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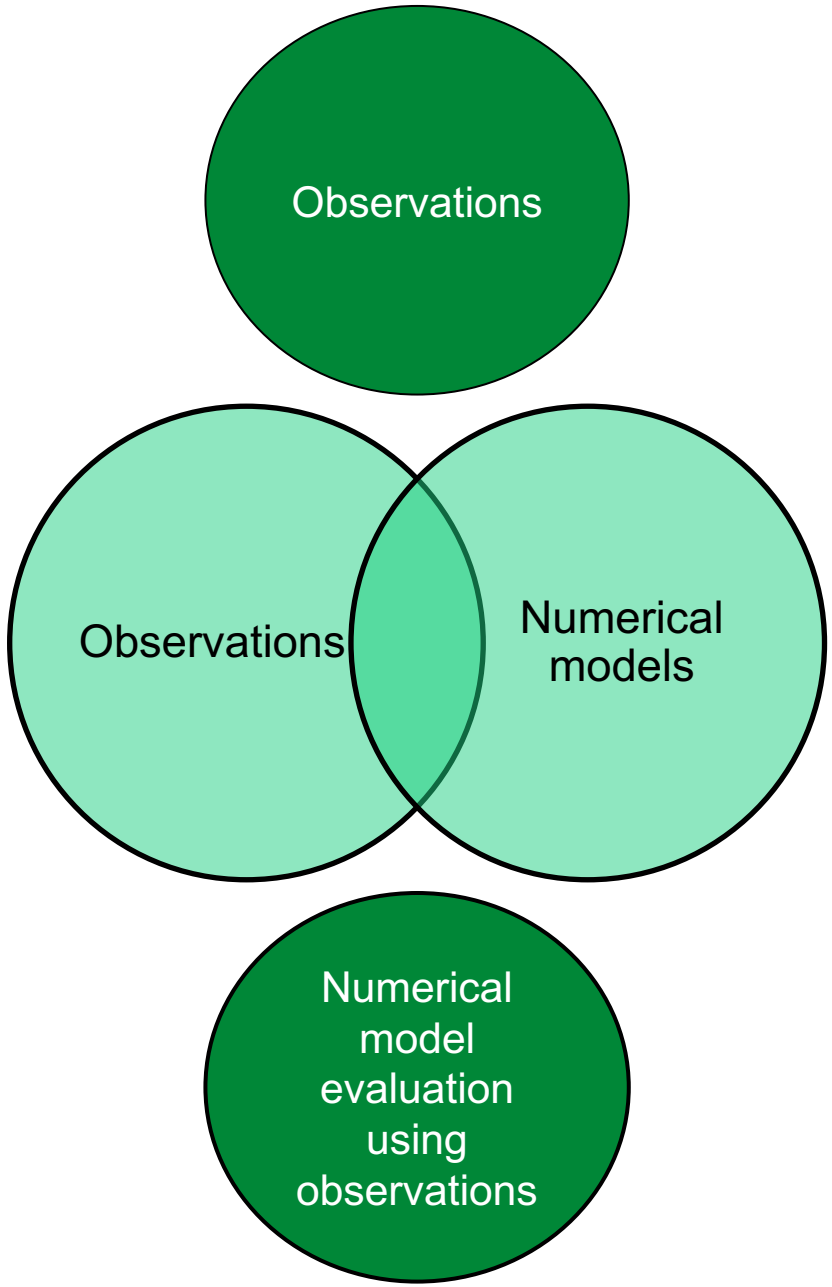
Pedro Alvim de Azevedo Santos

April 28th 2021

# Untangling atmospheric flows through the lenses of wind lidars

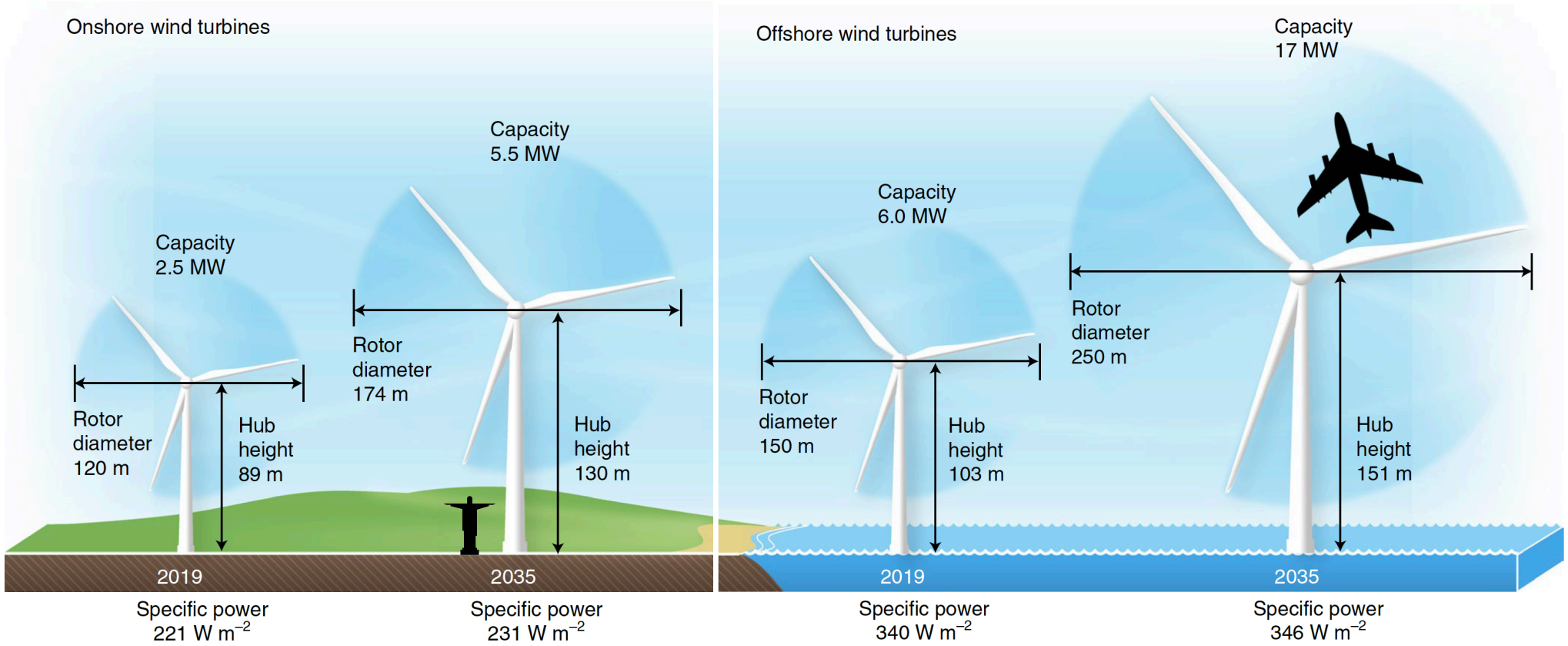
# Agenda

- Motivation
- Background
- Hypotheses
- Alaiz measurement campaign
- An atmospheric hydraulic jump at Alaiz
- *K*-theory departure in the boundary layer
- Conclusions



# Motivation - Wind energy scaling up

- Wind provided 4.7% of world's electricity in 2018. By 2050 is expected that wind energy will represent 31% of total electricity production (DNV, 2020).
- Onshore wind >> complex terrain, offshore wind >> tall wind profiles




Source: Wiser et al., *Nature Energy* (2021)

# Motivation – Tall wind profile and large-scale effects

- Modern wind turbines occupy a large portion of the atmospheric boundary layer (ABL)

- Grand challenges of Wind Energy

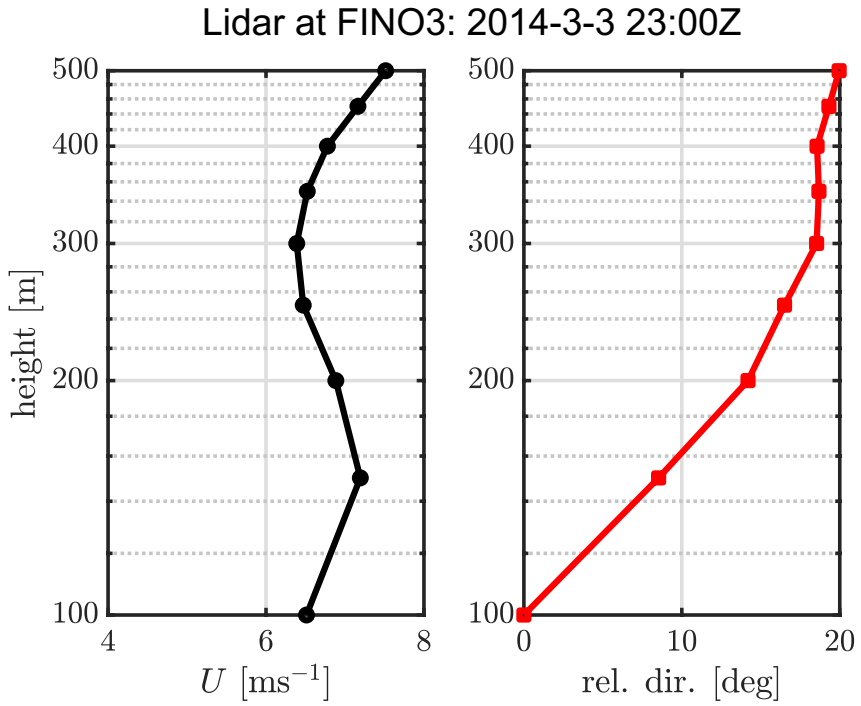
  “mastering the physics of [wind] resource across scales” (Veers et al., 2019).

- This thesis will focus on:

Onshore | Offshore

Tall wind profile behavior

Large-scale atmospheric phenomena due to terrain interaction



# Motivation – Tall wind profile and large-scale effects

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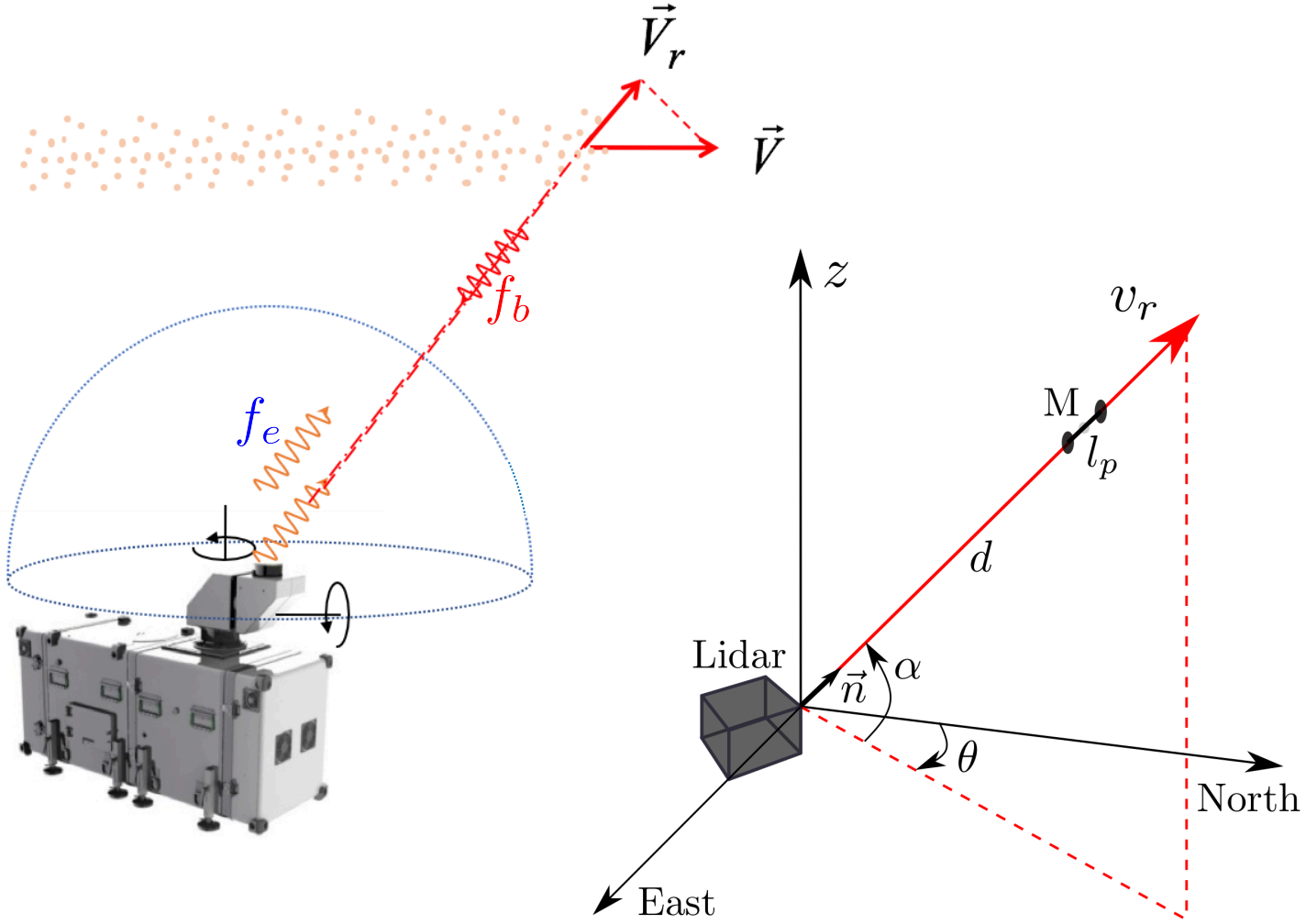
Photo: Wobben Wind Power (José F. S. Neto & Thomás V. S. Araújo)

