Data generation workflow for meso/microscale coupled offshore wind farm simulations

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U.S. DEPARTMENT OF ENERGY | Office of Science

Sandia National Laboratories

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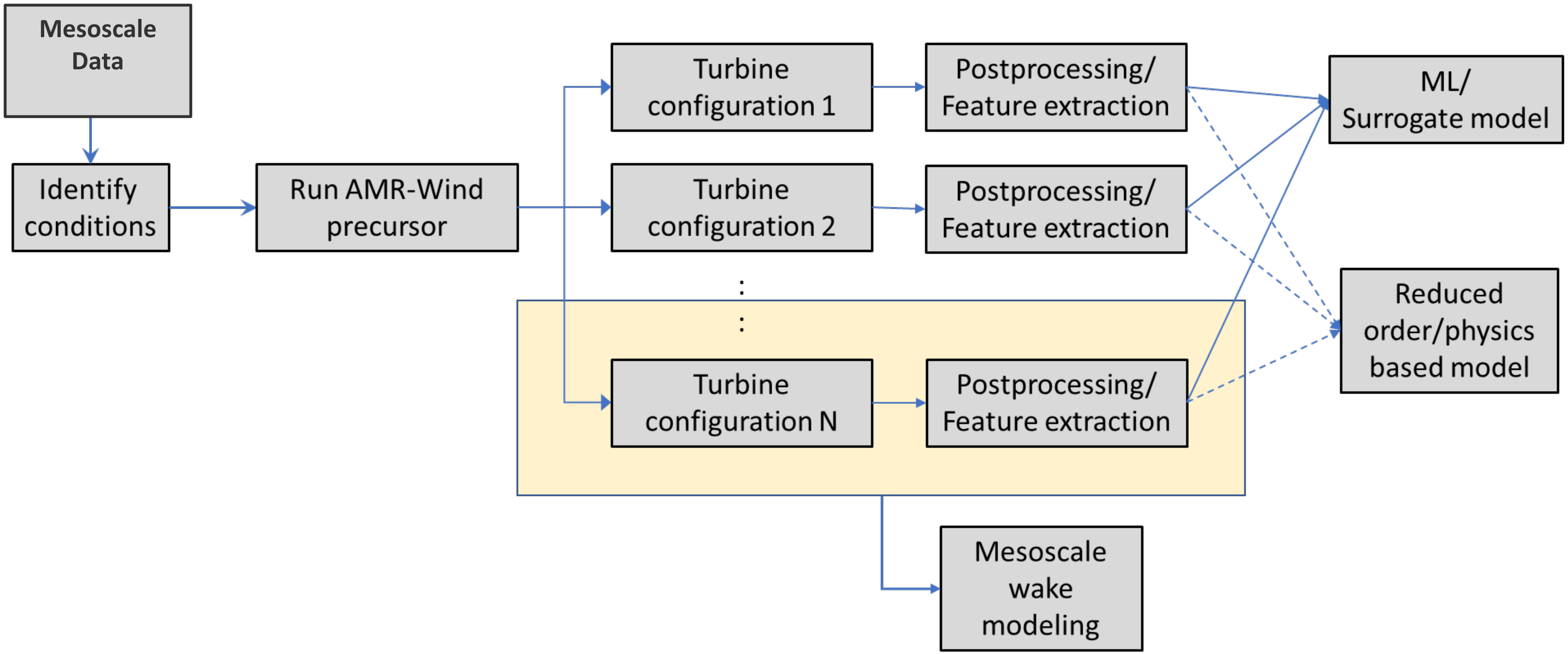
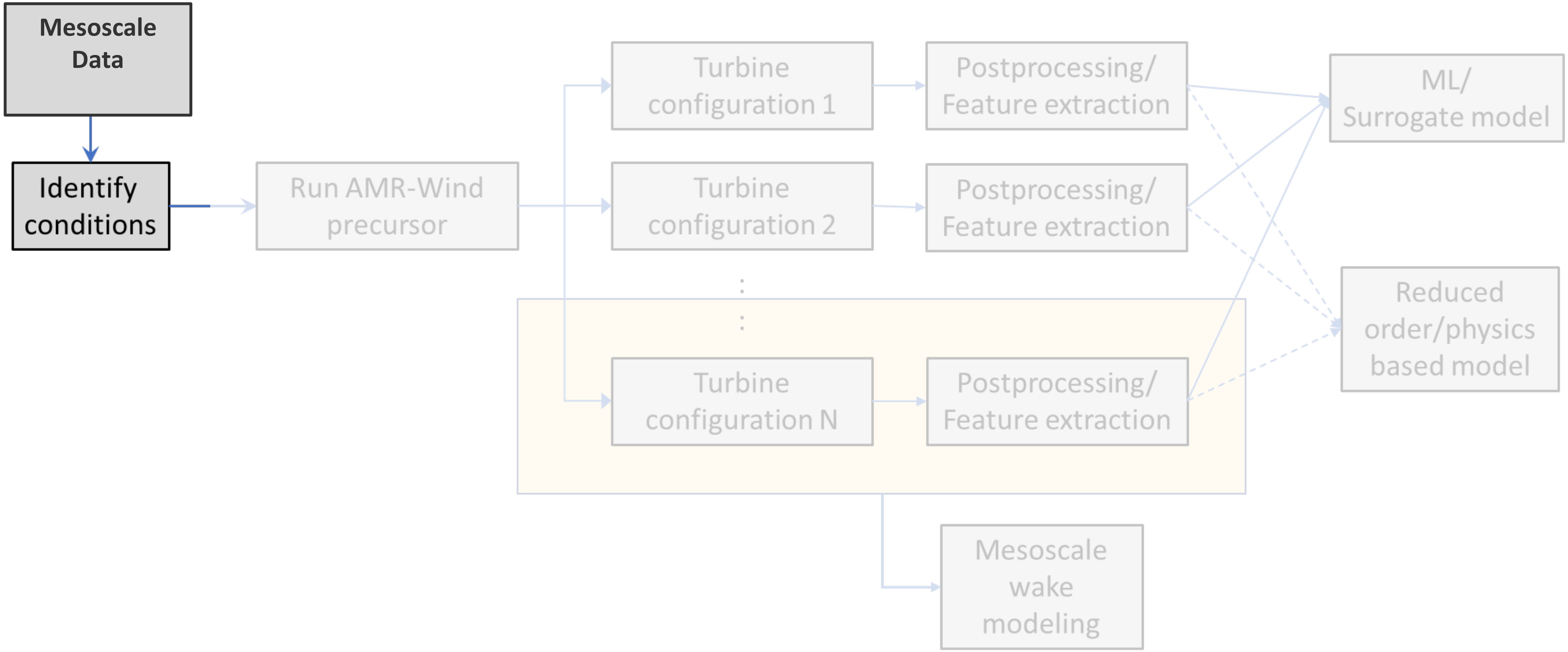
Motivation: Simulating wind farms under realistic atmospheric conditions

