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CFD Modelling of Wind Turbine Icing

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Wind Turbine Icing

- Wind turbine icing causes **production losses** and **safety issues**
- Weight and aerodynamic characteristics of accreted ice can induce substantial loads, potentially **damaging** the turbine
- More than **20% annual production loss** due to icing estimated at some wind farms
- A. Lacroix estimates annual losses in Canada to be **200 M$**

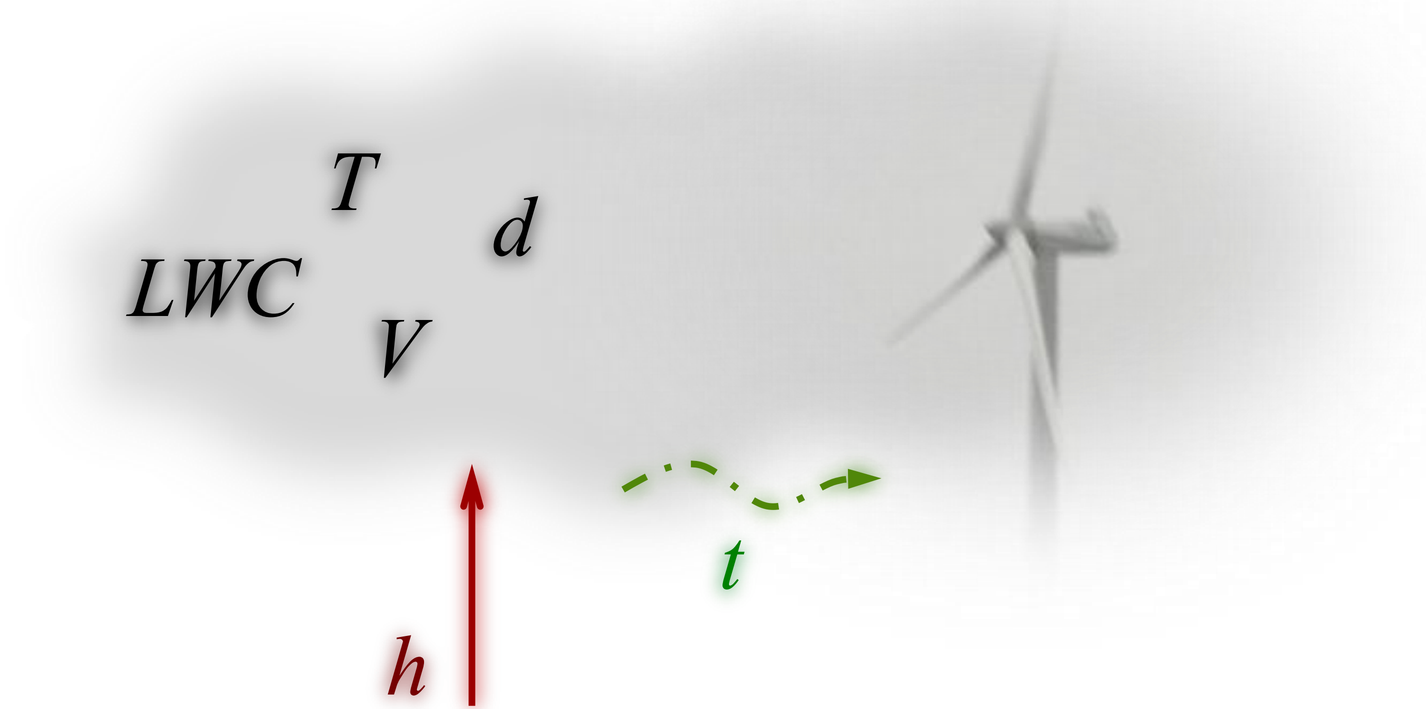
Wind Turbine Icing

- Icing data is required for **various** purposes:
  - Resource assessment
  - IPS system design
  - IPS cost/benefit analysis
  - Instrumentation
  - Control systems

- Various approaches are possible:
  - On-site measurements
  - Numerical weather modeling
  - Experimental
  - CFD

Wind Turbine Icing

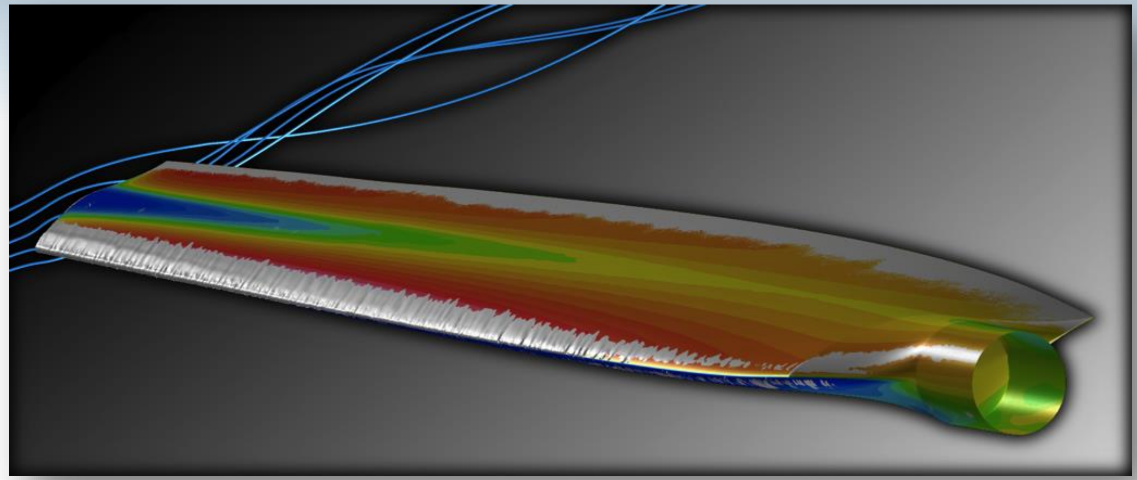
- Wind turbines are exposed to a **wide range** of icing conditions



- **Variability** and **uncertainty** must be taken into account

Wind Turbine Icing

Why CFD?



- Versatile
- Low cost
- Multiple levels of complexity can be considered
- Control of the icing conditions
- Data-rich results and post-processing possibilities

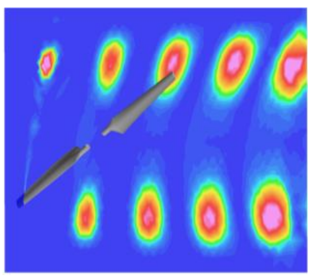
Wind Turbine Icing

- Icing occurs when freezing droplets impinge on surfaces exposed to a cold airflow stream
- Ice accretion results in substantial distortions of the flow and heat transfer characteristics
  - Shape
  - Roughness