# Lidars – *de facto* technology for remote wind sensing




Radial wind speed from Doppler shift:

$$\Delta f = f_b - f_e = \frac{2 f_e}{c} v_r$$

Radial speed as projection of wind vector,

$$v_r(d, l_p, \alpha, \theta) = \vec{n} \cdot \vec{V}(\vec{n}, d)$$

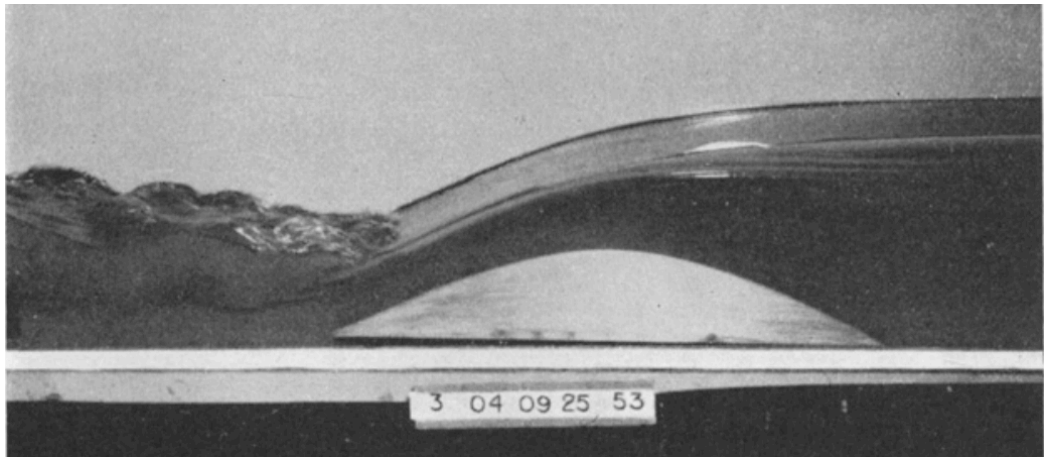
where,

$$\vec{n}(\theta, \alpha) = (\sin\theta \cos\alpha, \cos\theta \cos\alpha, \sin\alpha)$$

# Flow over mountainous terrain

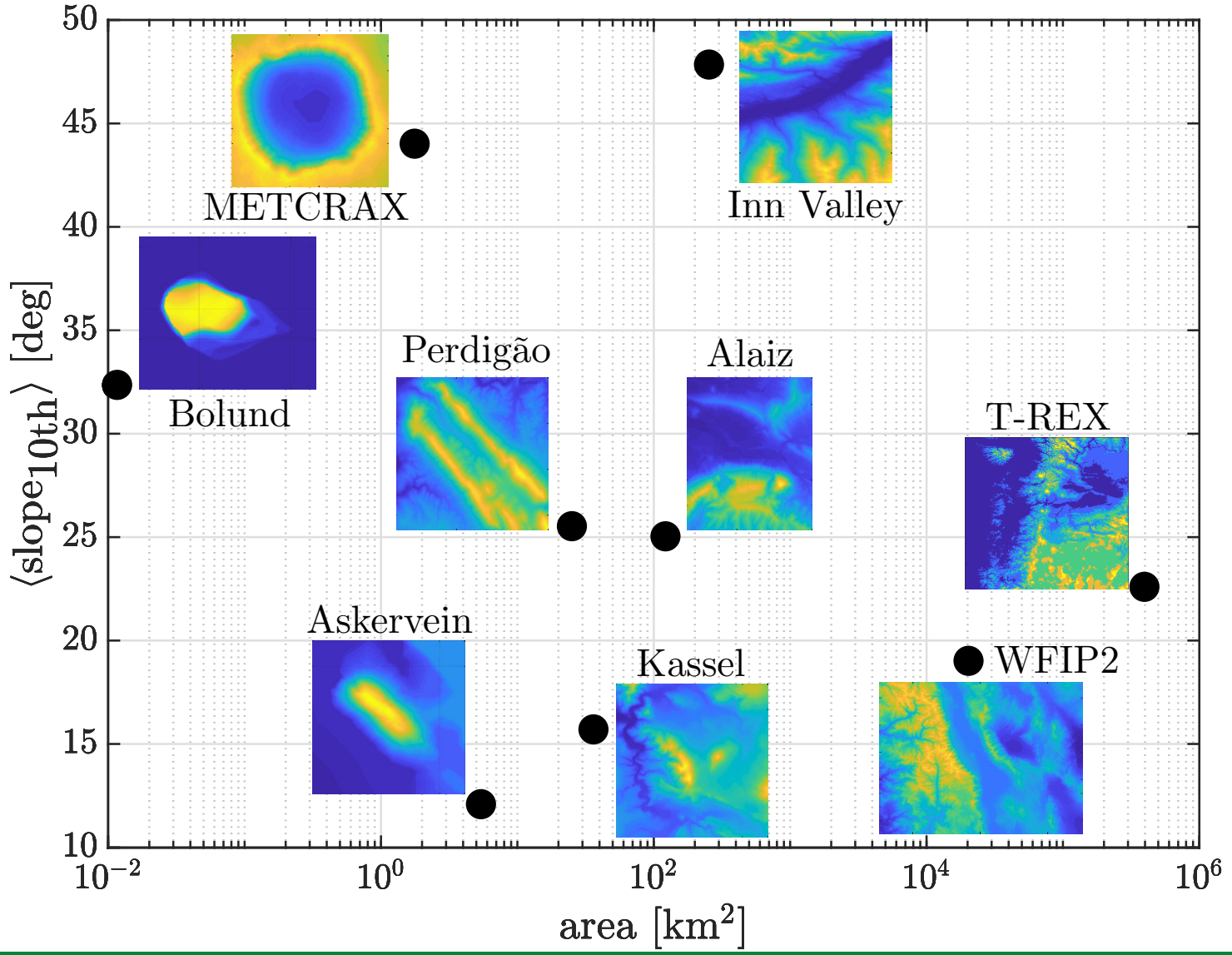
- When the topography has an elevation difference in order of the PBL height, Kaimal and Finnigan (1994) argue that buoyancy effects are significant to characterize the flow at all times.
- Brunt-Väisälä frequency (N) and Froude number (Fr) are two important parameters,

$$\mathrm{Fr}_L = \frac{U}{NL} \qquad \mathrm{N} = \sqrt{\frac{g}{\bar{\theta}}\frac{\partial \bar{\theta}}{\partial z}}$$

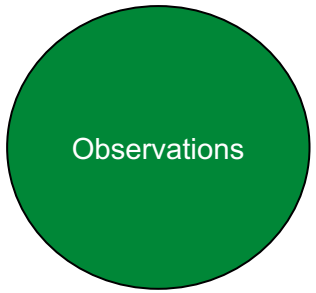



Source: Long (1954, *Tellus*)

# Panorama of observations and model evaluation

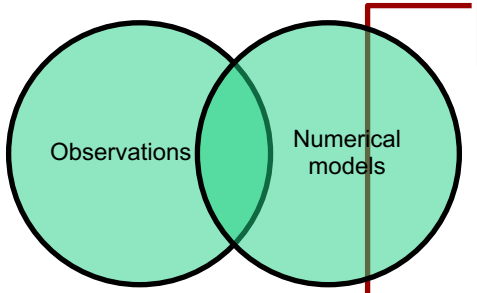


# Hypotheses



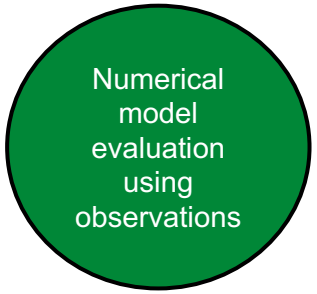

## Hypothesis 1:

- Multi-lidar measurements of the mean wind flow **portray** flow patterns of different scales, such as atmospheric mountain waves and recirculation zones with features from 100 m and 10 km in mountainous terrain




## Hypothesis 2:

- A multi-scale numerical weather prediction model **simulates** atmospheric hydraulic jumps with similar timing and flow properties as those observed by a multi-lidar setup