- Wind farm performance depends on:
  - interactions between wind turbines
  - **interactions between turbines and ABL**
- Resources for mesoscale data: **NOW-23**, HRRR, Lidar
- Objective:
  - Develop a robust, simple-to-use workflow to **enrich mesoscale information using microscale simulations** (LES)
  - **Streamline postprocessing** for a wide array of simulations
  - Create a **database of high-fidelity simulations** to **inform modeling/decision making**

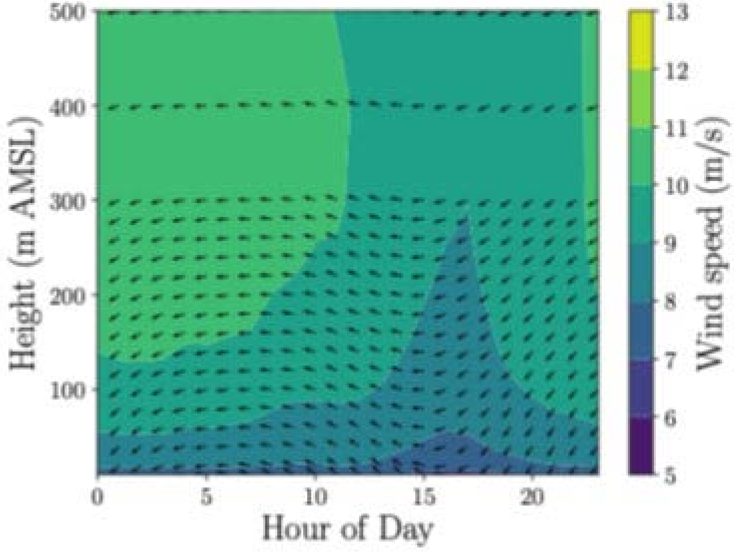
Motivation: Simulating wind farms under realistic atmospheric conditions

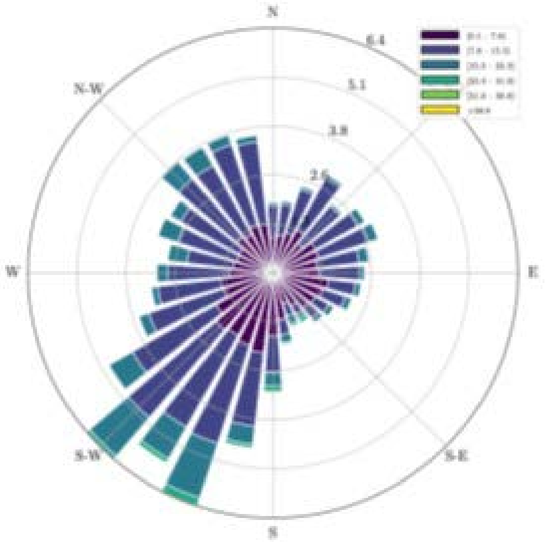


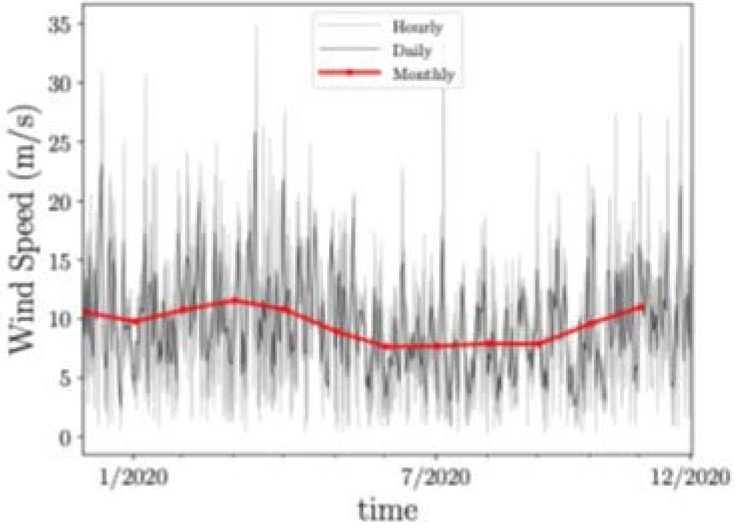
Identification of appropriate mesoscale conditions

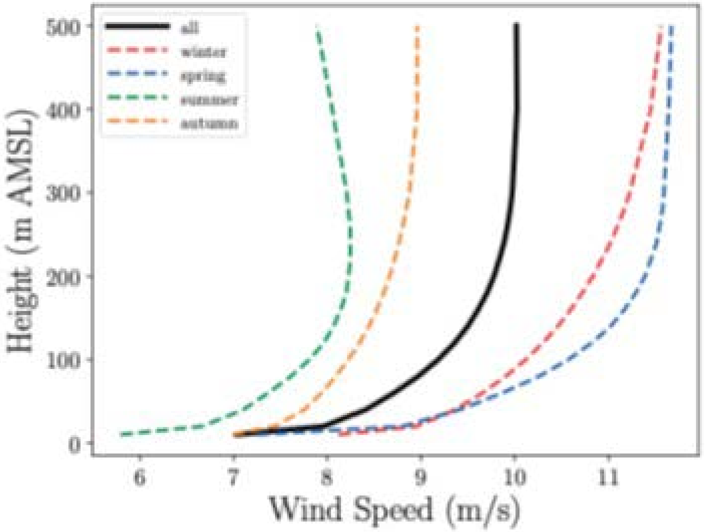


NOW-23 Dataset: Identification of appropriate mesoscale conditions









Available Data: (at 5min/2km resolution)

- Wind speed/direction : 10m – 500m
- Temperature: 10m – 500m
- Monin-Obukhov length
- Surface heat flux
- Friction velocity
- Sea surface temperature
- Boundary layer height
- TKE

