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Overview of LES for Use in Wind Farm Applications

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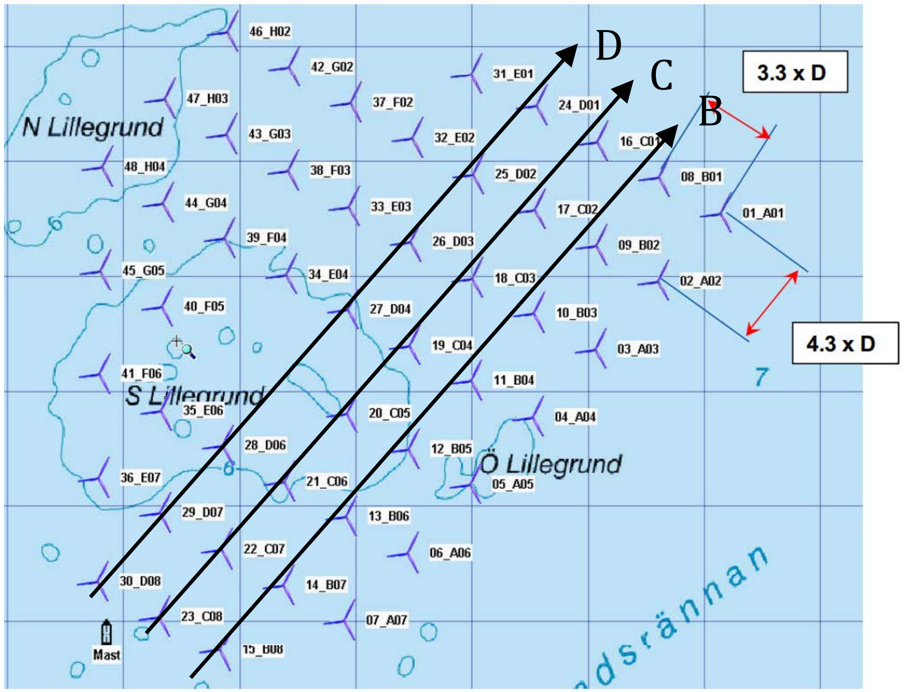
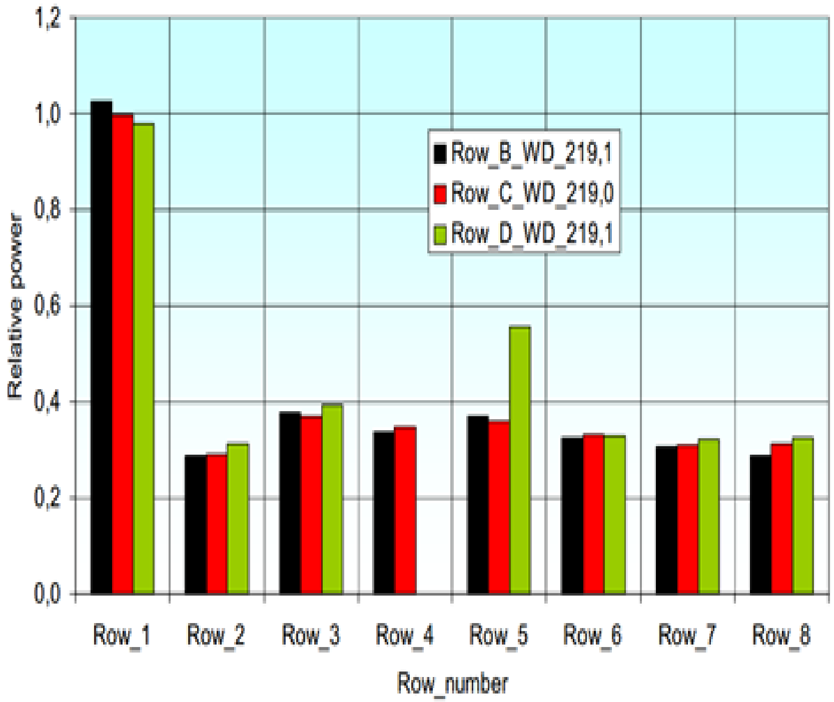
Motivation

- **Wind Plant Efficiency**
- **Turbulent Loading**
  - **Fatigue Issues**
- Acoustics
- Influence of Wind Farm on Atmosphere?

Wind Plant Efficiency



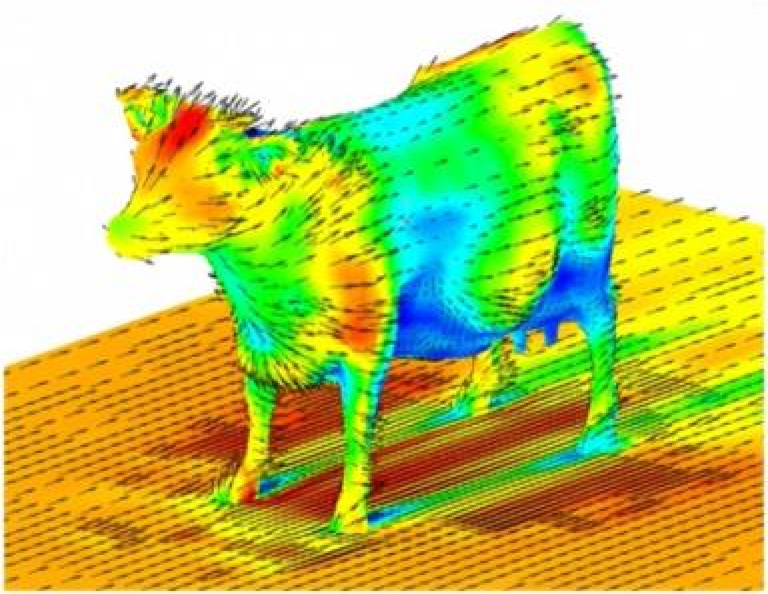


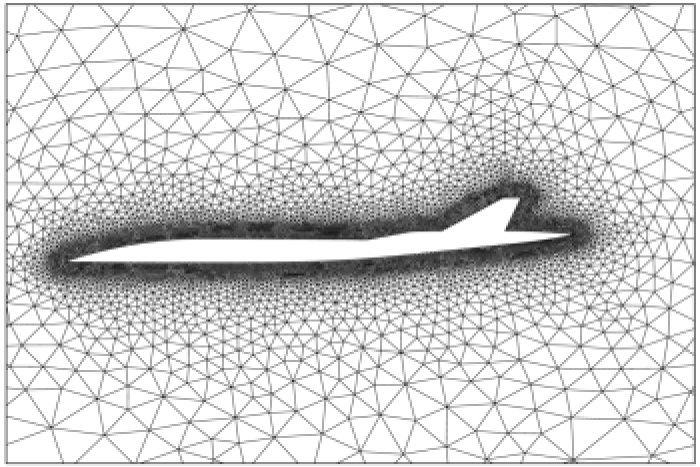
From: Assessment of Lillgrund (2008)