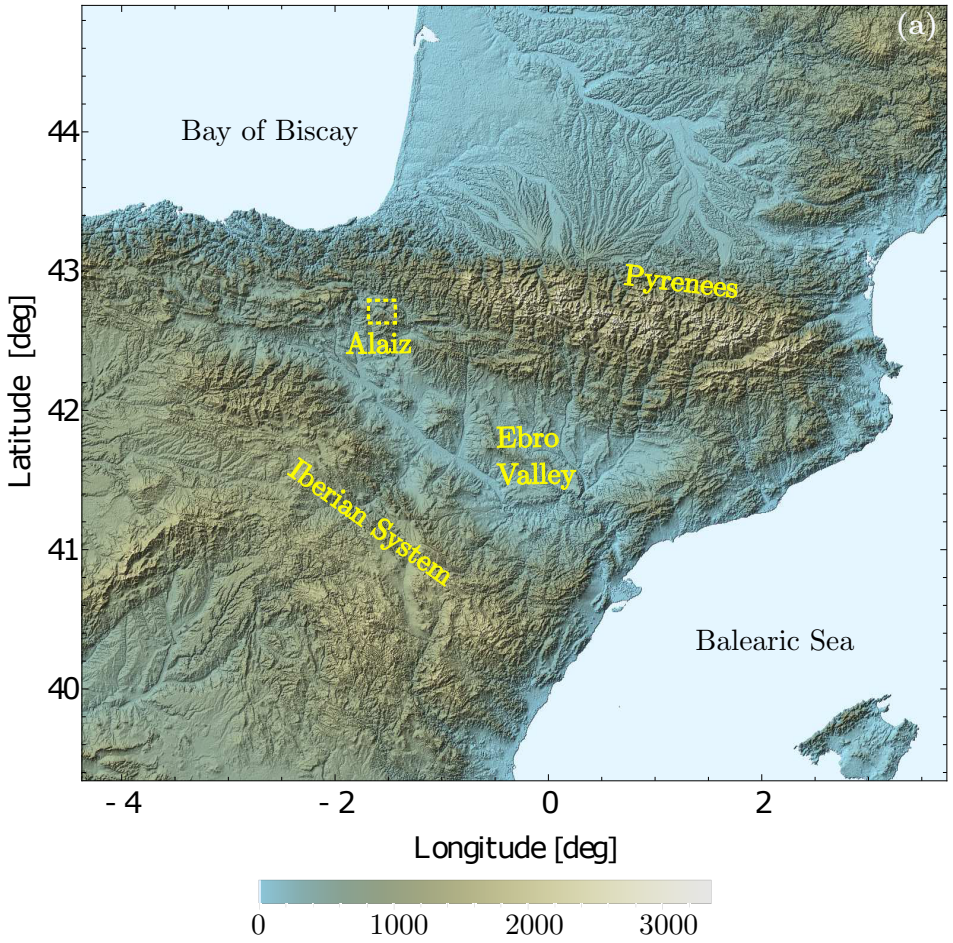


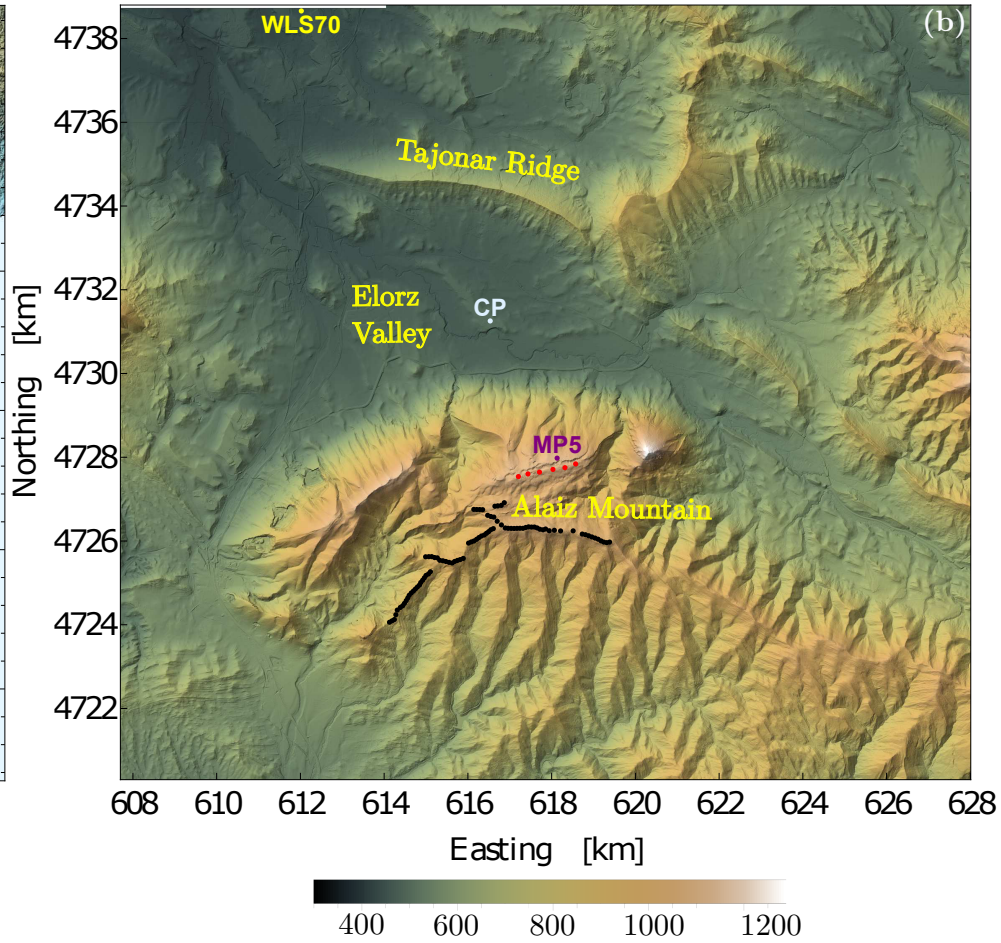

## Hypothesis 3:

- The vector of vertical flux of horizontal momentum and that of the mean vertical gradient of horizontal wind speed **are aligned** above the atmospheric surface layer.

# The Alaiz experiment (ALEX17)

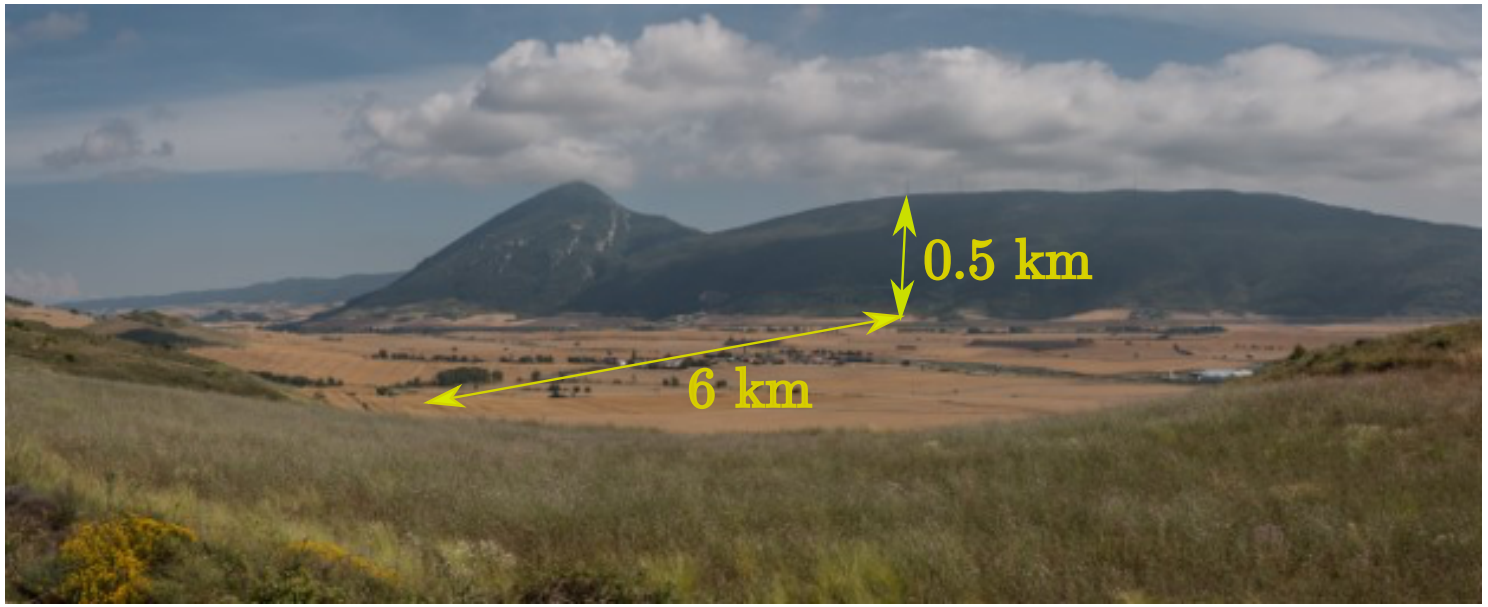
- A large-scale domain (20x20 km) with a mountain-valley-ridge configuration



# The Alaiz experiment (ALEX17)

- Observational campaign: May/2018 to Jan/2019

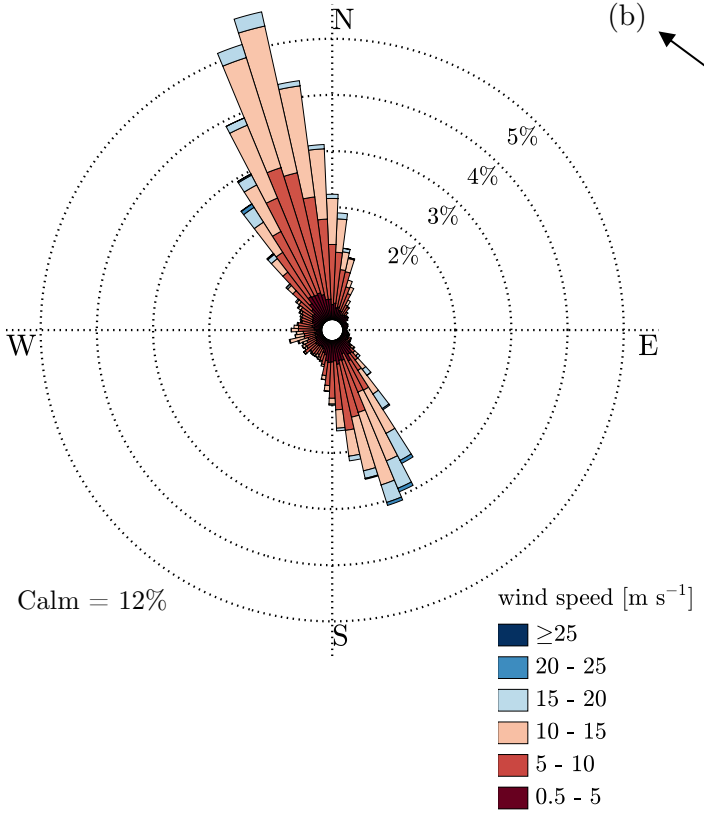


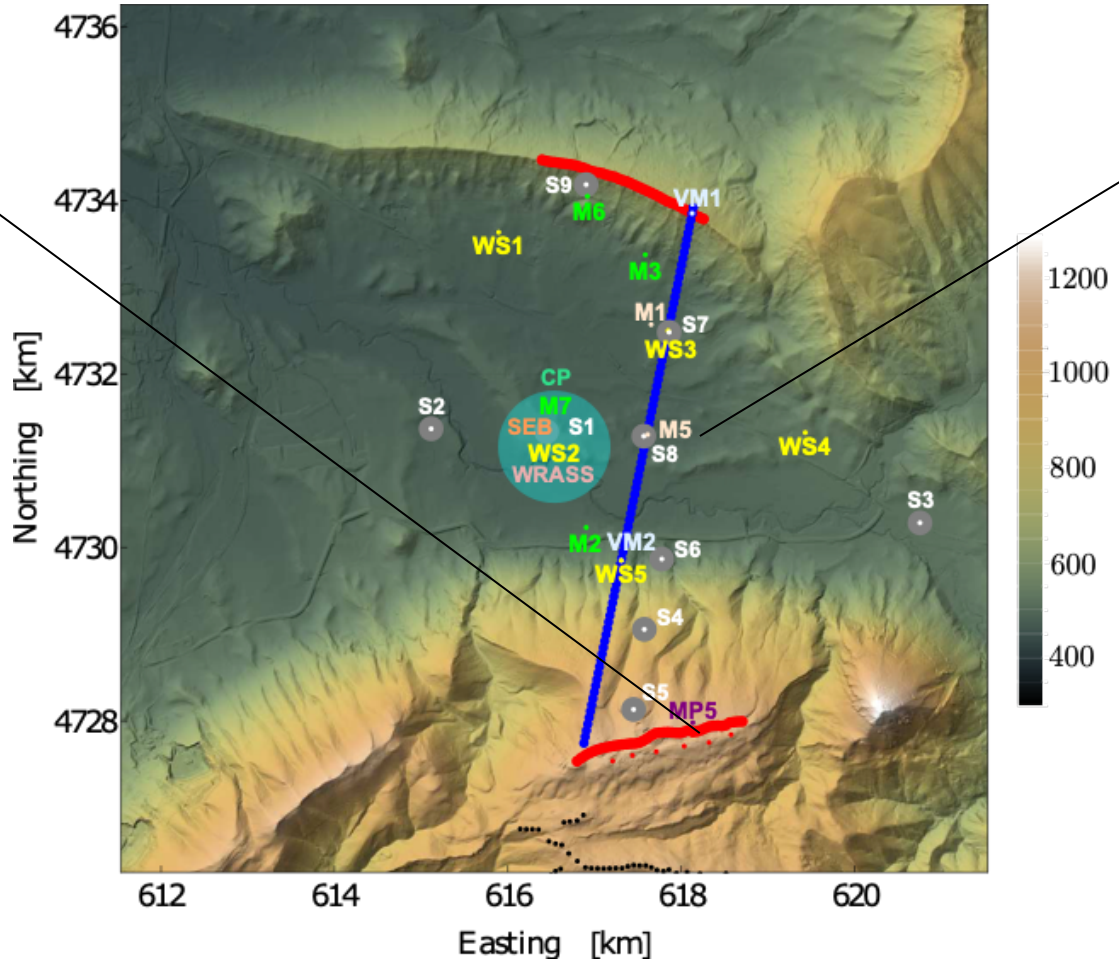

*View of the Alaiz mountain towards SE from Tajonar ridge*

# The Alaiz experiment (ALEX17)

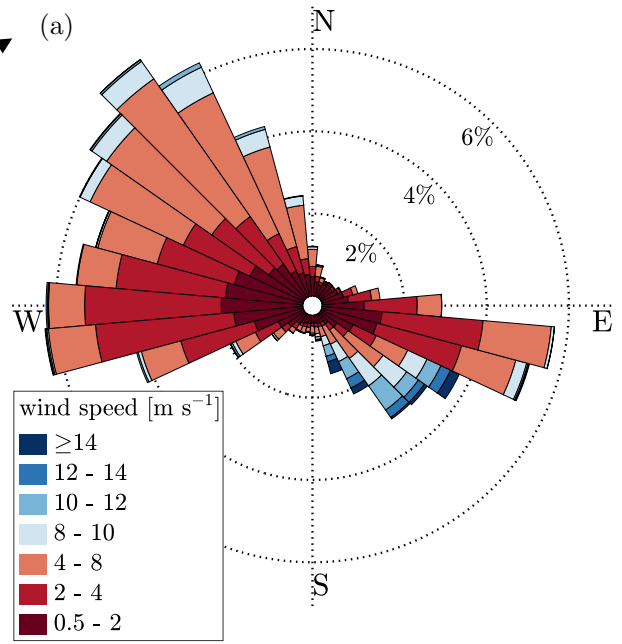
- A large-scale domain (20x20 km) with a mountain-valley-ridge configuration

