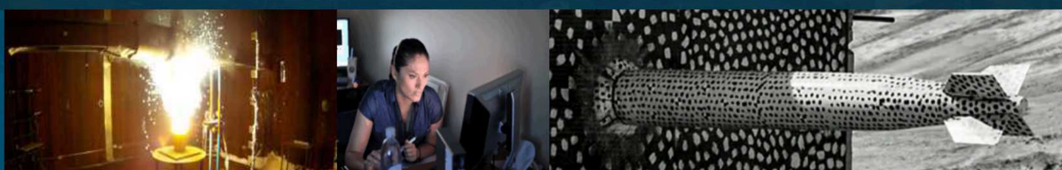
SAND2020-8772PE

Uncertainty Quantification Development and Application in the A2e Program



David C. Maniaci

Sandia National Laboratories

dcmania@sandia.gov

Wakebench, IEA Task 31 Interim Meeting

NAWEA/WindTech 2019

University of Massachusetts Amherst

October 14-16, 2019

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VV&UQ Multi-year Goals

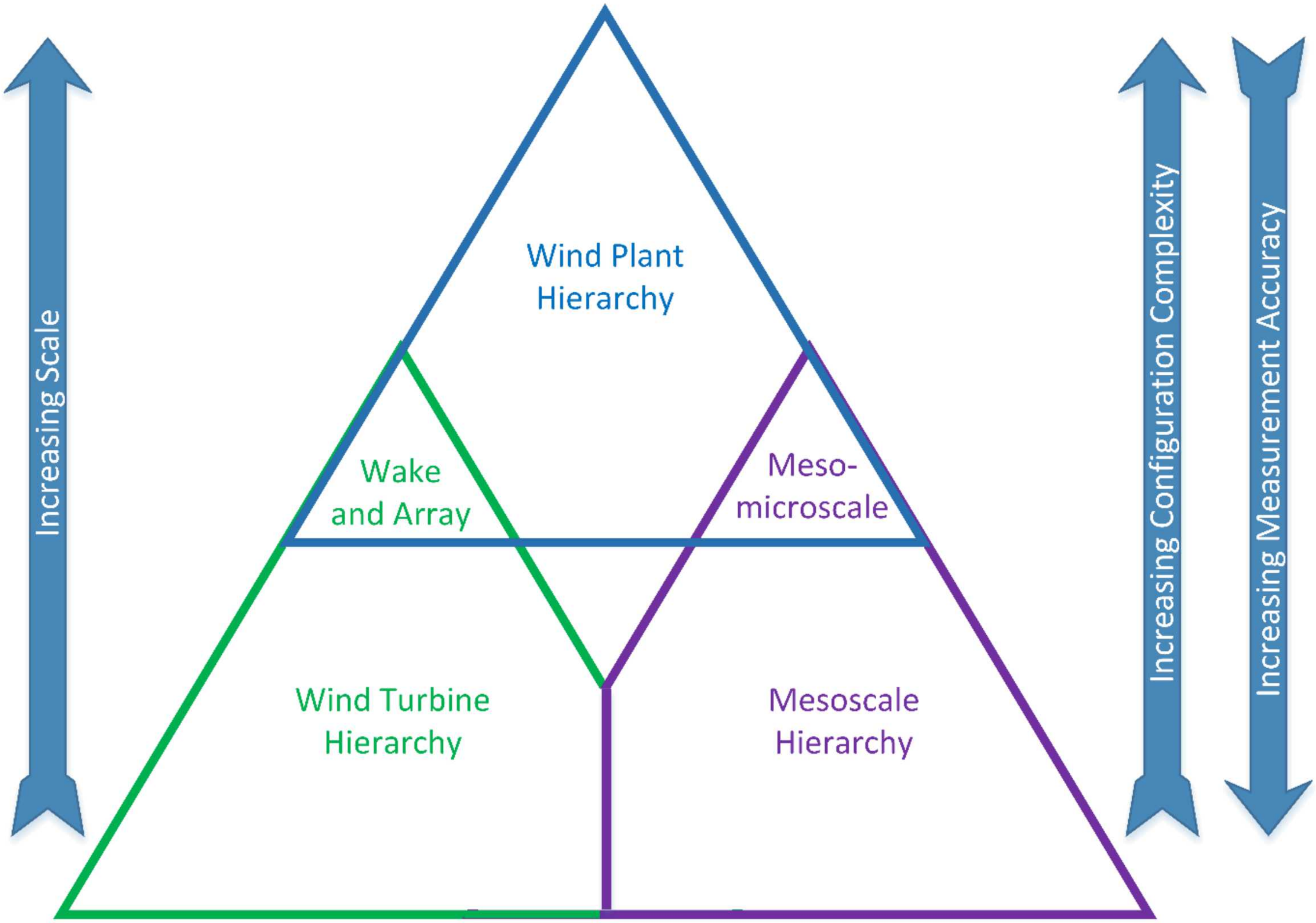
Enable simulation and design of optimized wind plants

Execute model validation campaigns across A2e to:

1. Improve the research community's physical understanding of wake dynamics and turbine interaction
2. Quantify model prediction uncertainty of wake flow dynamics and turbine interaction

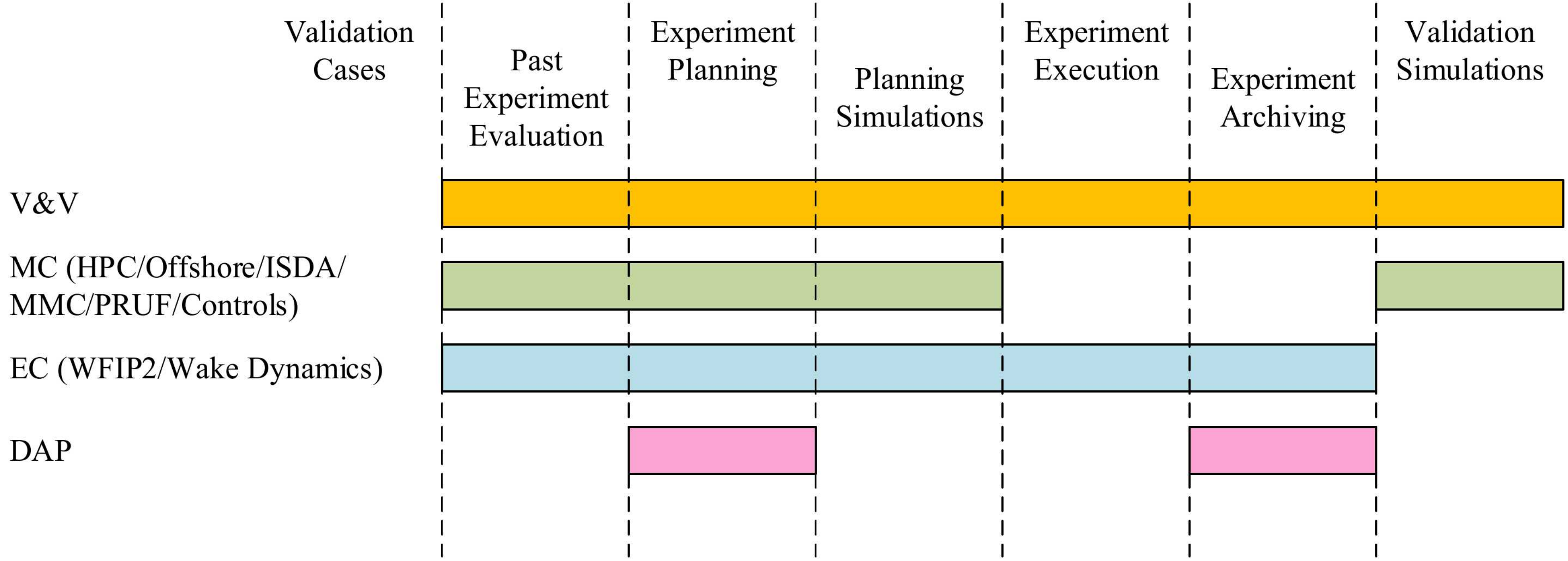
Develop and demonstrate uncertainty quantification tools and processes for wind energy applications

Engage with the public to disseminate results and progress on a regular basis.