Fatigue Life

- Fatigue: weakening of material due to variable loading, eventually leading to failure
  - Cyclical loading due to rotation of blades
  - Chaotic loading from turbulence
- Rainflow-Counting
  - Used to predict fatigue life
  - Used in conjunction with empirical turbulence models
    - Replace empirical models with CFD?

What is CFD?





CFD

Advantages

- Cheaper than wind tunnel or full-scale testing
  - Time & Money
- Easy to change parameters
- Can be used to validate test measurements
- Can extract a lot of data

Disadvantages

- Only as accurate as the physics model used
- Numerical errors
- Can be computationally expensive
- Boundary Conditions

CFD Models

- Numerical methods for solving partial differential equations (Matt F. talked about this)
- Turbulence modeled with varying degrees of fidelity
  - RANS – Low Cost, Low Fidelity
    - Time Averaged Solutions
  - **LES – Higher Cost, Higher Fidelity**
    - **Time Accurate Solutions**
  - DNS – Absurdly Expensive, Resolves Tiny Scales
    - Simulates even tiny scales

Navier-Stokes Equations

- Navier-Stokes Equation (Newton's 2nd Law):

$$\underbrace{\rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\vec{\nabla}\vec{v}\right)}_{\text{Inertia }(m*a)} = \underbrace{-\vec{\nabla}p + \mu\overrightarrow{\nabla^2}\vec{v} + \vec{f}}_{Forces}$$

- Incompressible (Mass Conservation):

$$\vec{\nabla}\cdot\vec{v} = 0$$

Large Eddy Simulation (LES)

$$u_i = \bar{u}_i + u_i'$$

- Low-pass filtering of Navier-Stokes (N-S) Equations
  - Filters small scales of motion (u_i') from solution (SFS/SGS)
  - Resolves large scale motion ($\bar{u}_i$) depending on available computational resource
- Models sub-filter (SFS) and sub-grid scales (SGS)

Wind Turbine Models (Porte´-Agel 2010)

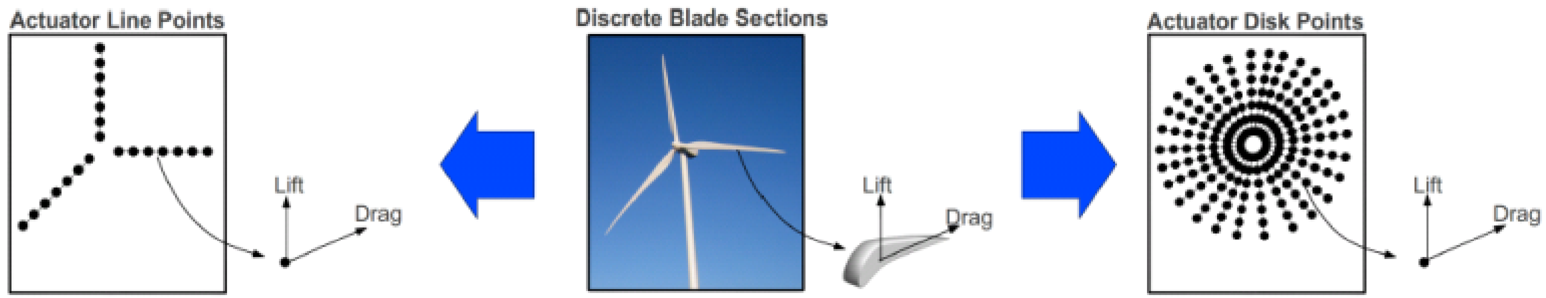
Actuator Disk

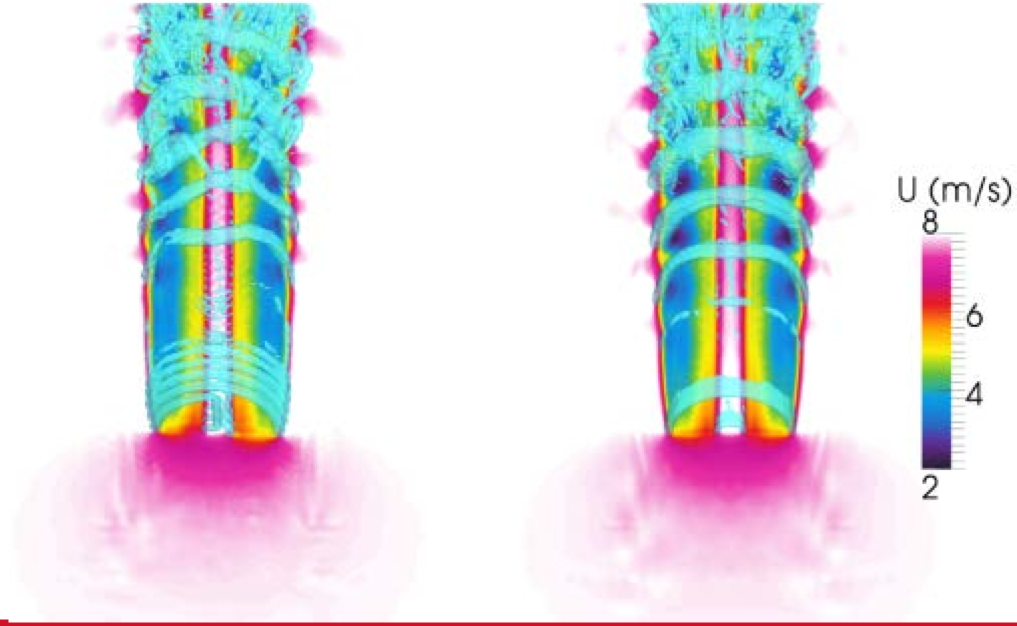
- Momentum Theory
- Used by Calaf (2010)
- Infinite number of blades
  - Divides swept area into many elements
  - Uses airfoil lookup tables to compute force on disk element
  - Force projected back on flow scaled with solidity

