2015-05-12 Japanese-French model studies of planetary atmospheres

Cloud tracking using sequential images from Venus Express VMC

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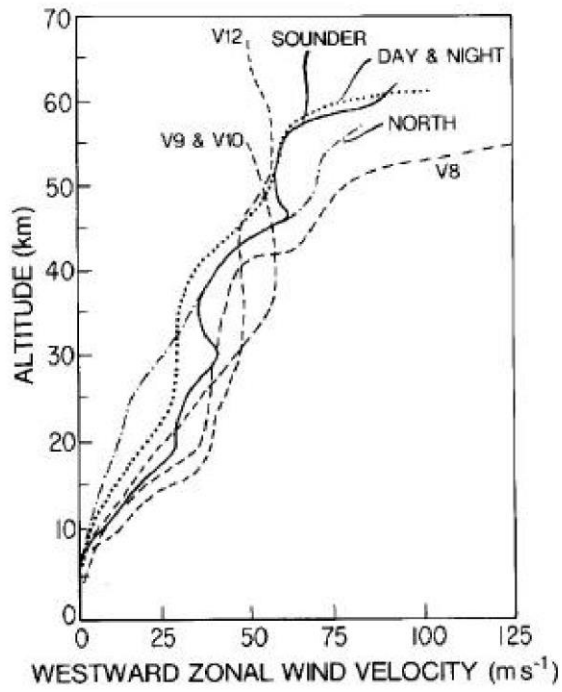
Paper: Ikegawa & Horinouchi (2015) *Icarus*, submitted: **IH15**

Venusian atmosphere: Remaining Frontier of GFD

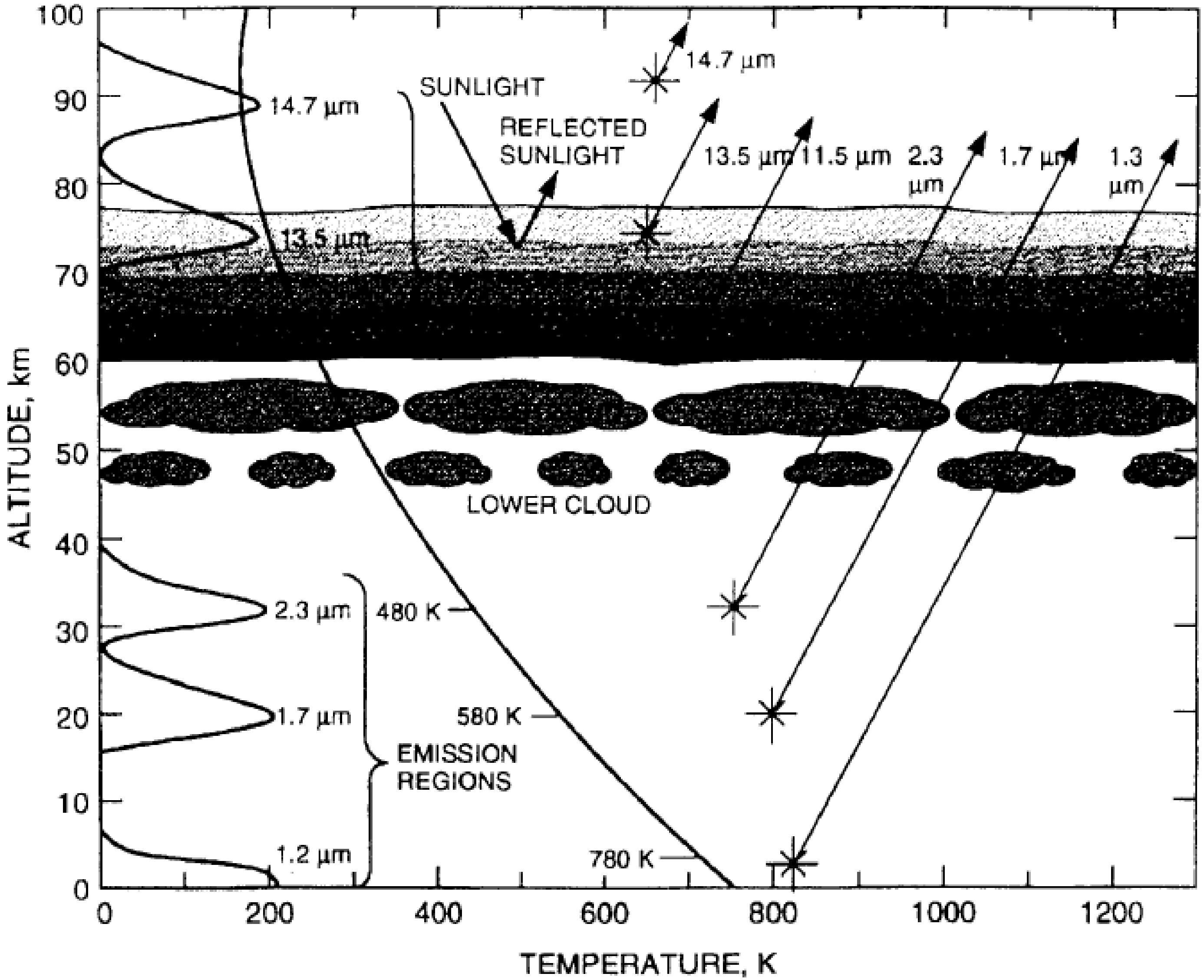
- General circulation
  - Super-rotation
  - Meridional circulation
  - (Angular) momentum transport/balance
- Waves, instabilities, turbulence,…

- Need observations for sound scientific progresses (although observation is inherently limited, of course)

Schubert,1983



Venus is covered with clouds



Tayler (1998)

Cloud tracking

- Long history
  - Mariner 10, Feb 1974 (fly-by)
  - Pioneer Venus Orbiter, 1979-1986
  - Galileo, Feb 1994 (fly-by)
  - Venus Express, 2006-2014
  - *ground-based observations*
- Coverage
  - Day-side: reflected sunlight (UV: 65-70 km; NIR ~1μm: ~60 km)
  - Night-side: shadow of clouds from low-level thermal emission (IR ~2μm: ~45 km)
  - (day&night: thermal infrared)

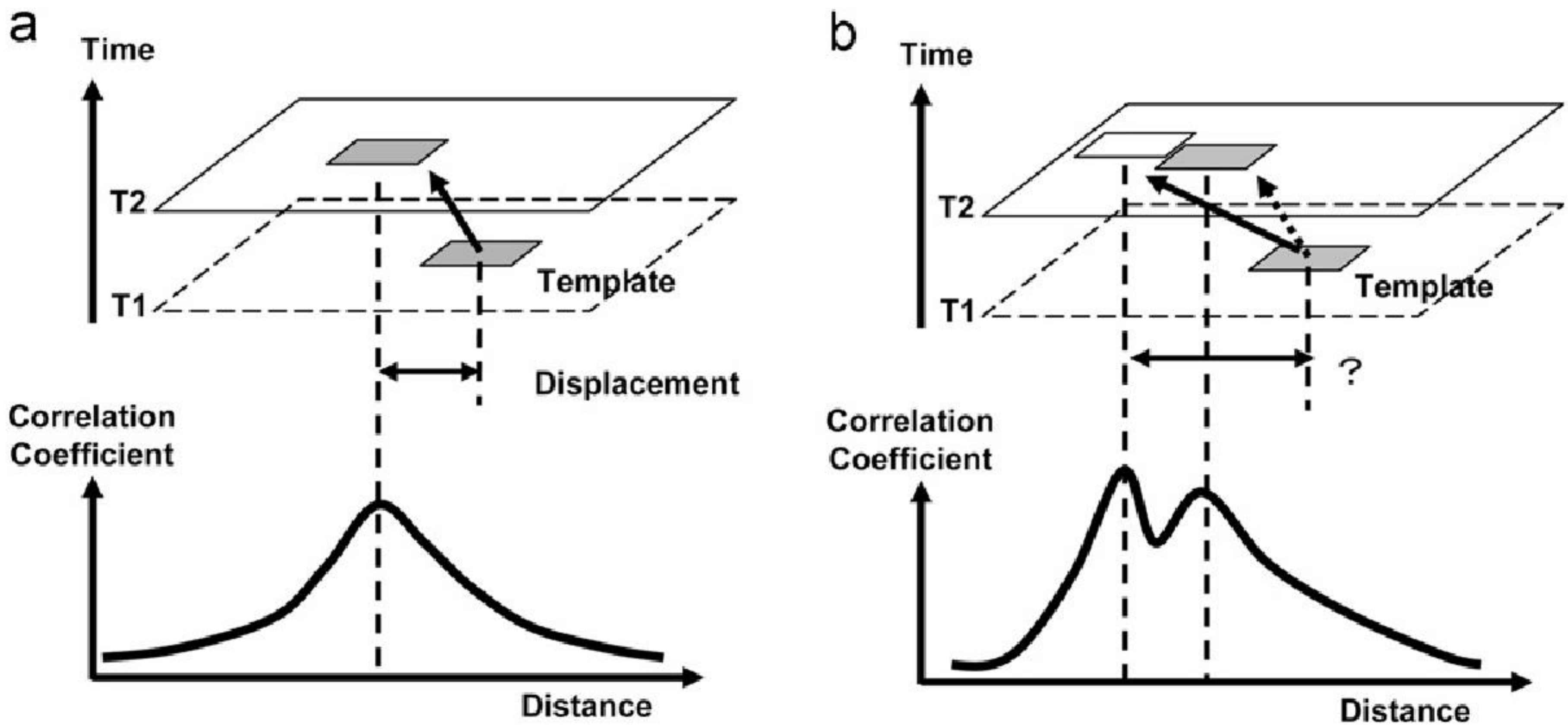
Cloud tracking studies with Venus Express (VEX)

- Mean winds & thermal tides (Sanchez-Lavega et al 2008; Moissl et al 2009; Hueso et al 2012; Khatuntsev et al 2013; Hueso et al 2014. – mostly based on manual tracking)
  - Also some case studies
- Planetary-scale waves (Kouyama et al 2013 – with automated digital tracking)

Tracking methods

- Manual
  - by human eyes
  - labor-intensive
  - supposed to be more reliable than automated tracking
  - resultant vectors tend to be sparse
- Digital (automated)
  - by using the cross-correlation method
  - produces many errors → need screening (e.g. Rossow et al 1990) or correction (e.g., Kouyama 2012)
  - provides dense data (whether reliable or not)

cross-correlation (CC) method

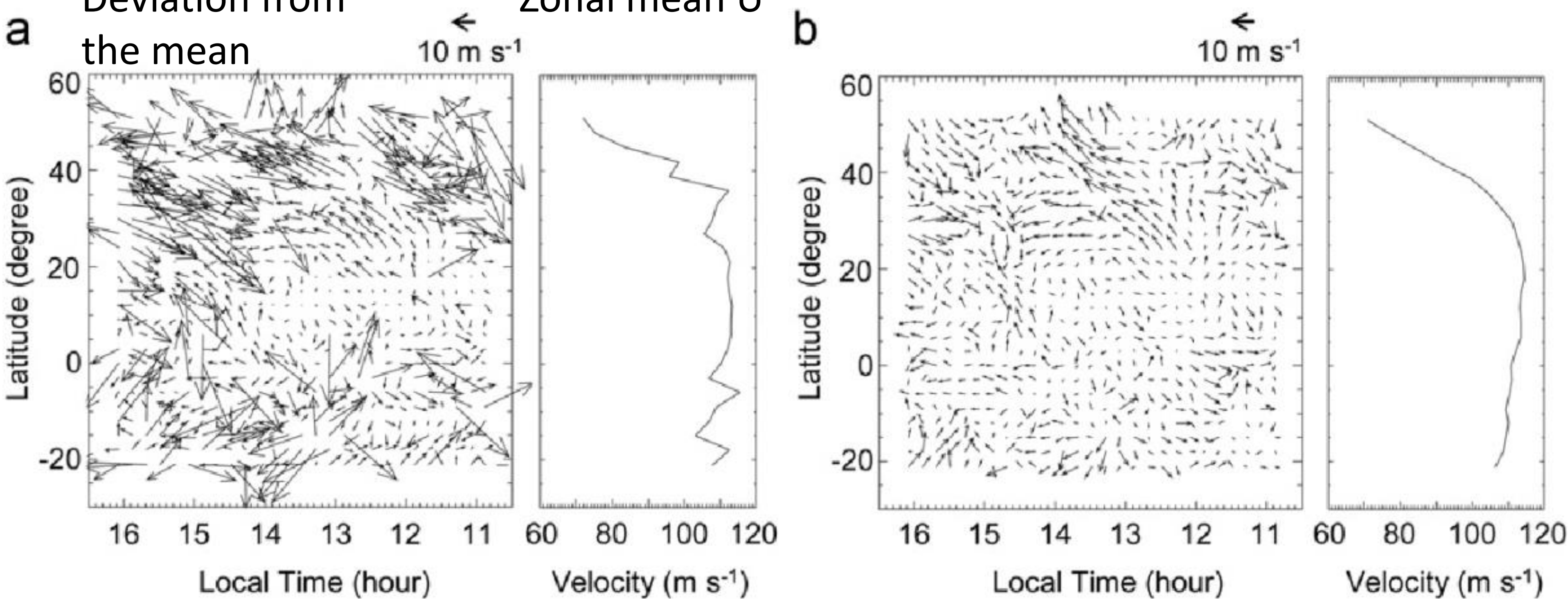


From Kouyama et al. (2012)

Kouyama et al (2012)
Example of results from Galileo images (violet)

Deviation from the mean

Zonal mean U



Simple CC

Corrected by selecting peaks

Purpose of this study

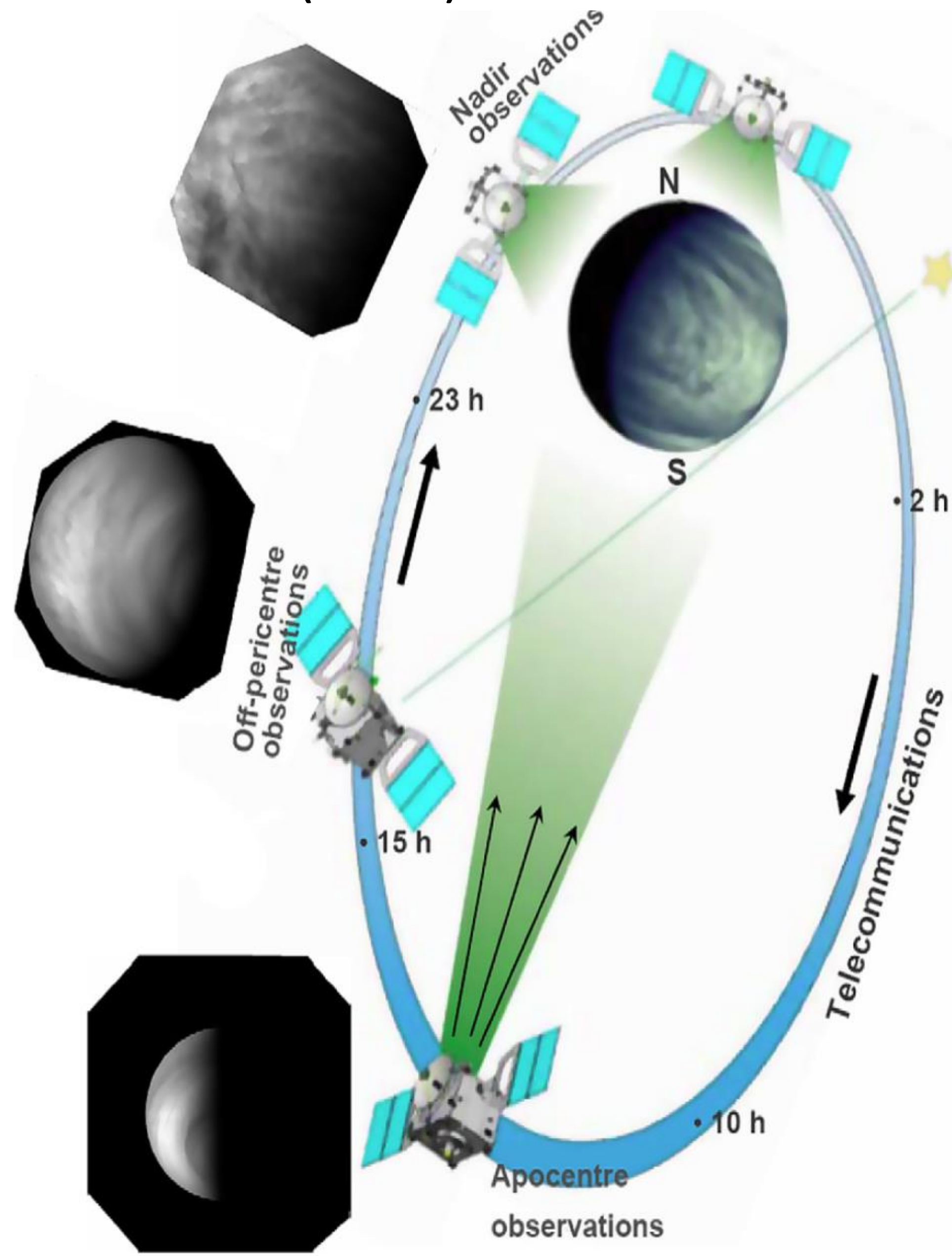
- To improve the CC method by jointly using many (not just two) images to derive cloud motion vectors (CMVs).

