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Session: HPC for the Energy Transition
Session Chair: Herbert Owen
Session Date: July 1, 2021
Speaker: Michael A Sprague
Title: *ExaWind: Predictive Wind Energy Simulations*

ExaWind:
Predictive Wind Energy Simulations

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ExaWind Funding & Development Team

U.S. Department of Energy Wind Energy Technologies Office

ATMOSPHERE TO ELECTRONS
U.S. DEPARTMENT OF ENERGY

U.S. Department of Energy Exascale Computing Project

ECP
EXASCALE COMPUTING PROJECT

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NATIONAL RENEWABLE ENERGY LABORATORY

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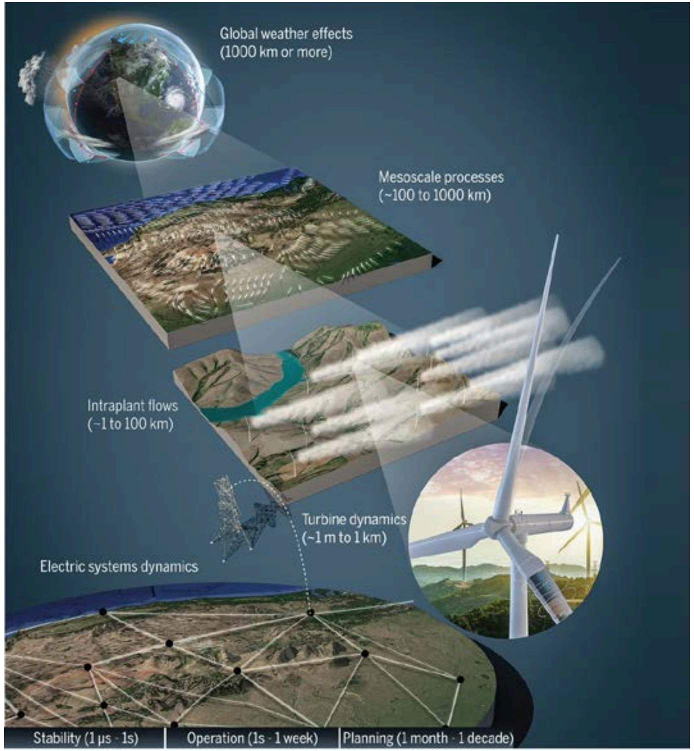
Parallel Geometric Algorithms, Inc.

- J. Sitaraman

Motivation for high-fidelity models and high-performance computing for wind energy

- More wind energy at low cost is a good thing
- High penetration of wind energy requires large wind farms composed of megawatt-scale turbines
  - *Both land-based and offshore*
- Wind farm flow dynamics and coupled turbine structural dynamics are extremely complex and models are lacking
  - *Relevant dynamics span many orders of magnitude*
- Only when we can **model well** the wind system can we **optimize** that system
  - *Maximize energy extraction*
  - *Maximize turbine life, minimize downtime*



Grand challenges in the science of wind energy
https://science.sciencemag.org/content/366/6464/eaau2027

Math model: Incompressible-flow Navier-Stokes equations + turbulence models

We model fluid motions through the incompressible-flow Navier-Stokes equations, e.g.,

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p + \mu\nabla^2\mathbf{u} + \mathbf{g}\alpha\,(T - T_0)$$

$$\nabla\cdot\mathbf{u} = 0$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \kappa\nabla^2 T$$

$\mathbf{u}(\mathbf{x}, t)$: velocity
$p(\mathbf{x}, t)$: pressure
$T(\mathbf{x}, t)$: temperature
$\mathbf{g}$: gravity
ρ: density
μ: viscosity
α: coefficient of thermal expansion
κ: coefficient of thermal diffusivity

The incompressible-flow constraint introduces a **pressure Poisson-type equation**; the solution of which dominates simulation time

We **model subgrid-scale turbulence**: large-eddy simulation (LES), Reynolds-Averaged-Navier-Stokes (RANS), or hybrid-RANS/LES

"Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity." - Lewis Richardson

Solving the discretized Navier-Stokes equations requires high-performance computing

HPC performance portability is central to ExaWind development

Supercomputer architecture is evolving rapidly

- U.S. Department of Energy supercomputers are increasingly relying on Graphical Processing Units (GPUs) for computational speed at low power
- The first U.S. **exascale** supercomputers will have hybrid CPU-GPU architectures
  - Coming online in ~2022 (AMD & Intel GPUs)
  - Aiming for power requirements below 30 MW
- Hybrid CPU-GPU architecture is expected to become more common amongst HPC clusters
- **Computational-fluid-dynamics (CFD) codes will need to be able to utilize GPUs!**

https://www.flickr.com/photos/olcf/41941941904/in/album-72157683655708262/

OLCF Summit:

- 200 x 10^{15} floating-point operations per sec.
- #2 fastest supercomputer (Top500; Nov. 2020)
- 4608 Nodes:
  - 2 IBM Power9 CPUs + **6 NVIDIA Volta GPUs**
- 10 MW system

Exascale systems will be at least five times faster

The open-source ExaWind software stack

ExaWind: An open-source **multi-fidelity** modeling & simulation software stack designed to run on **laptops** and **next-gen supercomputers**

Nalu-Wind

- https://github.com/exawind/nalu-wind
- Incompressible-flow CFD
- Unstructured-grid finite-volume discretization
- Built on Trilinos
- Leverages Trilinos and *hypre* linear-system solvers

Software described in NAWEA 2019 paper

https://iopscience.iop.org/article/10.1088/1742-6596/1452/1/012071/pdf

AMR-Wind

- https://github.com/exawind/amr-wind
- Incompressible-flow CFD
- Structured-grid finite-volume discretization
- Built on AMReX, a framework for block-structured adaptive mesh refinement

TIOGA

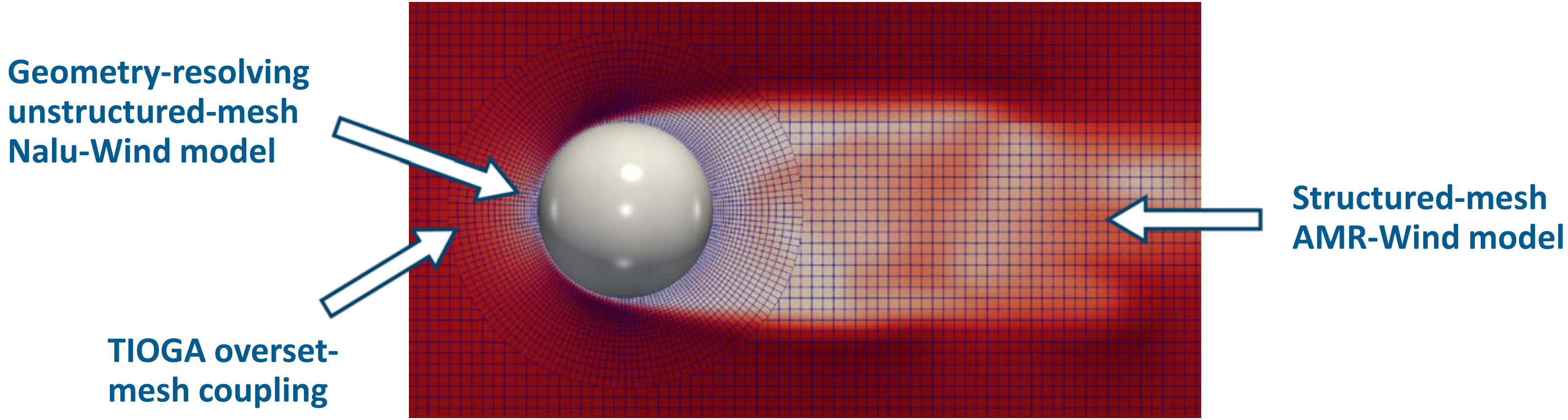
- https://github.com/jsitaraman/tioga
- Library for overset-grid assembly