FENSAP-ICE: Icing Simulation System

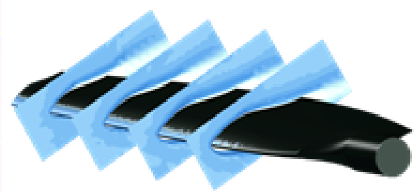
FENSAP

CFD Flow Solver



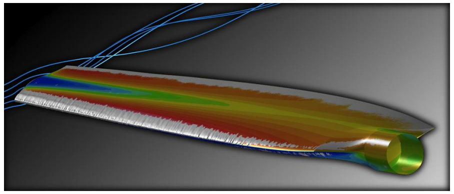
DROP3D

Droplet Impingement

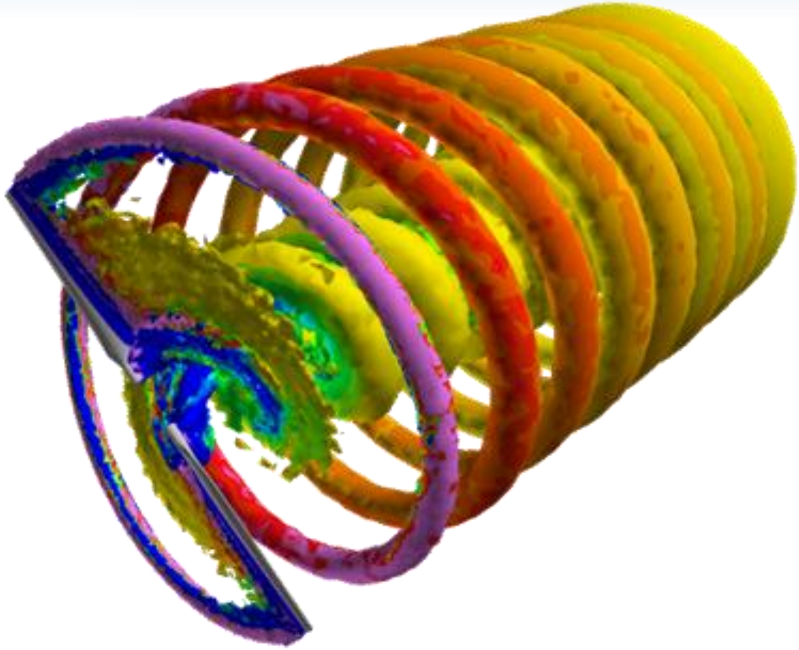


ICE3D

Water Runback, Ice Accretion

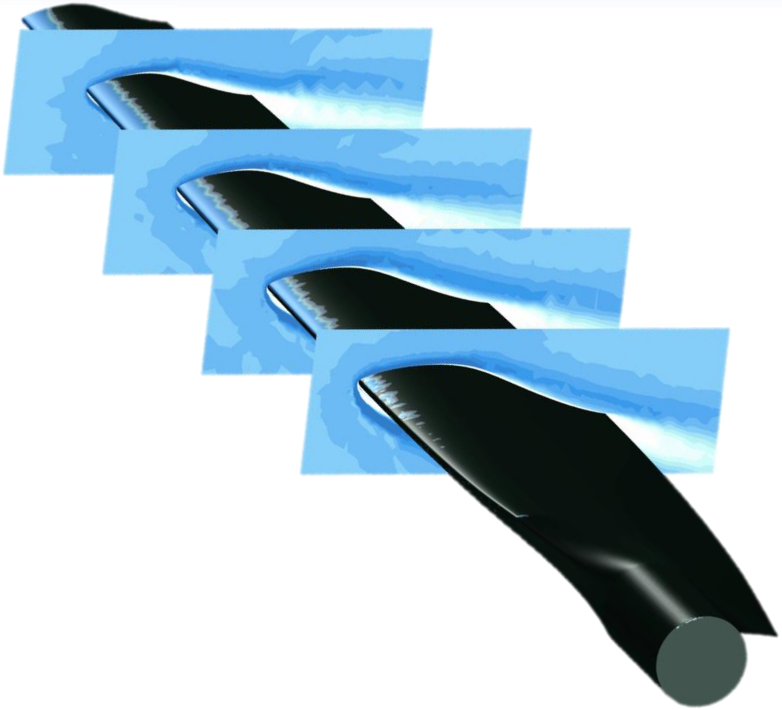


FENSAP – Air Flow



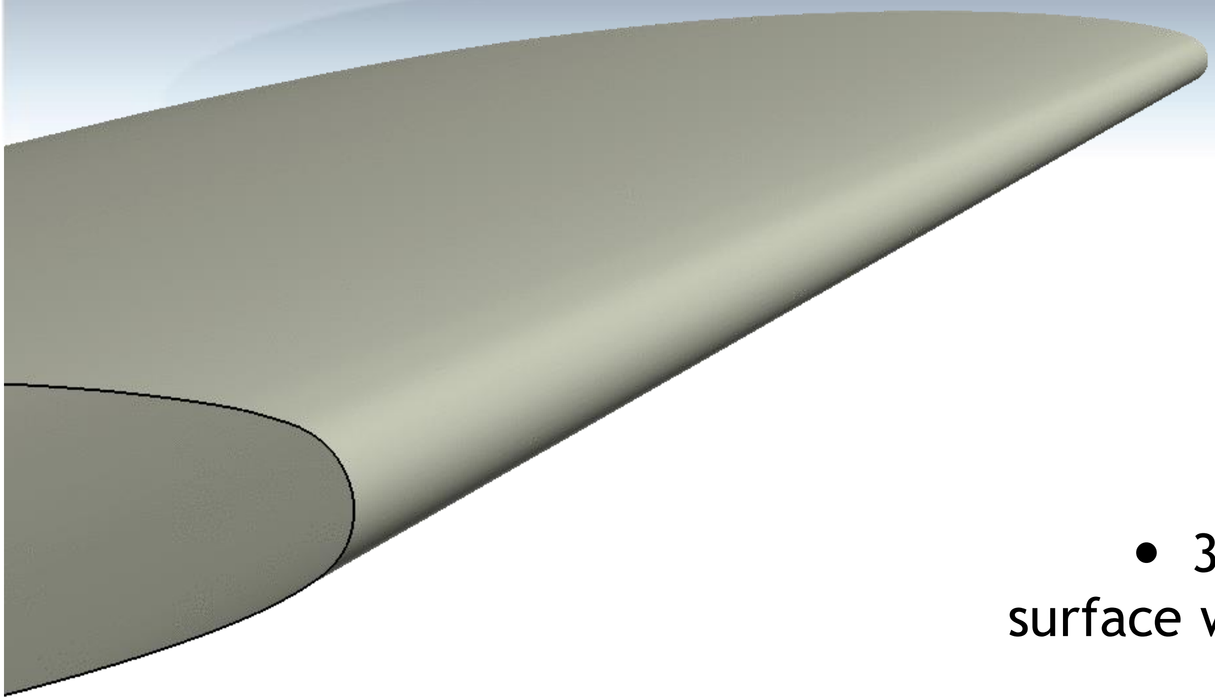
- 3D, viscous, turbulent
- Accurate shear stresses and heat fluxes
- Steady or unsteady
- Variable roughness: crucial for icing and performance analysis
- Particle tracking using Monte Carlo ice throw simulations

DROP3D – Impingement and Shadow Zones



- 3D water concentration model
- Delimits impingement *and* shadow zones automatically