- To develop methods to estimate the quality of each CMV

Data

- VEX VMC (Venus Monitoring Camera) V 2.0
  - Used: 365 nm (UV). 512x512 px
  - At apogee, Δx =~ 50 km at the sub-spacecraft point
- VEX:
  - orbital period: 24 h
  - observation during ascending nodes

from Titov (2012)



Corrected VMC images (Titov et al 2012)

Raw image

Corrected; published data

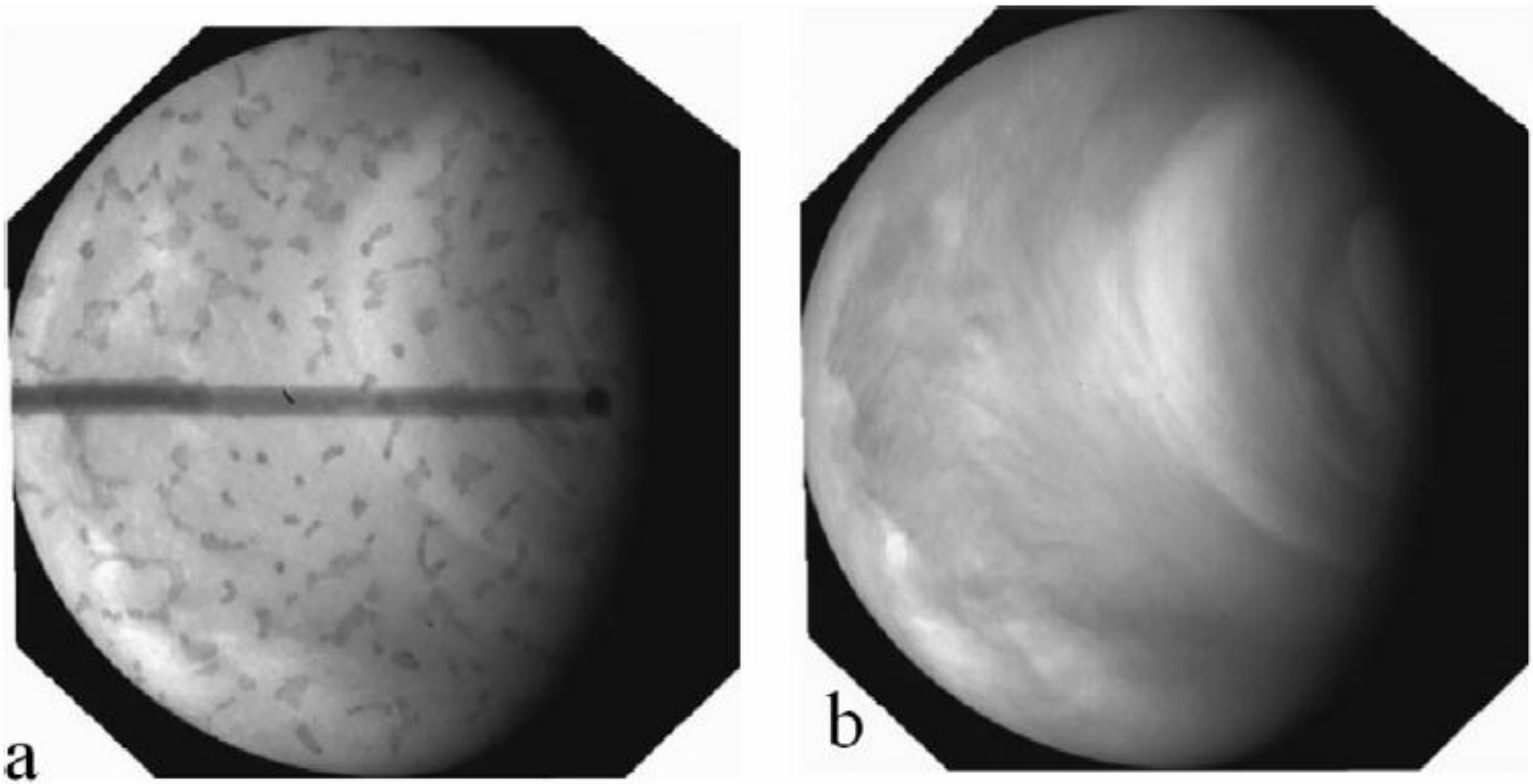


Fig. 3. Examples of the VMC data products in the UV channel: raw image (a), calibrated and flat fielded image (b), …

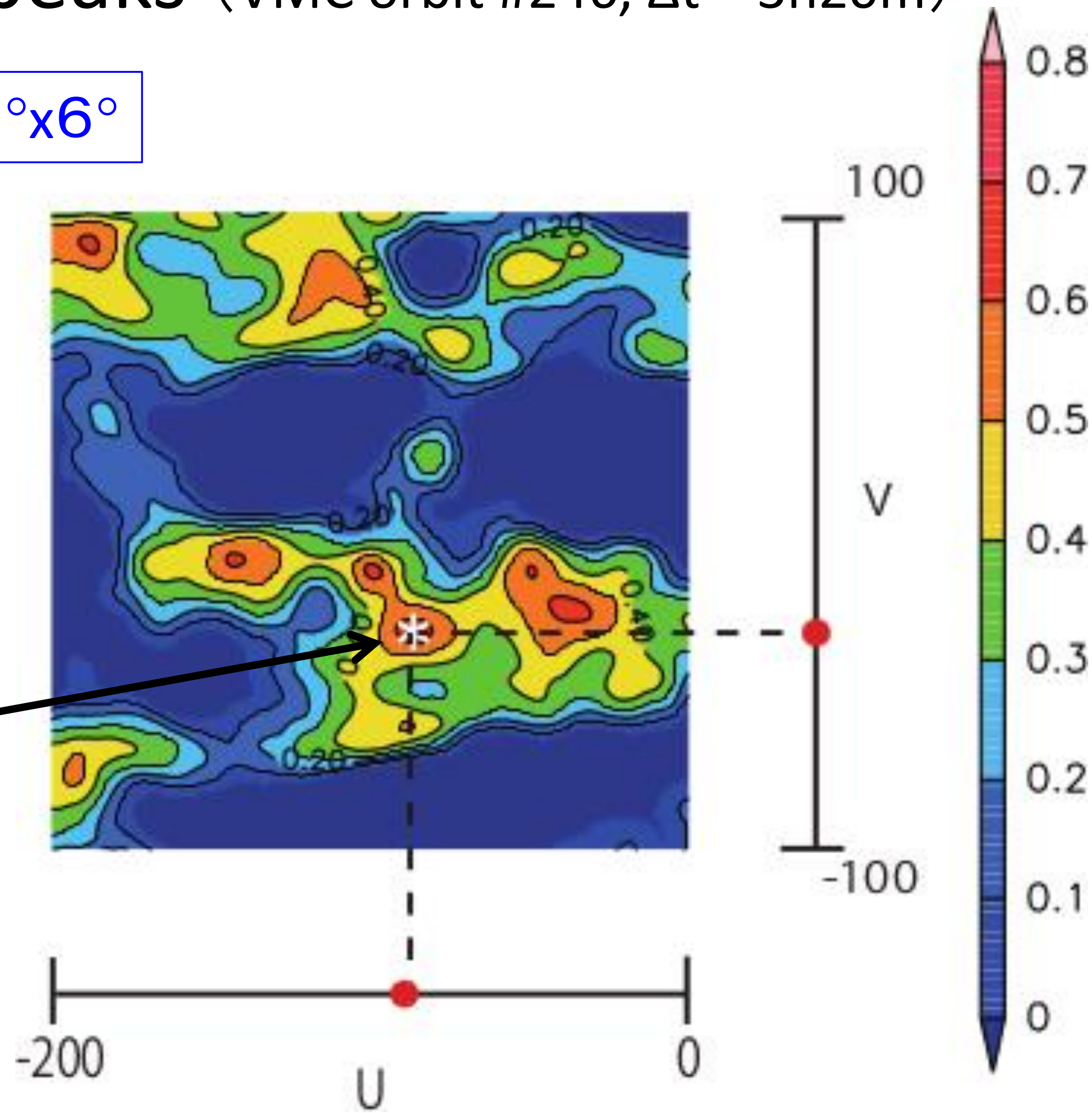
VMC 2.0 data

- Corrected, but noise still remains (sometimes only partially & faintly, sometimes largely & significantly)
- Noise patterns often have similar scales to signal scales → sometimes makes tracking difficult

⇒ We need a noise tolerant method

Example of the CC surfaces with multiple peaks (VMC orbit #246, Δt = 3h20m)

Template size 6°x6°

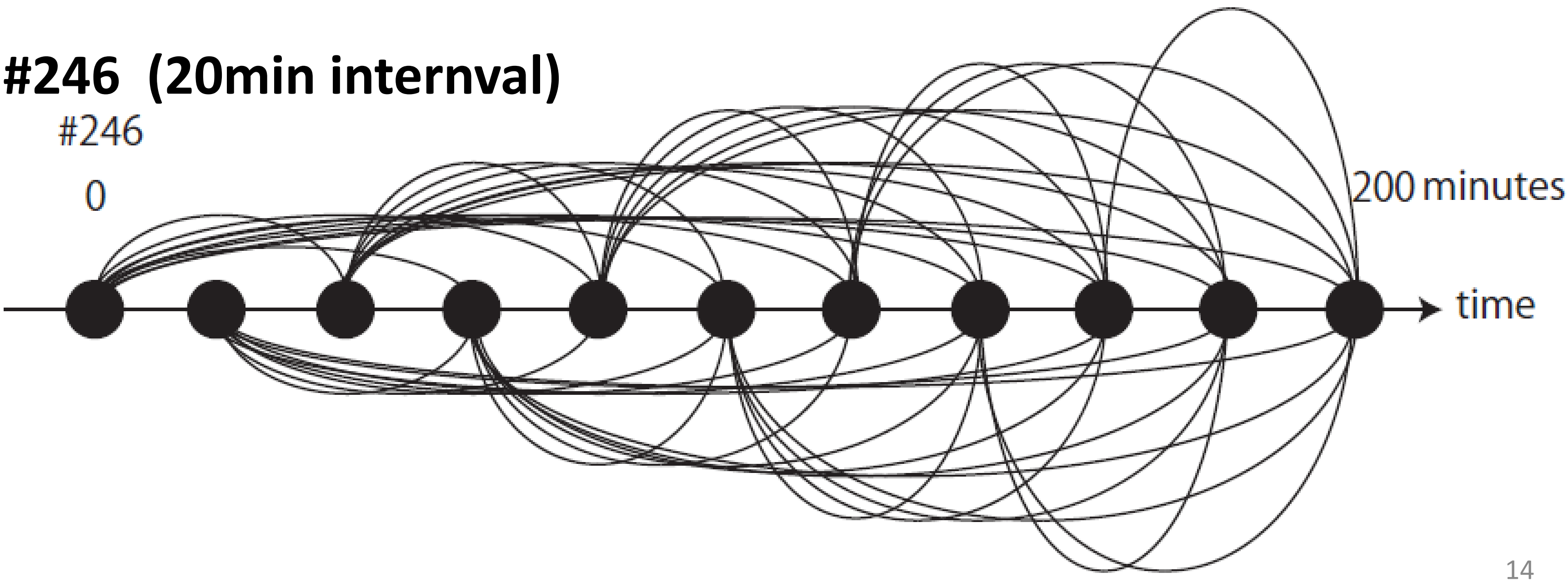


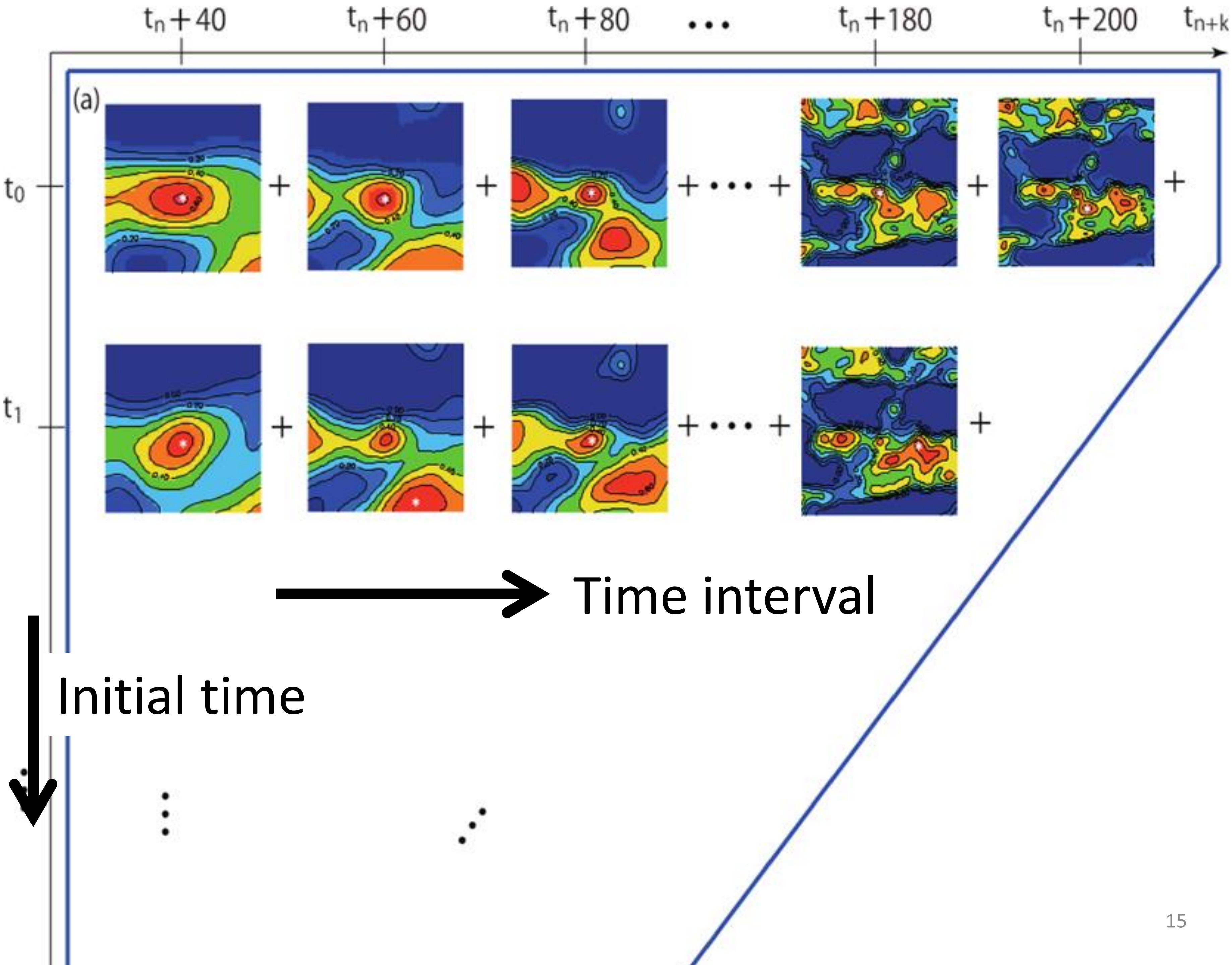
Maximum: wrong match

How to use multiple images

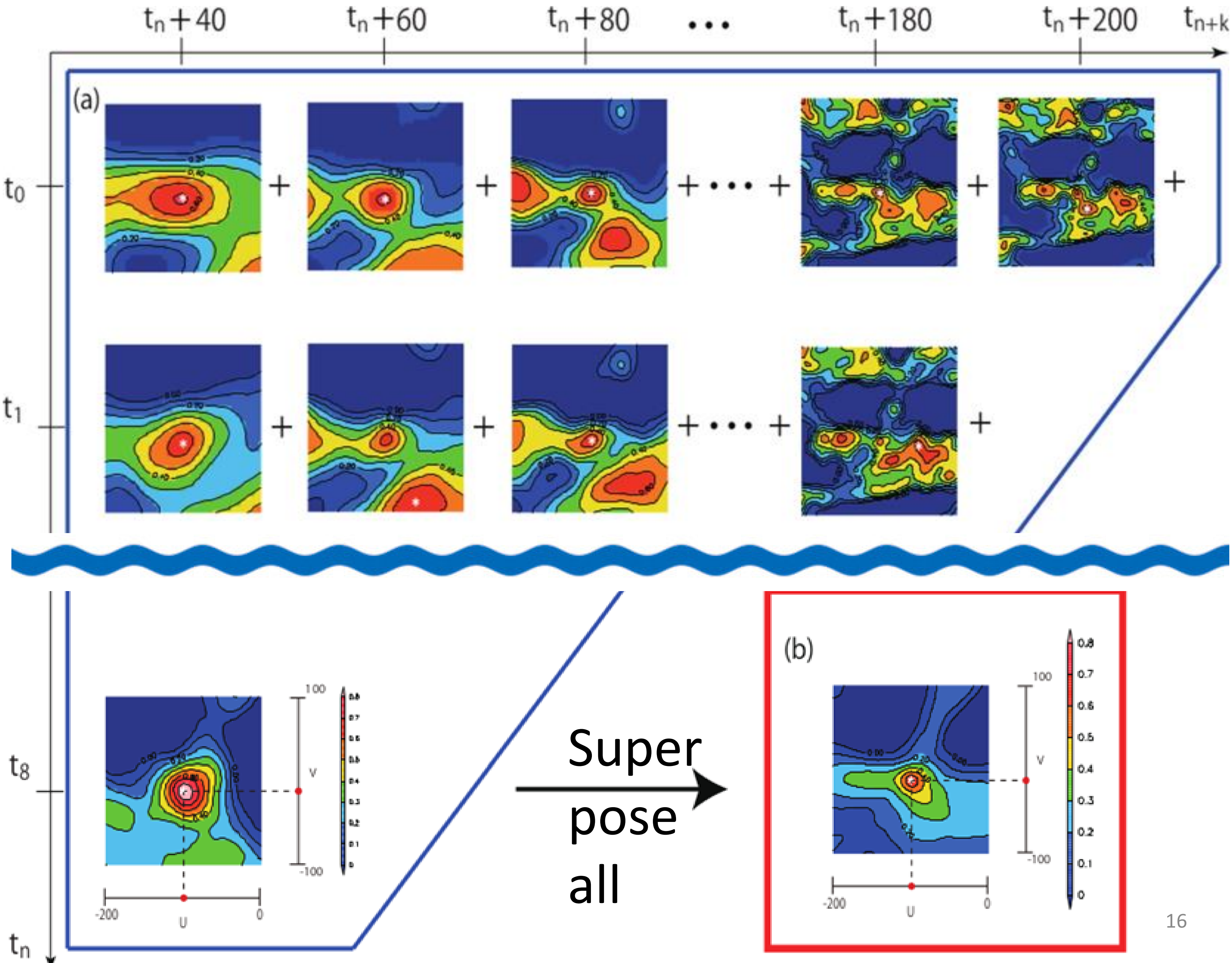
- Superpose the CC surfaces between 2 images for all combinations with $\Delta t >= \Delta t_{min}$ (=40 min in this study)
  - **Point:** superpose with respect to velocity (u,v)