OpenFAST

- https://github.com/openfast
- Whole-turbine simulation code

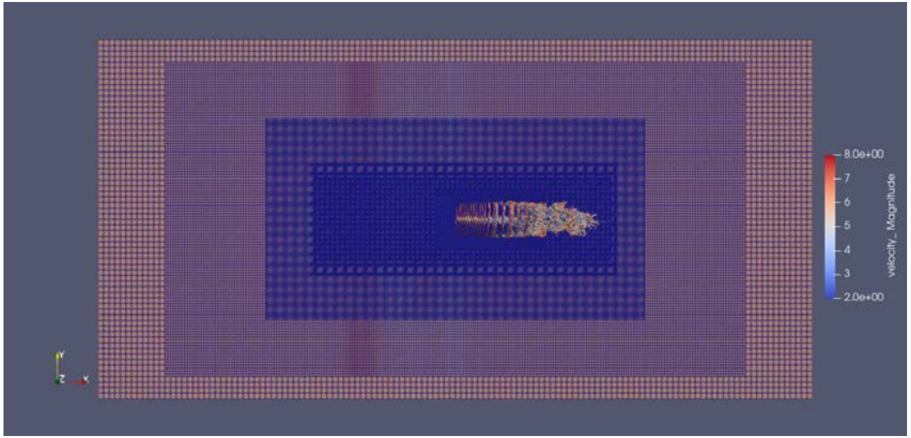
ExaWind hybrid solver: AMR-Wind + Nalu-Wind

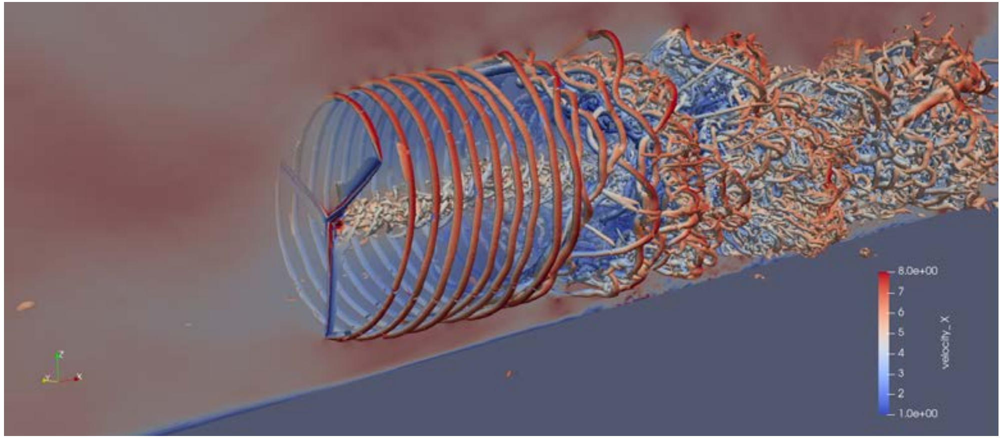
Nalu-Wind/AMR-Wind flow over a sphere



- Relies on loosely coupled solves of global linear systems
- Provides “optimal” solvers for the different grids
- Removes overset-mesh constraint equations from linear systems that degrade linear-system-solver performance
- Avoids the need to re-initialize linear systems in Nalu-Wind due to moving meshes