ICE3D – Ice Accretion and Water Runback



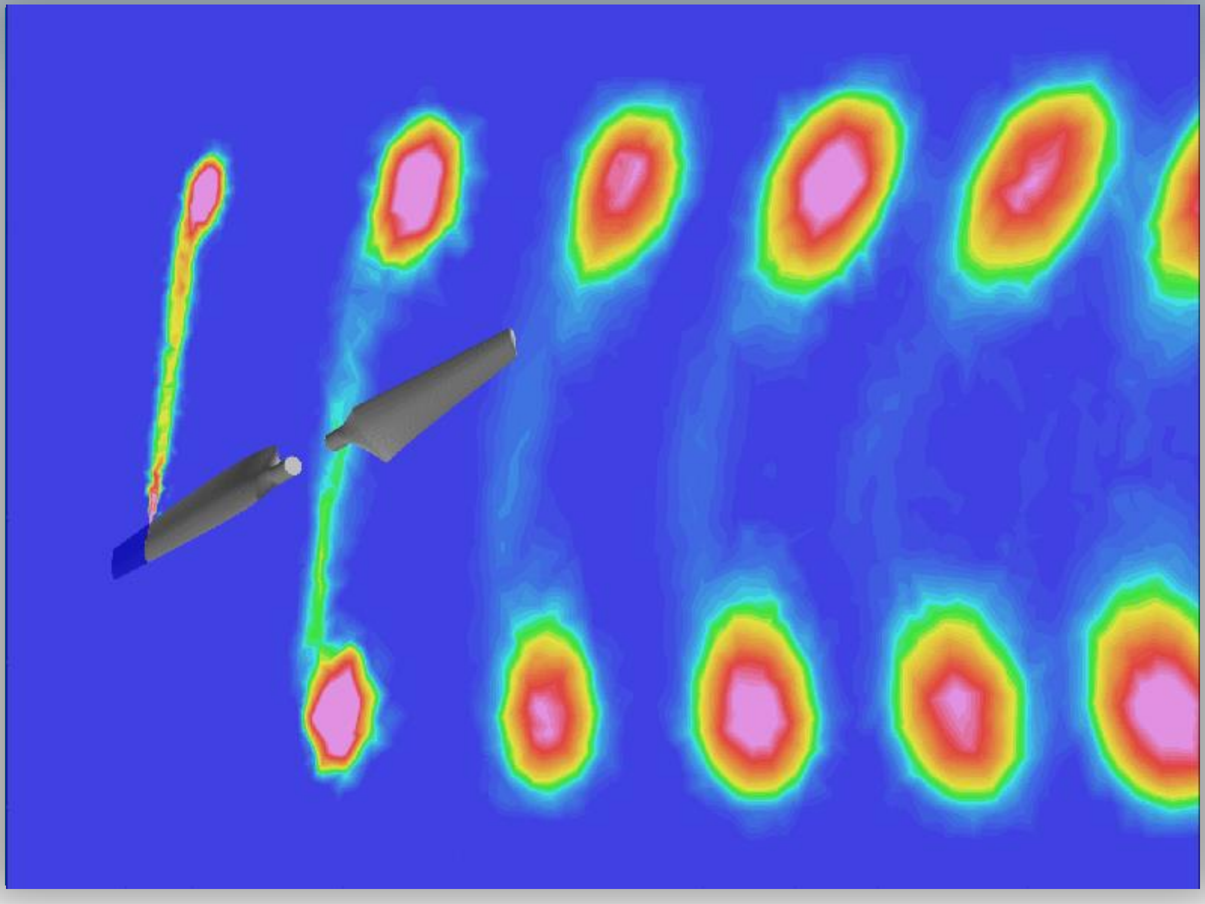
- 3D ice growth based on surface water thermodynamics
- Computes IPS power requirements
- Automatic iced grid generation for performance penalties

NREL Phase VI Rotor Icing

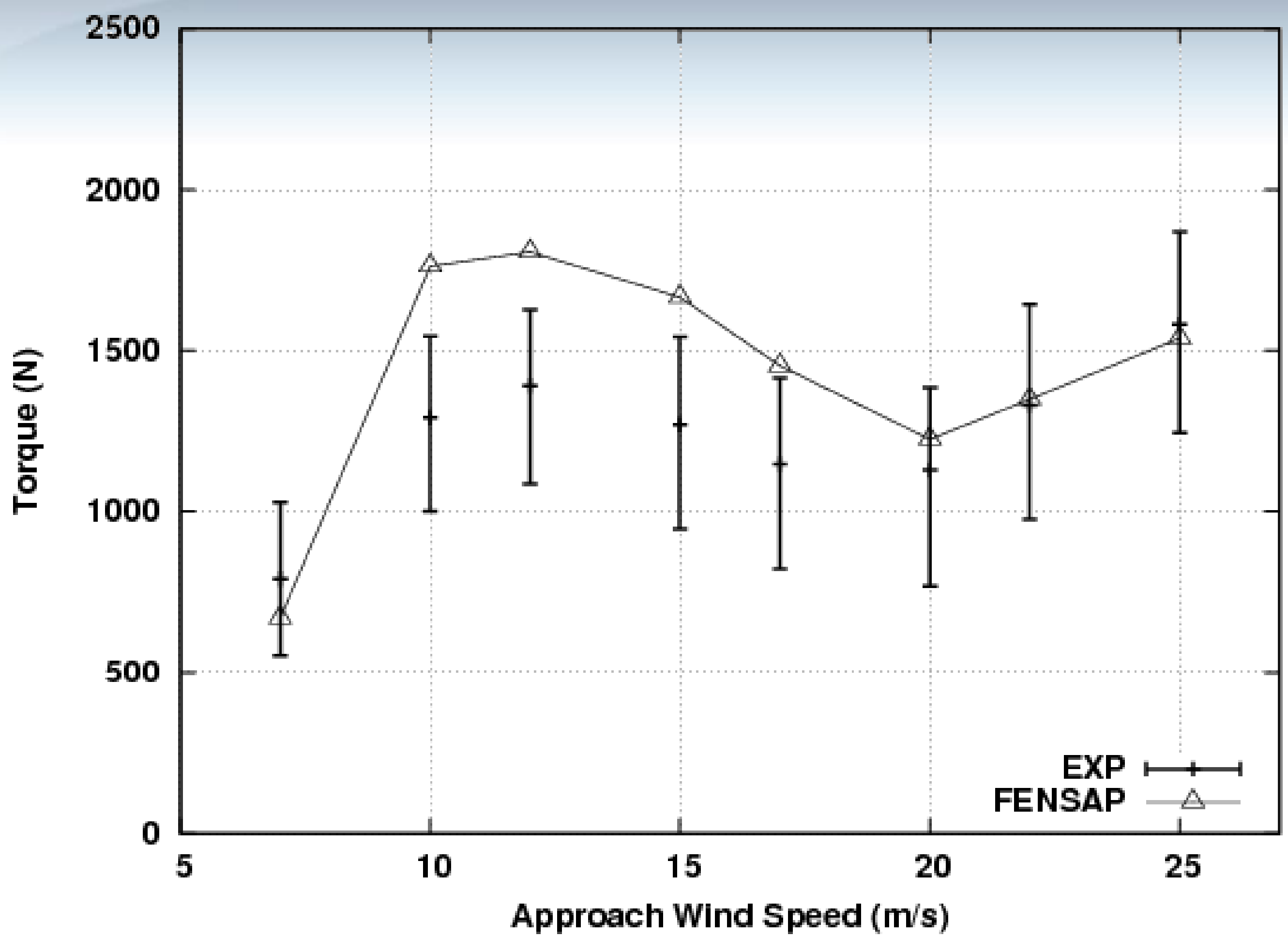
- Large performance database publicly available
- Experimental measurements: NASA Ames 80 x 120 ft. wind tunnel
- Other CFD simulations in the literature available for comparison

