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ATMOSPHERE TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

Improving Mesoscale-Microscale Coupling

July 28, 2023

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Wind turbines operate in a complex environment

- DOE designed the Mesoscale Microscale Coupling (MMC) project to create modeling approaches for real atmospheres
  - Turbulent inflow to the **wind farm**
  - Realistic cases with **non-steady** conditions

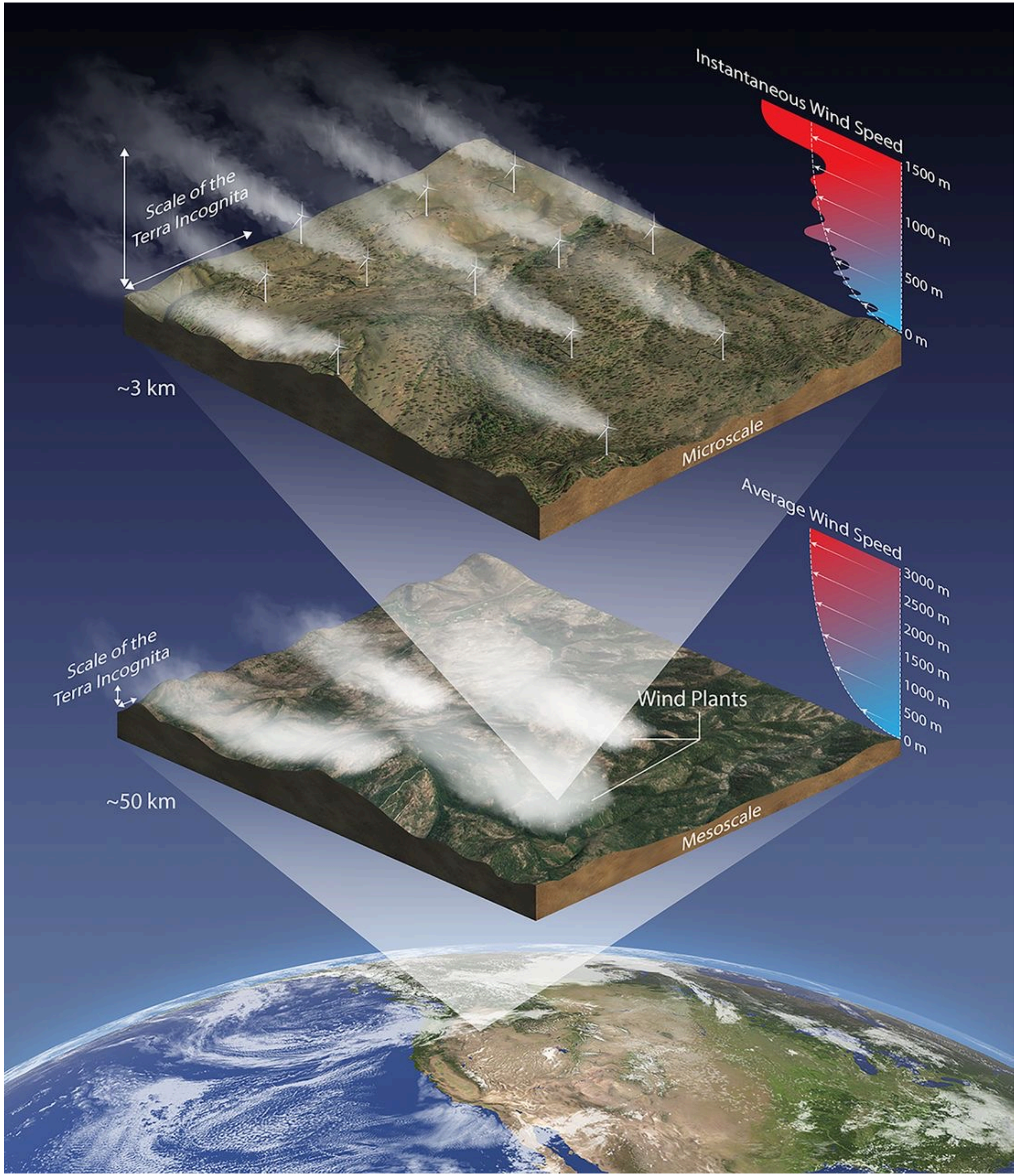

Figure from Veers et al., 2019

MMC was a large multi-lab project

Leverage experience of atmospheric and computational scientists from national laboratories across the US

ON BRIDGING A MODELING SCALE GAP

Mesoscale to Microscale Coupling for Wind Energy

SUE ELLEN HAUPT, BRANKO KOSOVIC, WILLIAM SHAW, LARRY K. BERG, MATTHEW CHURCHFIELD, JOEL CLINE, CAROLINE DRAXL, BRANDON ENNIS, EUNMO KOO, RAO KOTAMARTHI, LAURA MAZZARO, JEFFREY MIROCHA, PATRICK MORIARTY, DOMINGO MUÑOZ-ESPARZA, ELIOT QUON, RAJ K. RAI, MICHAEL ROBINSON, AND GOKHAN SEVER

This work has advanced coupled mesoscale to microscale modeling through the terra incognita, generating turbulence at the microscale, testing coupling techniques, and assessing results relevant for wind energy applications.

https://doi.org/10.5194/wes-2022-113
Preprint. Discussion started: 15 December 2022

eawe european academy of wind energy
Open Access WIND ENERGY SCIENCE DISCUSSIONS

Lessons learned in coupling atmospheric models across scales for onshore and offshore wind energy

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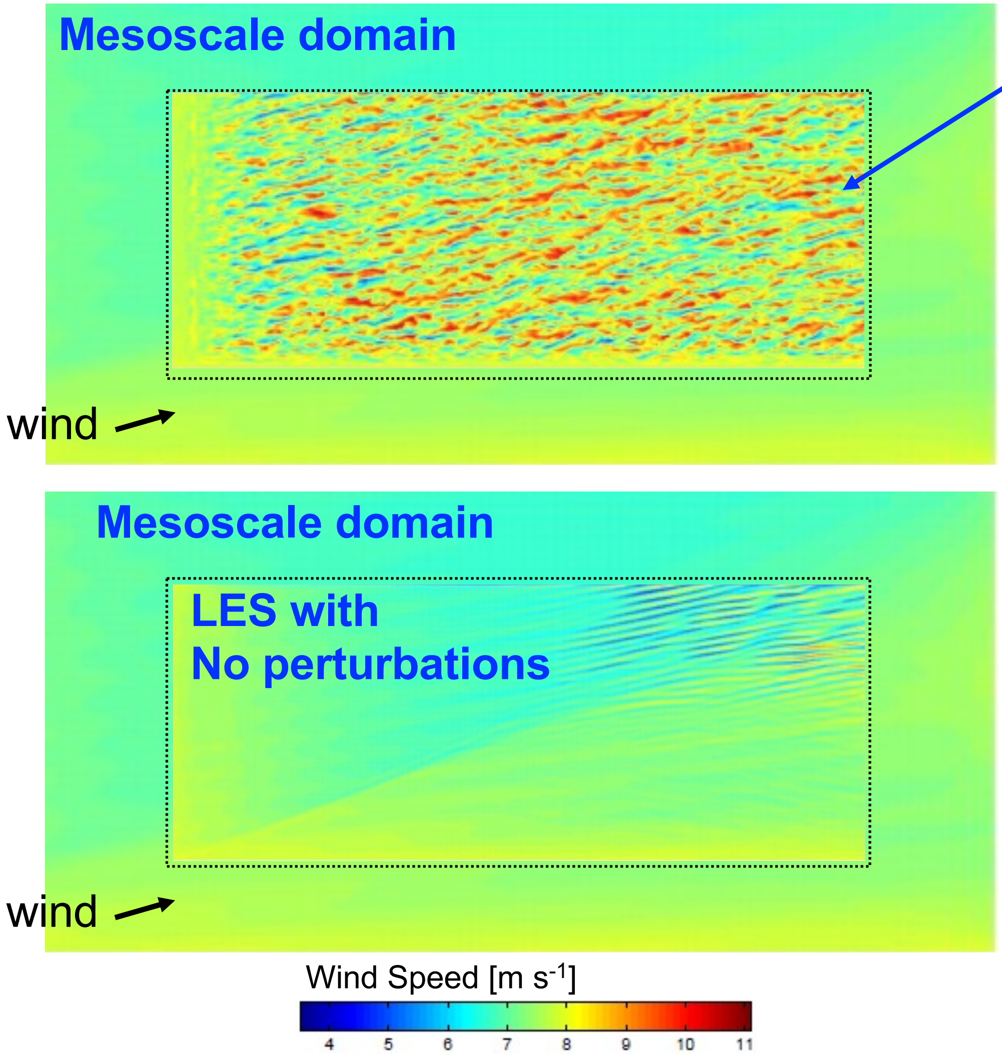
MMC project goals

- Improve computational performance of coupled MMC models through the development of methods to reduce turbulence spin-up time
- Develop guidance for the community describing the best ways to couple models, including specific spatial scales at which the handoff to the microscale model should occur
- Transition MMC approaches for offshore conditions
- Explore machine learning approaches for bridging meso- and microscales
- Prepare documentation and a suite of software tools that can be used by the community

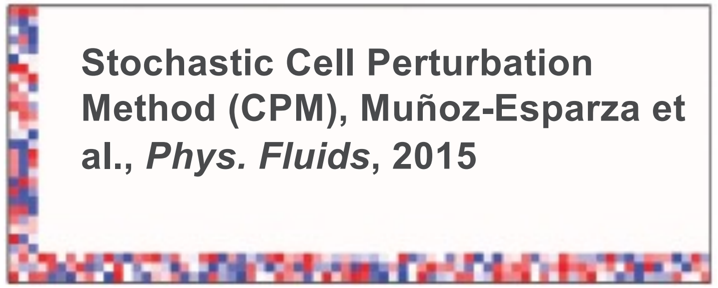
Inflow perturbation methods are critical to developing accurate turbulent flow fields in LES

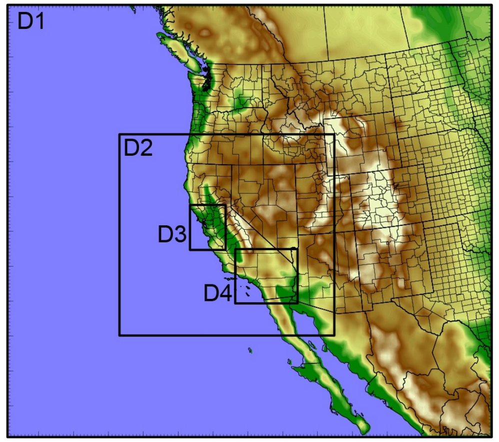
Slow turbulence development increases computational cost and reduces physical fidelity

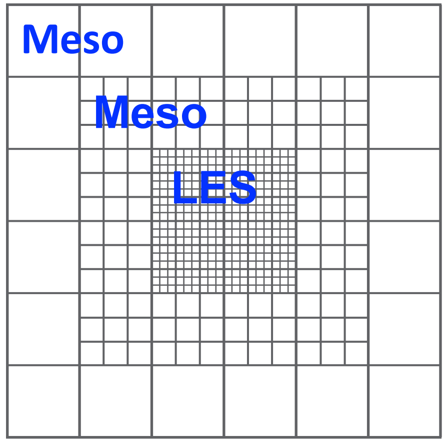
- Mesoscale simulations are too coarse to capture turbulence, effects on mean flow are parameterized
- Nested LES can explicitly resolve turbulence in the flow, but it takes time to develop
- Generalization of the approach



Nested LES domain with stochastic perturbations applied at inflow boundaries







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Lawrence Livermore National Laboratory

