Wind energy in complex terrain:
The Perdigão-2017 Campaign in Portugal

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DLR

Outline

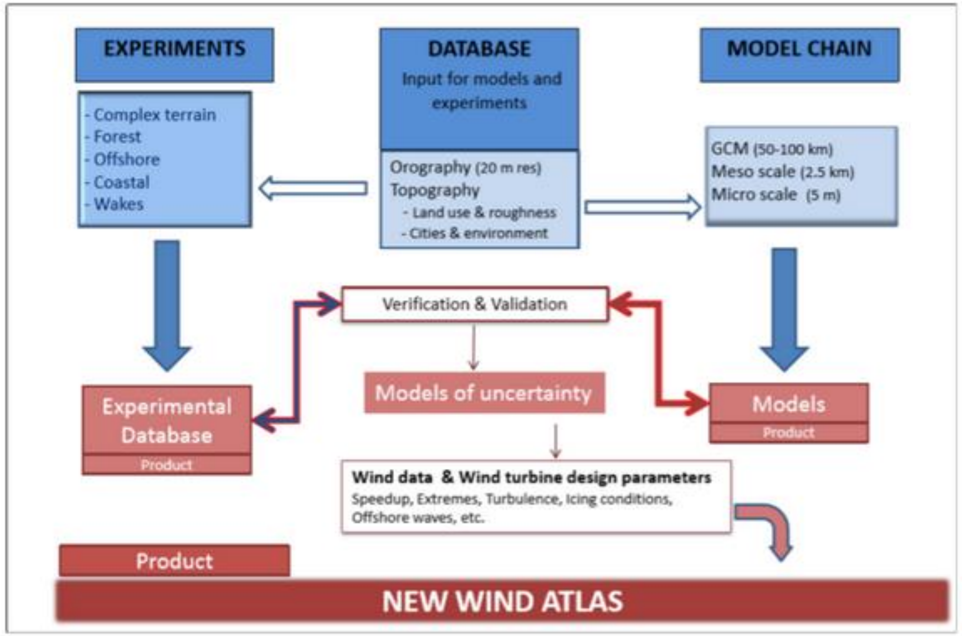
- Objectives, partners and research goals
- Site Overview: Why Perdigão ?
- Instrumentation
- Exemplary results
- Lessons learned
- Acknowledgements, publications and links

All-over objectives of European and USA participating groups

- Augment scientific knowledge for complex terrain processes (double hill, vegetation)
- Observe the flow and thermodynamic fields at unprecedented spatial and temporal resolutions
- Develop better parameterizations for microscale modelling for wind energy prospecting
- Understand the interaction of thermal circulation and synoptically driven flow in a heterogeneous domain

For **Europe**:

- Perdigão-2017 was one key experiment in NEWA



For **USA**:

- Understand complex terrain physical and thermodynamic processes
- create new models that better represent the physics of flow over complex terrain
- NSF-funded

Embedded in the EU ERANET+ Programme

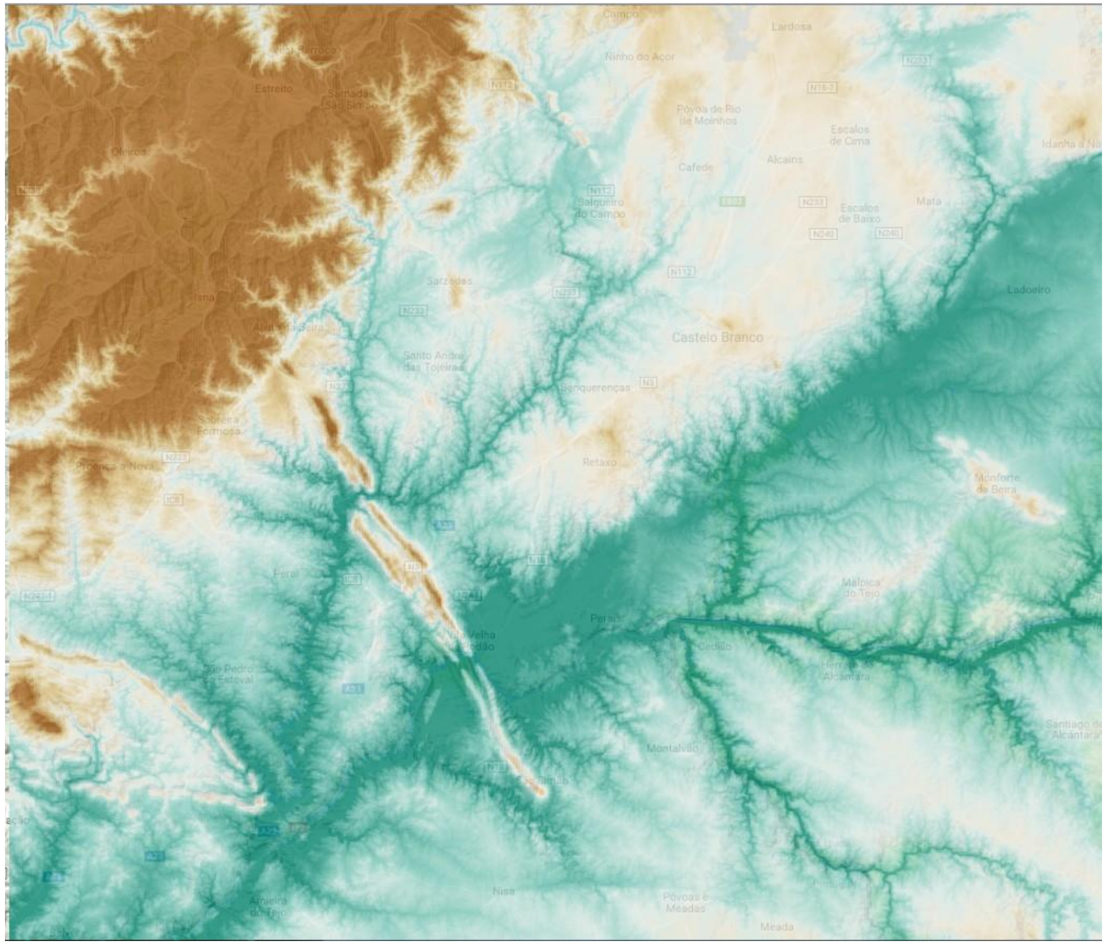
Mann et al. 2017, Philos. Trans. Roy. Soc., 375A, https://doi.org/10.1098/rsta.2016.0101

Research Goals of the partners

N.	Topic title	Lead	Participants
1	**Multi-scale flow interactions in complex terrain**	Fernando/Leo	Notre Dame group
2	**Influence of terrain heterogeneity**	Fernando/Leo	Notre Dame group
3	**Gap flows**	Fernando/Leo	Notre Dame group
4	**Transitions and diurnal cycle of the atmospheric boundary layer, and interactions between valley flows and boundary layer flow above**	Klein	University of Oklahoma
5	**Impacts of surface inhomogeneity**	Barthelmie	Cornell University
6	**Flow-turbine interactions and wake flows**	Barthelmie,	Cornell University
7	**Inflow, flow-turbine interaction, wake flow**	Wildmann, Kigle, Hagen, Wagner, Gerz	DLR
8	**Modeling**	Palma	UPORTO
9	**Weather-dependent sound patterns around a wind turbine**	Schady, Gerz	DLR
10	**Intermittent turbulence and turbulence dissipation rate measurements**	Lundquist/ Chow	CUB/UCB
11	**Flow-turbine interactions, especially interaction of wake with coherent structures**	Lundquist/ Chow	CUB/UCB
12	**Mesoscale-microscale modeling**	Lundquist/ Chow	CUB/UCB
13	**Wind energy resource estimation by measurements and models**	Mann	DTU/others

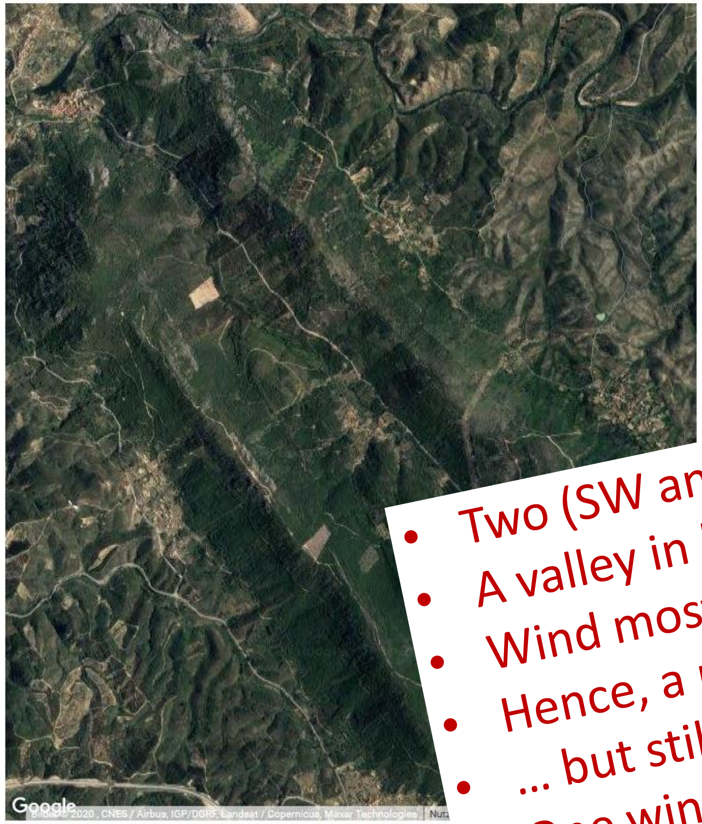
Why Perdigão ?

