Simulating the submesoscale rotating structures in the bora wind

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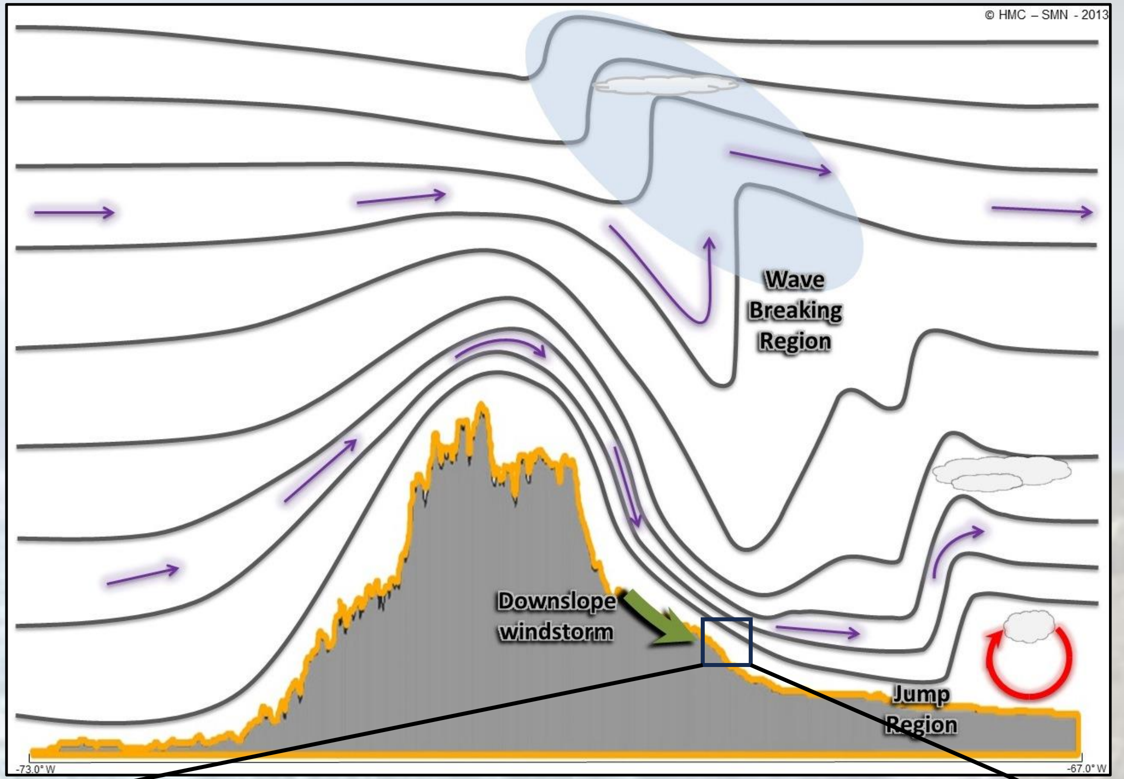
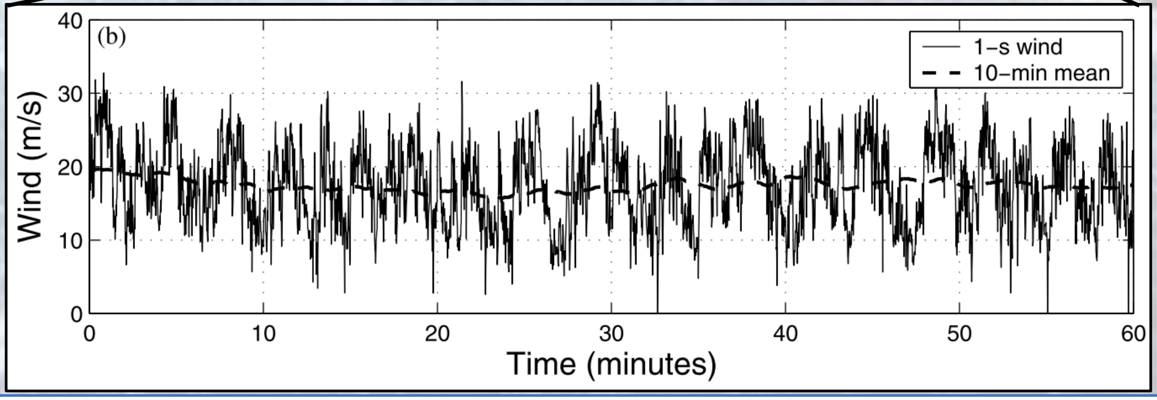
1. Introduction

- Bora – downslope windstorm along eastern coast of Adriatic

- **Pulsations** – quasi-periodic leeside motion
  - period 1 – 20 min
  - caused by secondary instability of the leeside flow

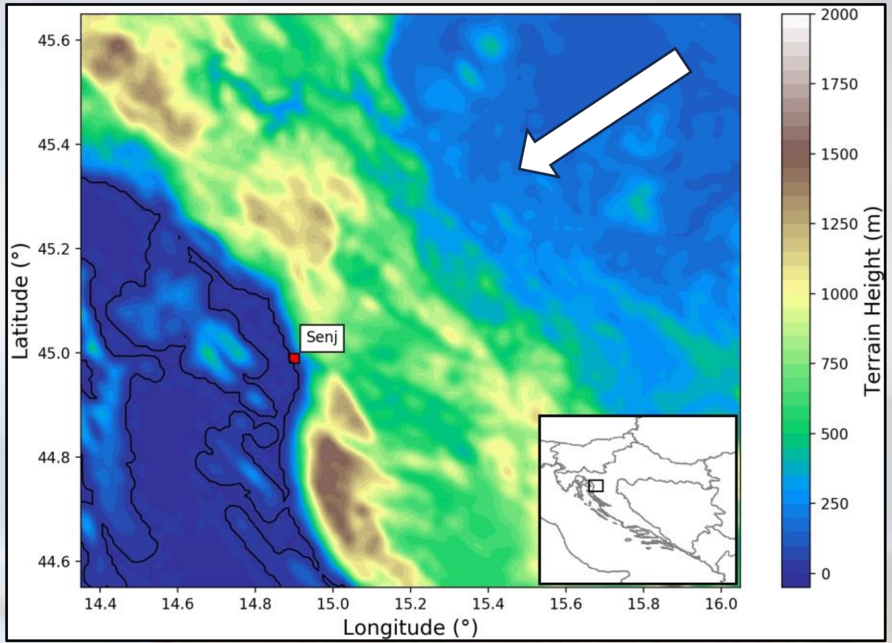
- Mechanisms causing pulsations
  - lateral instability of breaking mountain wave
  - KHI between low-level jet and stagnation zone
  - buoyancy waves





Figures: Zonda wind schematic (source: EUMeTrain)
Belušić et al. (2007)

- Golem et al. (2024) – studied bora events with pulsations near Senj, Croatia
- **Goal** – to examine characteristic motion of the horizontal velocity vector at the frequency of pulsations



- Rotational spectral analysis (RSA) method (e.g., Gonella 1972)

$$w = u + iv$$
$$F(\omega) = w_+(\omega)e^{i\omega t} + w_-(\omega)e^{-i\omega t}$$

- Rotational parameters
  - $S_\pm = |w_\pm^2|$ – PSD of rotational components
  - R_{ab} – ellipse semiaxis ratio – type and direction of motion ($\in [-1, 1]$; **Figure**)
  - α – orientation of axis of oscillation
  - C – stability parameter (coherence)