http://wind.nrel.gov/amestest/

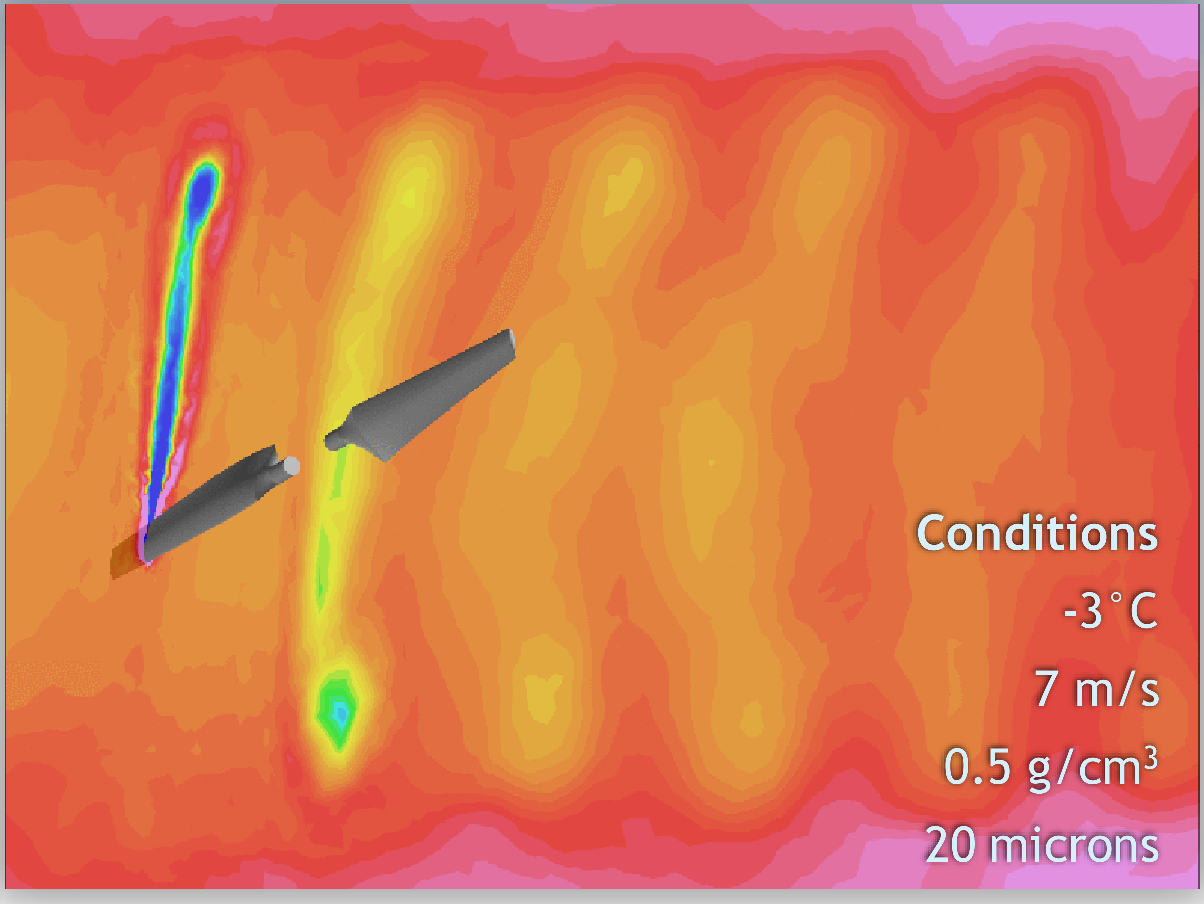
NREL Phase VI Rotor Icing



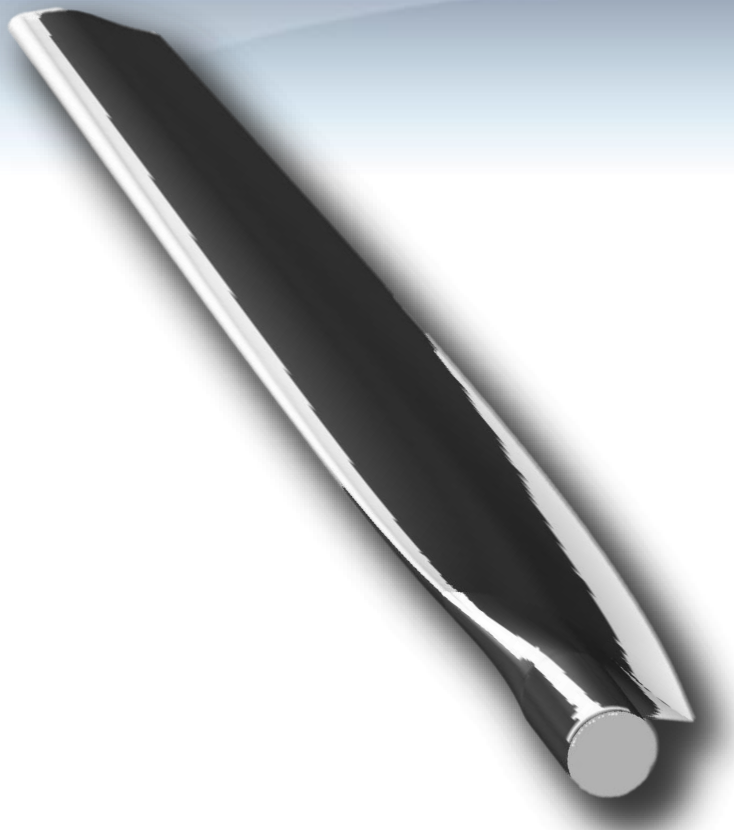
NREL Phase VI Rotor Icing



NREL Phase VI Rotor Icing

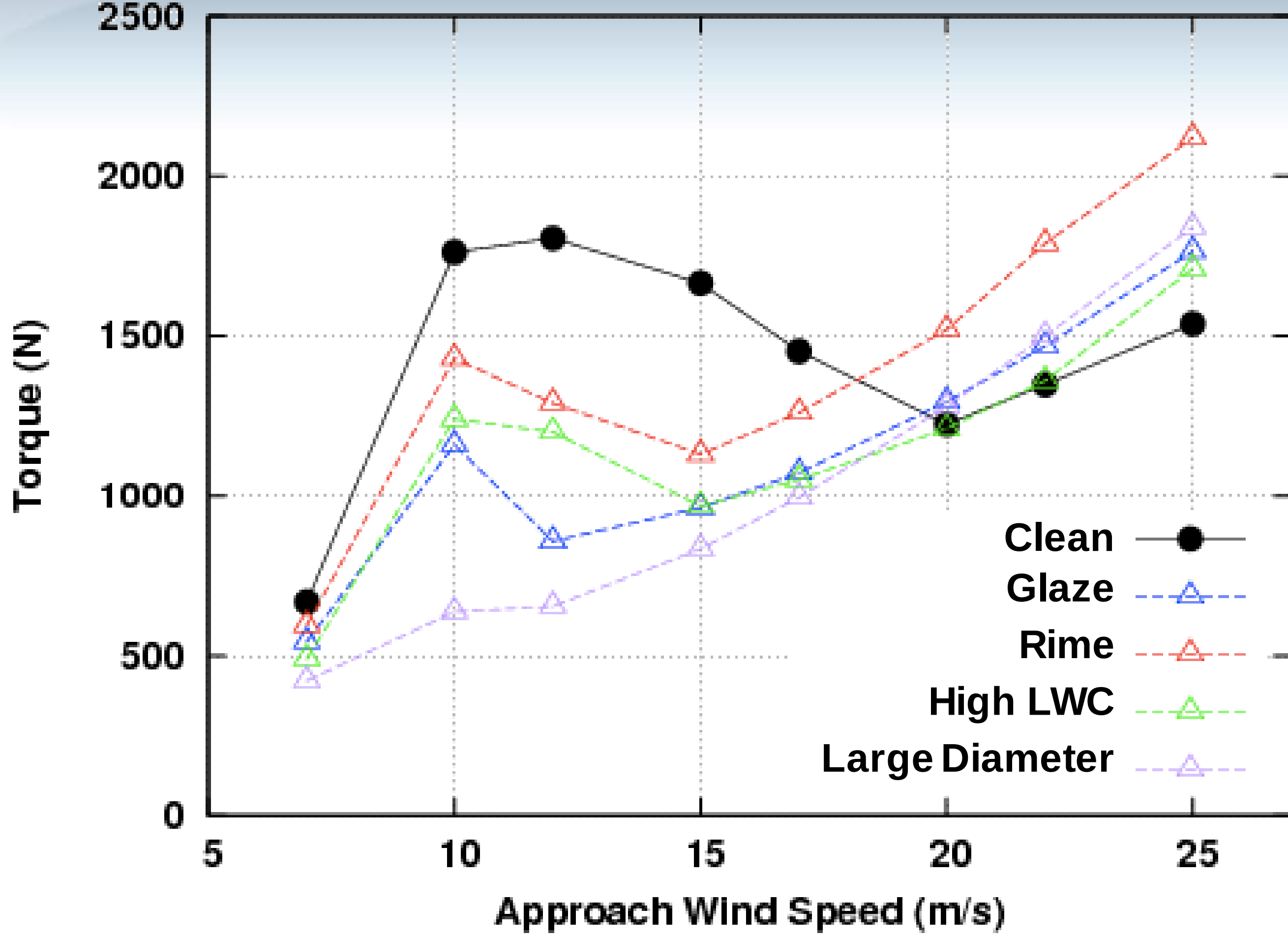


NREL Phase VI Rotor Icing