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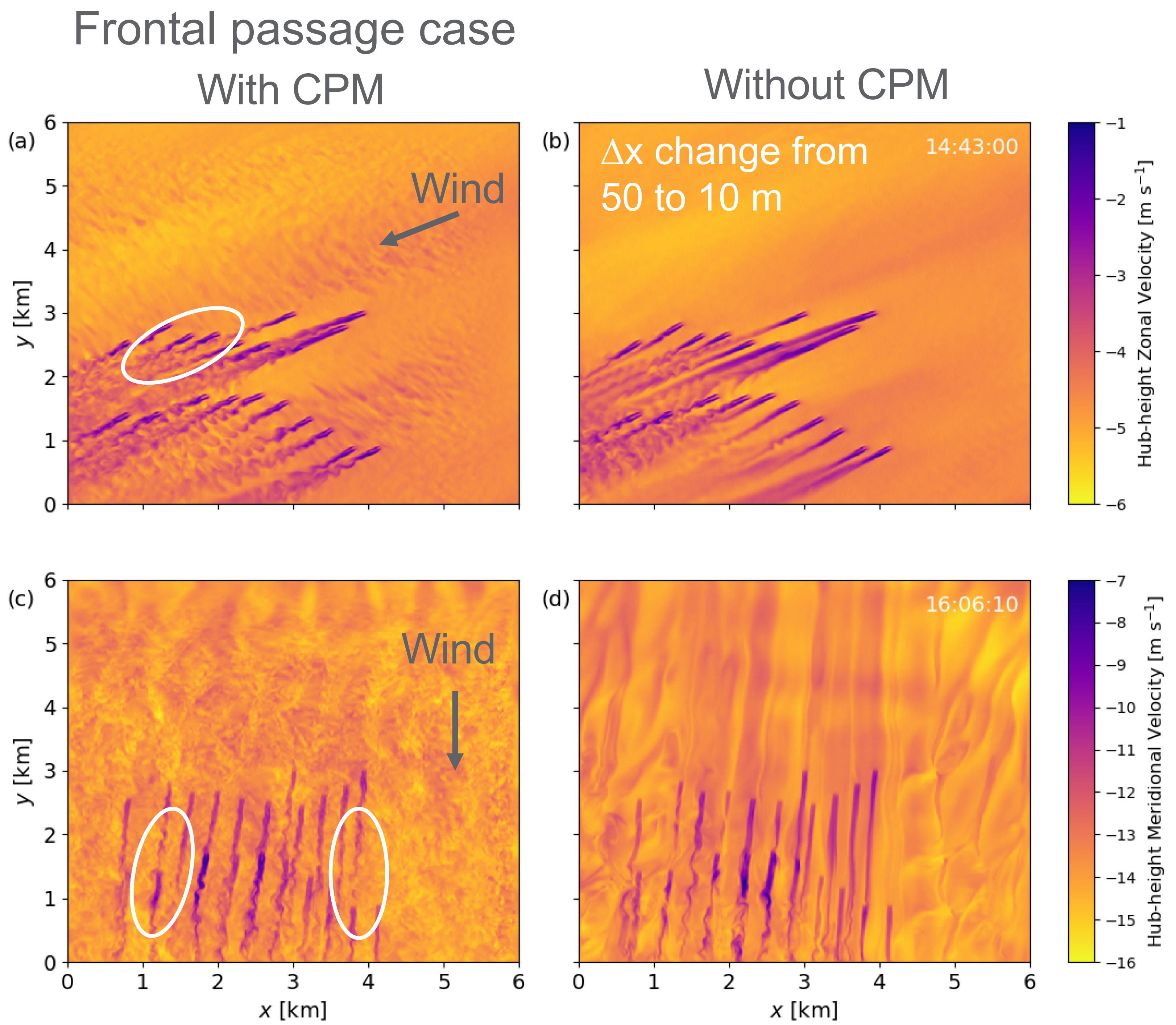
CPM has been applied in a multiscale wind plant simulation

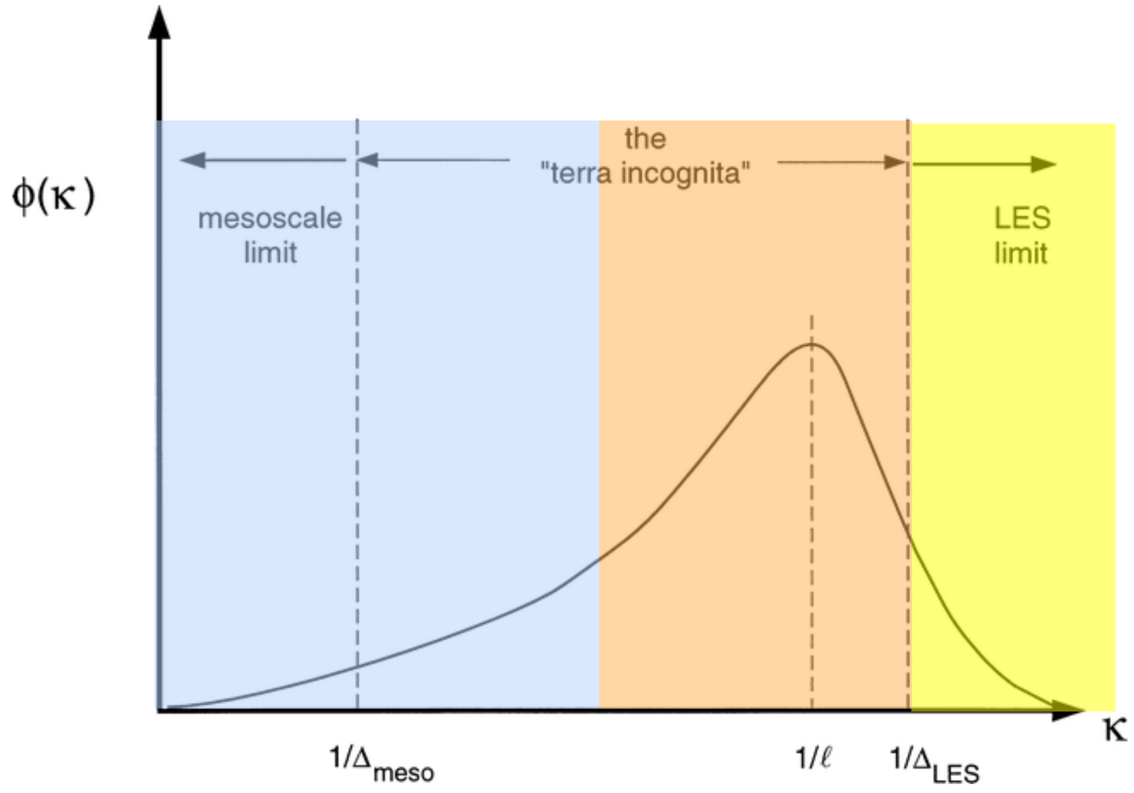
- 5 WRF domains with generalized actuator disk to represent wind turbines
- Addition of CPM adds additional detail to the inflow and wake



Arthur, R. S., J. D. Mirocha, N. Marjanovic, B. D. Hirth, J. L. Schroeder, S. Wharton, and F. K. Chow, 2020: Multi-scale simulation of wind farm performance during a frontal passage, *Atmosphere*, **11**, 245, https://doi.org/10.3390/atmos11030245

Accounting for Terra Incognita in coupled simulations

- Terra Incognita:
  - Mesoscale grid spacing does not allow sufficient eddies for spatial and temporal average
  - LES grid spacing close to the energy containing scales
- Coupled simulations of WRF-(WRF-LES) requires changes in grid spacing from 10’s of km to 10’s of meters
- How to handle Terra Incognita?

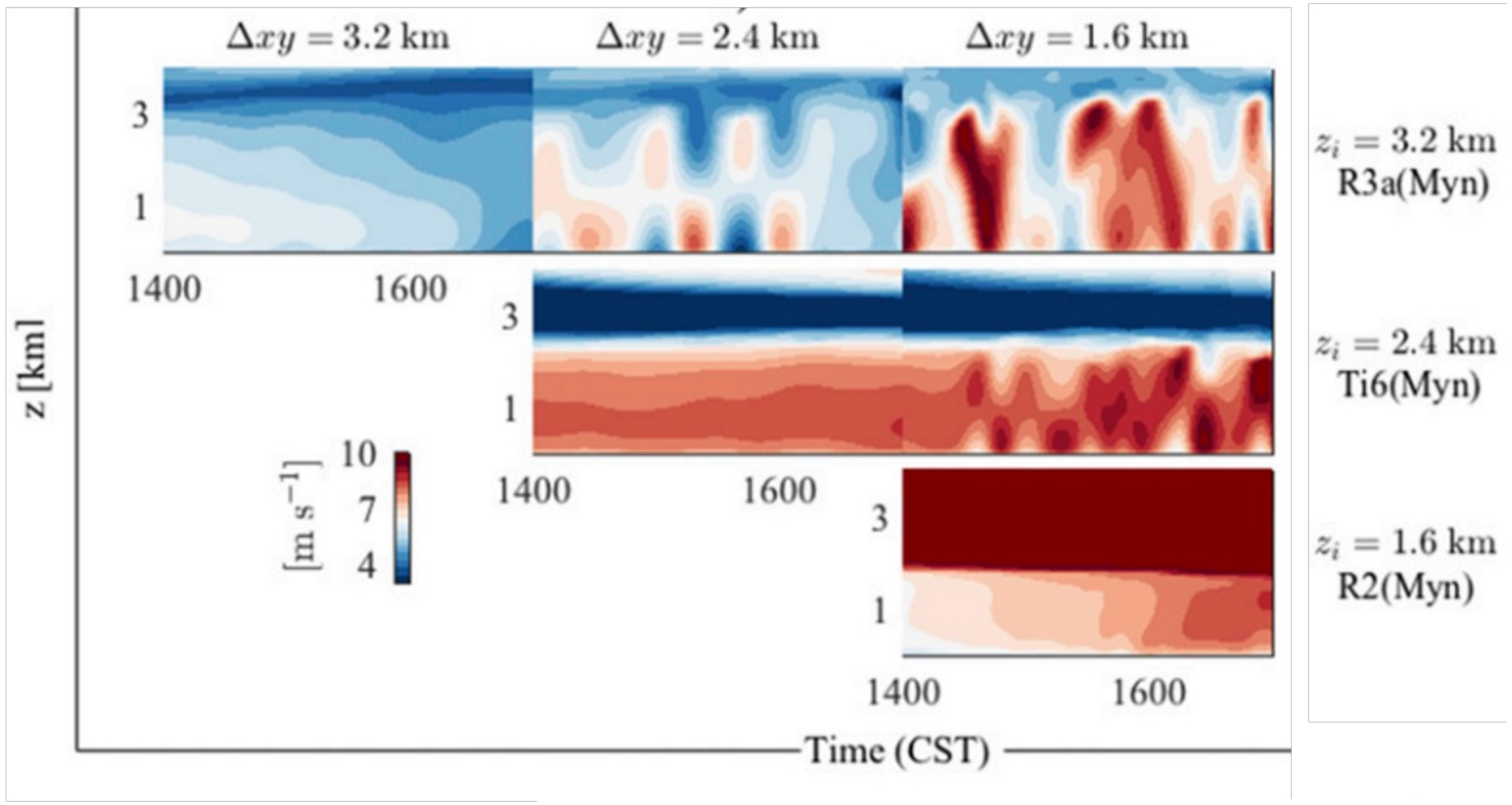


Wyngaard, JAS, 2004

Simulations in Terra Incognita: Horizontal grid spacing

- Spurious secondary structures (off diagonal panels) for grid spacing smaller than z_i
- Best practice: *Mesoscale simulations should be configured with $\Delta x > z_i$*

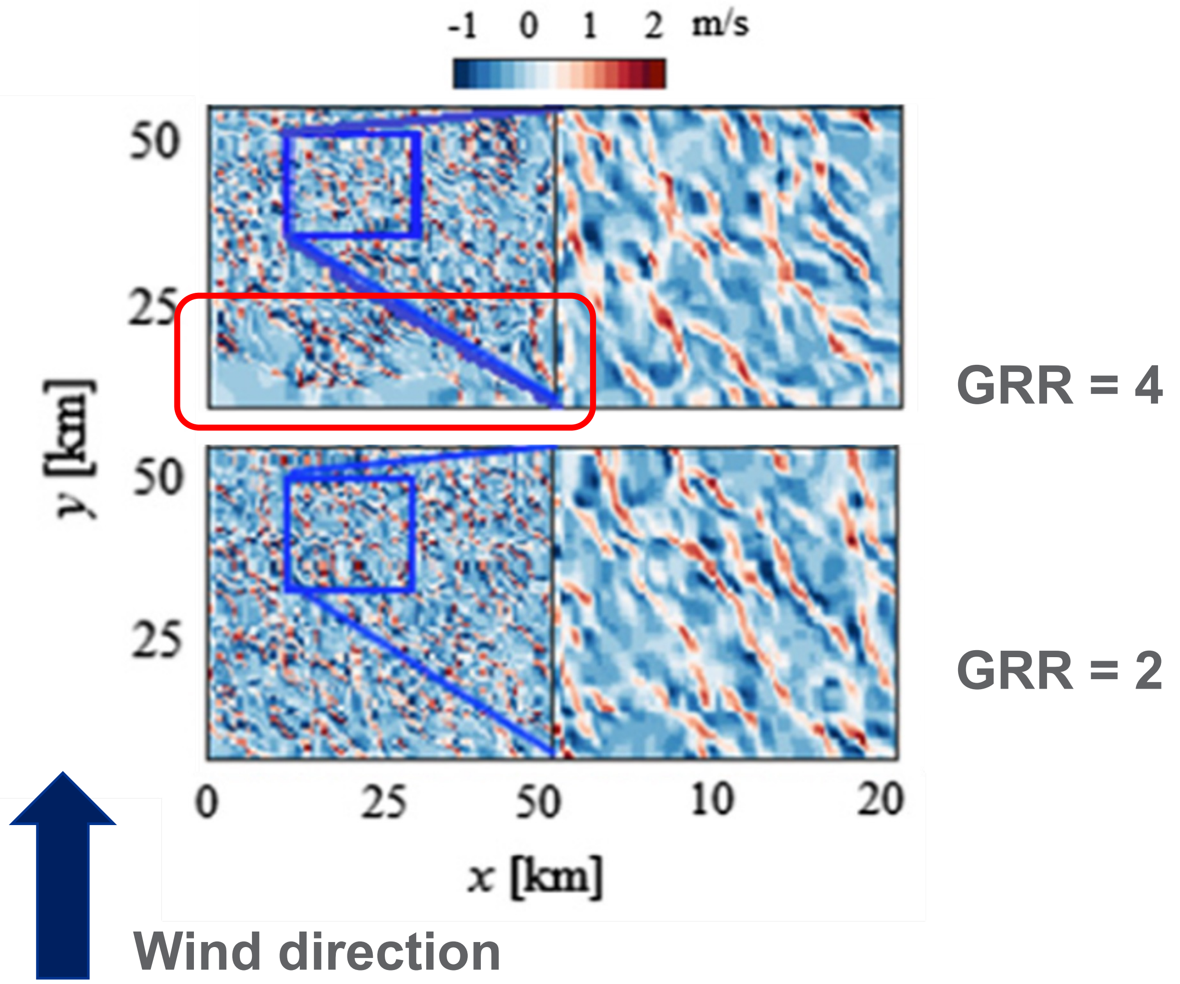
- Simulations with WRF using the MYNN turbulence parameterization
  - Boundary-layer depth (z_i): 3.2, 2.4, and 1.6 km
  - Grid spacing: 3.2, 2.4, and 1.6 km



Rai, R. K., Berg, L. K., Kosović, B., Haupt, S. E., Mirocha, J. D., Ennis, B. L., & Draxl, C. (2019). Evaluation of the impact of horizontal grid spacing in terra incognita on coupled mesoscale–microscale simulations using the WRF framework. *Monthly Weather Review*, *147*(3), 1007-1027.