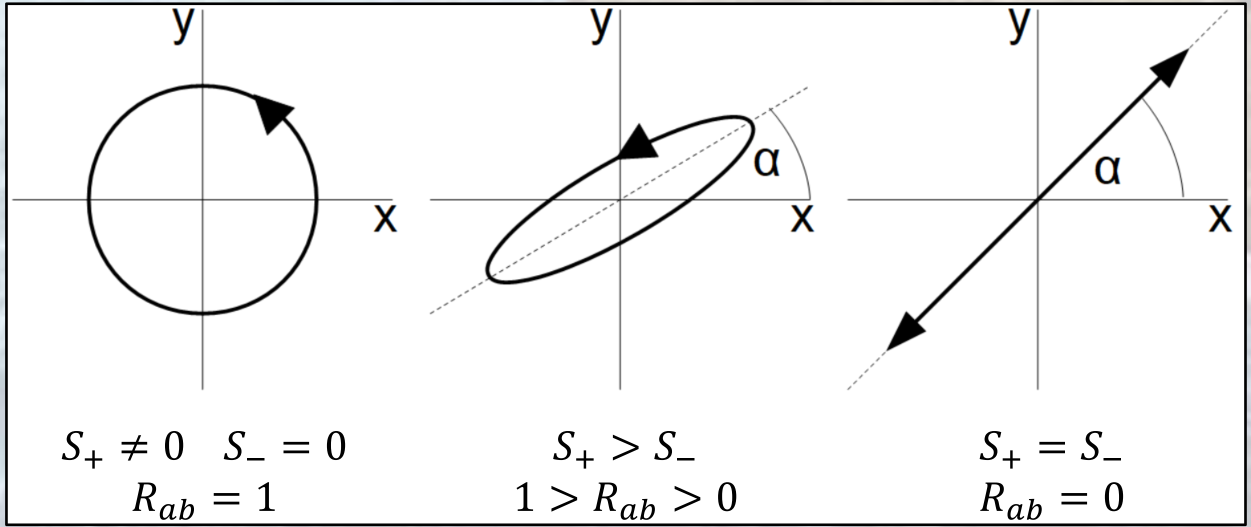
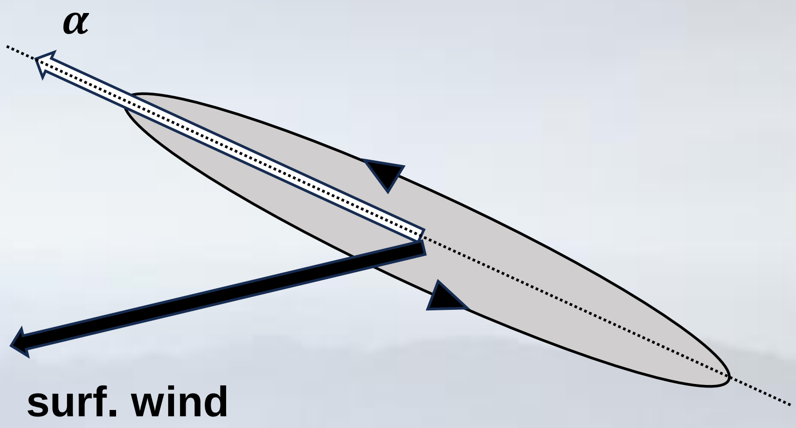


Figure: type of motion and characteristic rotational parameters. From left to right: (positive) circular, (positive) elliptical and rectilinear.

- Findings for ~ 40 bora events
  - high stability (C)
  - small R_{ab}, but **almost exclusively positive** (0.1–0.2)
  - α to the right of surface wind, aligned with shear vector at LLJ top
- Conclusion – pulsations likely associated with KHI



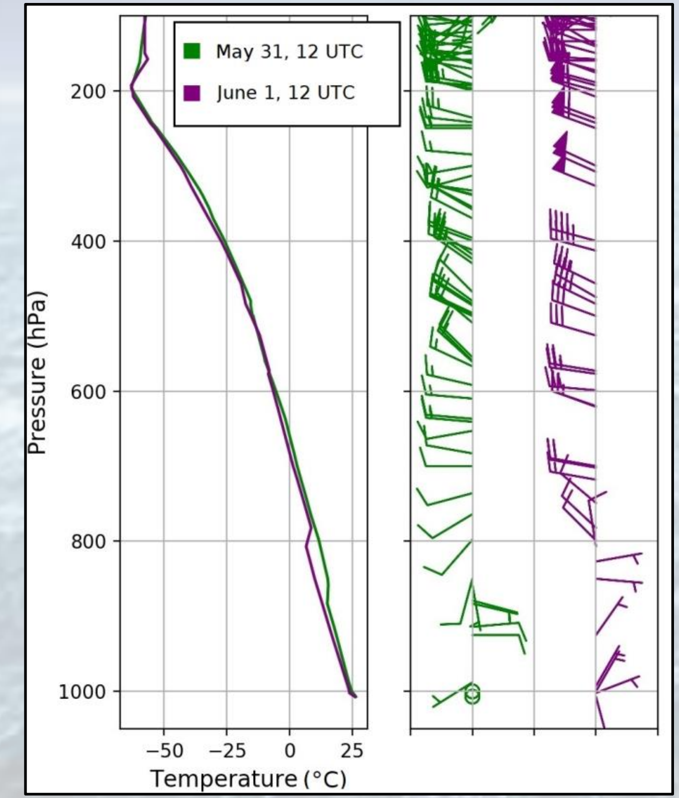
Goal of the present work:

