LES Simulations of Wind Turbines in a Turbulent Atmospheric Boundary Layer

Flavio C. C. Galeazzo
Andreas Ruopp
Ralf Schneider
HLRS – University of Stuttgart

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HLRS
High-Performance Computing Center | Stuttgart

Outline

- Introduction
- Simulation approach
  - Turbulent ABL
  - Wind turbine
- Codes
- Benchmark
- Results
- Conclusion / Next steps

Introduction

- The main objective is to perform a VVUQ study of the integration of meso- and microscale simulations, i.e., weather to wind turbine scale
- VVUQ - Verification, Validation and Uncertainty Quantification
  - Verification: Are equations solved correctly?
  - Validation: Are the right model/equations for the intended application being used?
  - Uncertainty Quantification: Determine the probability distribution of code outputs, given uncertainty in input factors
- In the first year, focus on Verification and Validation preparing the framework for the UQ

Simulation approach

- We are interested in the interaction of wind turbines in wind parks
- Large Eddy Simulation (LES) is the most appropriate approach
  - Predict the wake of wind turbines with high fidelity
  - Resolve the large turbulent structures
  - Requires large computational time: HPC

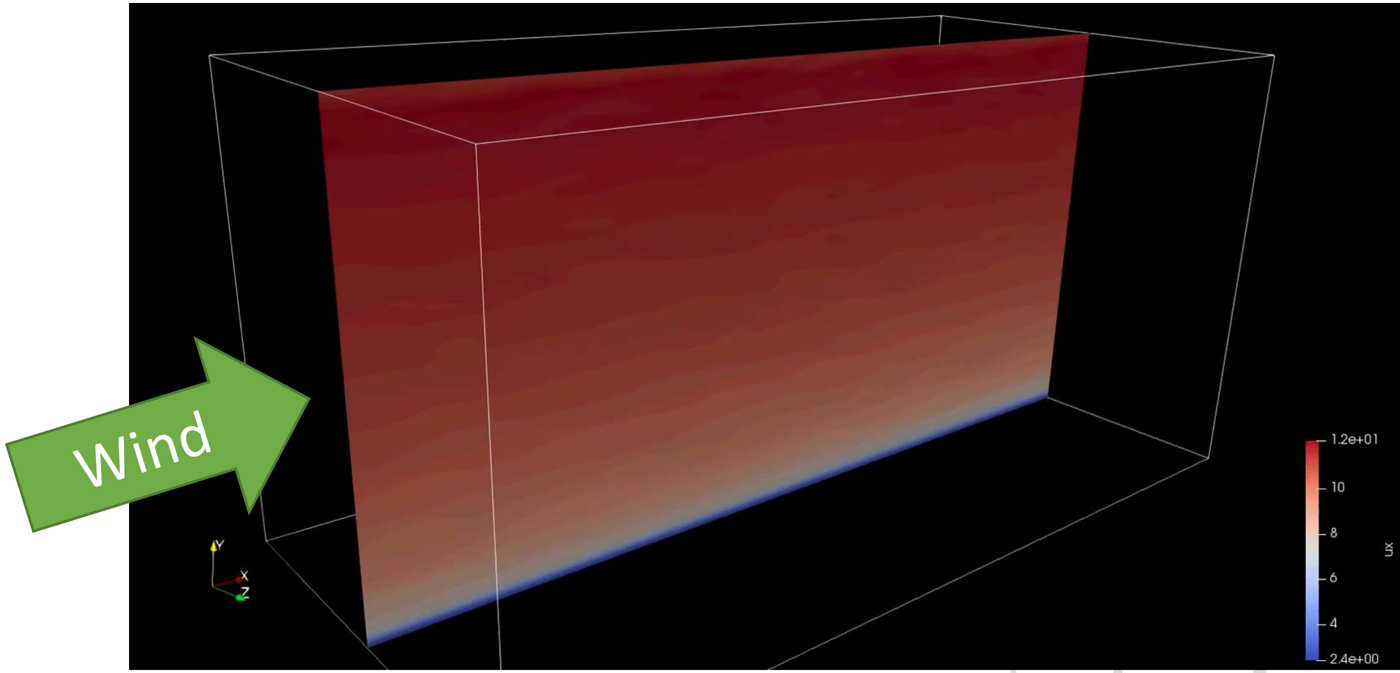
Hasager, C. B., Rasmussen, L., Peña, A., Jensen, L. E., & Réthoré, P-E. (2013). Wind Farm Wake: The Horns Rev Photo Case. *Energies*, *6*, 696-716.

Simulation approach

- Turbulent ABL
  - Mean velocity profile given by logarithmic function
  - Two different approaches to model the large-scale turbulent structures

$$u_{\text{mean}}(z) = \frac{u^*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

- Precursor simulation
  - The results of a simulation without the wind turbines is stored and used as inflow condition
  - Pro: very good turbulence representation
  - Contra: needs more computational time – difficult to match experimental values