Increasing Scale
Wind Plant
Hierarchy
Wake
and Array
Meso-
microscale
Wind Turbine
Hierarchy
Mesoscale
Hierarchy
Increasing Configuration Complexity
Increasing Measurement Accuracy

Integrated Experiment and Model Planning and Execution
Put the “Integration” into IEMPE

What roles do the different A2E efforts play



A2e Validation Coordination Working Group

A2e Area	Validation Leads
A2e Validation Coordinator	Jonathan Naughton (UWYO)
VV&UQ PI	David Maniaci (SNL)
DAP	Matthew Macduff, Chitra Sivaraman (PNNL)
Offshore	Amy Robertson (NREL)
ISDA-Systems	Garrett Barter (NREL)
ISDA-MV	Jason Jonkman (NREL)
HFM	Mike Sprague(NREL), Shreyas Ananthan(NREL), Paul Crozier (SNL)
Wake Dynamics	Pat Moriarty (NREL), Brian Naughton (SNL)
WFIP 2	Caroline Draxl (NREL)
MMC	Larry Berg (PNNL), Matt Churchfield (NREL), Sue Haupt (NCAR)
PRUF	Jason Fields (NREL)
Controls	Paul Fleming, Eric Simley (NREL)

- **Bi-annual Meetings with smaller focus groups meeting more regularly**
- **Summary reports of A2e validation progress and plans**

Ongoing V&V Coordination Work

Coordinating Efforts within A2e
- Have met with nearly all groups with validation interest over the last 4 months

Documenting and Disseminating V&V Materials
- IPP Document Published
- Interacting with Wind Community
  - IEA Tasks 29, 30, 31
  - Wind Energy Science Conference

Finalizing Validation Experiment Evaluation
- Applying to various previous experiments and ensuring all relevant issues addressed

Validation Roadmap
- Collecting input to develop roadmap(s)

Developing a short-term experiment as demonstration for V&V process
- Working with several possibilities suggested by A2e tasks
  - OC6 experiments
  - Unsteady aerodynamics experiments
  - Aero-elastic experiments
- One or more may be chosen for demonstration purposes
- Considering what methods to engage community
  - Workshops

Stakeholder Meetings

MDC8

V&V: Communication and Documentation

1. **IEA Task 31, Wakebench.** Working toward a collaborative validation process.
   1. WAKEBENCH Best Practice Guidelines for Wind Farm Flow Models First Edition (2015)
   2. WAKEBENCH Model Evaluation Protocol for Wind Farm Flow Models First Edition (2015)

2. **V&V Framework** (September 2015): the development and execution of coordinated modeling and experiential programs to assess the predictive capability of computational models of complex systems through focused, well structured, and formal processes.

3. **A2e High Fidelity Modeling: Strategic Planning Meetings** (November 2015) : A report on the foundational planning for the A2e High Fidelity Modeling effort for predictive modeling of whole wind plant physics.

4. **V&V Integrated Program Planning for Wind Plant Performance** (June 2019): This document outlines the integrated program planning (IPP) process and applies it to wind plant performance prediction.

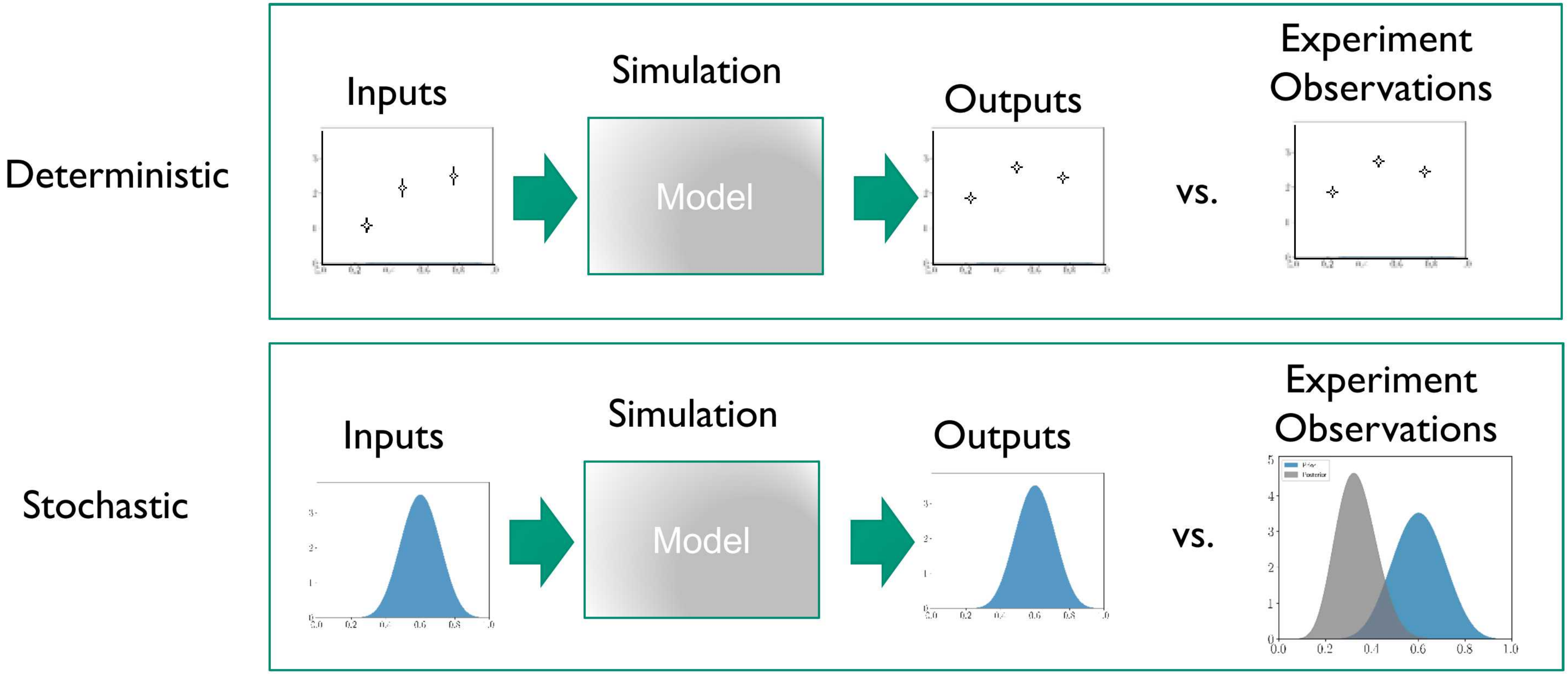
5. **A2e High Fidelity Modeling Validation Roadmap** (October 2019): This document outlines a comprehensive validation program for high fidelity wind plant models.

Slide 7

MDC8 Add reference to LEE Dap and SNl sites
Maniaci, David C, 10/13/2019

What is Uncertainty Quantification?