#246 (20min internval)



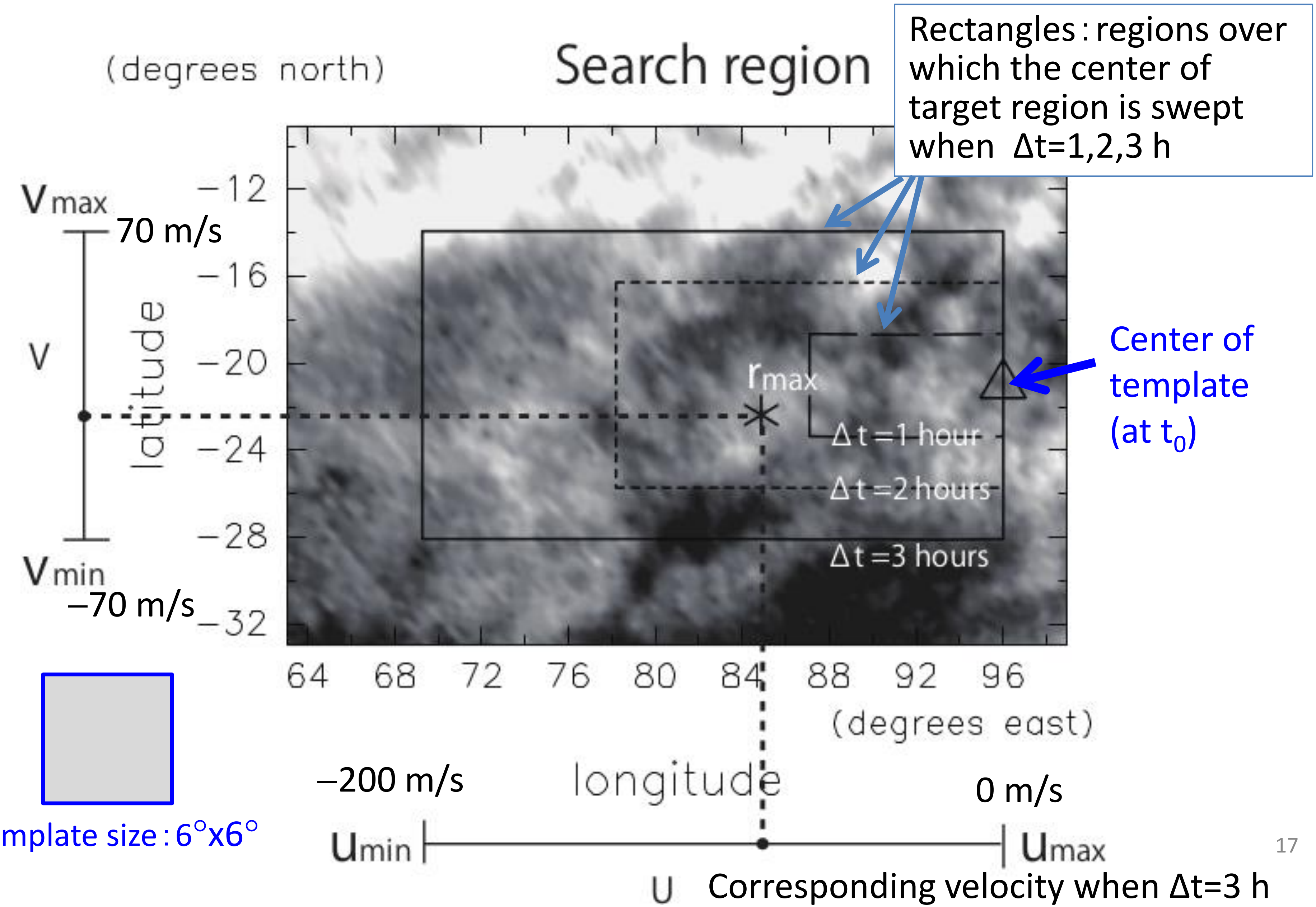


t_n+40
t_n+60
t_n+80
t_n+180
t_n+200
t_{n+k}
(a)
t_0
t_1
Time interval
Initial time



t_n+40
t_n+60
t_n+80
t_n+180
t_n+200
t_n+k
(a)
t_0
t_1
t_8
t_n
100
-100
V
-200
U
0
Super pose all
(b)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Δt greater ⇒ Search region wider



Template size : 6°x6°

Essence of the CC superposition

$$r(x,y,t) = \frac{1}{P}\sum_{(t_1,t_2)} \langle f'(x+\bar{u}t_1, y+\bar{v}t_1, t+t_1) f'(x+\bar{u}t_2, y+\bar{v}t_2, t+t_2)\rangle$$

- $\langle\ \rangle$: average over small *x*&*y* ranges (6°x 6° in IH15)
- P : the number of the (t_1, t_2) combinations
- f' : normalized brightness deviation
- $\bar{u}$ and $\bar{v}$: the velocity to be derived.

(Traditional one-pair method: $P = 1$ & $t_1 = 0, t_2 = \Delta t$)

Why does the superposition enhance (reduce) the correct (wrong) peak(s)?

- For match with actual similar features
  - Suppose (at $t = t_0$) similar cloud features A around (x, y) and B around $(x + c, y + d)$; both are advected by (u, v) (assume a common velocity, since they are nearby)
  - Correlation between A at t_0 and B at $t_0 + \Delta t$ → peaks at velocity = $(u + c/\Delta t, v + d/\Delta t)$
    - Varies by Δt unless $c = d = 0$ → peak reduced ($c = d = 0$ means correct match)
    - Point: to have various Δt values
- Match by noise or error
  - is also reduced by superposition, if noise/error is independent among images (regardless Δt values)

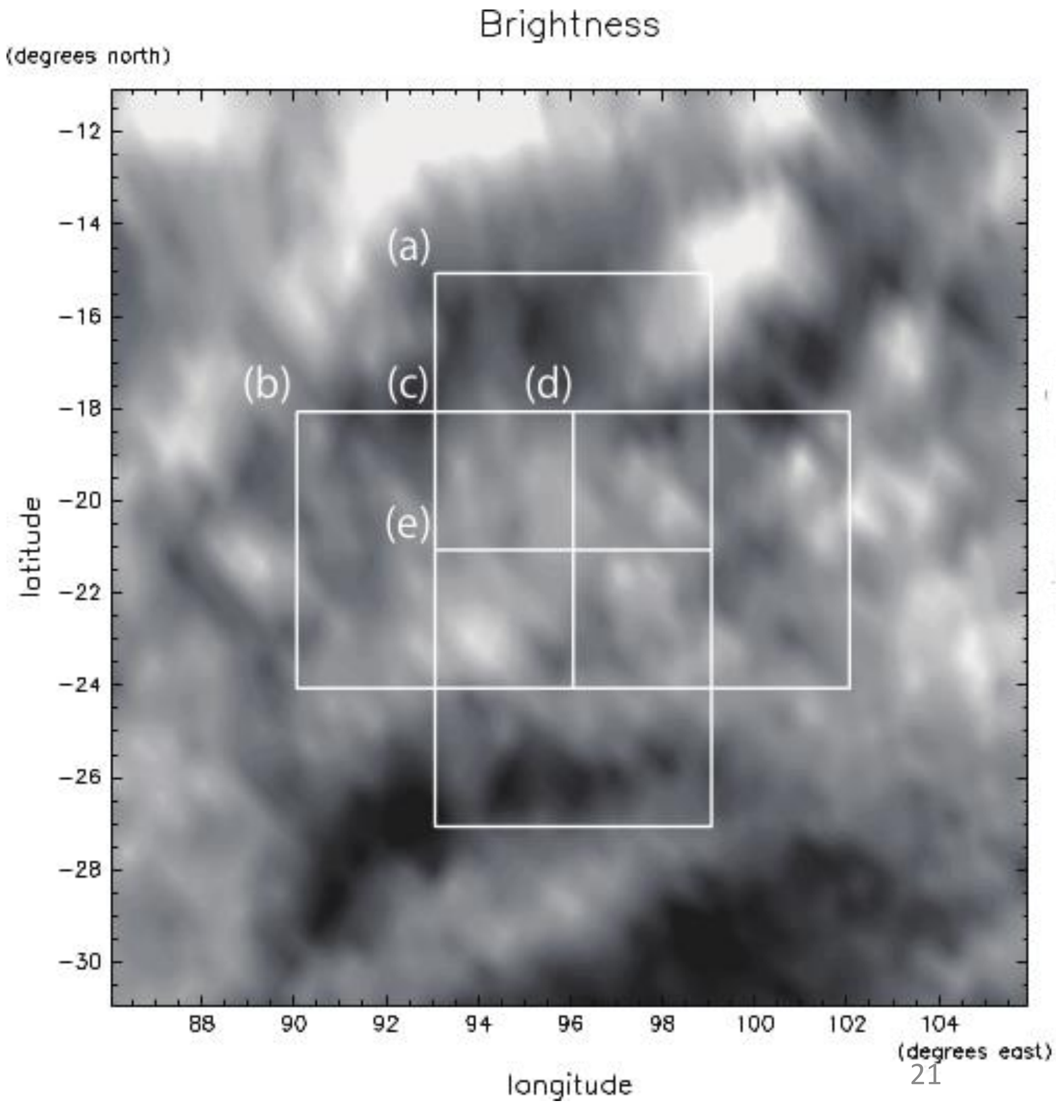
Why does the superposition increase the accuracy too?

- Because it reduces the random peak shift by noise and pixel discretization

The $1/\sqrt{N}$ effect

Spatial superposition (~running mean) of CC surfaces (additional; STS in IH15)

- Adequate when the desired spatial resolution is coarser than the template size.
- Overlay the 5 CC surfaces before deriving velocity
  - Trade off between spatial resolution and accuracy
  - **The default** procedure in IH15 (used in what follows)

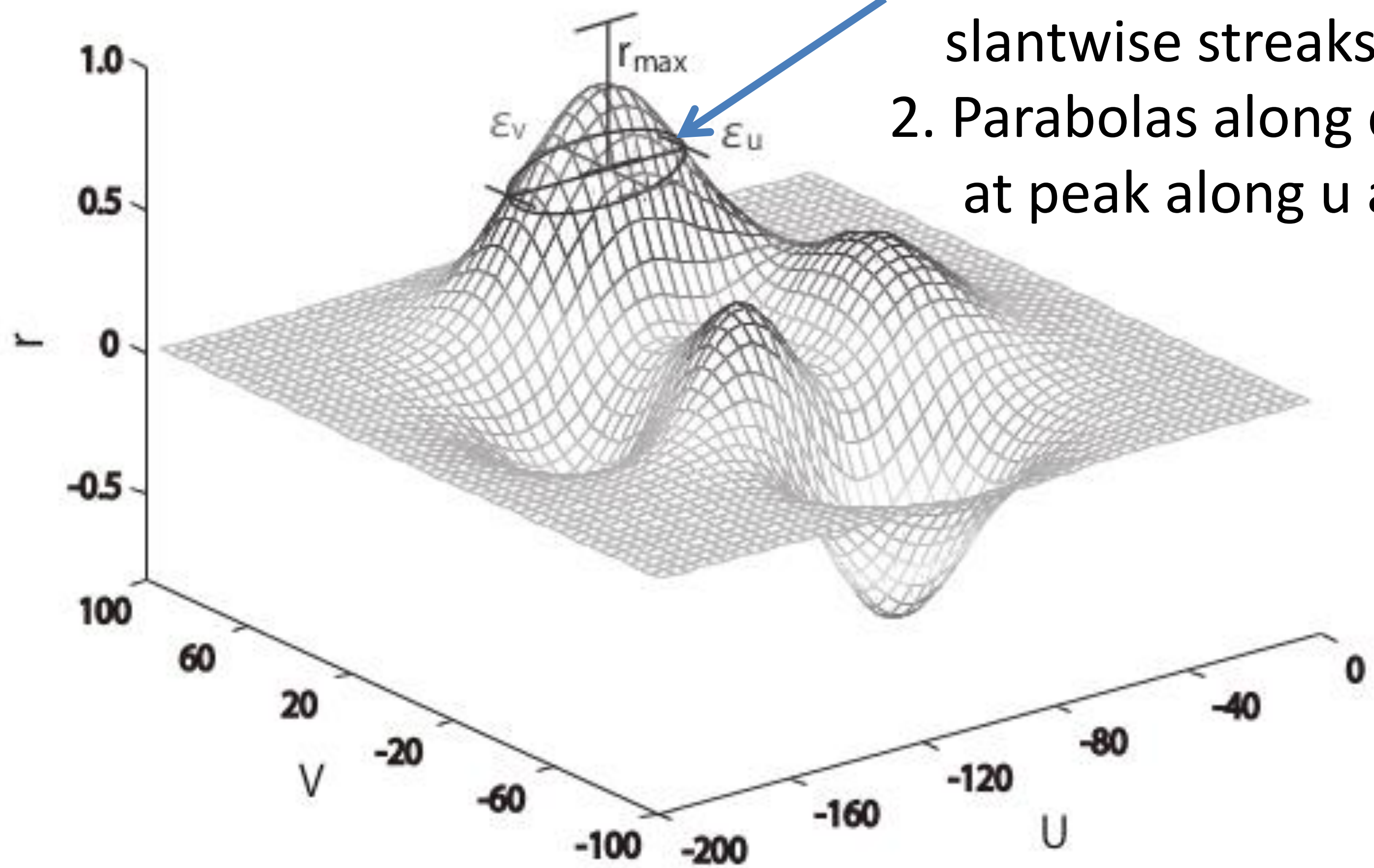


Error estimation: Necessity

- **Crucial!** Needed to judge what we can do (to what extent) with the data!
  - error level sets the effective resolution.
  - Clouds are some times featureless: accuracy varies significantly.
- Previous studies used σ (std.dev.; e.g. against zonal mean), which includes natural (true) variability.
  - Since $\langle \sigma^2 \rangle = \left\langle \sigma_{\mathrm{natural}}^2 \right\rangle + \langle \sigma_{\mathrm{err}}^2 \rangle$, it's safe to use σ, but it is useless as a measure of error if $\langle \sigma_{\mathrm{err}}^2 \rangle \ll \left\langle \sigma_{\mathrm{natural}}^2 \right\rangle$, but to achieve it is the very thing that we need to study atmospheric disturbances.