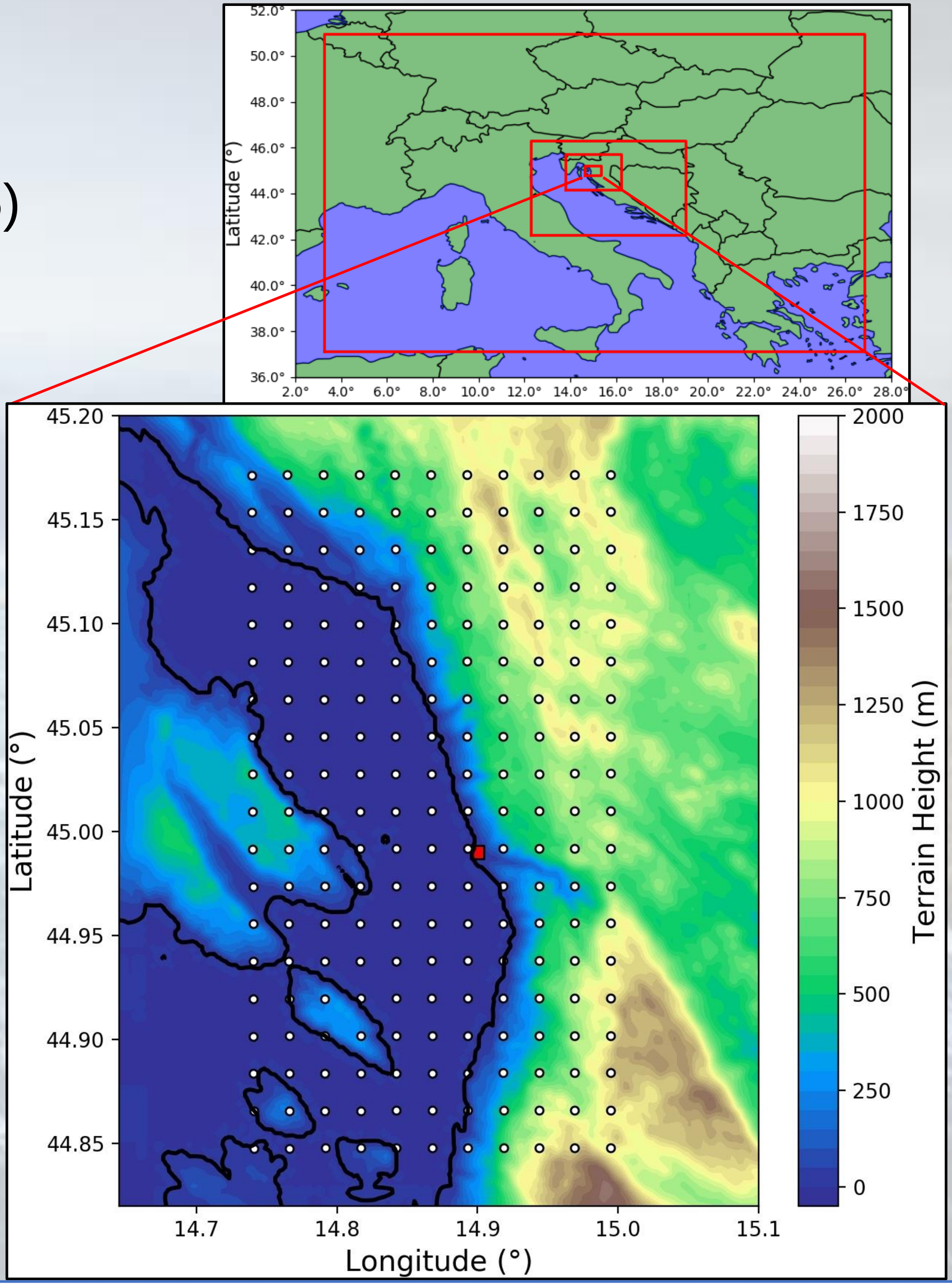
- Can numerical model (WRF) reproduce the characteristic motion (parameters)?
- Why the predominant positive rotation in horizontal plane?
  - For idealized KHI, $R_{ab} \approx 0$ is expected instead

2. Case study & simulation setup

- Case study – summer bora event (May 31 – June 2, 2005)
- Simulation – WRF-ARW 4.3.3
  - 4 domains (9, 3, 1, 0.2 km); 0.2 km – “LES” mode
  - dense vertical coordinate (Umek et al. 2021)

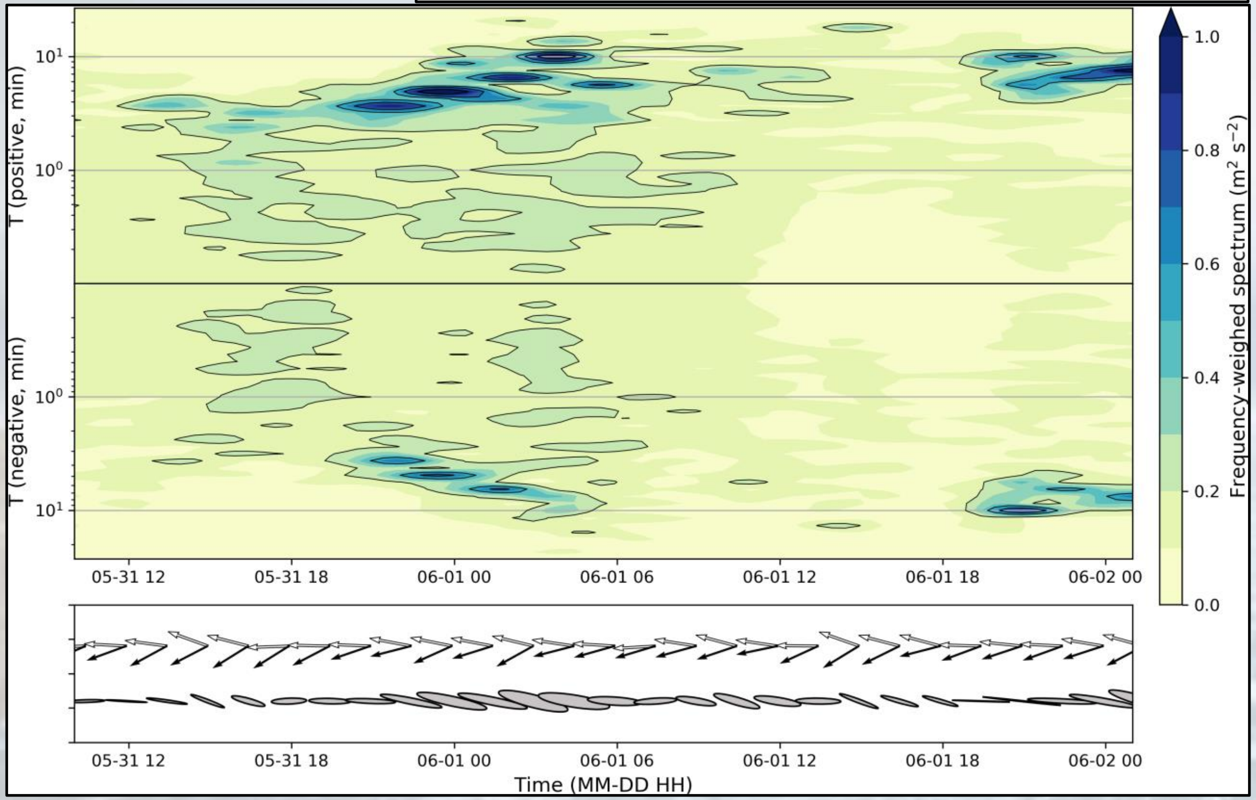
- Grid of points – extracted hor. velocity components (1 Hz, 10 m a.g.l.)
  - enables plotting of **spatial distributions of rotational parameters**
  - but first – **validation**



