vectors than manual tracking)

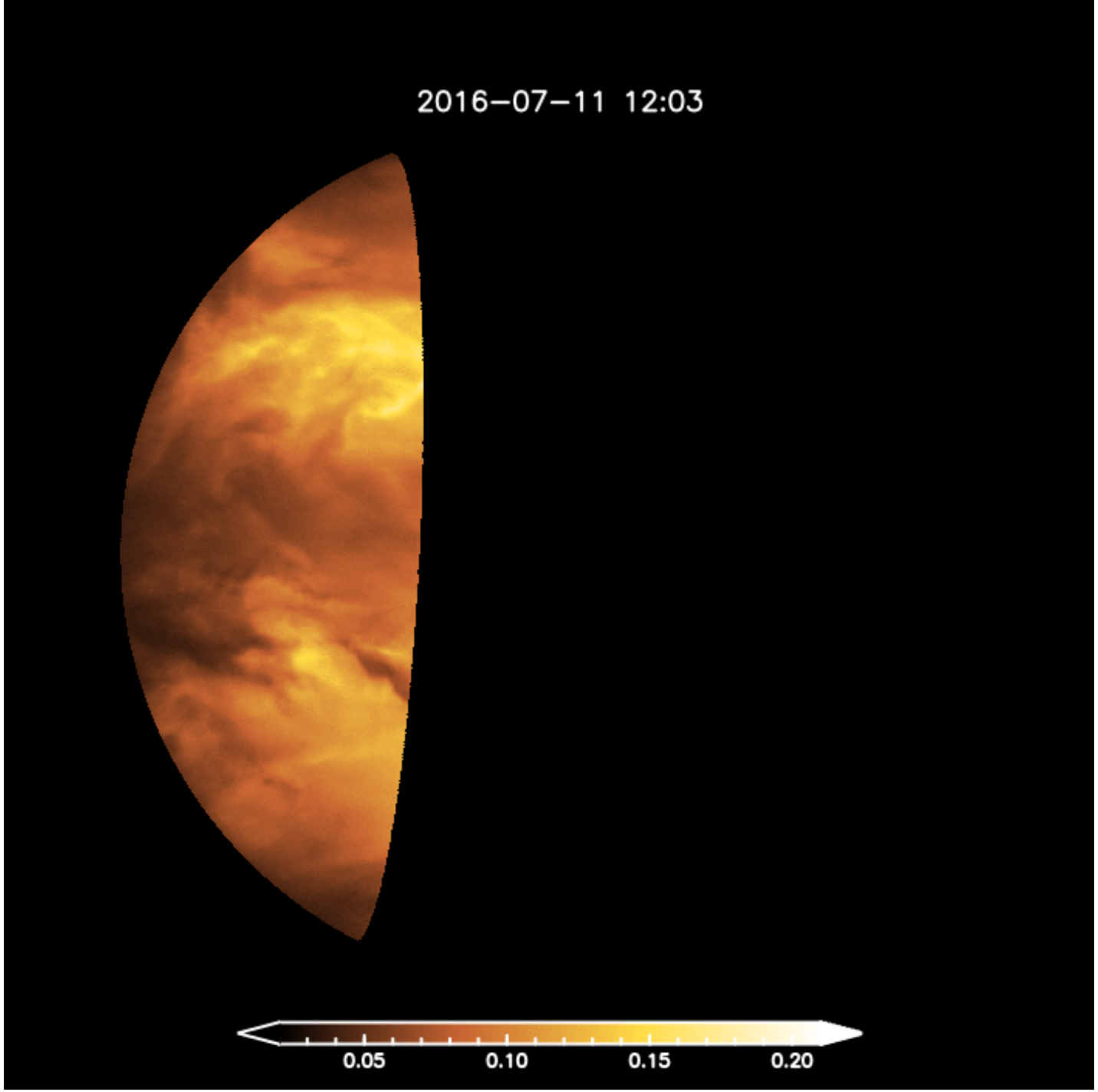
Equatorial jet in the lower and middle cloud regions
(Horinouchi et al 2017b)

- Used nightside images from the 2-μm camera IR2
  - Near-infrared “window”
  - Visualizes the opacity contrasts mainly in the lower and middle clouds (45-60 km)
  - Analysis period: Mar & Jul-Aug, 2016



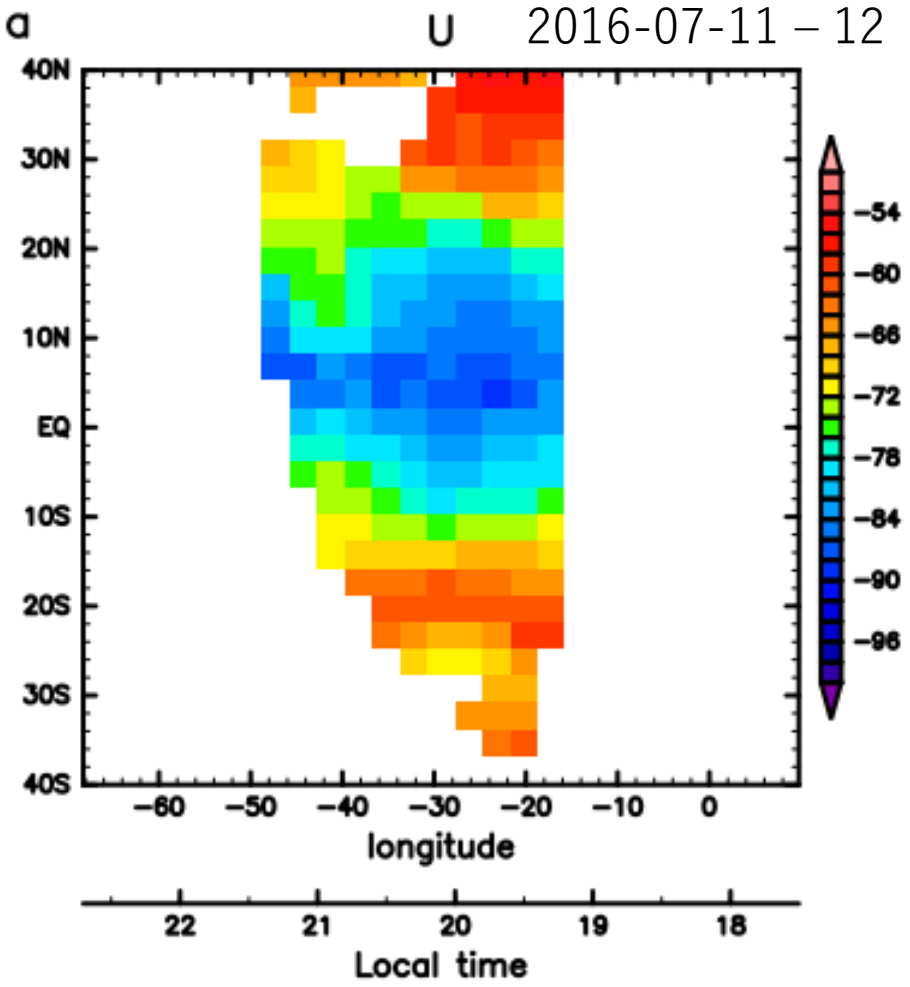


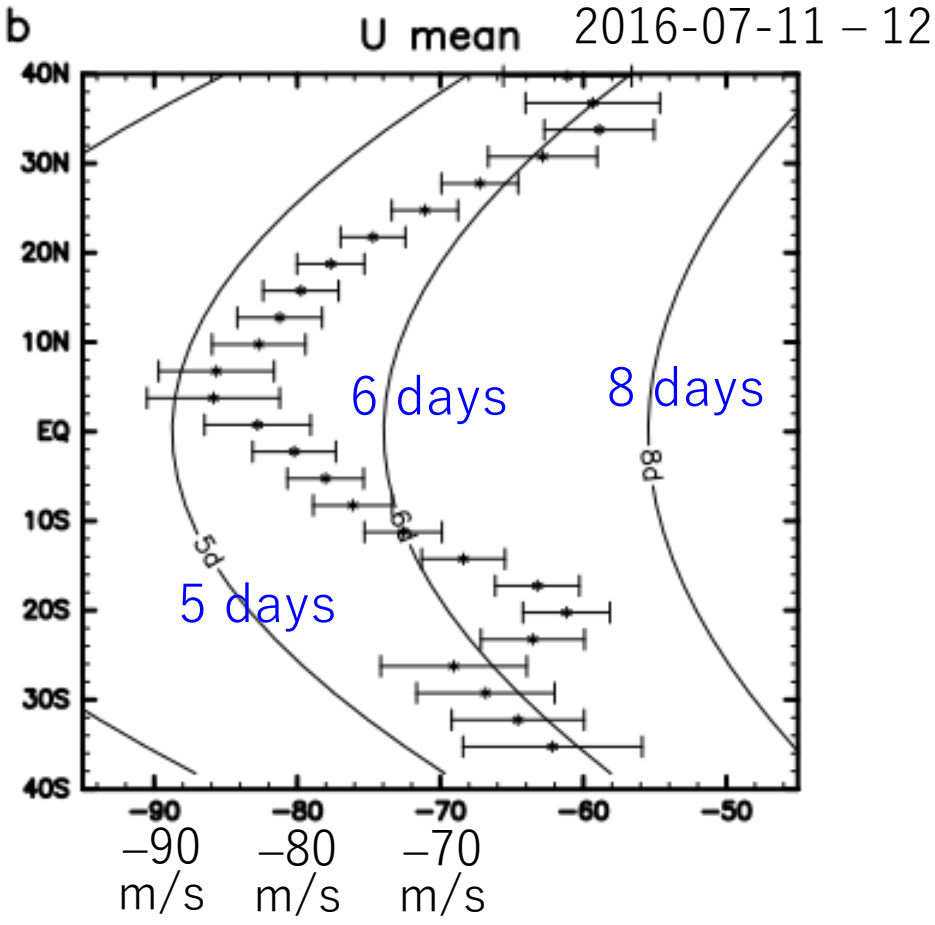
Taylor (1998)



- 2 hourly 2.26μm radiance
- (2016-07-11 – 12; orthographic map projection)
- Moves westward: superrotation
- **White-out: from dayside (not in the deonvolved version: Poster by Satoh)**

Zonal flow: exhibits a jet-like feature at low latitude: "equatorial jet" (observed through July and Aug, but not in Mar)