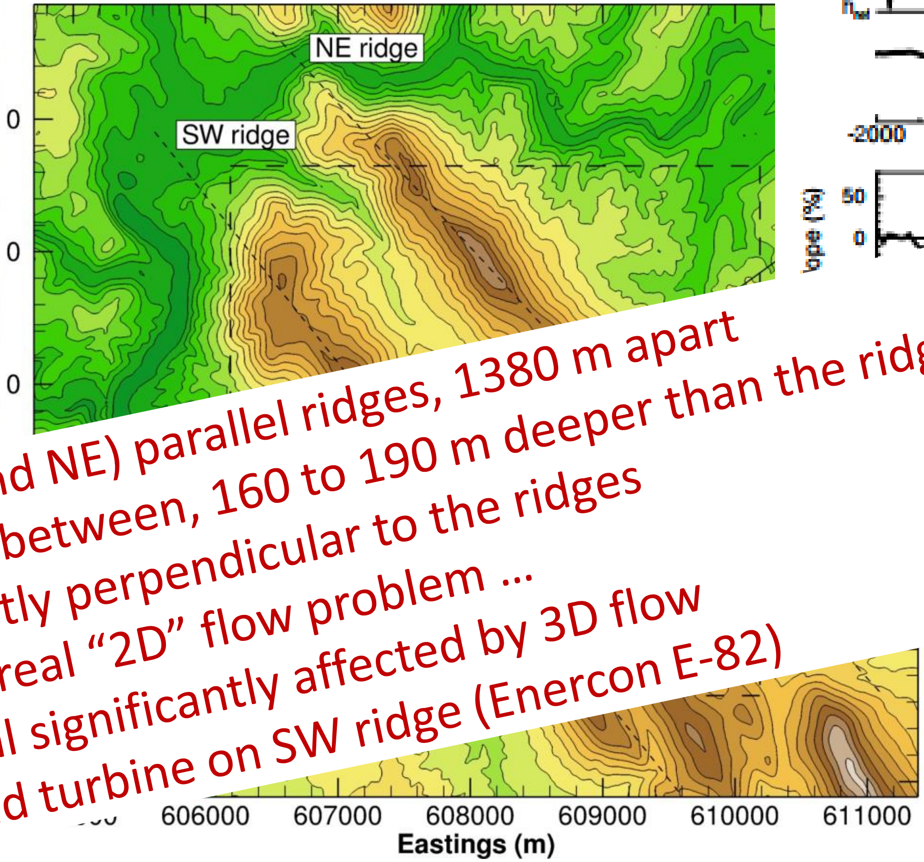
Site location



Regional Topography

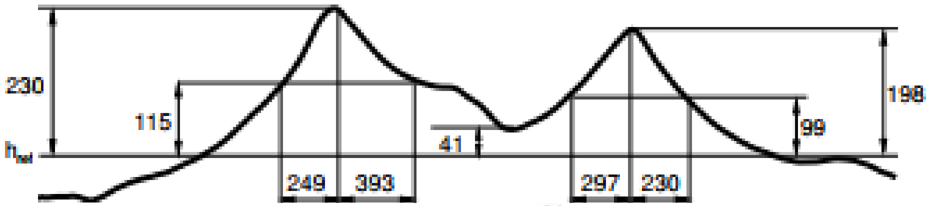
Why Perdigão ?

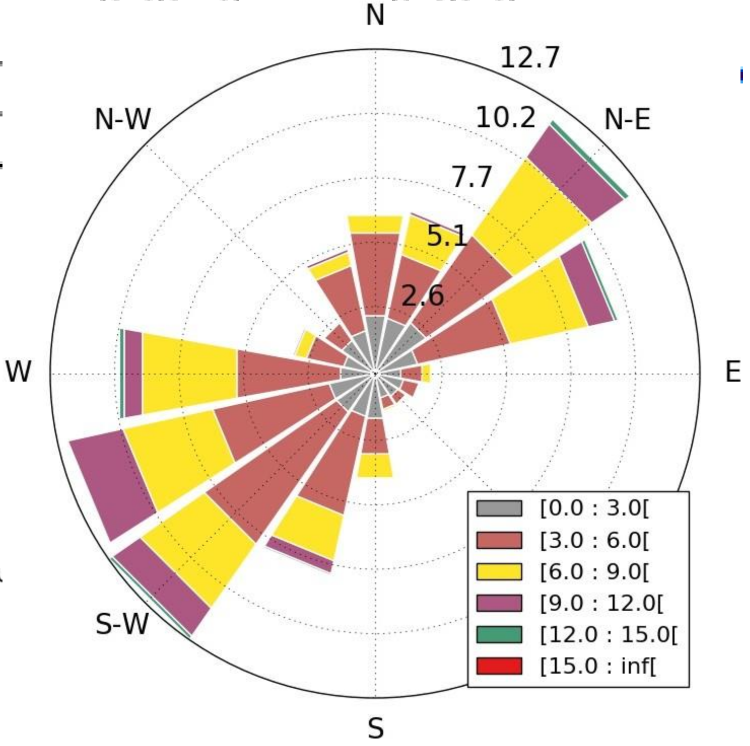




- Two (SW and NE) parallel ridges, 1380 m apart
- A valley in between, 160 to 190 m deeper than the ridges
- Wind mostly perpendicular to the ridges
- Hence, a real "2D" flow problem …
- … but still significantly affected by 3D flow
- One wind turbine on SW ridge (Enercon E-82)