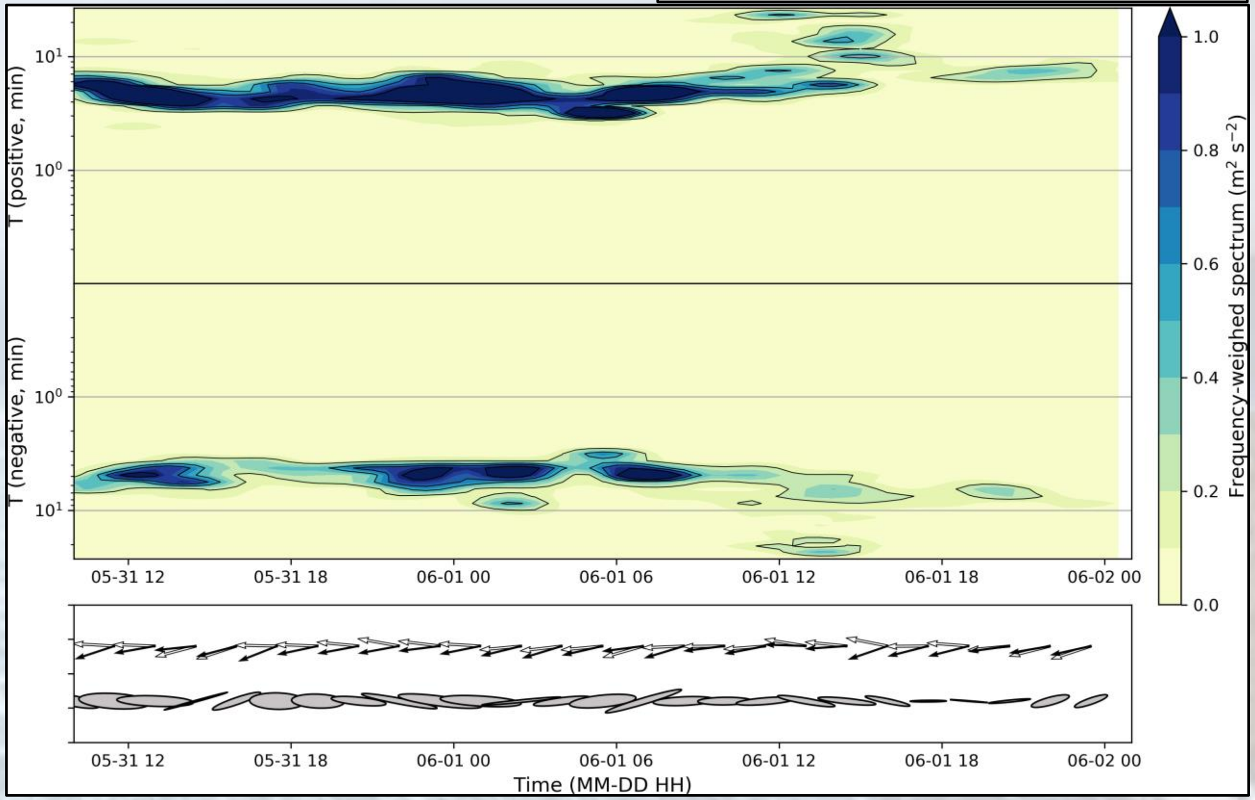


3. Results

Measurements (anemometer in Senj)



Simulation (nearest point)

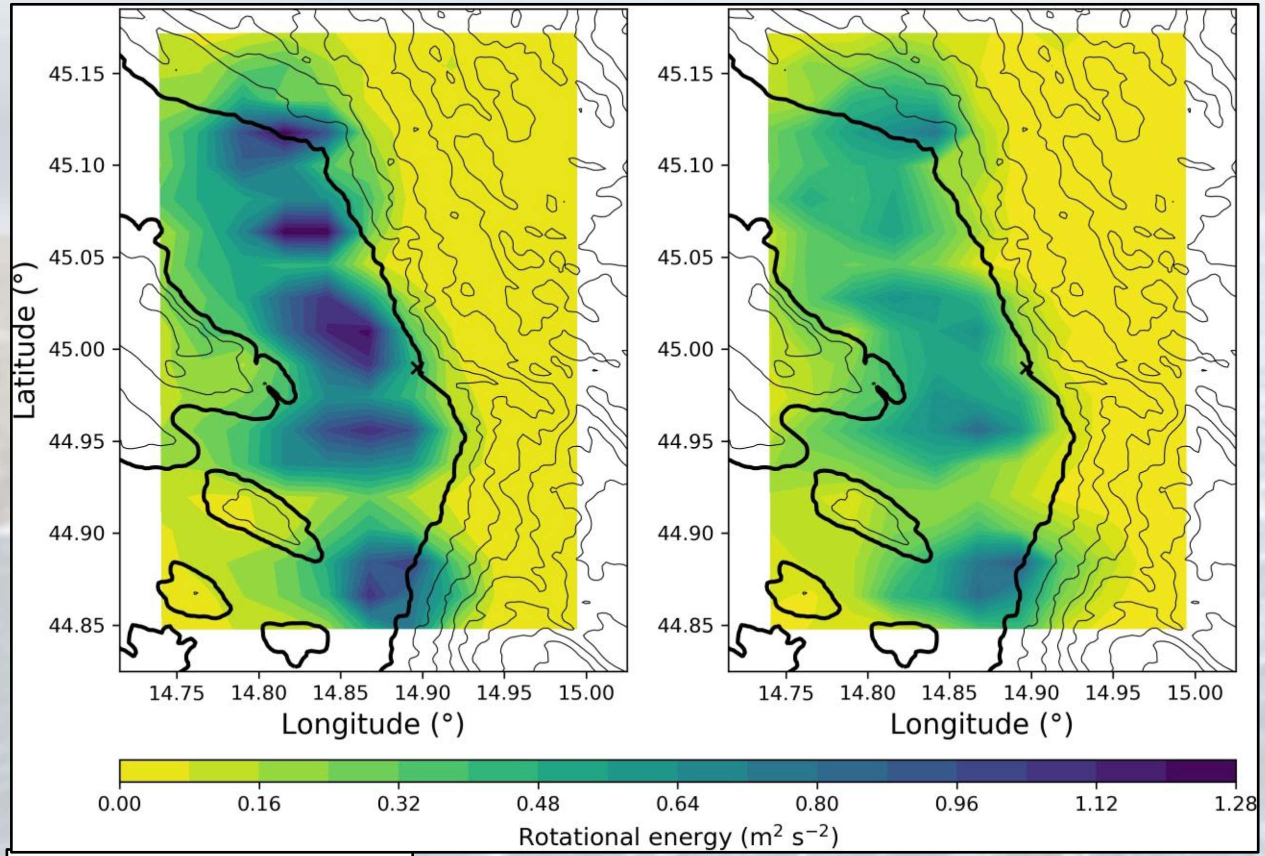


- Period reproduced well (3 – 11 min)
- Positive rotating component larger than negative (R_{ab} > 0)
- Axis of oscillation (α;) to the right of near-ground wind ( )
- Pulsations caused by KHI (Additional slides)

Structure and orientation of the motion reproduced

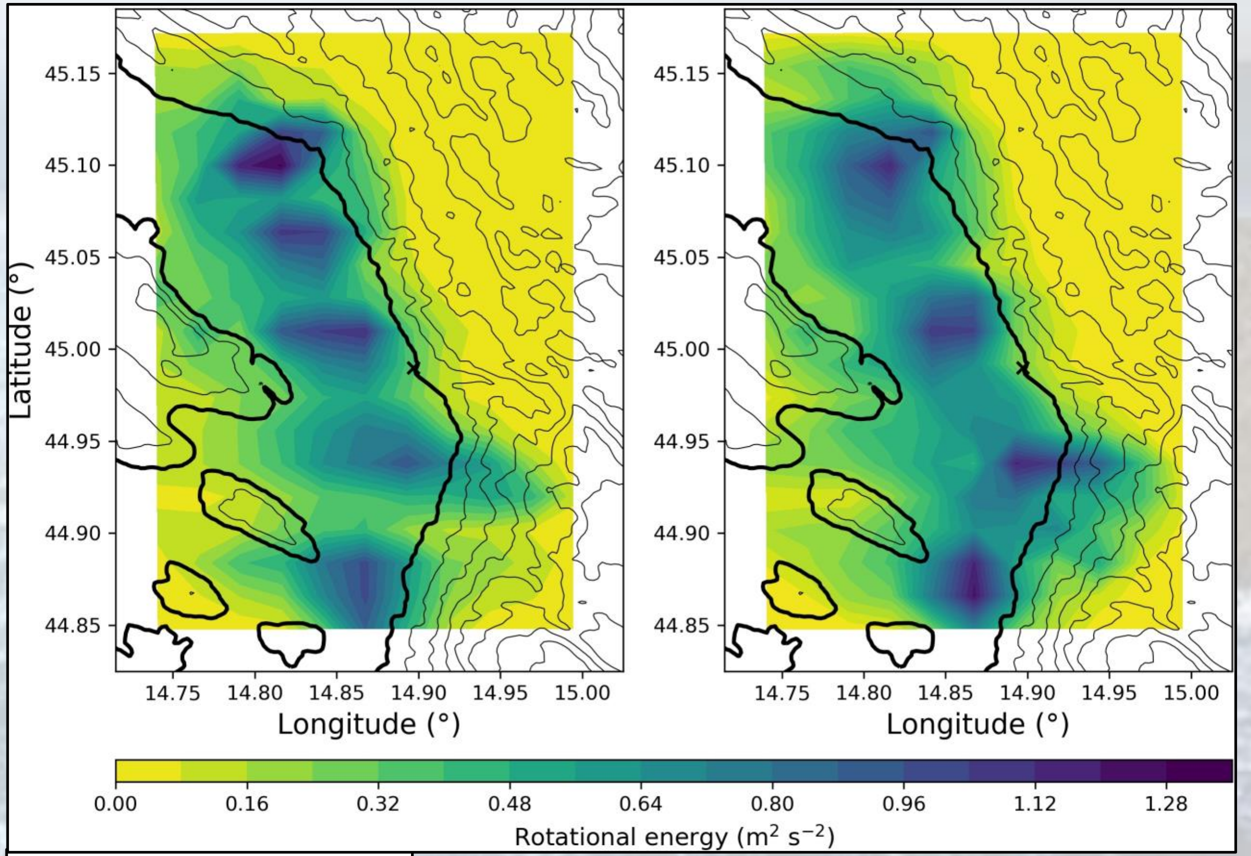
- Pulsation amplitude (average spectral peak between 3 and 11 min)
  - Simulation average – positive component > negative over almost entire domain
  - However, **their ratio is time-dependent → why?**