Simulations in Terra Incognita: Grid refinement ratio (GRR)

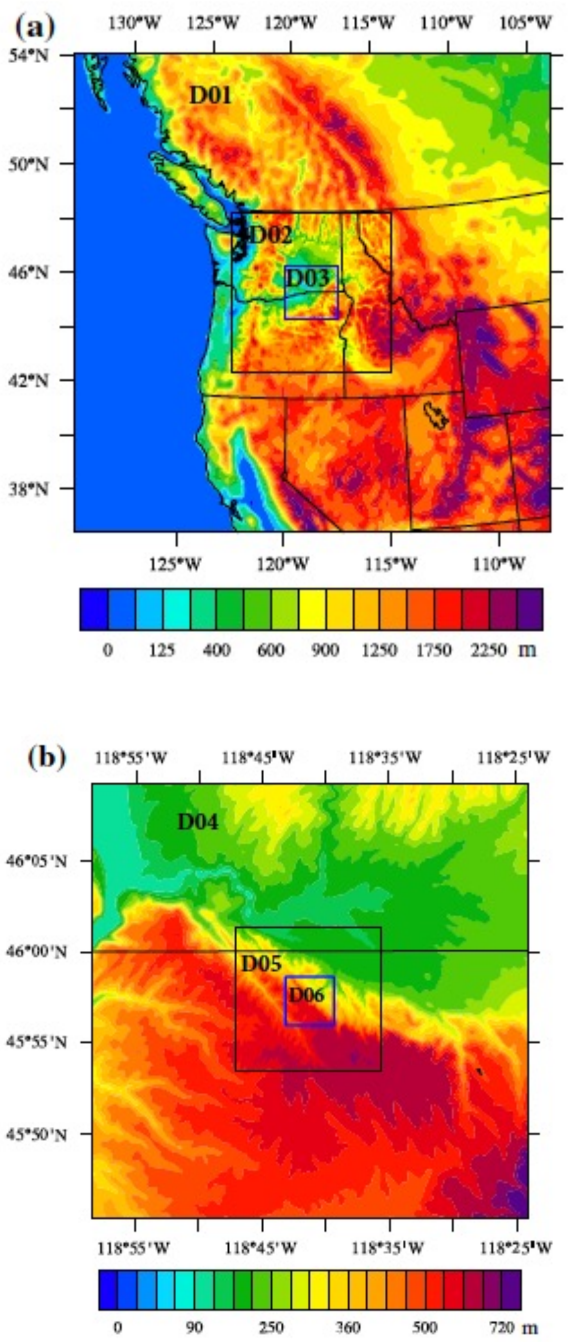
- Larger GRR requires longer fetch, benefits from using approaches to increase the turbulence spin up.
- Small GRR may result in more domains in Terra Incognita
- Best practice: *Use larger GRR with perturbations along the inflow boundary*

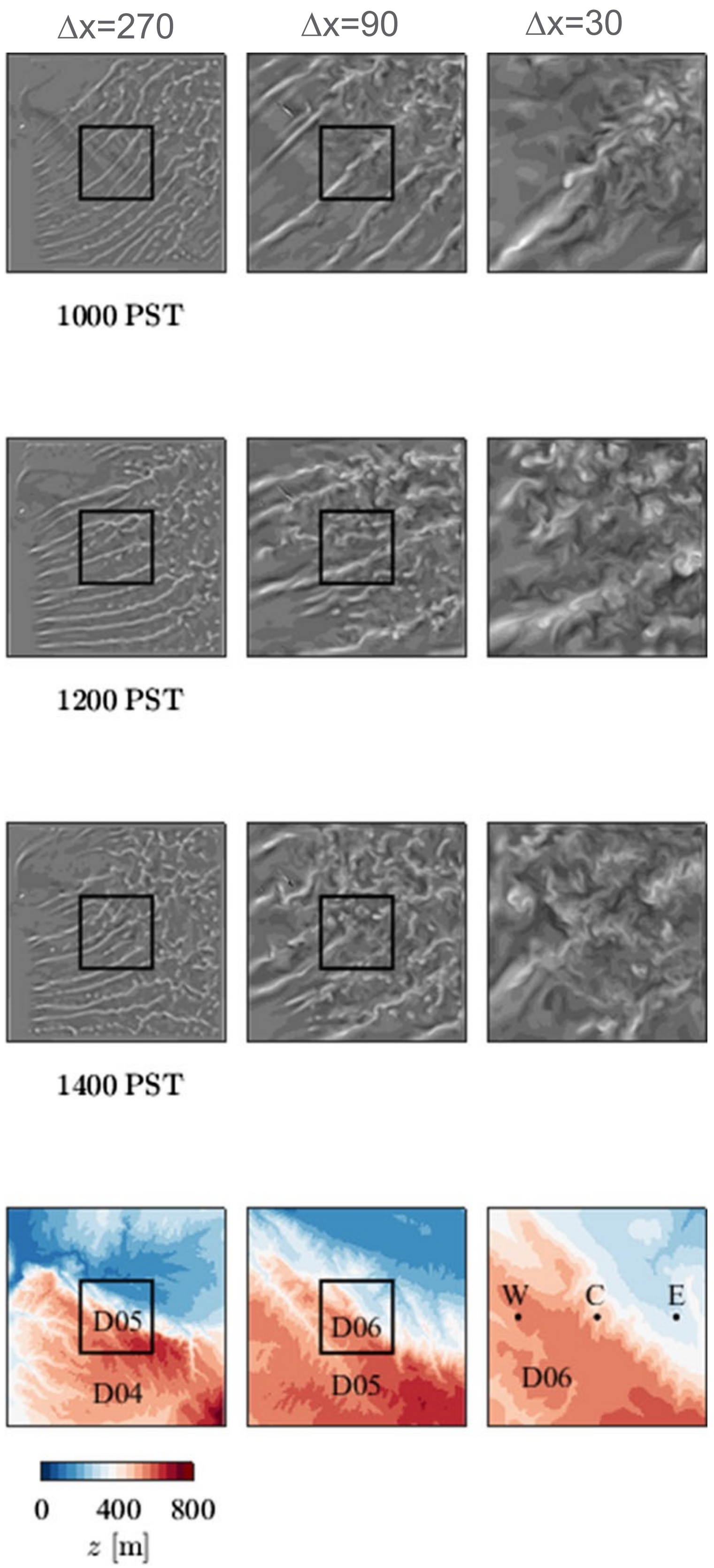


Rai, R. K., Berg, L. K., Kosović, B., Haupt, S. E., Mirocha, J. D., Ennis, B. L., & Draxl, C. (2019). Evaluation of the impact of horizontal grid spacing in terra incognita on coupled mesoscale–microscale simulations using the WRF framework. *Monthly Weather Review*, *147*(3), 1007-1027.

How well does LES represent structures in the turbulent wind field?

- Simulations show changes from streaks to cellular structures as the flow moves over the ridge
- How do simulated structures compare to observations?

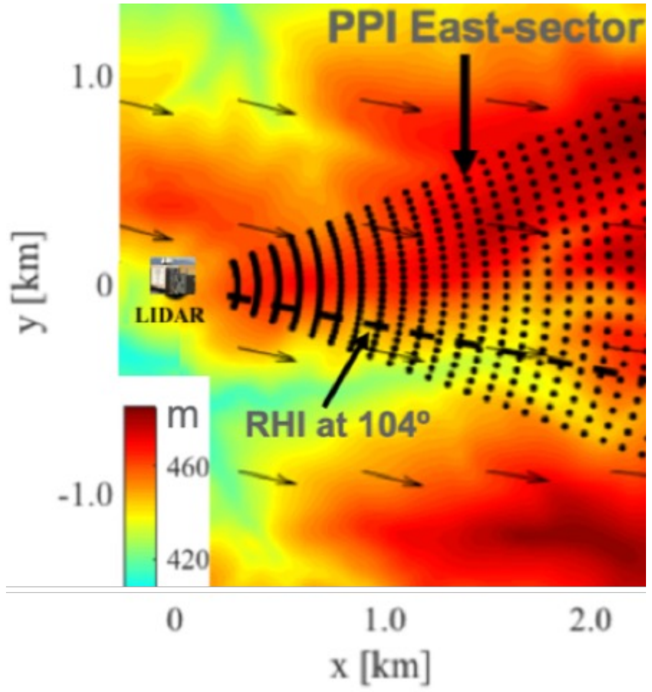


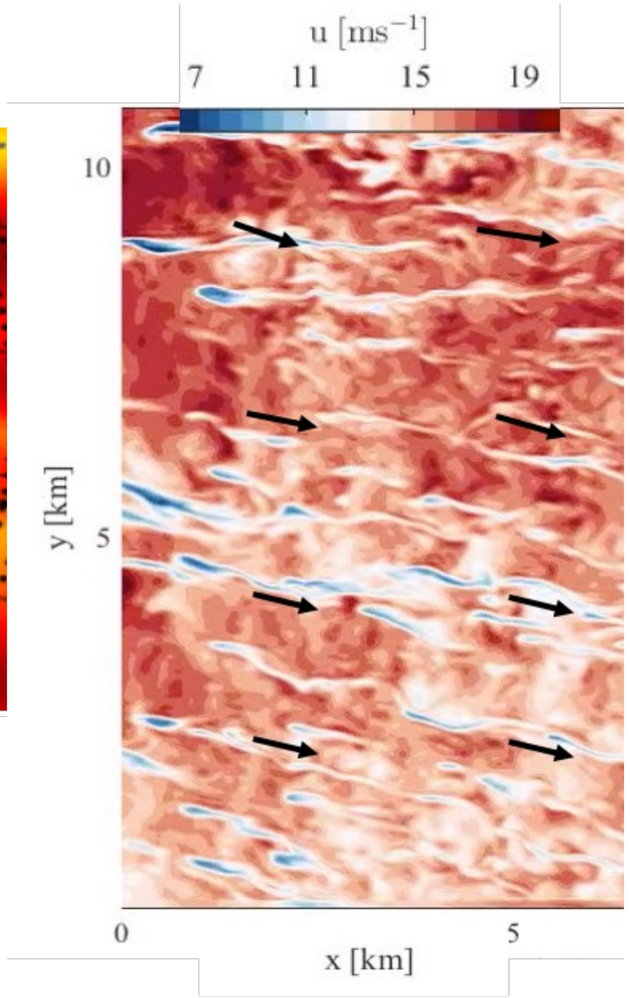


Rai et al., 2016: Comparison of measured and numerically simulated turbulence statistics in a convective boundary layer over complex terrain. Bound. Layer Meteor., https://link.springer.com/article/10.1007/s10546-016-0217-y

WFIP2 provides opportunity to examine flow structures

- **Wind-Cube 200S lidar** near Wasco Oregon
- **Scanning**
  - Plan Position Indicator (PPI) mode at 2.5º and 4º elevations
  - Range Height Indicator (RHI) mode at 104° azimuthal angle
- **Resolution**
  - 100 m in radial dir. and 1° (for PPI) and 0.5 ° (for RHI) in azimuthal dir.
  - dt = 1 s (for PPI) and 0.5 s (for RHI) scanning