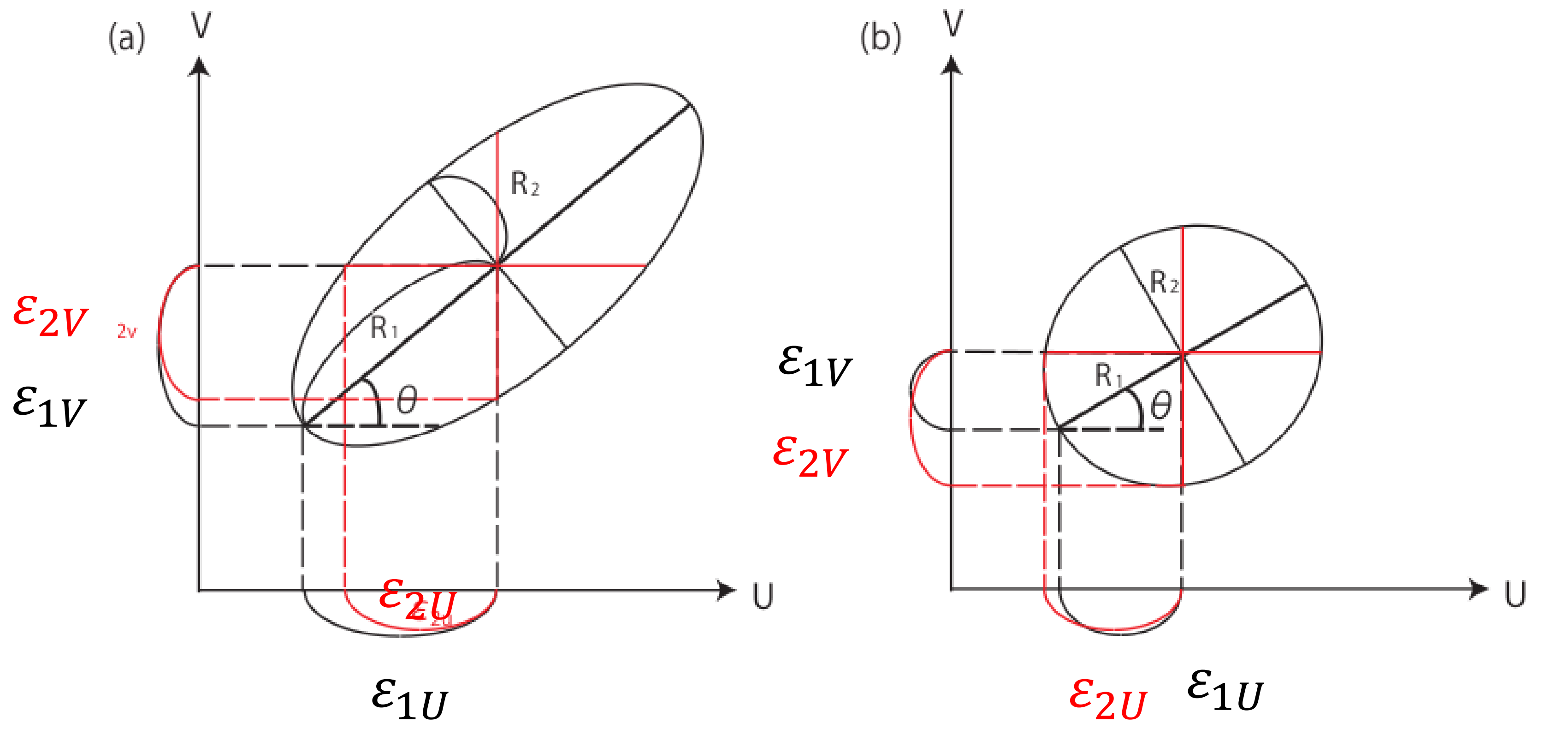
Error evaluation 1 (precision)

- Utilize the lower confidence bound of CC
  - Use the effective degree of freedom.
  - Covers streaky clouds（then CC surfaces are also streaky）
  - Applicable to one-pair estimates
  - Cannot tell anything about peak selection (drawback)



CC surface above the lower confidence bound (90%) is fit by

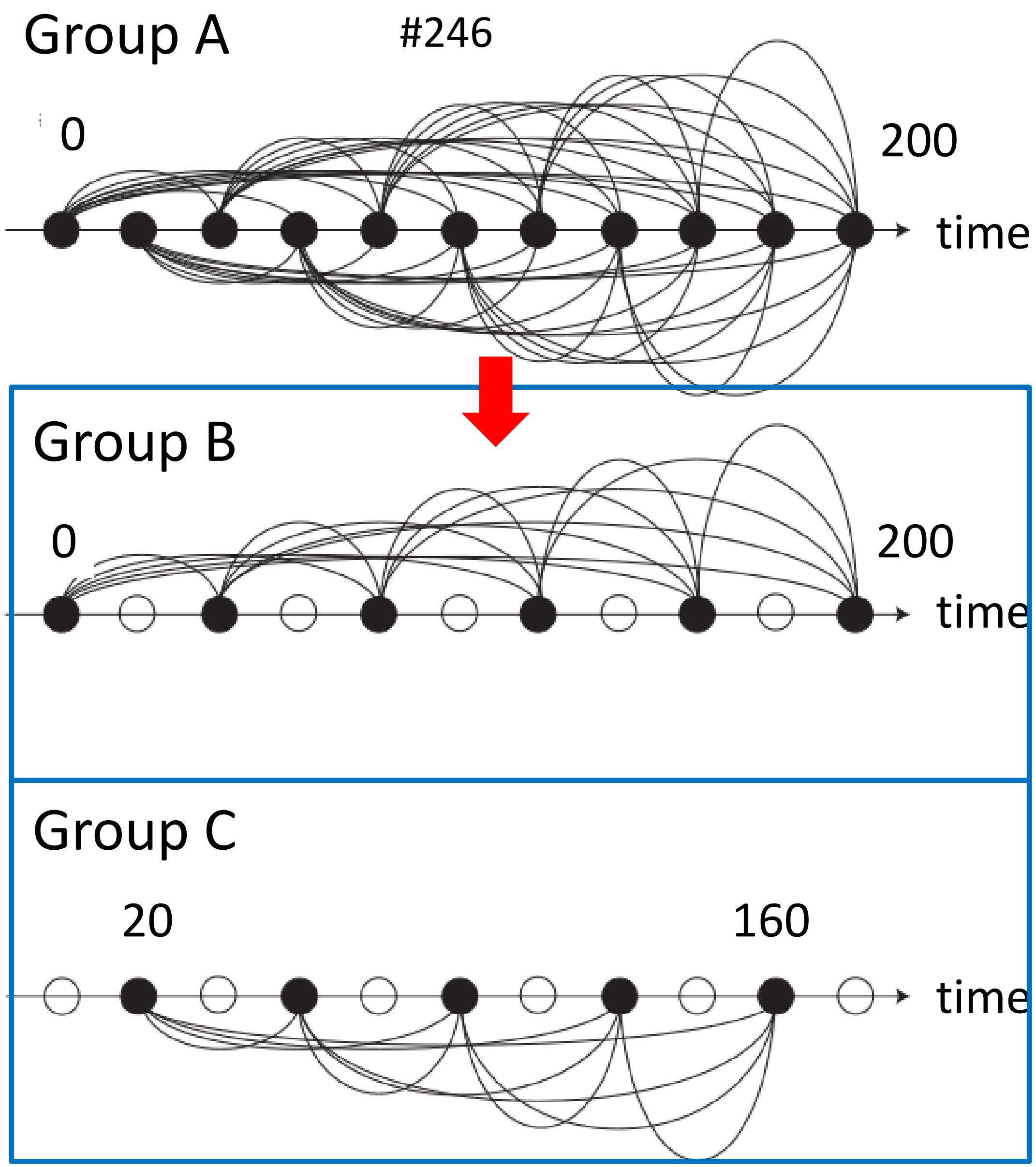
1. Elliptic paraboloid (for slantwise streaks)
2. Parabolas along cross sections at peak along u and v axes



$\varepsilon = \max(\varepsilon_{1U}, \varepsilon_{1V}, \varepsilon_{2U}, \varepsilon_{2U})$: the worst of the four params.

Caveat: confidence percentage (90%, here) is only applicable to CC.
Cannot be converted to the confidence level of (*u*,*v*).
But ε may be used as a relative measure of the precision of (*u*,*v*).

Error evaluation 2



- Entire images (A) are divided into 2 groups (B,C) and winds are estimated from each
  - Use the rms between the two.
  - Note: B & C are expected to have greater error than A, since the number of pairs are smaller

absolute values of vector differences as

From IH15

$$\sigma_X(\lambda_a, \phi_b) \equiv \sqrt{\{u_t(\lambda_a, \phi_b) - u_X(\lambda_a, \phi_b)\}^2 + \{v_t(\lambda_a, \phi_b) - v_X(\lambda_a, \phi_b)\}^2} \quad \text{for } X = \mathrm{A}, \mathrm{B}, \mathrm{C}, \tag{22}$$

and

$$\sigma_{\mathrm{BC}}(\lambda_a, \phi_b) \equiv \sqrt{\{u_{\mathrm{B}}(\lambda_a, \phi_b) - u_{\mathrm{C}}(\lambda_a, \phi_b)\}^2 + \{v_{\mathrm{B}}(\lambda_a, \phi_b) - v_{\mathrm{C}}(\lambda_a, \phi_b)\}^2}. \tag{23}$$

If we assume that CMVs derived from a single pair has error with a normal distribution and the error is independent among pairs, we can expect the following relations:

$$\langle \sigma_{\mathrm{B}}^2 \rangle = \frac{P}{P_{\mathrm{B}}} \langle \sigma_{\mathrm{A}}^2 \rangle, \tag{24}$$

$$\langle \sigma_{\mathrm{C}}^2 \rangle = \frac{P}{P_{\mathrm{C}}} \langle \sigma_{\mathrm{A}}^2 \rangle, \tag{25}$$

$$\langle \sigma_{\mathrm{BC}}^2 \rangle = \langle \sigma_{\mathrm{B}}^2 \rangle + \langle \sigma_{\mathrm{C}}^2 \rangle, \tag{26}$$

(P, P_A, P_B : the number of pairs in the groups A,B,C)

⇒ **Expected error** (here, the factor of 1.96 is for the 95% confidence level)

$$\chi(\lambda_a, \phi_b) \equiv 1.96 \left(\frac{P}{P_{\mathrm{B}}} + \frac{P}{P_{\mathrm{C}}} \right)^{-\frac{1}{2}} \sigma_{\mathrm{BC}}(\lambda_a, \phi_b)$$

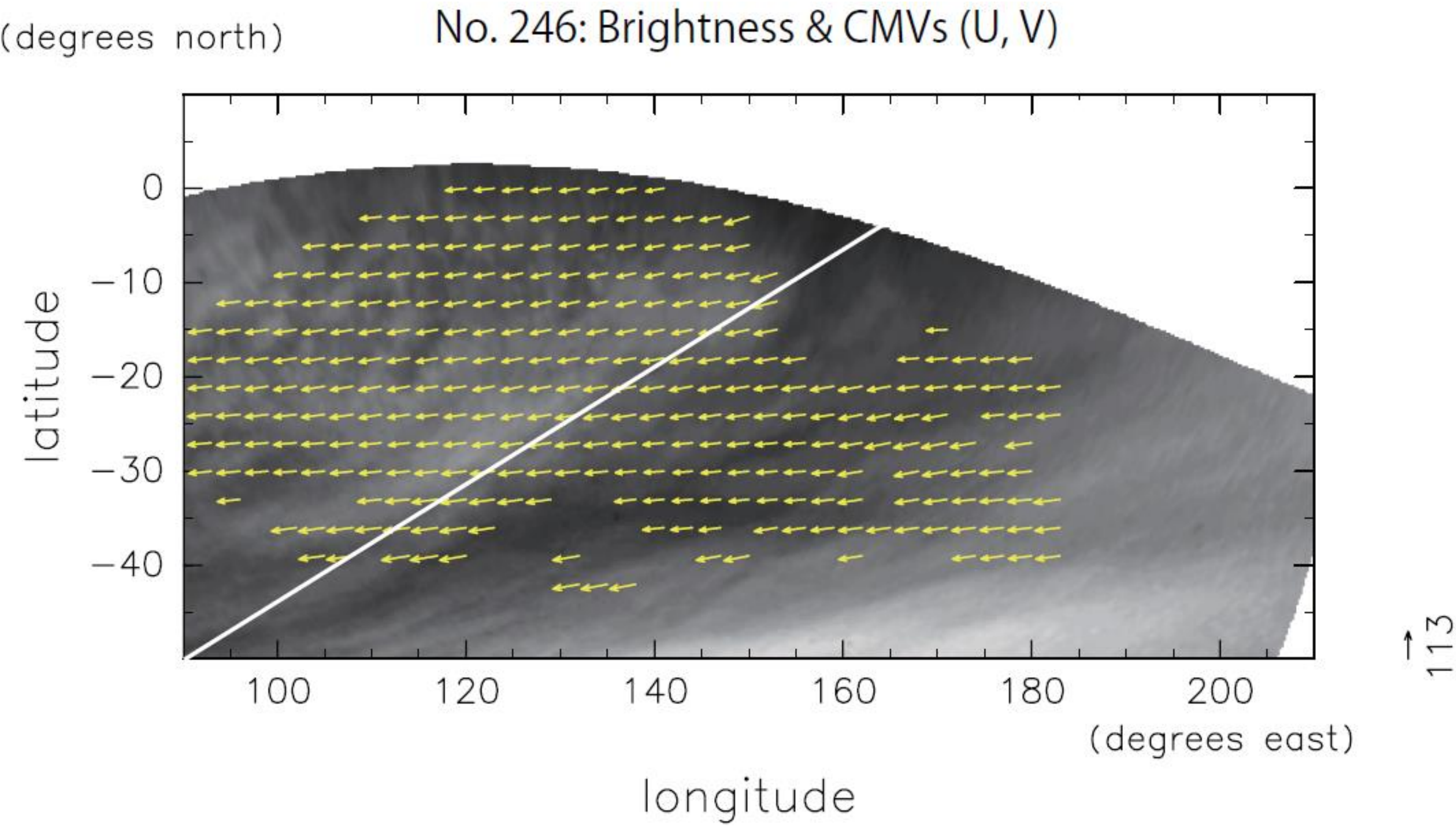
Characteristics of χ

- Merit: Direct measure of errors in (u, v)
- Limitation: Deals with peak selection, but only partially (peaks in B and C may differ, though agreement does not guarantee correctness).

Our screening

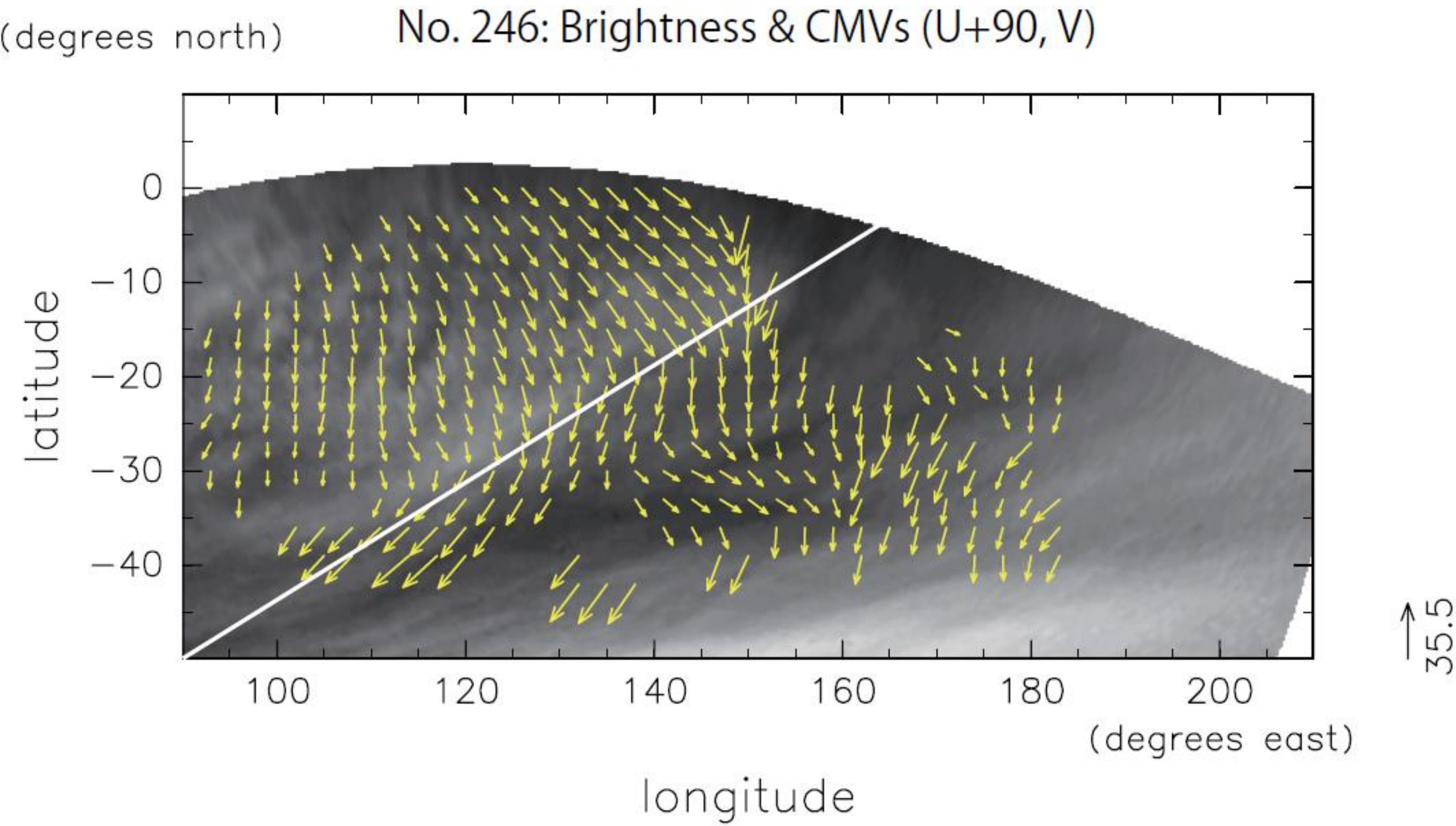
- Made by
  1. Peak CC value: $r_{max} \geq 0.6$
  2. Mapped CC lower bound: $\varepsilon \leq 20$ m/s
  3. Error form 2-group comparison: $\chi \leq 10$ m/s
- No correction of erroneous vectors (can be introduced, but simply not have been tried)