Mountain top (118 m)



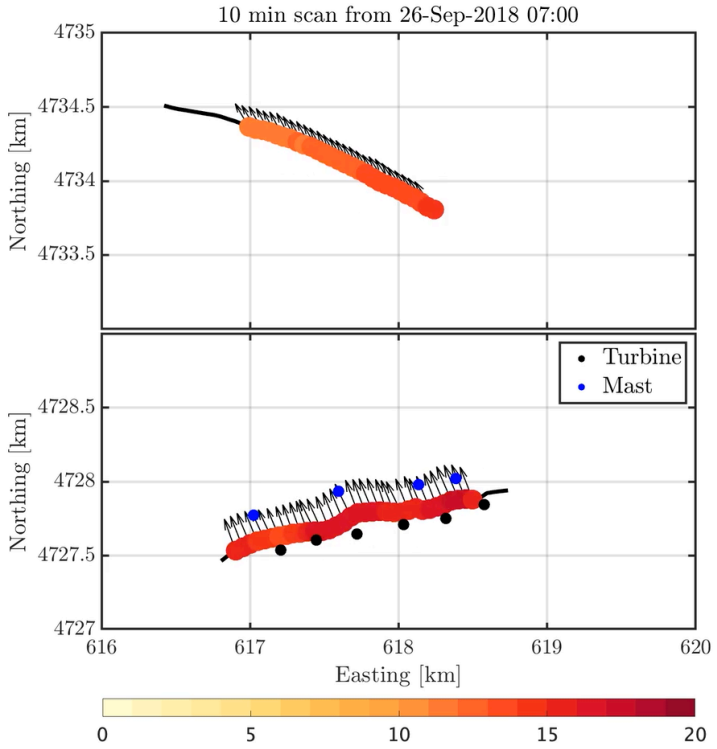




Valley floor (80 m)

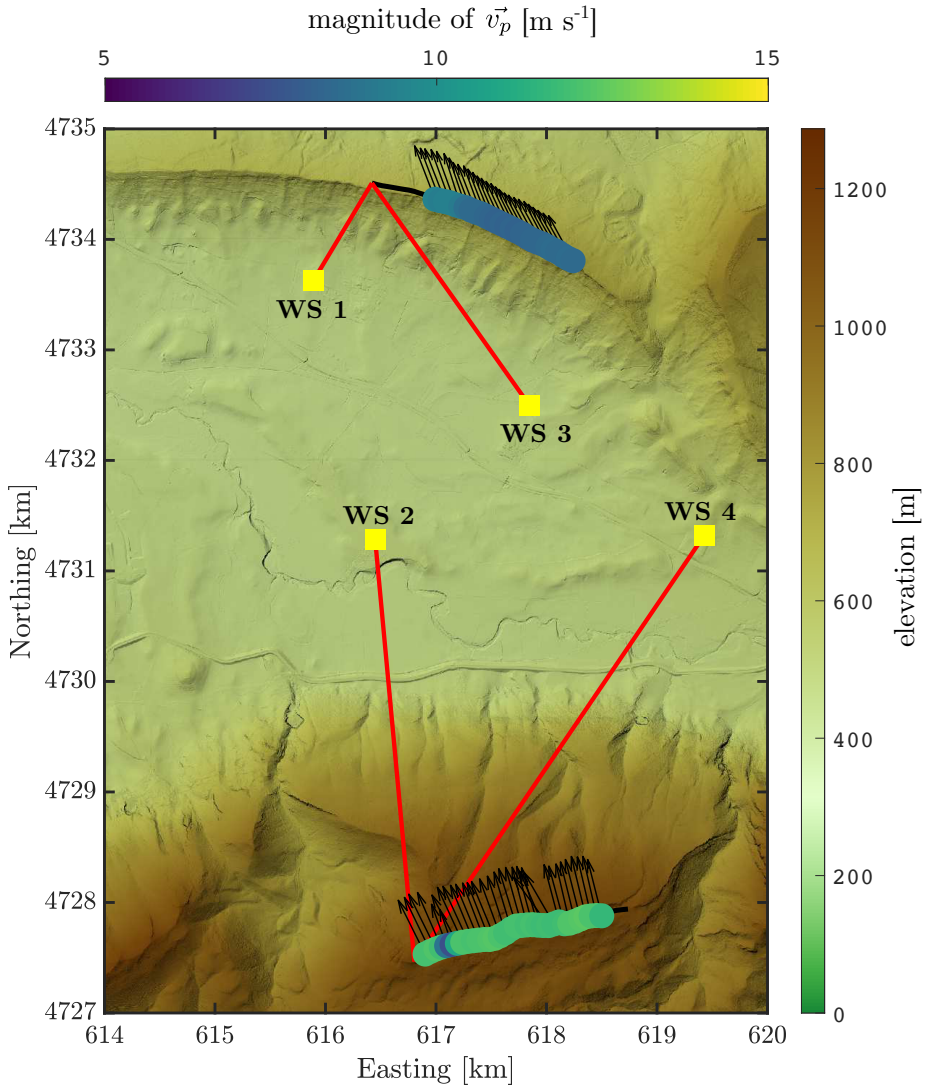


# The Alaiz experiment (ALEX17)

- Dual-Doppler along the Alaiz mountain & Tajonar ridge:
  - Recovery for 3-full months: 75.2% at the ridge, 30% at the mountain.

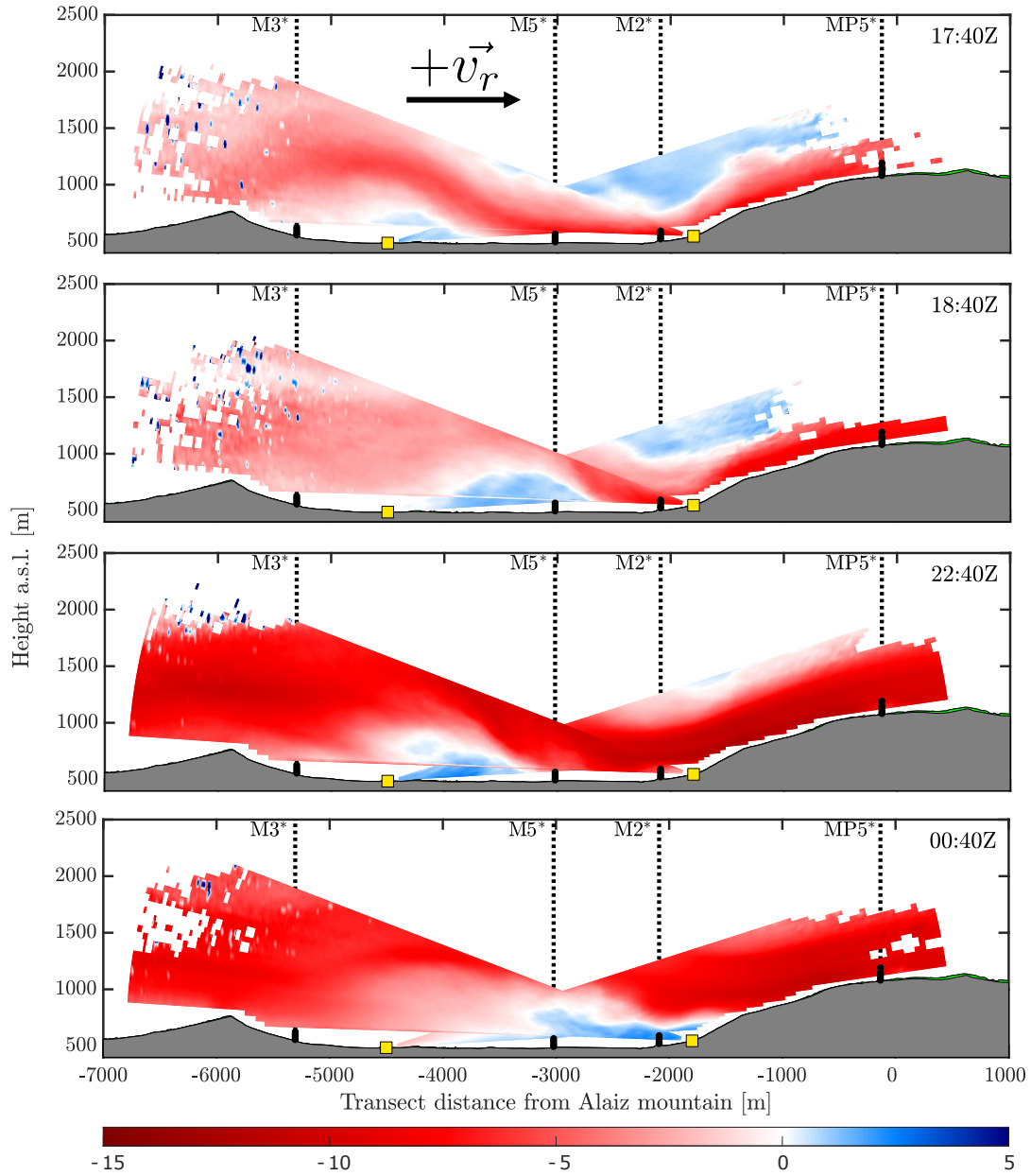



Source: http://doi.org/10.11583/DTU.13003184



# A hydraulic jump at Alaiz

- Observations between Oct 5th – Oct 6th 2018

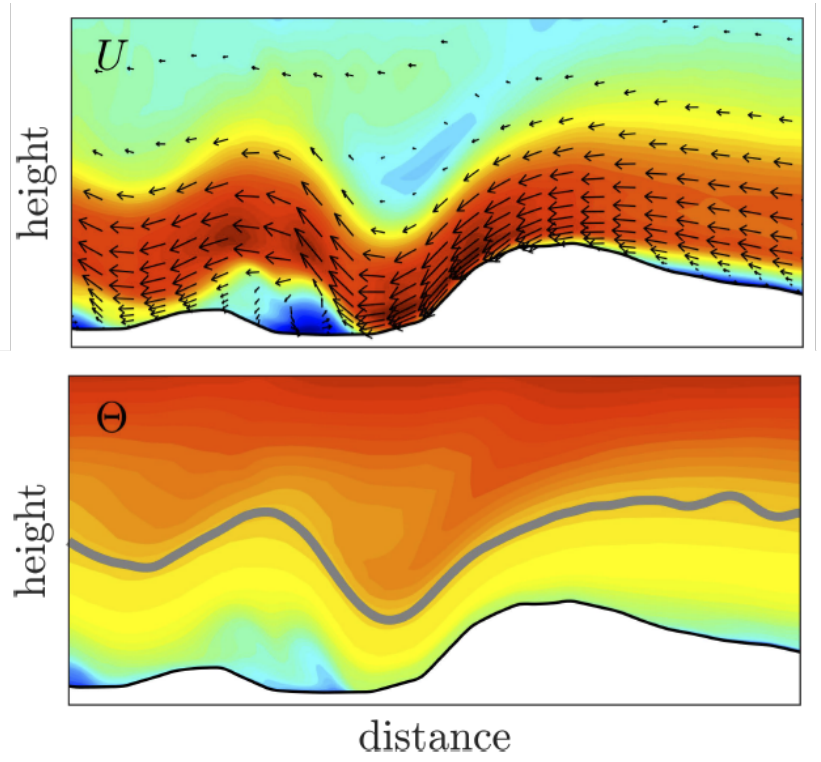


# What characterizes a hydraulic jump?

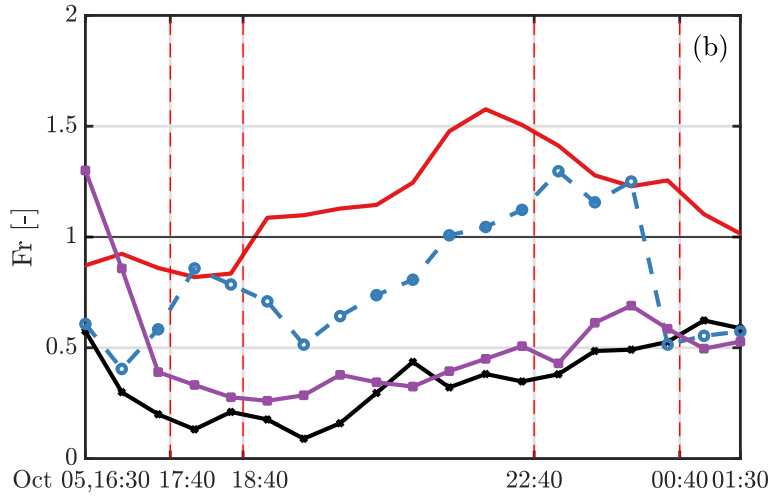
- A hydraulic jump can be interpreted as a flow discontinuity with dissipation of turbulence.
- Long (1954) showed that a Froude transition, i.e. from supercritical (>1) to subcritical (<1), might trigger an atmospheric hydraulic jump