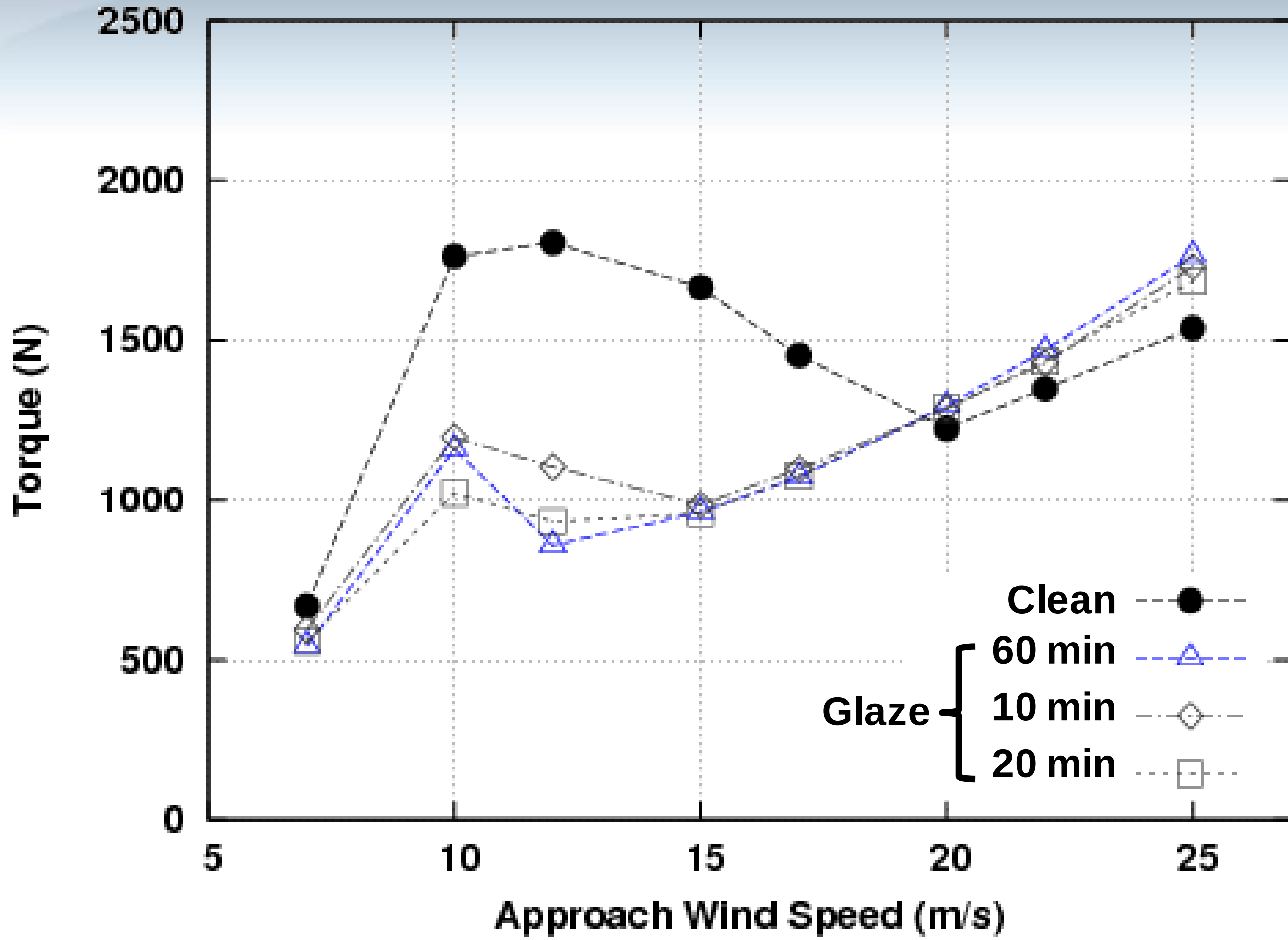


Rime **Glaze** **High-speed glaze** **Large diameters**

Performance Degradation: Effect of the Icing Conditions

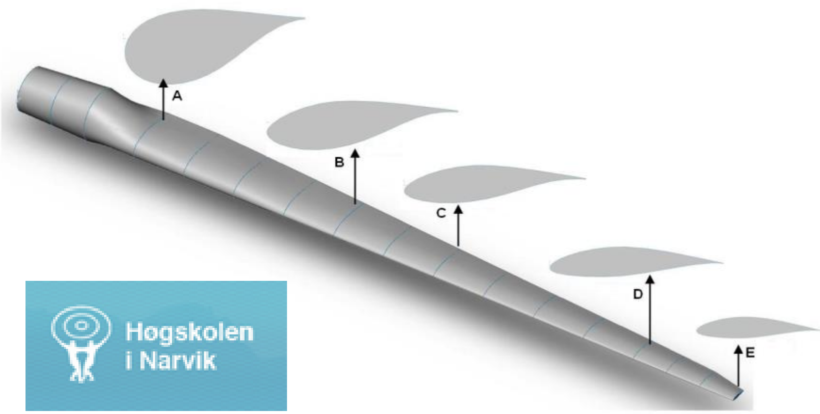


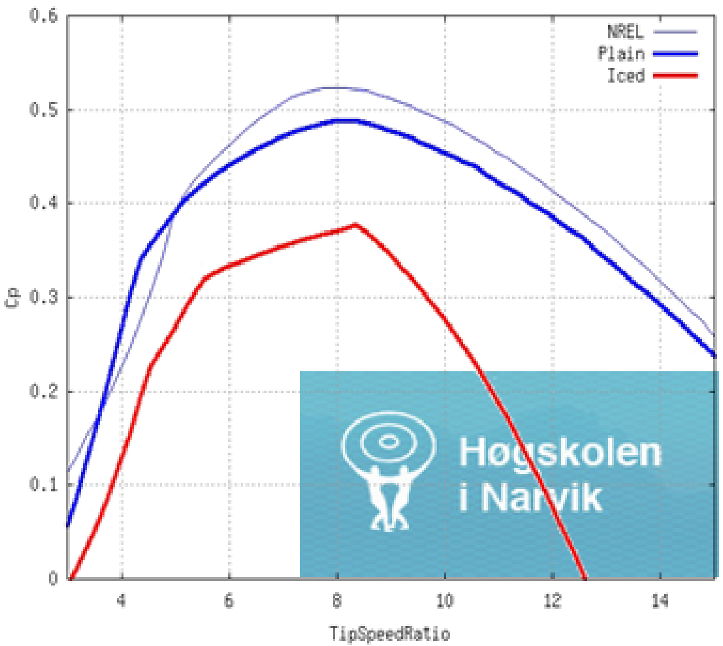
Performance Degradation: Icing Event Duration – Ice Class