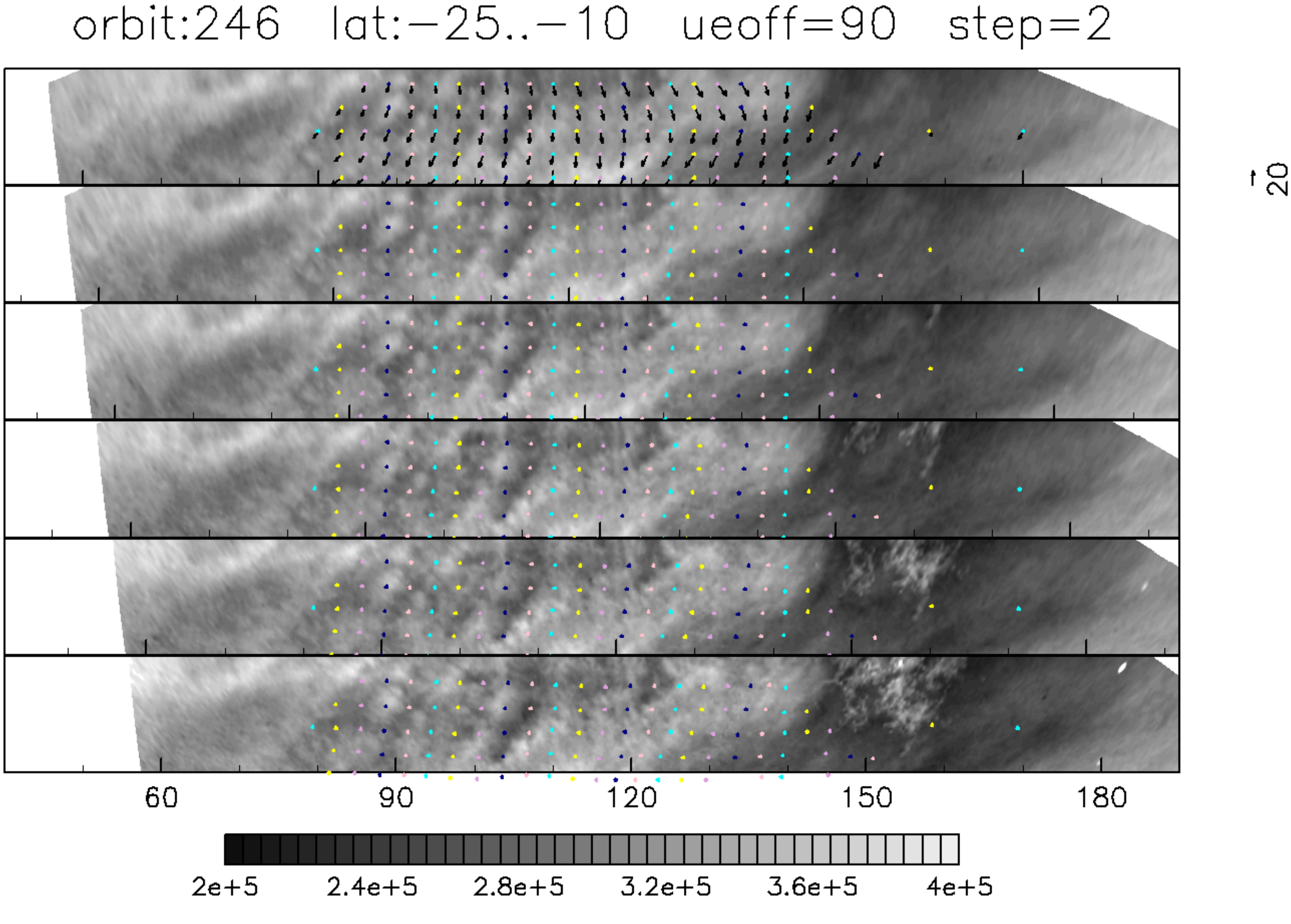
Result example (Orbit 246)



Our estimation is limited down to 45°S

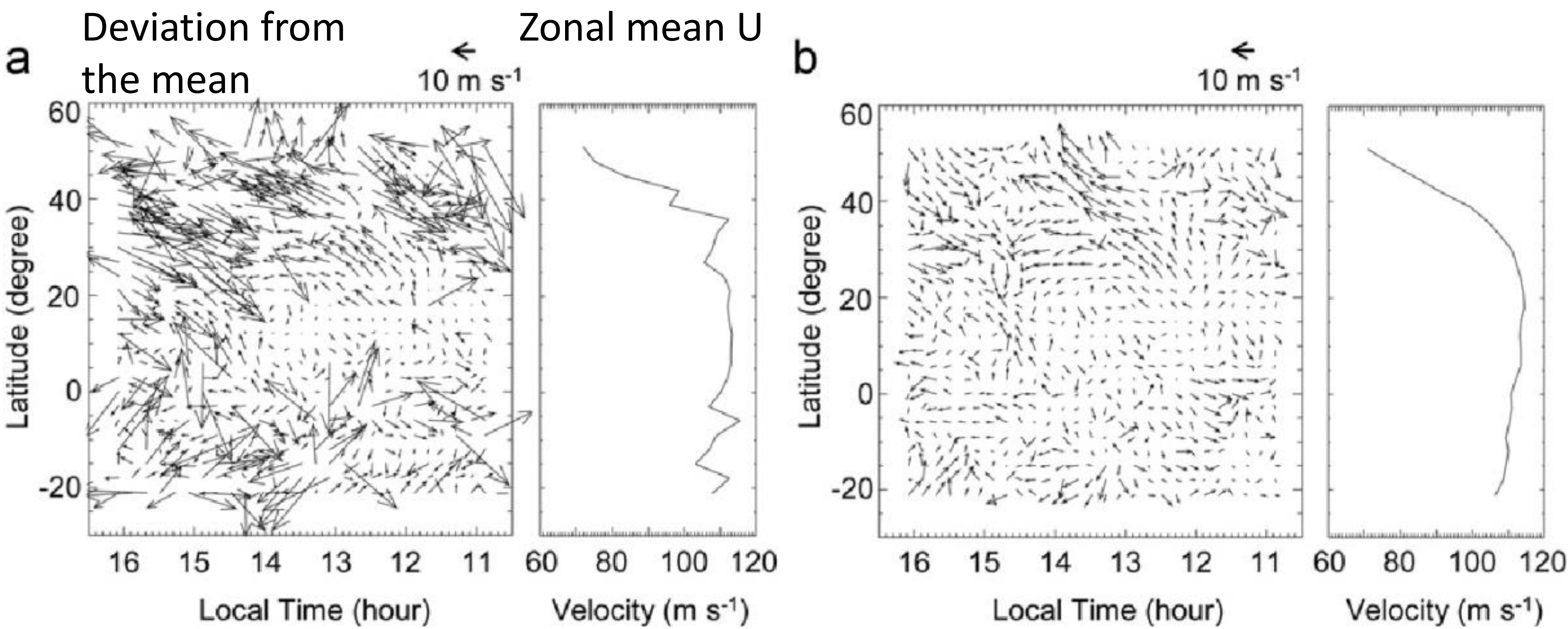
Added a uniform zonal flow: (90,0) m/s





orbit:246 lat:-25..-10 ueoff=90 step=2
20
60
90
120
150
180
2e+5
2.4e+5
2.8e+5
3.2e+5
3.6e+5
4e+5

Ref：Kouyama et al (2012) Example of wind from Galileo images (violet)



Simple CC

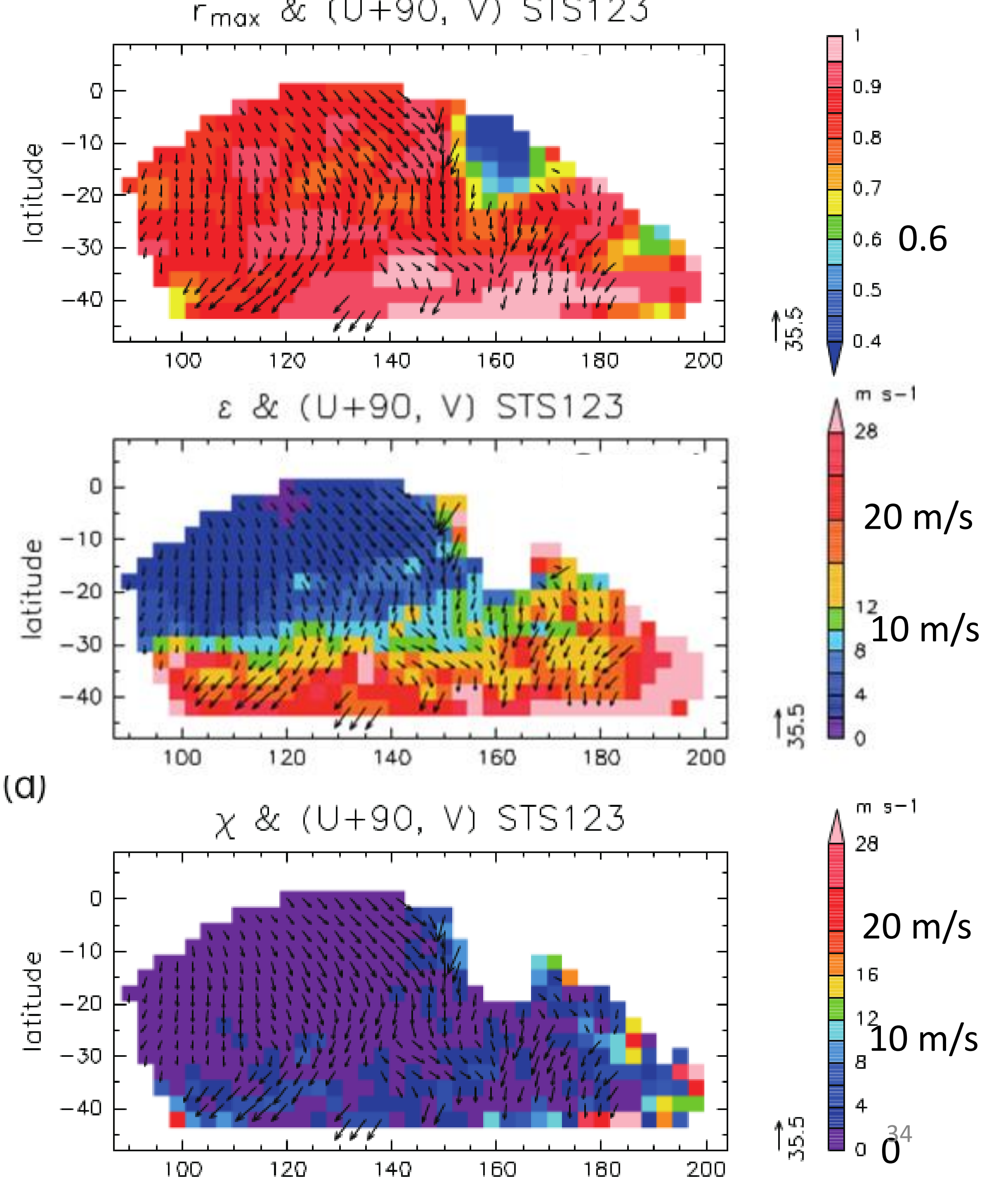
Corrected by selecting peaks

Error evaluation
(#246)

Max CC r_{max}

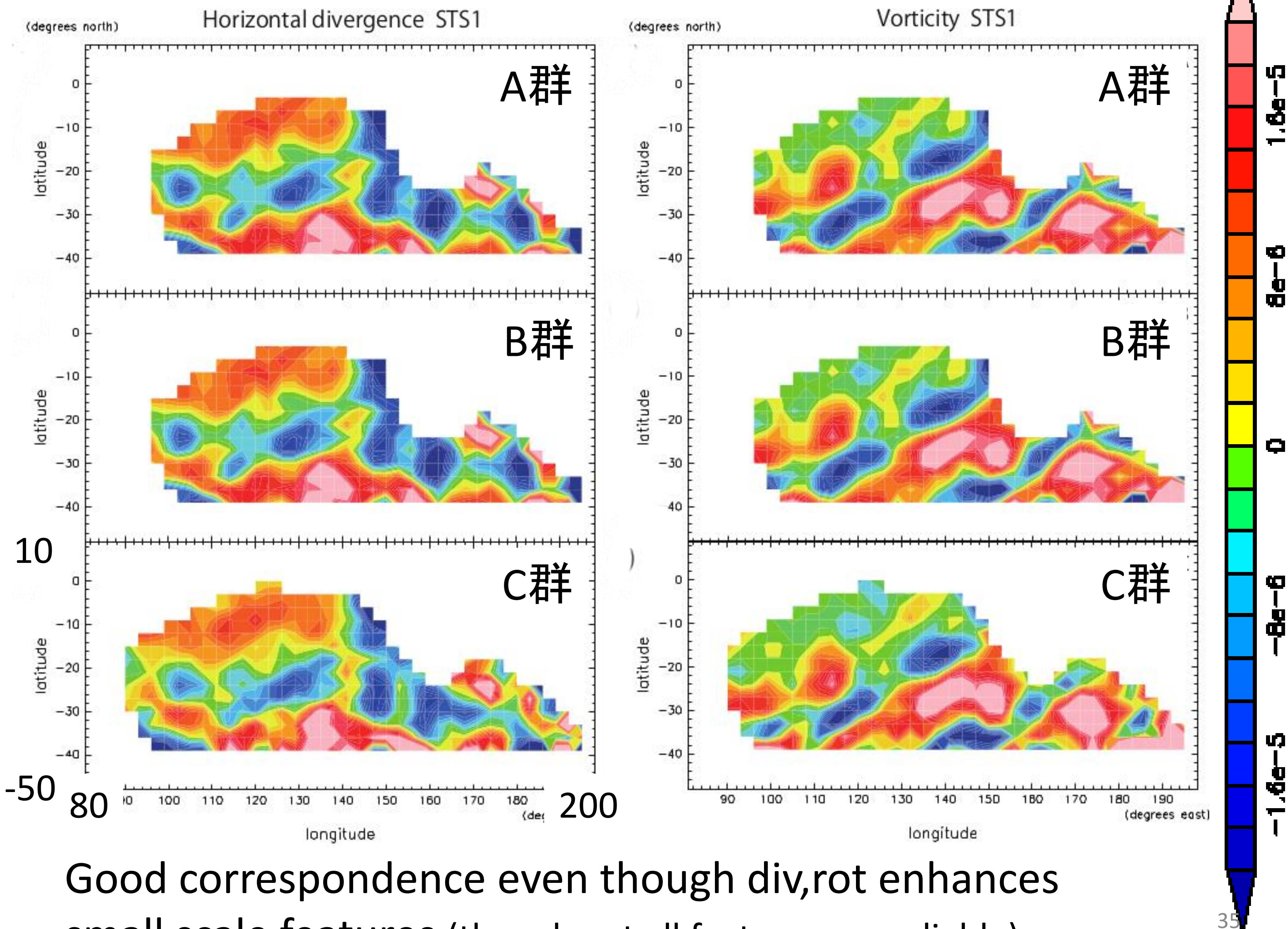
Mapped CC lower bound ε

Error from 2-group comparison χ



Screened on by r_{max}

div & rot



Good correspondence even though div,rot enhances small scale features (though not all features are reliable)

Summary of the error estimates (After the screening. Orbits 243-267)

χ (from 2-group diff.)

	low latitude		mid latitude	
	rms value	median value	rms value	median value
wind velocity (χ)	2.4 m s^{-1}	1.5 m s^{-1}	3.0 m s^{-1}	2.0 m s^{-1}
horizontal divergence (χ_δ)	7.7×10^{-6} s^{-1}	2.9×10^{-6} s^{-1}	1.8×10^{-5} s^{-1}	6.4×10^{-6} s^{-1}
vorticity (χ_ζ)	7.8×10^{-6} s^{-1}	3.0×10^{-6} s^{-1}	1.6×10^{-5} s^{-1}	5.3×10^{-6} s^{-1}

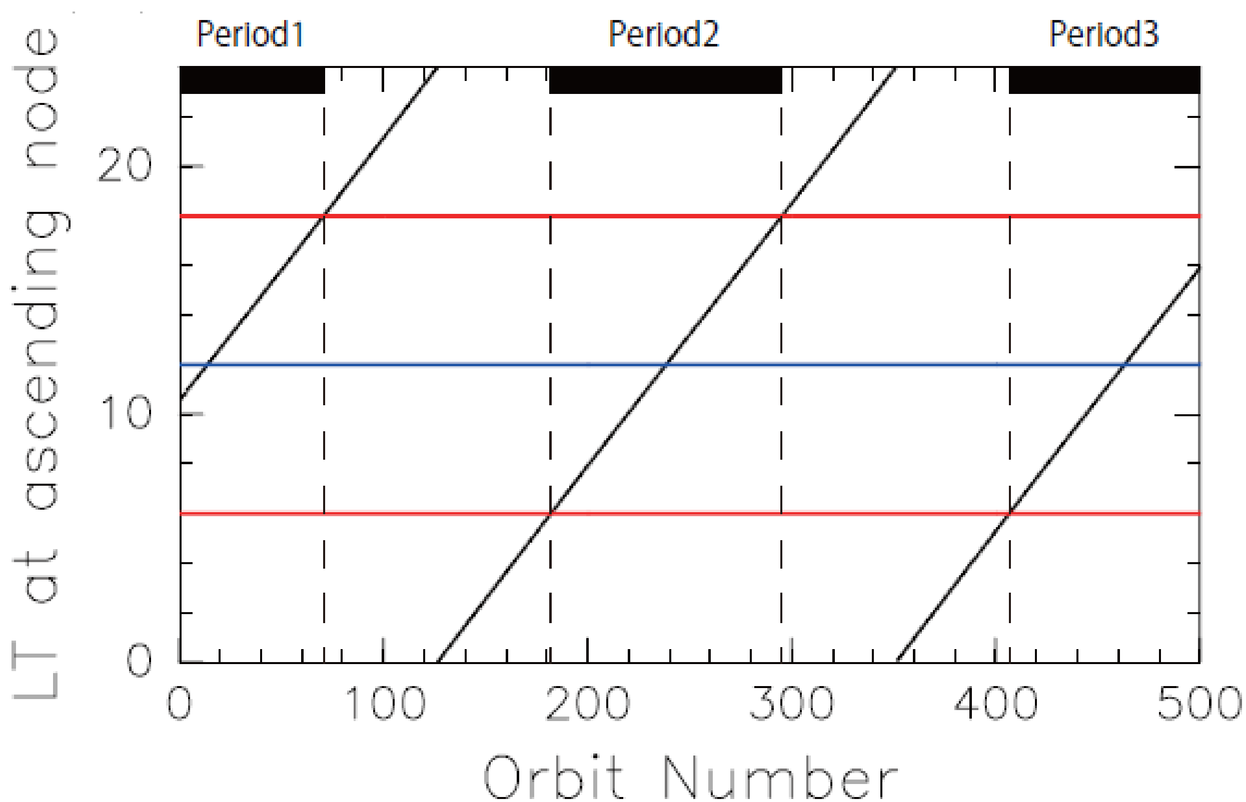
ε (from CC confidence)

accuracy evaluation	low latitude		mid latitude	
	rms value	median value	rms value	median value
statistical accuracy	9.4 m s^{-1}	7.8 m s^{-1}	14.8 m s^{-1}	15.0 m s^{-1}