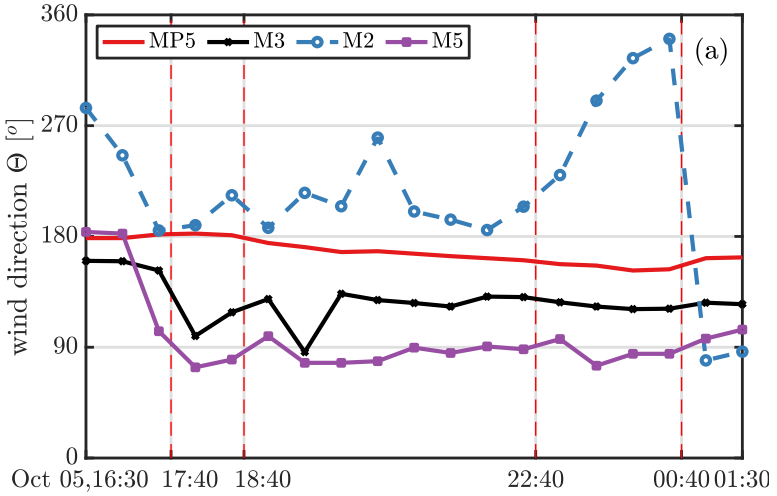
$$\mathrm{Fr}_L = \frac{U}{NL}$$

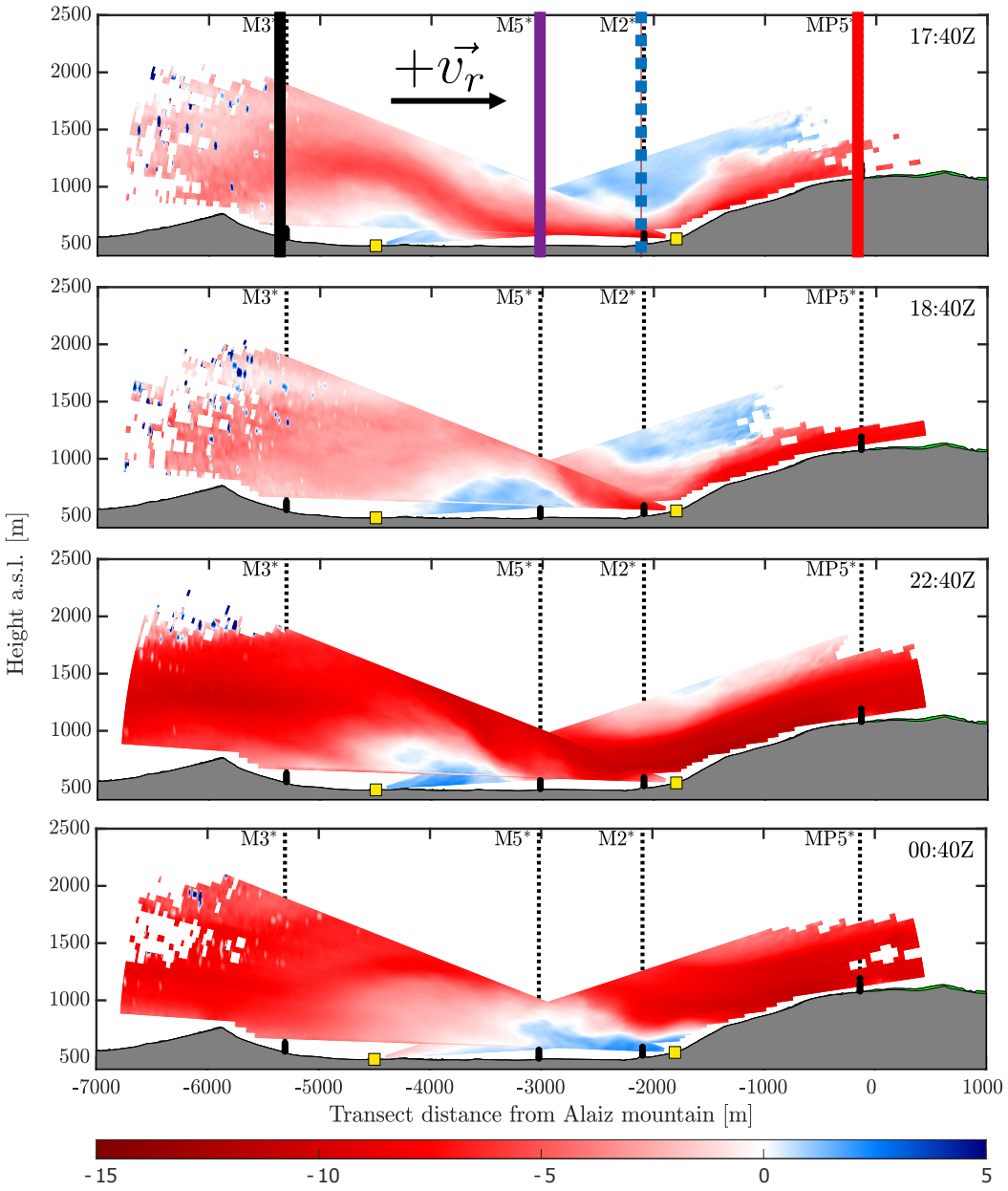
$$\mathrm{N} = \sqrt{\frac{g}{\bar{\theta}}\frac{\partial \bar{\theta}}{\partial z}}$$



# A hydraulic jump at Alaiz – Froude transition



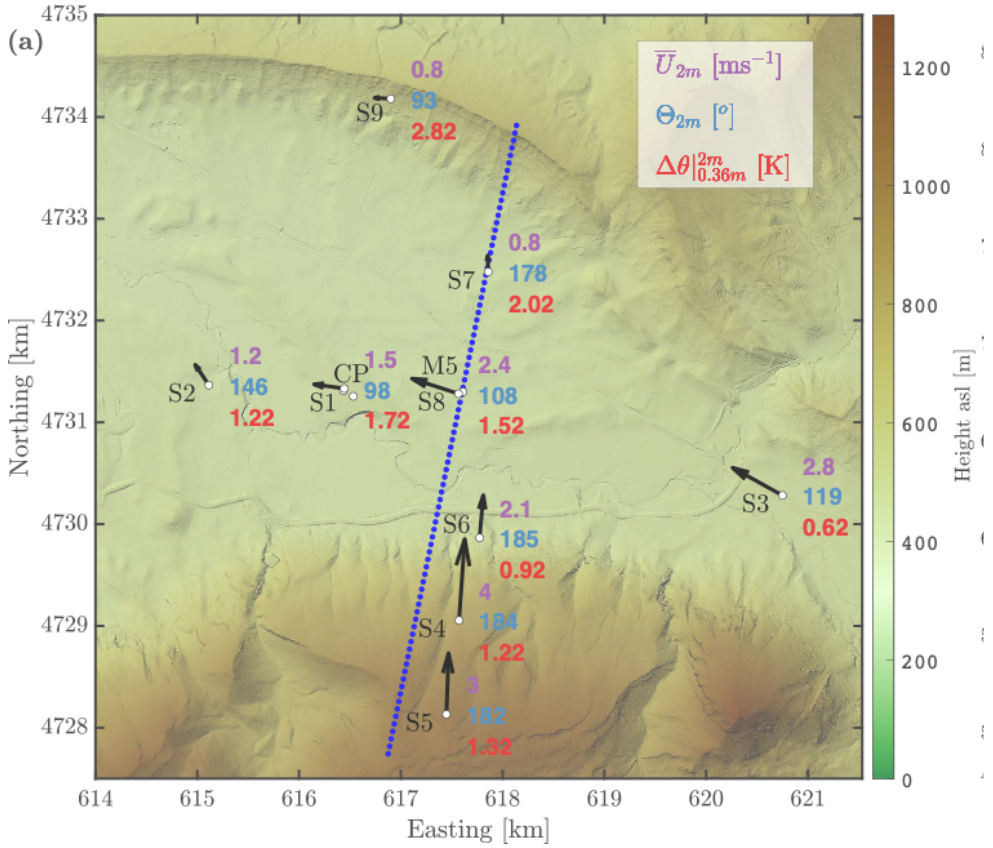



# A hydraulic jump at Alaiz – how often does this happen?

- The surface stations show the horizontal distribution of the hydraulic jump phenomenon, with a funnel effect in the valley.

**This is a single case, how often does this happen?**

- Measurements over a 1-year period show that the Froude number transition for southerly winds happens $\approx 10\%$ of the time.



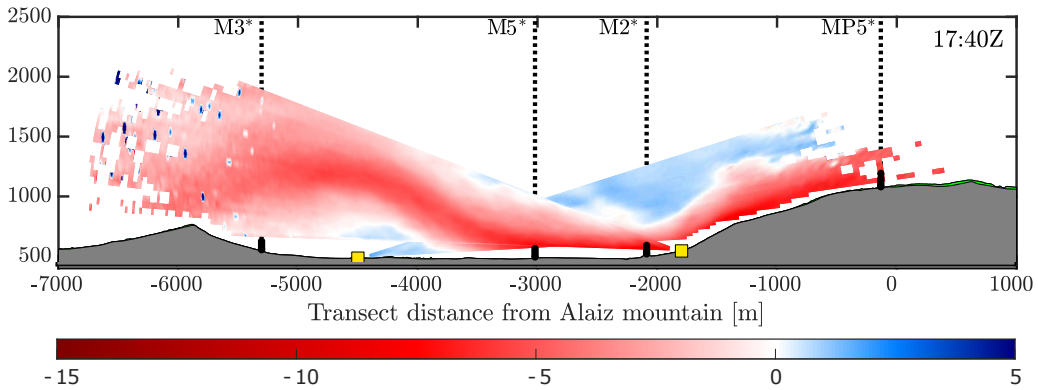
# A hydraulic jump at Alaiz – measurement results

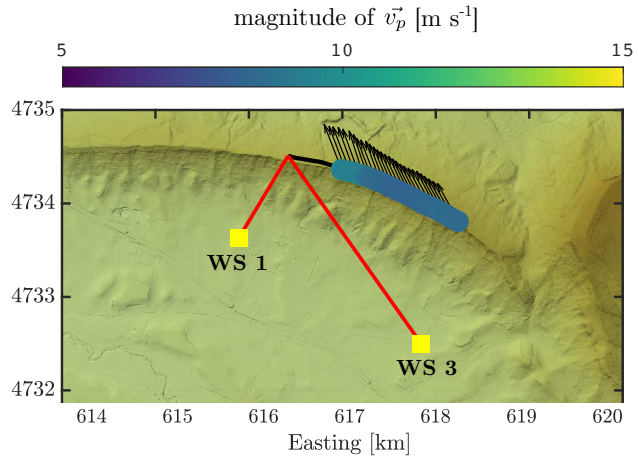
- Hypothesis 1 is not falsified

**Hypothesis 1:**

- Multi-lidar measurements of the mean wind flow **portray** flow patterns of different scales, such as atmospheric mountain waves and recirculation zones with features from 100 m and 10 km in mountainous terrain