Performance Degradation: Variability

- The exploration of the icing envelope requires a large amount of simulations
- Blade Element Momentum theory, combined with 2D CFD, allow **fast computation of rotor performance**

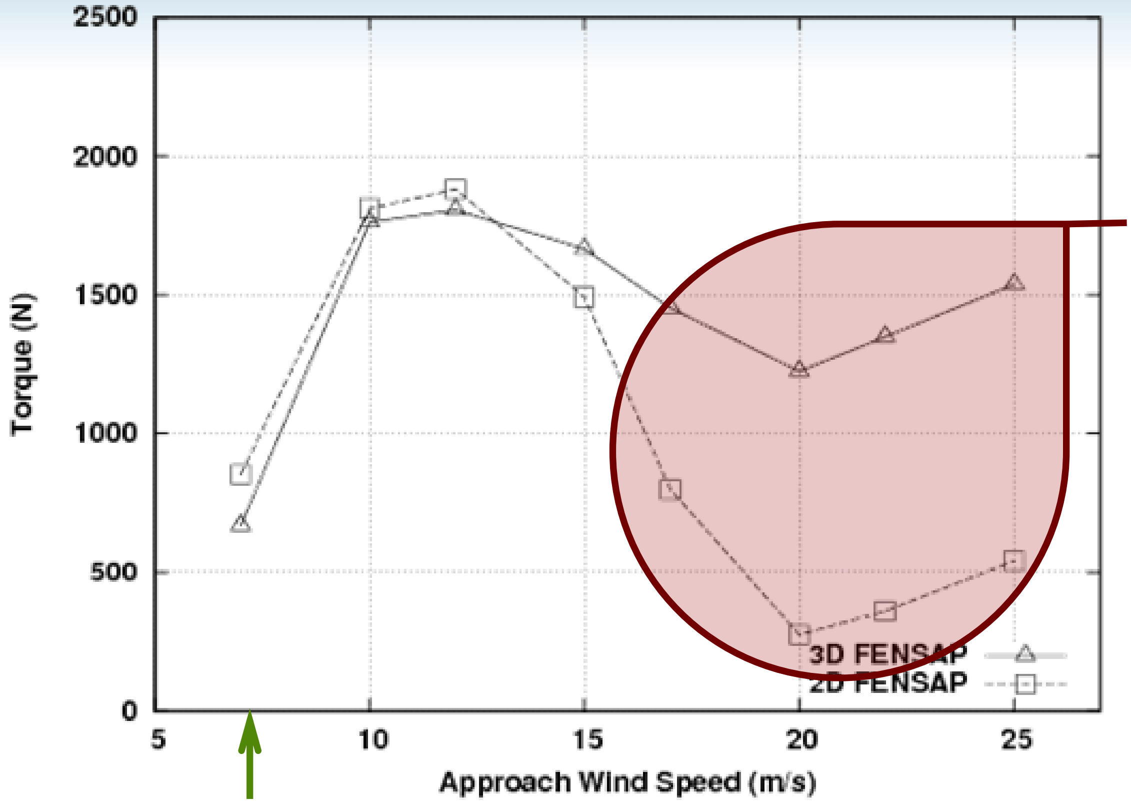




Source: M.C. Homola, M.S. Virk, P.J. Nickalsson, P.A. Sundsbø, 2011

Performance Degradation: Variability

- NREL Phase VI rotor: 3D vs. 2D-BEM (w/o 2D performance correction)



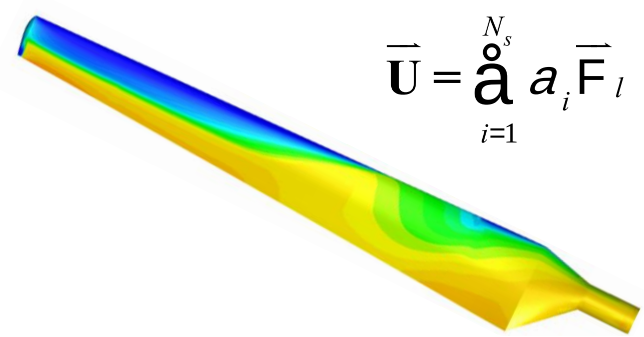
Important 3D-effects

Selected case for icing performance analysis

Performance Degradation: Variability

- To further increase the number of solutions, one applies Proper Orthogonal Decomposition (POD)
- POD extracts modes (eigenvalues) from a set of snapshots
- Reduced Order Modeling then drastically reduces the computation time of intermediate solutions

CFD	Computation
CFD	24hours on 64CPUs
ROM	A few seconds on 1 CPU



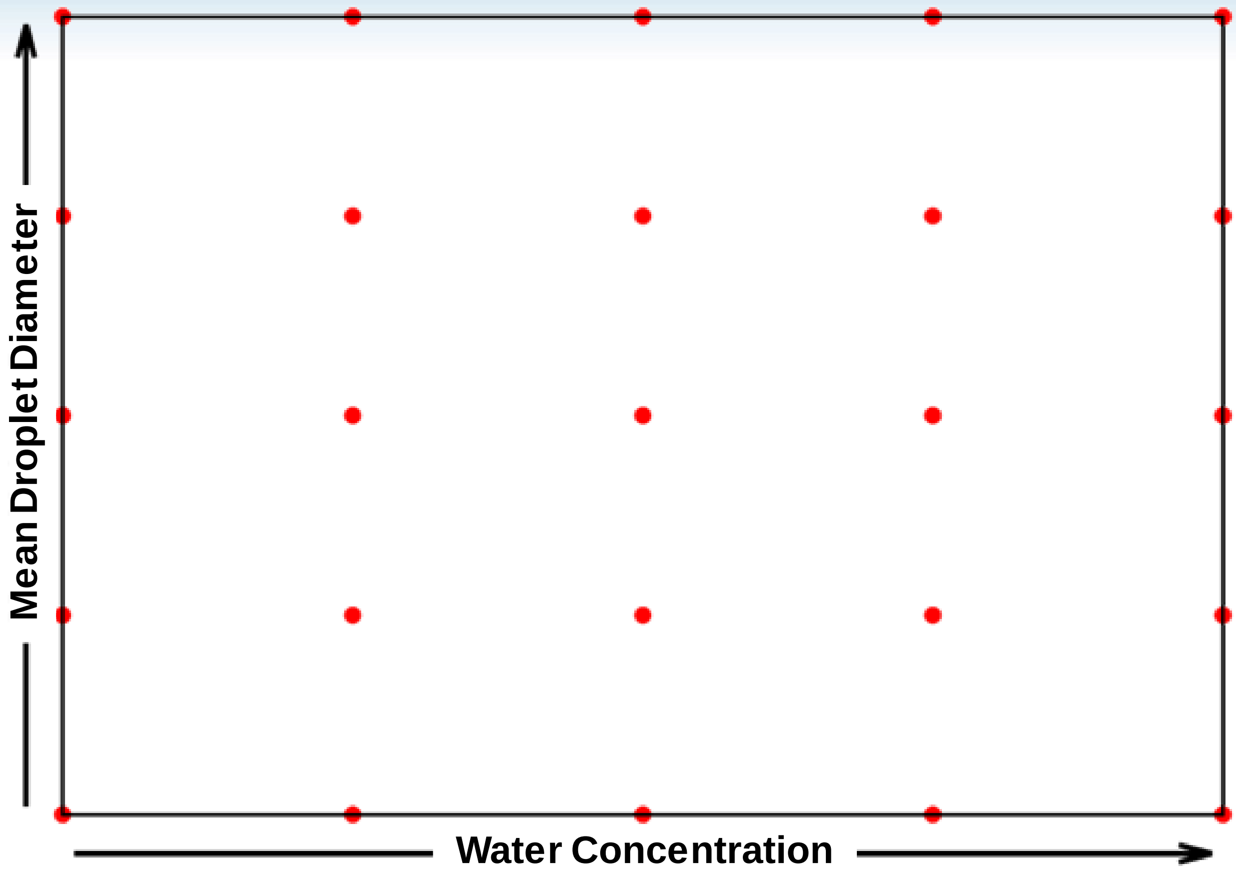
$$\vec{U} = \sum_{i=1}^{N_s} a_i \vec{\Phi}_i$$