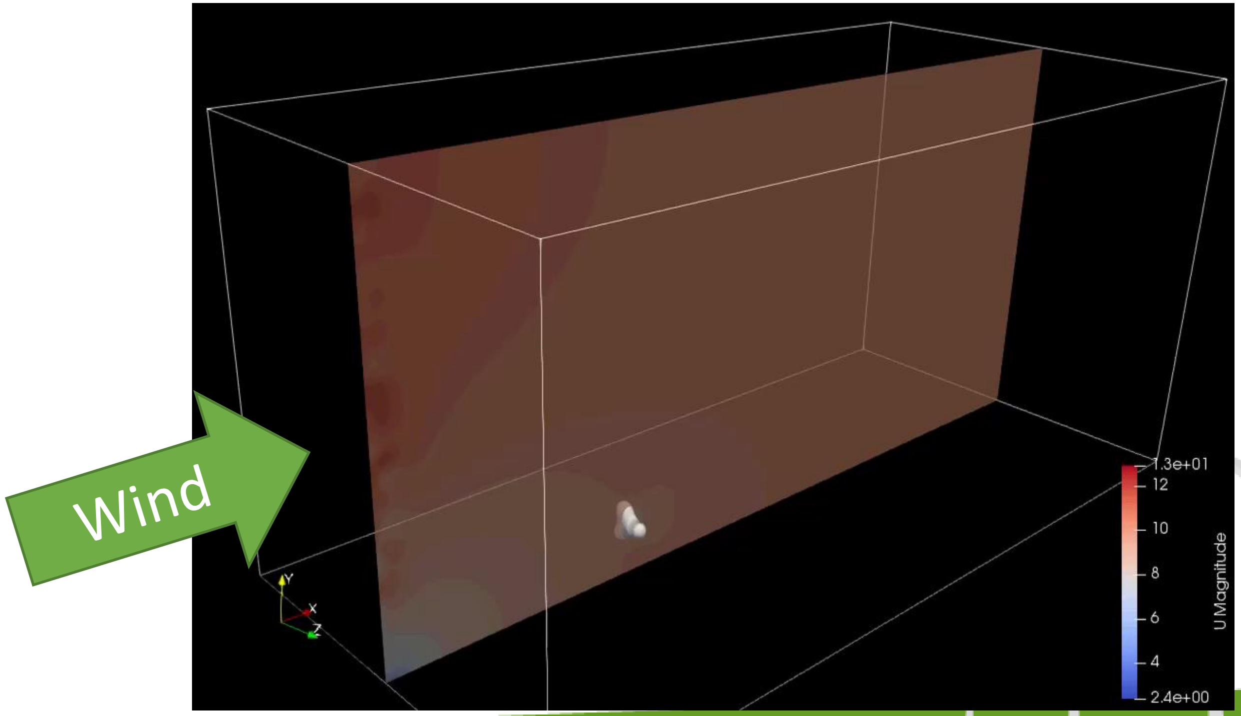


Simulation approach

- Turbulent ABL
  - Mean velocity profile given by logarithmic function
  - Two different approaches to model the large-scale turbulent structures

$$u_{\text{mean}}(z) = \frac{u^*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

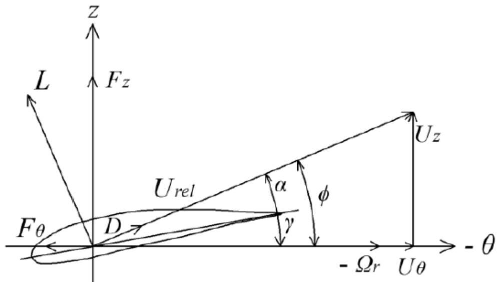
- Synthetic turbulence
  - Synthetic turbulent structures are generated and used in the inflow condition
  - Pro: saves computational time – allow fine adjustment of desired quantities
  - Contra: not readily available in all codes



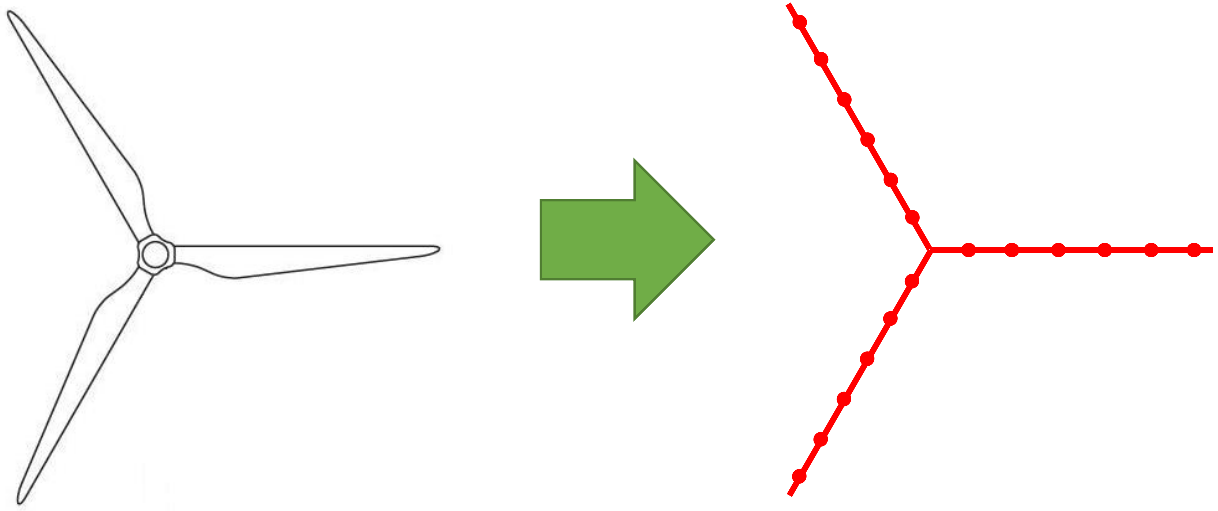
Klein, M., Sadiki, A., & Janicka, J. (2003). A digital filter based generation of inflow data for spatially developing direct numerical or large eddy simulations. *Journal of Computational Physics*, *186*(2), 652–665.

Simulation approach

- Wind turbine
- Actuator line model
  - Divide the turbine blades in smaller elements, and retrieve the forces exerted by the turbine on the air from 2D airfoil data.
  - Non-uniform velocity and load distributions are modelled



Source: Yu Z. 2018, Appl. Sci. **2018**, 8, 434



Codes

- WInc3D
  - Open source - Developed by the partner Imperial College London
  - Finite Difference Method – 6th order discretization
  - Scalability up to 100k ranks [1]
  - Actuator line model for wind turbines
  - Use in neutral ABL
  - https://github.com/ImperialCollegeLondon/WInc3D

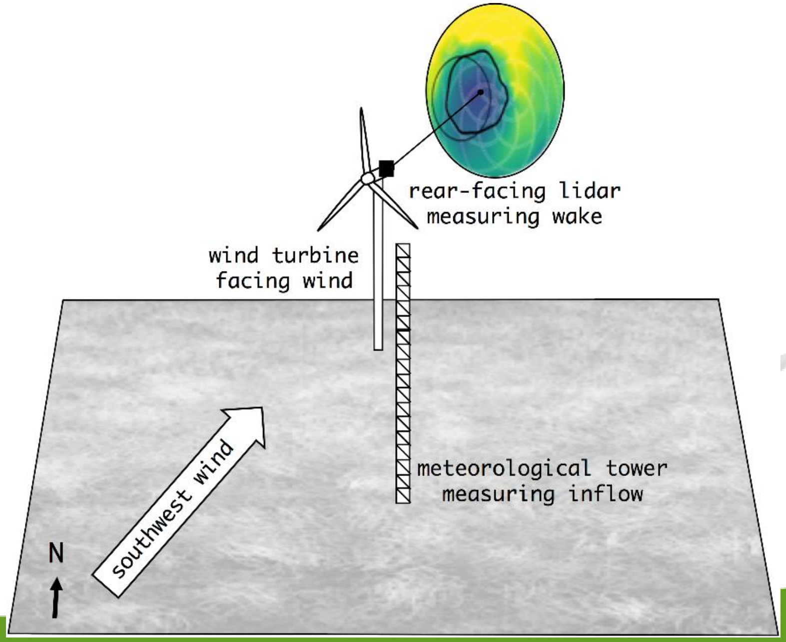
- OpenFOAM with turbinesFOAM
  - Open source
  - Finite Volume Method – 2nd order discretization
  - Scalability up to 5k ranks [2]
  - Actuator line and actuator disc models for wind turbines
  - Use in neutral, stable and unstable ABL
  - https://github.com/turbinesFoam

[1] Laizet, S. & N. Li (2011). Incompact3d: A powerful tool to tackle turbulence problems with up to O(10^5) computational cores. Int. J. for Numerical Methods in Fluids 67(11), 1735–1757.