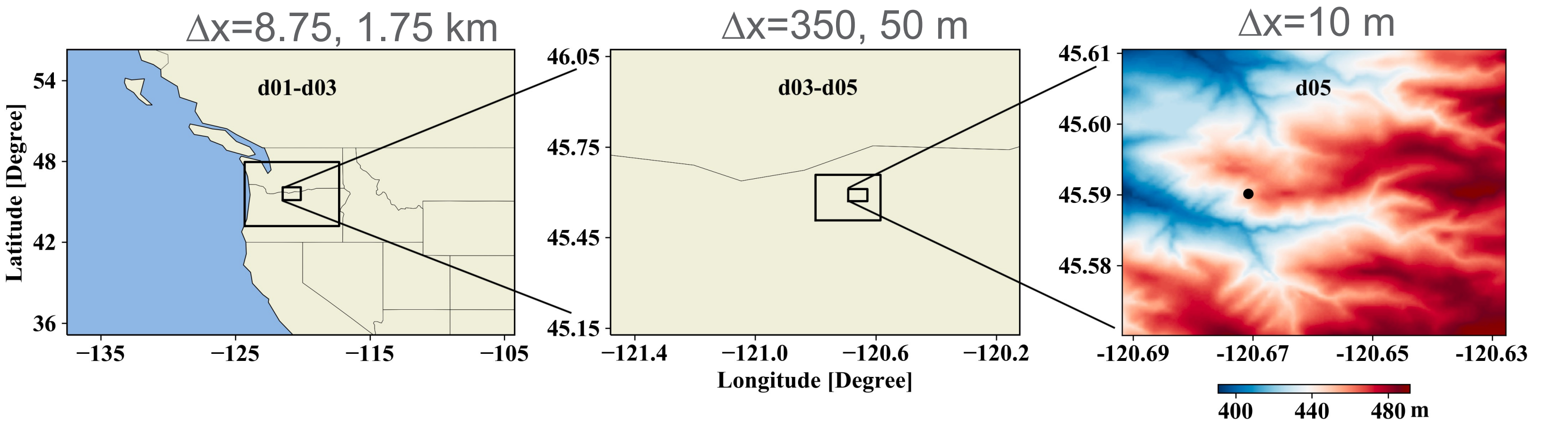


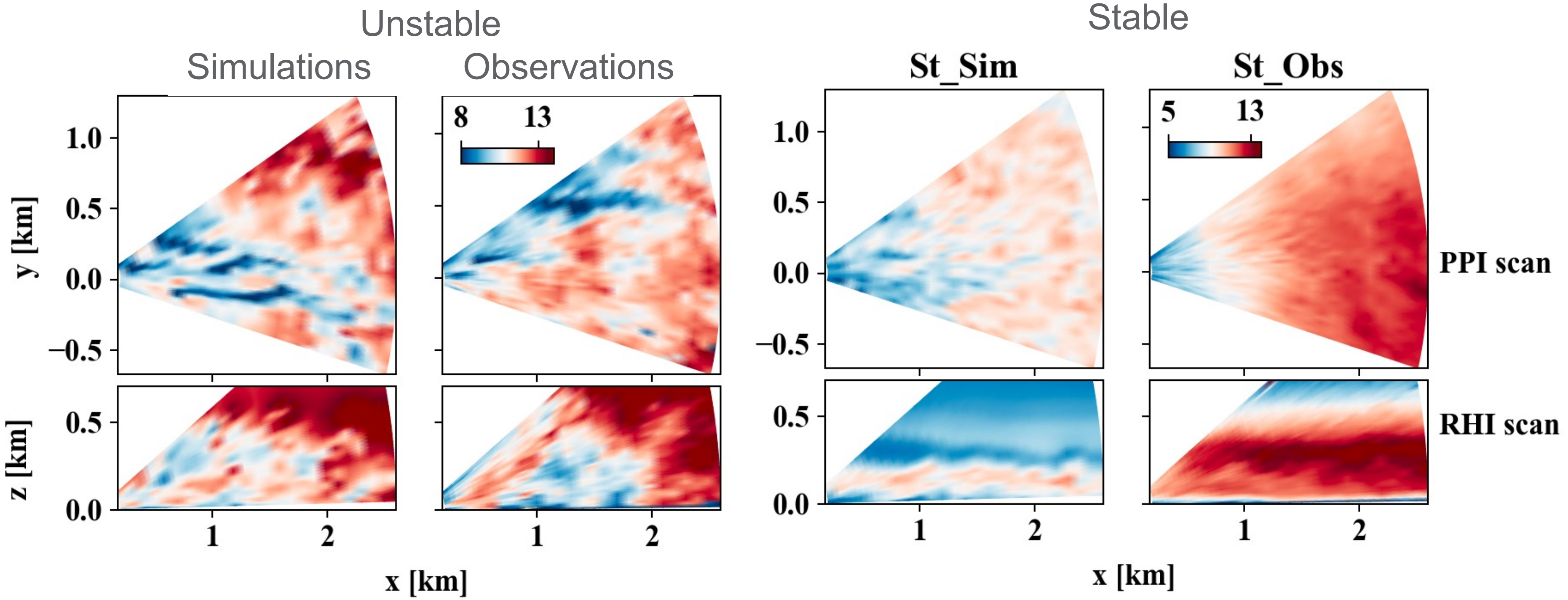
Simulated wind velocity 90 m above the surface during unstable conditions

Rai, R.K., L.K. Berg, R. Newsom, C.M. Kaul, J.D. Mirocha, A. Choukulkar, Y. Pichugina, R. Banta, and W. A. Brewer, 2023: Assessment of flow structures in the surface layer under different stability conditions reveals using scanning lidar and virtual scanning lidar data. JAS. In review

WRF and WRF-LES used to simulate selected cases

- Five nested domains
  - Two convective cases and one stable case
  - Δz = 10 m below 1 km
- Convective cases: July 7 and August 21, 2016
- Stable case: August 17, 2016





Wind Speed (ms^{-1})

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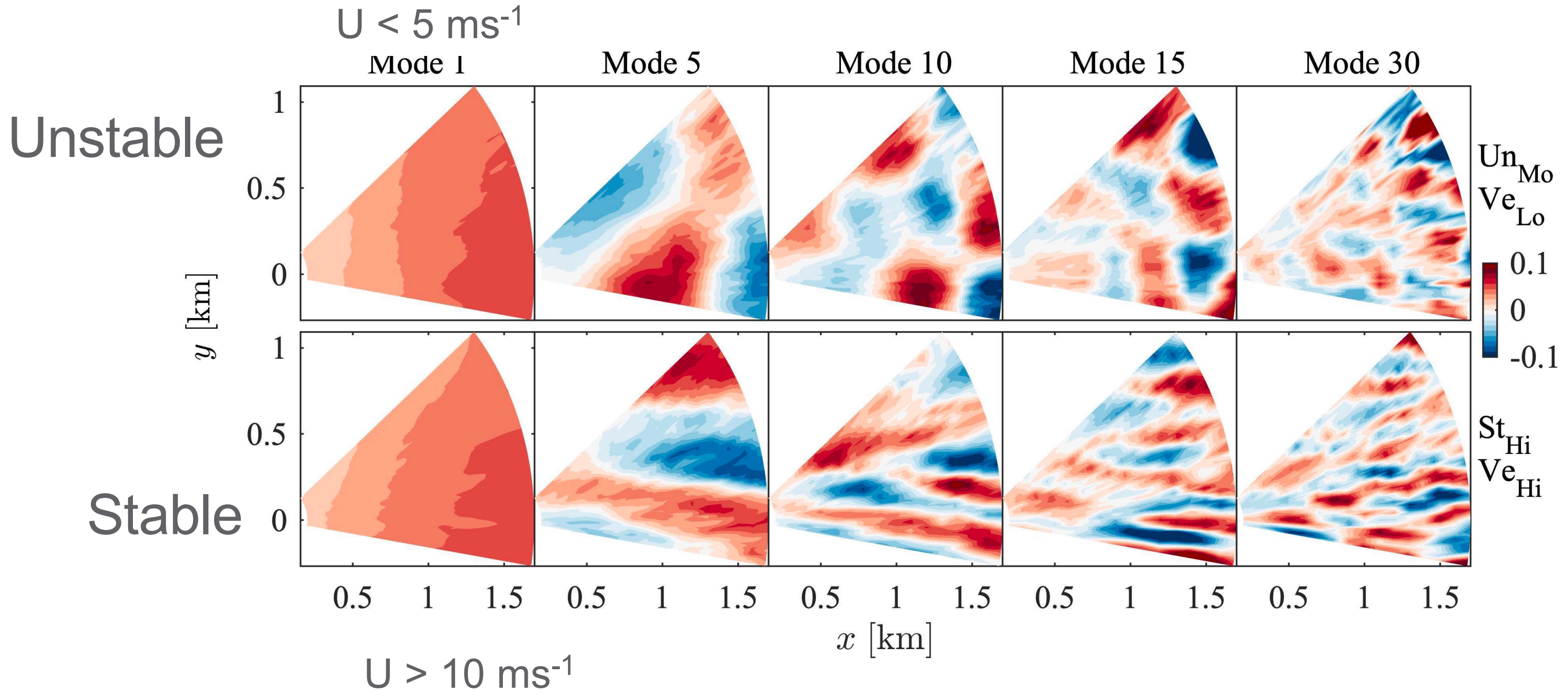
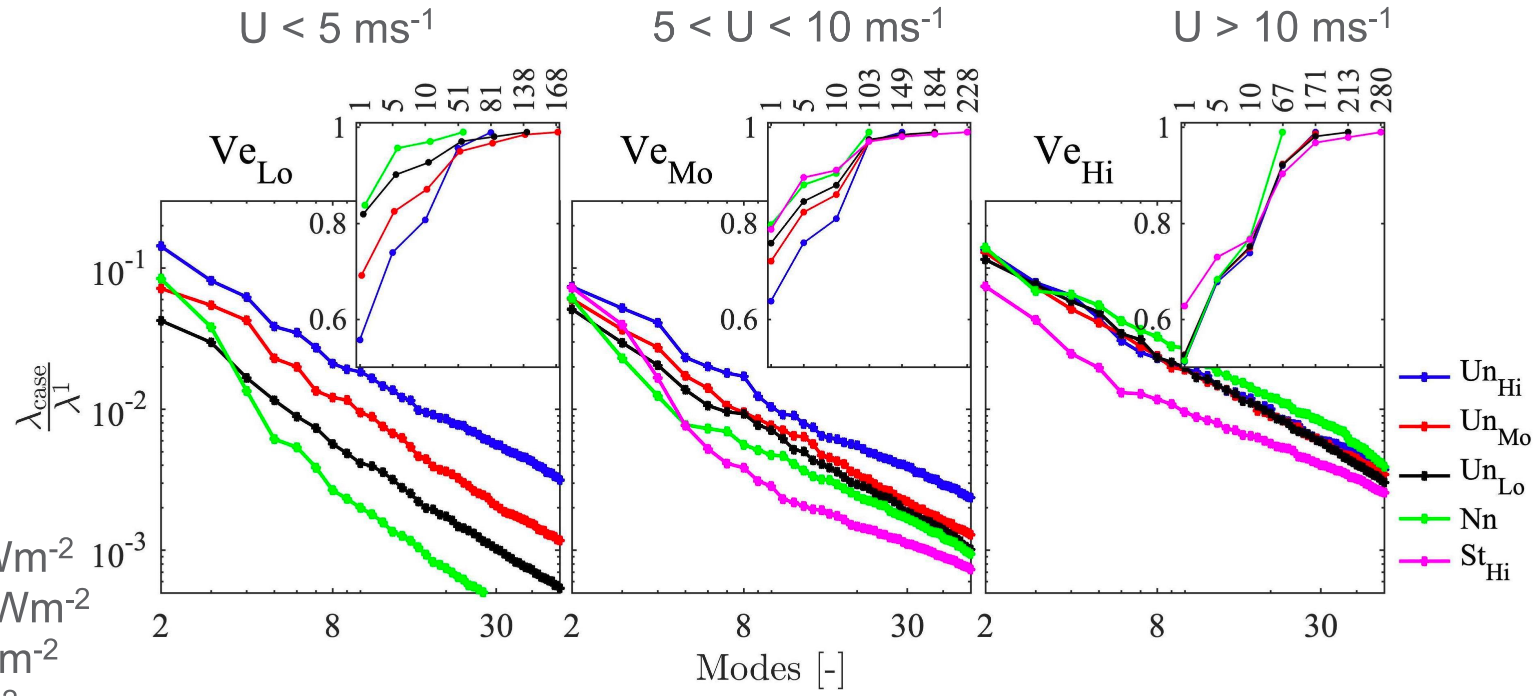
Flow structures determined from lidar scans

- Proper orthogonal decomposition (POD) used to look at flow structures
- Observations and simulations sorted by surface heat flux