ExaWind hybrid solver: Blade-resolved simulations





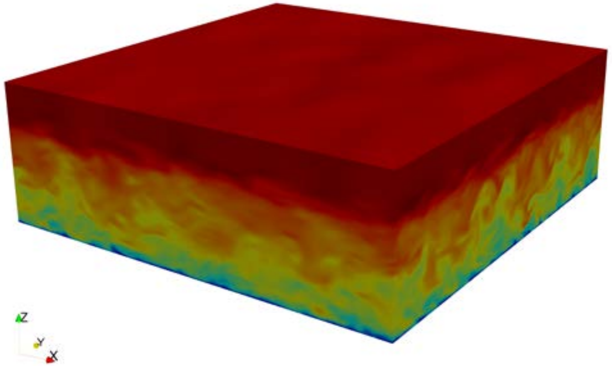
- AMR-Wind/Nalu-Wind CPU-only simulation on the NREL Eagle Supercomputer
  - NM-80 DanAero wind turbine rotor in turbulent flow with 122M grid points
  - Hybrid-RANS/LES coupling
  - Moving meshes with overset coupling
  - Simulation resolves 8 orders of magnitude in spatial scales:
    - $O(10^{-5})$ m boundary layer to $O(10^{3})$ m domain size
- Simulations performed as part of the International Energy Agency Wind Task 29 validation

Key team members: Vijayakumar, Ananthan, Brazell, Sharma, Sitaraman

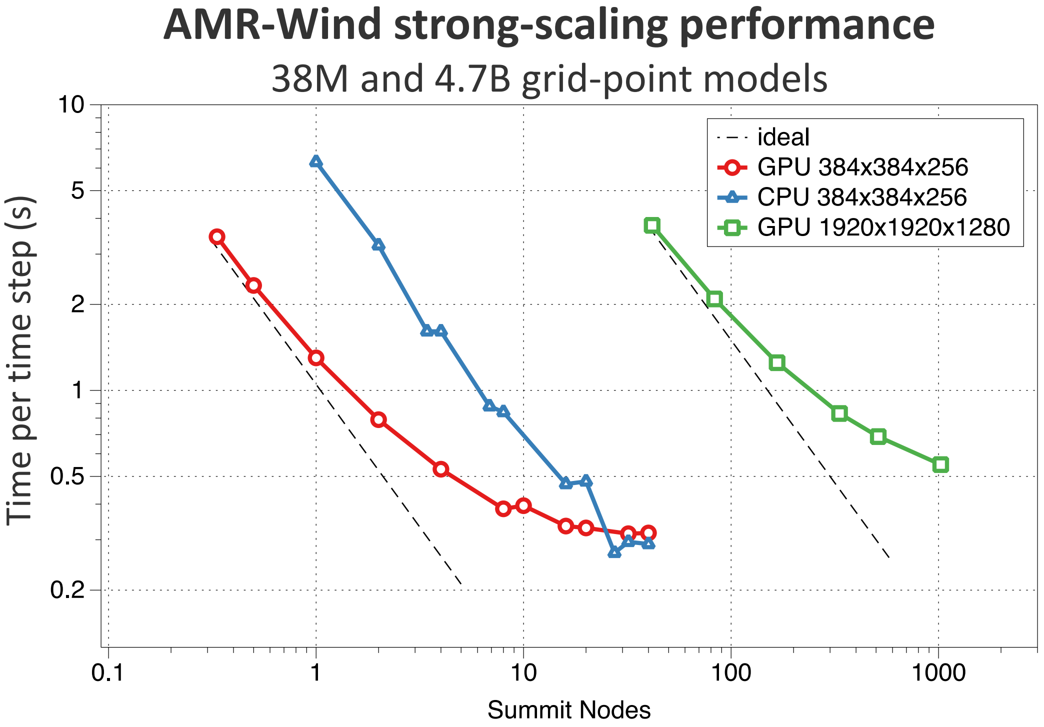
Source: Sprague, et al., 2021, ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling, 2021 Exascale Computing Project Annual Meeting, Tech. Report NREL/PO-5000-80015

AMR-Wind strong-scaling performance for CPUs and GPUs on Summit

3D flow field from atmospheric boundary layer (ABL) simulation



ABL LES *precursor* simulation on a 3 km x 3 km x 2 km domain with uniform mesh resolution on OLCF Summit. GPU and CPU calculations used all GPUs and CPU-cores, respectively, on each node.