[2] Culpo, M. (2011), Current Bottlenecks in the Scalability of OpenFOAM on Massively Parallel Clusters, PRACE-1IP Whitepaper

Benchmark

- Experimental data: The SWiFT Benchmark
  - International Energy Agency (IEA) Wind Task 31, operated by Sandia National Laboratories
  - Flat terrain
  - Variable-speed, variable-pitch, modified Vestas V27 wind turbine generator
  - Meteorological tower collected freestream atmospheric measurements
  - Rear-facing, nacelle-mounted scanning LIDAR measured the wake
  - Power and loads measurements were collected at the wind turbine



https://wakebench-swift.readthedocs.io/en/latest/

Benchmark

- Measurements of nearly neutral, stable and unstable atmosphere available
- Neutral ABL used for the validation
- High-frequency measurements of the inflow conditions and turbine operation were first averaged over a 10-minute period.
- Each 10-minute period selected for the benchmarks is referred to as an ensemble. There are 6 different ensembles for the neutral ABL

Parameter – neutral ABL	
Velocity at hub height	8.7 m/s
Turbulence intensity at hub height	10.7 %
Wind speed profile exponent	0.3224
Roughness length	0.05 m
Friction velocity	0.45 m/s

$$u(z) = \frac{u^*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

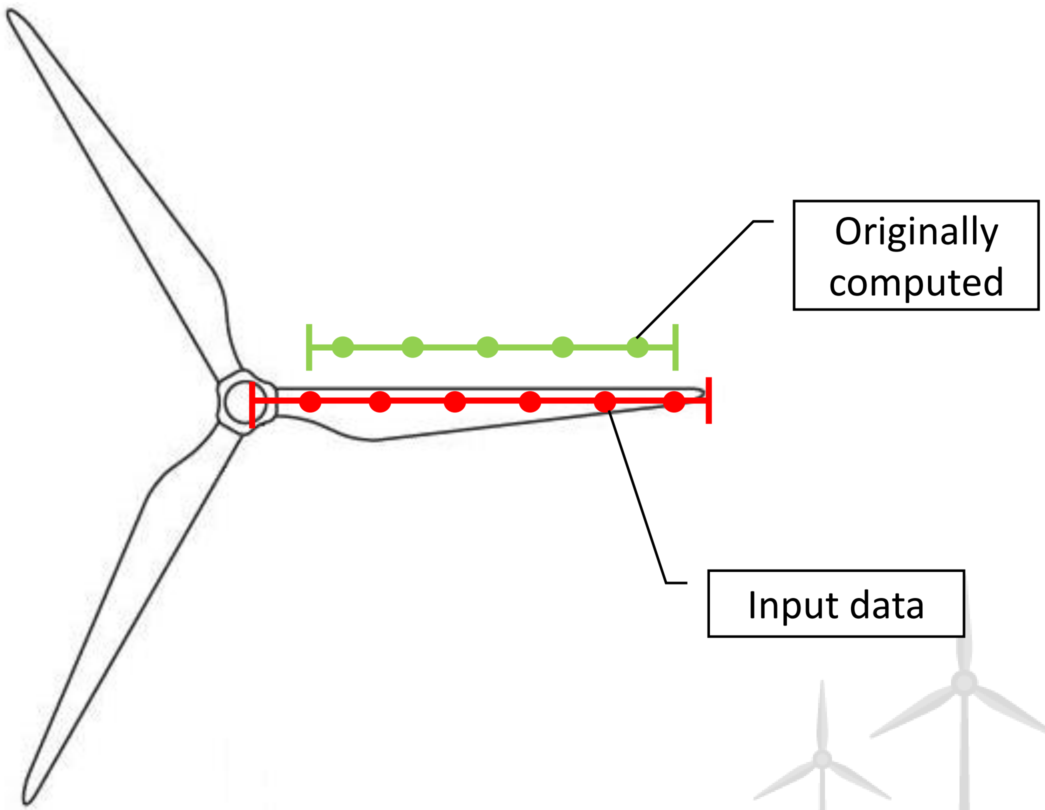
Results

- **Verification – Winc3D**

1. Inconsistency related to how the blade elements are computed from the input data.
   - Error is relevant, as imply not using the full length of the blade

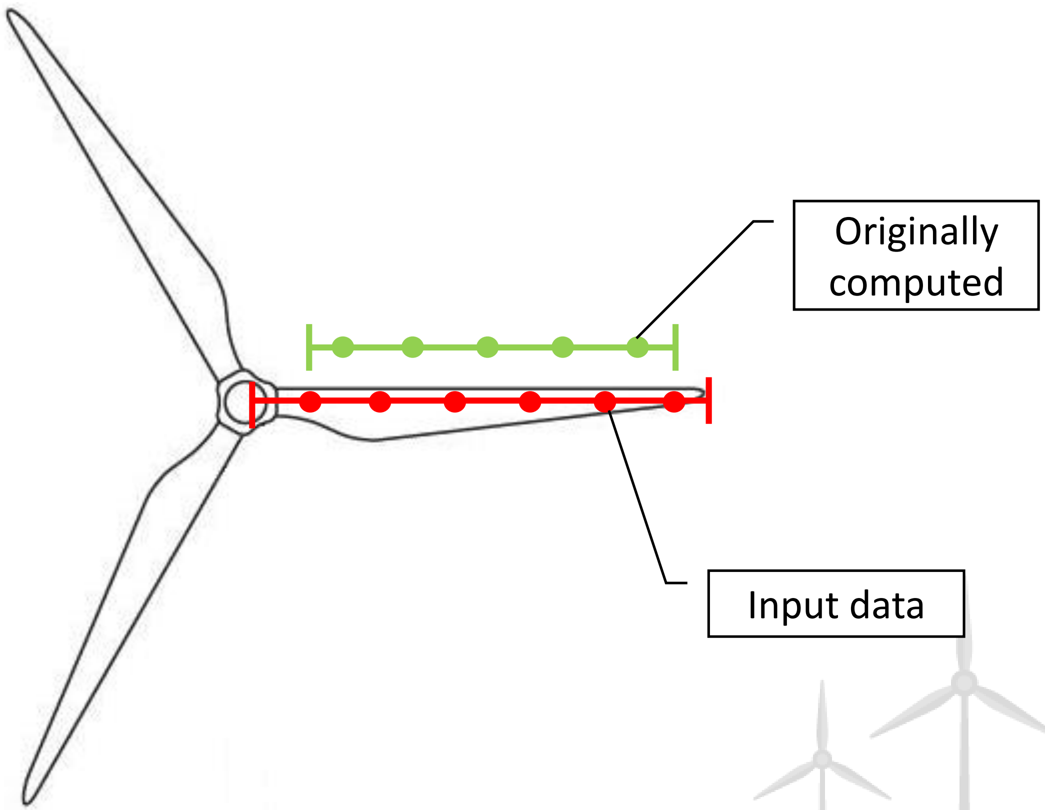
2. The random noise generator had a bias toward positive values horizontal velocity component (uz)