Actuator Line

- Sorensen and Shen (2002)
- Models each blade
  - Divides blade into elements
  - Uses airfoil lookup tables to compute force on blade element
  - Projects force back onto flow using Gaussian projection

Wind Turbine Models (Martinez 2012)



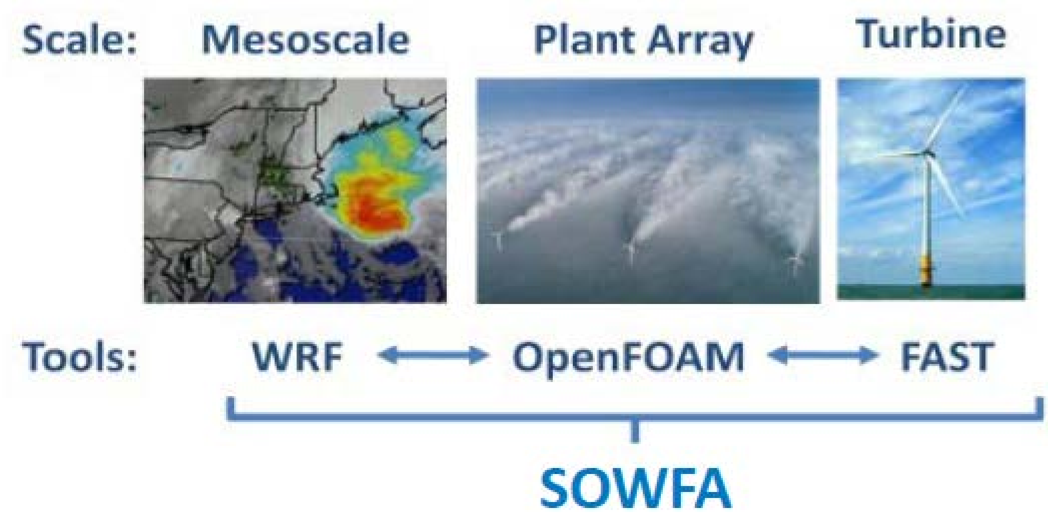


Simulator for Offshore Wind Farm Applications

SOWFA

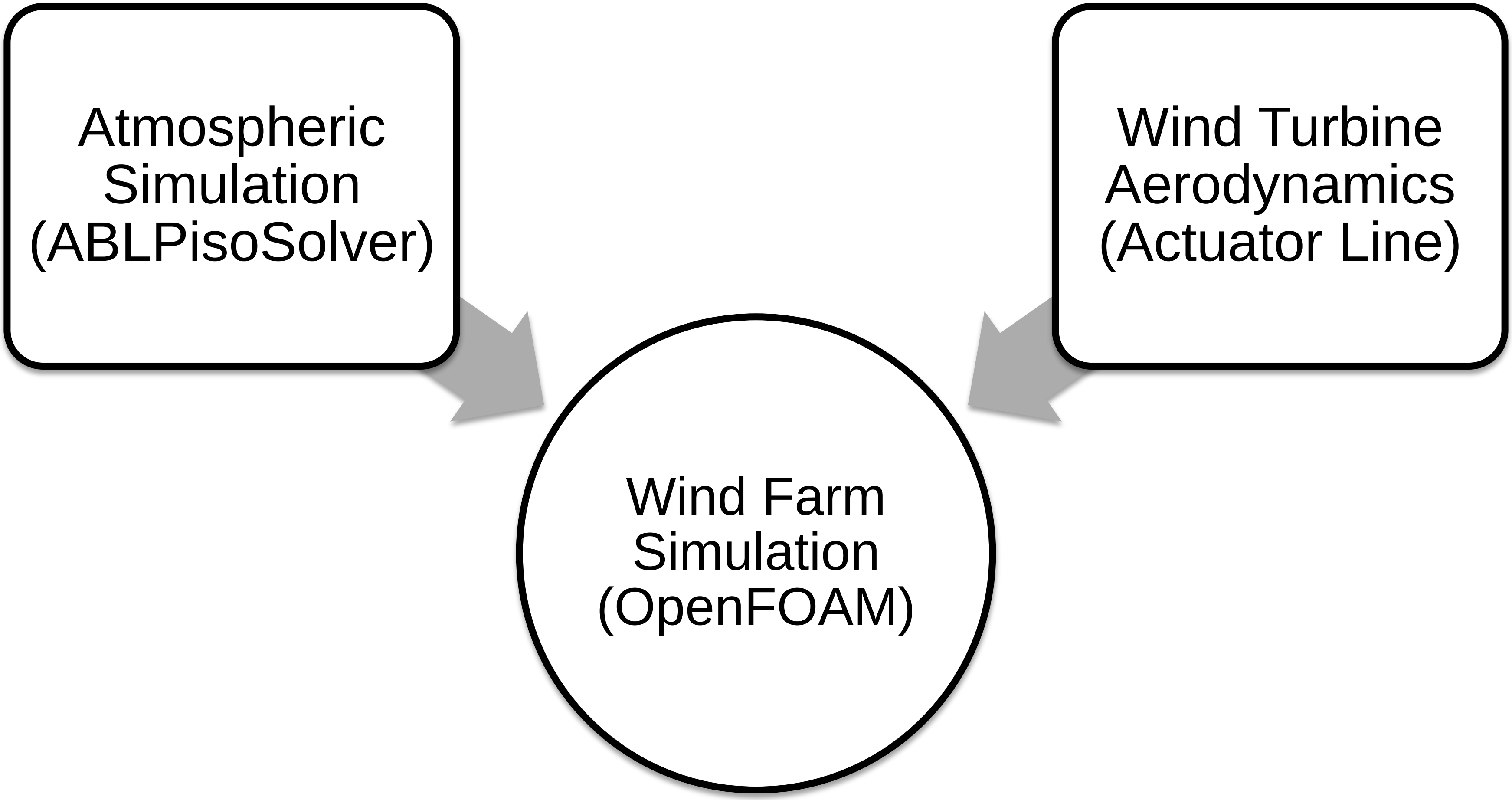
Background

- Developed at NREL by Churchfield and Lee
- *“High-fidelity analysis of fluid physics and structural response using Large-Eddy Simulations and FAST”*