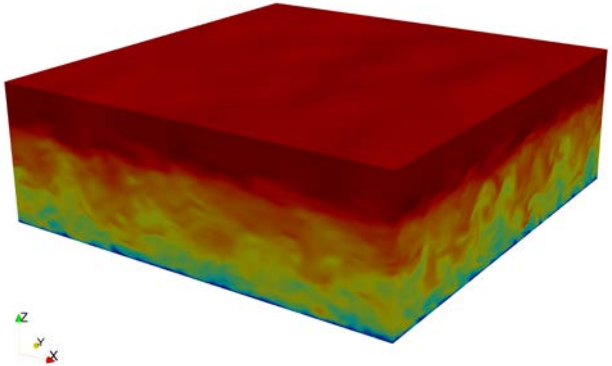
- GPUs can be faster than CPUs
- Preliminary observations show AMR-Wind strong-scaling limits at about
    - 1.2M grid points per GPU, or
    - 30,000 grid points per CPU-core

Key team members: Brazell, Ananthan, Rood, Almgren, Mullowney, Thomas

Source: Sprague, et al., 2021, ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling, 2021 Exascale Computing Project Annual Meeting, Tech. Report NREL/PO-5000-80015

AMR-Wind weak-scaling performance for CPUs and GPUs on Summit

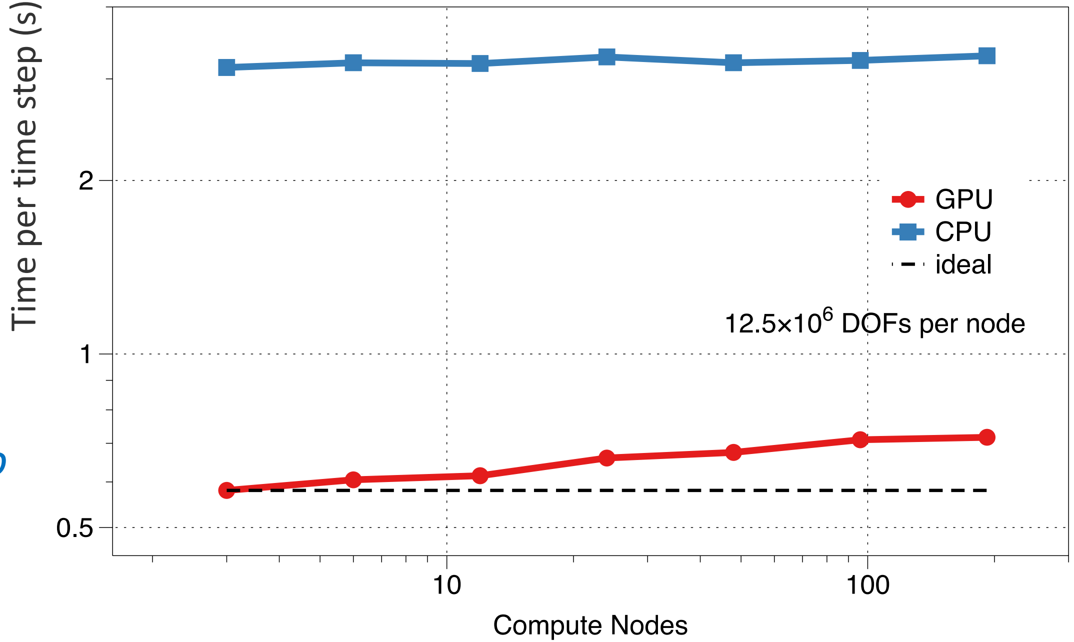
3D flow field from atmospheric boundary layer (ABL) simulation



We have run ABL simulations on up to 4,096 Summit nodes (i.e., 24,576 GPUs, 90% of Summit)