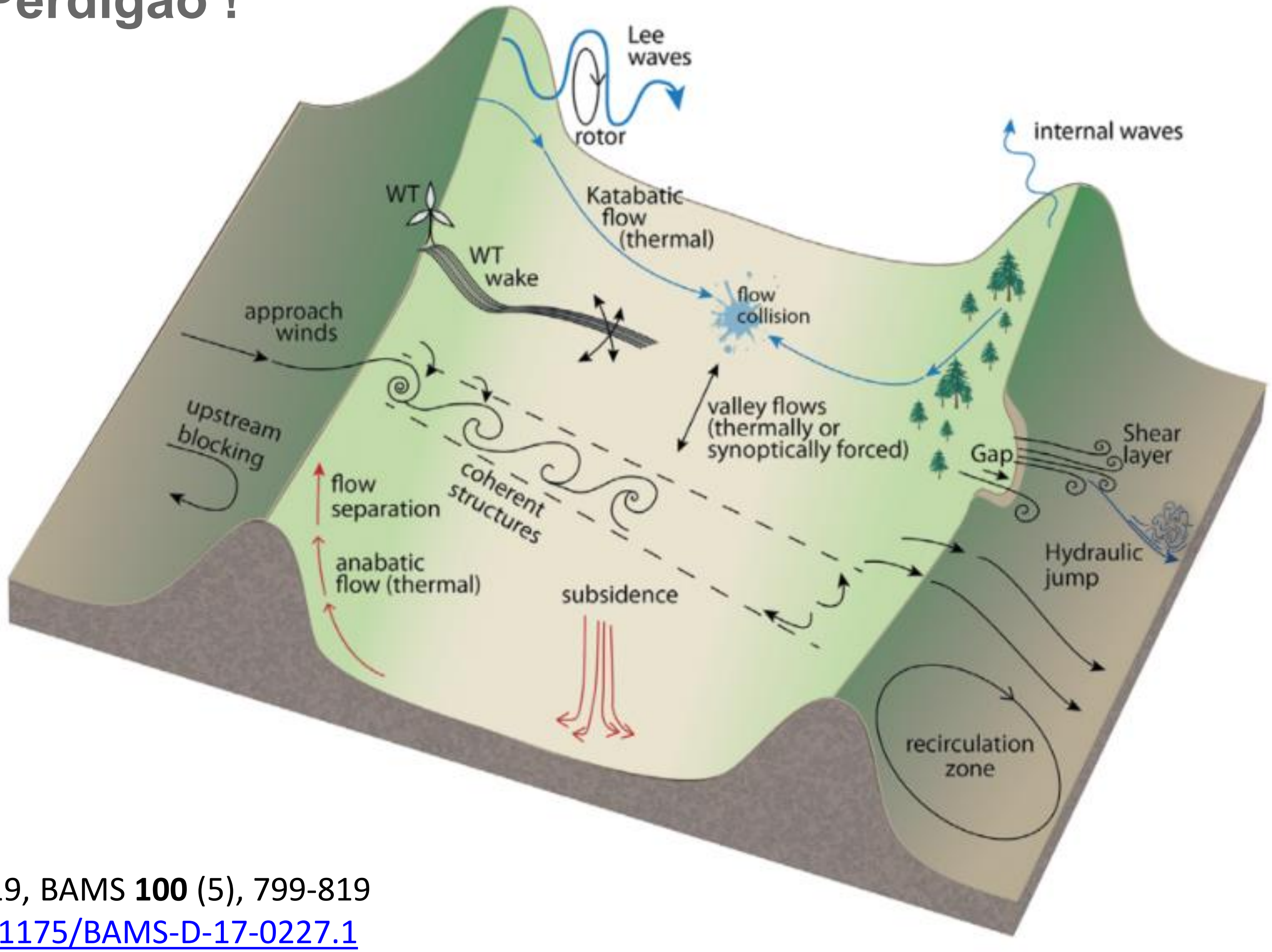
Local topography





Wind rose, April-June 2017

So, that's why Perdigão !



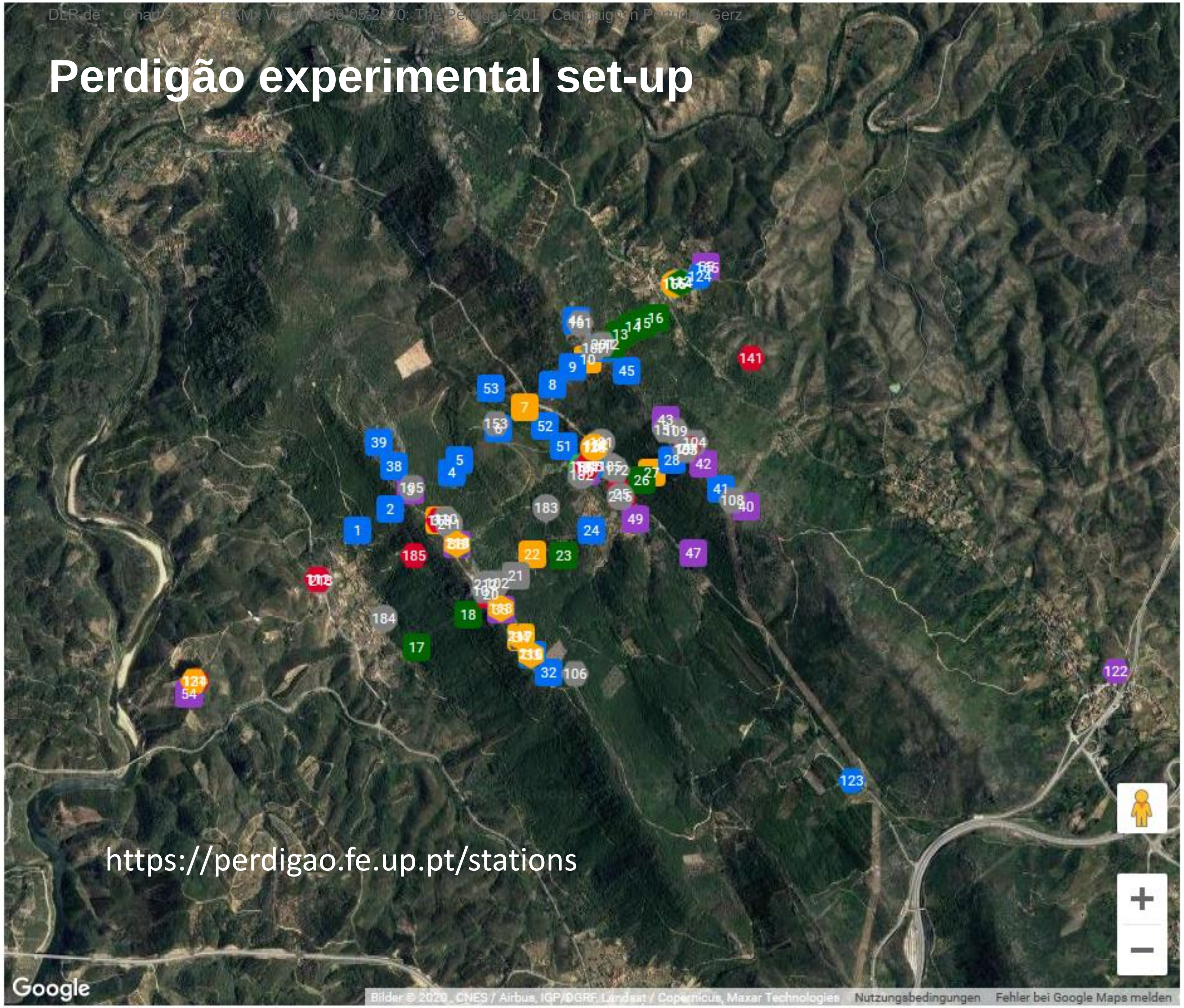
Fernando et al. 2019, BAMS **100** (5), 799-819
https://doi.org/10.1175/BAMS-D-17-0227.1

Perdigão experimental set-up

Originally designed as a NEWA validation experiment, the Perdigão experiment has become the largest of its kind through the contribution of international research groups.

- More than **180** sonic anemometers were installed on more than **40** towers
- **21** scanning and **7** profiling lidars were continuously measuring the flow field
- MWR, AERI, Sodar, Wind profiler, RASS, radiosondes, TLS and more...
- Area about 4 x 2 km² (across, parallel to the ridges)

Perdigão experimental set-up



https://perdigao.fe.up.pt/stations

Filter by category

Towers — All | None

- Towers-030
- Towers-060
- Towers-020
- Towers-010
- Towers-100
- Towers-002

Remote sensing — All | None

- Water vapor DIAL
- SODAR - RASS
- Scanning LIDAR
- MWR
- Profiling LIDAR
- Microbarometer
- Ceilometer
- AERI
- Profiling RADAR - RASS
- Scintillometer
- Profiling RADAR