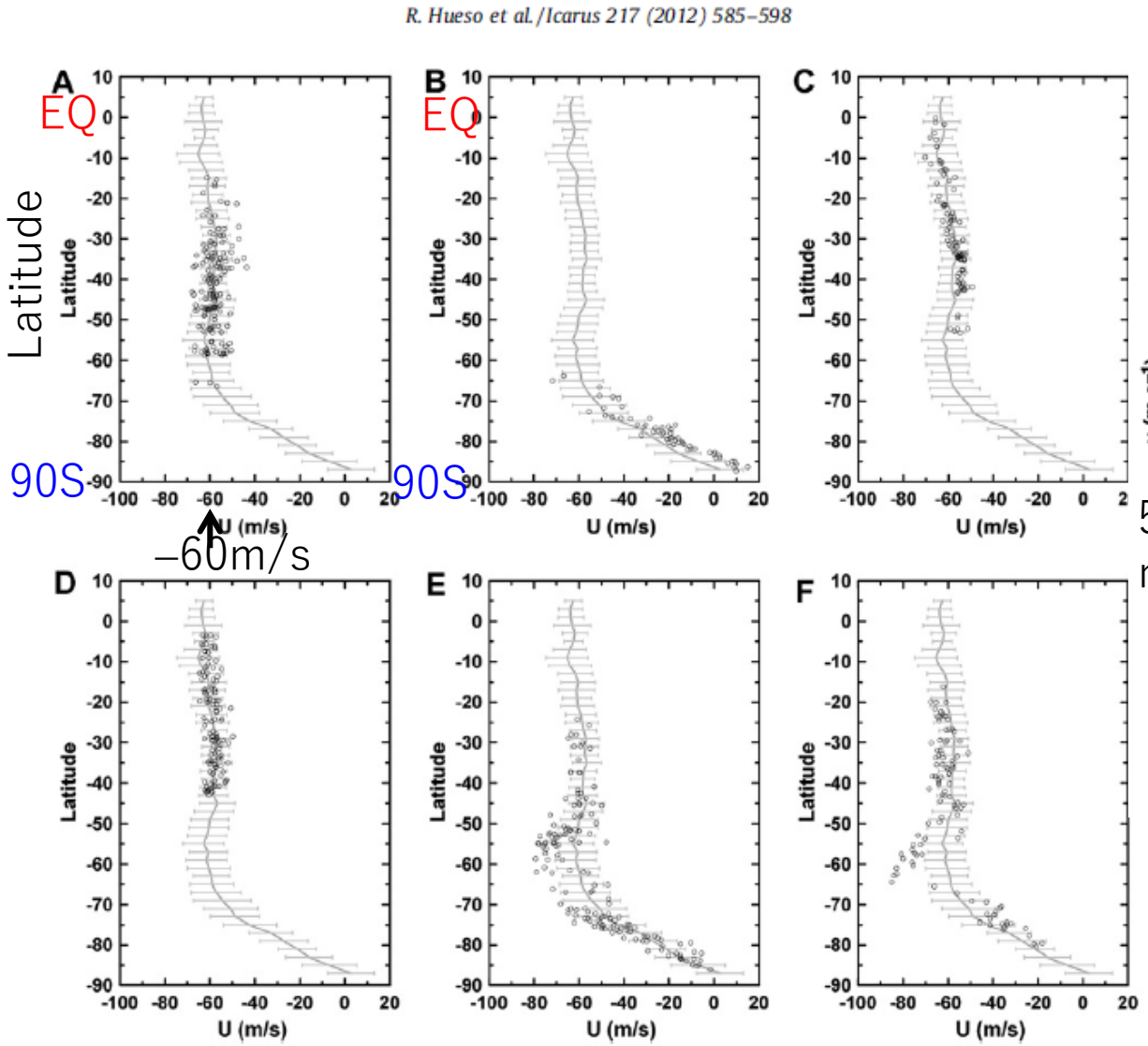


Solid curves: corresponding rotational periods (Earth day)

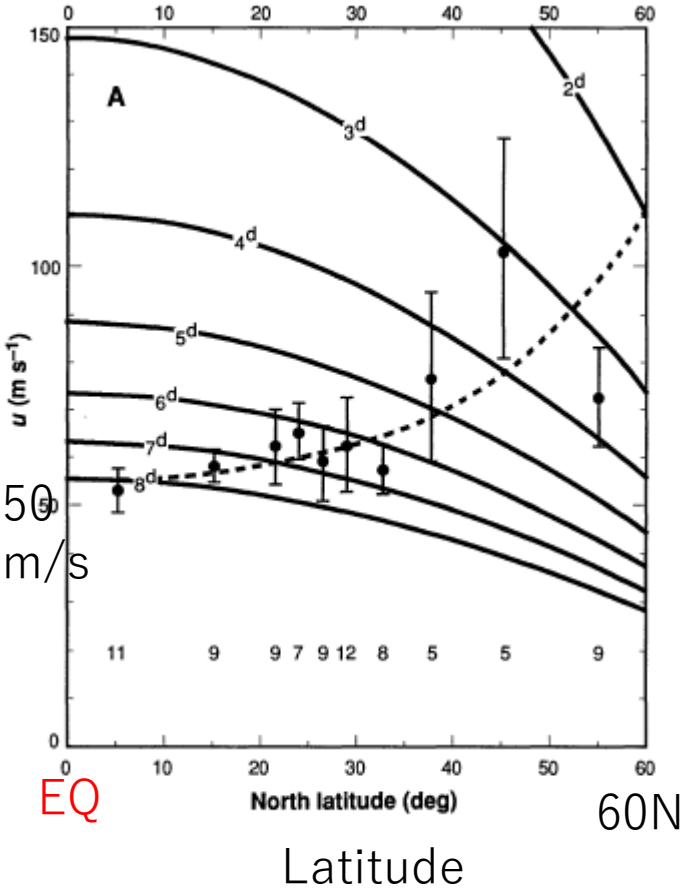
Cloud top wind from UV images (Akatsuki UVI) → no equatorial jet

Previous studies using near-IR nightside images did not detect an equatorial jet. --- because time sampling was limited?

VEx VIRTIS IR 1.74 tracking example
Hueso et al. (2012) obs: 2007-2008

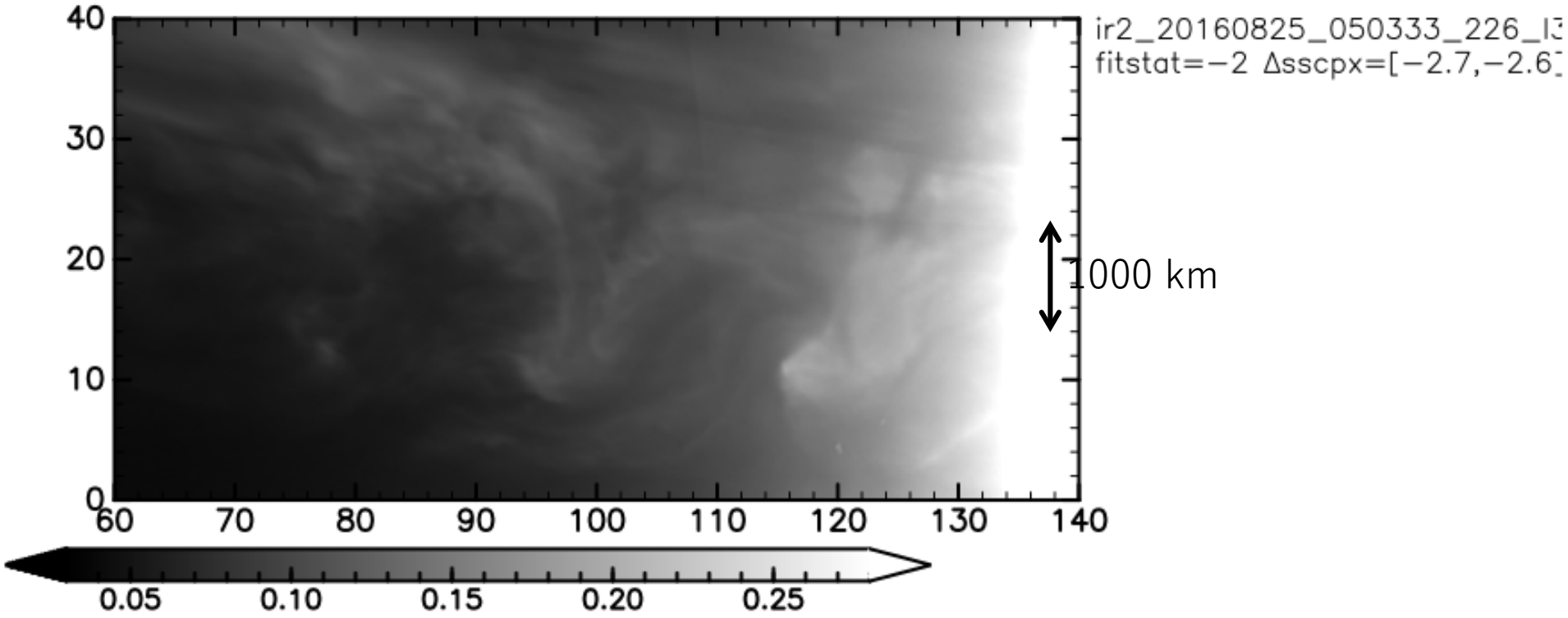


Galileo
Carlson et al. (1991)



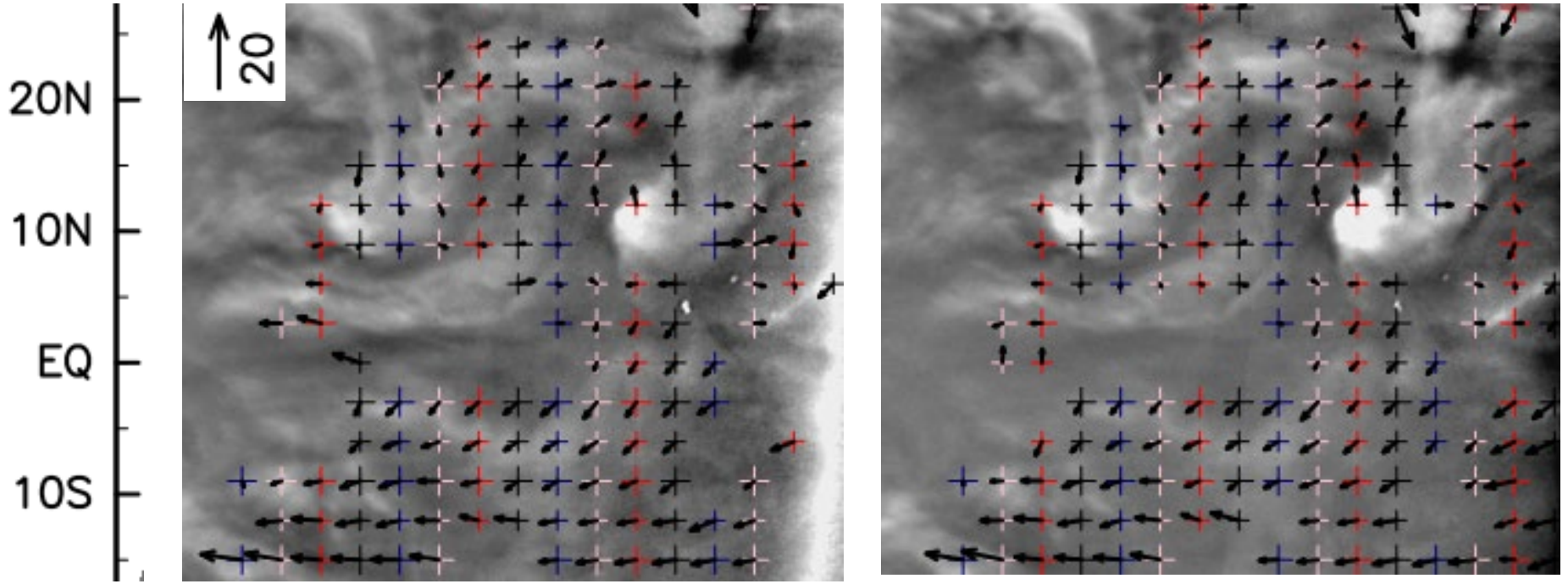
IR2 nightside images exhibit rich dynamical features: e.g. **Peralta et al, 2018,9 Limaye et al 2018**

A feature like vortices due to barotropic/baroclinic instability (2016-08-25)



Really rolling-up? – Yes, likely.