AMR-Wind weak-scaling performance

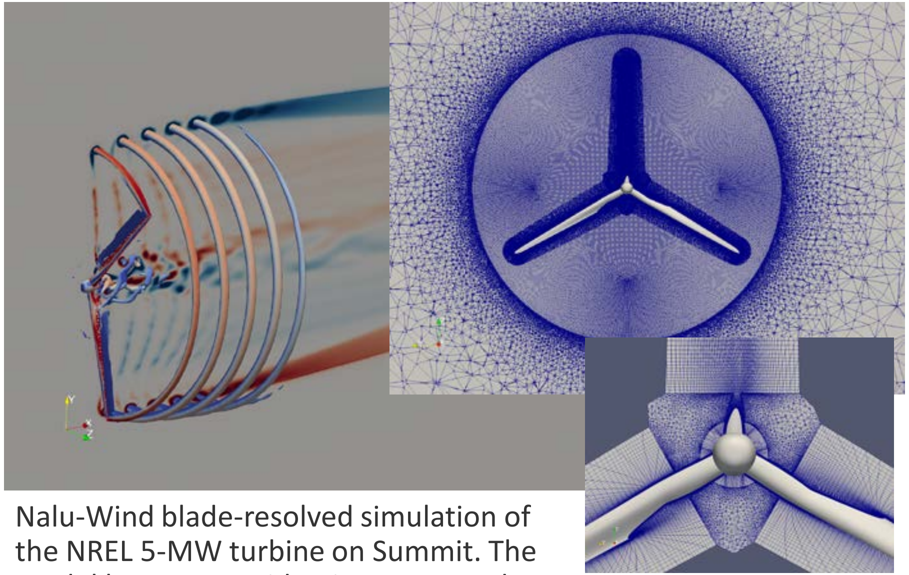
- Weak scaling from 3 to 200 compute nodes
- 38M to 2.5B cells



Source: Sprague, et al., 2021, ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling, 2021 Exascale Computing Project Annual Meeting, Tech. Report NREL/PO-5000-80015

Nalu-Wind/*hypre* strong-scaling performance for CPUs and GPUs on Summit

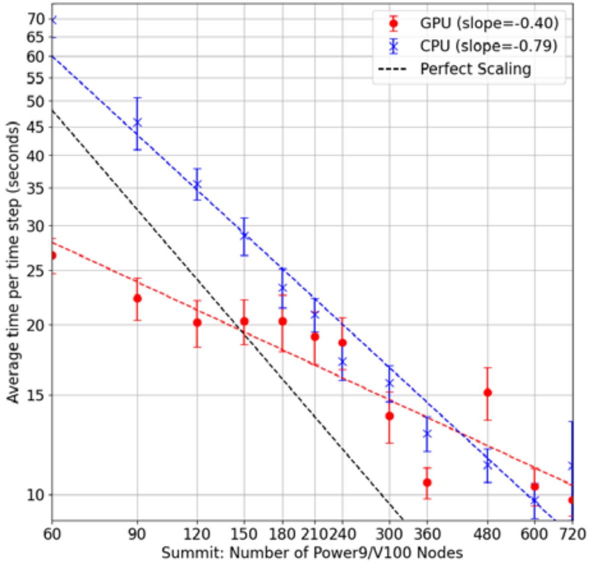
Blade-resolved Nalu-Wind turbine simulation with overset meshes



Nalu-Wind blade-resolved simulation of the NREL 5-MW turbine on Summit. The model has 640M grid points. GPU and CPU calculations used all GPUs and CPU-cores, respectively, on each node.