From: Overview of SOWFA (webinar)

Structure


Atmospheric Simulation (ABLPisoSolver)
Wind Turbine Aerodynamics (Actuator Line)
Wind Farm Simulation (OpenFOAM)

Atmospheric Simulation: Numerical Scheme

- ABLPisoSolver (Finite Volume)
  - Runs the atmospheric simulation on a large grid
  - Save planes of data at every time interval
  - Impose these planes as periodic boundary conditions on a smaller grid representing the wind farm
- Top boundary is a rigid lid
  - Prevents Convection

Atmospheric Simulation

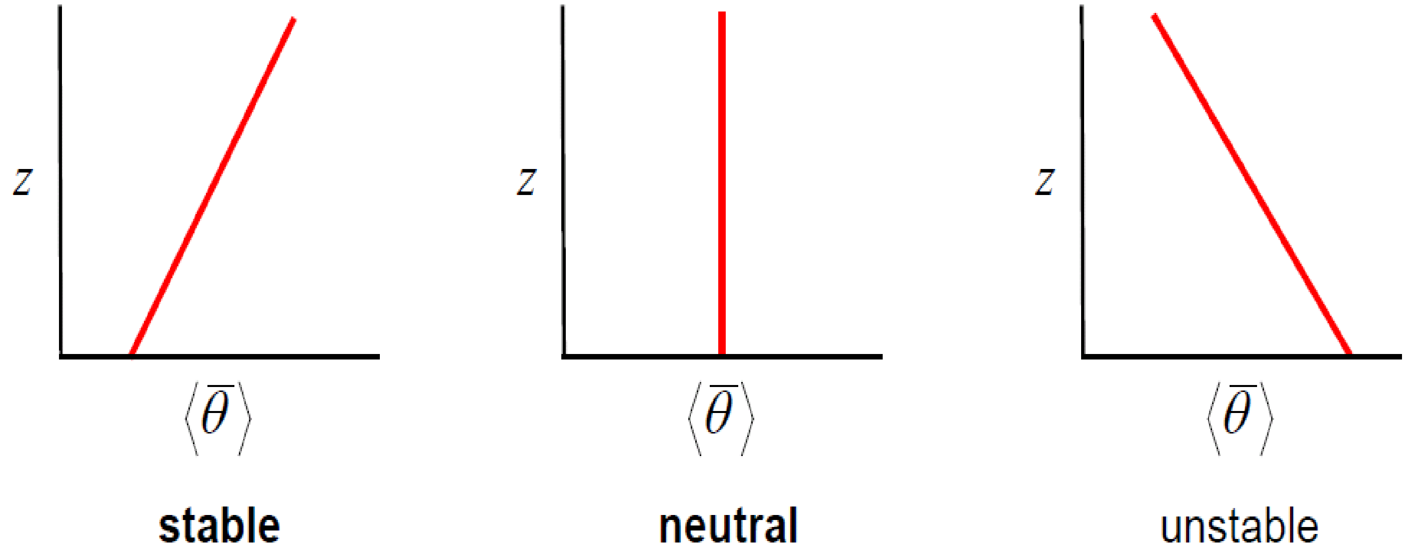
Momentum transport

$$\underbrace{\frac{\partial \overline{u}_i}{\partial t}}_{\text{I}} + \underbrace{\frac{\partial}{\partial x_j}\left(\overline{u}_j \overline{u}_i\right)}_{\text{II}} = \underbrace{-2\varepsilon_{i3k}\Omega_3\overline{u}_k}_{\text{III}} \underbrace{- \frac{\partial \widetilde{p}}{\partial x_i}}_{\text{IV}} \underbrace{- \frac{1}{\rho_0}\frac{\partial}{\partial x_i}\overline{p}_0(x,y)}_{\text{V}} \underbrace{- \frac{\partial}{\partial x_j}\left(\tau_{ij}^D\right)}_{\text{VI}} \underbrace{- g\left(\frac{\overline{\theta} - \theta_0}{\theta_0}\right)\delta_{i3}}_{\text{VII}} + \underbrace{\frac{1}{\rho_0} f_i^T}_{\text{VIII}}$$

- **I. time rate of change**
- **II. convection**
- **III. Coriolis force due to planetary rotation**
- **IV. density-normalized pressure gradient (deviation from hydrostatic and horizontal-mean gradient)**
- **V. horizontal-mean driving pressure gradient**
- **VI. SFS momentum fluxes (stresses)**
- **VII. buoyancy**
- **VIII. other density-normalized forces (from turbine actuator line model)**