Sounding sites — All | None

- Tethersonde
- Radiosonde

Ground sensors — All | None

- Seismometer

Noise monitoring — All | None

- Monitoring

Filter by overlays

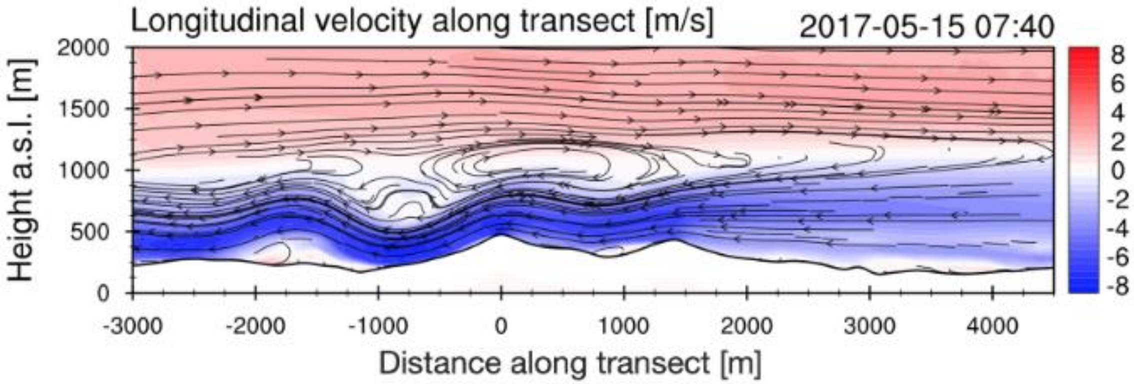
All | None

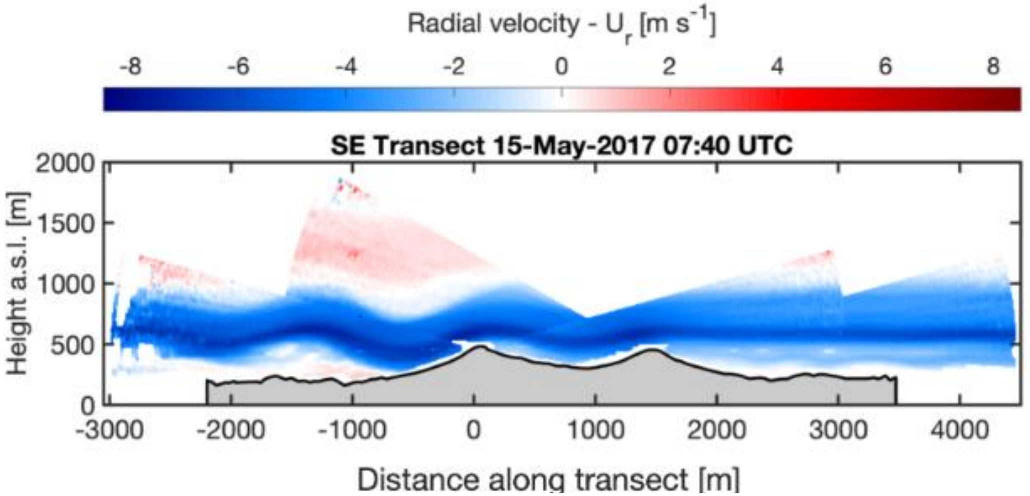
Exemplary results

Development of a nocturnal low-level jet from NE in a SW synoptic flow

Menke et al. 2019, Atmos. Chem. Phys., 19, 2713-2723, https://doi.org/10.5194/acp-19-2713-2019
Palma et al. 2019 *J. Phys.: Conf. Ser.* **1222** 012006 https://iopscience.iop.org/article/10.1088/1742-6596/1222/1/012006

WRF (3 domains) + VENTOS®/M (U-RANS) simulations by UPorto





RHI scans (2D) with long-range lidar by DTU (from 100 m to 3000 m)

On 14 May 2017, lidar scans show

- a SW flow prevailing in all layers

At midnight on 15 May 2017

- a low-level jet over the ridges is observed roughly until 11:00
- gravity waves with length equal to the inter-ridge distance occur with the LLJ
- stationary rotor 1500 m downstream of the downwind ridge

VENTOS®/M simulation

- with 40 m x 40 m x 4m resolution
- captures the flow well (incl. recirculation) until convection (turbulence) dominates (~15:00)

See video at DTU at: doi.org/10.11583/DTU.7863482

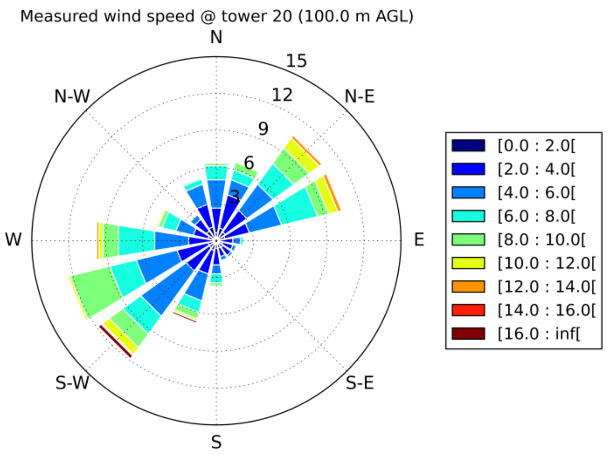
DLR

Exemplary results

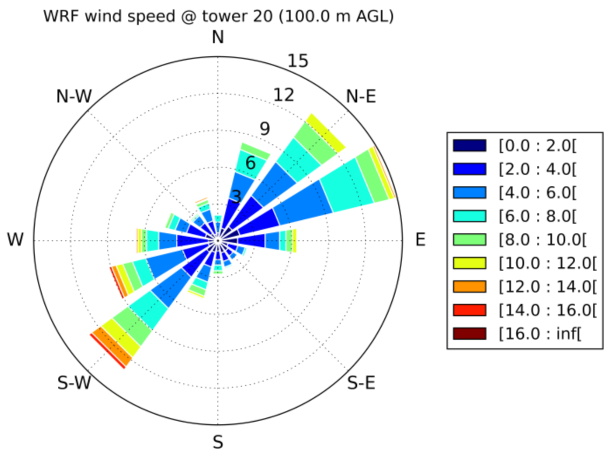
WRF simulations by DLR: long run (6 weeks) - D3 with tower 20 data (SW ridge)

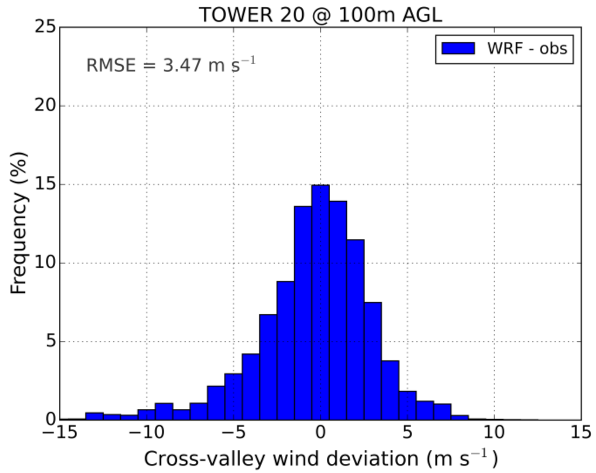
Wagner et al. 2019, Atmos. Chem. Phys., 19, 1129-1146, https://doi.org/10.5194/acp-19-1129-2019,