- Methods to codify the assimilation of observational data
  - UQ methods are critical for quantitative model validation focused on enabling predictive numerical simulations in research and advanced design
- The characterization of errors, uncertainties, and model inadequacies
- Forward predictions with confidence for untested/unstable regimes

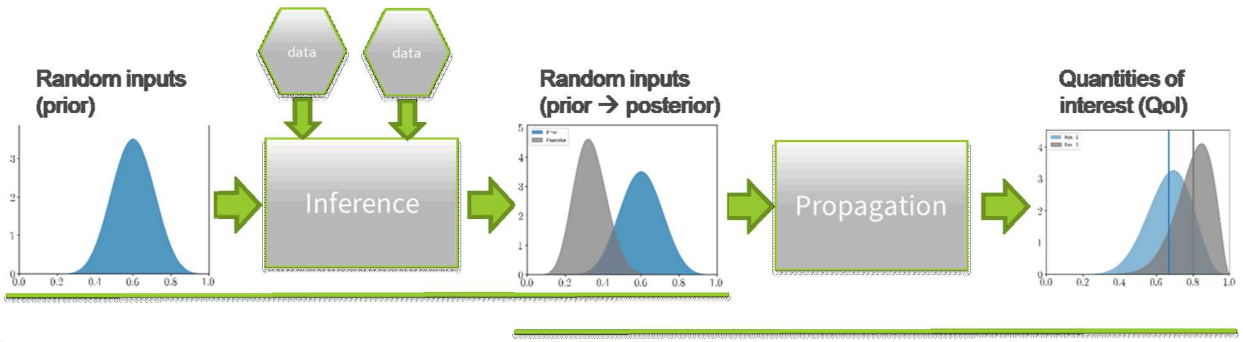


Modified from M. Eldred, 2019

Uncertainty Quantification Workflow

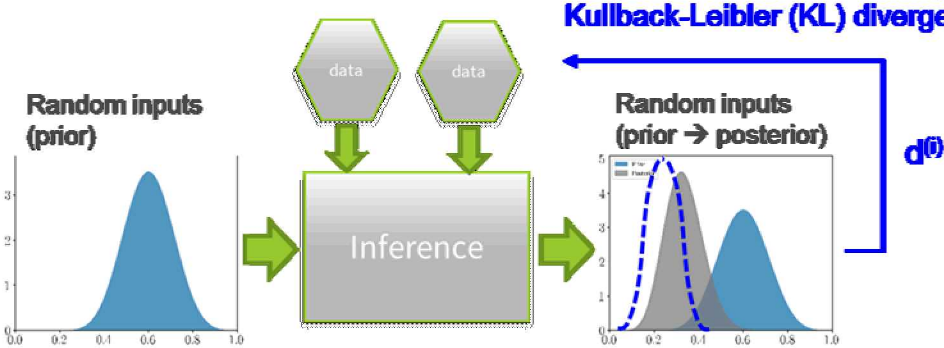
Characterization of input uncertainties through assimilation of data

Propagation of input uncertainties to response QoI

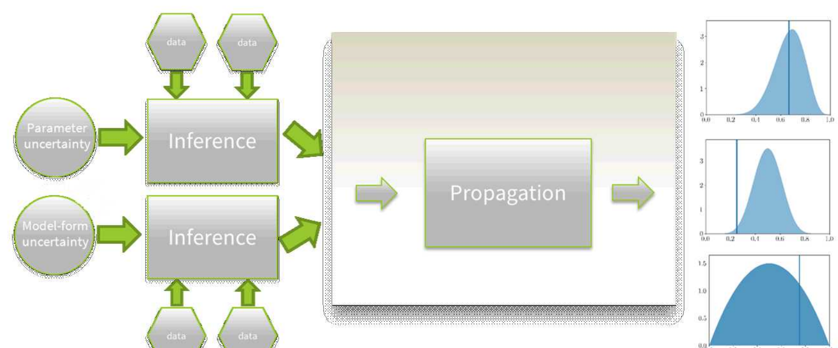


Optimal Experimental Design (OED) Workflow

Maximize expected utility from new data $d^{(i)}$, e.g.
D-optimal: max information gain / relative entropy /
Kullback-Leibler (KL) divergence from $\pi_0 \rightarrow \pi_{post}^{(i)}$



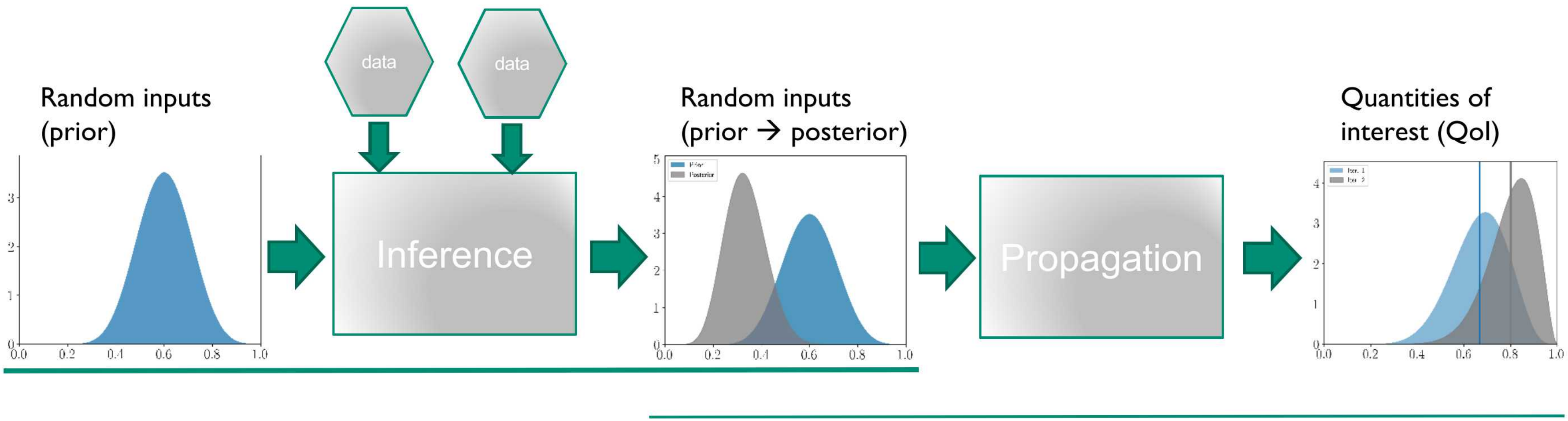
Optimization Under Uncertainty (OUU) Workflow



Uncertainty Quantification Workflow (M. Eldred)

Characterization of input uncertainties through assimilation of data

- Prior distributions based on *a priori* knowledge
- Observational data (experiments, reference solns.) → infer posterior distributions via Bayes rule
    - Use of data can reduce uncertainty in obj./constraints (priors are constrained)
    - Design using prior uncertainties can be overly conservative
    - Reduced uncertainty of data-informed UQ can produce designs with greater performance



Propagation of input uncertainties to response QoI

- Push forward of posterior distributions
- Compute statistics that reflect goals of OUU process (i.e., moments, failure probabilities)