- arrows: deviation from the solid-body rotation of -75 m/s at the equator (CAUTION: based on previous version of geographical mapping)



174 μ m 05 to 17 dt=2h
(background image: high-passed)

226 μ m 05 to 17 dt=2h
(background image: high-passed)

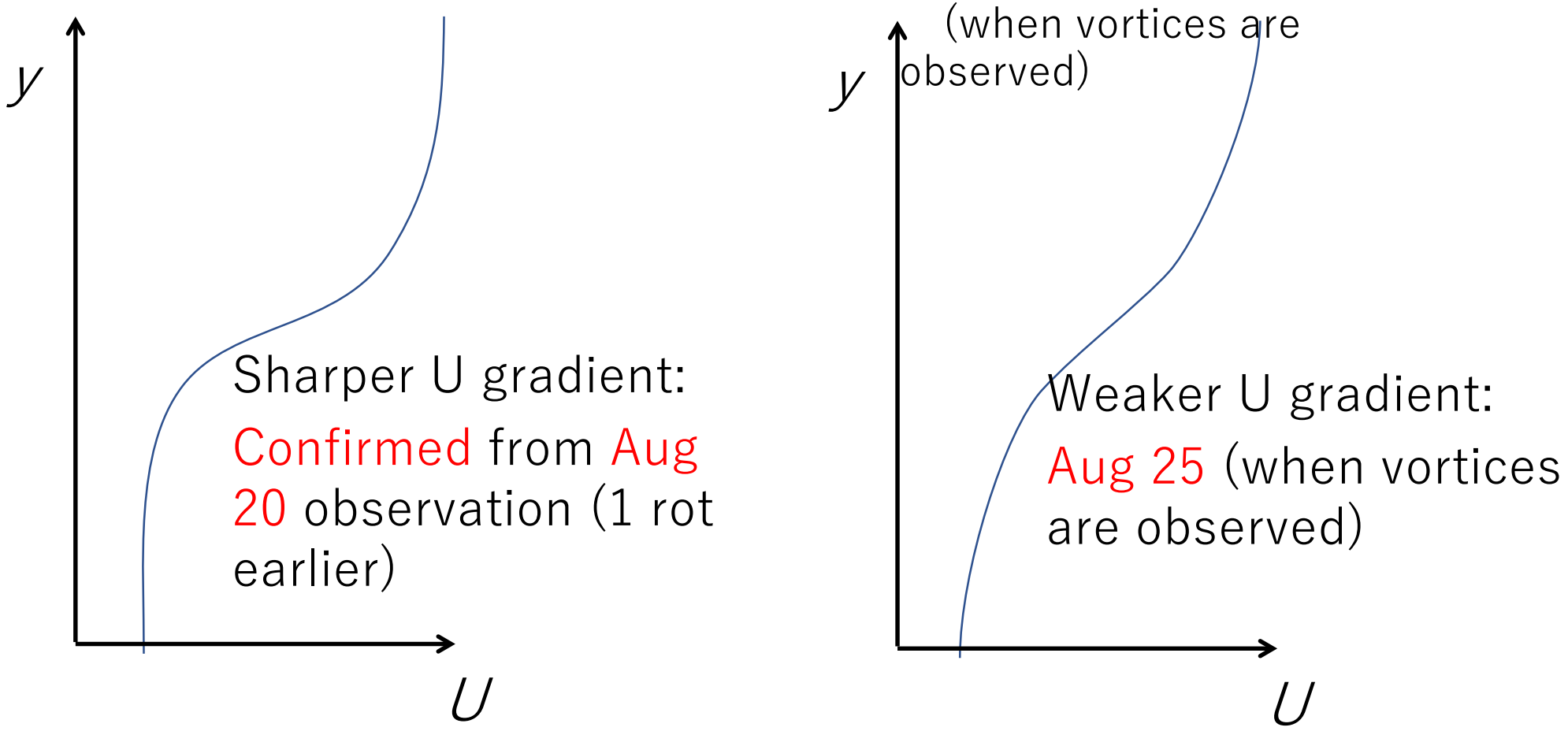
Wind estimation will be updated by further refining geographical mapping

Consistent with barotropic instability

Note: planetary vorticity is small

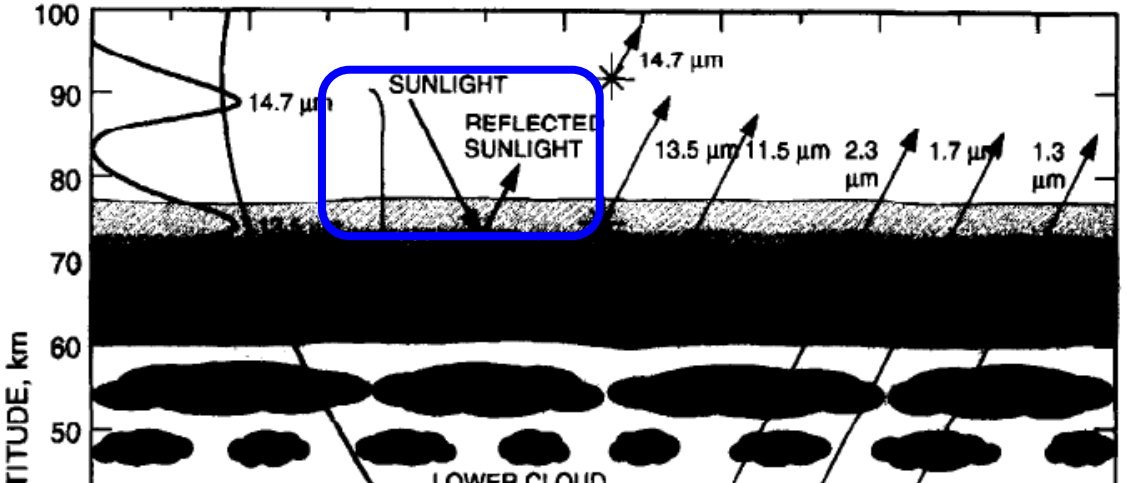
→ **Rayleigh's inflection point theorem** applies (near the equator)

• Before → Erodes the curvature → • After

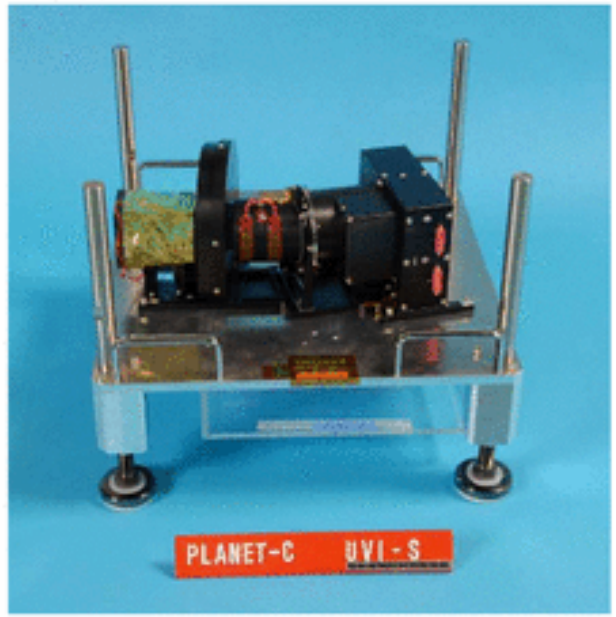


Cloud top mean winds and shear
(updated from Horinouchi et al 2018 E.P.S.)

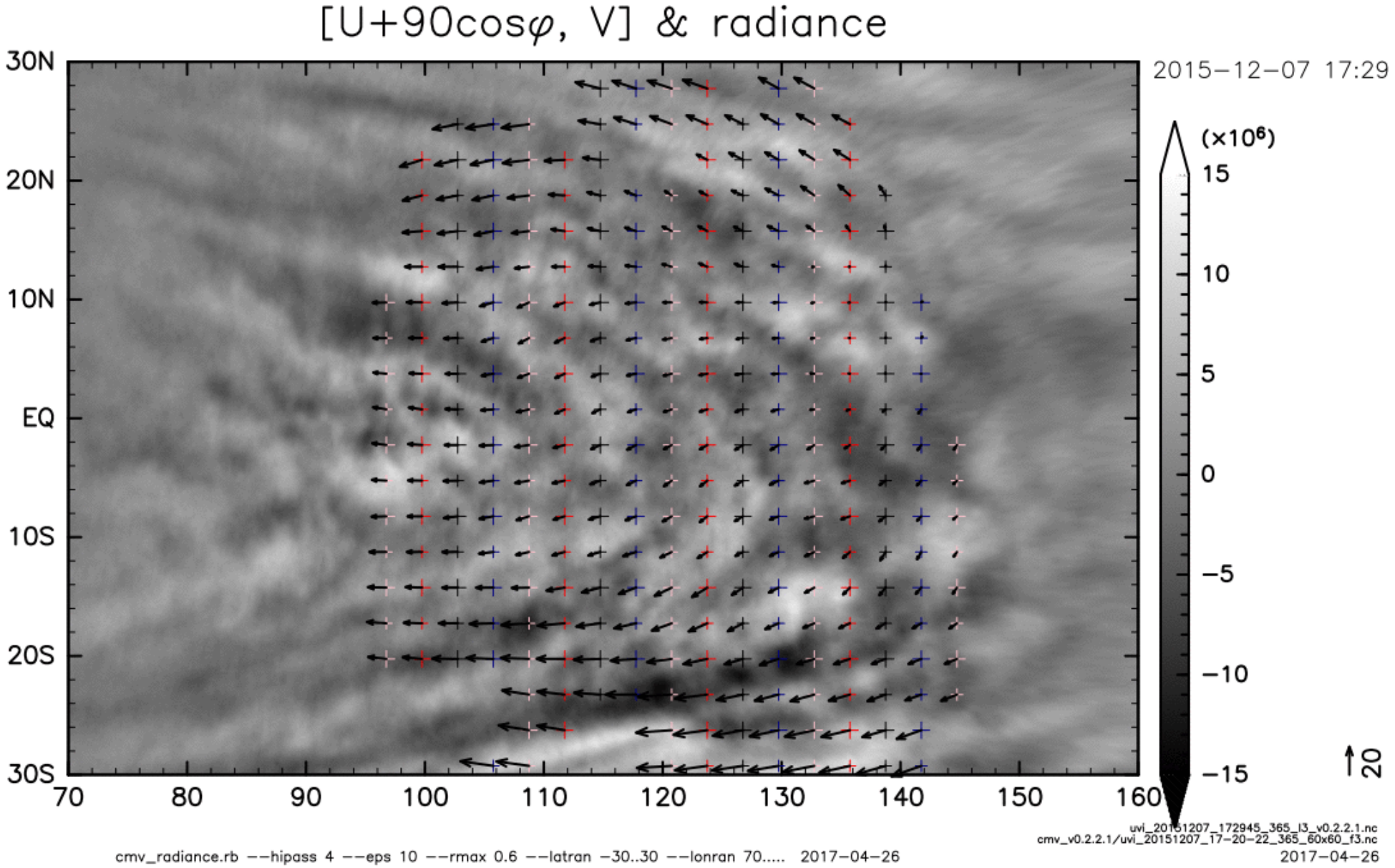
- Merit of Akatsuki: can observe both hemispheres equally, etc.
- We used dayside images from the UV camera UVI
  - 365 nm (traditional, unknown UV absorber)
  - 283 nm (SO2; novel – limited obs by PVO)
  - Analysis period: Dec 2015 – Dec 2018