- Both bugs have been corrected, publishing is ongoing



Results

- **Verification – OpenFOAM with turbinesFOAM**
- Similar inconsistency as Winc3D, related to how the blade elements are computed from the input data
  - Corrected code published and available https://github.com/turbinesFoam/turbinesFoam/pull/302

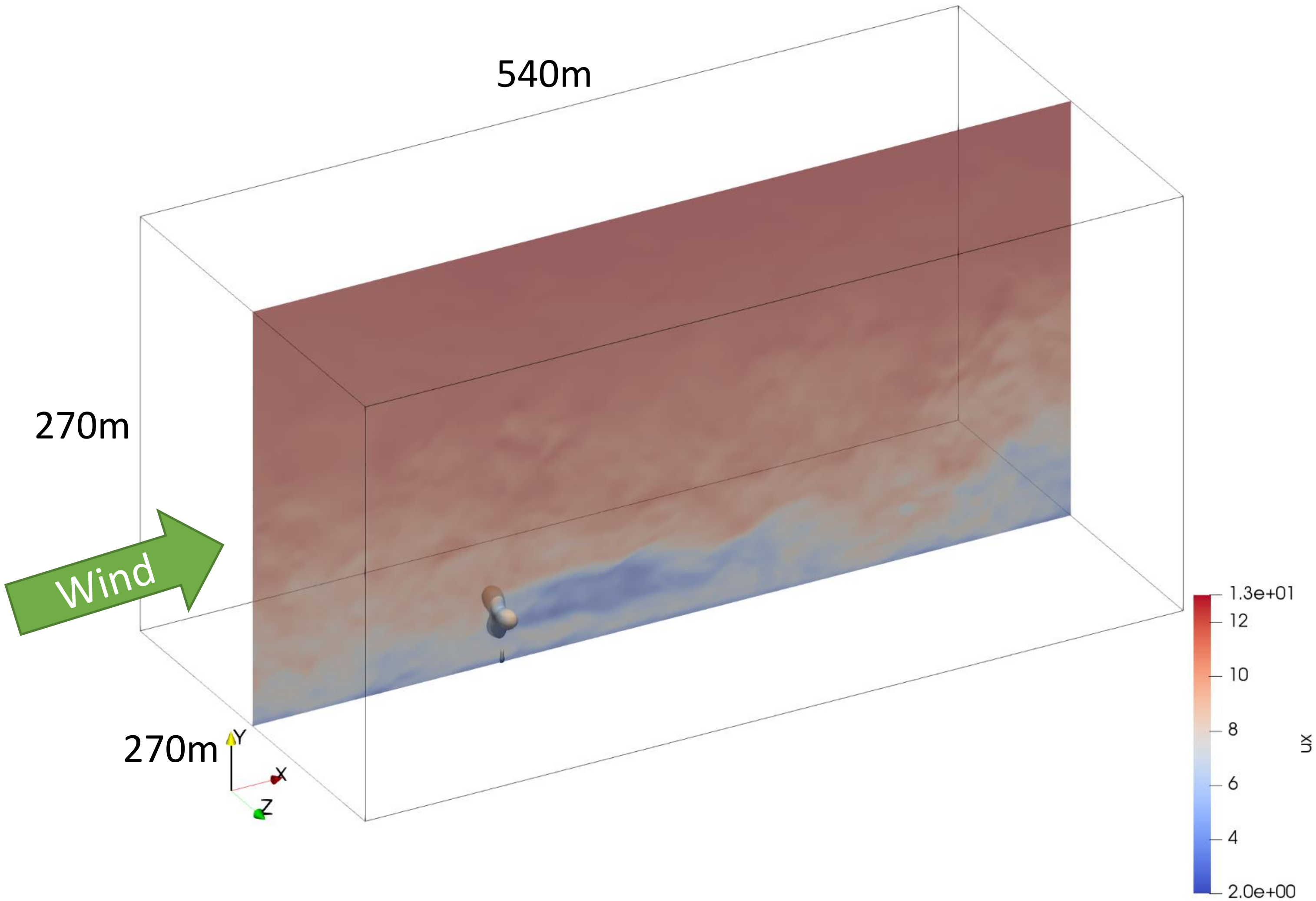


Results

Simulation setup	**WInc3D**	**OpenFOAM with turbinesFOAM**
Simulation type	LES	
SGS model	Smagorinsky	WALE
Method	Finite Difference Method	Finite Volume Method
Grid type	Structured	Unstructured
Discretization	6^{th} order in space 3^{th} order in time	2^{nd} order in space and time
Wind turbine model	Actuator line model	

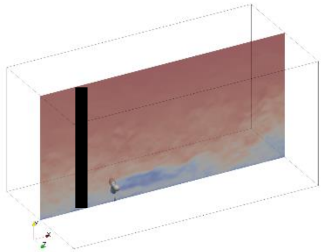
Results

- **Validation**
  - Rotor diameter D=27m
  - Grid spacing = 2m
    - Approx. 13 elements per rotor diameter
  - ~ 4.9 million hexahedral elements
  - Time step = 0.05s
  - Simulation time = 600s (as the measurements)