TOWER

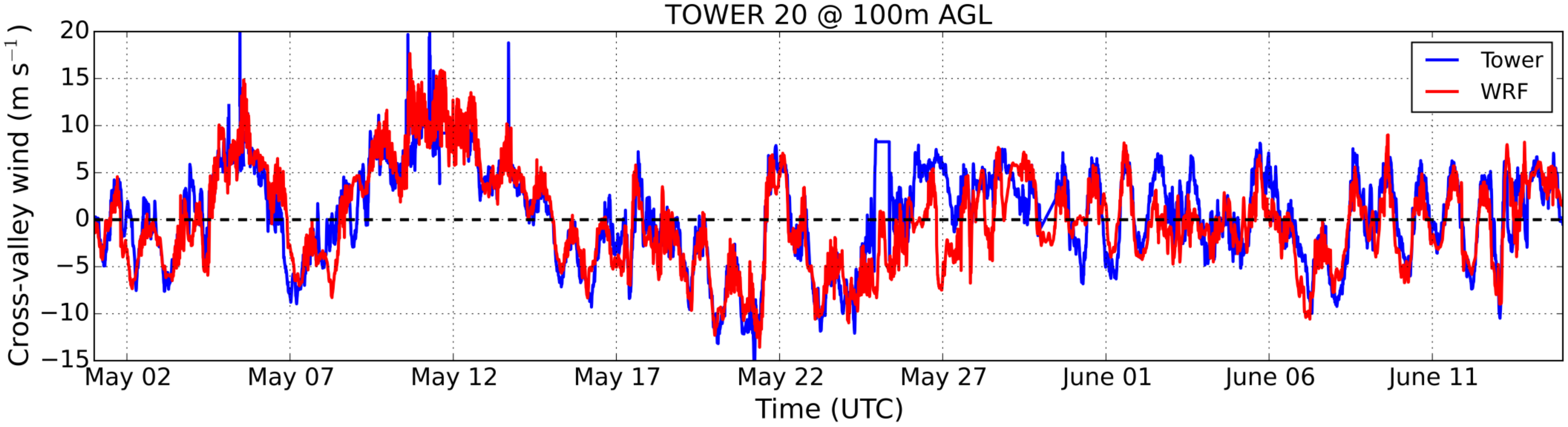


WRF





Cross-valley wind



DLR

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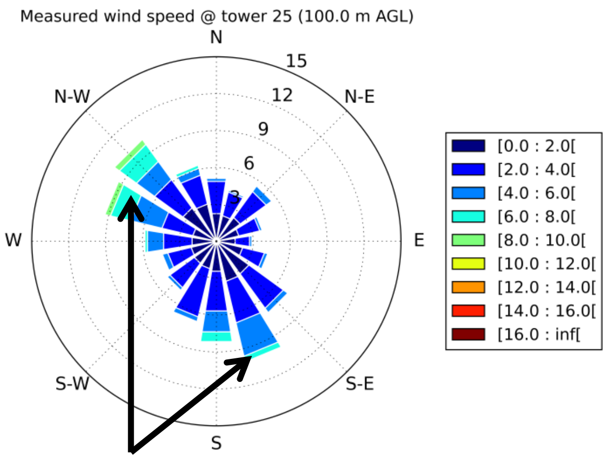
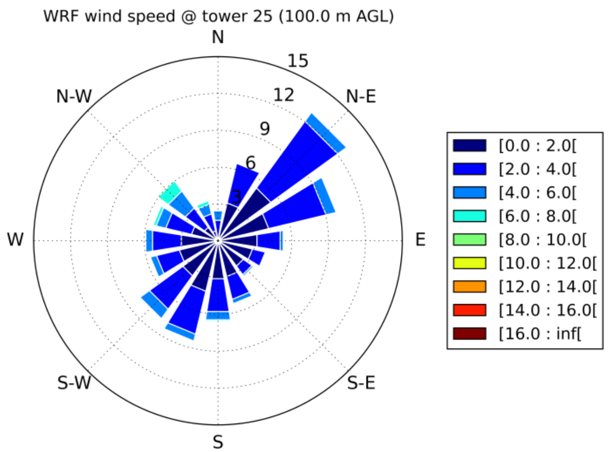
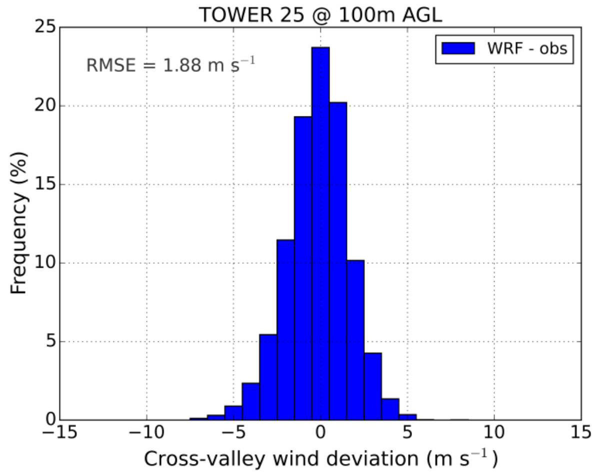
Wagner et al. 2019, Atmos. Chem. Phys., 19, 1129-1146, https://doi.org/10.5194/acp-19-1129-2019,

TOWER

WRF

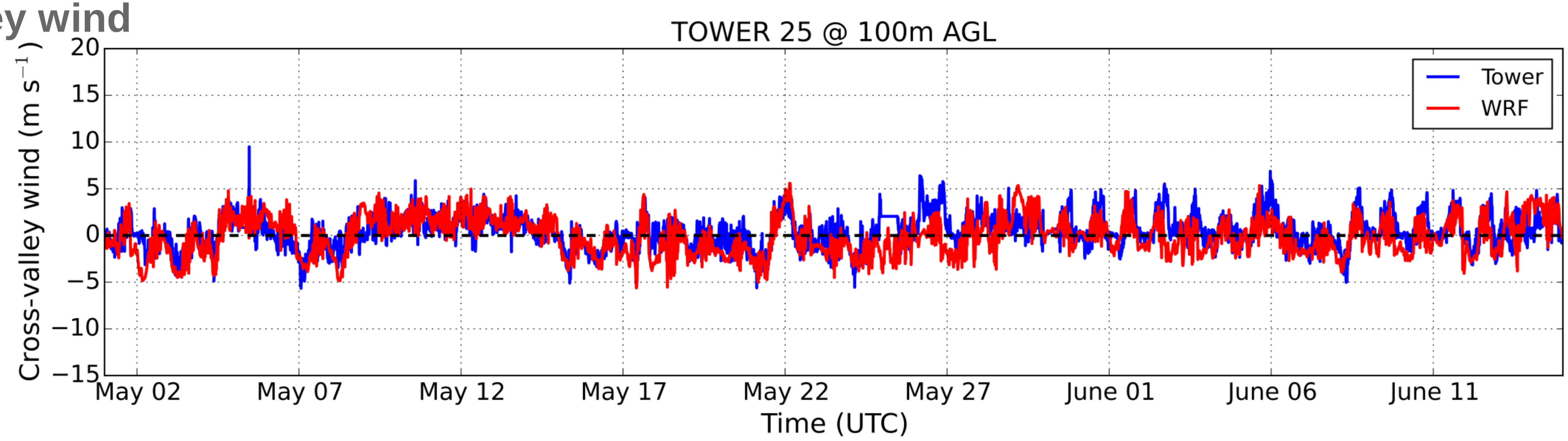






flow around topography ?

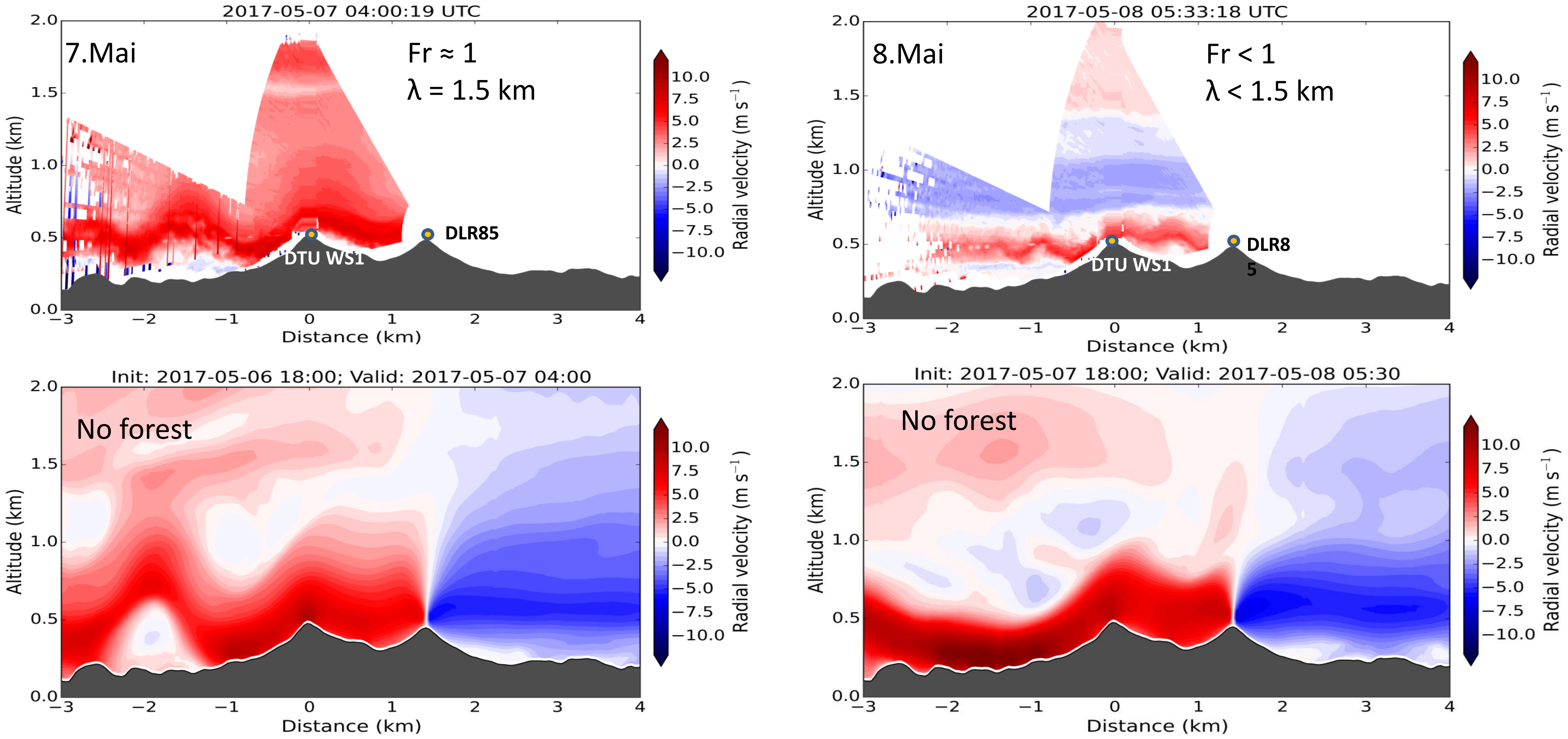
Cross-valley wind



Exemplary results

WRF by DLR: short runs – radial velocity of real and simul. lidar – LLJ from NE

Wagner et al. 2020, Wind Energy Sci. Discussion, 19, 1129-1146, https://doi.org/10.5194/wes-2019-77