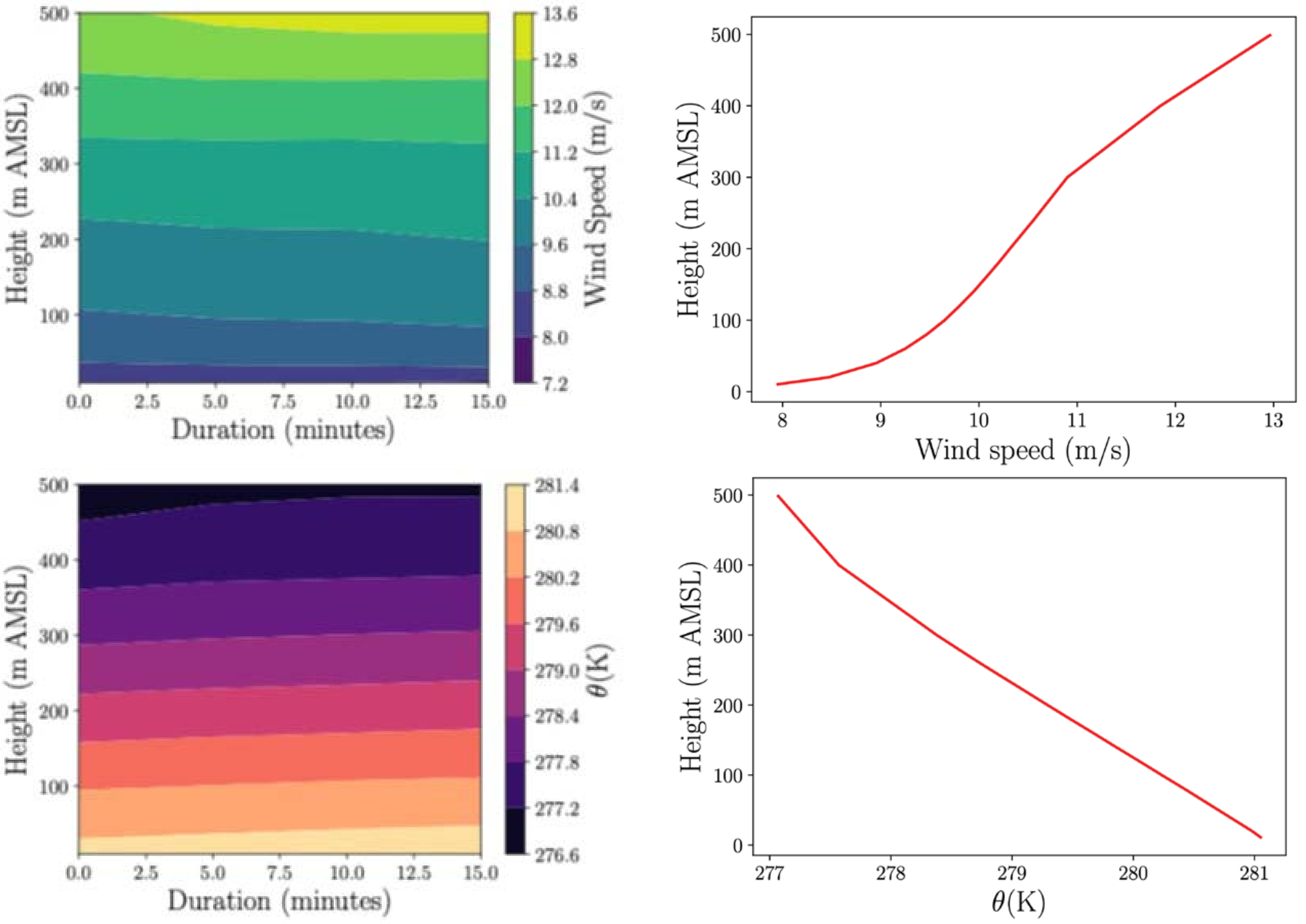
Large seasonal and diurnal variations in wind

Earth Syst. Sci. Data, 16, 1965–2006, 2024
https://doi.org/10.5194/essd-16-1965-2024

NOW-23 Dataset: Identification of appropriate mesoscale conditions

- Python package for identifying conditions:
  - Filtering criteria:
    - Hub-height wind speeds
    - Stability states (using M-O length)
    - LLJ identification
    - Complex criteria:
      - High veer change in 1hr window
      - High windspeed change in 1hr window
      - Extreme sheer/veer
  - Future work:
    - Given a time range (e.g., **1 year**), identify **N** distinct profiles lasting **X** hours
    - Goal is to get a representative set of mesoscale data