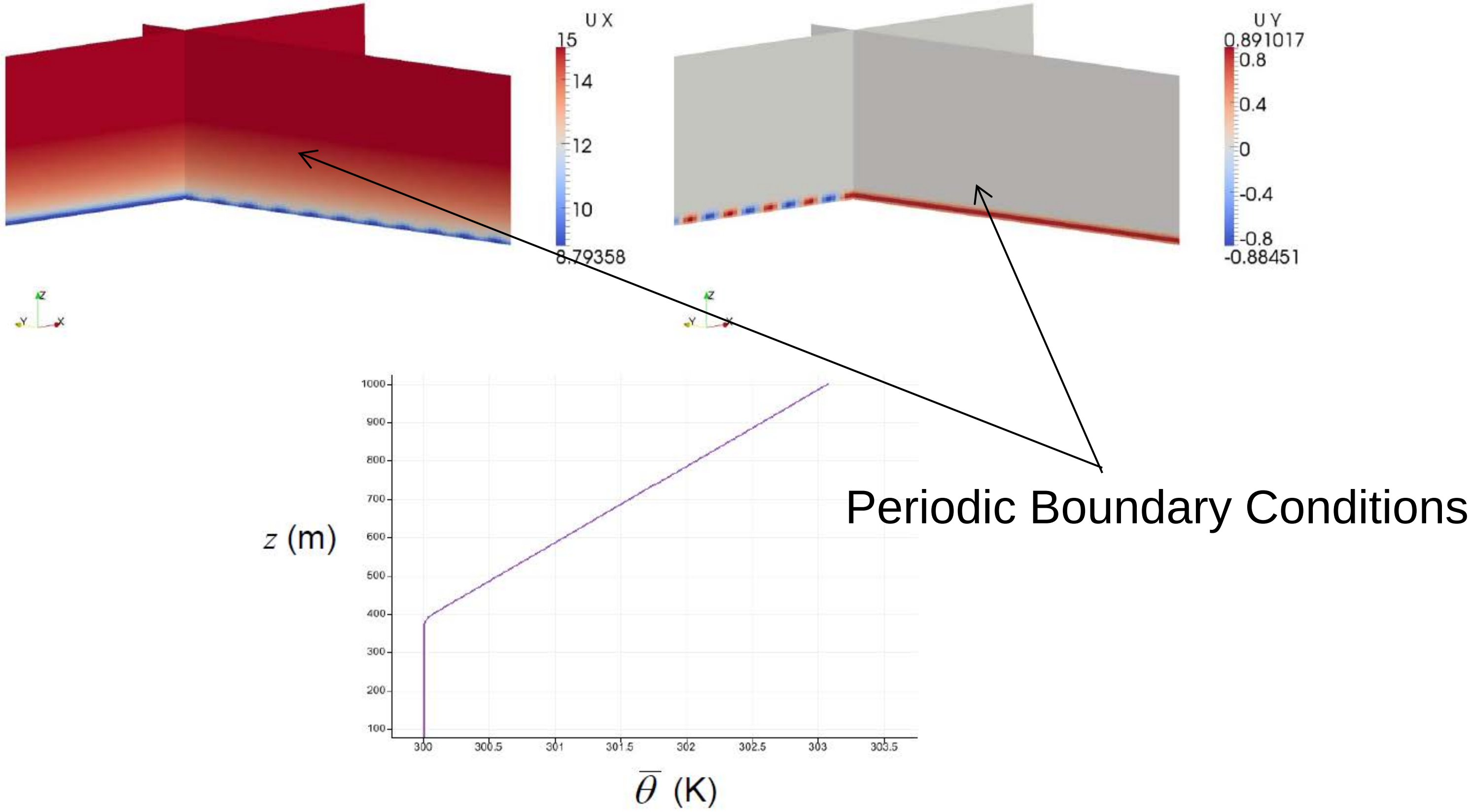
From: Overview of SOWFA (webinar)

Atmospheric Simulation: Input



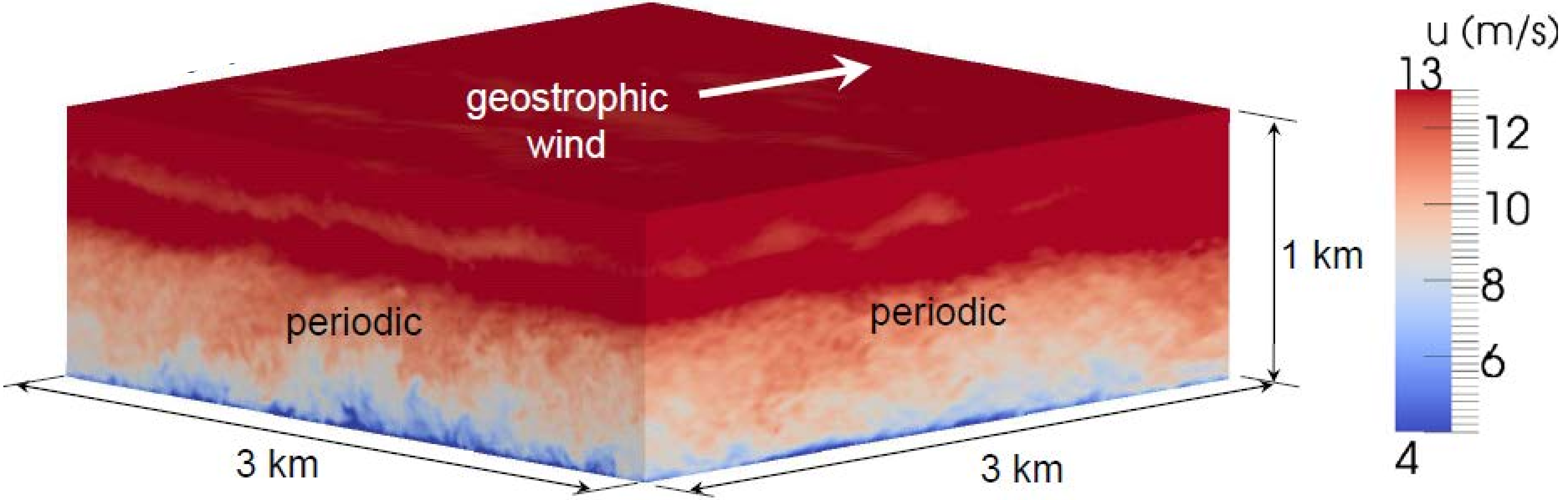
From: Overview of SOWFA (webinar)

Atmospheric Simulation: Input



From: Overview of SOWFA (webinar)

Atmospheric Simulation: Output



From: Overview of SOWFA (webinar)

Wind Turbine Model

- Full high-Re LES of turbine blade is too expensive
  - Requires fine grid
- Actuator line model (Sørensen and Shen)
  - Uses airfoil look-up tables
  - Creates wake, tip, root, and bound vortices
  - Does not create blade boundary layer turbulence
  - Projects a normalized force on the flow
  - Finer Grid used near turbine
- Ignores tower and nacelle
- Can be coupled with NREL's FAST