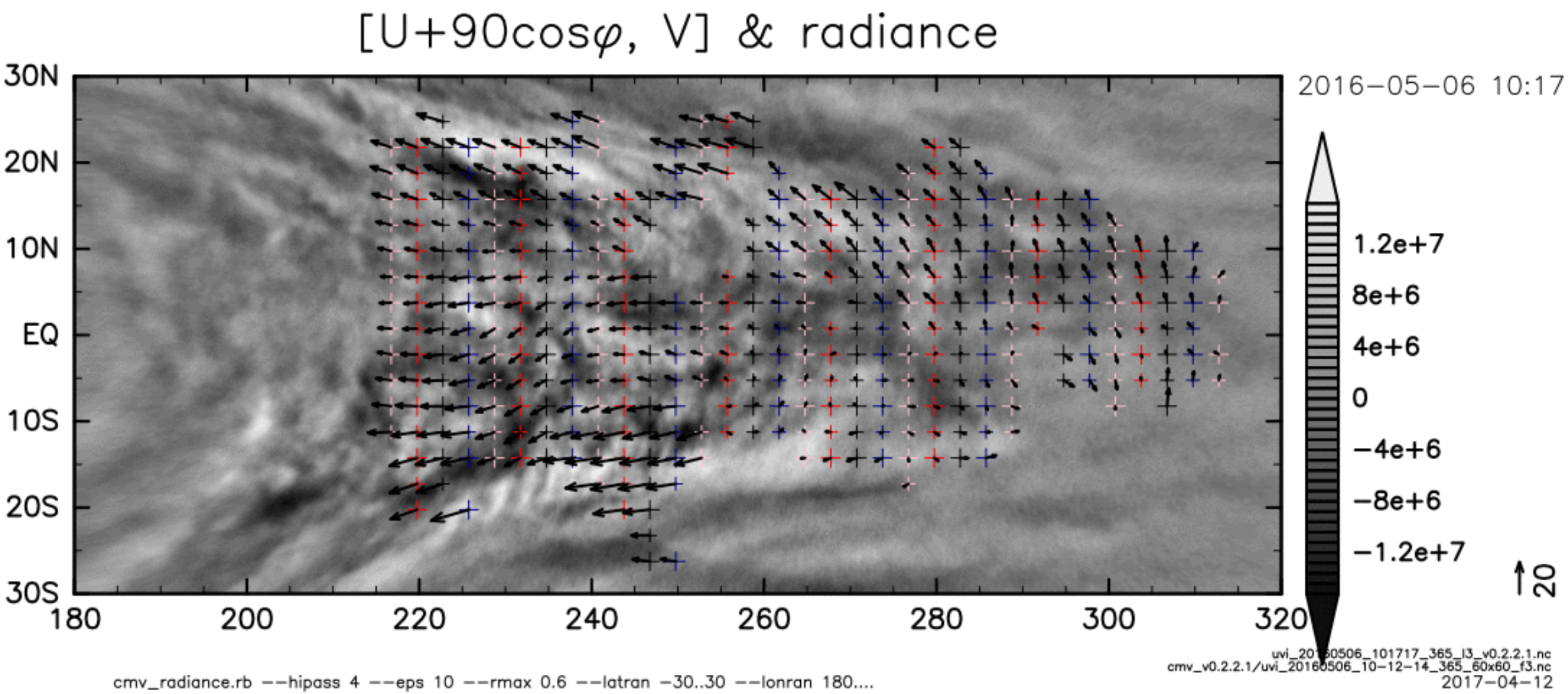
UV Imager on Akatsuki



Example 2015-12-07 365nm
(deviation from a solid-body rotation: 90 m/s at EQ)



Example 2016-05-06 365nm
(deviation from a solid-body rotation: 90 m/s at EQ)



Mean wind & tide

SO2 abs

U(283 nm)

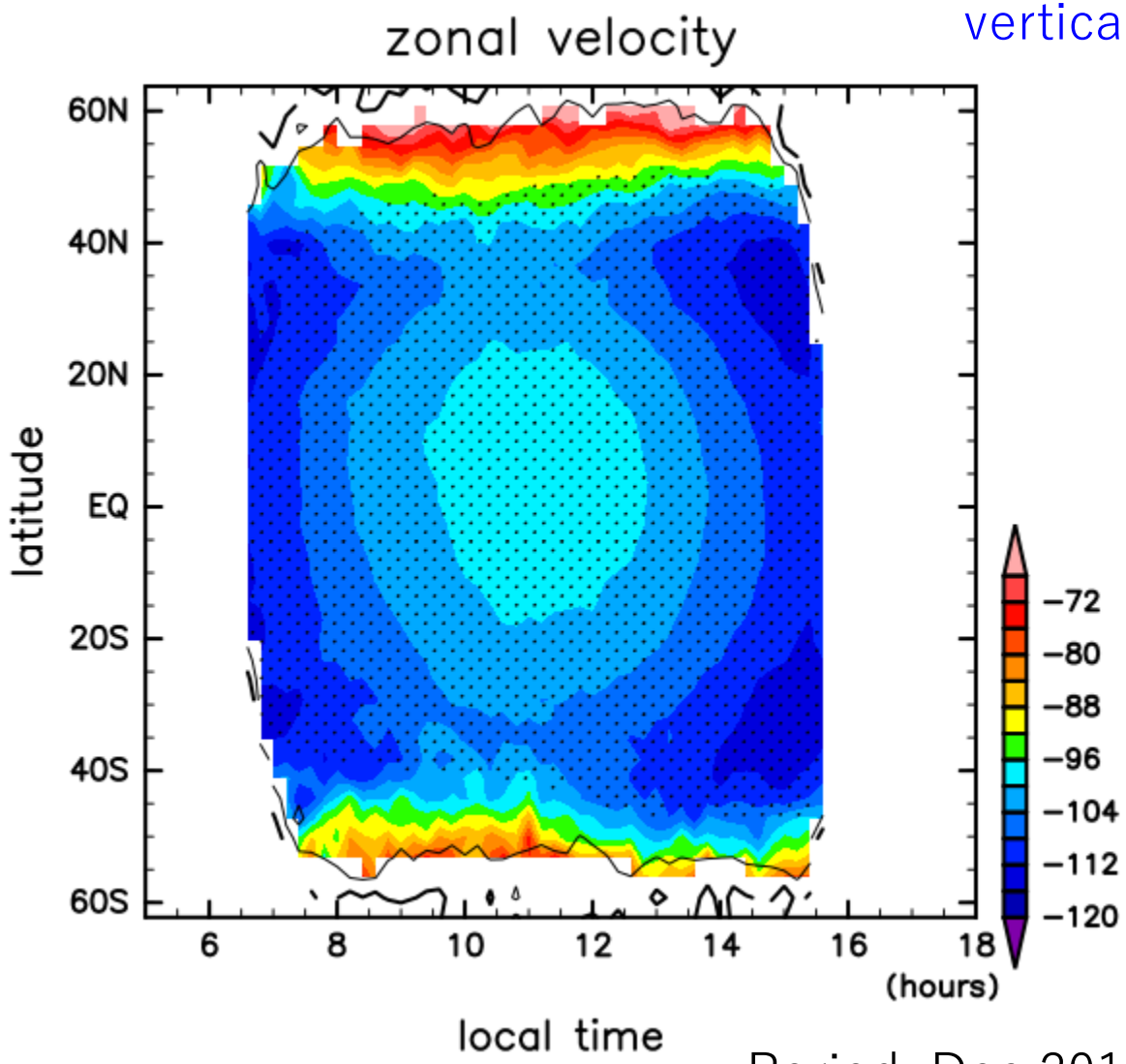
Faster!

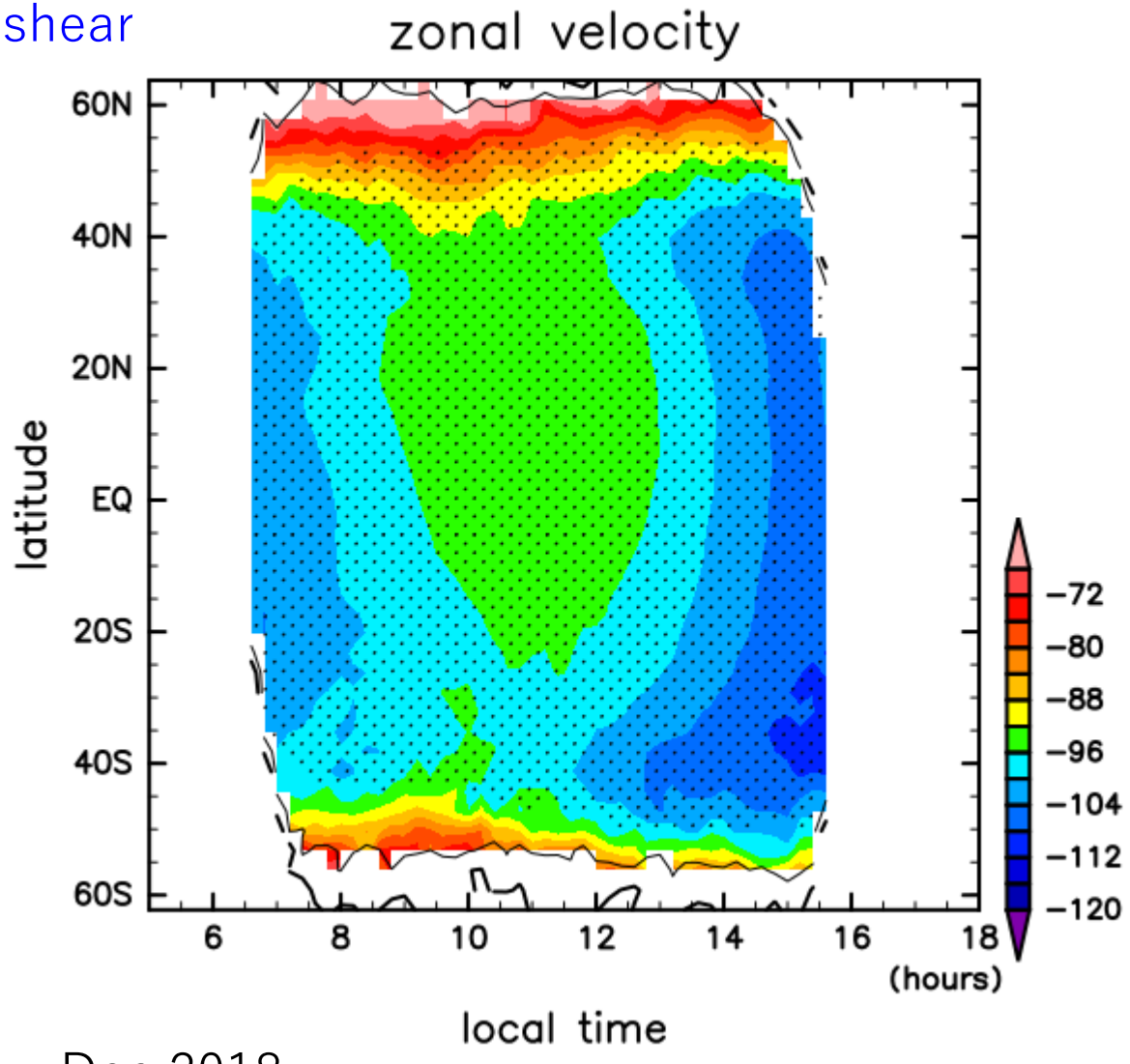
Indicates mean vertical shear

Traditional, unknown abs

U(365 nm)

Slower!