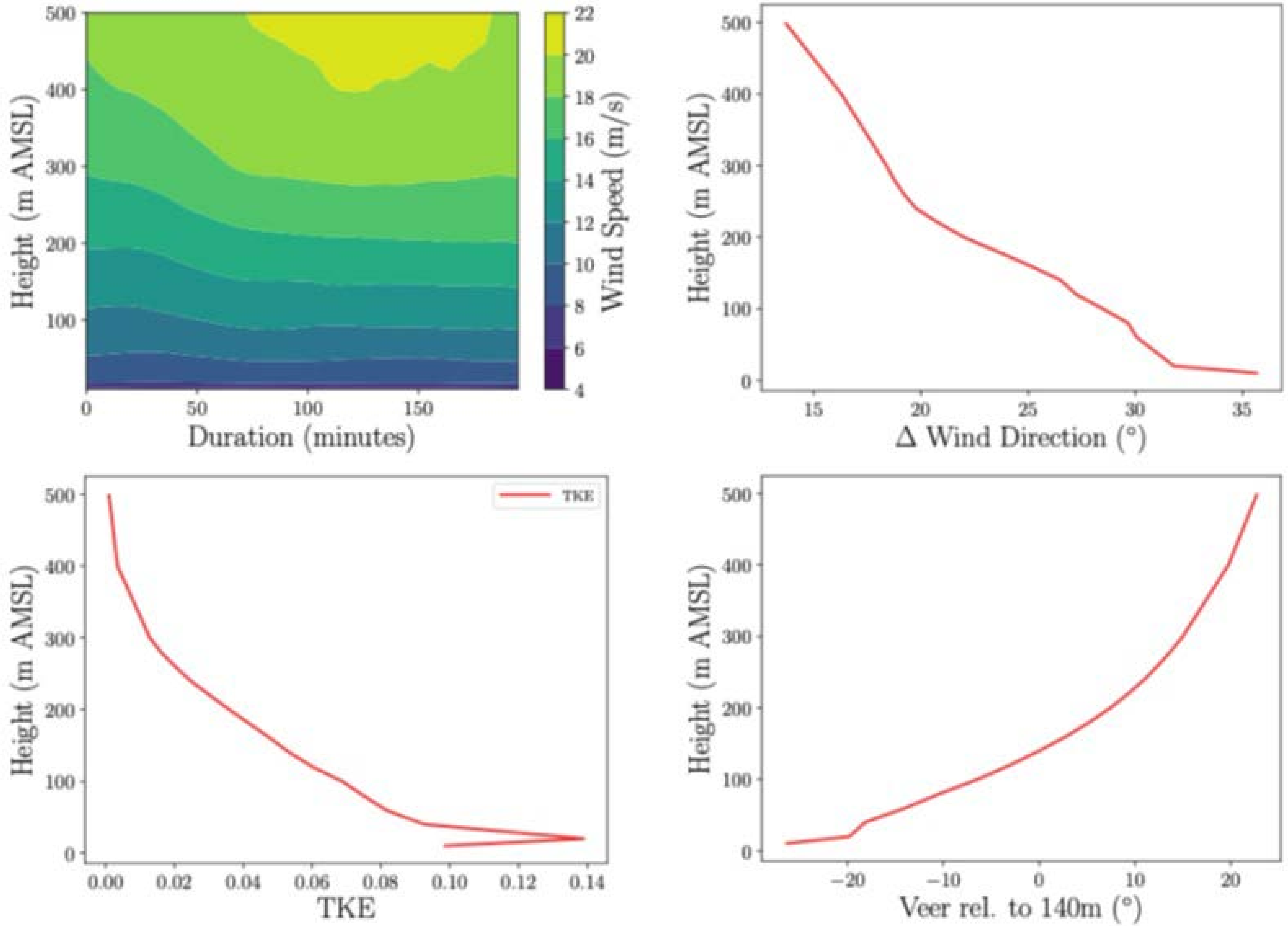
NOW-23 Dataset: Neutral ABL example



Example ABL from NOW-23 dataset with a **neutral** stability filter:

- 15 min duration
- No substantial change in wind speed/direction
- Effectively treated as a steady-state 1D profile

NOW-23 Dataset: Stable ABL example

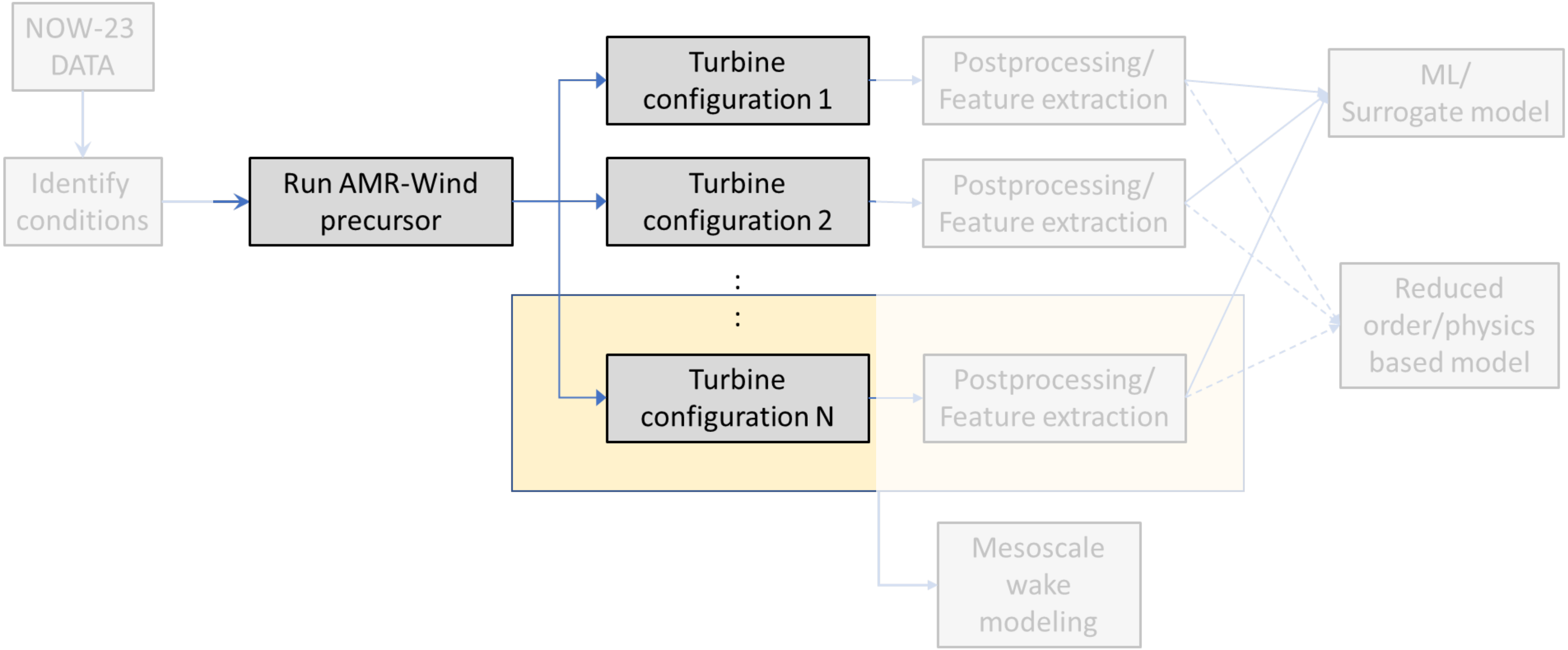


Example ABL from NOW-23 dataset with a **stable** stability filter:

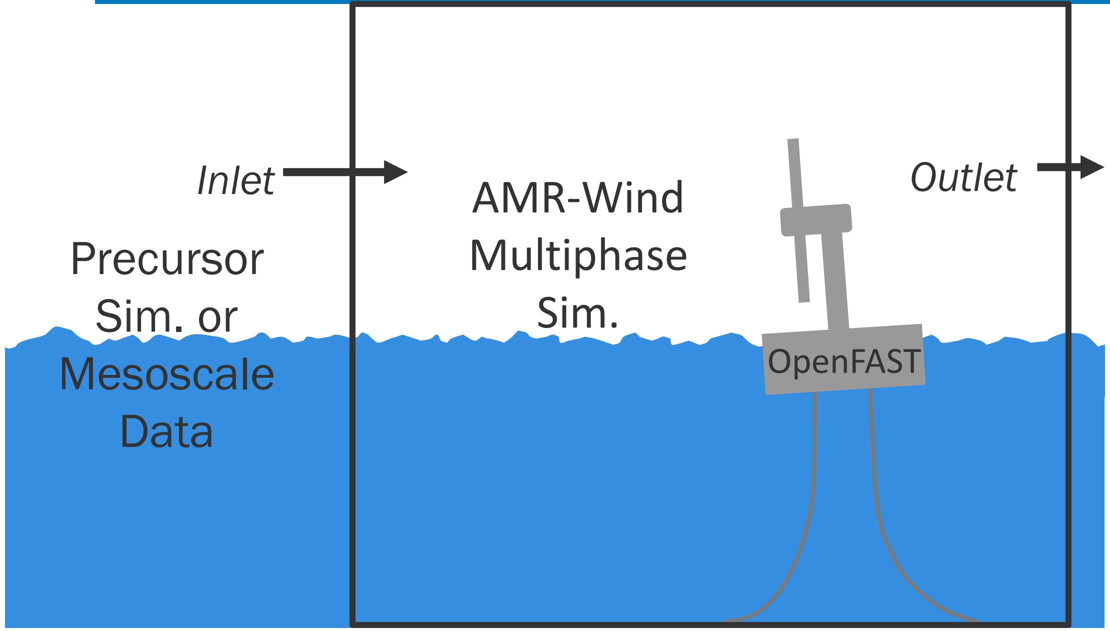
- 200 min duration
- High veer
- Substantial change in wind speed/direction
- Needs to be assimilated as a time-varying profile