Exemplary results

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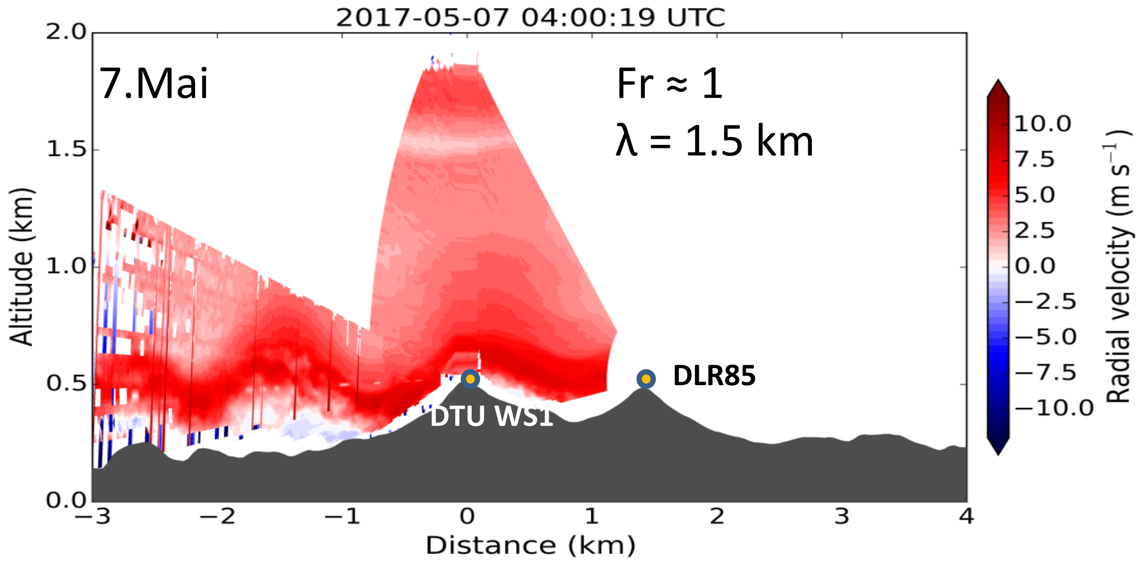
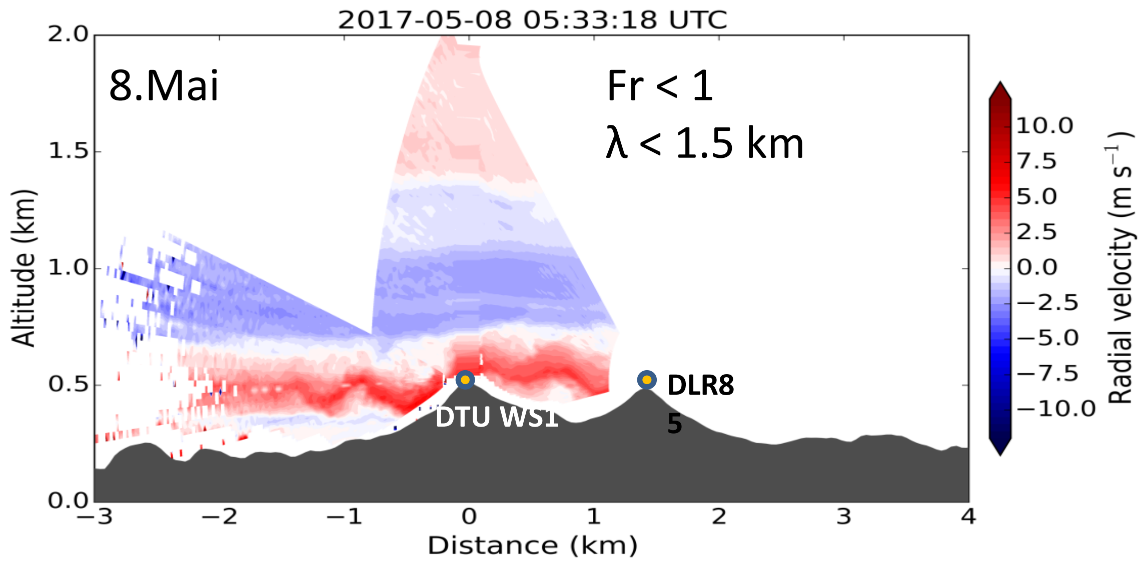
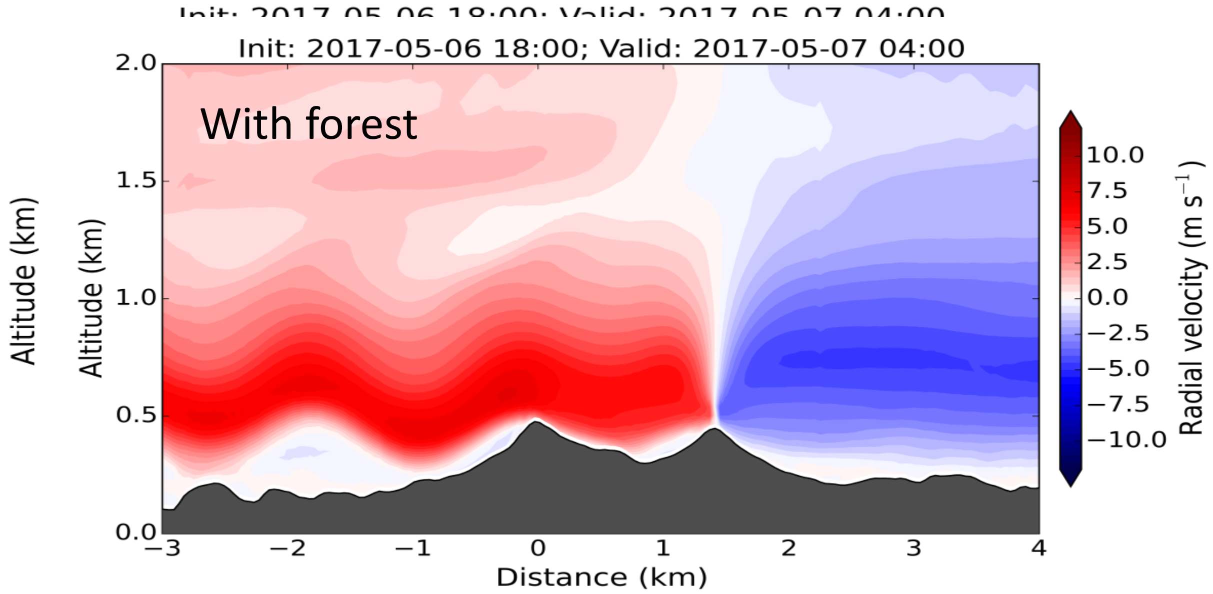
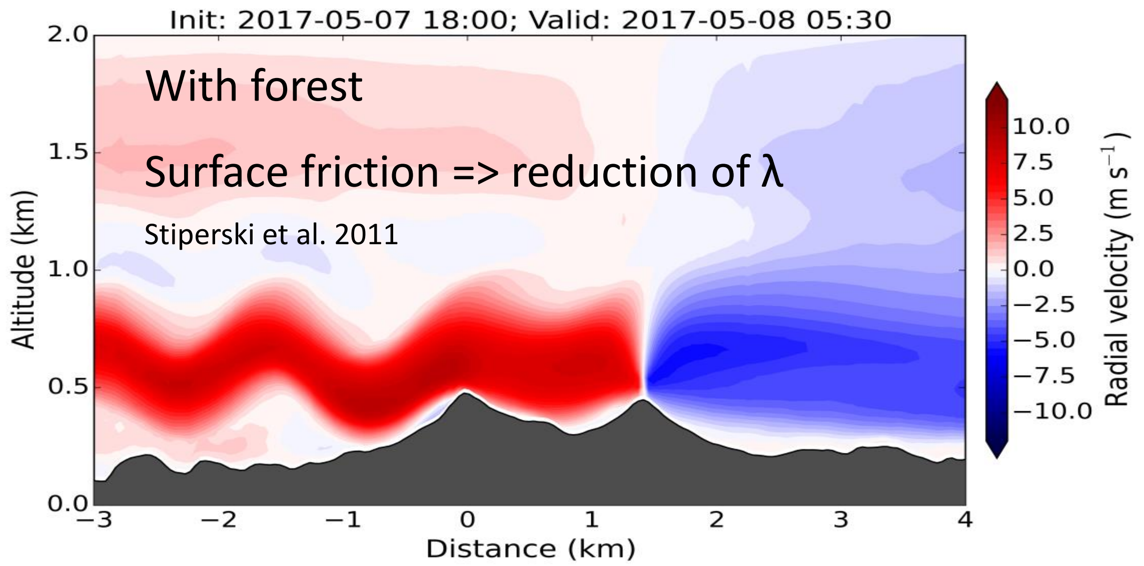