Period: Dec 2015 – Dec 2018

Mean wind & tide

SO2 abs

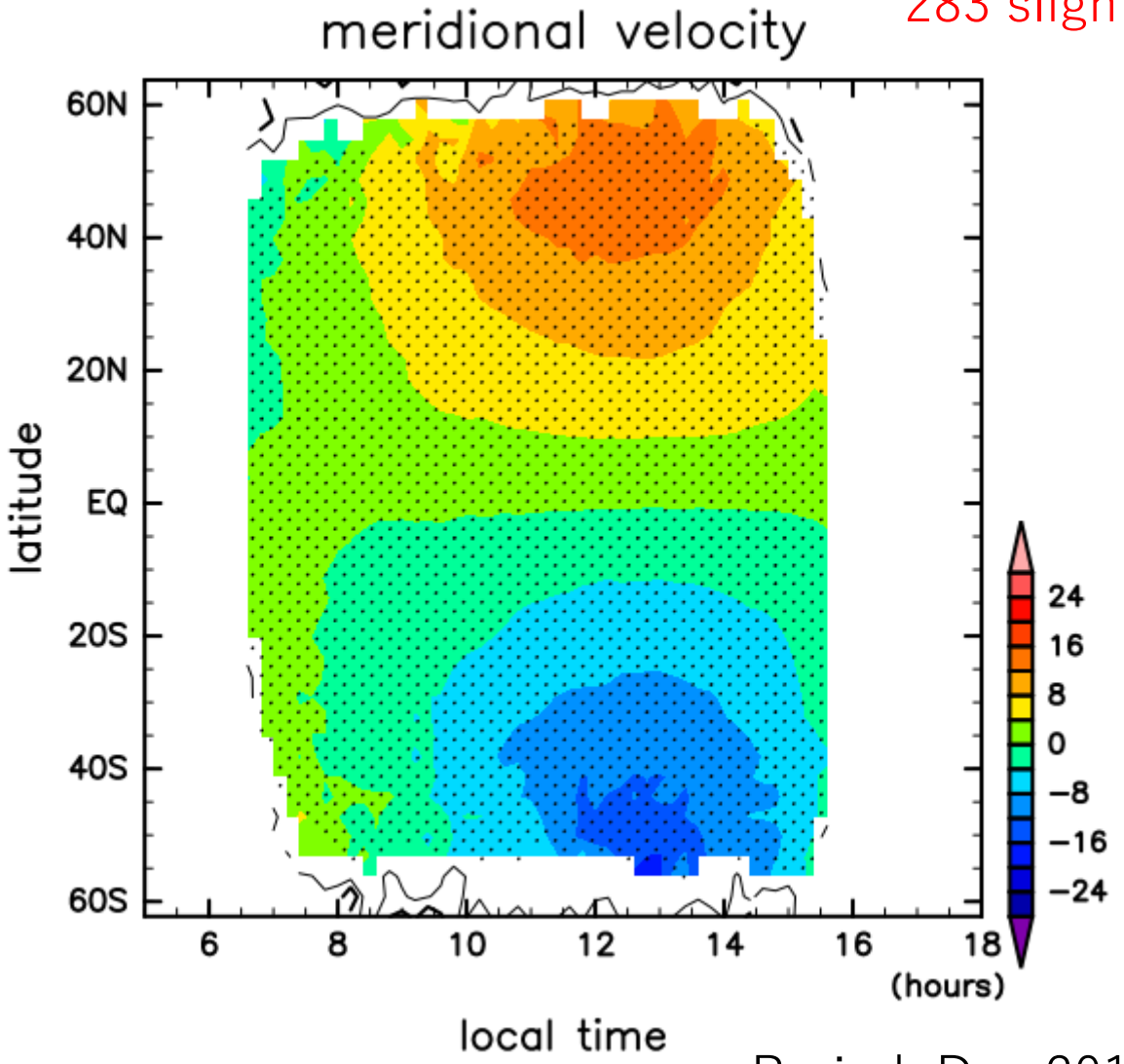
V(283 nm)

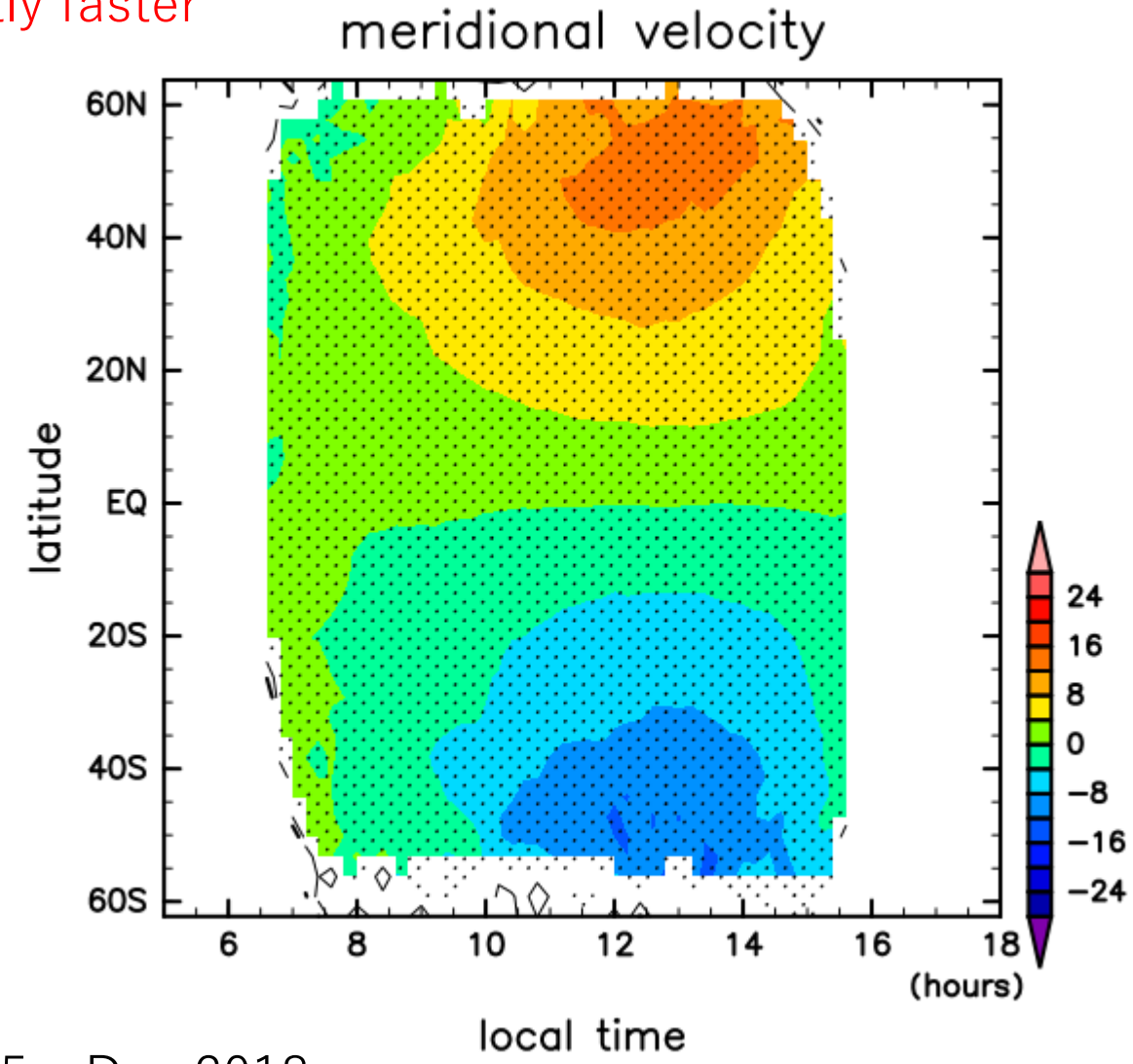
Traditional, unknown abs

V(365 nm)