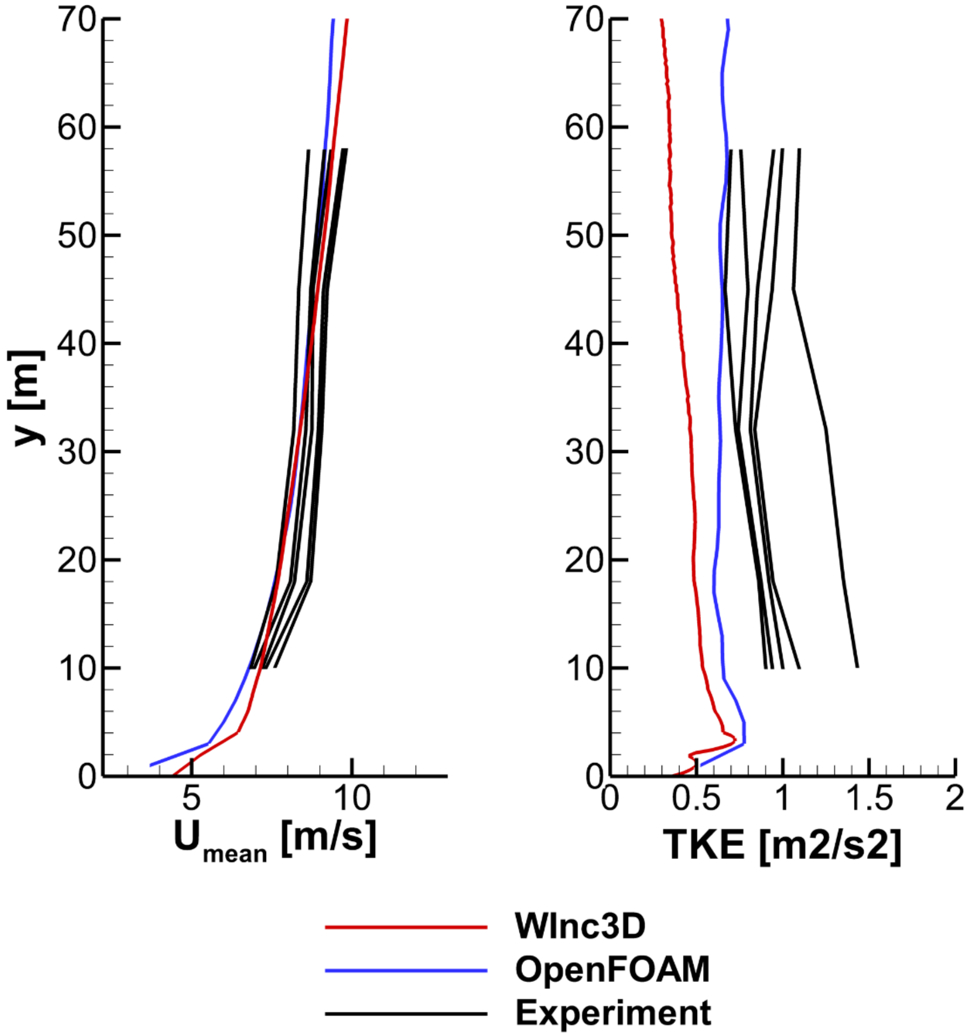
Results

- Vertical profiles



  - Mean wind velocity U_{mean}
  - Turbulent kinetic energy TKE

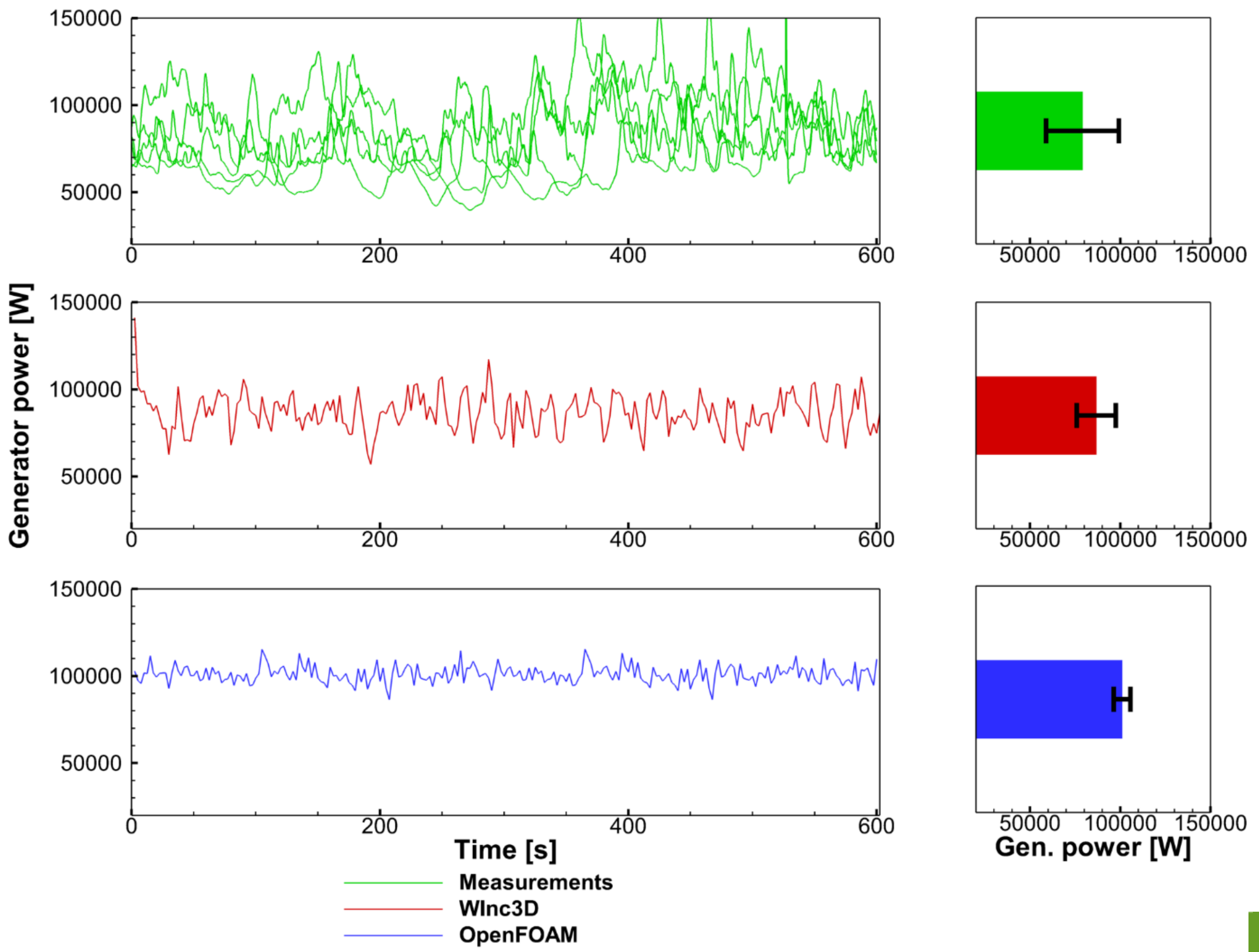
  - Mean velocity shows good agreement for both simulations
  - TKE is underpredicted