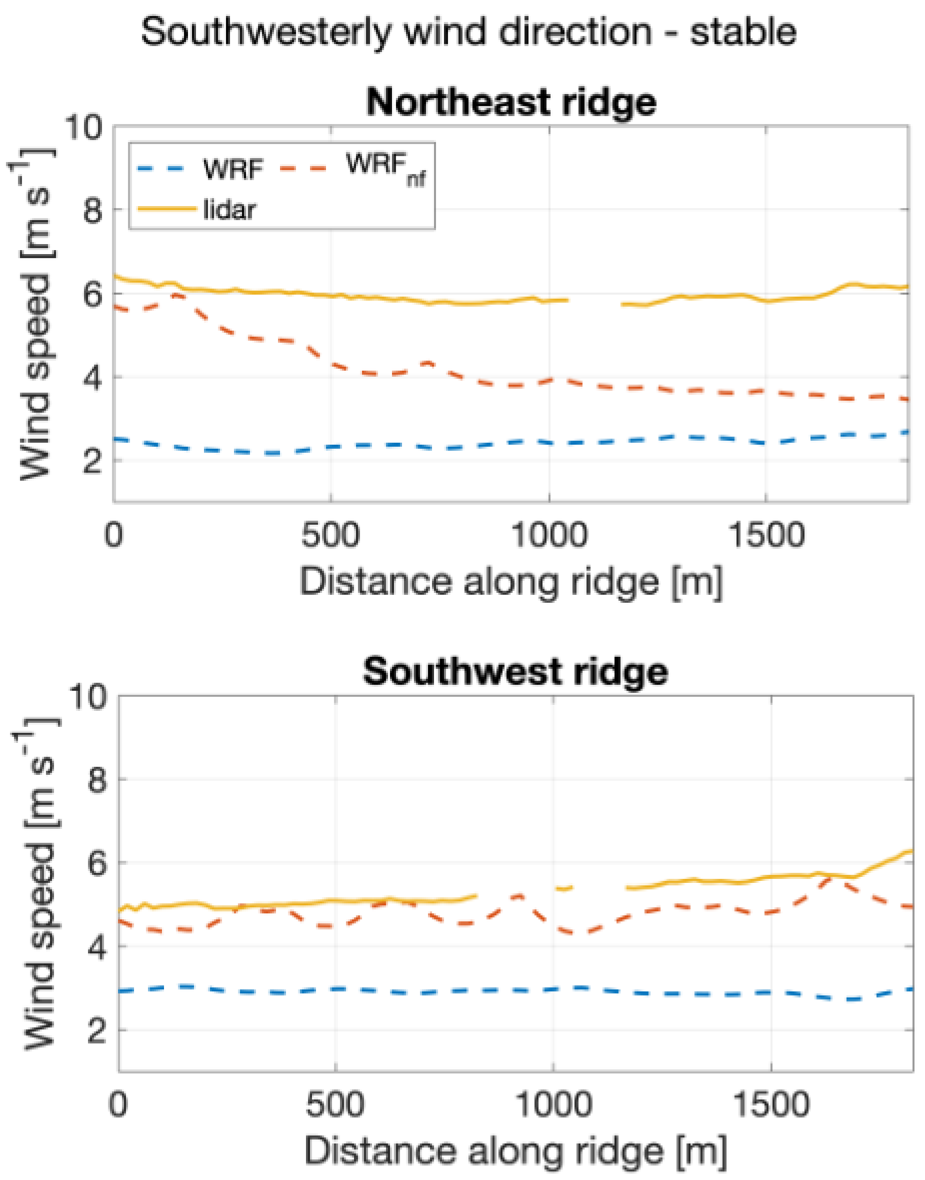


Exemplary Results

Wind speed along ridges: DTU lidars versus DLR WRF

South-westerly flow under stable conditions (averaged over all ridge-scan periods)

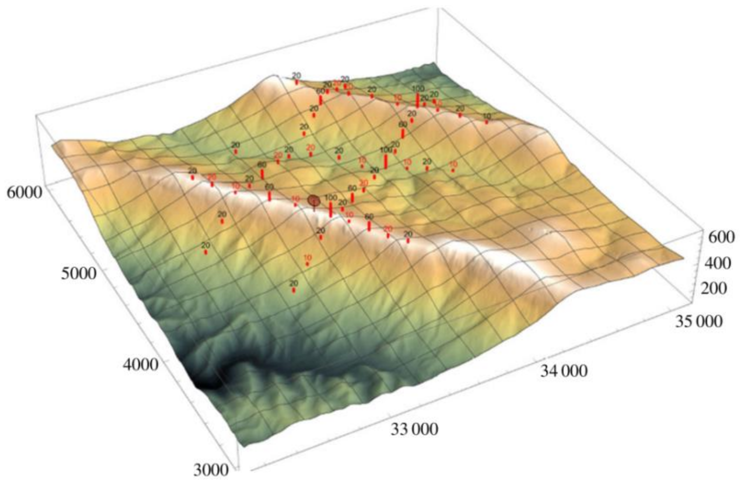
- Better agreement for WRF **without** forest drag parameterization
- WRF **with** forest drag underestimates wind speeds significantly ~30%, but:
  - correlation coefficients are improved
  - changes along ridges more similar to lidar measurements
  - better performance for masts located on slopes
- Forest drag is probably over-represented due to incorrect forest coverage on the ridge tops and too high trees in the model.

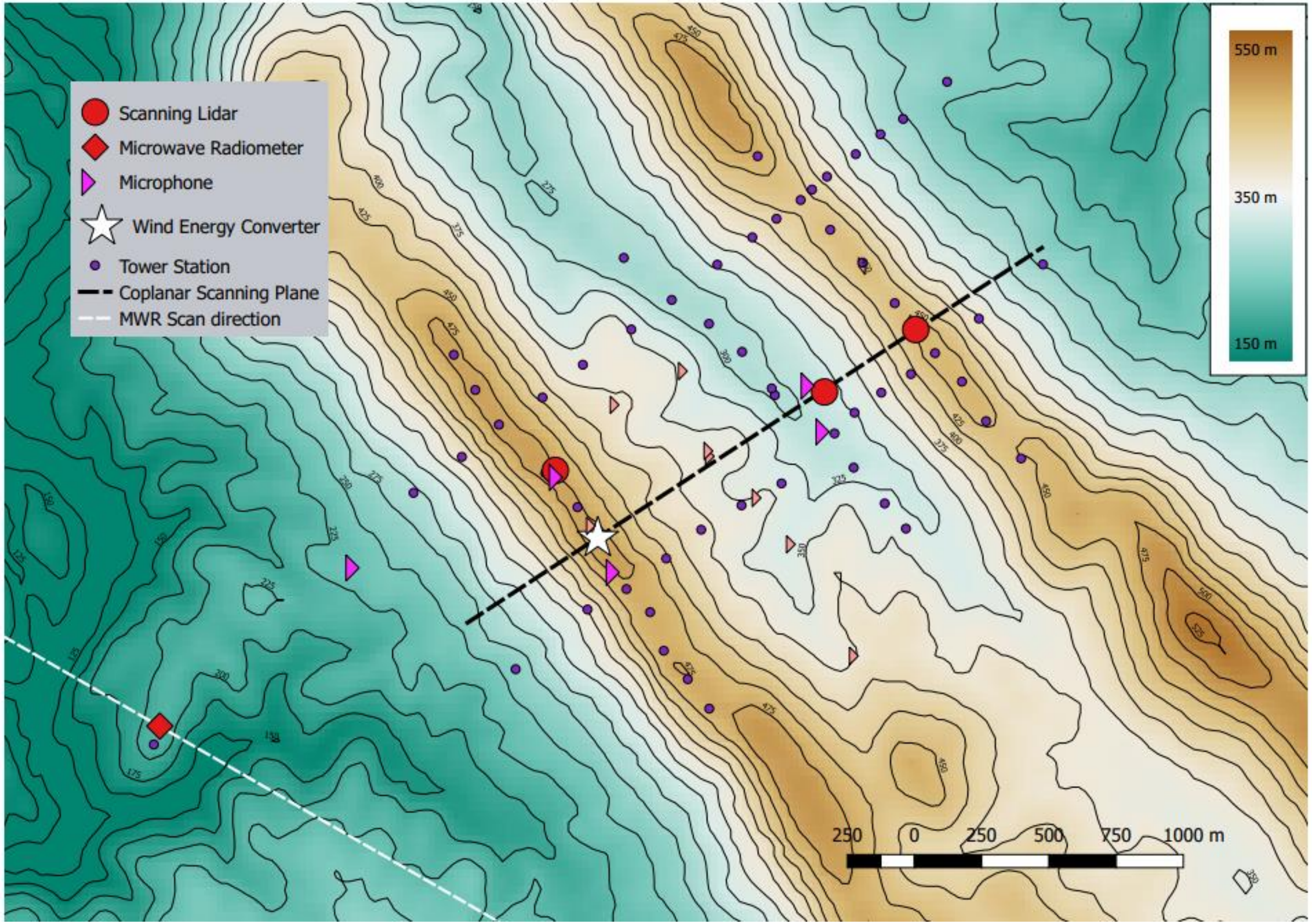


Menke et al. 2020, Wind Energy Sci.-Discussion, https://doi.org/10.5194/wes-2019-85