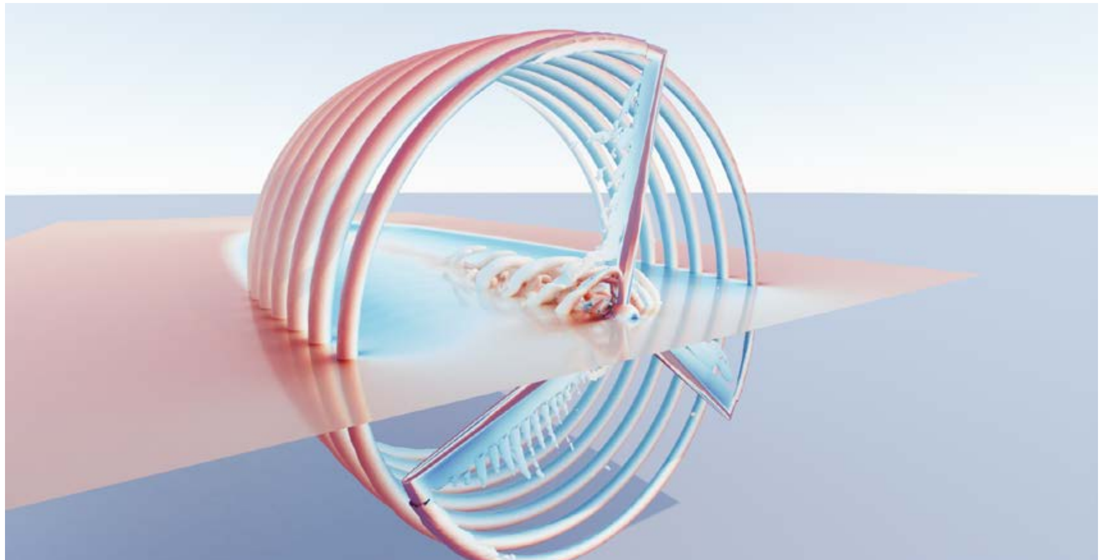
Microscale simulations: AMR-Wind

Meso-Micro coupled simulations



Microscale simulations: AMR-Wind



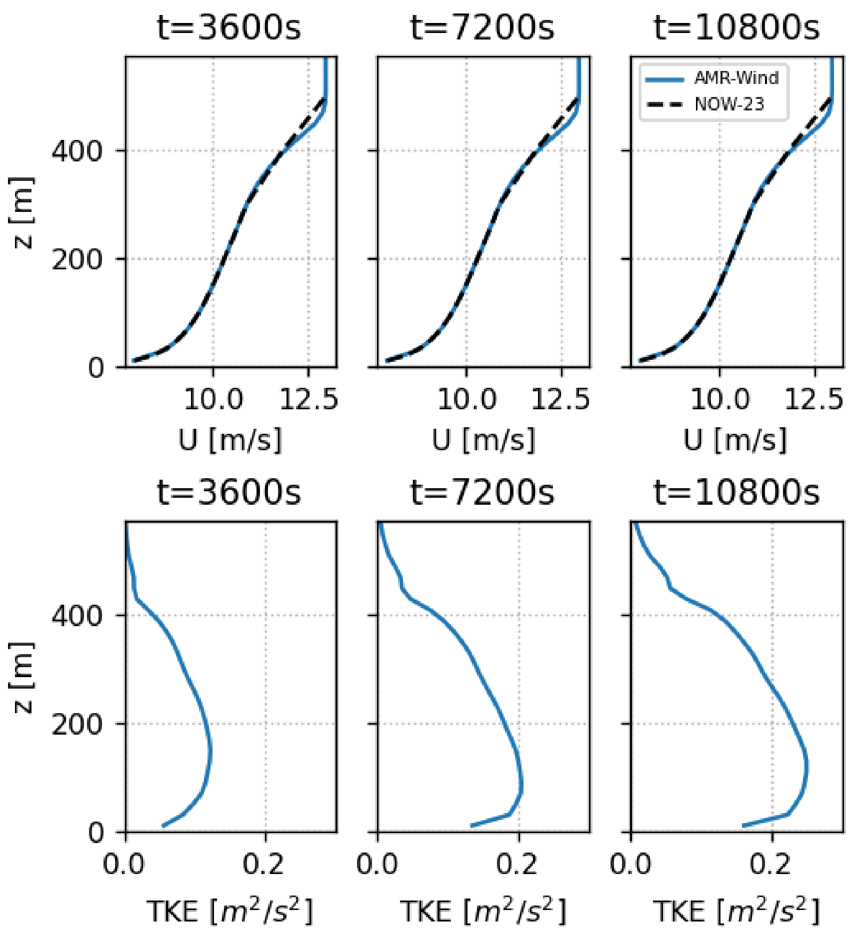


AMR-Wind is a massively parallel, block structured, adaptive-mesh, incompressible flow solver for wind farm simulations:

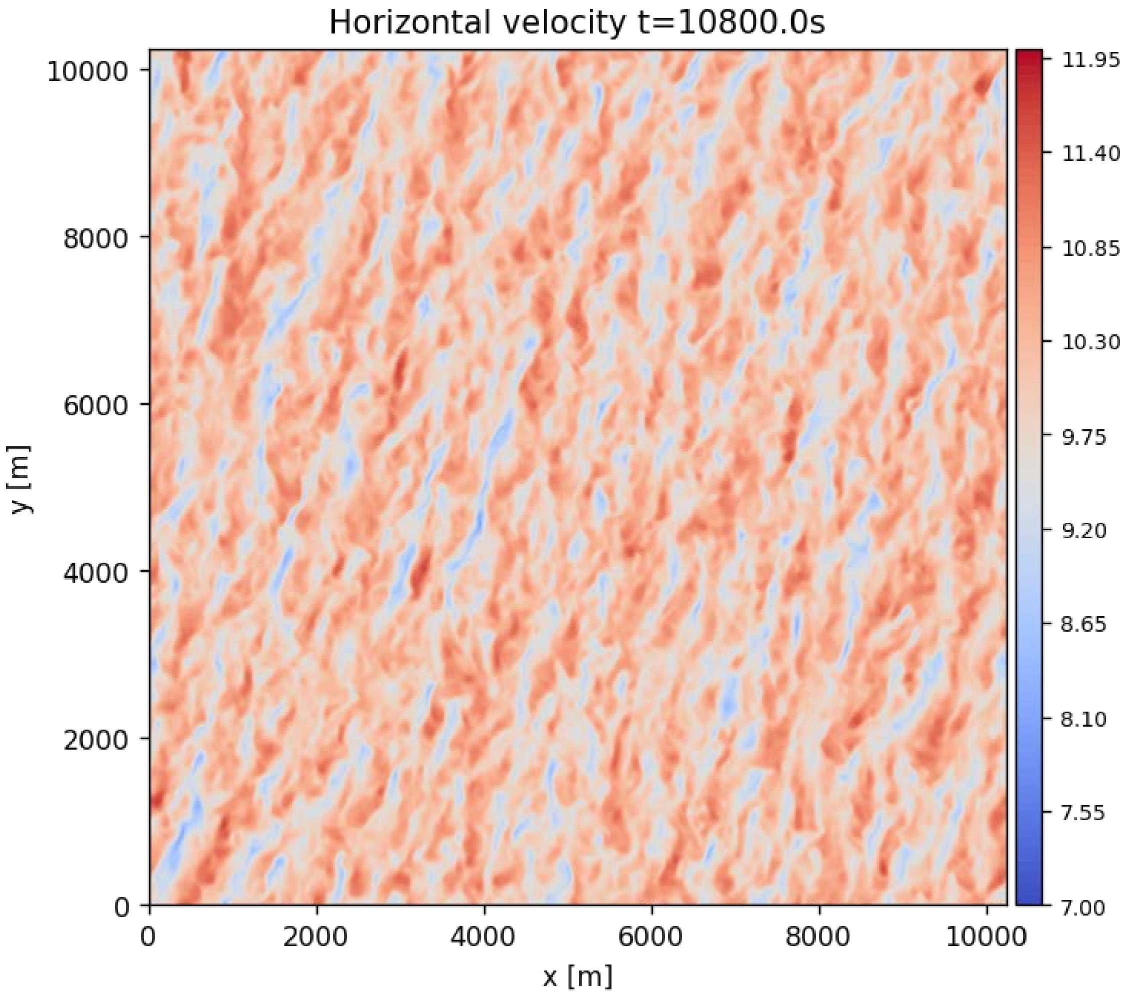
- Built on top of AMReX library for performance portability
- LES for ABLs and wind farms (with OpenFAST for ALM/ADM)
- MMC capabilities: can assimilate mesoscale information via a source term
- Actively maintained by a multi-lab team
- Typical workflow:
  - Run a precursor ABL simulation (with MMC)
  - Use the precursor data as inflow for wind farm simulations