Positive **Negative**



May 31, 11 UTC $R_{ab} > 0$

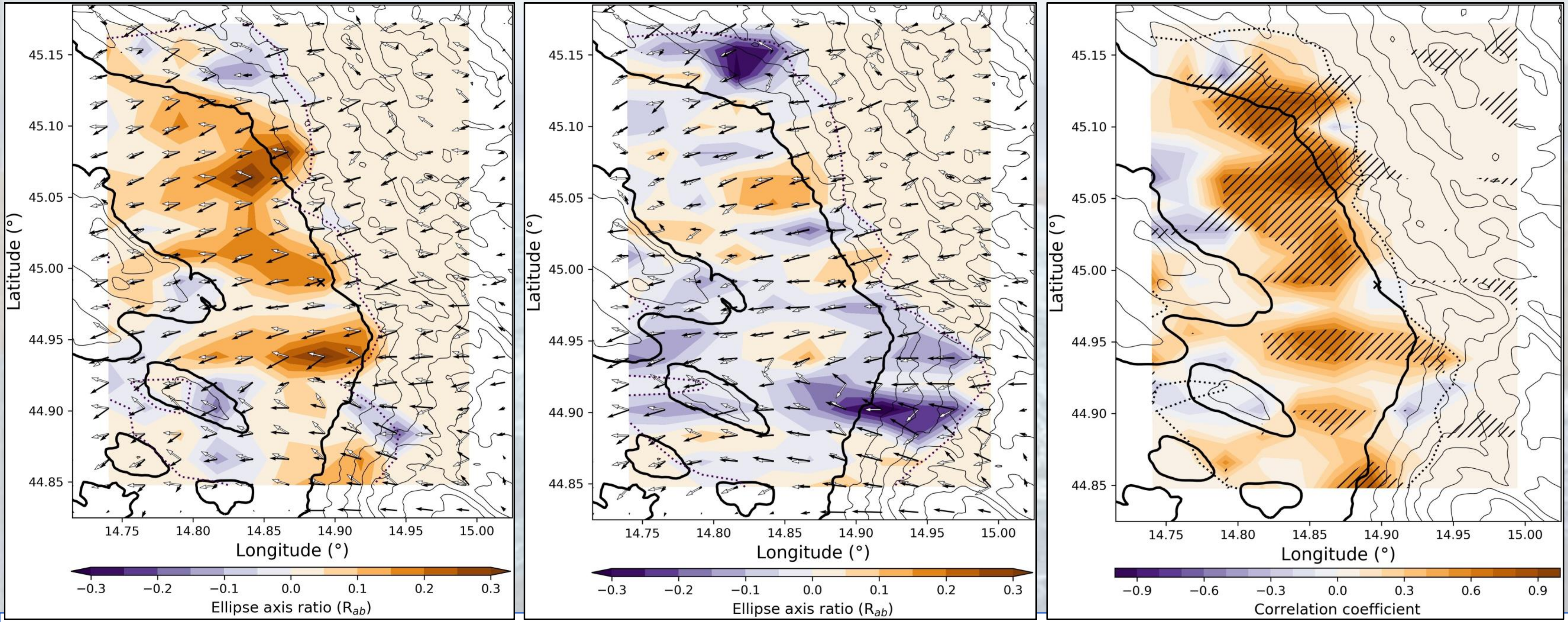
Positive **Negative**

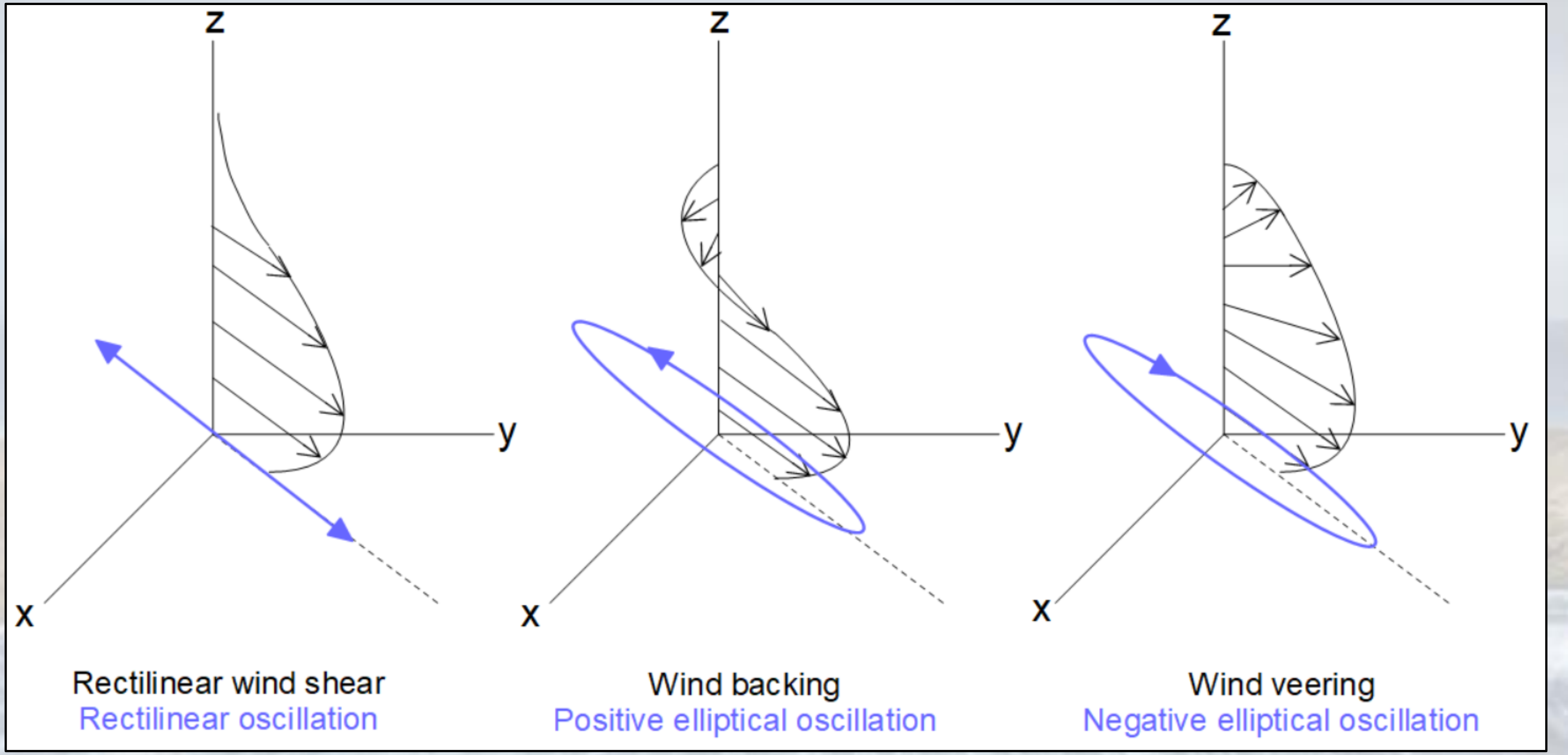


June 1, 07 UTC $R_{ab} \approx 0$

- Angle ϕ between surface wind ( ) and axis of oscillation (α;)
  - ϕ is **large** → $|R_{ab}|$ > 0 (May 31, 11 UTC case, R_{ab} > 0)
  - ϕ is **small** (α and surface wind parallel) → R_{ab} ≈ 0 (June 1, 07 UTC case)

R_{ab} on May 31, 11 UTC | **R_{ab} on June 1, 07 UTC** | **Correlation (ϕ, R_{ab})** Hatches – significant (p < 0.05)



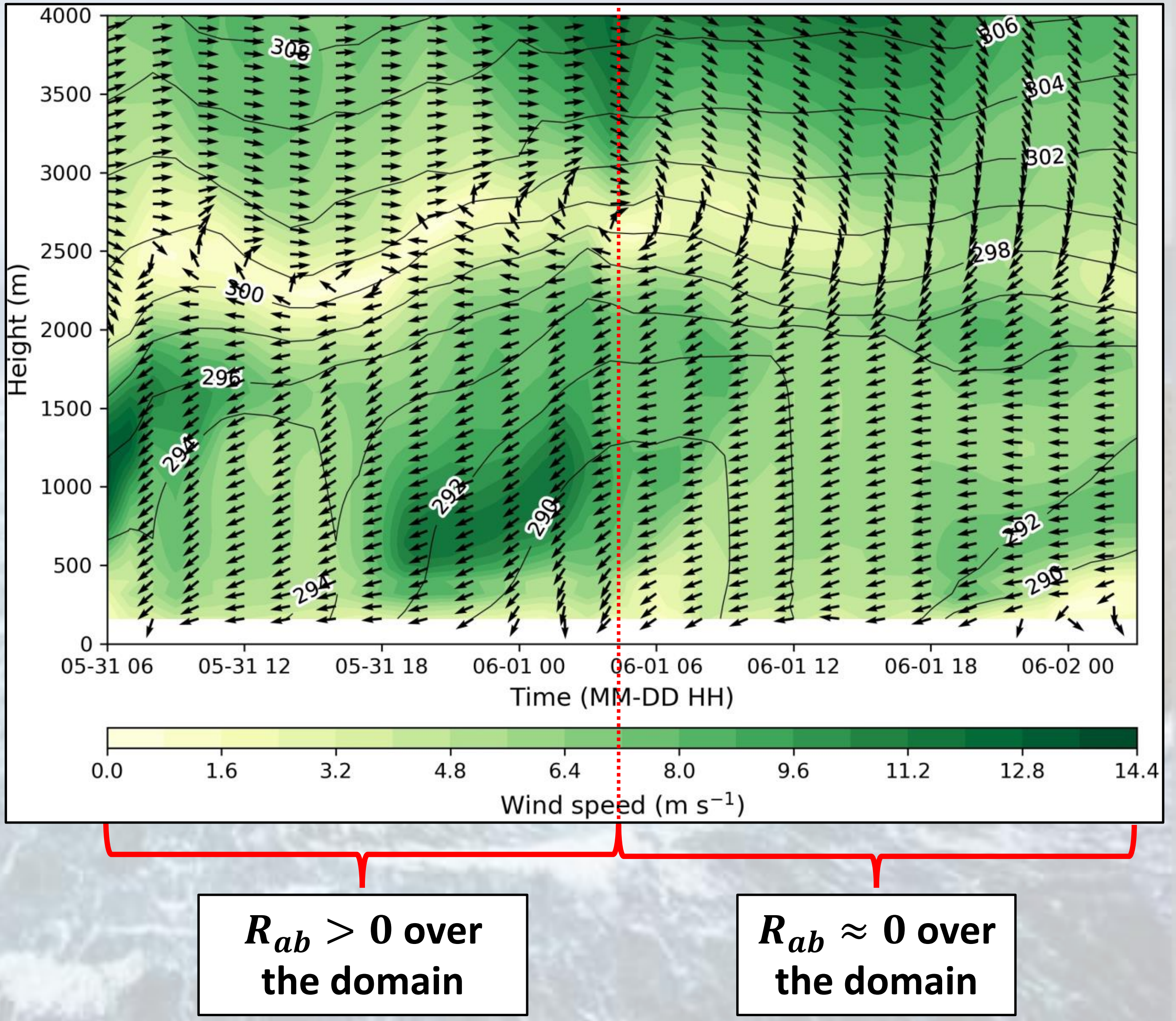


- KHI – α lies along the shear vector at the leeside low-level jet (LLJ) top
- **Conclusion: directional shear determines the predominant rotation direction**
  - Rectilinear shear (no direction change) → no predominant rotation direction
  - Directional shear → predominant rotation direction (sign opposite to direction of shear)

4. Future work

- Change in R_{ab} coincident with change in upstream wind profile
- Does upstream (synoptic) directional shear determine directional shear in LLJ, and thus rot. parameters (like R_{ab})?