Actuator Line Method

- Remember:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_j \overline{u}_i\right) = -2\varepsilon_{i3k}\Omega_3 \overline{u}_k - \frac{\partial \widetilde{p}}{\partial x_i} - \frac{1}{\rho_0}\frac{\partial}{\partial x_i}\overline{p}_0(x,y) - \frac{\partial}{\partial x_j}\left(\tau_{ij}^D\right) - g\left(\frac{\overline{\theta} - \theta_0}{\theta_0}\right)\delta_{i3} + \frac{1}{\rho_0} f_i^T$$

- What is f_i^T?
  - Gaussian projection of actuator element force
  - Airfoil lookup table to find force on blade
  - Force on flow is equal and opposite of force on blade

Actuator Line Method

- Gaussian Projection (Martinez et al, AIAA)

$$f_i^T(r) = \frac{F_i^A}{\varepsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{r}{\varepsilon} \right)^2 \right]$$

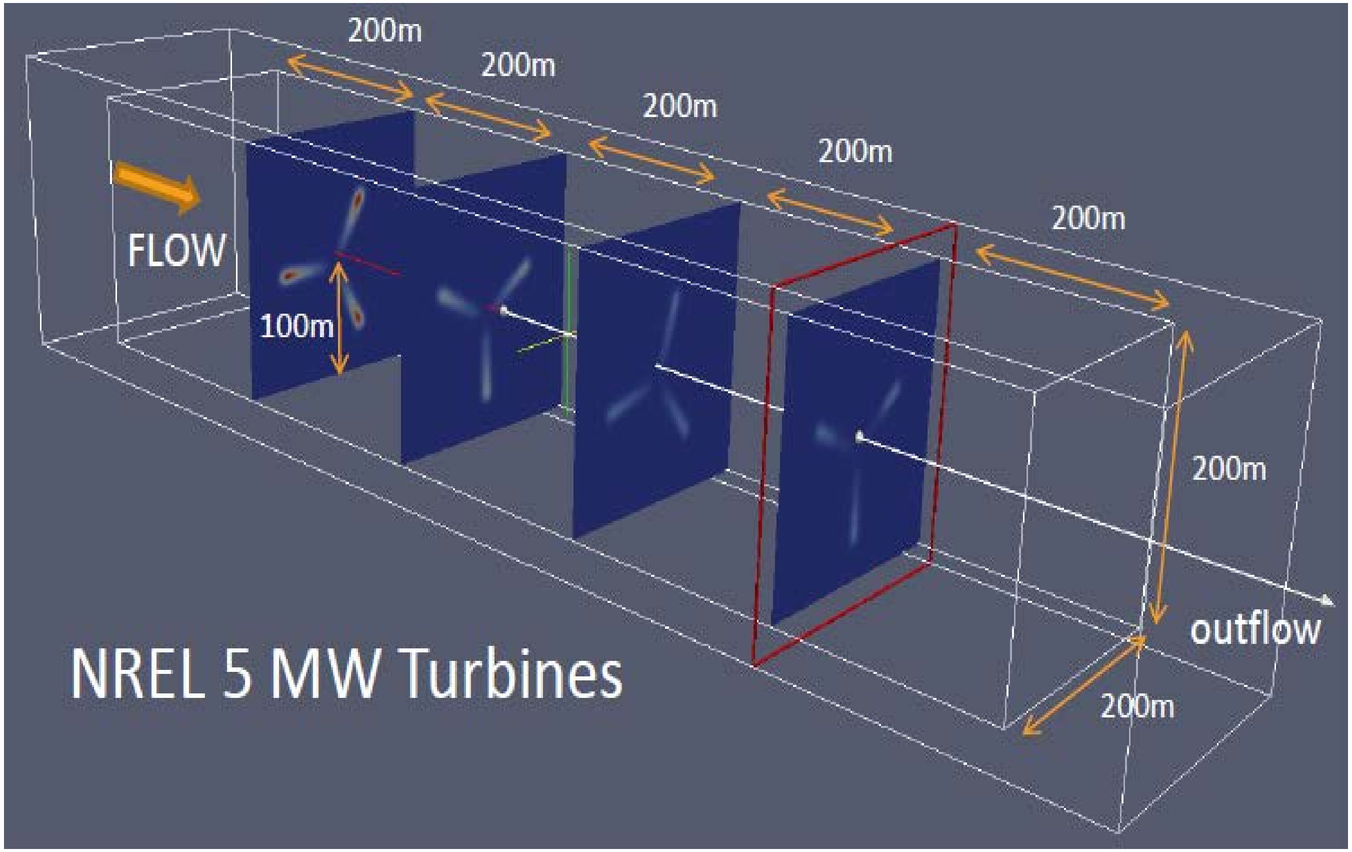
  - F_i^A: Actuator Force (Lift + Drag)
  - r: Distance between cell center and actuator point
  - ε: Controls width of projection
    - $\varepsilon = 2\Delta x$ is recommended (Troldborg)

Output

- Global Turbine Quantities
  - Rotor Speed
  - Thrust
  - Torque
  - Etc...
- Blade Local Quantities
  - Angle of Attack
  - Fluid Velocity
  - Force Components
  - Etc…

From: Overview of SOWFA (webinar)

Sample Runs: Flow Through Duct



U=8 m/s
From: Overview of SOWFA (webinar)