Optimal Experimental Design (OED) Workflow

Characterization of input uncertainties through assimilation of data

- Prior distributions based on *a priori* knowledge
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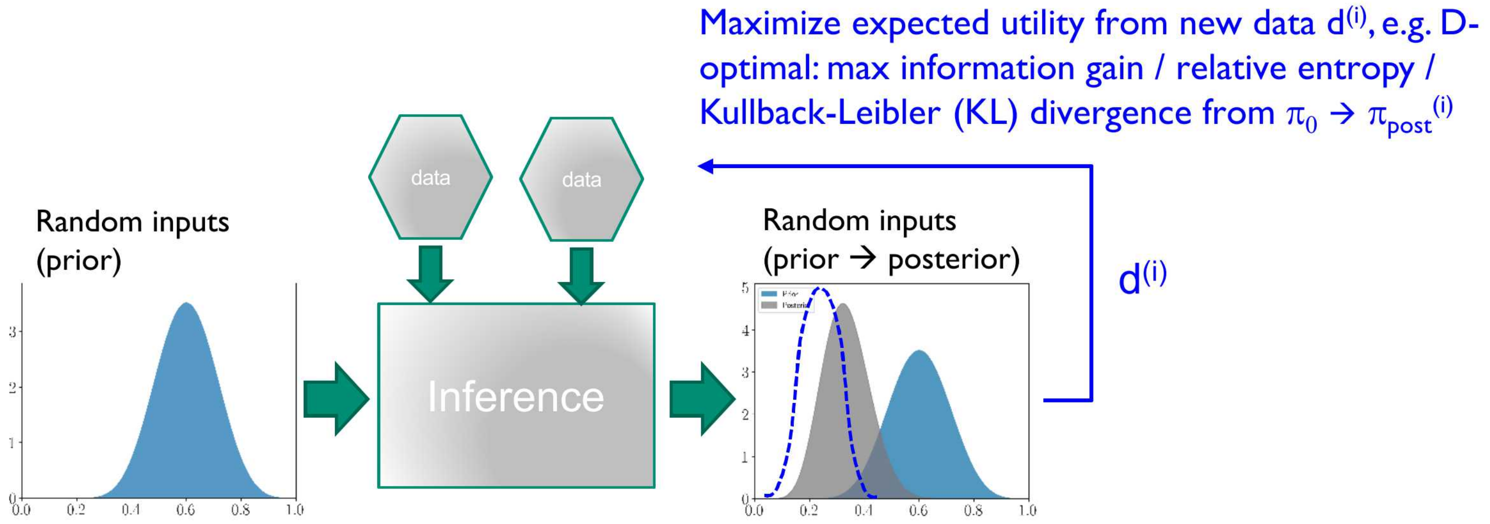


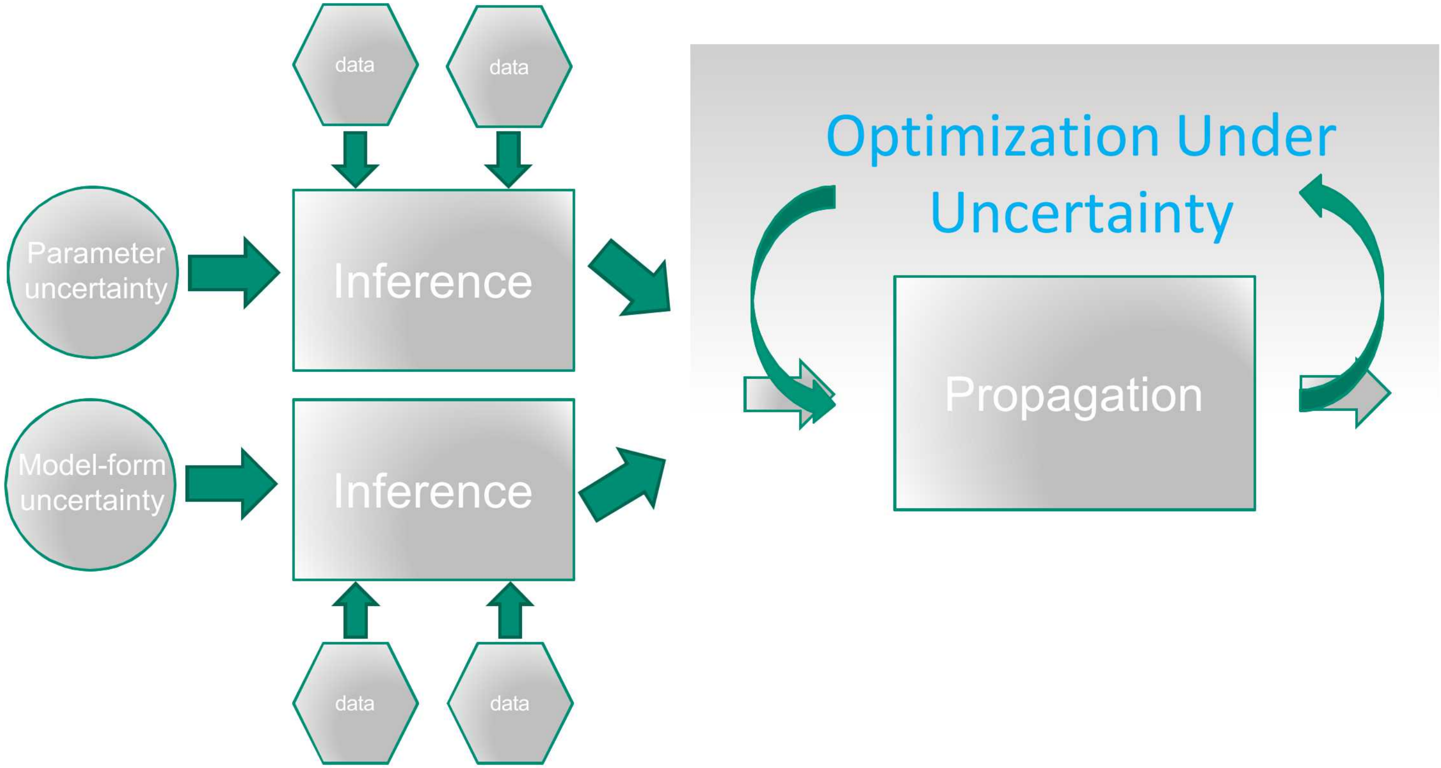
Optimization Under Uncertainty (OUU) Workflow

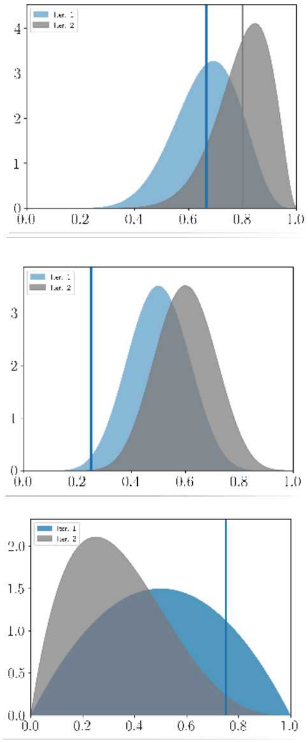
Roll up of capabilities

- Inference for parametric + model form uncertainties
- Scalable forward propagation
- Leverage surrogates: Active SS, ML-MF, ROM

Achieve desired statistical performance

- Common OUU goals:
  - Robustness → minimize QoI variance
  - Reliability → constrain failure probability





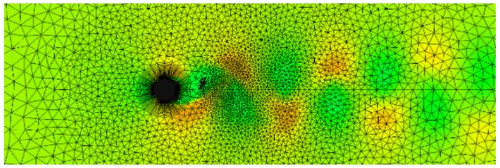
Summary of Wind UQ Studies under A2e

Previous: Forward UQ
- Cylinder wake in Nalu (initial demo at right)
- SWiFT Site with Nalu + OpenFAST

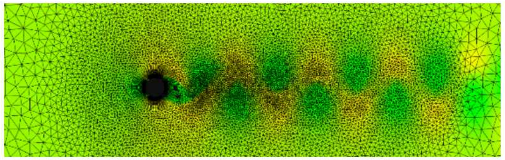
Current: Inverse UQ
- Infer upstream conditions from SwiFT data sets
  - OpenFAST + WindSE (+ Nalu)

Future: OED / OUU
- Determine best configurations (locations in random parameter space) to collect more data
- Design of wind plants for an uncertain operational environment

Coarse Mesh: 10 minute time to soln.