https://exawind.github.io/amr-wind/

Meso-Micro coupled simulations: Results from neutral ABL

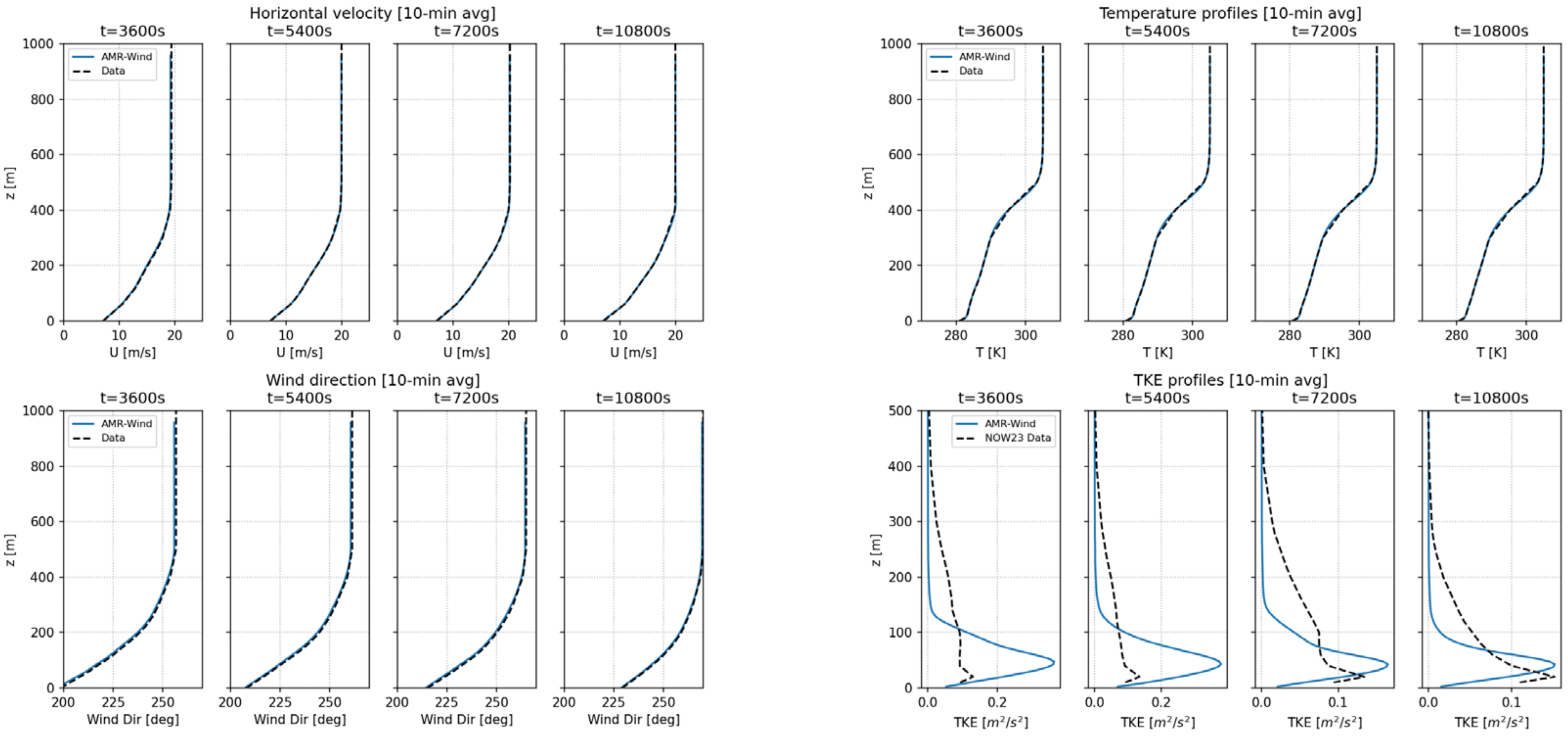


LES matches 1-D mesoscale quantities



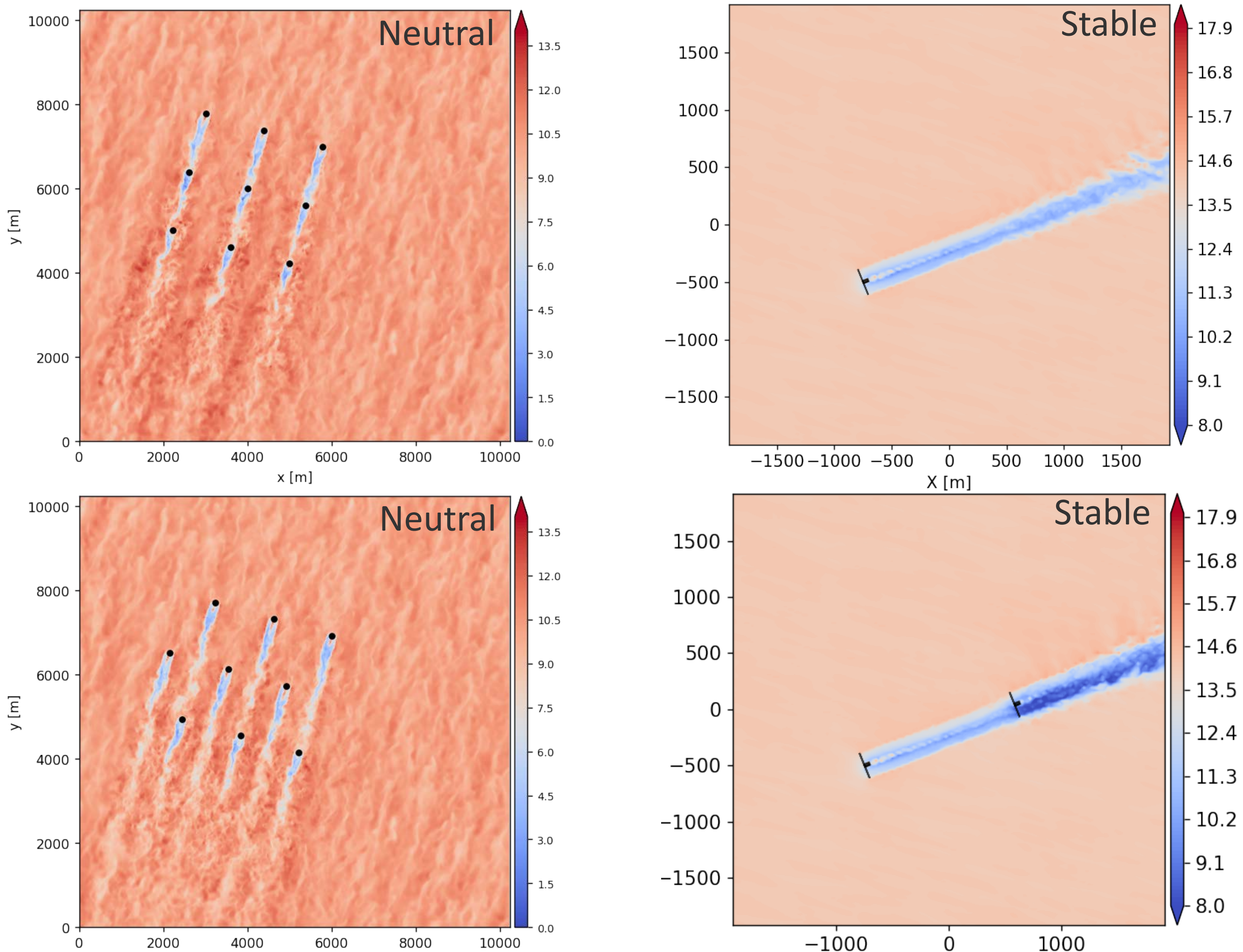
Instantaneous velocity snapshot from LES

Meso-Micro coupled simulations: Results from stable ABL



NOW-23 profiles vs spatial averages in AMR-Wind: **LES captures the time-varying mesoscale quantities** form data