Results

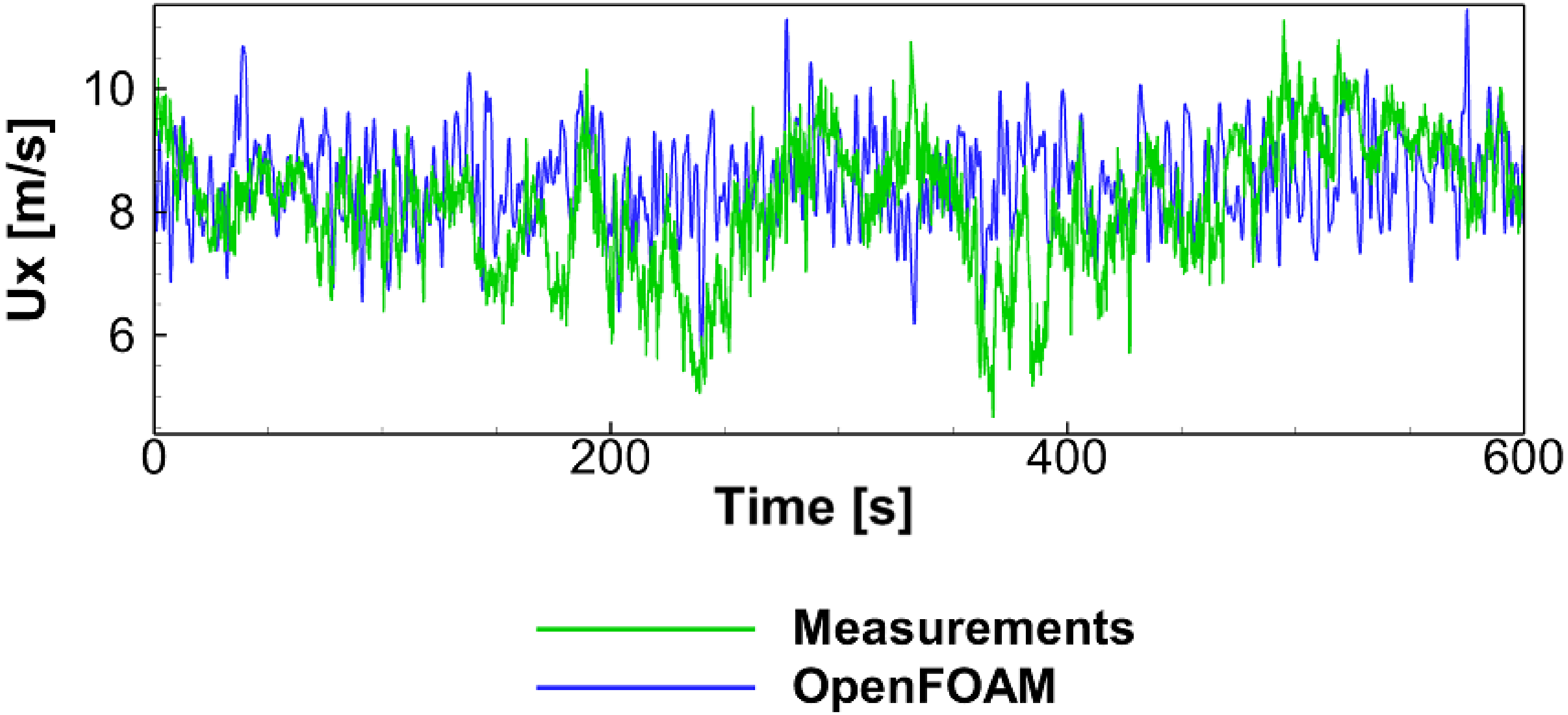
- Generator power over time (left)
- Mean value and standard deviation (right)

- Mean power is overpredicted
  - +9.6% WInc3D
  - +27.7% OpenFOAM
- While standard deviations are underpredicted
  - Corroborates with underpredicted TKE



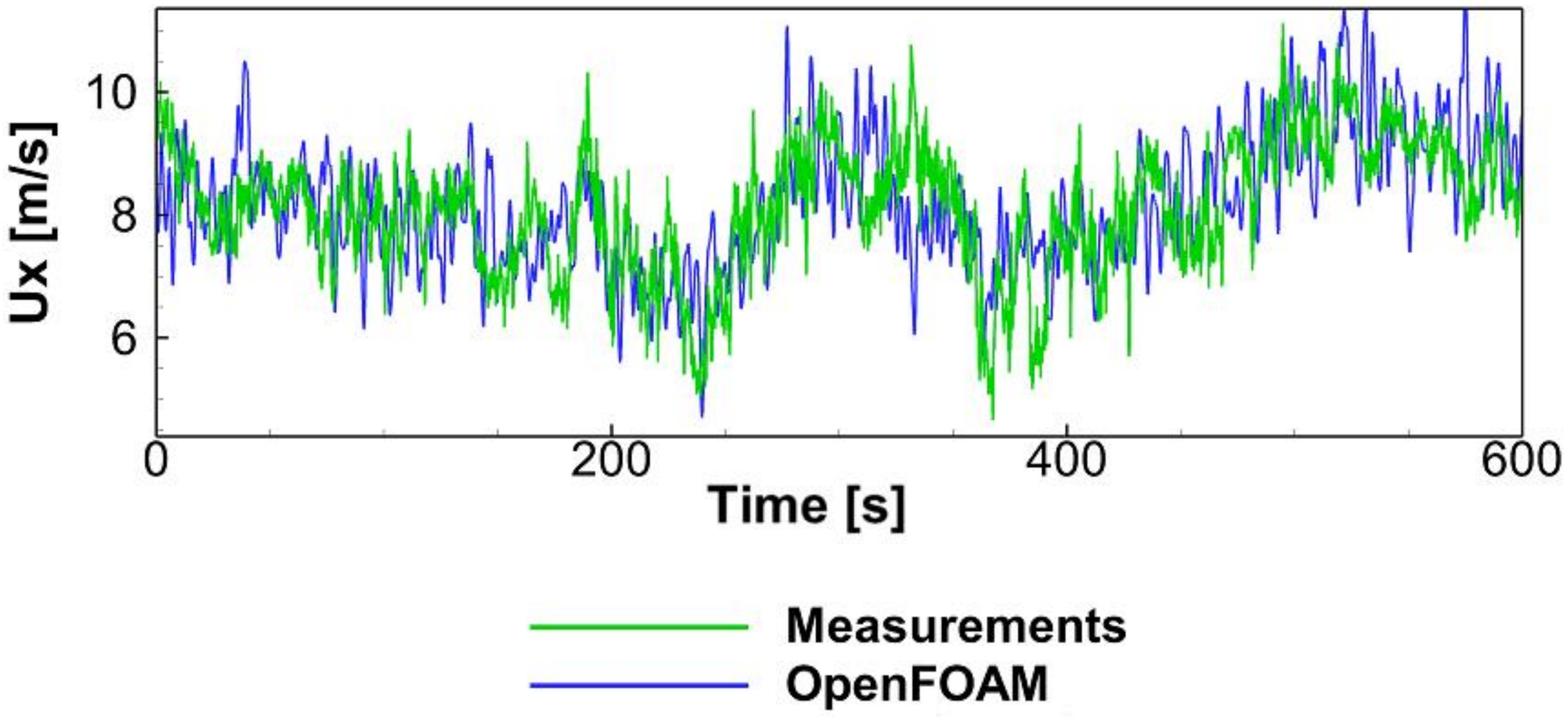
Results

- Possible cause: the mean velocity changes considerably in the 10-minutes interval