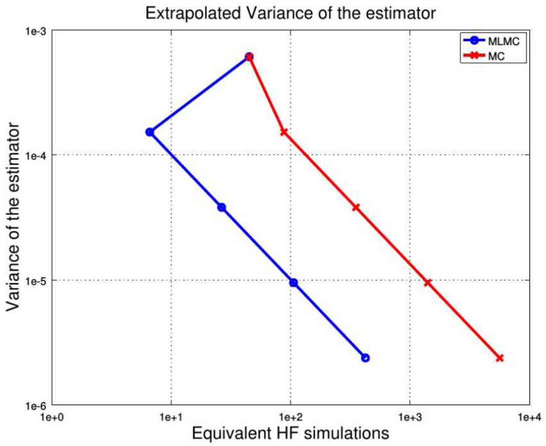


Medium Mesh: 4 hours time to soln.



Accuracy	Multilevel simulations				Equivalent Cost	
	Coarsest	Coarser	Coarse	Medium	MLMC	MC
6.08e-05	28	20	4	1	18	221
6.08e-06	2796	194	37	3	167	2202
6.08e-07	27952	1935	364	25	1657	22140
6.08e-08	279520	19345	3640	242	16551	220130

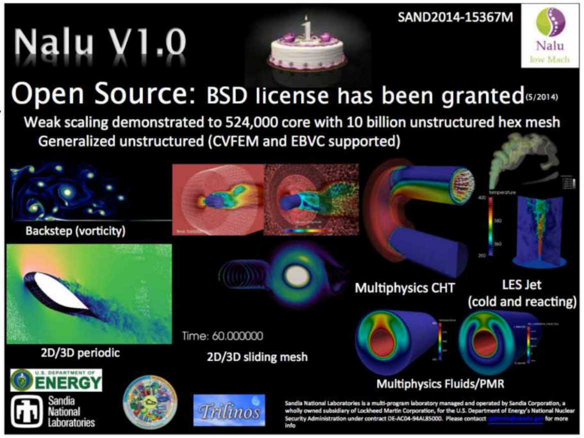
TABLE: Optimal MLMC samples allocation Vs MC allocation



Computational Approach

- Low Fidelity: **OpenFAST-AeroDyn-Turbsim** (https://github.com/OpenFAST)
  - Turbsim generates turbulent atmospheric boundary layer flow field, semi-empirical
  - AereoDyn models the aerodynamic forces on the rotor
  - OpenFAST models the structural and controls response of the rotor (same for Nalu)

- High Fidelity: **Nalu** (https://github.com/NaluCFD)
  - LES, Solves the Navier-Stokes equations in the low-Mach number approximation with the one-equation, constant coefficient, TKE model for SGS, unstructured massively parallel.
  - Actuator Line model of the rotor
  - Single, uniform mesh (no nesting)



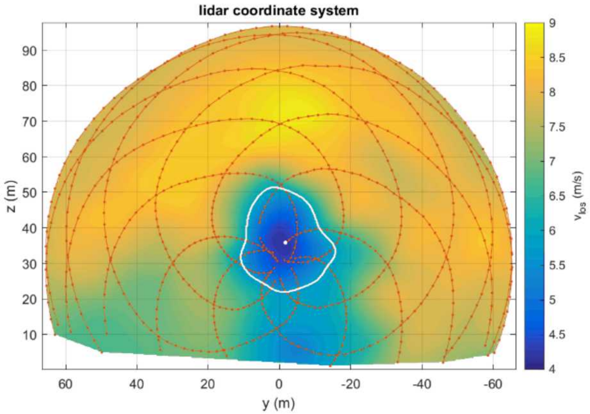
Cost estimates for Nalu and OpenFAST simulations.

Case	Mesh size	Simulation time (seconds)	CPUs	Cost (CPU-hours)	Cost (relative)
OpenFAST		500	1	0.42	1
Coarse	100x50x50	2000	80	240	576
Medium	200x100x100	2000	160	960	2304
Fine	400x200x200	2000	400	6860	16500
Reference	800x200x200	2000	400	38400	91400

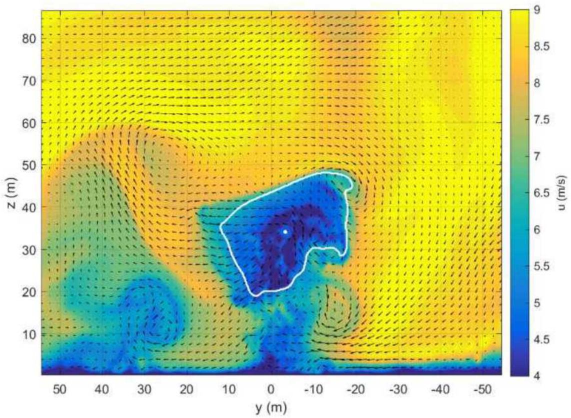
Domino, S. "Sierra Low Mach Module: Nalu Theory Manual 1.0", SAND2015-3107W, Sandia National Laboratories Unclassified Unlimited Release (UUR), 2015. https://github.com/NaluCFD/NaluDoc

Nalu-Wind Wake Assessment, SWiFT

Comparisons between neutral atmospheric boundary layer inflow experimental data were compared with Nalu-Wind simulations, including uding power, loads, and wake data.



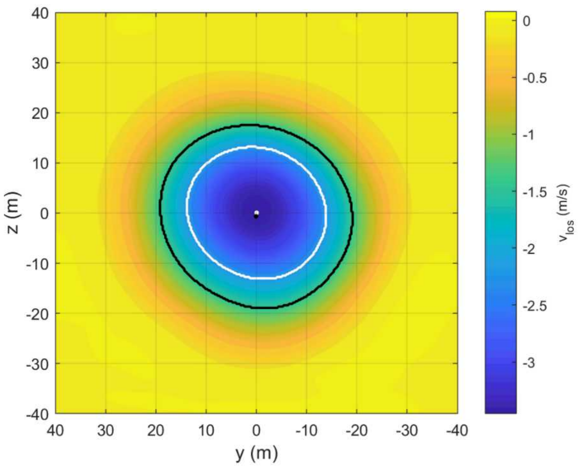
Sample of the wake date from the measured Spinnerlidar at the SWiFT facility.



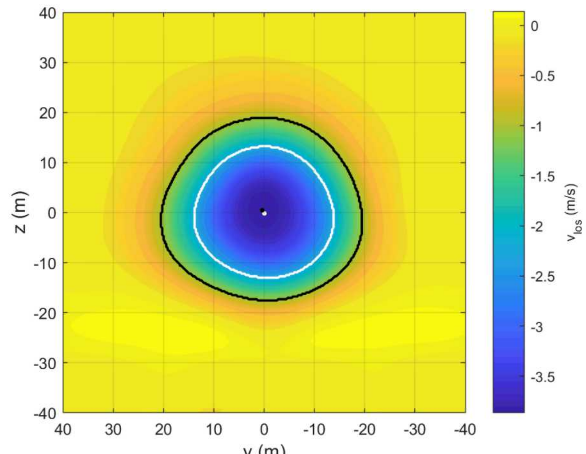
Nalu-Wind Simulated wake data 5D downwind.