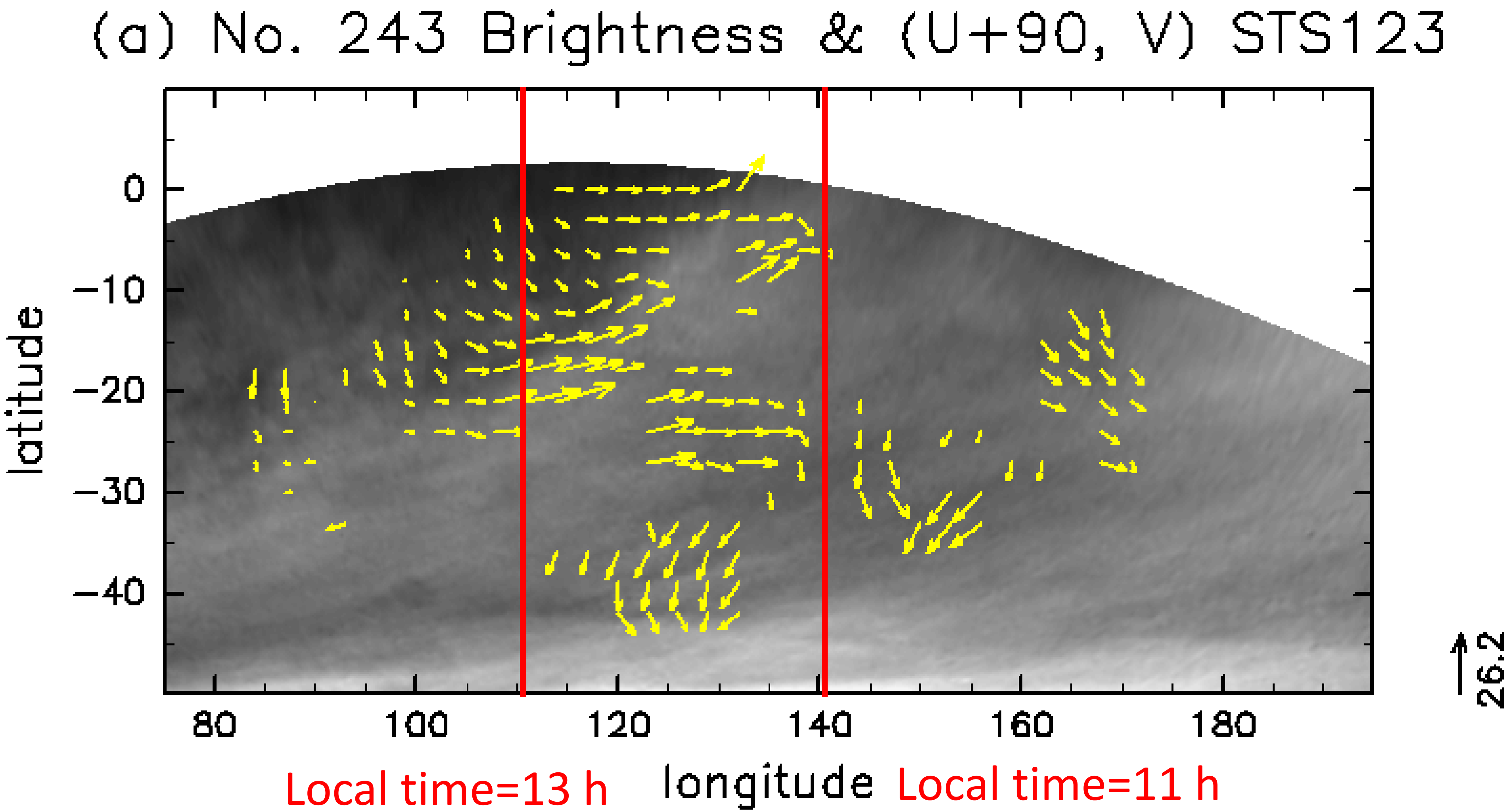
- In general, $\chi < \varepsilon$
- If measured by χ, typical error is 2 m/s. (Too good for manual (human-eye) verification. Q: actually good beyond the limit of manual tracking, or χ is too good?)
- Low lat (EQ-30S) better than mid lat (30S-45S)
- χ : median < rms (∵big values are outliers)

Results (#200s)

- 10 orbits from 243 to 267
  - Other orbits (in this period) are not available since the number of images ＜4
  - For each of the 10 orbits, 8-11 images are used.
  - Caveat (from subjective verification)： some results (vectors) are likely invalid beyond the χ value.

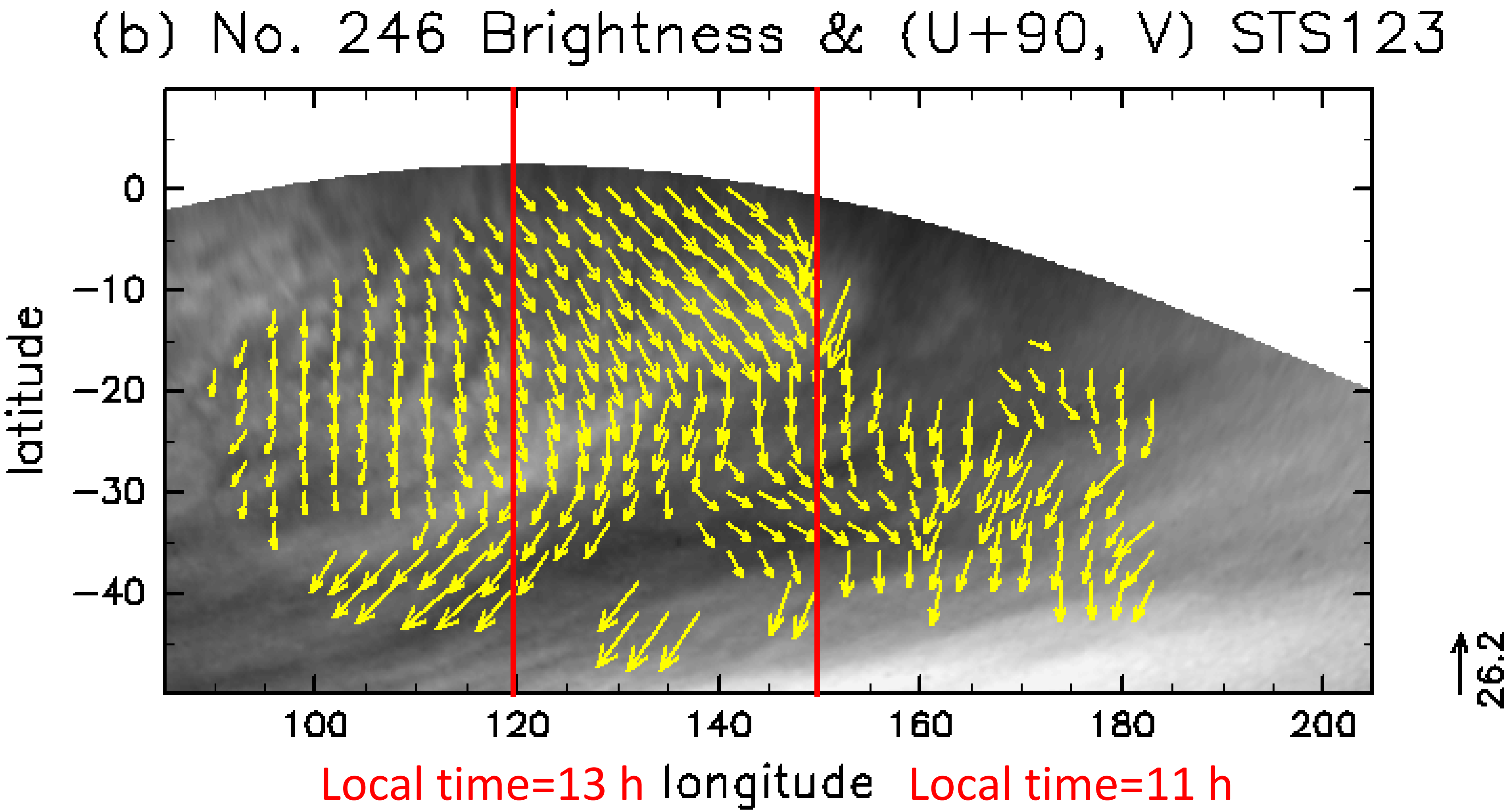


Orbit 243

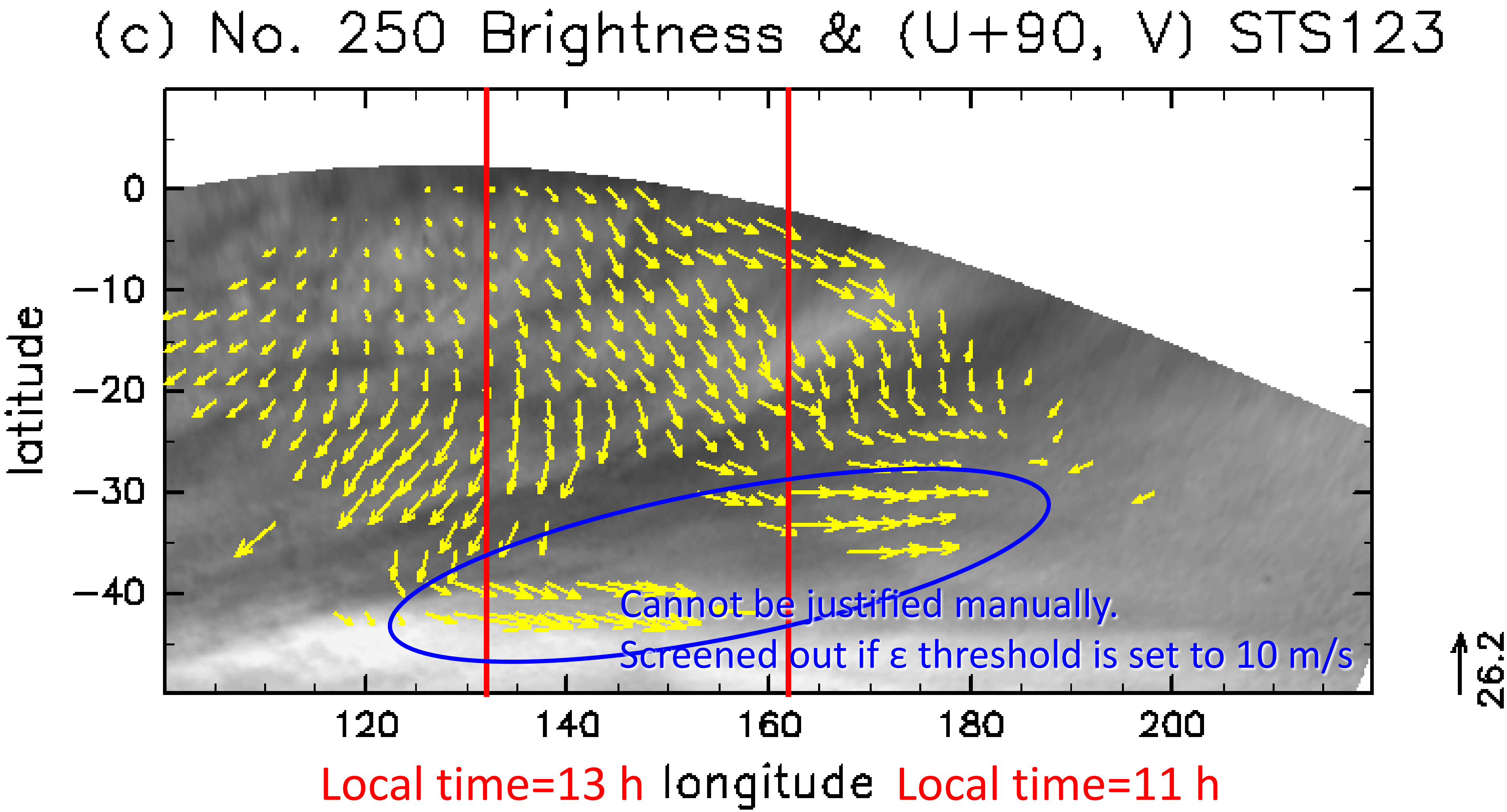


(a) No. 243 Brightness & (U+90, V) STS123
0
−10
−20
−30
−40
latitude
80
100
120
140
160
180
longitude
Local time=13 h
Local time=11 h
26.2

Orbit 246

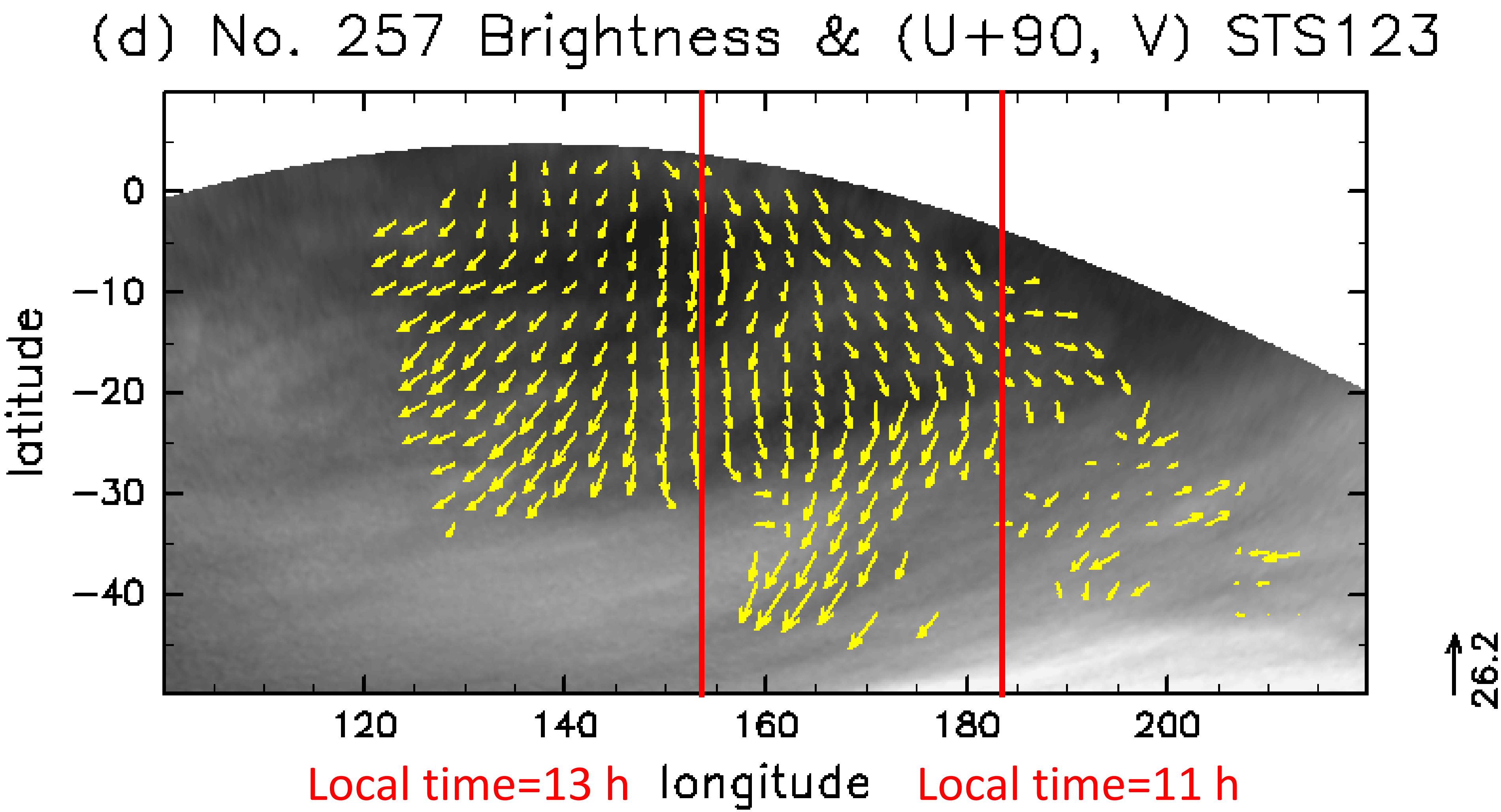

(b) No. 246 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
100
120
140
160
180
200
longitude
26.2
Local time=13 h
Local time=11 h