Similar

283 slightly faster

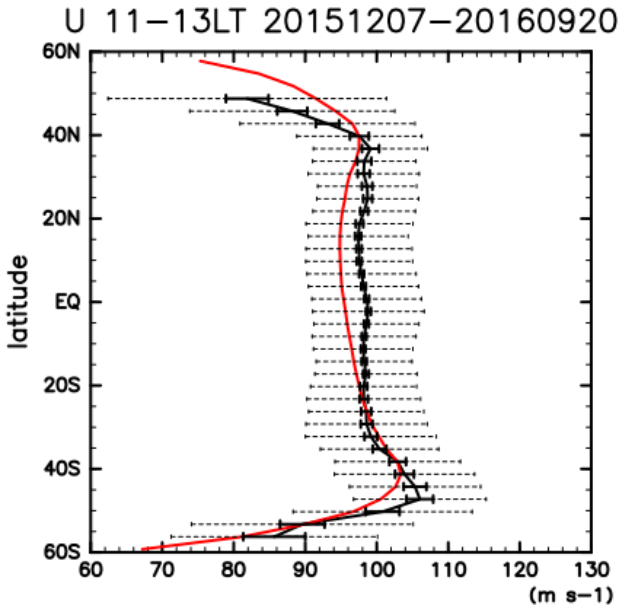


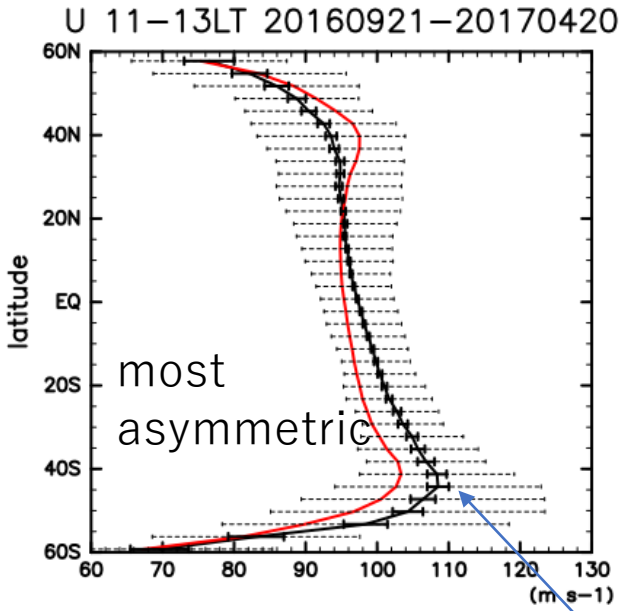


Period: Dec 2015 – Dec 2018

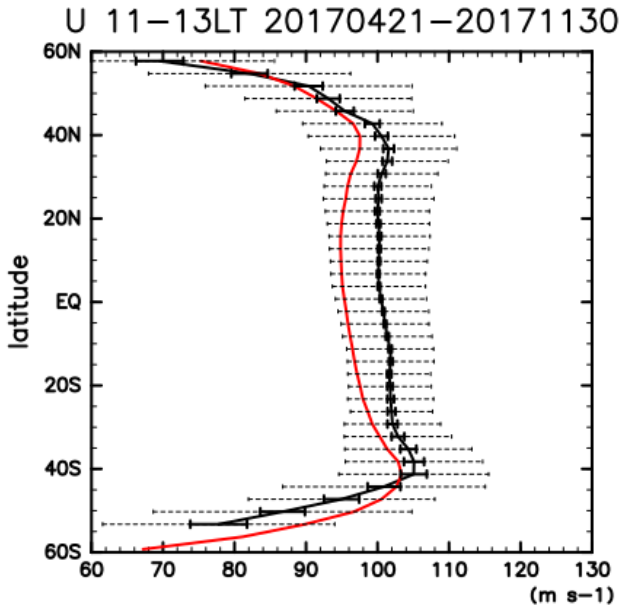
U 365nm 11-13LT

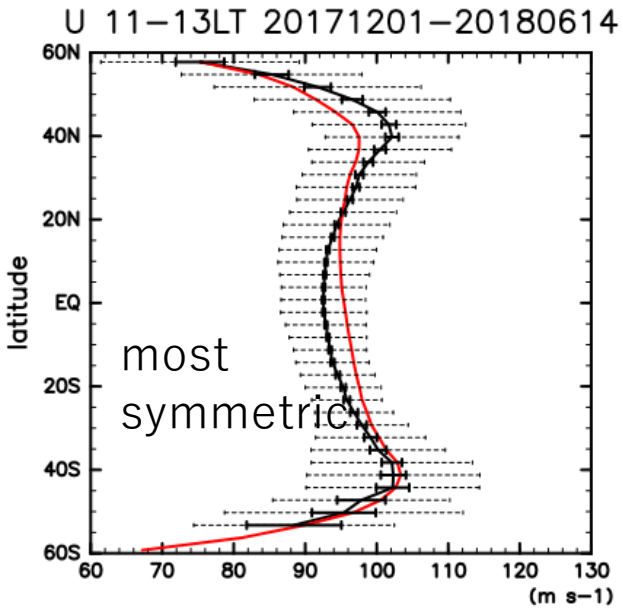
Bars. thick: expected error from ε
dotted: standard deviation w/ t



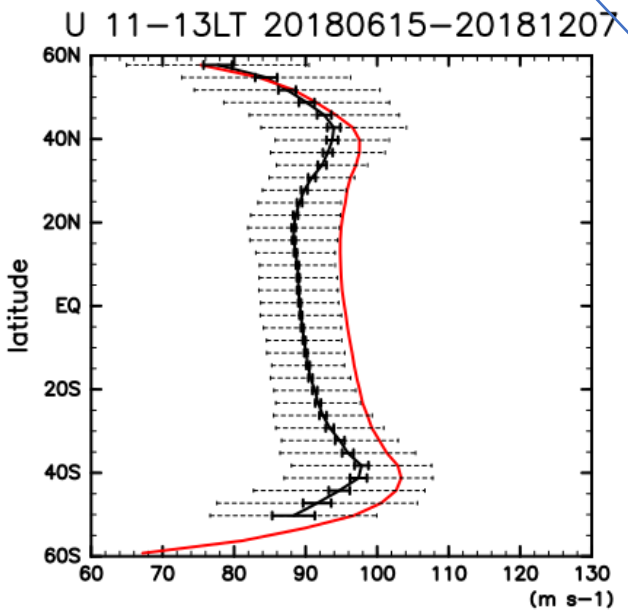


most asymmetric





most symmetric



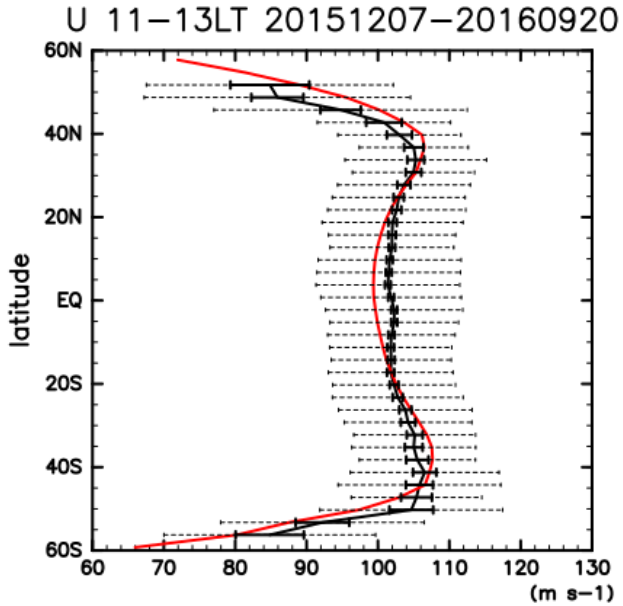
least mid-lat diff btwn 365&283: a matter of z-distribution of SO2 and the unknown absorber?

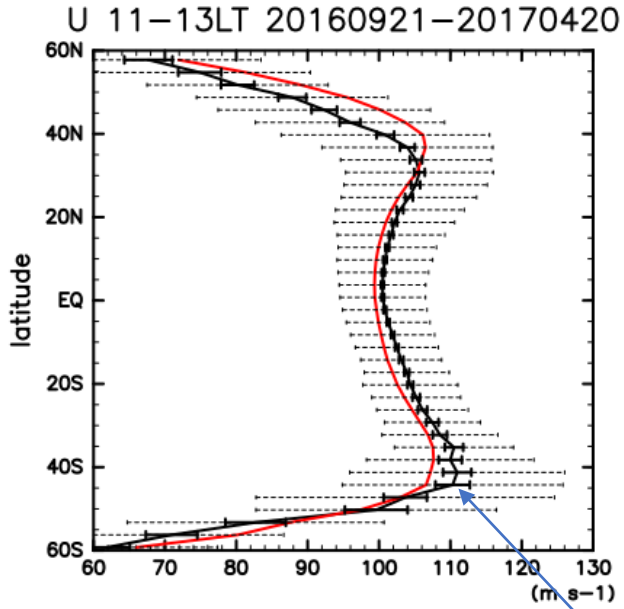
Red: mean over 201512 – 201812

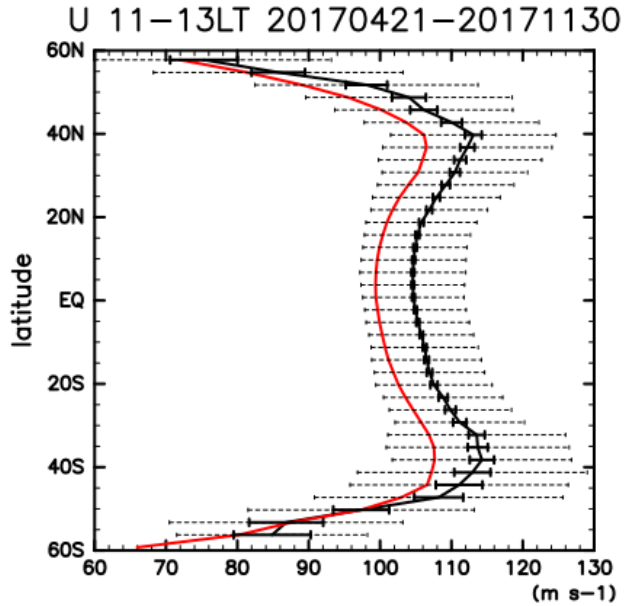
ltm_winds_lines.rb --eps_errbar cmv_v20190201_nt3ll/daily_uvi_365_eps20_pp0hvlen2.0_LT.nc --tstr 2015-12-07,2016-09-21,2017-04-21,2017-12-01,2018-06-15 --tend 2016-09-2... 2019-04-14

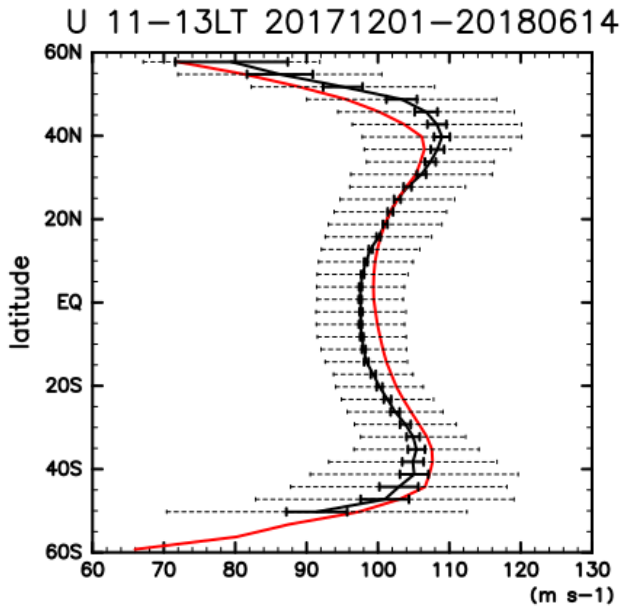
U 283nm 11-13LT

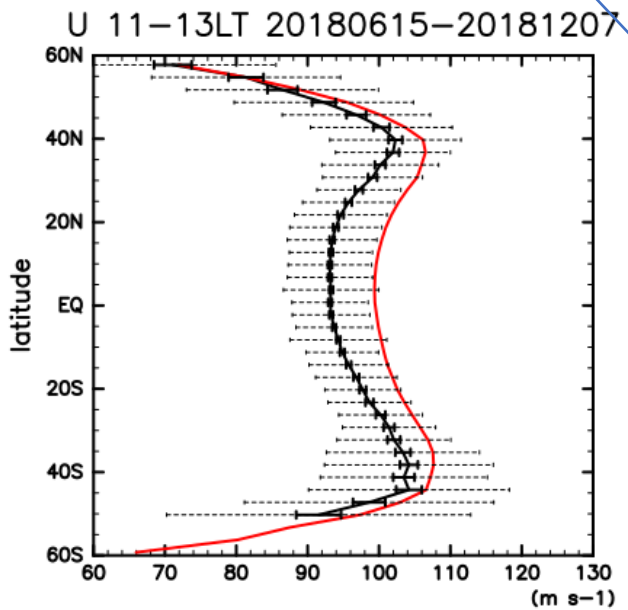
Bars. thick: expected error from ε
dotted: standard deviation w/ t











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

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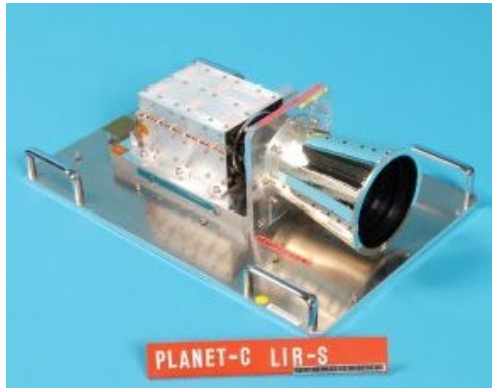
ltm_winds_lines.rb --eps_errbar cmv_v20190201_nt3ll/daily_uvi_283_eps20_pp0hvlen2.0_LT.nc --tstr 2015-12-07,2016-09-21,2017-04-21,2017-12-01,2018-06-15 --tend 2016-09-2... 2019-04-14

Cloud top angular momentum & heat fluxes (submitted)

- Previous studies
  - Momentum flux: Rossow et al (1990), Limaye (2007) → inconclusive
  - Heat flux: None
- Here we used
  - Winds from UVI 365 nm images
  - ~Cloud-top temperature from LIR (obs at high emission angles)