	Simulation	Experiment
OOP Blade Bending (kN m)	37.0 ± 6.0	37.1 ± 6.2
Rel. Flapwise DEM (sim./exp.)	1.06	1.00
Generator Power (kW)	88.4 ± 17.3	81.2 ± 19.3

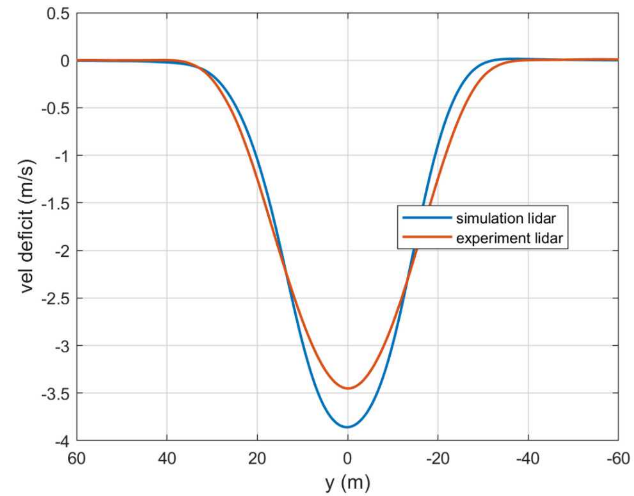
Upstream turbine (WTGa1) comparison between experimental and simulation results of the 10-minute averages of the mean out-of-plane (OOP) blade-root bending moment for the three blades (kN m), relative flapwise DEM (simulation/experiment) and generator power (kW) for yaw = 0° case.



Average over 10 minutes of the wake data from the measured Spinnerlidar.



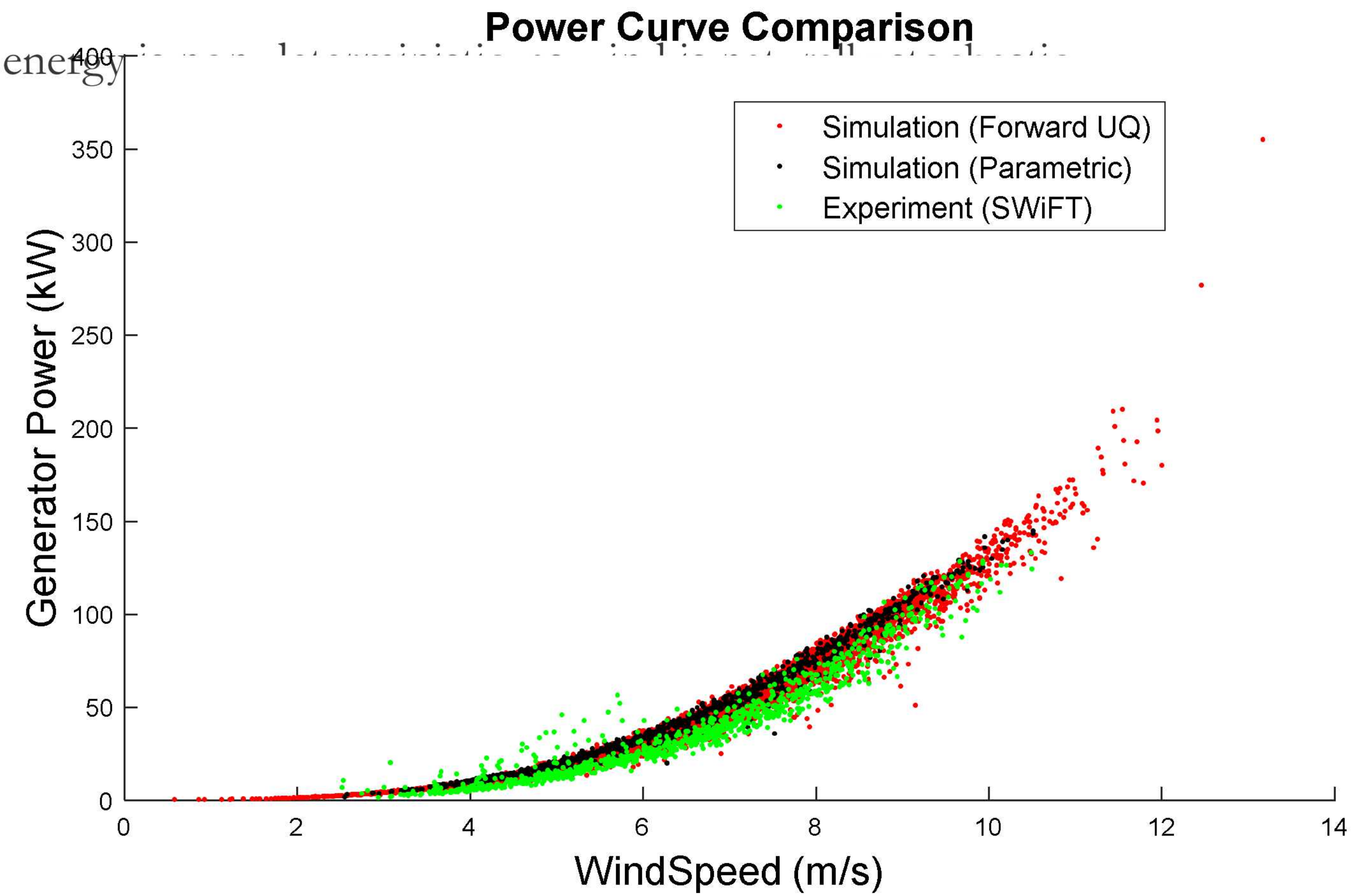
Average over 10 minutes for the simulated wake data 5D downwind, sampled to match the experimental lidar data.



Comparison of wake velocity deficit for the experiment and the Nalu-Wind simulated lidar data.

Wind Turbine Power Curve Example

Wind energy



A. Hsieh, WESC 2019

MDC1

Wind Turbine Sensitivity Analysis (Jonkman et al.)

***Project Objective:** Identify input parameters with high uncertainty / variability that are most influential to ultimate & fatigue loads during normal operation*

- This work:
    - Overview of sensitivity assessment of inflow & full turbine properties (aerodynamic, structural, control) – Publication submitted to *Wind Energy Science*
- Outcome of this research could inform:
    - Probabilistic design approaches
    - Better site-suitability analyses
    - Development of surrogate models
    - Propagation of uncertainty to support model validation

- Related work:
    - Sensitivity assessment of inflow turbulence (profile, spectrum coherence, correlations) – Paper / presentation @ *AIAA SciTech 2018*; updated in publication submitted to *Wind Energy Science*
    - Sensitivity assessment of aerodynamic subset of turbine properties – Paper / presentation @ *AIAA SciTech 2019*

Slide 17

MDC1 Maybe turn A2e VV&UQ work into a Quad chart slide. would need to add work by Caroline in WFIP2 and Ryan King in ISDA-SE

Maniaci, David C, 10/11/2019

IEA Wind Task 30 – V+V of Offshore Wind Modeling Tools (Robertson)

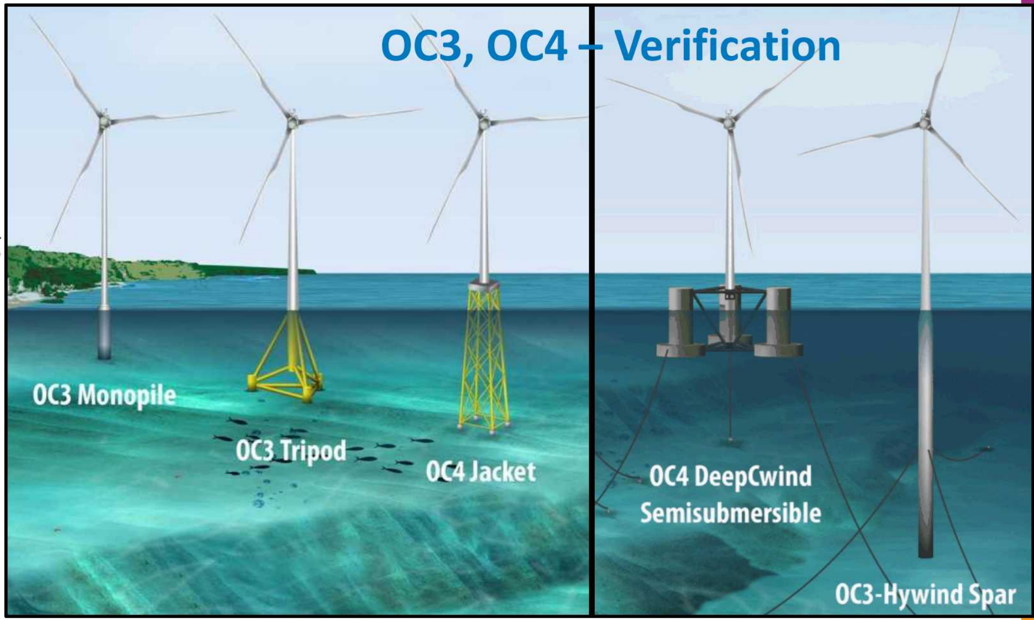
Offshore Code Comparison Collaboration (OC3) – run under IEA Wind Task 30