- Results are published in Wind Energy Science, Santos et al. (2020)

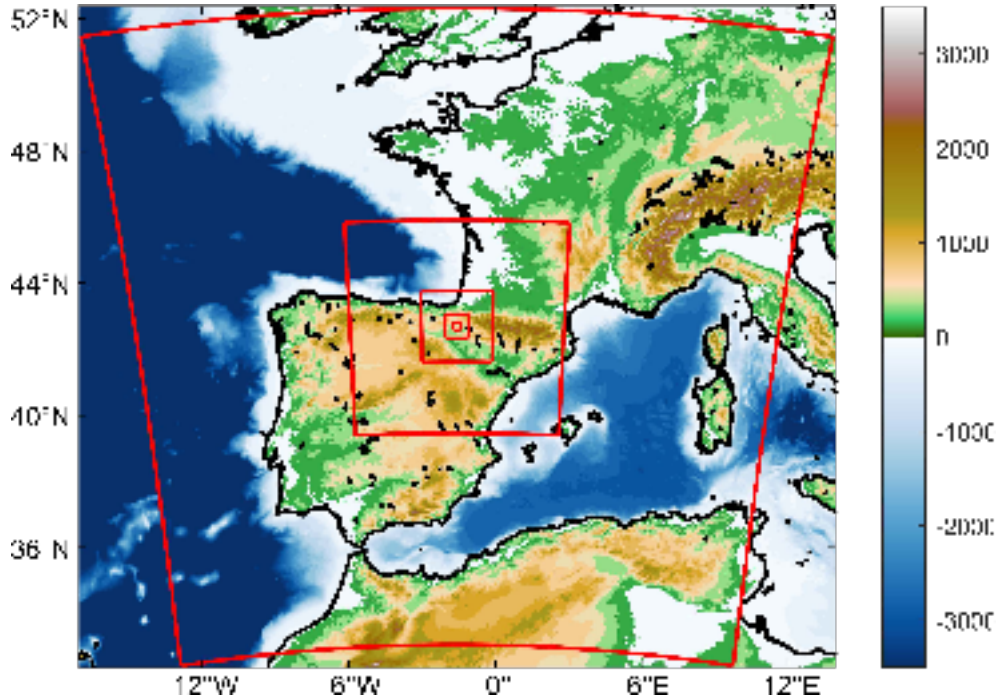


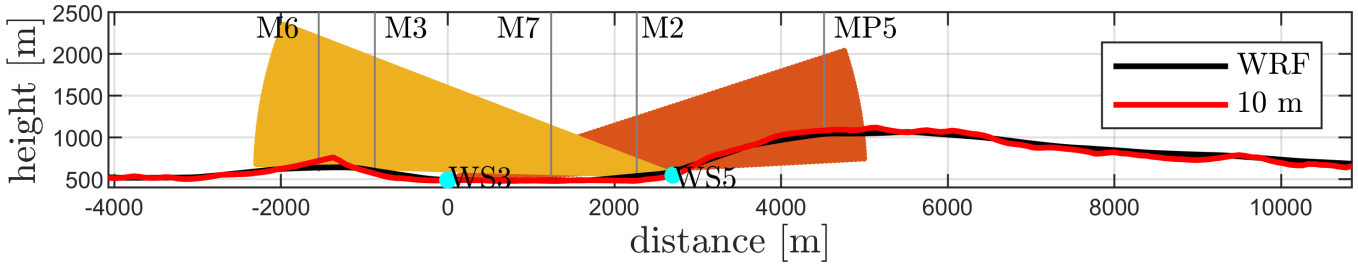




**How does these results compare with state-of-the-art numerical models?**

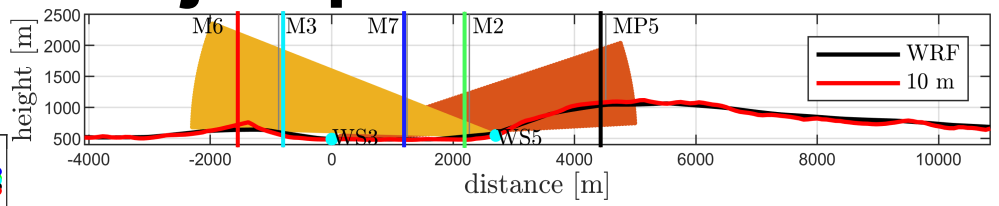
# Numerical simulations of hydraulic jump and mountain waves

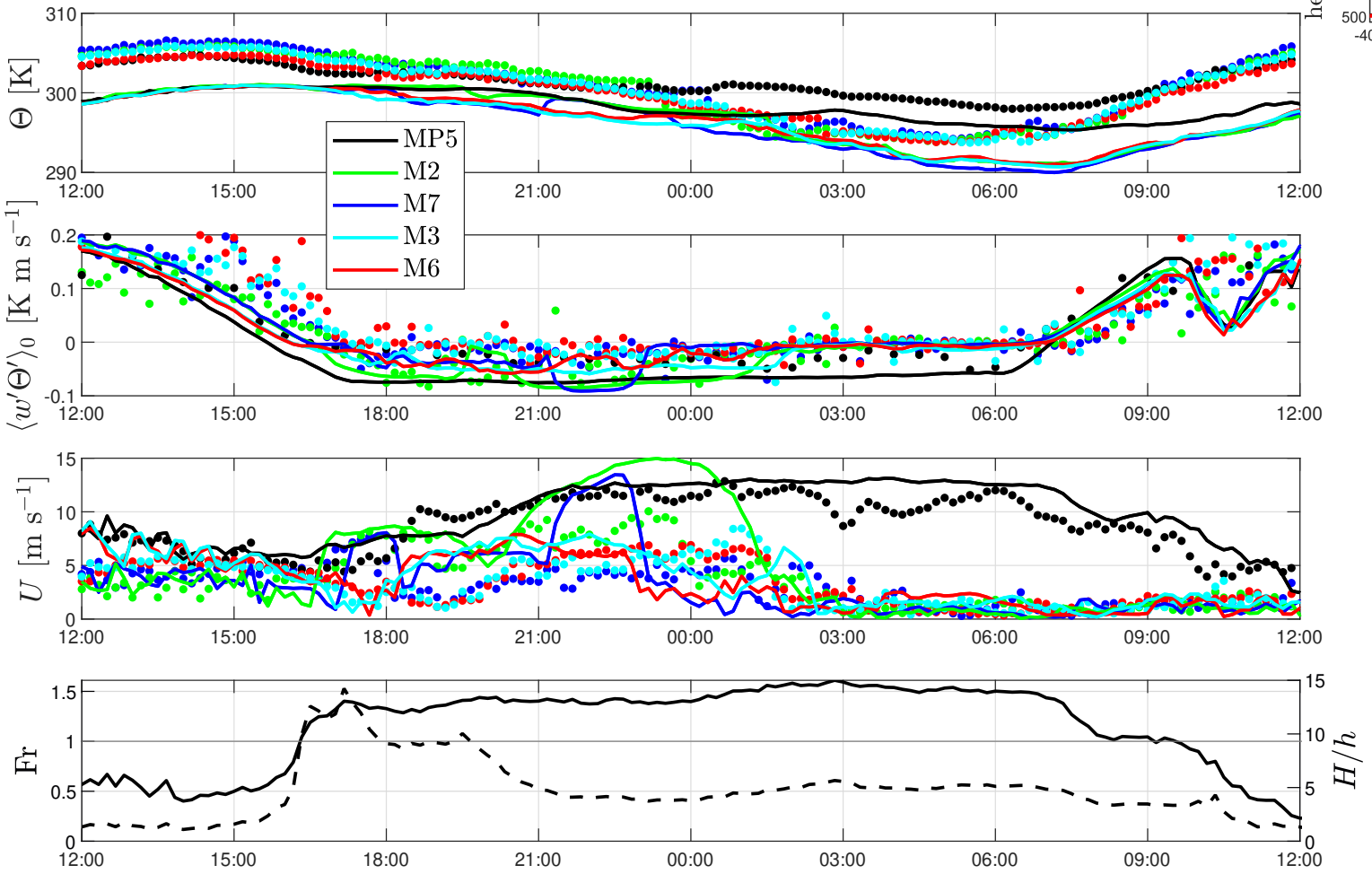
- WRF 4.0.1 simulation conducted by A. Peña



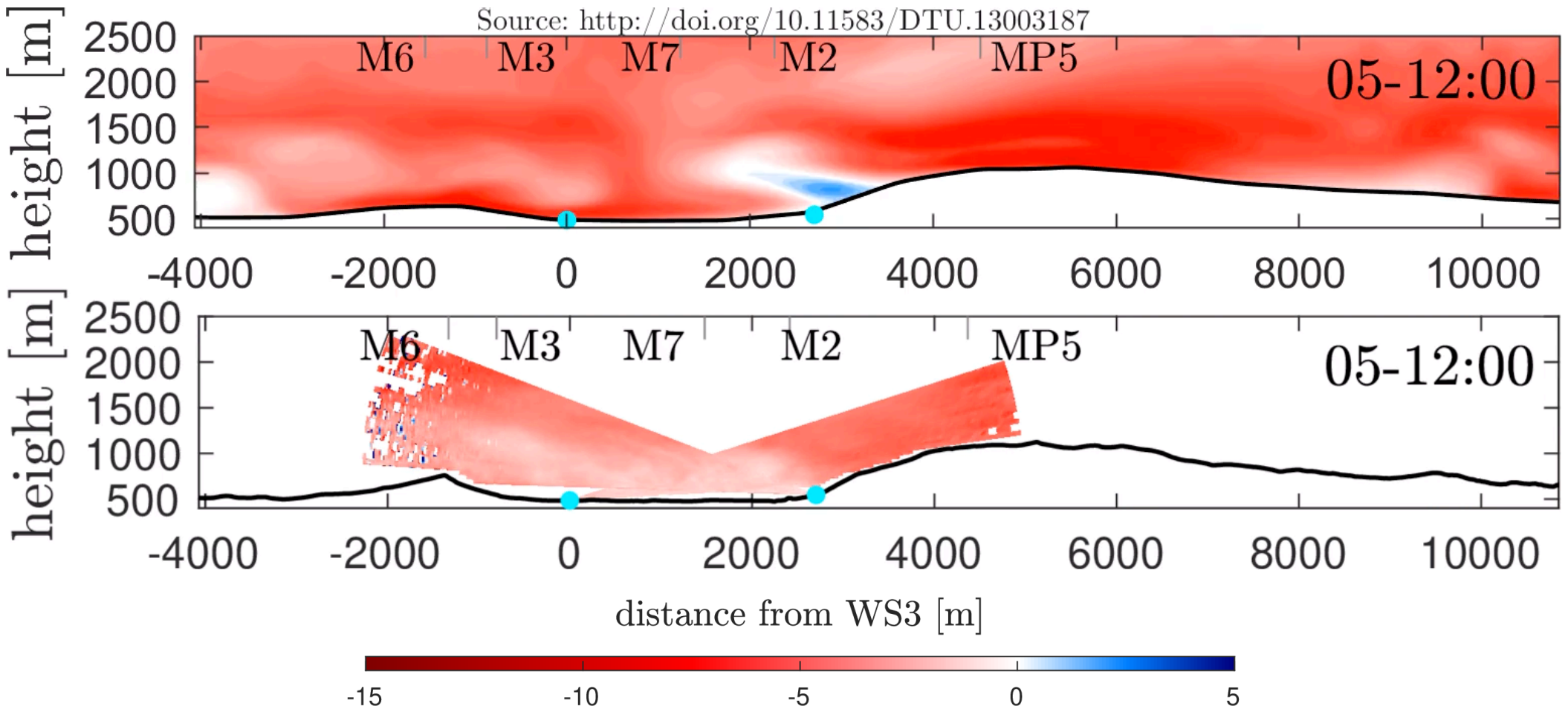



# Numerical simulations of hydraulic jump and mountain waves



# Numerical simulations of hydraulic jump and mountain waves



# Numerical simulations of hydraulic jump and mountain waves

- WRF simulations simulated the atmospheric hydraulic jump with similar timing and flow structures
- Meteorological observations show both agreements and mismatches with simulations.
- Simulations point that both the hydraulic jump and mountain waves occur under supertrical Froude

**This is one case, are such results robust?**

- Four other hydraulic jump cases were identified using the multi-lidar scans
  - All cases also with strong (> 5 $ms^{-1}$) and southerly winds at the mountain top with a Froude number transition at the valley.
- Other observed episodes can be the focus of further studies.