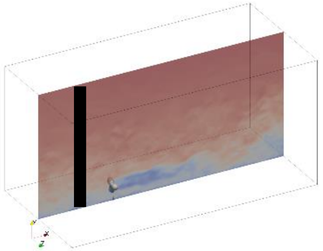
Results

- Solution: implemented a variable-velocity inflow condition, based on a moving average of the experimental data



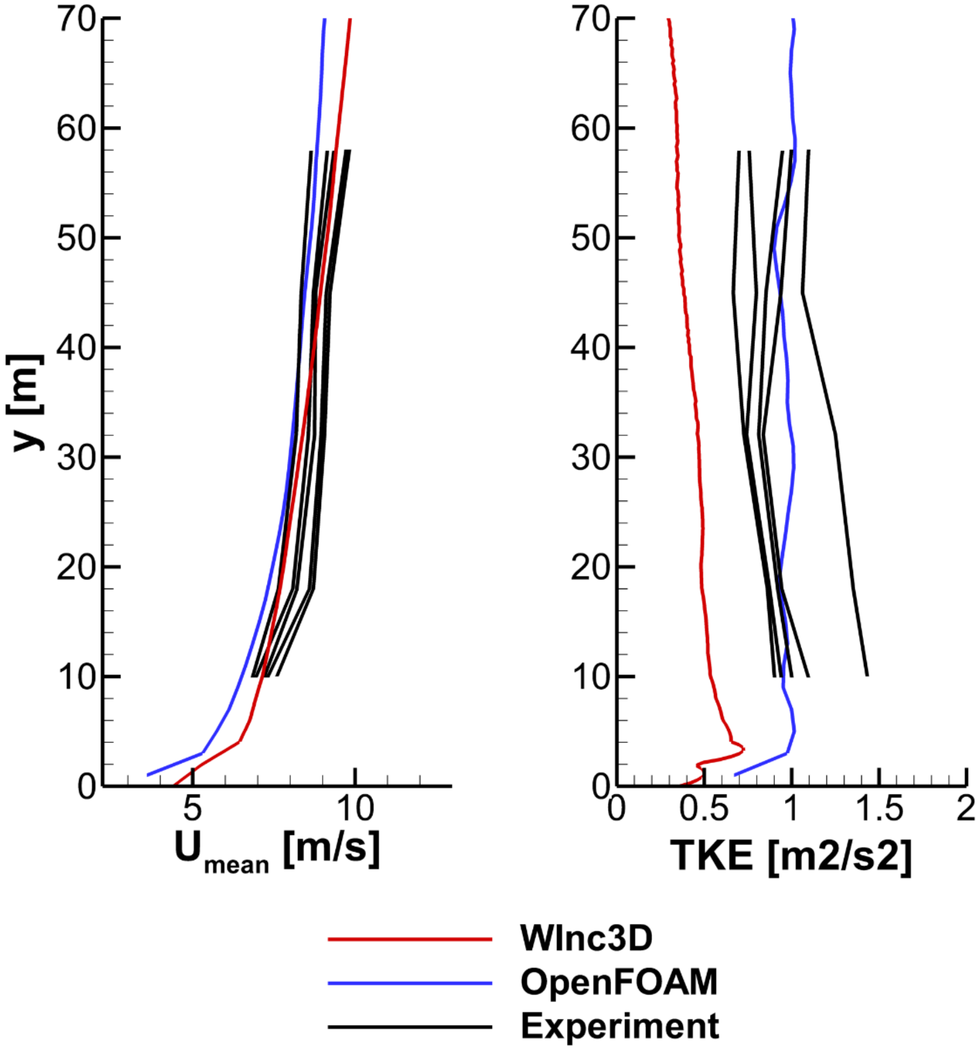
Results

- Vertical profiles



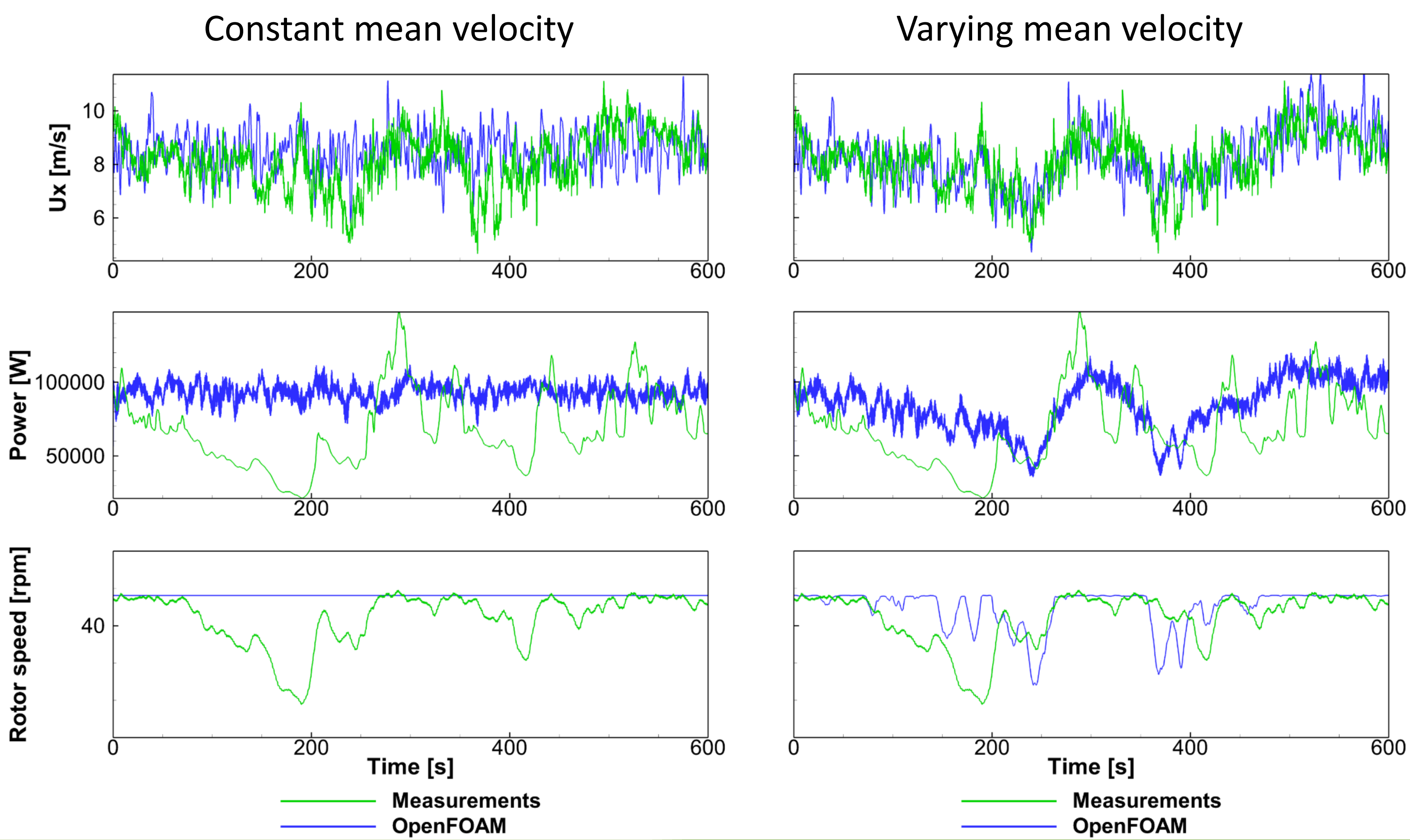
  - Mean wind velocity U_{mean}
  - Turbulent kinetic energy TKE