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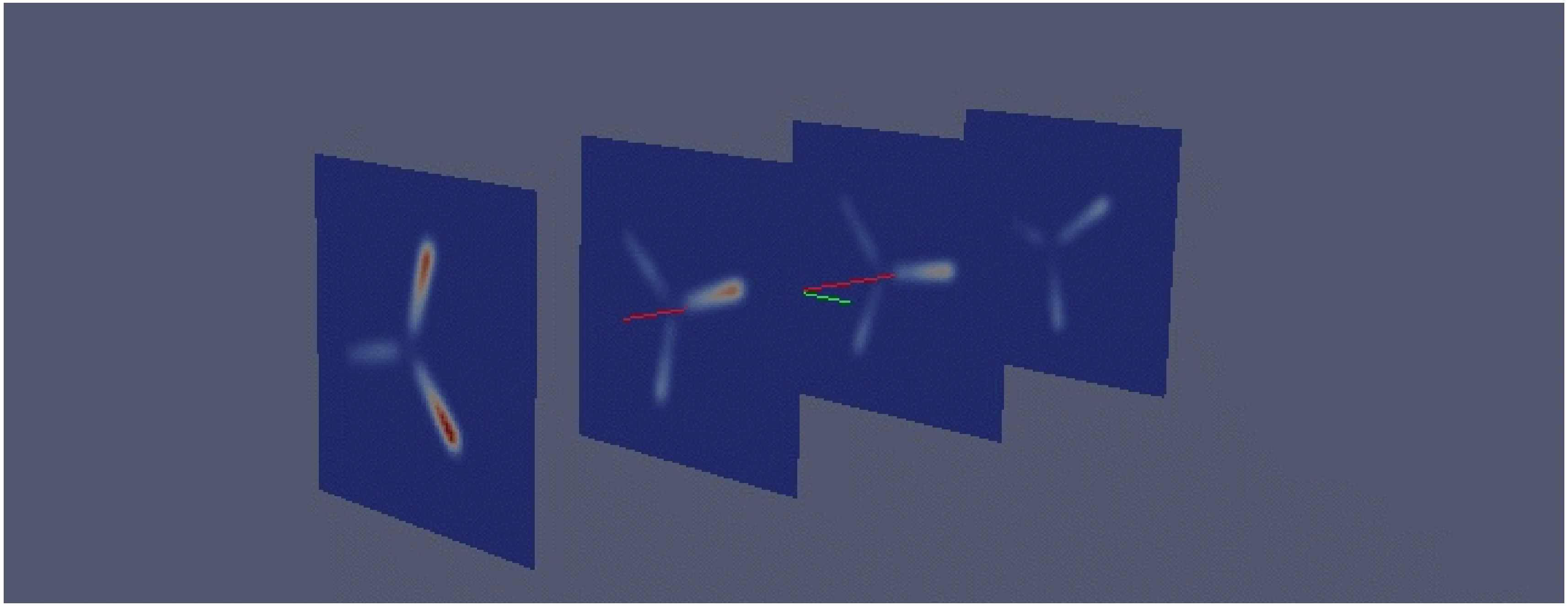