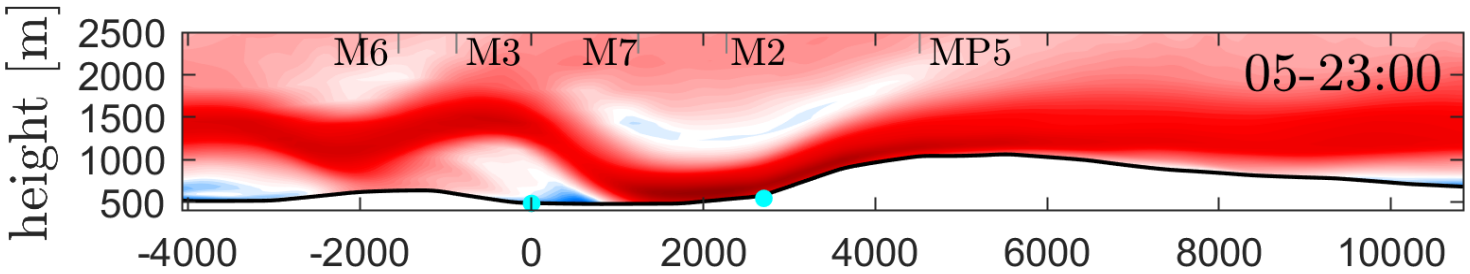
# Numerical simulations of hydraulic jump and mountain waves

- Hypothesis 2 is not falsified

**Hypothesis 2:**

- A multi-scale numerical weather prediction model **simulates** atmospheric hydraulic jumps with similar timing and flow properties as those observed by a multi-lidar setup

- Results are published in JGR Atmospheres, Peña and Santos (2021)



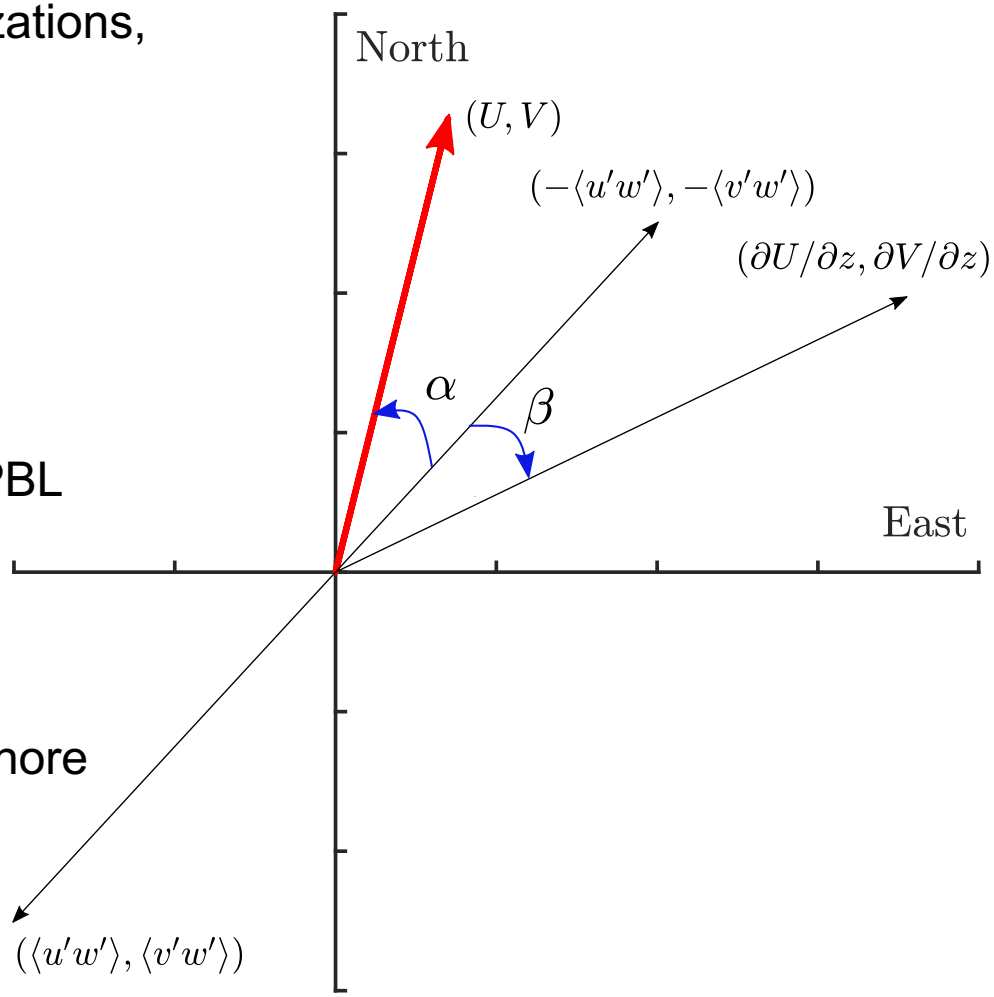

**How to use lidar observations to better understand numerical model capabilities?**

# *K*-theory departure from PBL - hypothesis

- **Objective**: Evaluate assumption used in PBL parameterizations, common in numerical weather models
- Local PBL schemes in mesoscale models express the momentum fluxes as

$$\overline{u_i' w'} = -K_m \frac{\partial U_i}{\partial z}$$

- Considering this K-theory hypothesis, $\beta = 0°$ across the PBL
- Using NEWA-WRF and a long-range profiling lidar
  - What is the validity of the K-theory hypothesis both onshore and offshore?



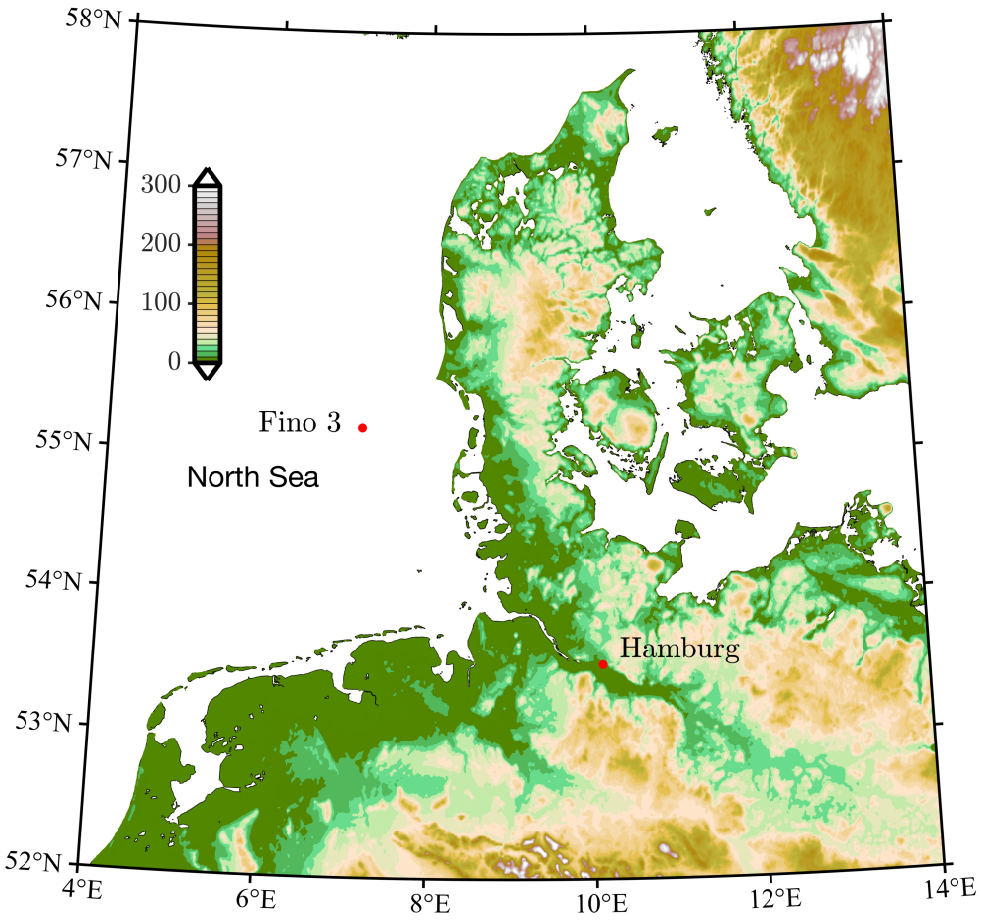
# K-theory departure from PBL - methodology

- **Observations**
  - 1-yr at FINO3 and 3-months at Hamburg
  - Valid 30-min lidar data from 100 m to 500 m
  - Final time series ≡ valid lidar ∩ WRF data
  - Momentum flux from lidars:

$$\begin{pmatrix} \langle u'w' \rangle \\ \langle v'w' \rangle \end{pmatrix} = \frac{1}{2 \sin 2\phi} \begin{pmatrix} \sigma^2(v_{r,E}) - \sigma^2(v_{r,W}) \\ \sigma^2(v_{r,N}) - \sigma^2(v_{r,S}) \end{pmatrix}$$

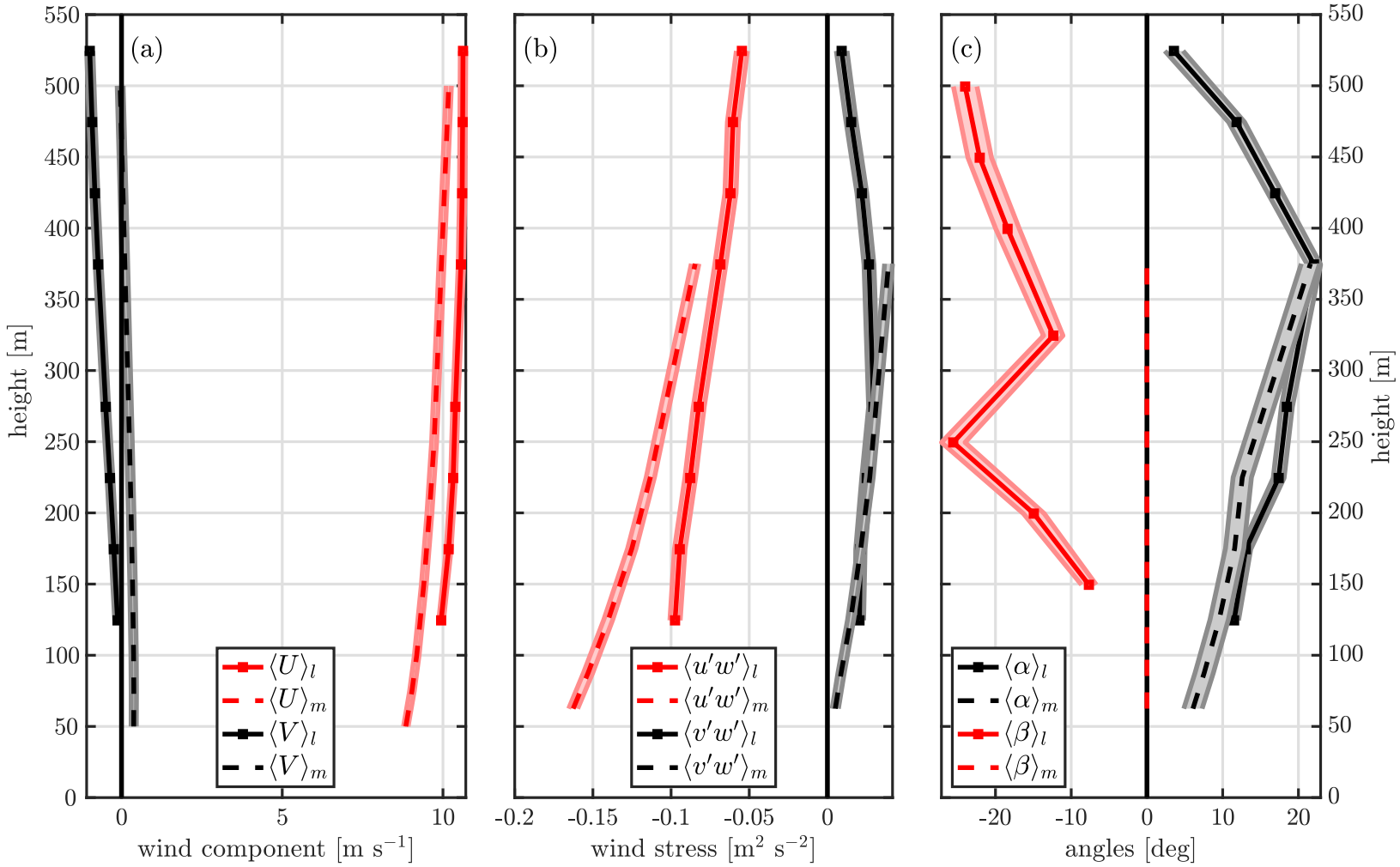
- **Numerical model (NEWA-WRF)**
  - 30-min time series at FINO3 and Hamburg
  - Mellor-Yamada-Nakanishi-Niino level 2.5 is used, i.e.