Orbit 250



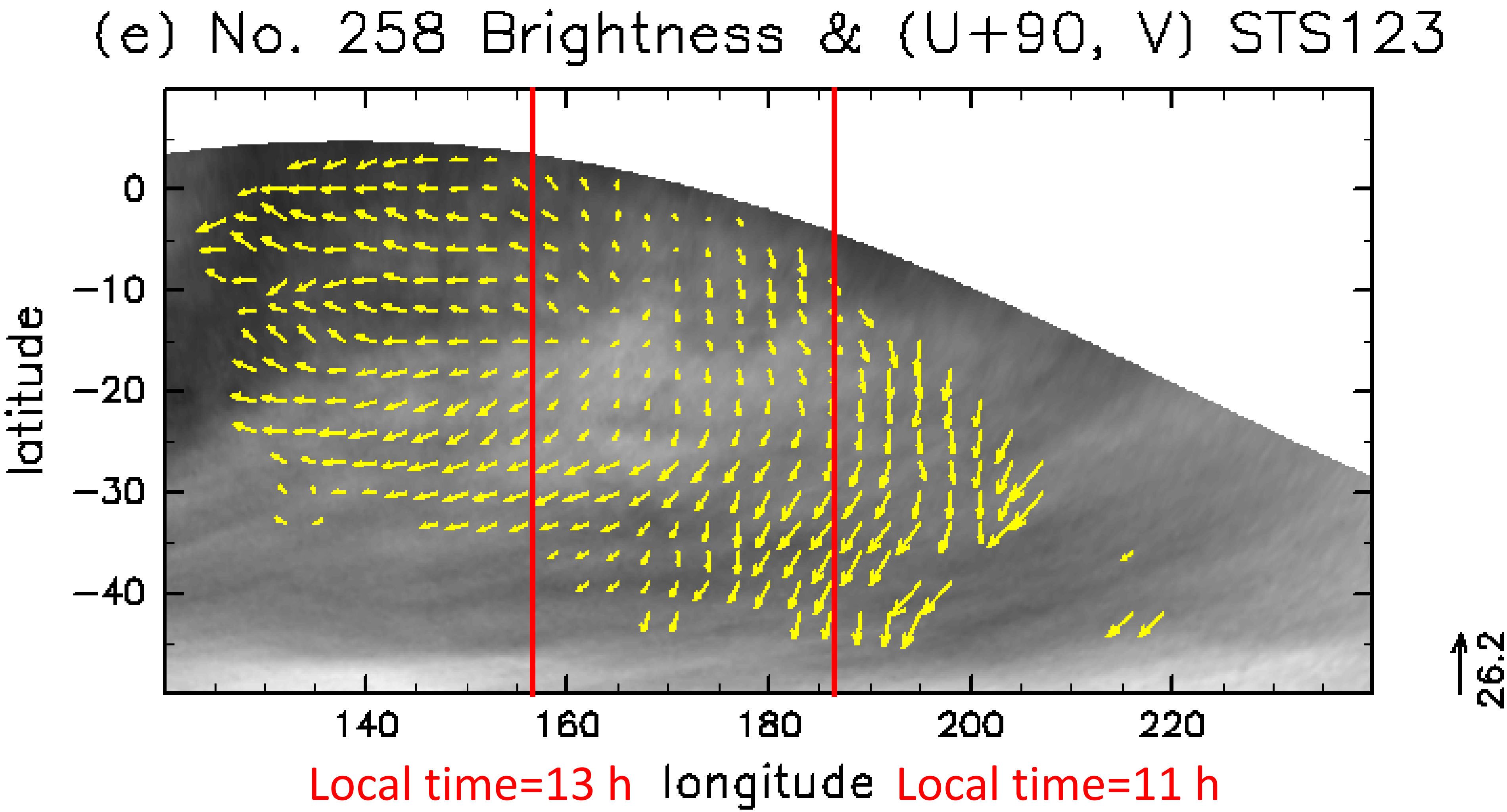
(c) No. 250 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
120
140
160
180
200
longitude
Local time=13 h
Local time=11 h
Cannot be justified manually.
Screened out if ε threshold is set to 10 m/s
26.2

Orbit 257



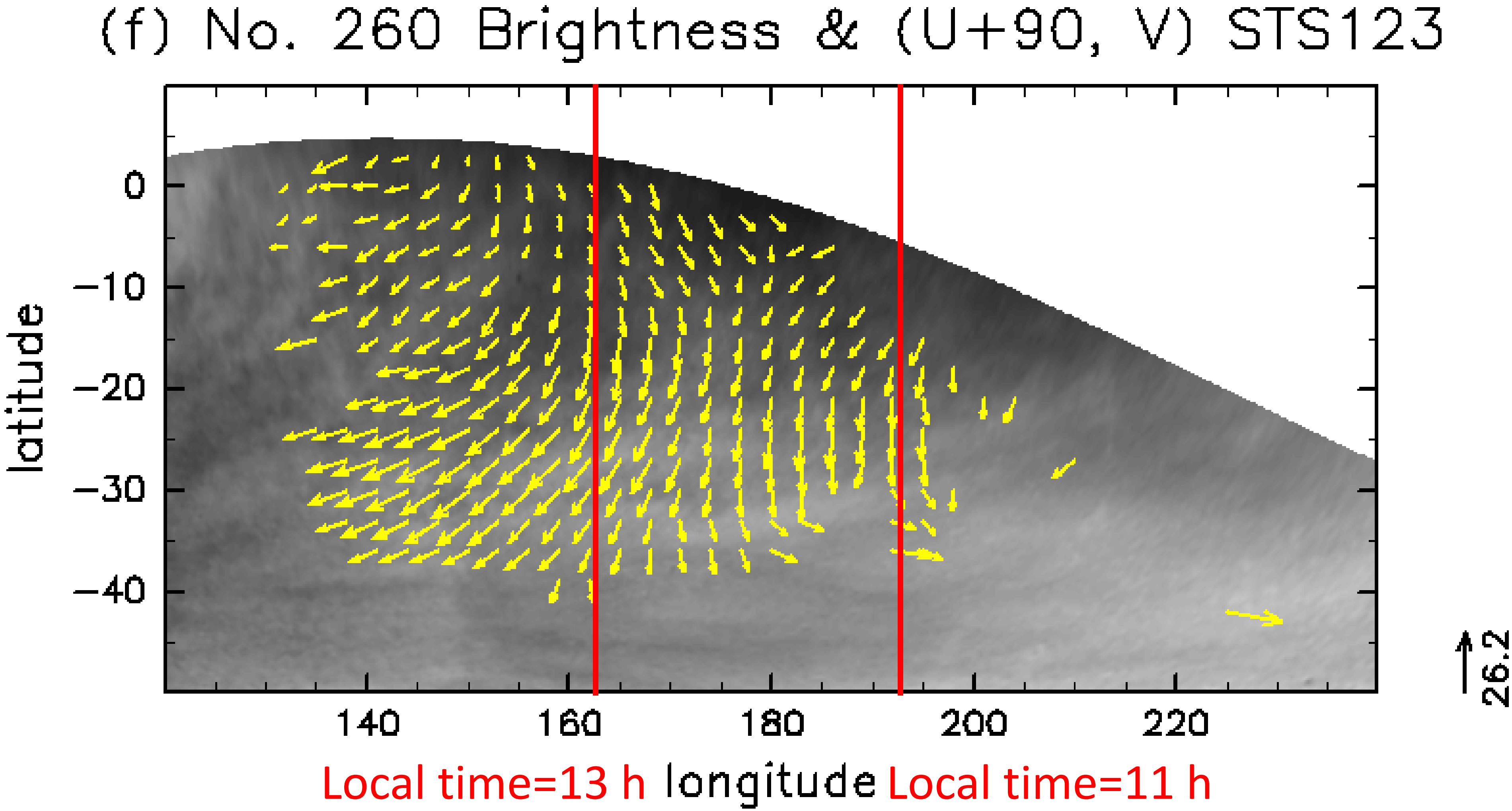
(d) No. 257 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
120
140
160
180
200
longitude
26.2
Local time=13 h
Local time=11 h

Orbit 258

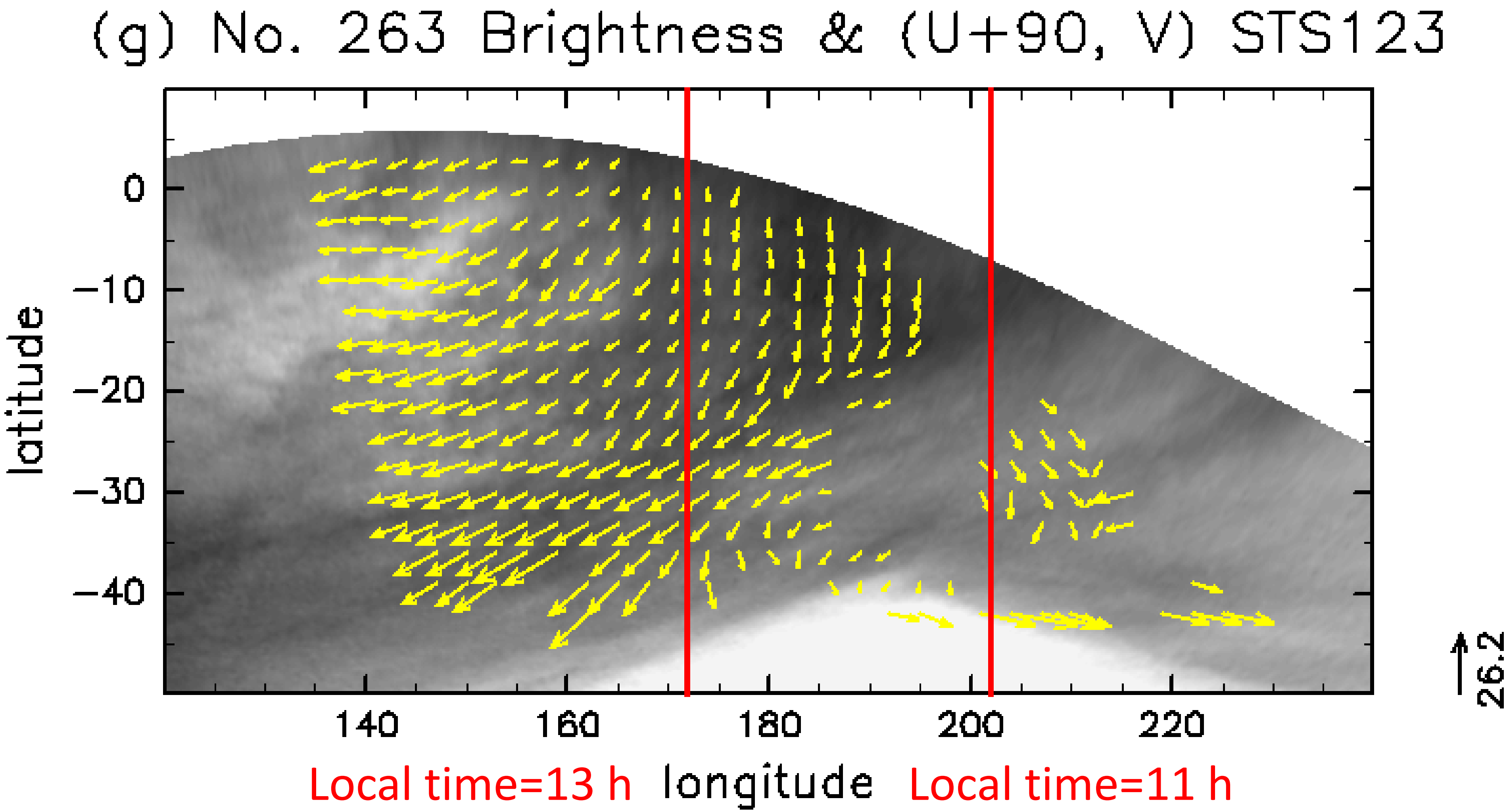


(e) No. 258 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
140
160
180
200
220
longitude
26.2
Local time=13 h
Local time=11 h

Orbit 260

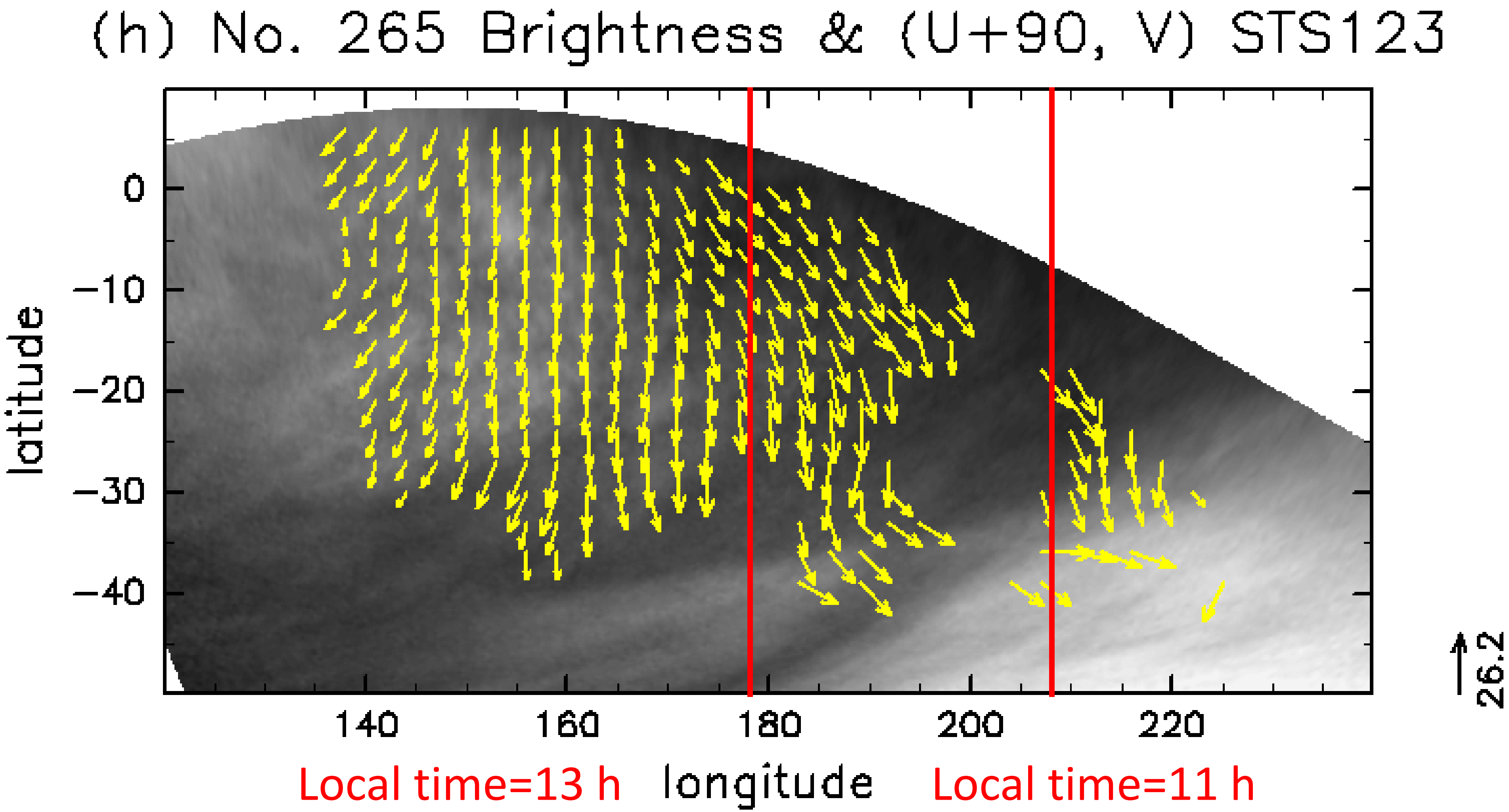

(f) No. 260 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
140
160
180
200
220
26.2
Local time=13 h
longitude
Local time=11 h

Orbit 263



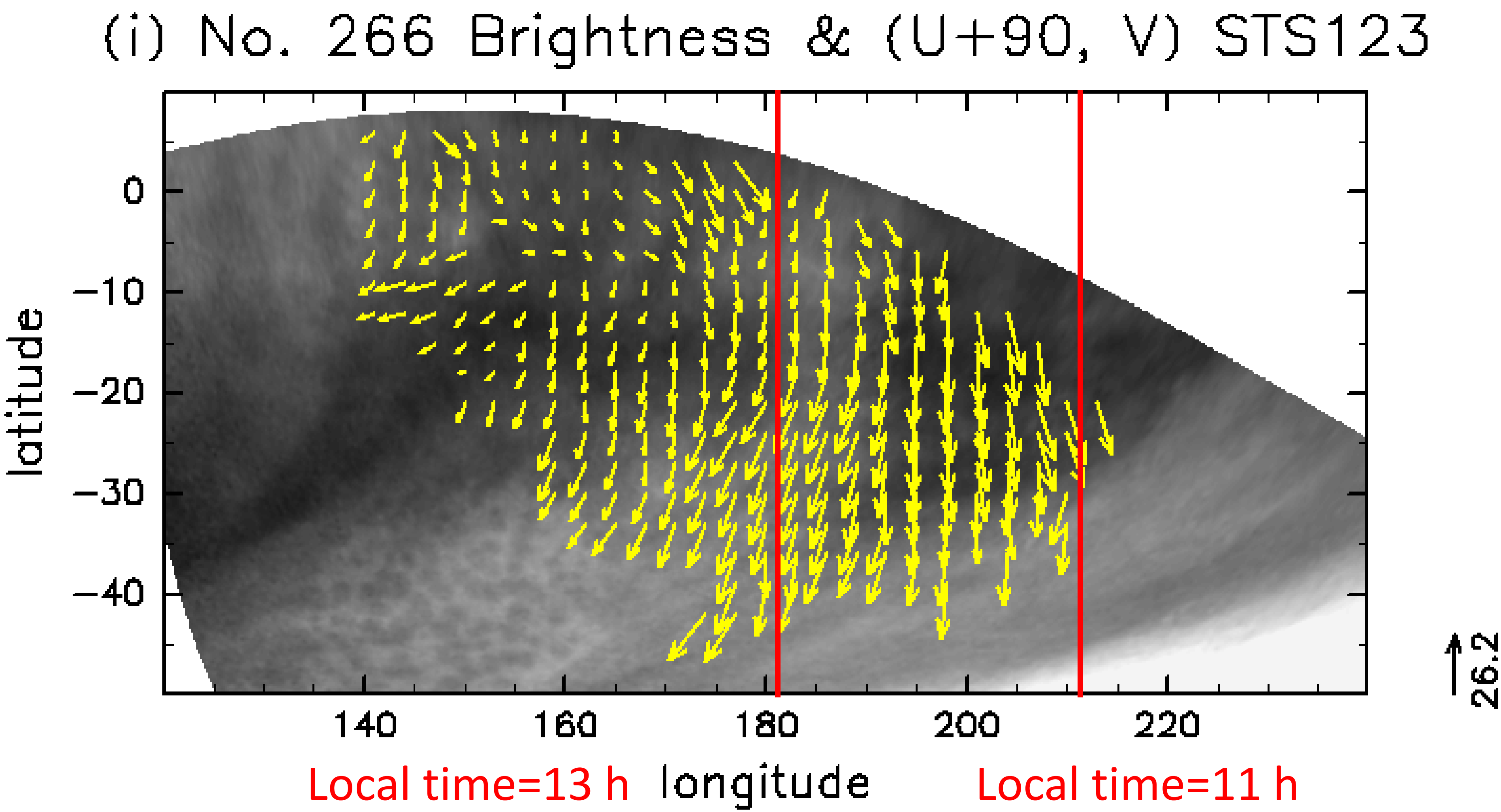
(g) No. 263 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
140
160
180
200
220
longitude
26.2
Local time=13 h
Local time=11 h