⟹ **Idealized simulations**



5. References

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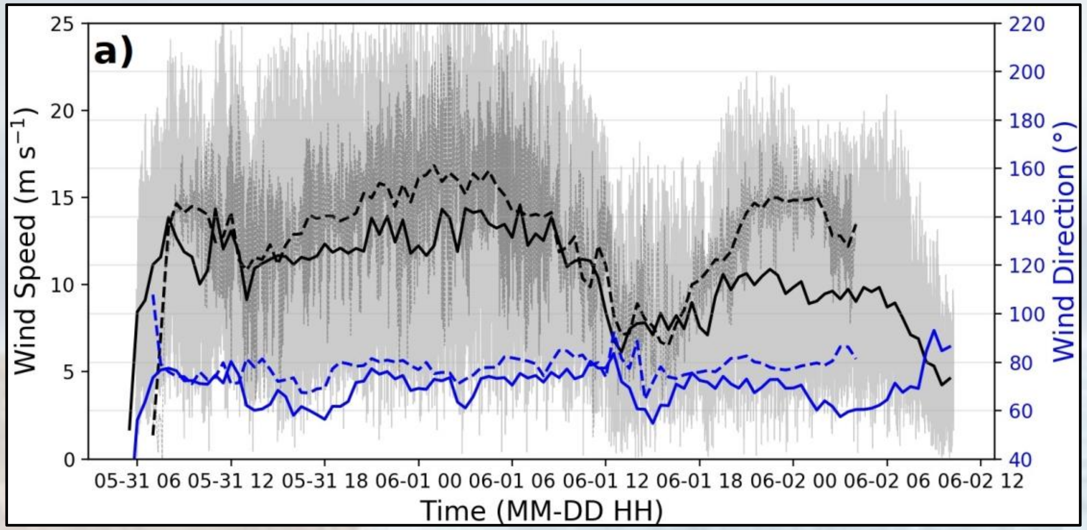
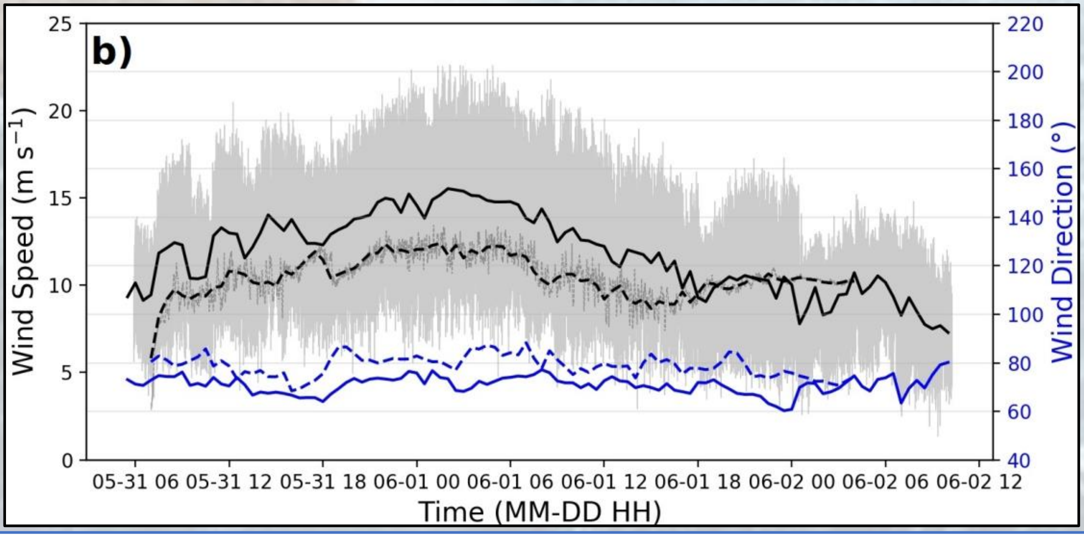
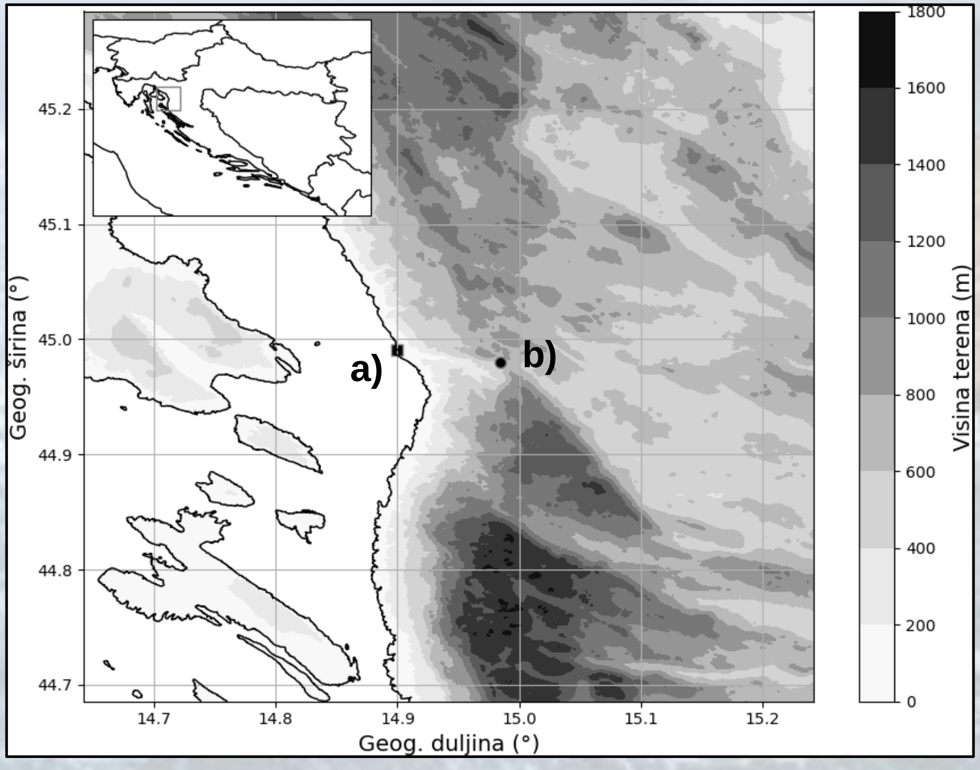
6. Additional slides

- Mean wind speed/direction validation



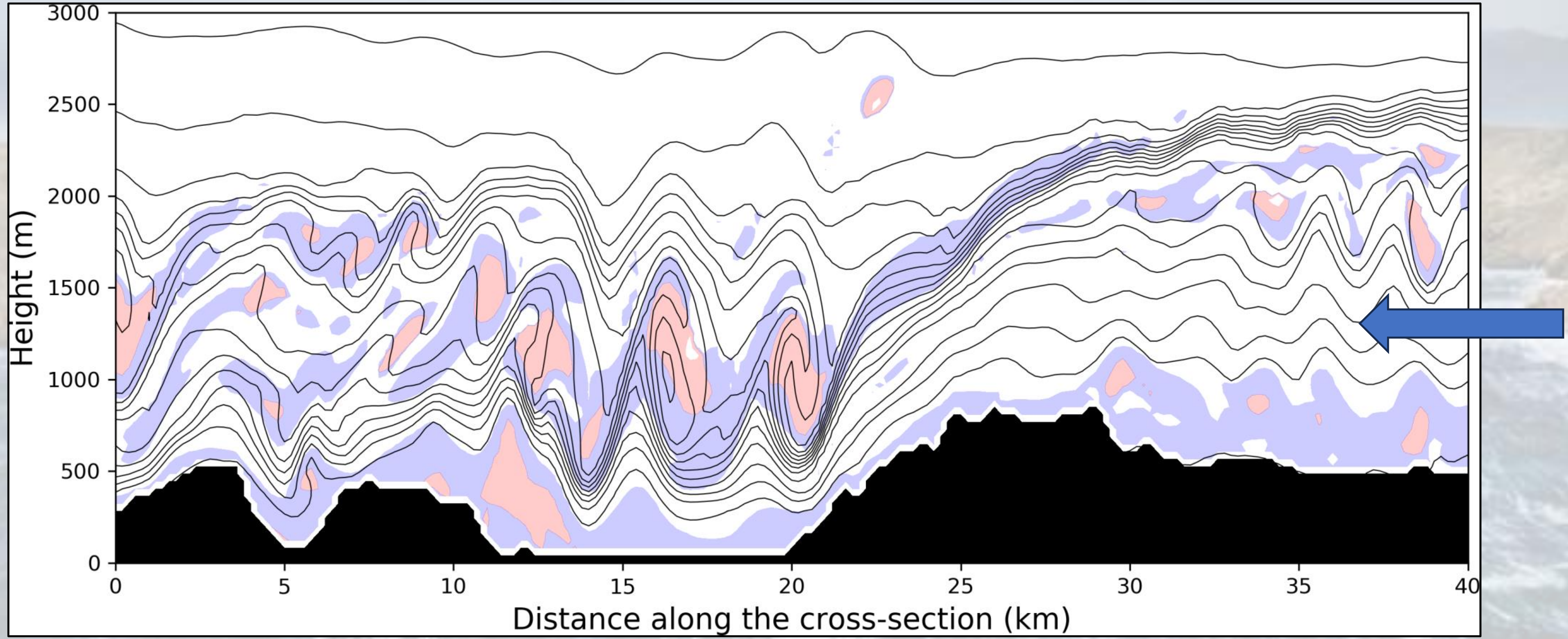


a) Senj (44.90°N, 14.90°E)
b) Vratnik (44.98°N, 14.98°E)