Meso-Micro coupled simulations: Turbine simulations

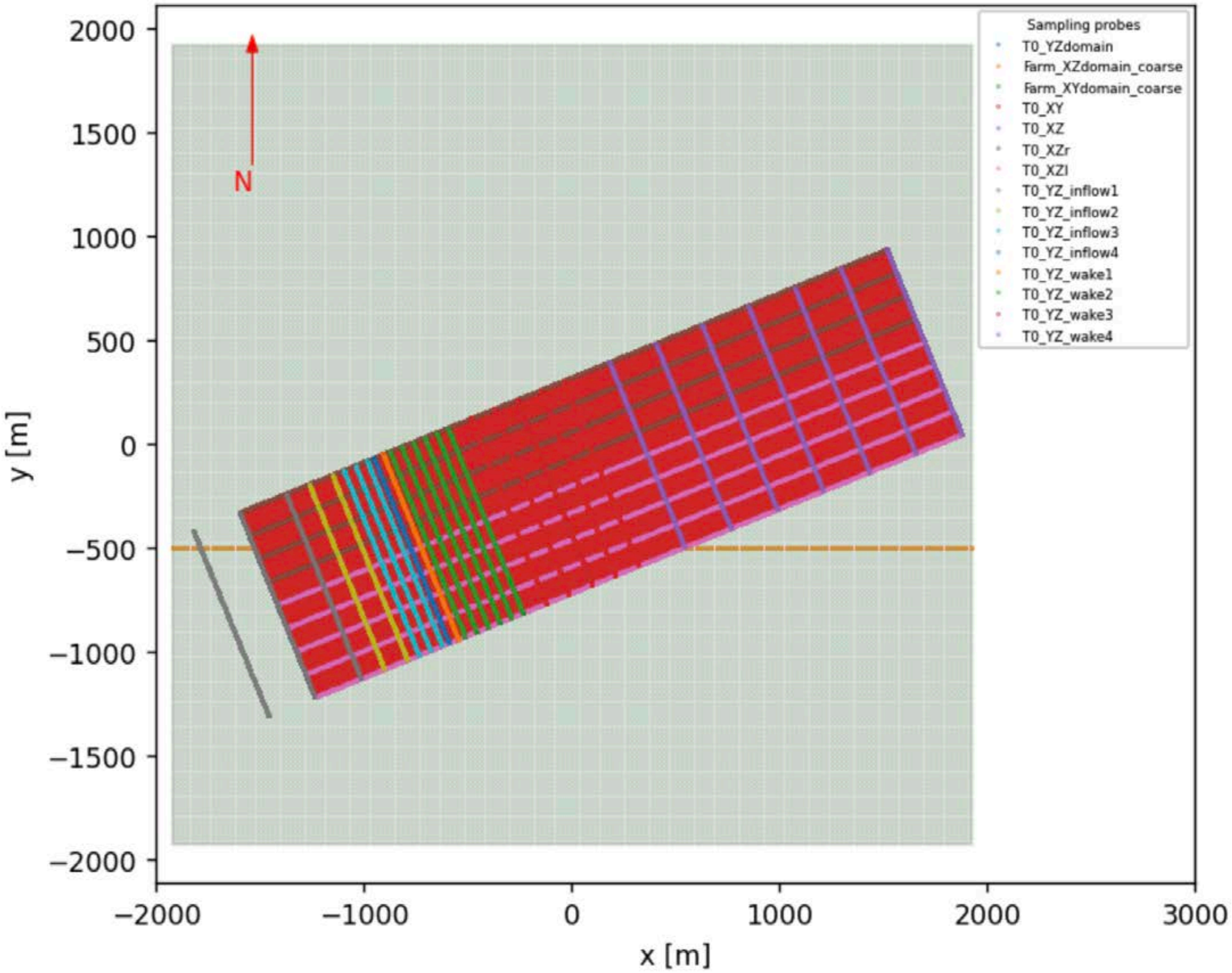


Turbine simulations are expensive!

- IEA 15 MW turbines
- 150-300 Million cells for the single turbine cases
- 1.6 Billion cells for 3x3 turbine cases
- Provides invaluable insights into unsteady wake behavior
- **`amr-wind-frontend`** helps to programmatically setup cases

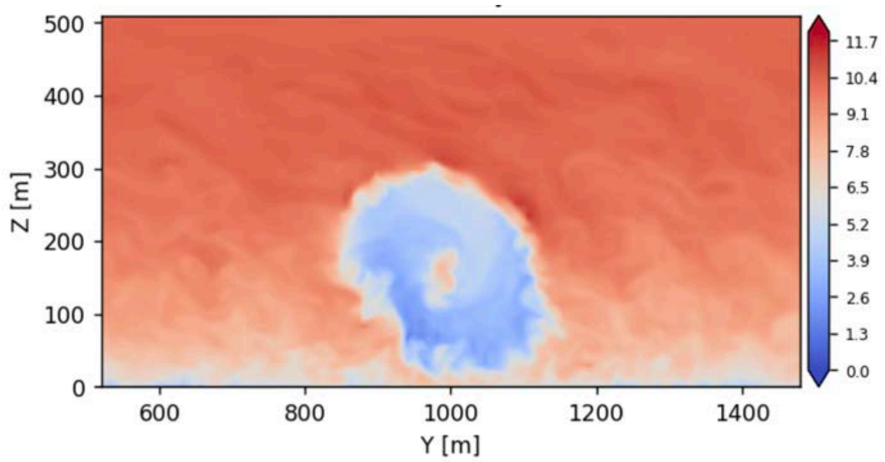
`https://github.com/Exawind/amr-wind-frontend`

Post-processing workflow



Wake details are collected on sampling planes:

- Several sampling planes setup both upstream and downstream of each turbine
- Postprocessing engine from **`amr-wind frontend`** helps automate getting relevant wake stats
- High resolution wake snapshots provide detailed wake characteristics to aid modeling



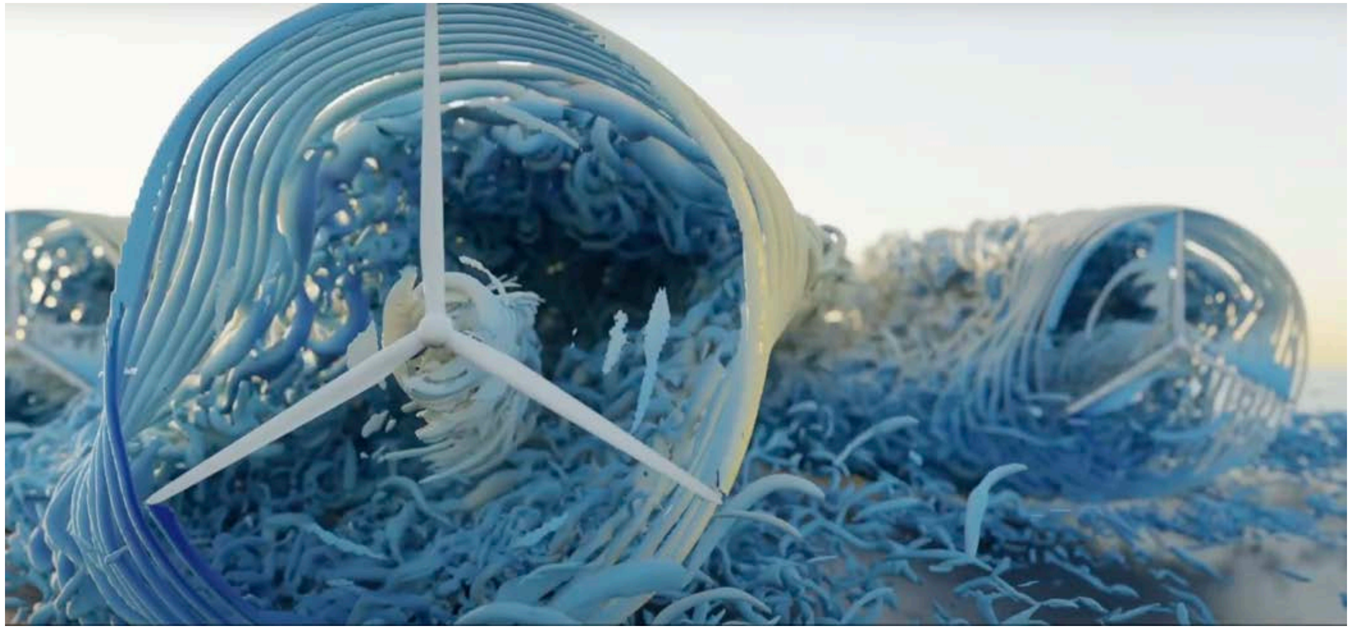
Summary and future work

Developed a workflow for running **wind farm simulations in realistic atmospheric conditions**:

- Uses **NOW-23 for mesoscale data**, and **AMR-Wind + OpenFAST for microscale simulations**
- Developed software for **filtering mesoscale data**, setting up LES and postprocessing the results
- Multiple DOE projects are utilizing the dataset for **model development** and **decision making**

Future work:

- More cases – multiple wind farm configurations, stability states
- Extremes – (e.g., LLJs, extreme sheer/veer) to improve/develop new wake models



Thanks!

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