LIR



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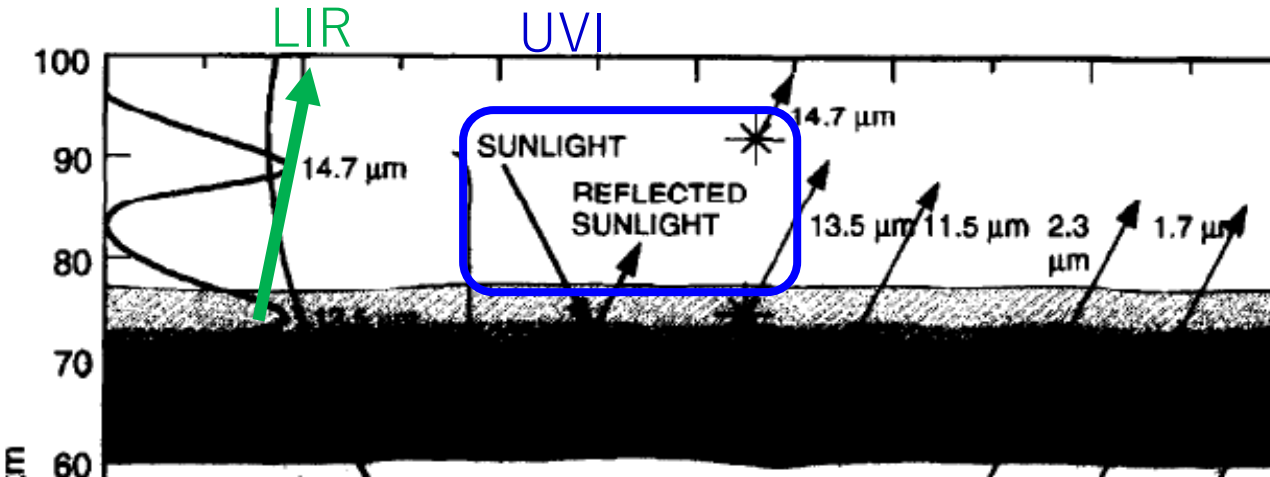
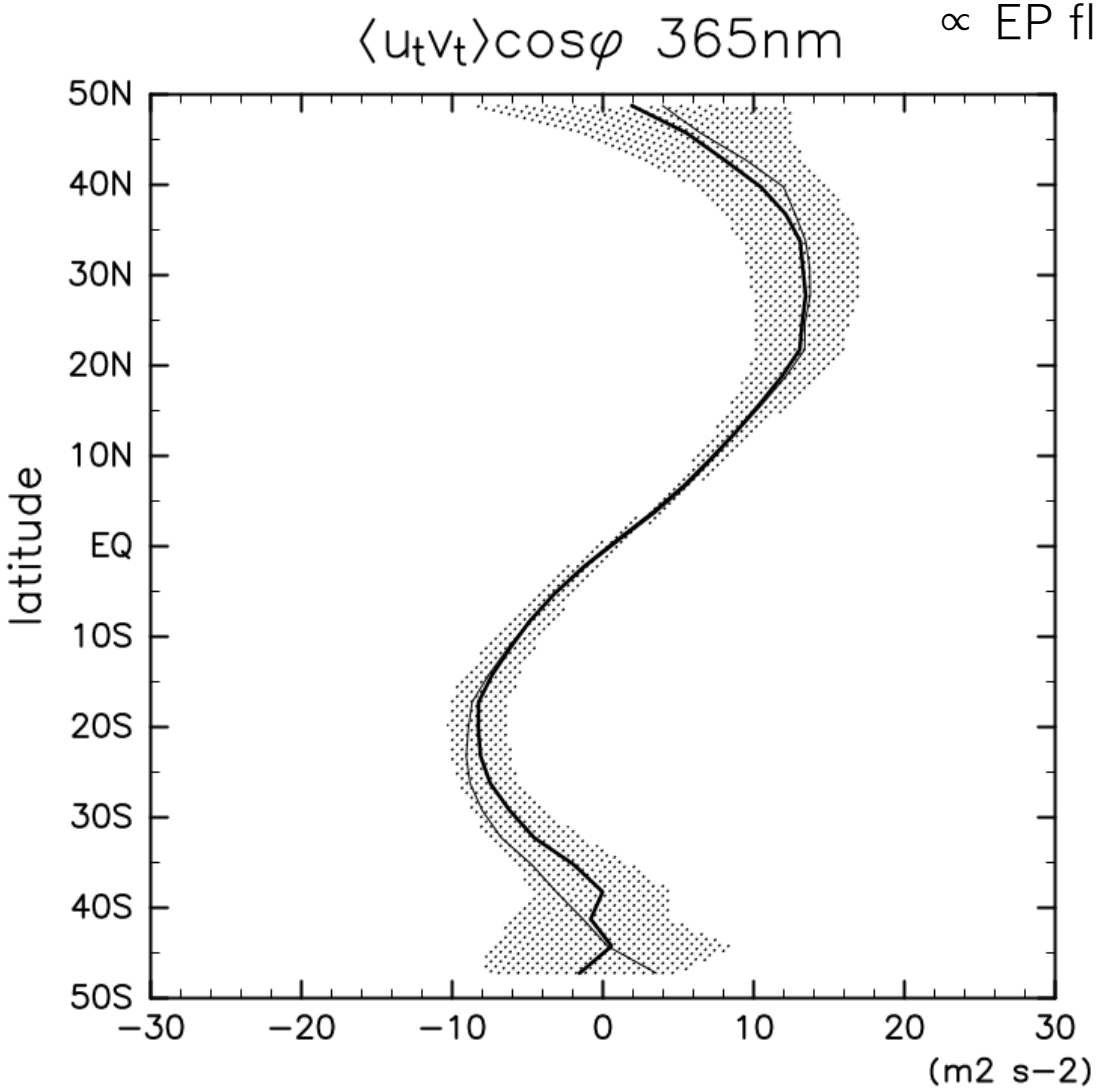
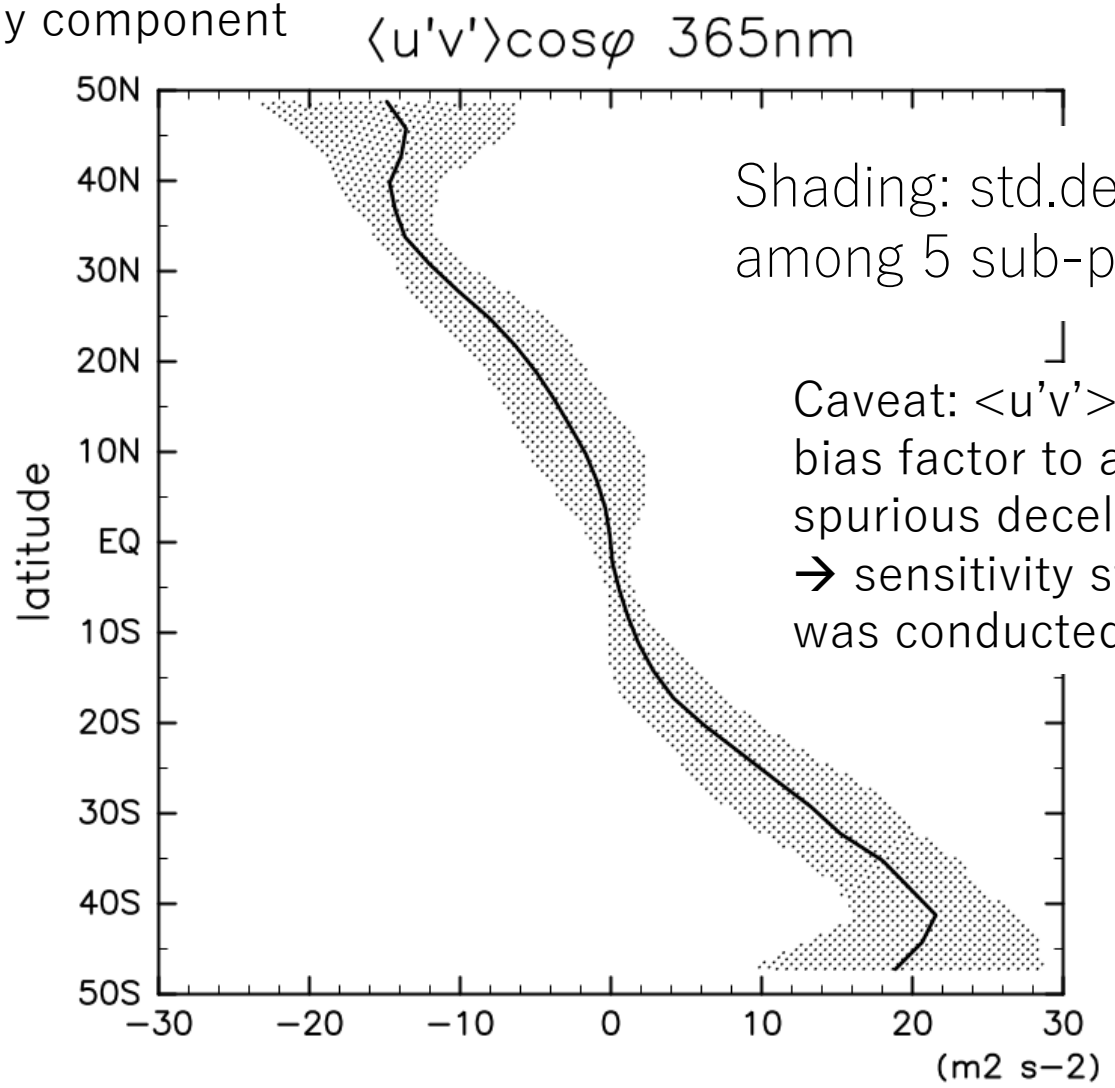


Mom flux by thermal tide:
accelerating super-rotation at low lat.