Key team members: Mullowney, Li, Thomas, Ananthan

Nalu-Wind/*hypre* strong-scaling performance



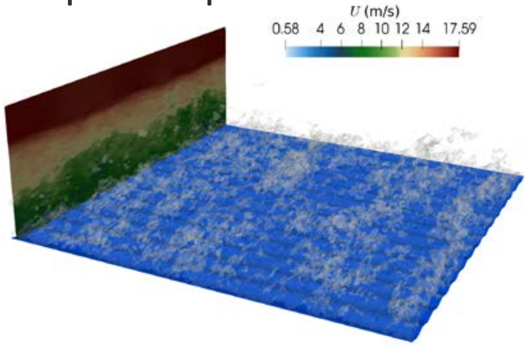
- GPUs can be faster than CPUs
- Preliminary observations show Nalu-Wind strong-scaling limits at about
  - 300,000 grid points per GPU, or
  - 26,000 grid points per CPU core

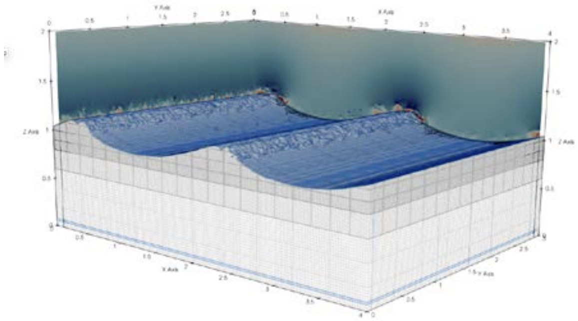
Source: Sprague, et al., 2021, ExaWind: Exascale Predictive Wind Plant Flow Physics Modeling, 2021 Exascale Computing Project Annual Meeting, Tech. Report NREL/PO-5000-80015

Concluding remarks

- ExaWind is a new open-source multi-fidelity wind turbine and wind farm simulation tool
  - High-fidelity blade-resolved models (hybrid-AMR-Wind/Nalu-Wind solver)
  - Mid-fidelity actuator-disk and actuator-line models (AMR-Wind and Nalu-Wind)
- Codes and models are backed by rigorous verification and validation
- We have promising GPU-based results for AMR-Wind and Nalu-Wind separately
  - GPU simulations with the hybrid solver are in progress
- The next development phase for ExaWind is for floating offshore wind

Simulation of wind over water waves using the Nalu-Wind fluid solver (Deskos)

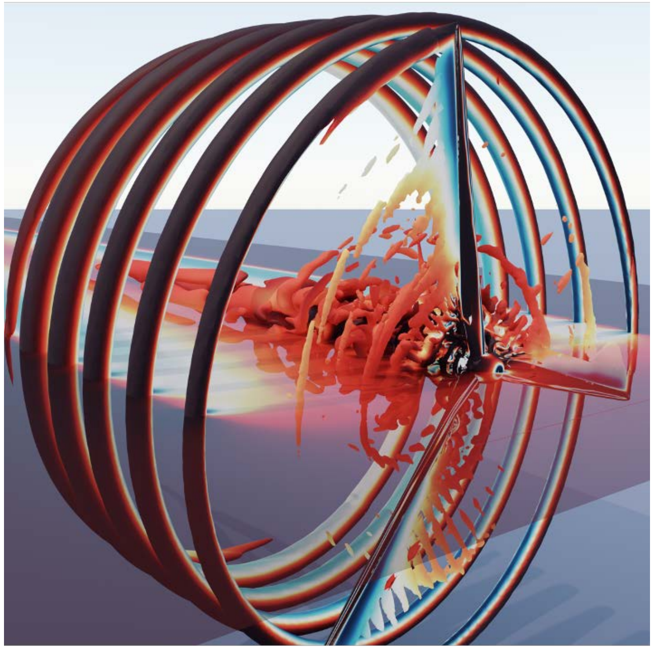




Multi-phase flow for floating offshore wind in AMR-Wind (Deskos)

Source: Deskos et al., 2021, “Review of wind-wave coupling models for large-eddy simulation of the marine atmospheric boundary layer,” *Journal of the Atmospheric Sciences*, 10.1175/JAS-D-21-0003.1

Nalu-Wind simulation of the NREL 5-MW turbine (Ananthan, Vijayakumar, Binyahib, et al.)



Thanks!

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