Verify and validate the engineering-level tools used to design offshore wind systems to advance the overall accuracy of offshore wind computer modeling tools, to improve their predictive capability for estimating structural loads.

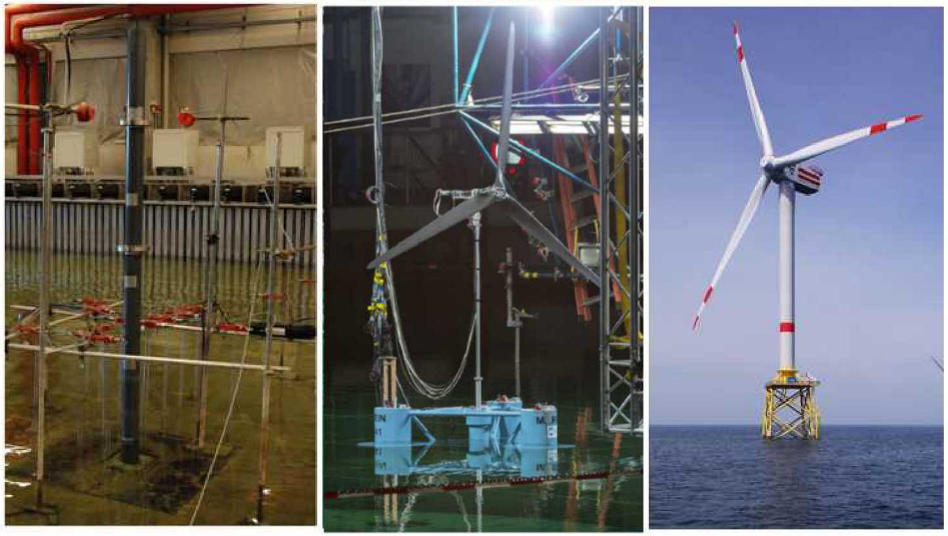
- Project running since 2010 (OC3/OC4/OC5)
- Coupled tools (aero-hydro-servo-elastic) used to predict motions/global loads in a system, ensuring the design meets IEC standards
- Example tools: FAST, Bladed, HAWC2, FLEX

Group models benchmark problems, and compares solutions between codes and to measurement data from scaled testing and full-scale prototypes

- Identify errors, examine differences in modeling theories/approaches, improve tools, train analysts, identify R+D needs



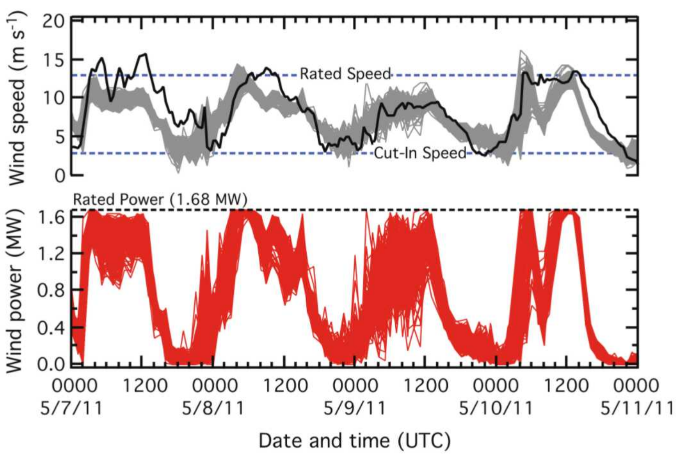
OC5 - Validation

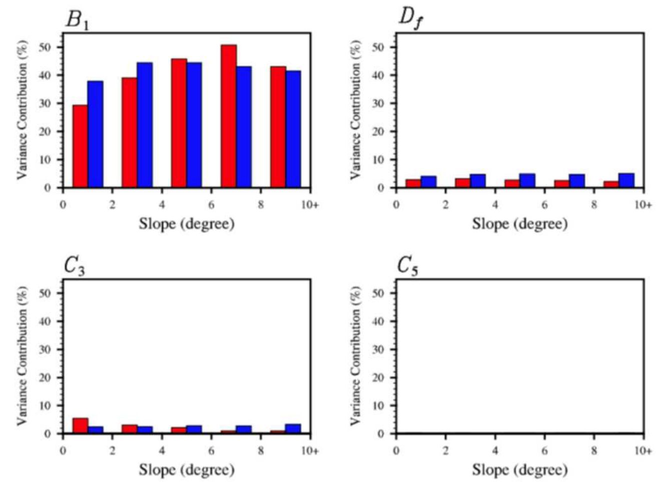


Phase I **Phase II** **Phase III**

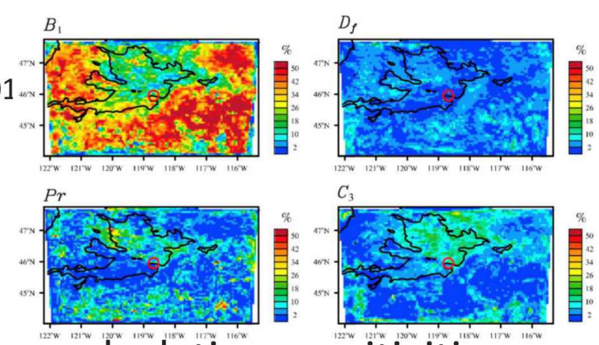
Mesoscale Uncertainty Quantification
(Berg, Kravitz, et al.)

- Bottom line: If you get the inflow wrong, you get everything wrong.
- How "right" do we need to be? What are the key controls on uncertainty in modeling the mesoscale flow?