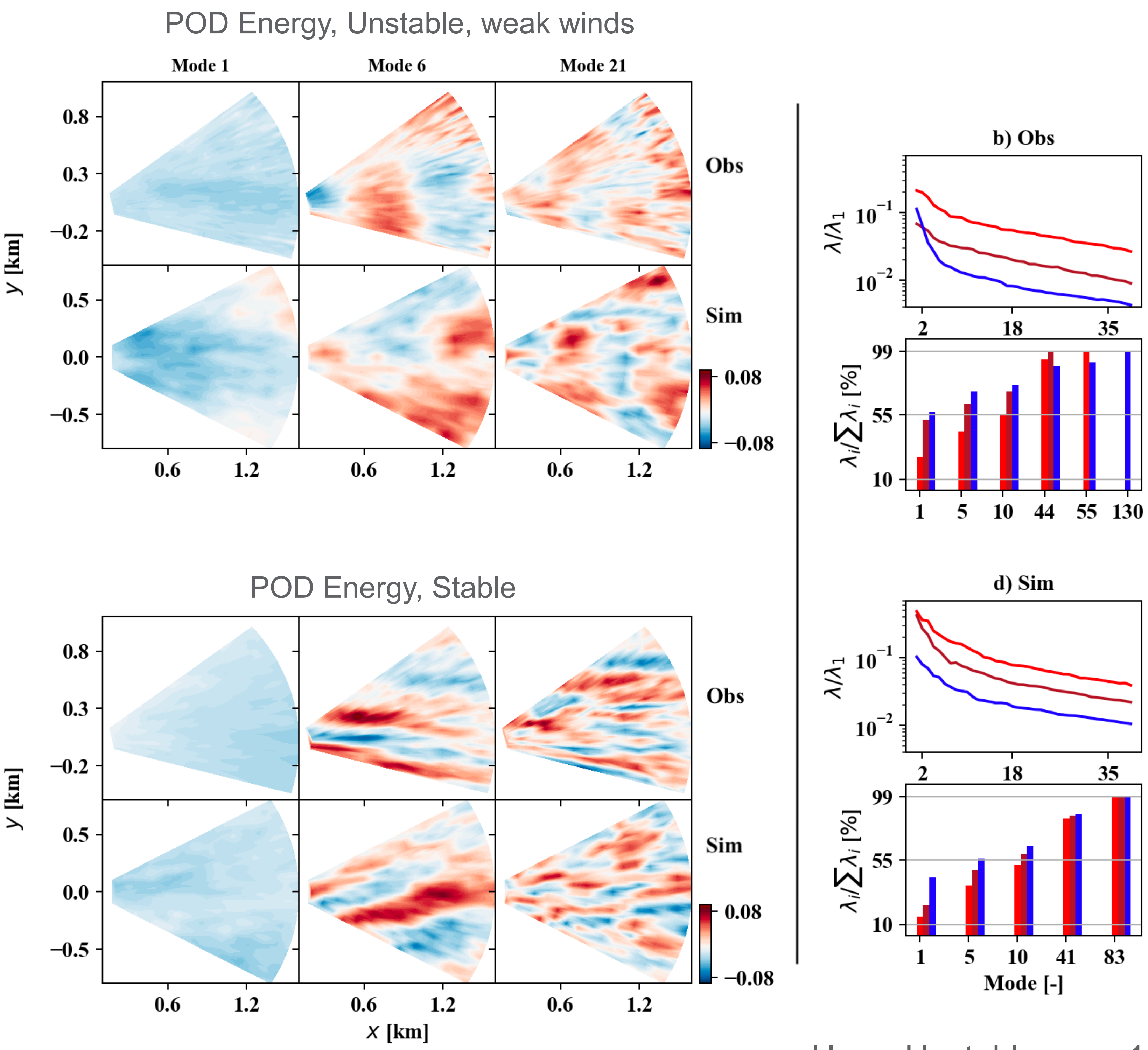




Un_{Hi} = 250 to 350 Wm^{-2}
Un_{Mo} = 150 to 250 Wm^{-2}
Un_{Lo} = 50 to 250 Wm^{-2}
Nn = -10 to 10 Wm^{-2}
St_{Hi} = -50 to -10 Wm^{-2}

WRF-LES and observed flow structures are similar

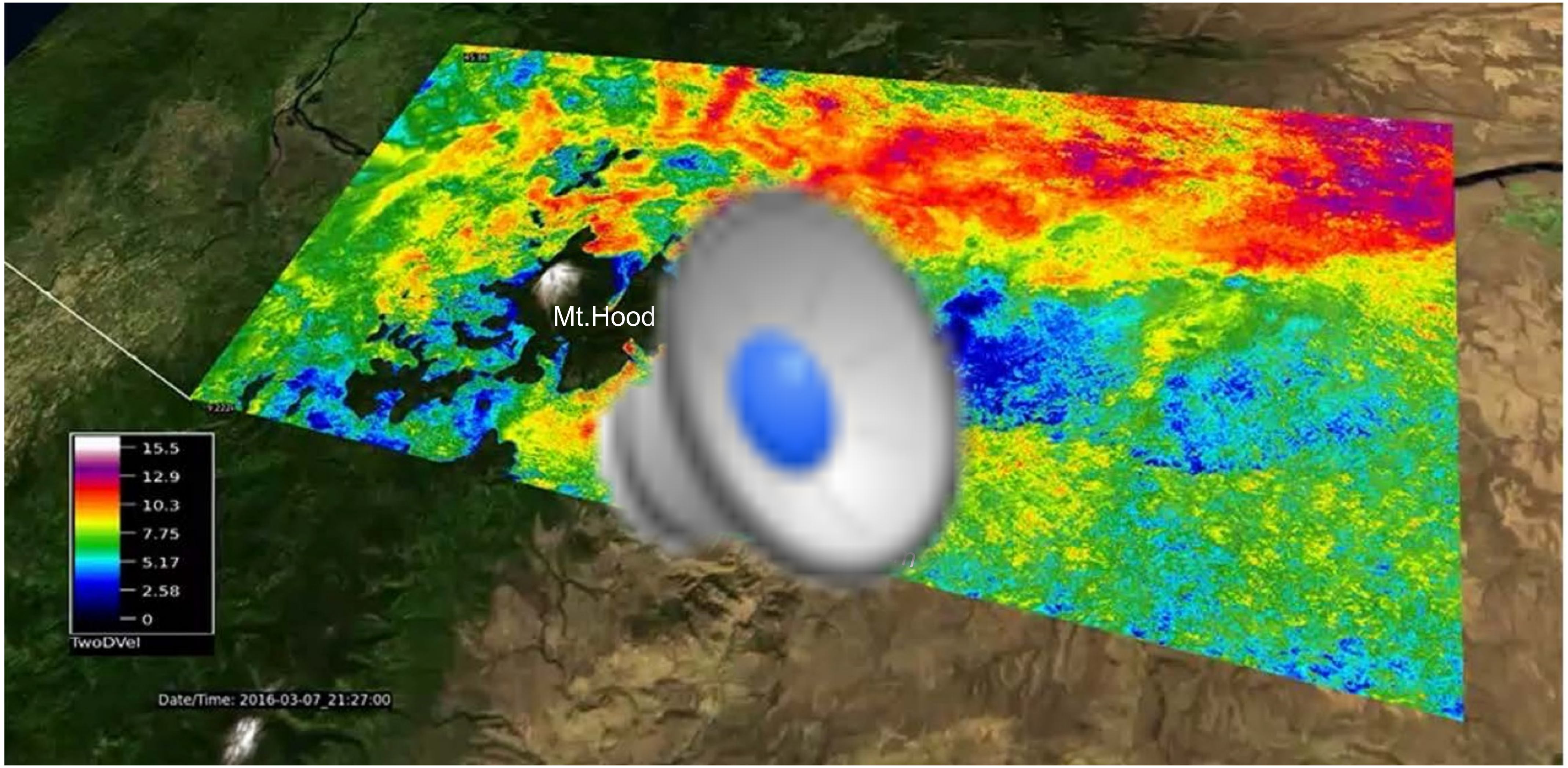
- Both observations and simulations show cellular and streaks
- Observations have relatively more energy for low modes than simulations



Un_1 = Unstable case 1
Un_2 = Unstable case 2

High-resolution simulations are computationally expensive

90 x 180 km simulation domain

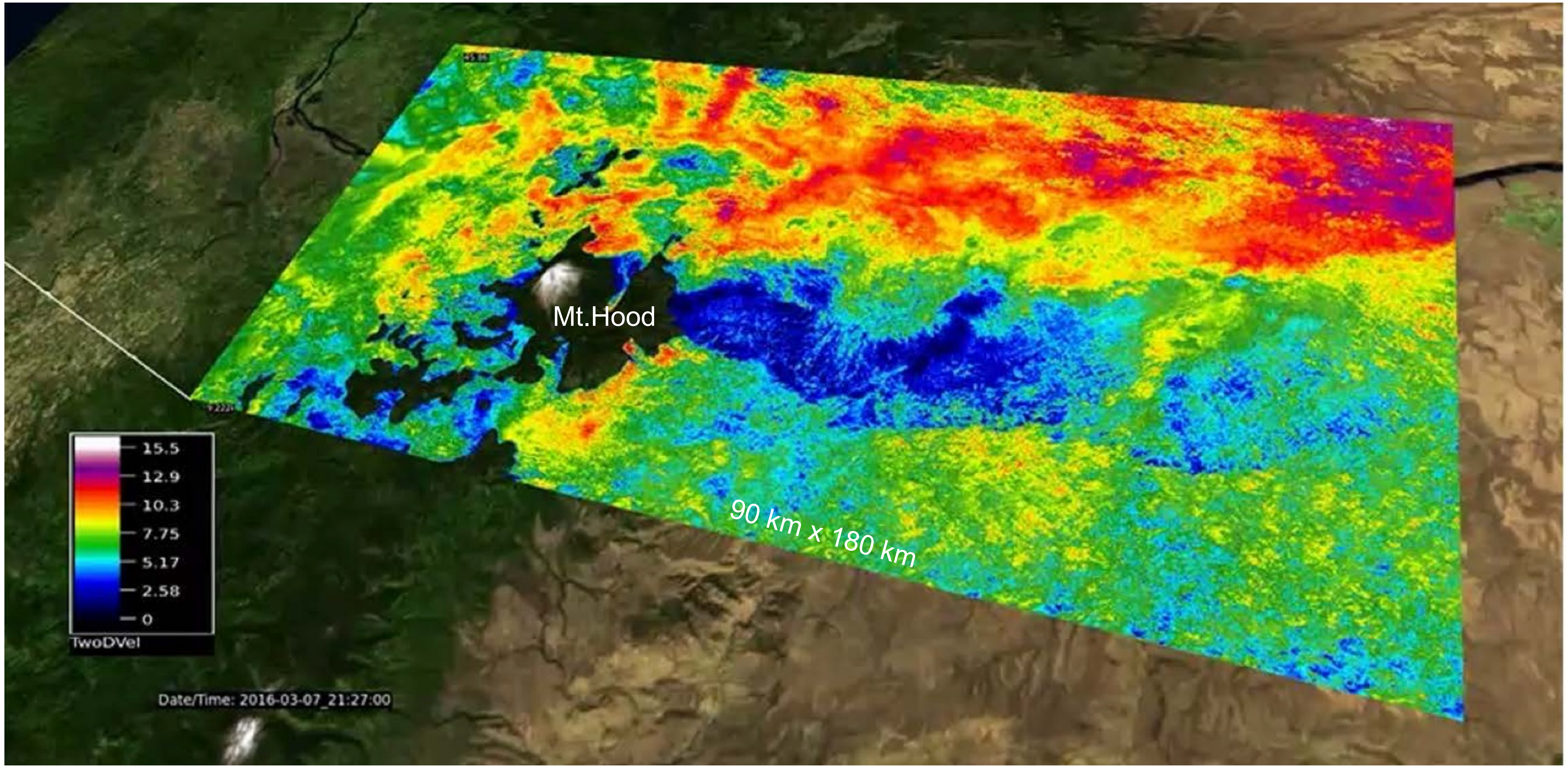


Computing resources

- 8650 cores
- ~15,000,000 core hours over several weeks

Simulation by Branko Kosovic and Pedro Jimenez
Visualization Scott Pearse NCAR Accelerated Scientific Discovery