Mom flux by transient disturbances:
decelerating super-rotation (more weakly)

∝ EP flux y component

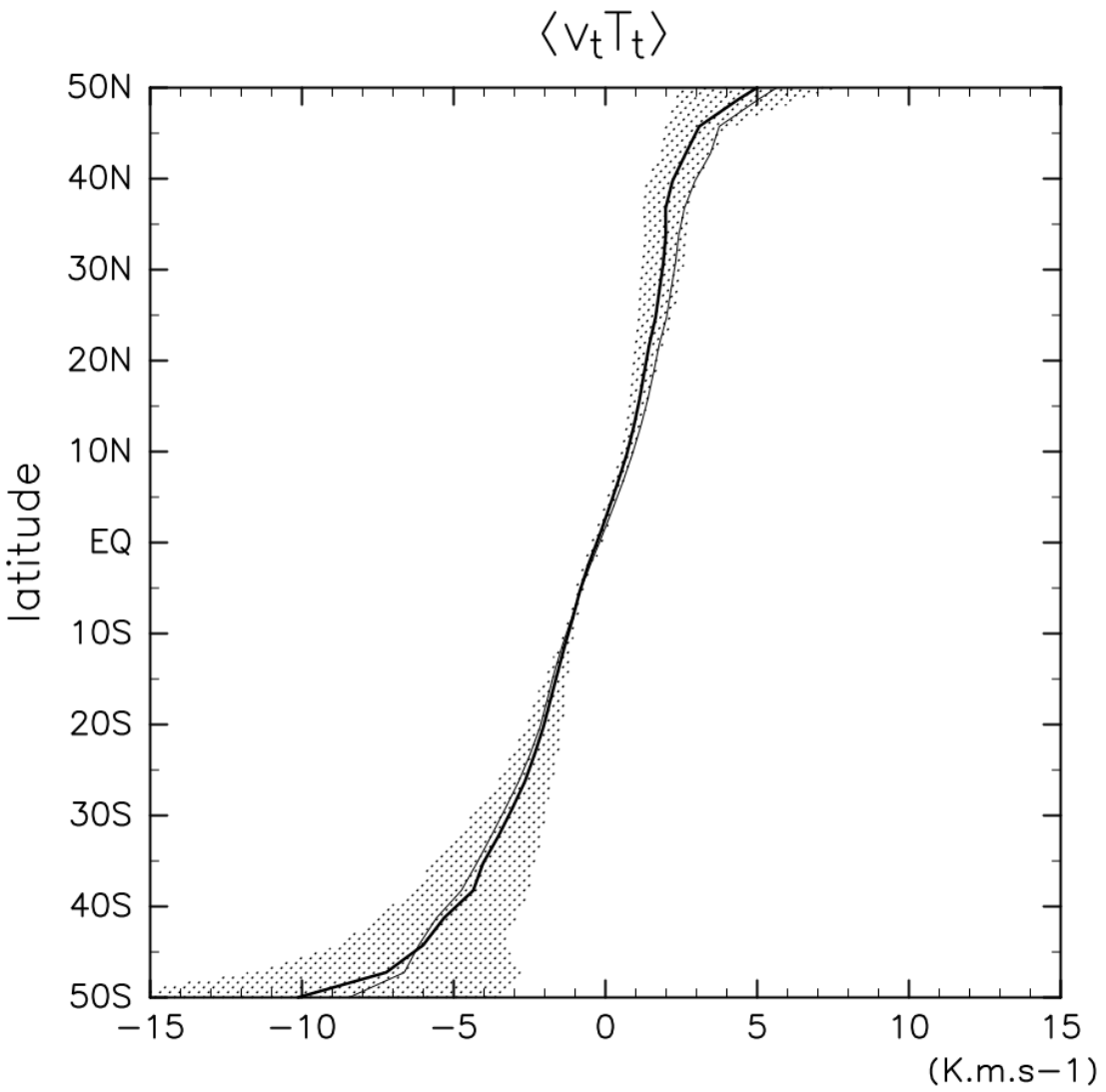




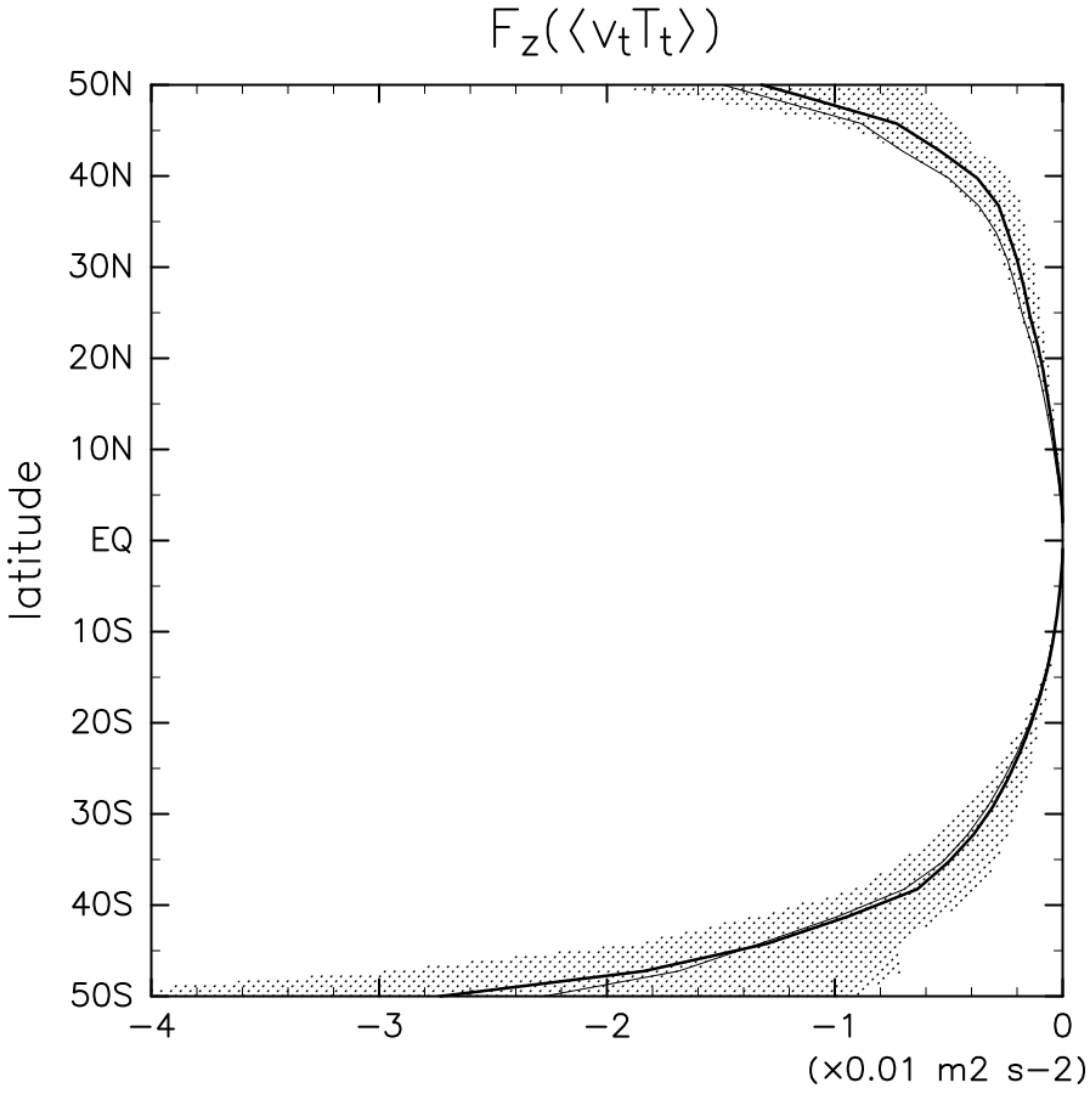
Shading: std.dev.
among 5 sub-periods

Caveat: <u'v'> has a bias factor to add spurious deceleration
→ sensitivity study was conducted

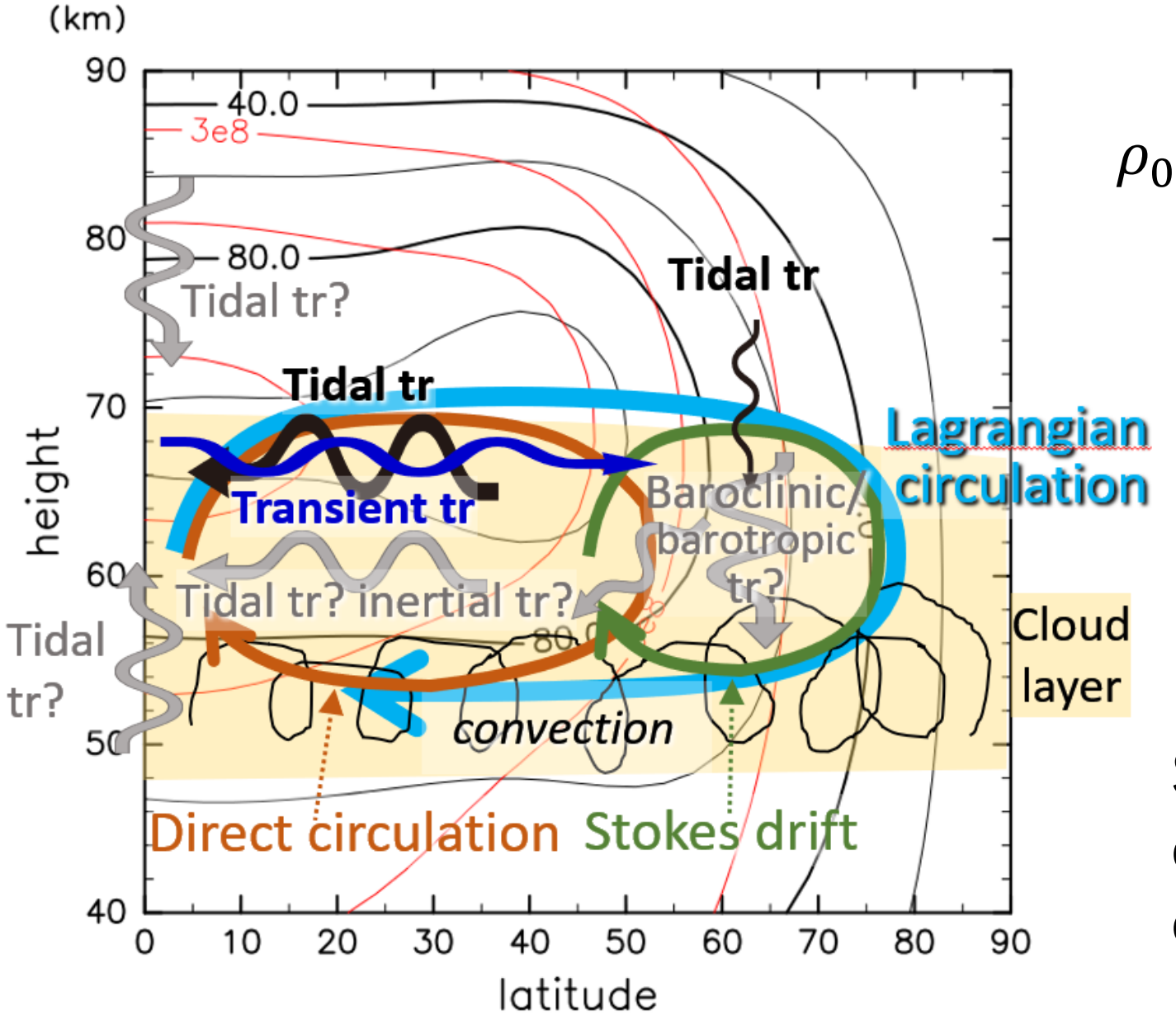
Meridional heat flux by zonal wavenumber 1 tide



Vertical component of the EP flux associated with the tidal heat flux



Suggested angular-momentum balance and meridional circulation in the cloud layer of Venus



$$\rho_0 m_t + \boldsymbol{\nabla} \cdot \rho_0 m(v^*, w^*) = \boldsymbol{\nabla} \cdot \boldsymbol{F}$$

$\boldsymbol{F}$: EP flux (wavy arrows)

(v^*, w^*) : "residual circulation" (mean Lagrangian meridional circulation including the Stokes drift by eddies)

Suggested overall circulation in the Venusian cloud layer is Earth-like

Conclusions

- Cloud tracking using data from Akatsuki provided new knowledge on the Venusian atmosphere
  - From the nightside through-cloud imaging
    - Variability of flows in the lower-to-middle cloud layers: e.g. equatorial jet (formed tentatively), unstable vortices,…
  - From cloud top winds
    - Mean vertical shear near the cloud top
    - Meridional asymmetry (which may be due to the asymmetry in the vertical distribution of UV absorbing substances)
  - From cloud top winds and temperature
    - Meridional angular momentum flux and heat flux
    - Providing insights on the meridional circulation and angular momentum balance → super-rotation maintenance processes
- Further observations and studies will elucidate more and provide deeper understanding of the Venusian atmosphere