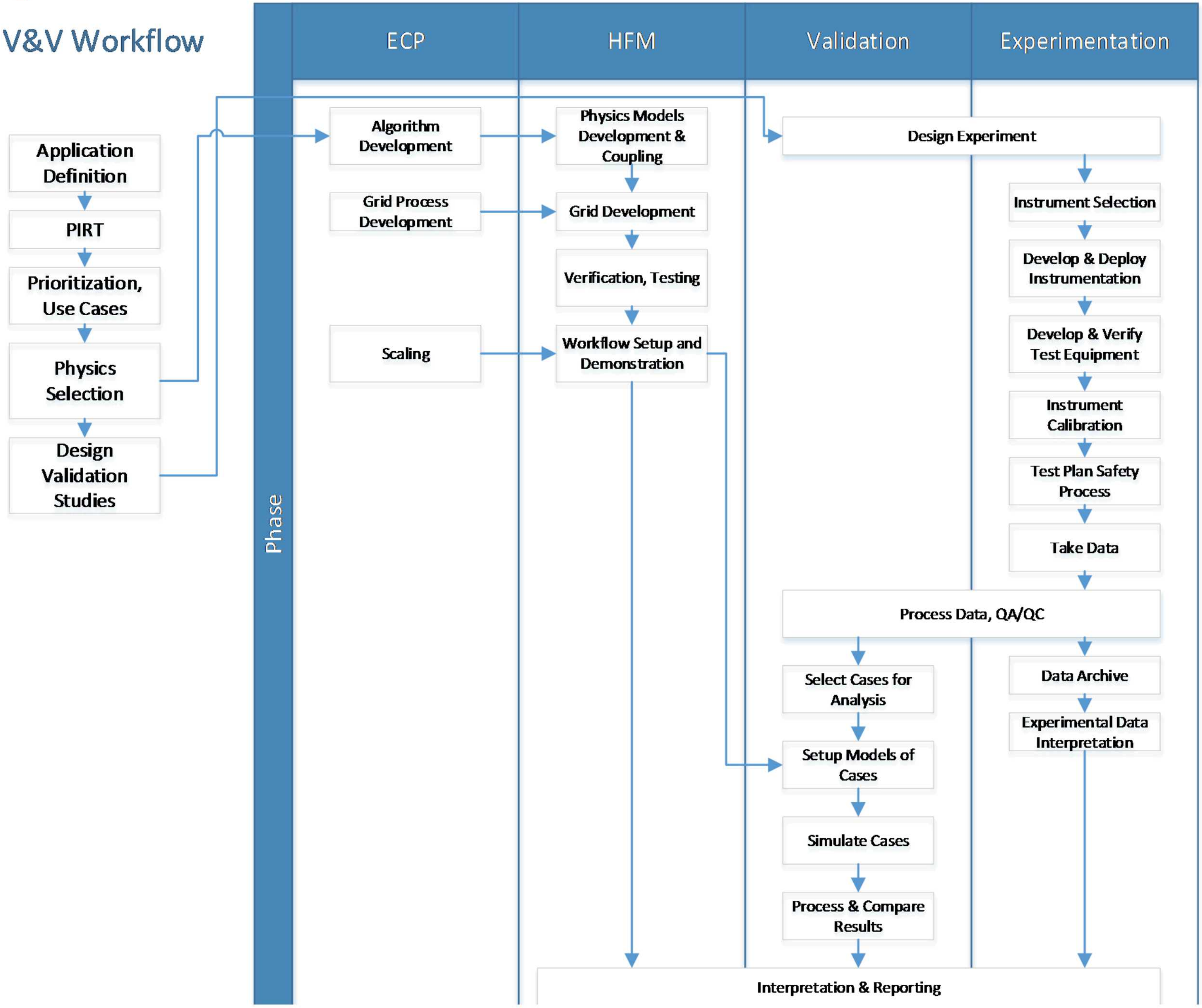


Yang et al. (201



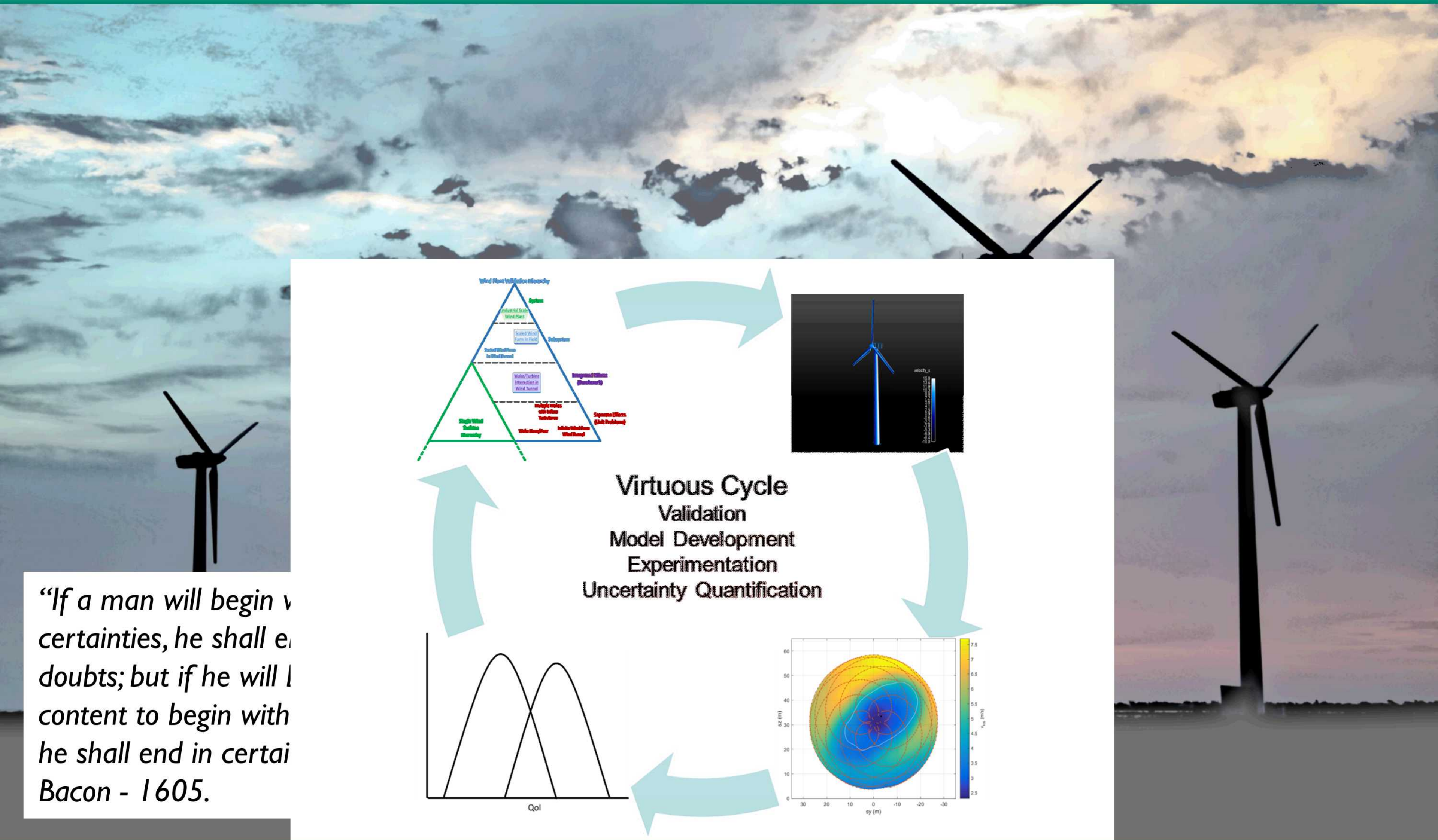
When calculating sensitivities, we can't just average over the entire domain

V&V Workflow



ECP
HFM
Validation
Experimentation
Phase
Application Definition
PIRT
Prioritization, Use Cases
Physics Selection
Design Validation Studies
Algorithm Development
Grid Process Development
Scaling
Physics Models Development & Coupling
Grid Development
Verification, Testing
Workflow Setup and Demonstration
Design Experiment
Instrument Selection
Develop & Deploy Instrumentation
Develop & Verify Test Equipment
Instrument Calibration
Test Plan Safety Process
Take Data
Process Data, QA/QC
Select Cases for Analysis
Setup Models of Cases
Simulate Cases
Process & Compare Results
Data Archive
Experimental Data Interpretation
Interpretation & Reporting

Uncertainty Quantification development and application in the A2e program (David Maniaci, SNL)



"If a man will begin w
certainties, he shall e
doubts; but if he will b
content to begin with
he shall end in certai
Bacon - 1605.