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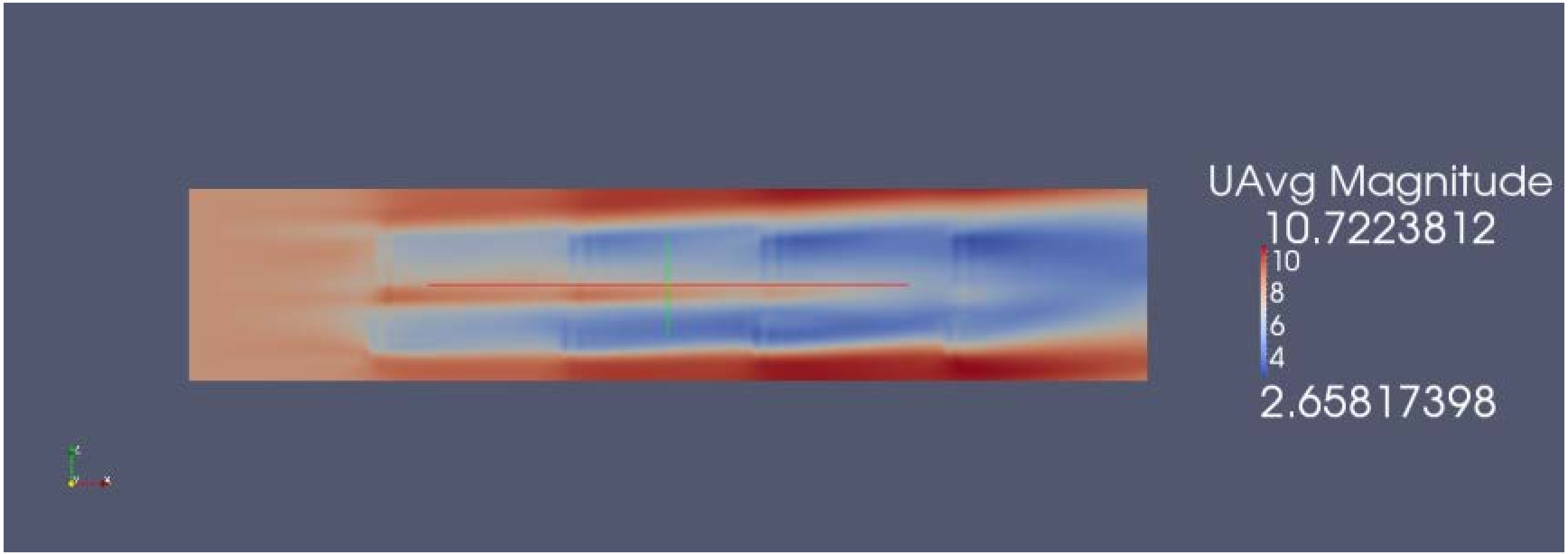
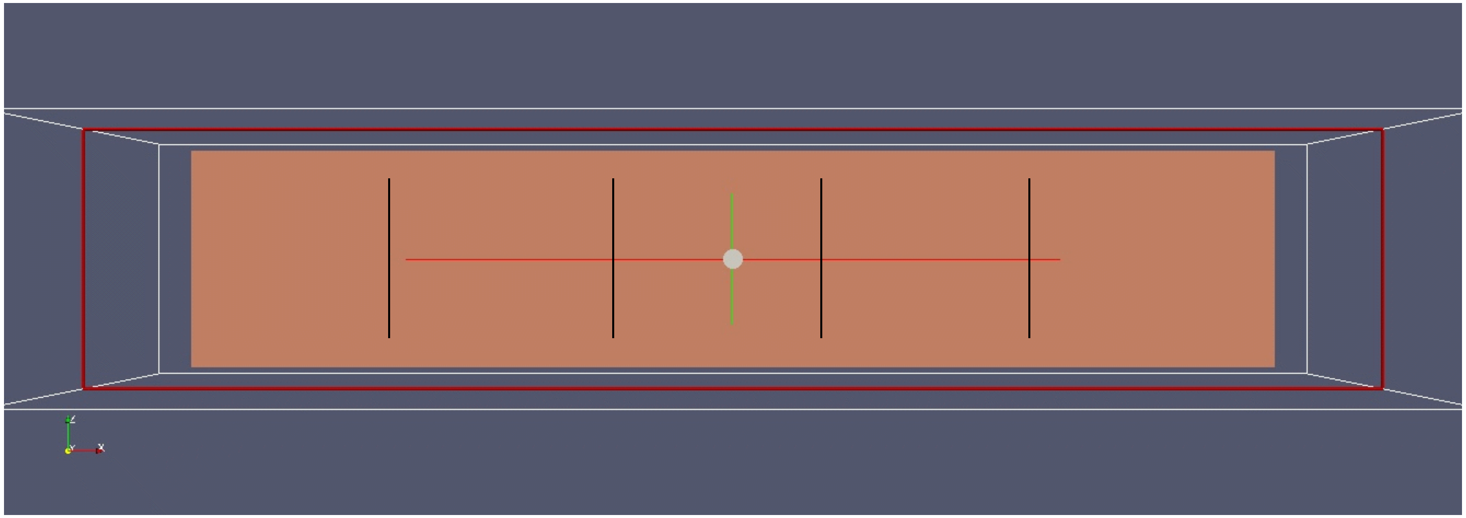
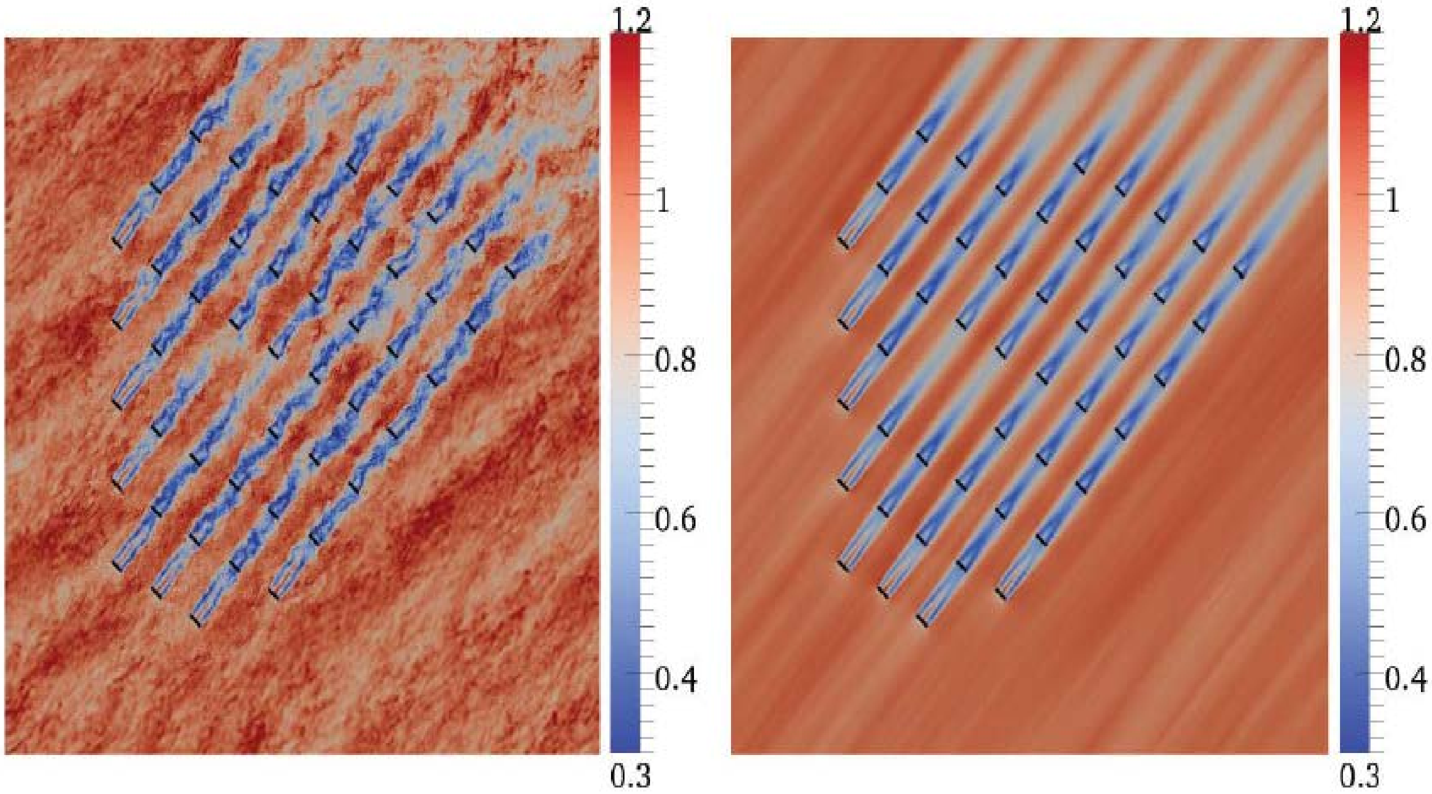


Sample Runs: Flow Through Duct



T=300 s

Sample Runs: Wind Farm Simulation



Normalized Wind Speeds at Lilligrund Offshore Wind Farm
(L: Instantaneous R: 10-Min Time Averaged)
From: Overview of SOWFA (webinar)

References (partial list)

- M. Churchfield, S. Lee, J.Michalakes, P. Moriarty, “A Numerical Study of the Effects of Atmospheric andWake Turbulence on Wind Turbine Dynamics”, invited paper: Journal of Turbulence, Vol. 13, No. 14,1-32, 2012 .
- Martinez, L. A., Leonardi, S., Churchfield, M. J., Moriarty, P. J., “A Comparison of Actuator Diskand Actuator Line Wind Turbine Models and Best Practices for Their Use,” AIAA Paper AIAA-2012-900, 2012.
- Sorensen, J. N., and Shen, W.Z., “Numerical Modeling of Wind Turbine Wakes,” *Journal of Fluids Engineering*, Vol. 124, 2002, pp. 393-399.

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