m snapshots (solutions)

$$\Phi_i, \quad i = 1, 2, \ldots, m$$

Performance Degradation: Variability

- Performance is computed for a wide range of icing conditions



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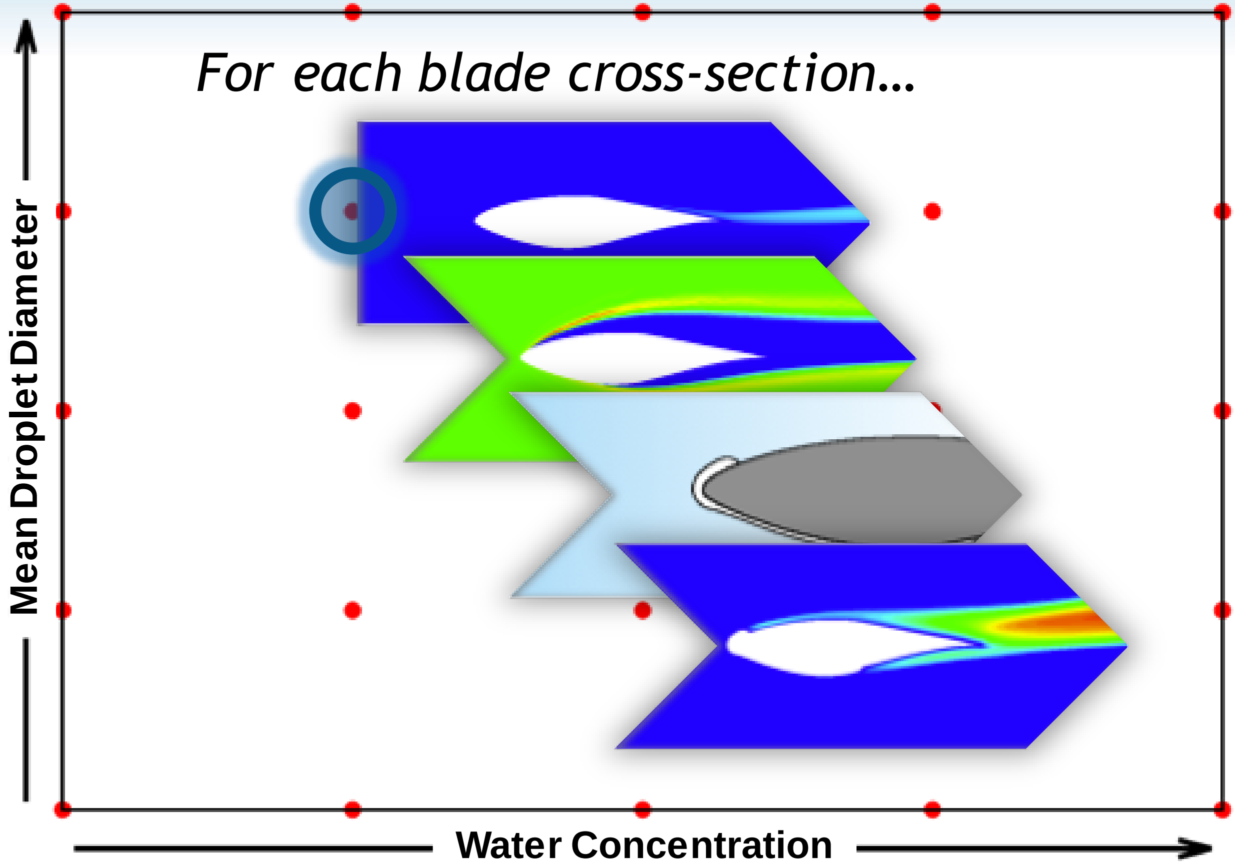
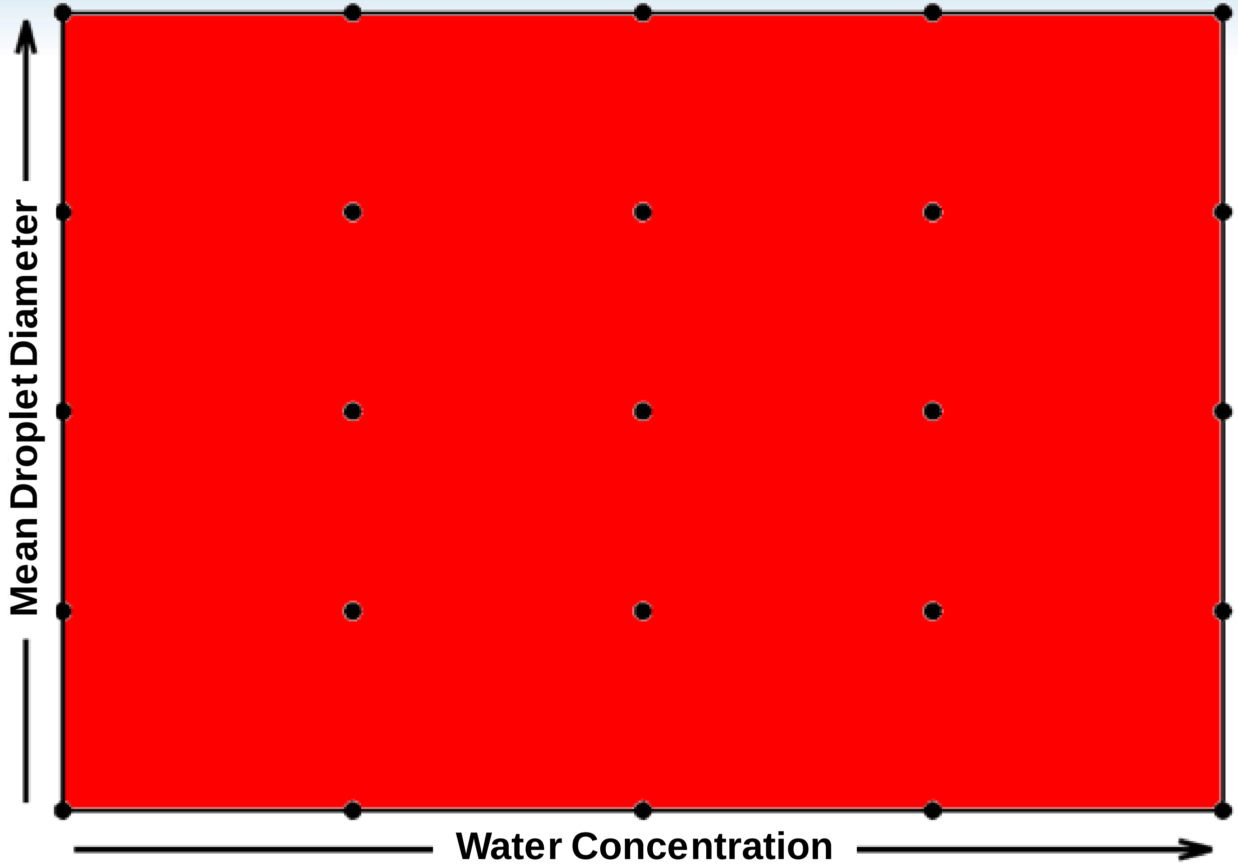