  - Same parameters of synthetic turbulence as previous simulation
  - Mean velocity profile remain in good agreement
  - TKE in much better agreement with the experimental data
    - Observed fluctuations are not only turbulent in nature – TKE maybe inappropriate nomenclature



Results

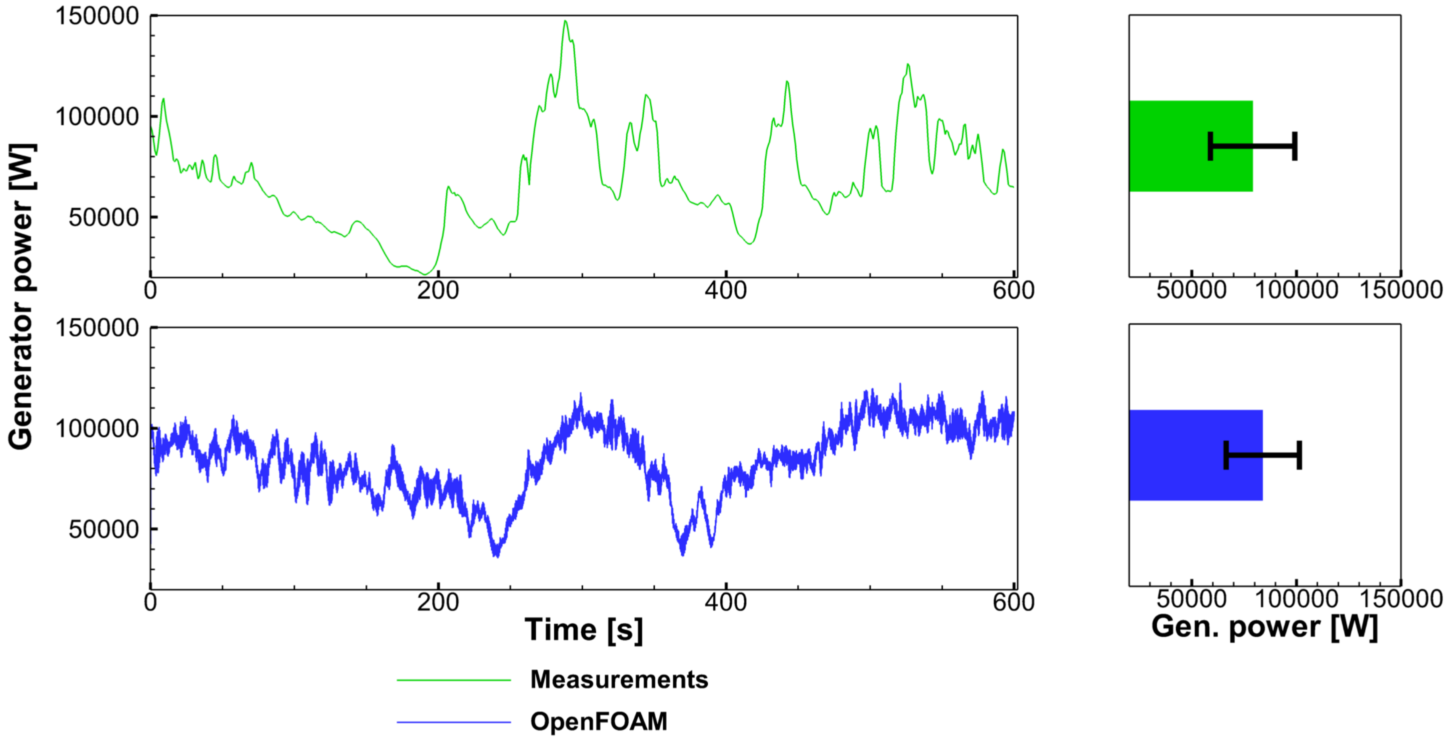
- The varying mean velocity affects the power output and rotor speed



Results

- Generator power over time (left)
- Mean value and standard deviation (right)

- Power prediction in better agreement using new BC
    - From +27.7% overprediction to +6%
- Standard deviations also with better agreement



Results

- HPC resources
  - Vulcan cluster, 2 nodes with 40 cores of Intel Xeon Gold 6138 @ 2.0GHz (Skylake) processors
  - OpenFOAM utilizes fewer resources than WInc3D
    - 25% of the WInc3D computing time when considering precursor + main run
    - 55% of the WInc3D computing time when considering main run only
  - WInc3D using a different inflow BC is currently being investigated

	Main run [CPU-hours]
WInc3D - precursor	403.9
WInc3D - main	505.1
OpenFOAM	255.1

Conclusion

- Successful verification of two CFD codes for wind turbine simulation
  - WInc3D and OpenFOAM with turbinesFOAM module
  - Code corrections to be published
- Successful validation using experimental data from the SWiFT Benchmark
- Development of a variable-velocity inflow condition

- Next steps
  - Investigate the influence of mesh refinement in the results
    - Considering the differences of WInc3D and OpenFOAM regarding grid generation and discretization order
  - Proceed with the Uncertainty Quantification (UQ) study

Thank you

Flavio C. C. Galeazzo

Andreas Ruopp

Ralf Schneider

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