$$-\overline{u_i' w'} = l\sqrt{2e} S \partial U_i / \partial z$$



# K-theory departure from PBL – offshore results

- Offshore profiles from WRF vs. Lidar from $270° \pm 45°$



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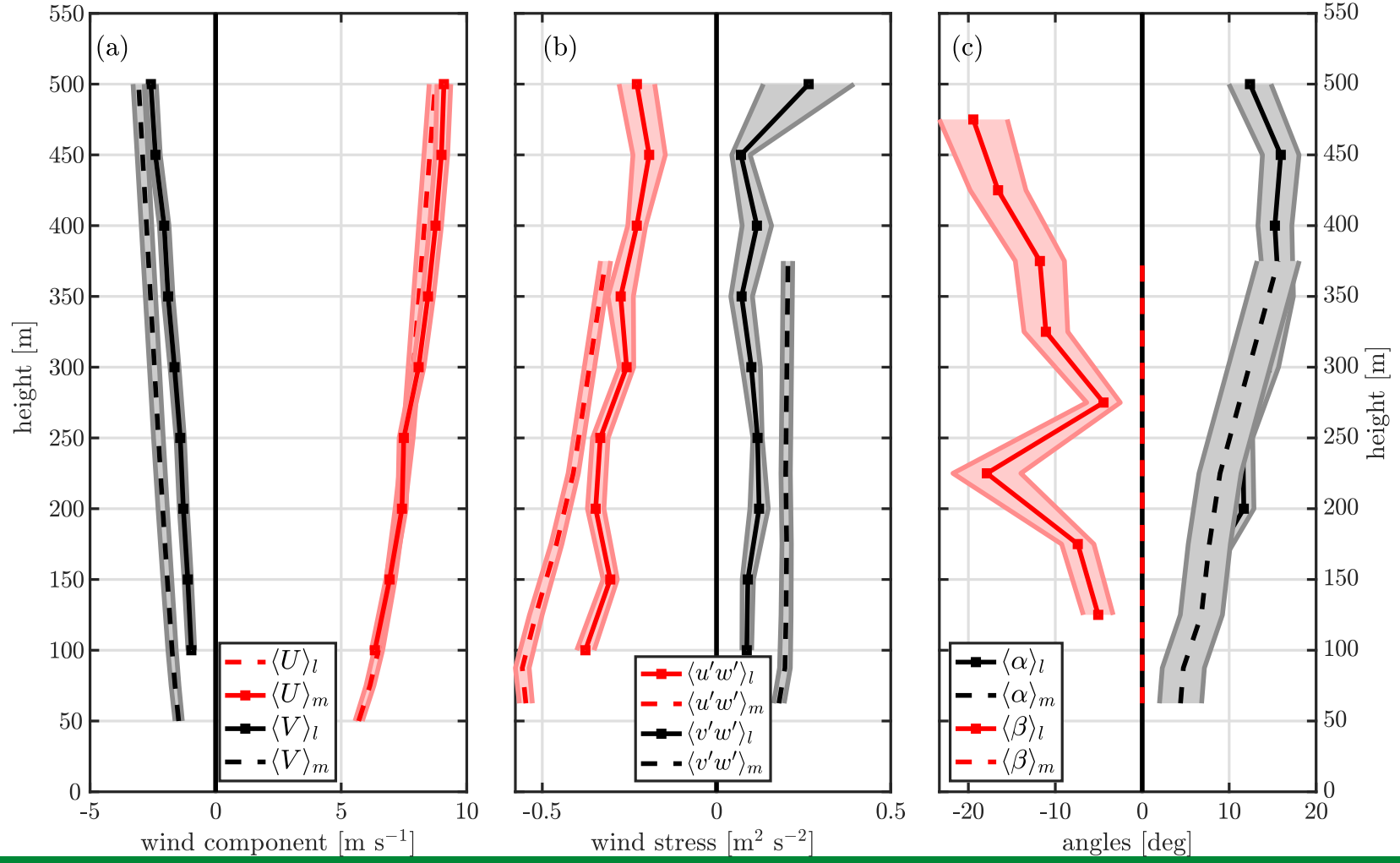
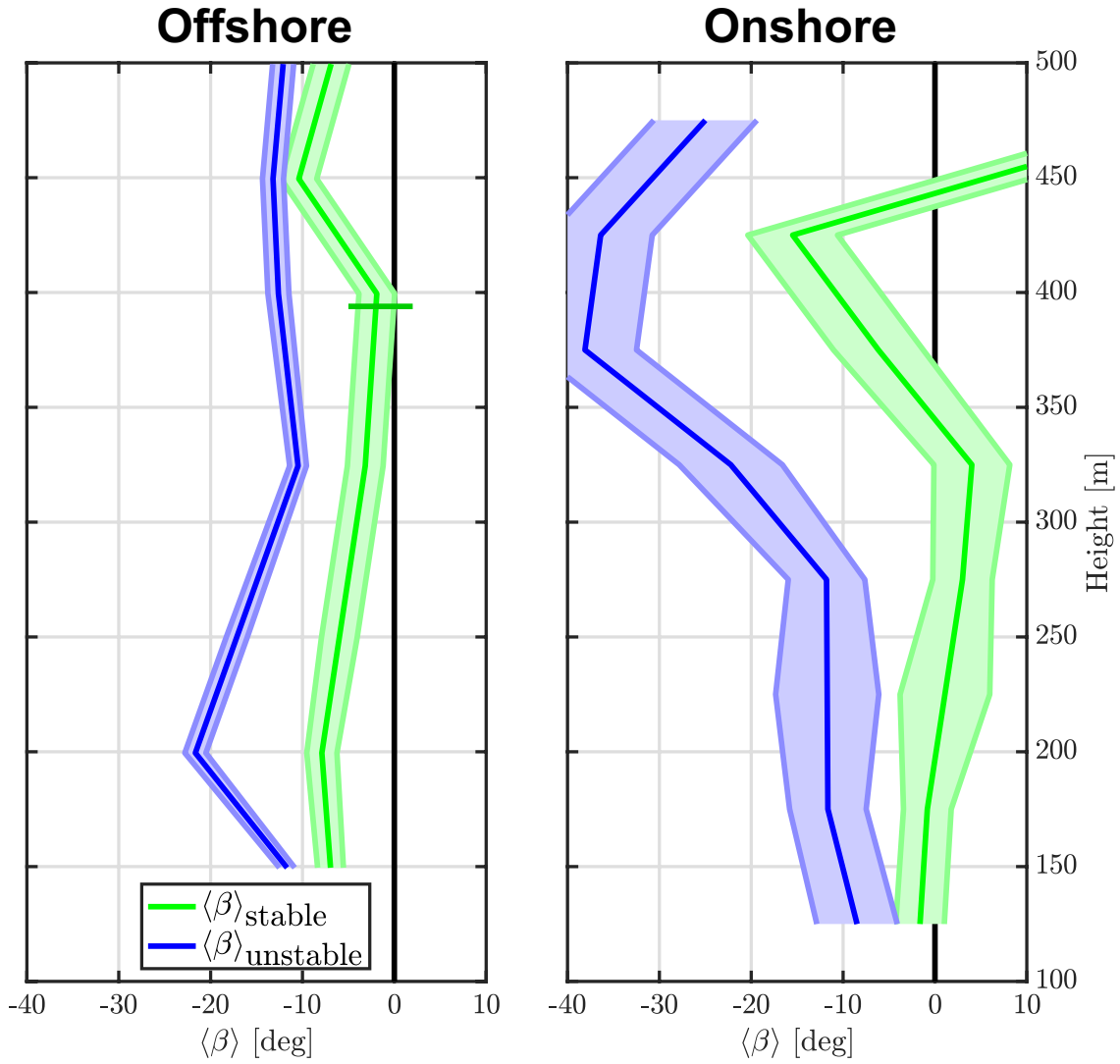


# K-theory departure from PBL – stability impact

- Strain-stress misalignment as a function of atmospheric stability
- K-theory tends to be valid under stable conditions onshore and on PBL top for offshore conditions



# K-theory departure from PBL

- Lidar observations show that between 100-500 m, on average, $\beta \approx -18°$ offshore and $\beta \approx -12°$ onshore
- $\beta = 0°$ assumed by NEWA-WRF **does not** reflect reality
- Hypothesis 3 is falsified

**Hypothesis 3:**

- The vector of vertical flux of horizontal momentum and that of the mean vertical gradient of horizontal wind speed **are aligned** above the atmospheric surface layer.

- Results are under review: Santos, Peña and Mann (in review)

# Conclusion

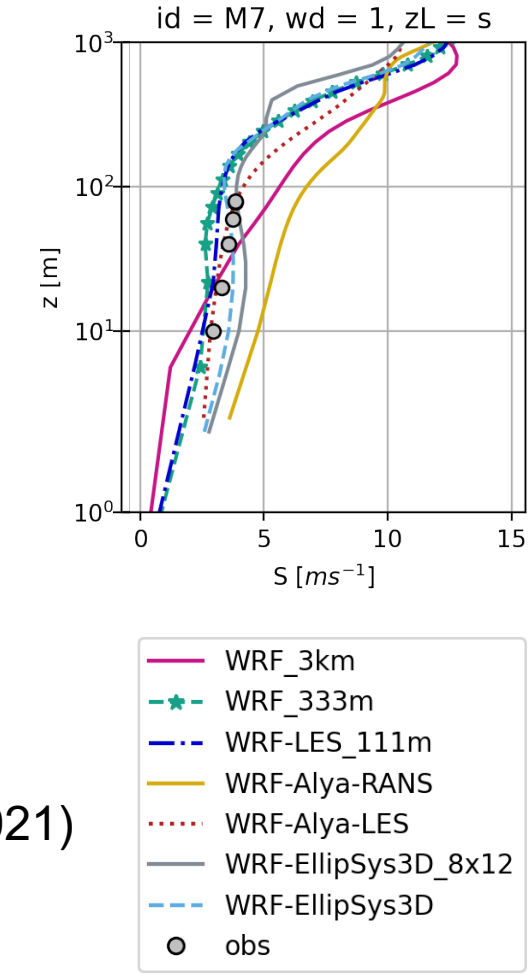
- Alaiz full-scale experiment
  - Full dataset is publicly available, Santos et al. (2019)
  - The multi-lidar transect scan and Dual-Doppler analysis resulted in a flow catalogue for Alaiz

- Hydraulic jump at Alaiz
  - Multi-scanning lidar setup was able to capture flow patterns O(10 km)
  - High-resolution mesoscale simulations match qualitatively the observed hydraulic jump both in time and flow features
  - Froude number analysis and numerical simulation inputs indicate that this phenomenon is frequent and relevant for the studied site

- K-theory departure on PBL
  - First results that indicate stress-strain misalignment both onshore and offshore above the ASL
  - Impact of these results in development of PBL schemes

# Outlook

- Further advancement of multi-lidar campaigns
- New dataset for model evaluation and validation
  - Two numerical model benchmarks are ongoing (IEA Task 31)




- First step towards time-resolved numerical modelling at Alaiz
  - More studies on the hydraulic jump are being performed (WESC 2021)
- Stress-strain misalignment to be connected with atmospheric processes (e.g. cloud formation)

# Thank you for the attention!
# Obrigado!
# Tusind tak!