High-resolution simulations are computationally expensive



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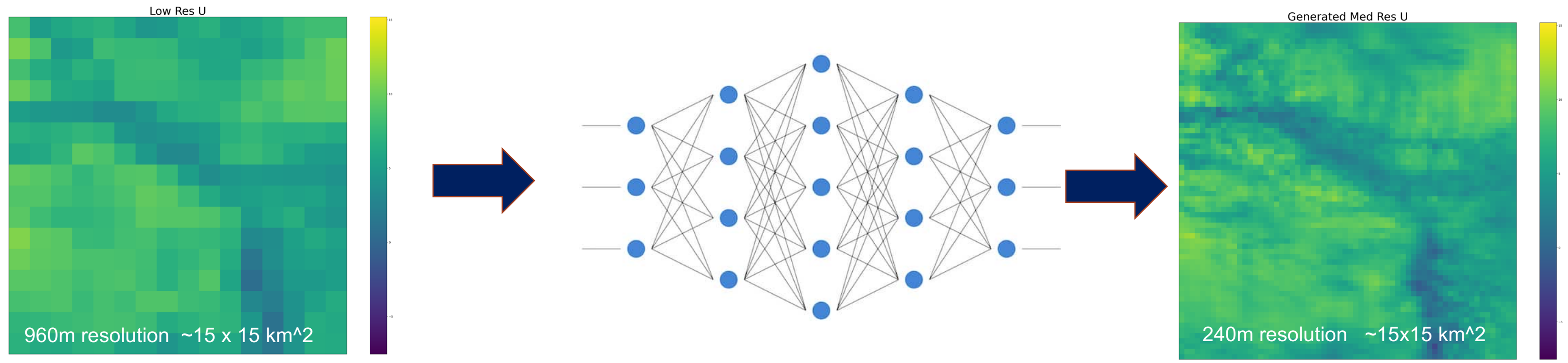
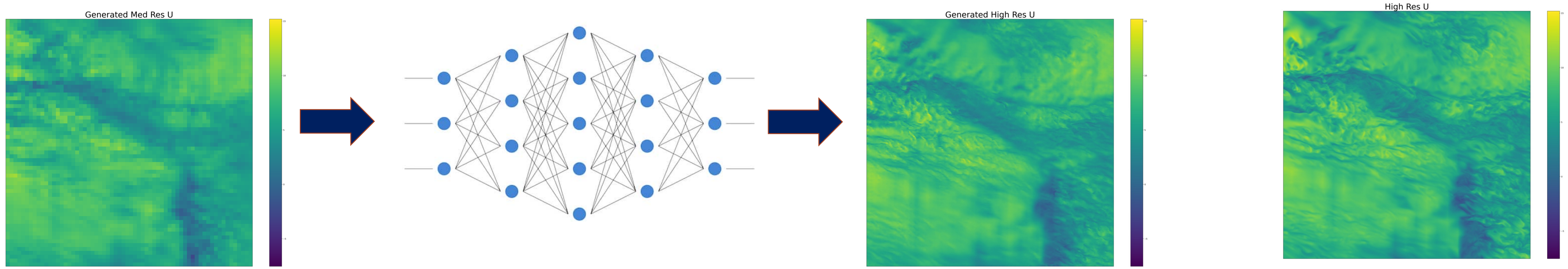
Can ML be used to efficiently emulate LES?

- Compound deep learning architecture: Two Generative Adversarial Networks (GANs) are trained and applied sequentially



GAN 240 m U

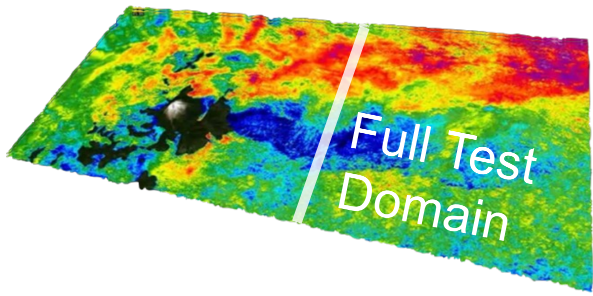
Sue Dettling, Tom Brummet, Branko Kosovic, Sue Haupt, Pat Hawbecker, David John Gagne



GAN 30 m U

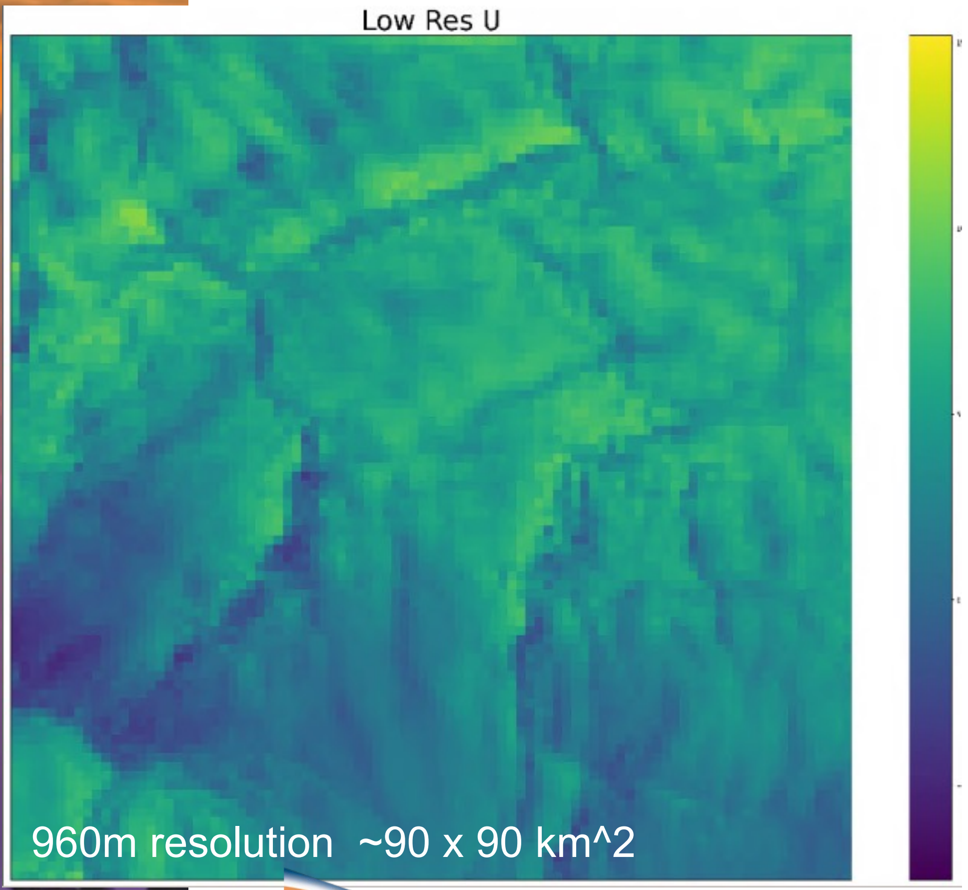
Truth (WRF LES 30 m)

Test domain results

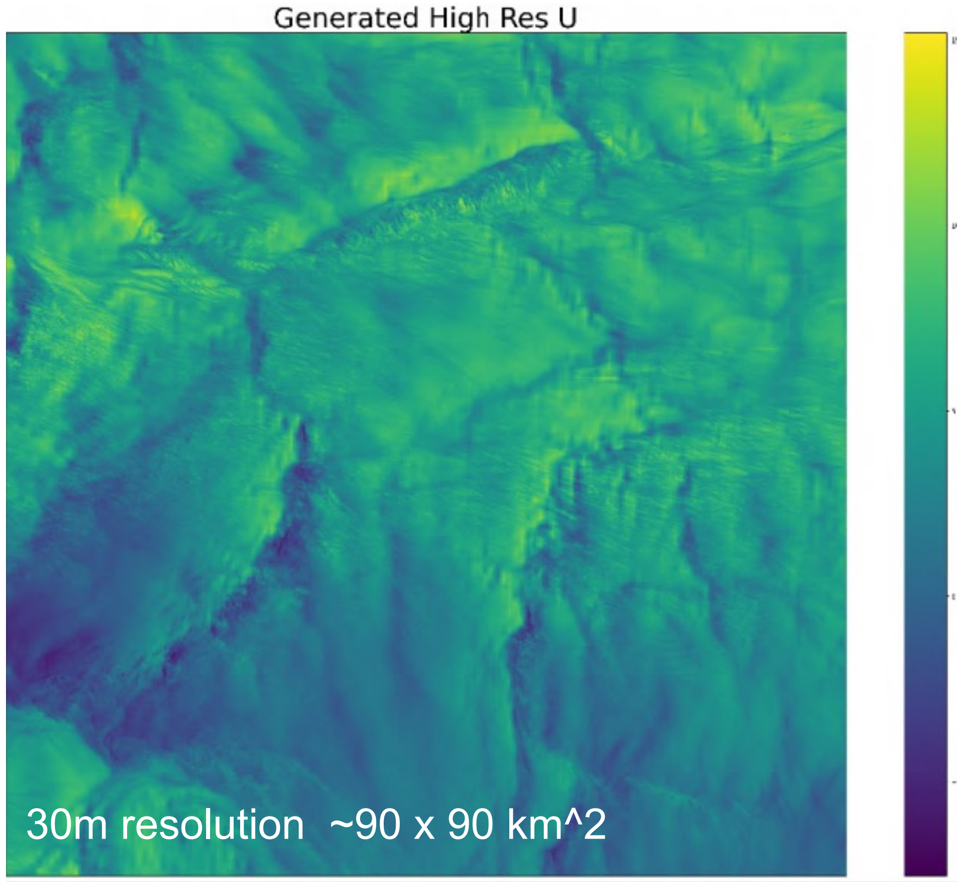


- Models train on domain sub-tiles
- Trained models run on domain of ANY SIZE

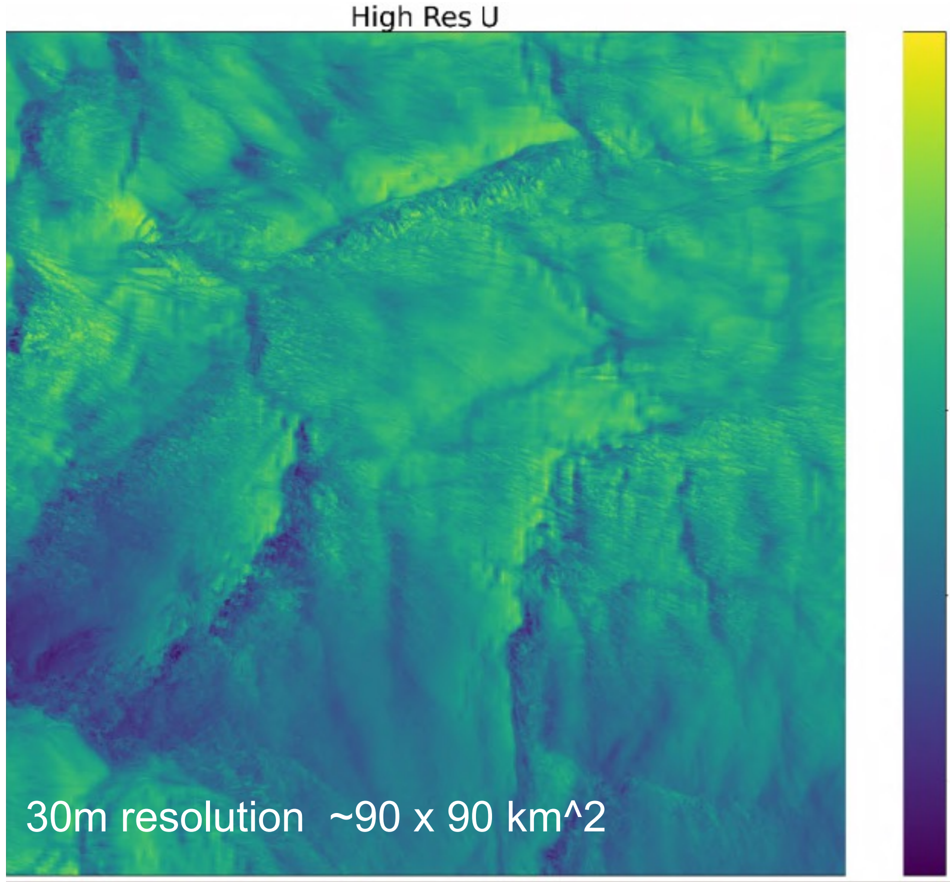
GAN INPUT



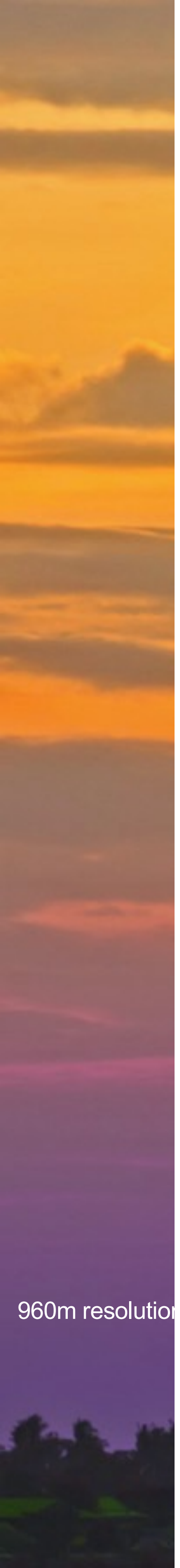
GAN OUTPUT



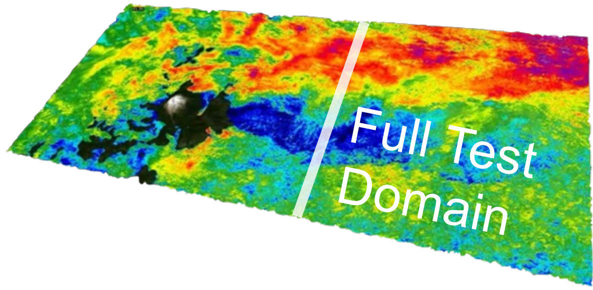
Truth (WRF LES)