Orbit 265



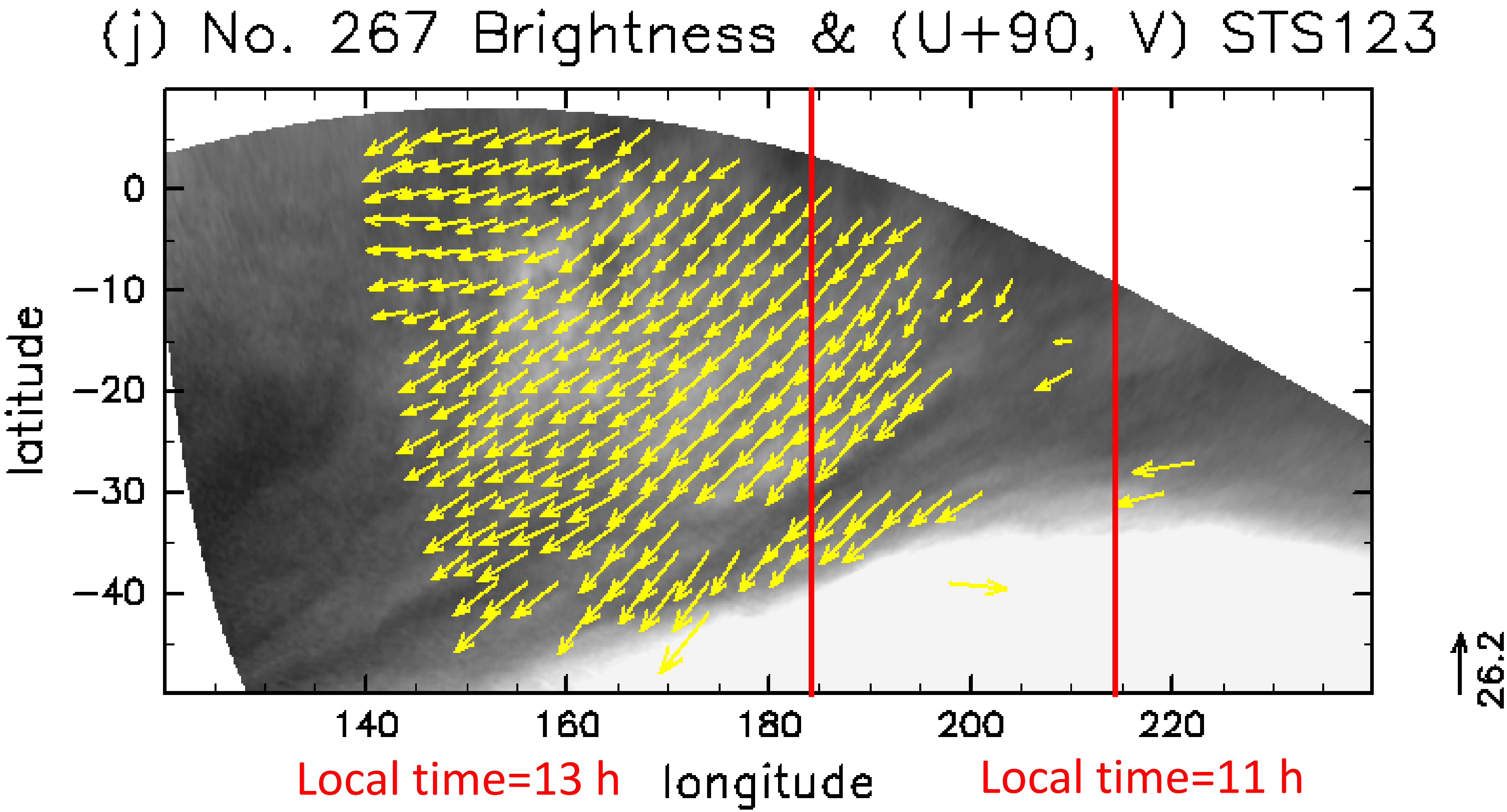
(h) No. 265 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
140
160
180
200
220
longitude
Local time=13 h
Local time=11 h
26.2

Orbit 266



(i) No. 266 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
140
160
180
200
220
longitude
26.2
Local time=13 h
Local time=11 h

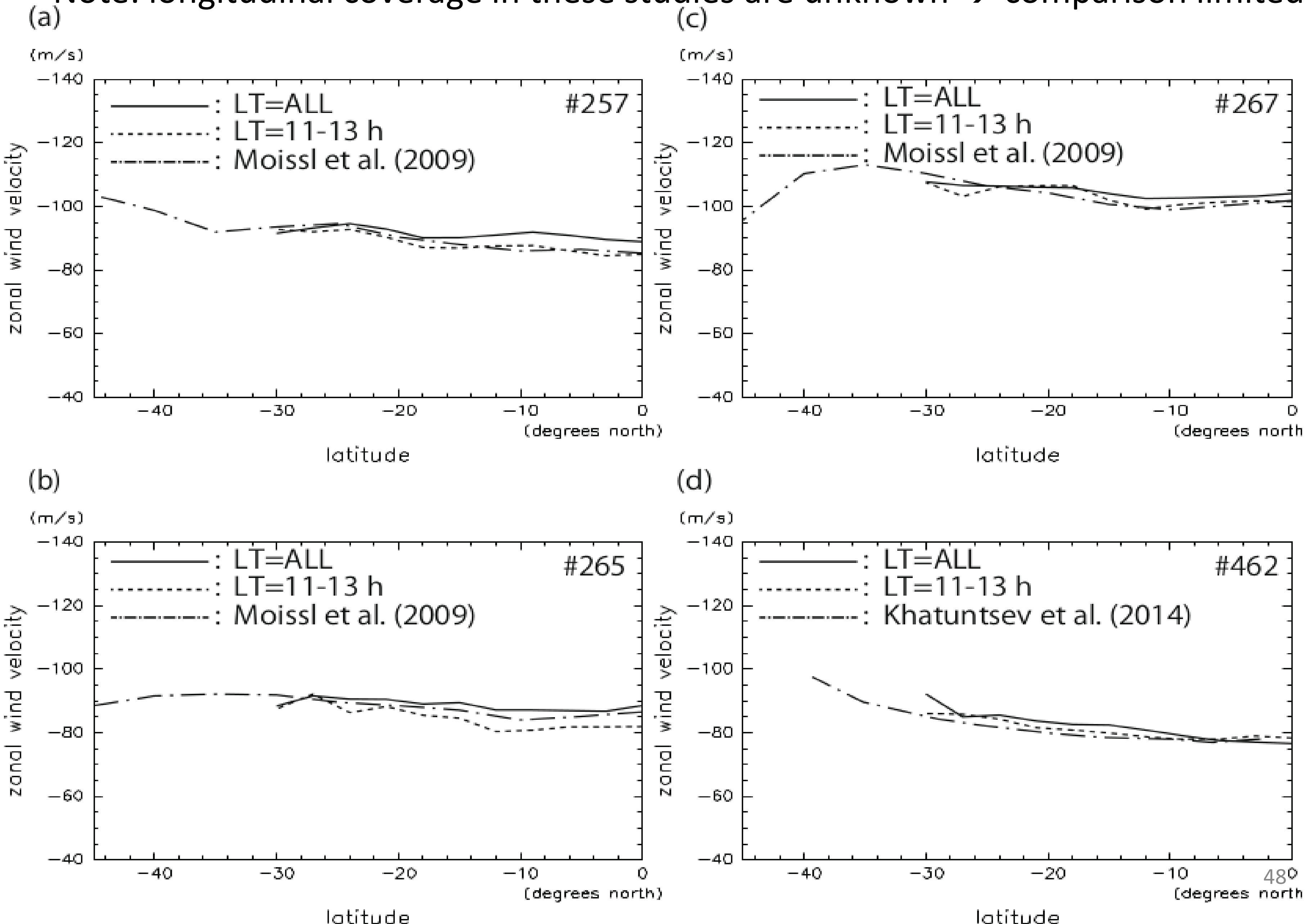
Orbit 267



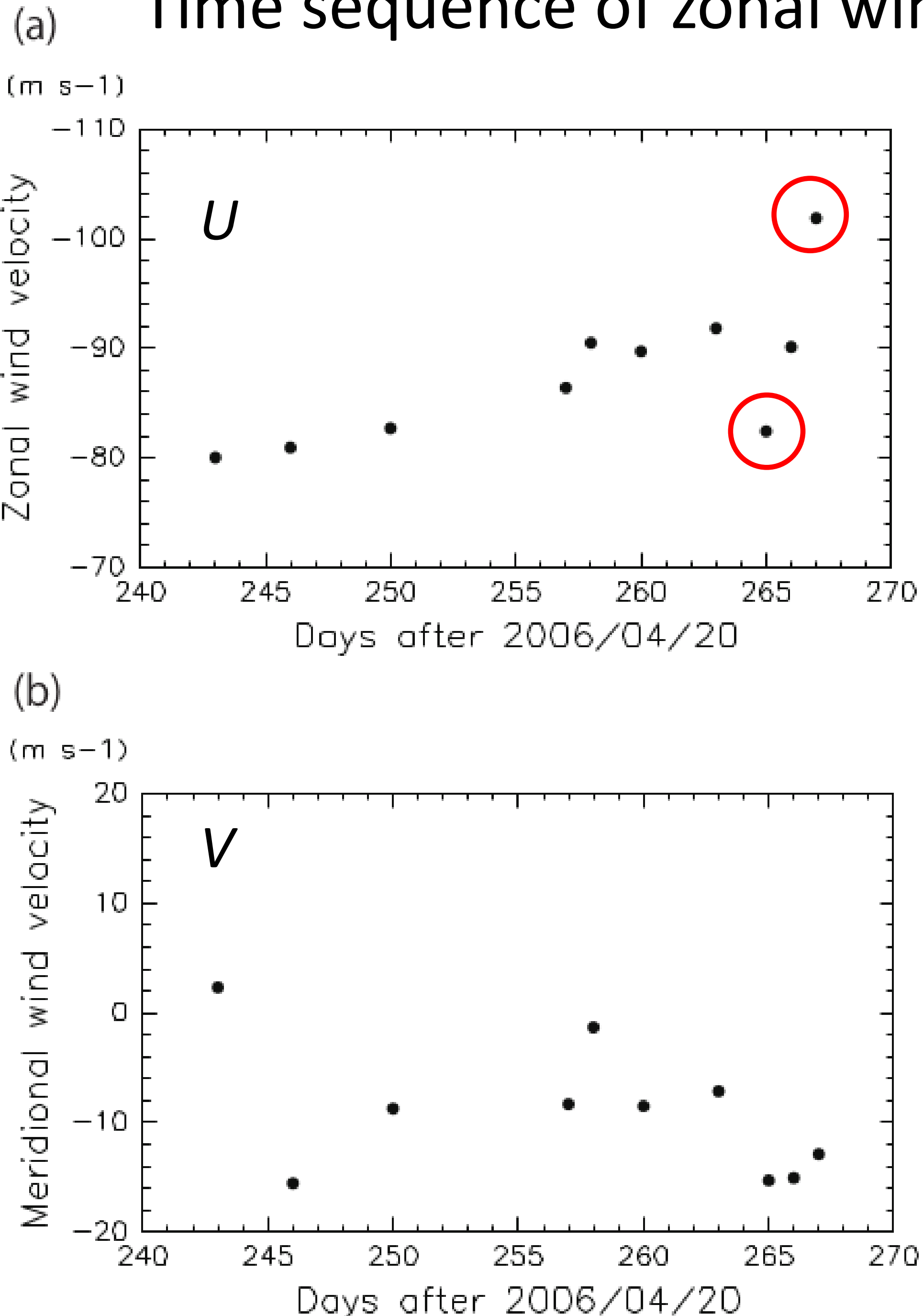
(j) No. 267 Brightness & (U+90, V) STS123
latitude
0
−10
−20
−30
−40
140
160
180
200
220
longitude
26.2
Local time=13 h
Local time=11 h

Comparison with earlier studies (mean zonal wind)

Note: longitudinal coverage in these studies are unknown → comparison limited

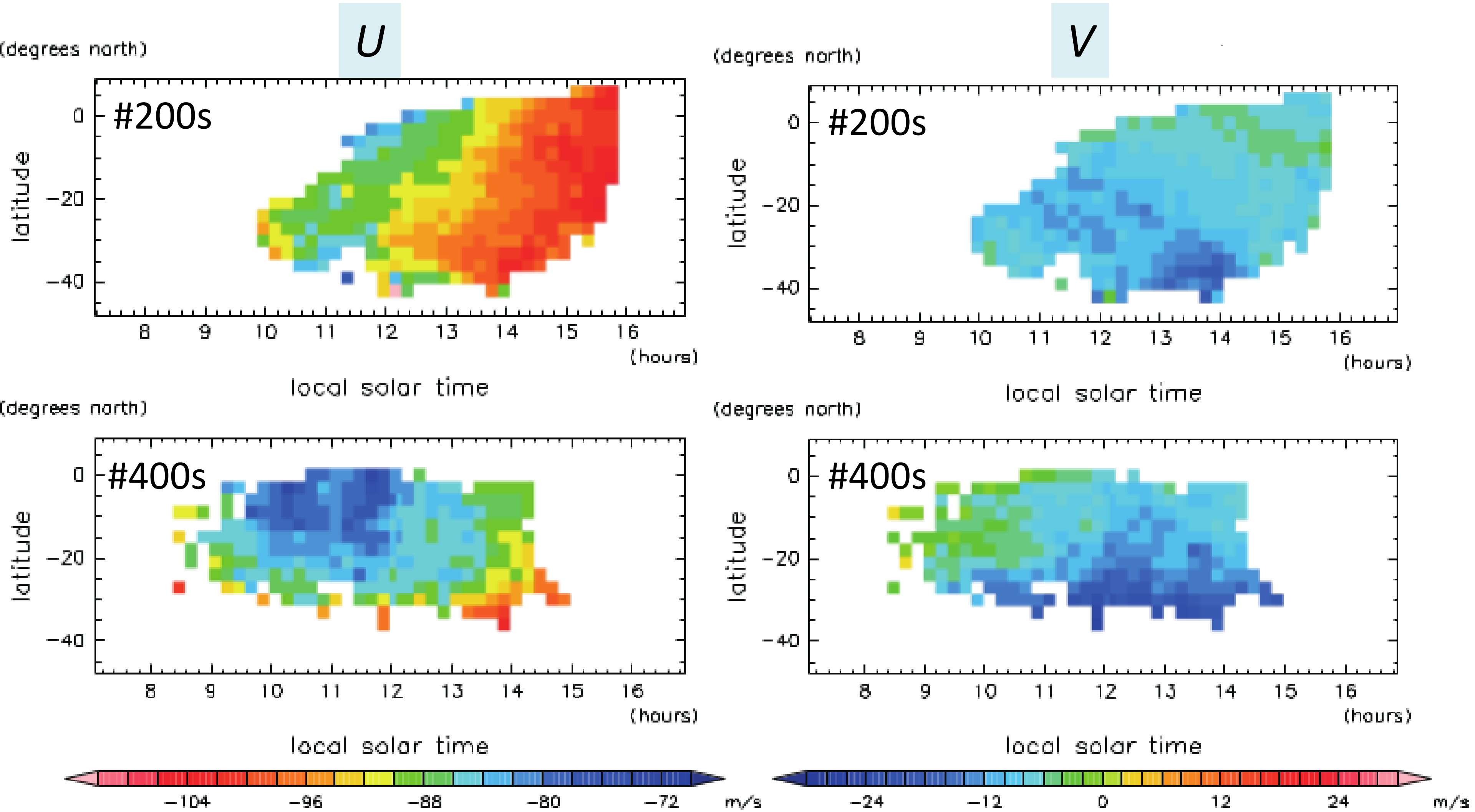


Time sequence of zonal winds (avg: 20S-EQ,LT11-13h)



- Exists day-by-day fluctuation
  - No obvious periodicity → unable to explain by a single planetary-scale wave
  - U, V fluctuations: similar magnitude
  - ○ : Confirms the rapid intensification pointed out by Moissl et al (2009)

Tidal components (time average as func of LT&lat)



- Mean zonal wind : Period 2 (200s) > Period 3 (400s)
- Roughly speaking, consistent with preceding studies

Summary, Problems, Future outlook

- Improved the digital cloud tracking by superposing CC surfaces (significantly better than preceding studies).
  - *It's always nice to use all good data than to throw a part away.*
- Developed methods to evaluate the accuracy of **each** CMV.
  - Mapped CC lower bound (ε) and error from 2-group comparison (χ). Can be used together for screening.
  - Results of VEX 200s → Typical value of χ is 2 m/s. Typical ε value is 8 m/s at low latitude & much greater at mid latitude.
  - Epoch making, **if** the error is as small as χ → enables one to study atmospheric disturbances (mom flux; waves; turbulence…)
    - Question: Is this really so? (manual impression is closer to ε)
- Improve the algorithm (Vary the template size and select according to ε and χ. Alternative peak selection as done by Koyama. Iteration, etc.)
- Further development of error estimation