Perdigão experimental set-up of DLR

Wind turbine wake flow





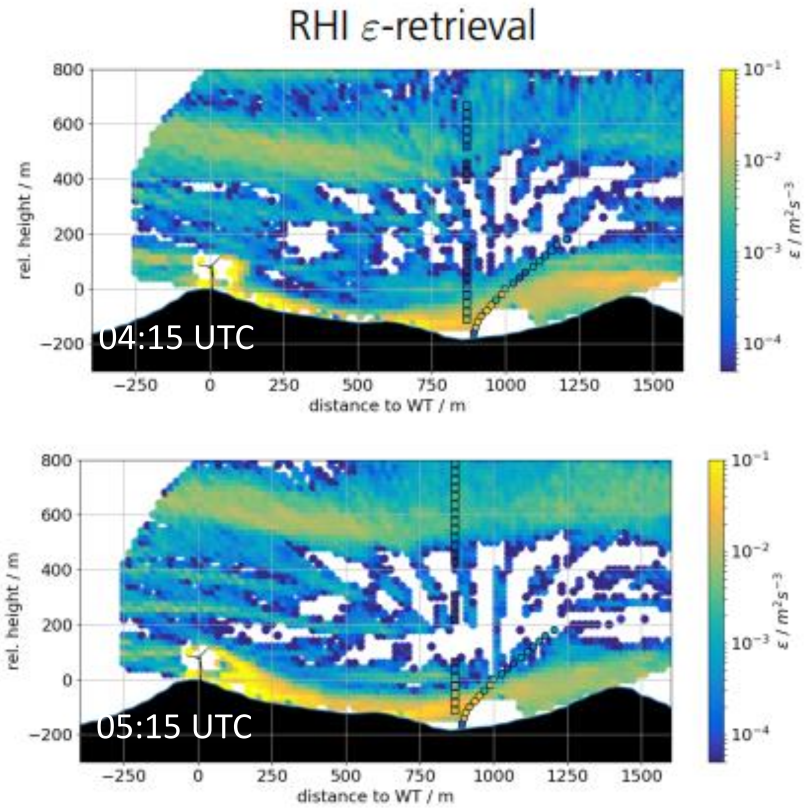
Wildmann et al. 2018, Atmos. Meas. Tech., 11, 3801–3814, https://doi.org/10.5194/amt-11-3801-2018

Perdigão experimental set-up of DLR

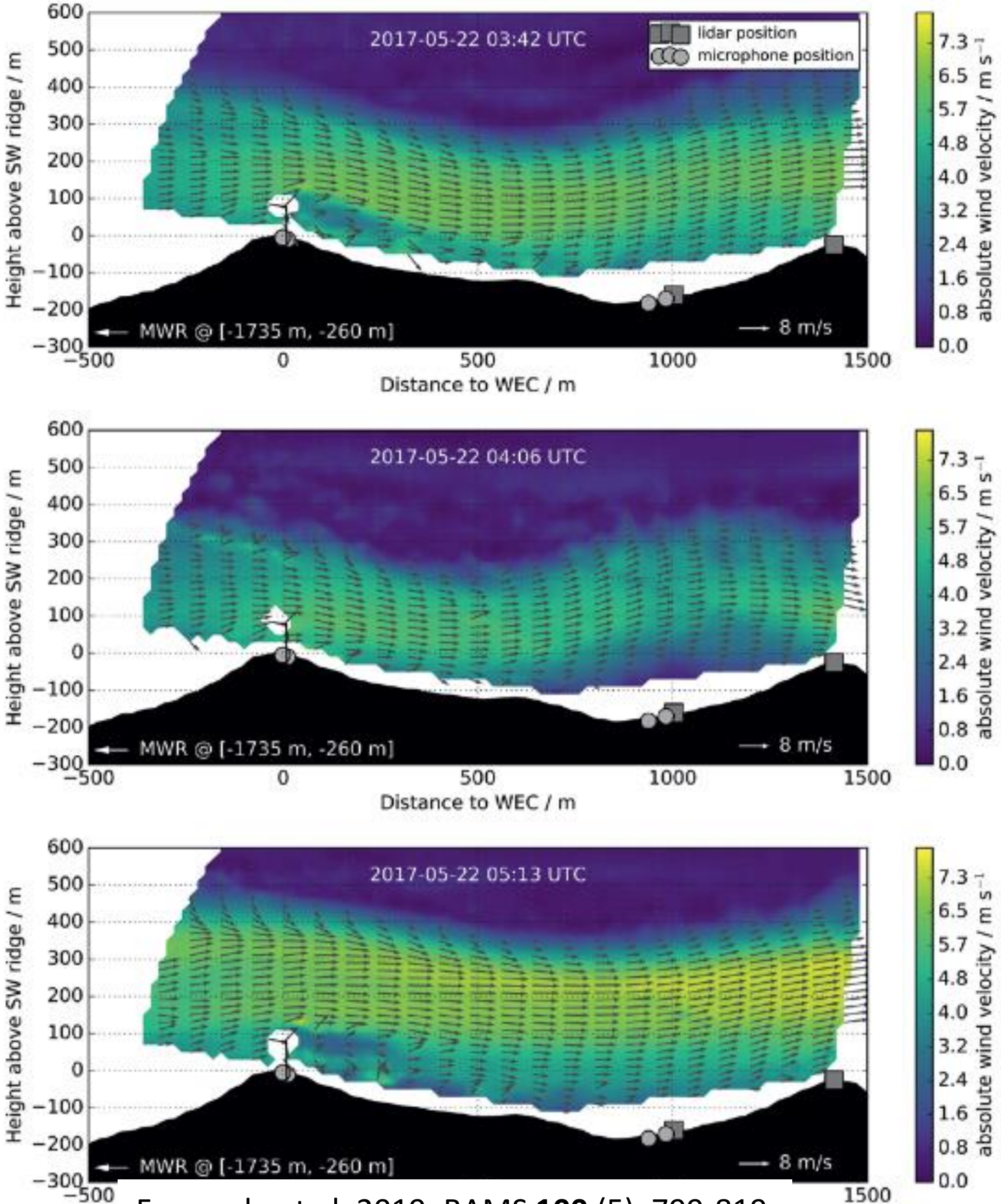
Coplanar scans for wind and turbulence

Low-level jet and wake flow, 22 May 2017

- At 04:06 UTC the wind turbine stopped for on hour
- Visible in wind and turbulence lidar data
- Lidar provides spatial distribution of turbulence



Wildmann et al. 2019, *Atmos. Meas. Tech. Disc.*
https://doi.org/10.5194/amt-2019-171



Fernando et al. 2019, BAMS **100** (5), 799-819
https://doi.org/10.1175/BAMS-D-17-0227.1

Lessons learned

Instrumentation

- “Think big !“
- In complex terrain, the number of instruments makes a difference to study micro-scale effects
- Combination of in-situ and remote sensing instruments has proven to be very valuable
- Simple, continuous lidar measurements with the same measurement strategy are most valuable
- Combine multiple lidar and radar (x-band) ?
- Stronger focus on along-valley flow with scanning lidars would have been beneficial
- (state-of-the-art) scanning lidars are subject to continuous maintenance and availability can be low if systems fail (backup for important measurements is advisable, see also Dissertation of Robert Menke, 2020)
- More inflow measurement would be important for initialization of numerical models (Temperature, humidity, wind profiling)
- UAV (fixed-wing and multirotor) systems could fill a missing gap in flexible in-situ (turbulence) measurements above tower heights

Numerical Modelling with WRF

- High resolution (“blended”) topography and (up-to-date) land-use data mandatory (beneficial) to model microscale processes (Perdigão high resolution scan was two years old)
- Better roughness length data probably not so useful ?
- Instead modelling “porous topography” explicitly to obtain sufficient drag in the lowest model levels

Acknowledgements, publications and data access

Presentation based on work from

- Norman Wildmann, Martin Hagen, Johannes Wagner (DLR)
- The USA research groups: U of Notre Dame, Colorado, Oklahoma, Cornell, Berkley; NCAR; ARL
- The European research groups: U of Porto, DTU, IPMA, INEGI, LNEG

Publications

- World's largest wind-mapping project spins up in Portugal: Nature, International weekly journal of science, Feb 2017
- Monitoring Wind in Portugal's Mountains Down to Microscales: Earth & Space Science News, 98, May 2017
- The Perdigão: Peering into Microscale Details of Mountain Winds: American Meteorol. Soc. Bulletin (BAMS), May 2019
- WES/ACP/AMT joint special issue https://www.atmos-meas-tech.net/special_issue636_946.html
- Further publications at https://www.eol.ucar.edu/node/11767/publications

More information at and data access via

- https://perdigao.fe.up.pt/
- http://doi.org/10.17616/R31NJMN4
- https://www.eol.ucar.edu/field_projects/perdigao