Eastern Half of WFIP2 WRF LES Domain

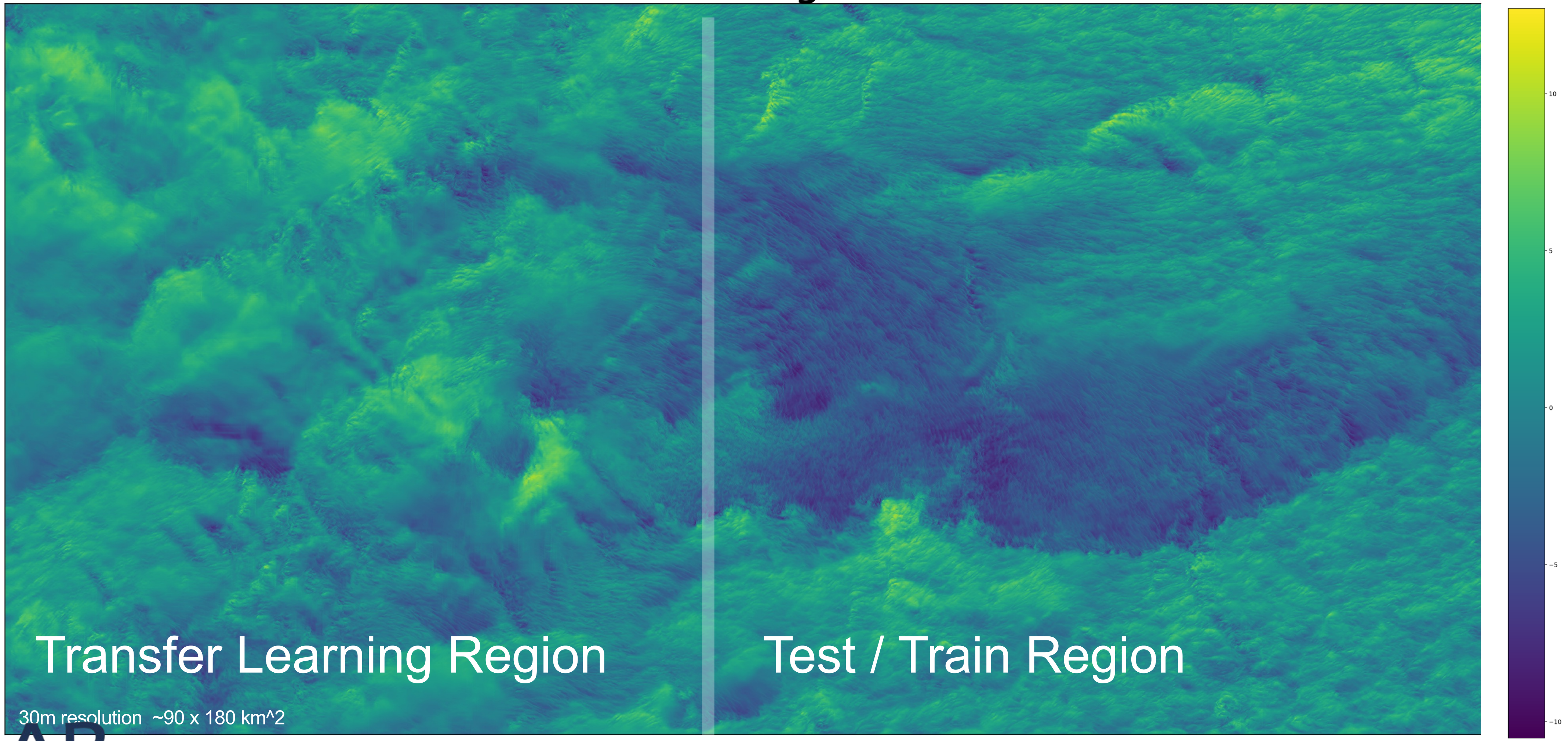


Transfer Learning applied to the area around the Columbia Gorge



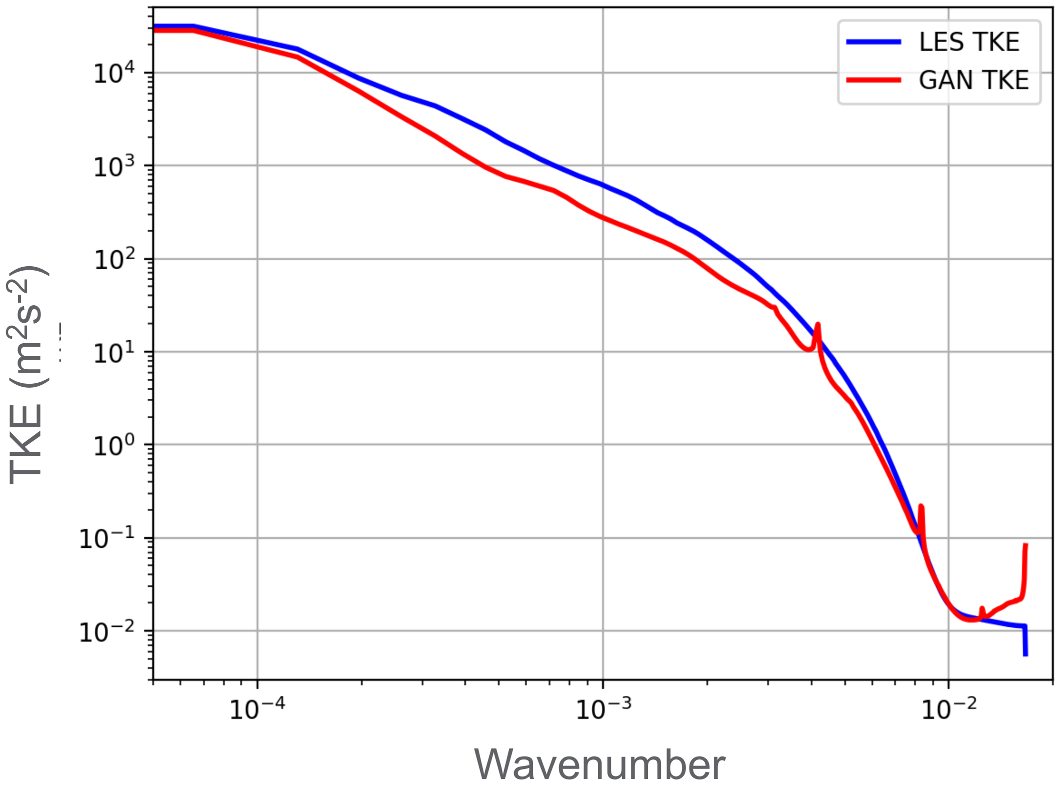
- Testing region extended to entire WFIP2 LES domain
- Western region has significantly more complex terrain compared to training region

Generated High Res V

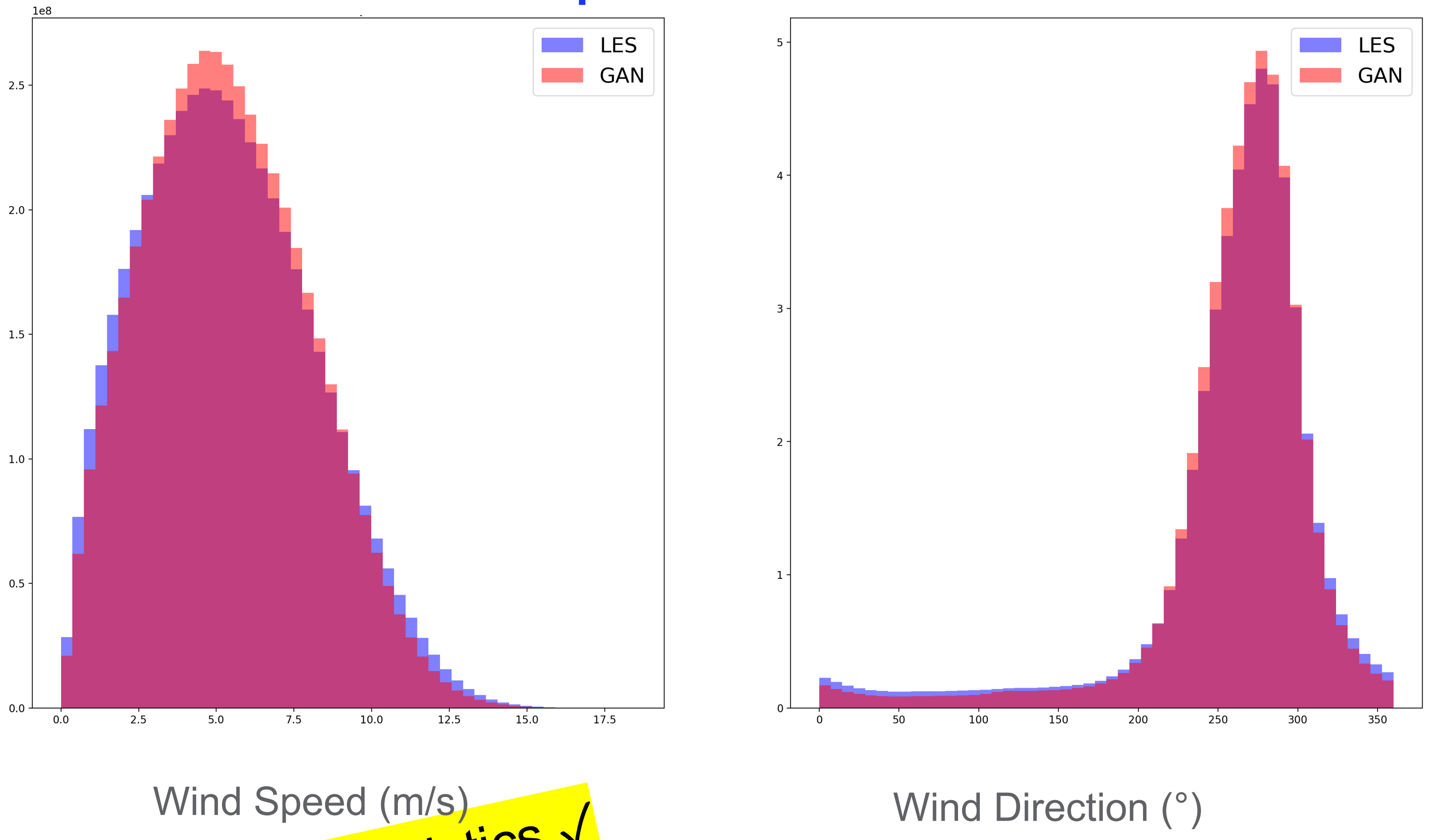


Statistical comparison of GAN and WRF-LES for transfer region

TKE as a Function of Wave Number



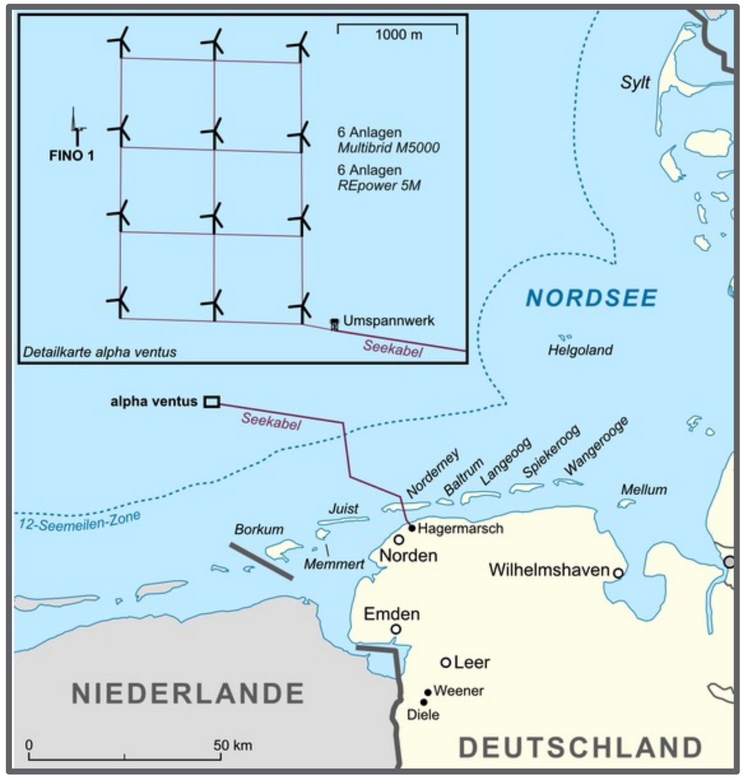
Wind Speed and Wind Dir



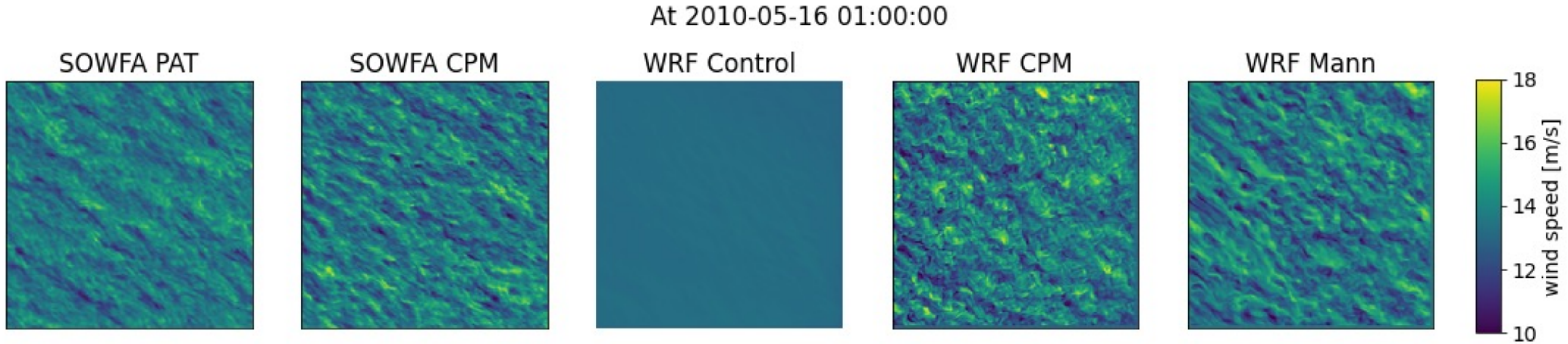
Encouraging Comparative Statistics ✓

Turbulence in LES for Offshore Flow

- Case study over North Sea
  - FINO1 and Alpha Ventus wind farm
- Objective: assess performance of downscaling techniques
  - Offline through profile assimilation
  - Offline through direct coupling with perturbations
  - Online with different perturbation techniques