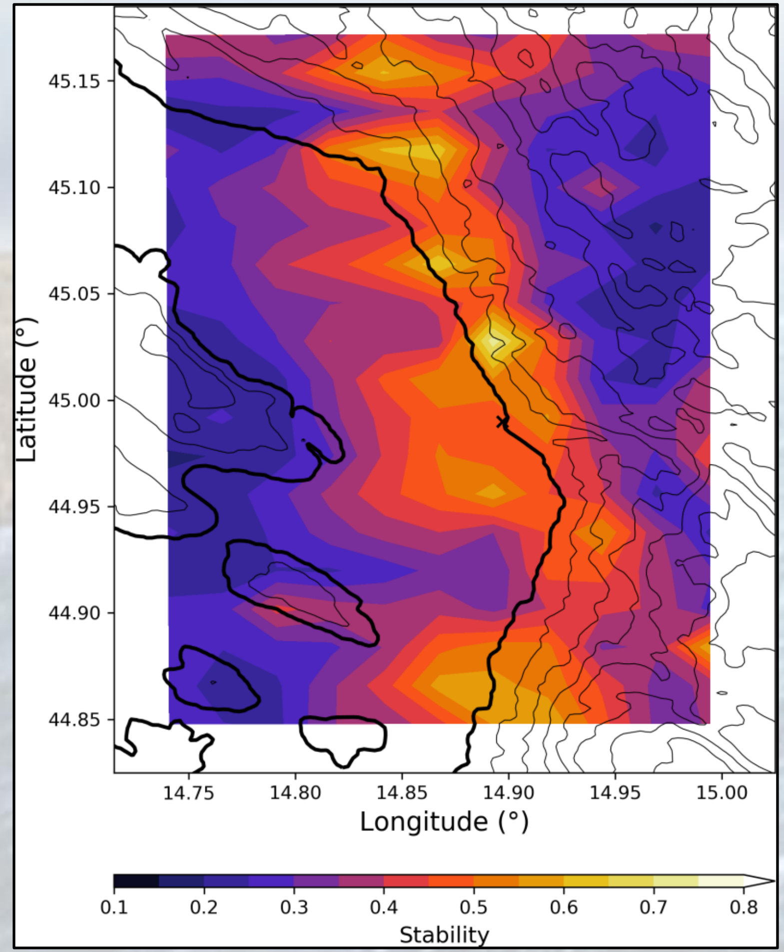
6. Additional slides

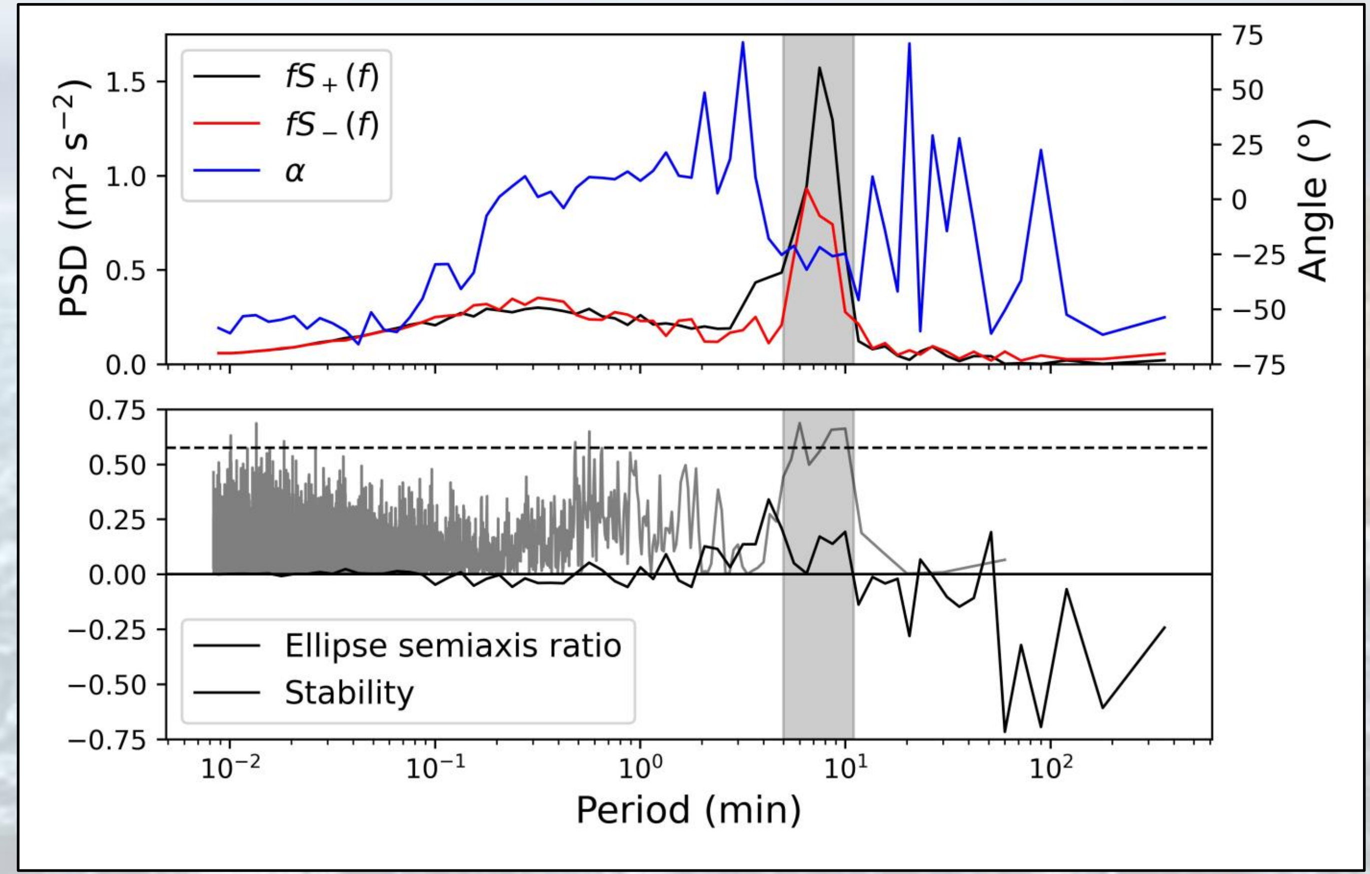
- Cross-section of KH billows
  - Blue – $0 < Ri_g < 0.25$
  - Pink – $Ri_g < 0$



6. Additional slides

- Stability parameter (C) plot
- Example of rotational spectra and parameters for a 6 h interval





6. Additional slides

- Location of the upstream cross-section