Work led by Pat Hawbecker, NCAR

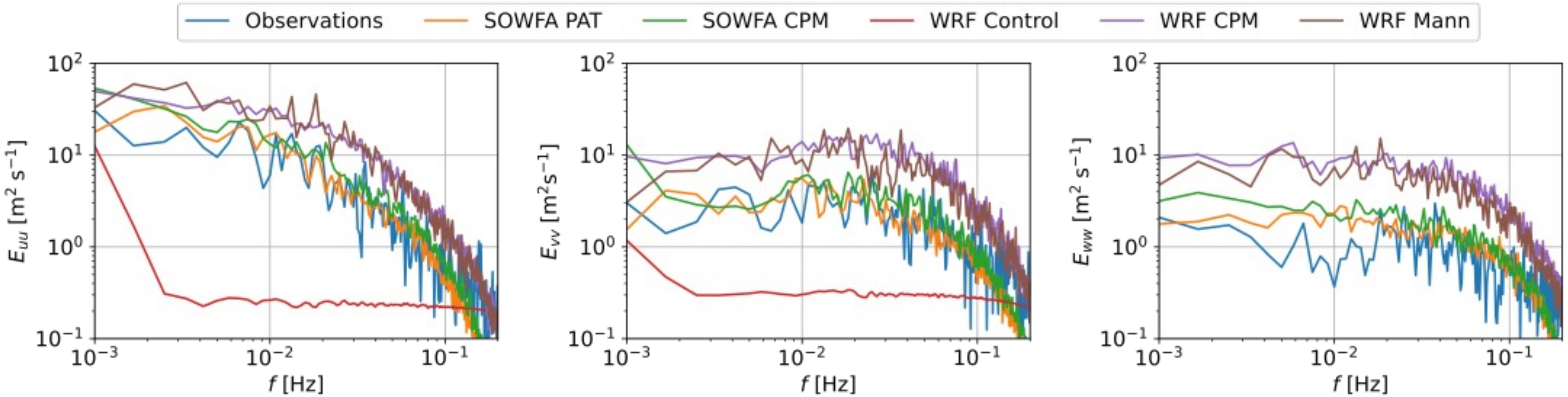


Wind speed from subdomains of the simulations

PAT= Profile Assimilation Technique

NCAR Lawrence Livermore National Laboratory NREL Pacific Northwest National Laboratory

Turbulence in LES for Offshore Flow



- Many of the perturbation strategies generated turbulence on par with observations,
    - But without a perturbation method, *insufficient turbulence was produced*
- All are different and no one approach is considered to be “best” overall

PAT= Profile Assimilation Technique

Community resource

- Symposium held 9/14-9/15, 2022
- MMC team, academia and industry partners
- Sessions were recorded and are available at https://ral.ucar.edu/events/5041/agenda

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Tools for the community

mmctools

- Data analysis
- Data processing
- Case setup

github.com/a2e-mmc

- Free and publicly accessible
- Everything is version controlled

Read the Docs

docs

- Professional online documentation automatically generated

WRF-setups
SOWFA-setups
…

WRF
…

jupyter

assessment

- Interactive notebooks combine (python) code and analysis outputs
- Archivable, shareable from GitHub

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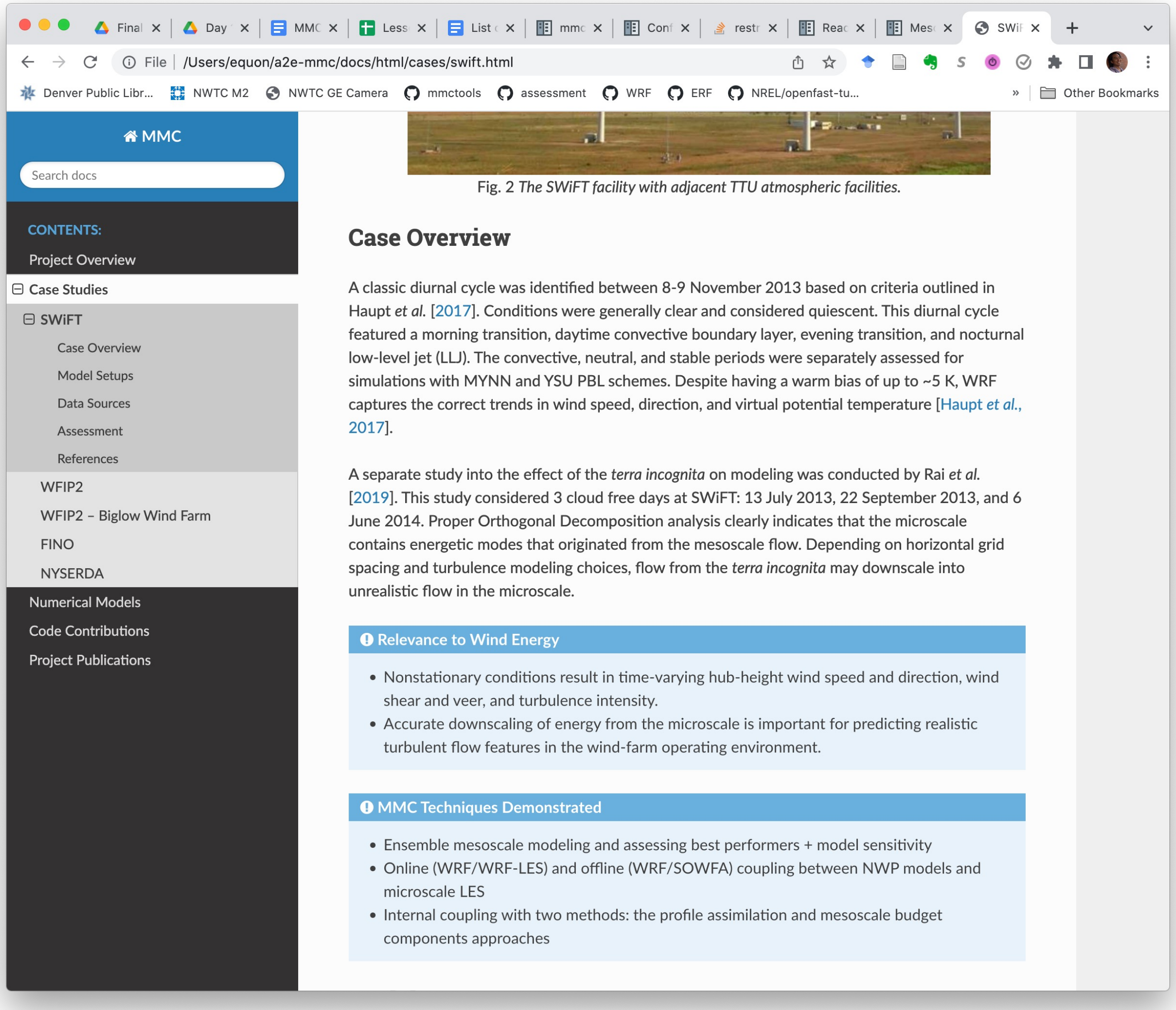
Case study example: Diurnal cycle

Relevance to Wind Energy

- Nonstationary conditions…
- Accurate downscaling of energy…

MMC Techniques Demonstrated

- Ensemble mesoscale modeling…
- Online and offline coupling…
- Internal coupling with two methods…



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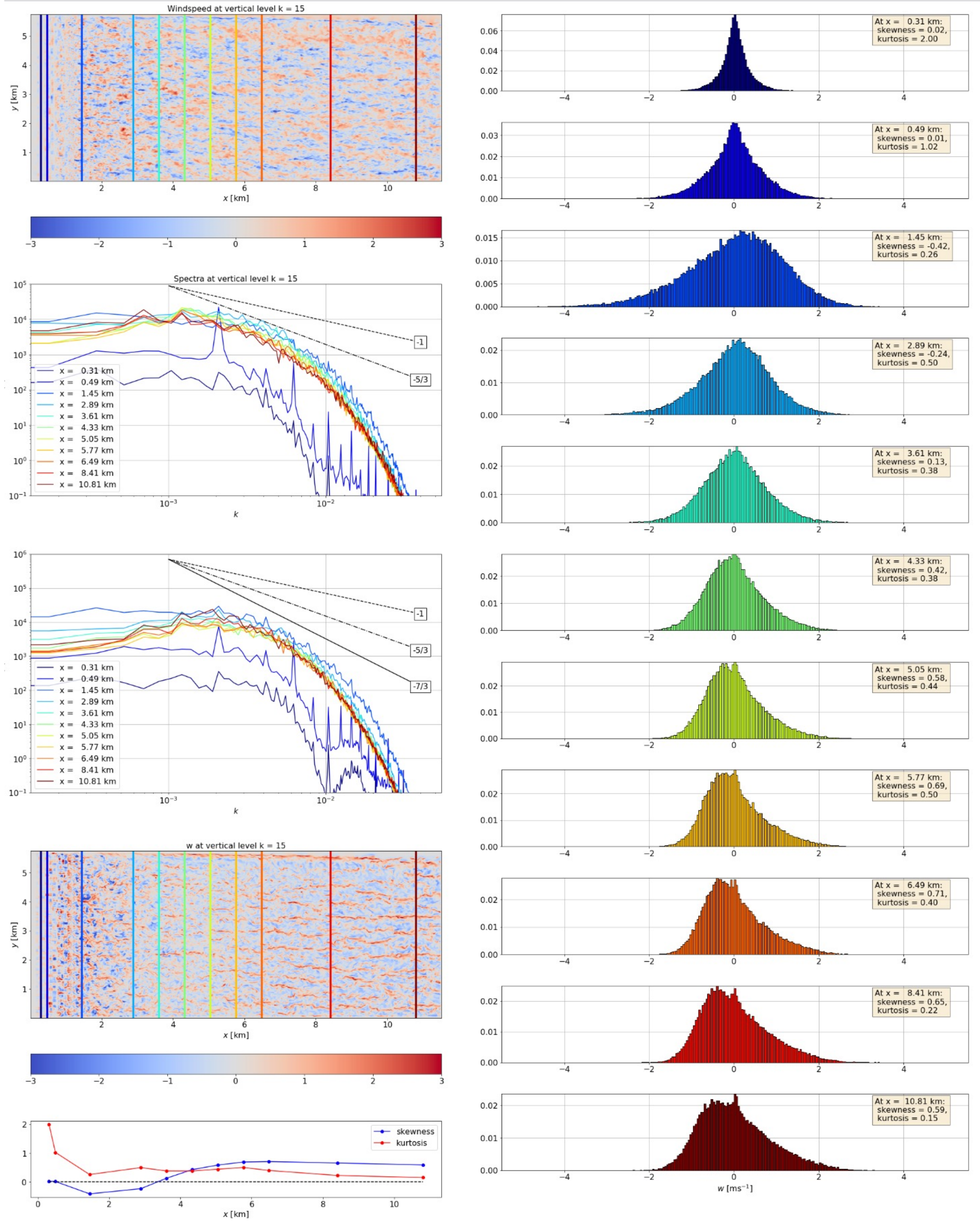
Code/notebook templates facilitate intercomparisons

- Plug-and-play **notebook template provides a dashboard view of resolved quantities of interest** created for perturbations study
- **Identical analyses** given different input datasets

From:
assessment/studies/perturbation_methods/PMIC-Microscale-analysis_template.ipynb



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Thank you