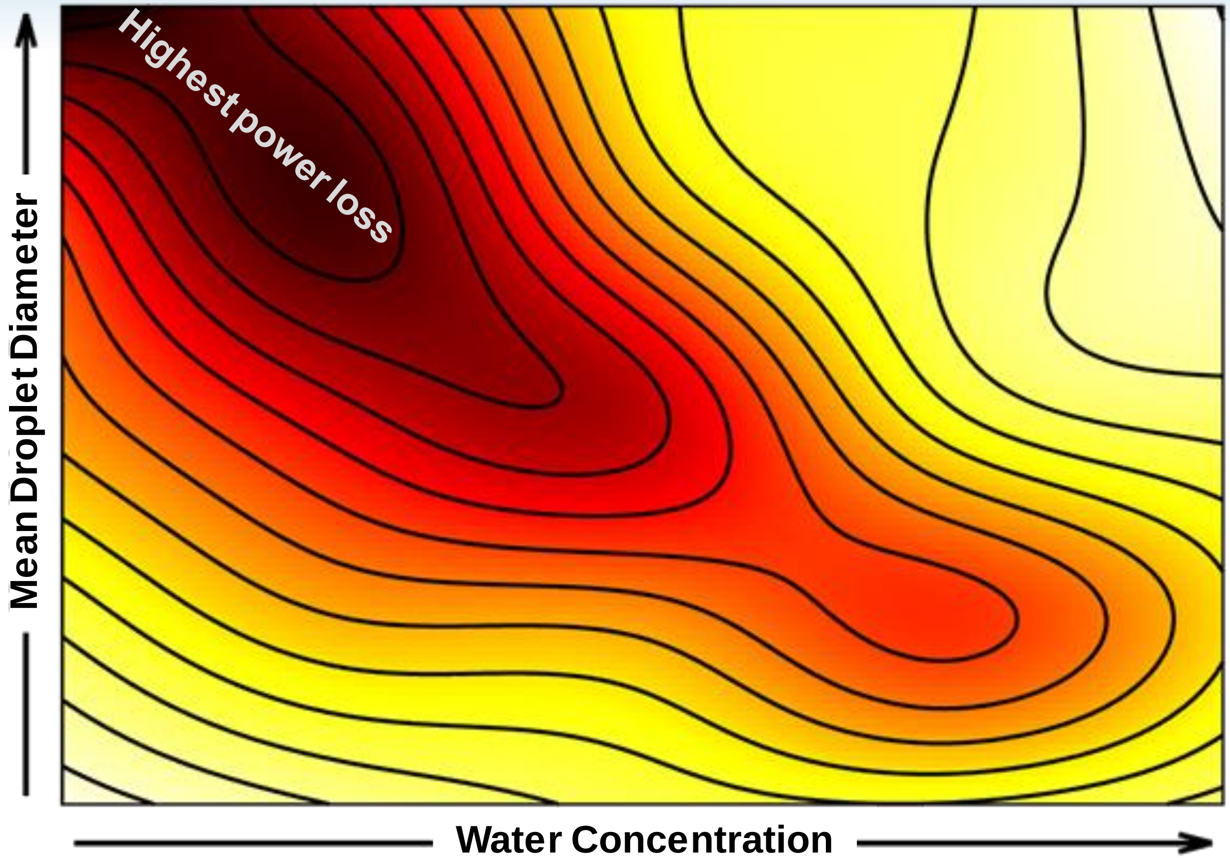
Performance Degradation: Variability

- Results for any intermediate condition can be obtained by ROM



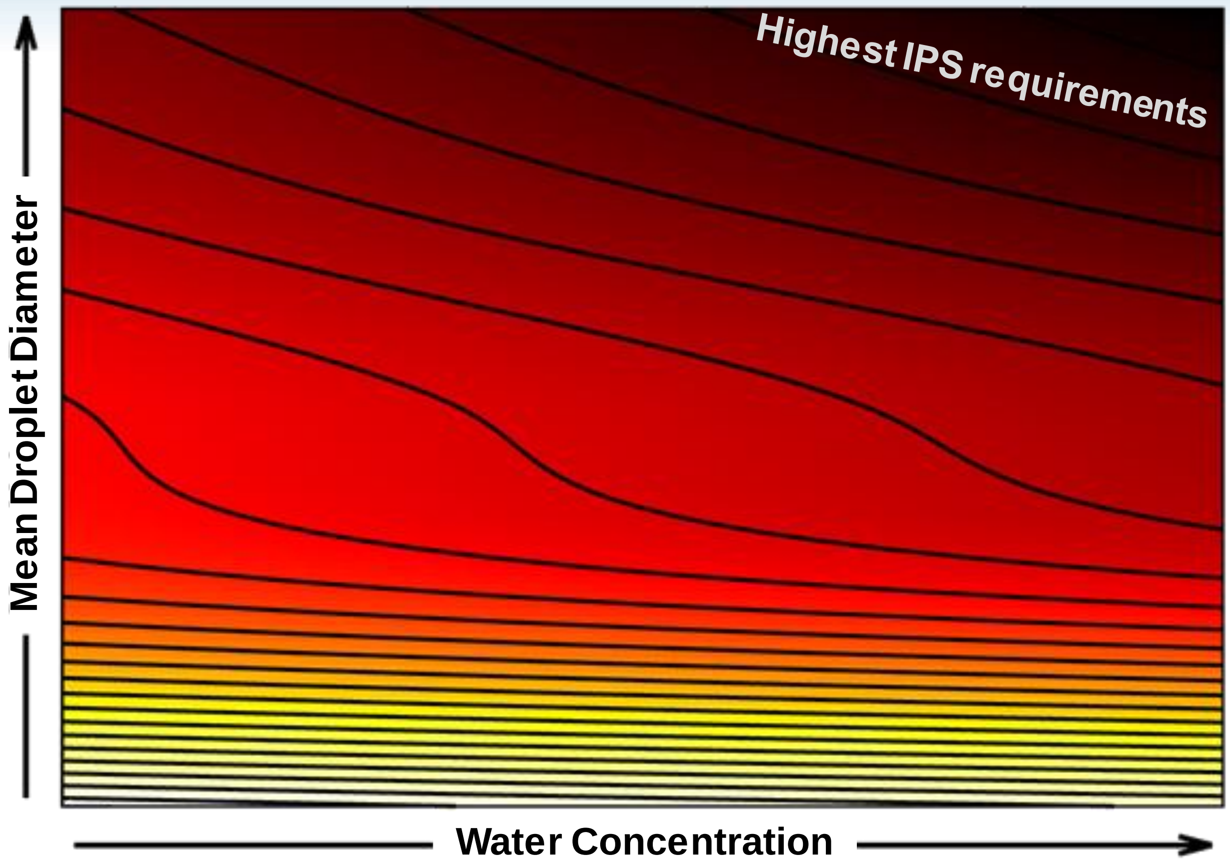
Performance Degradation: Variability

- NREL Phase VI icing power map



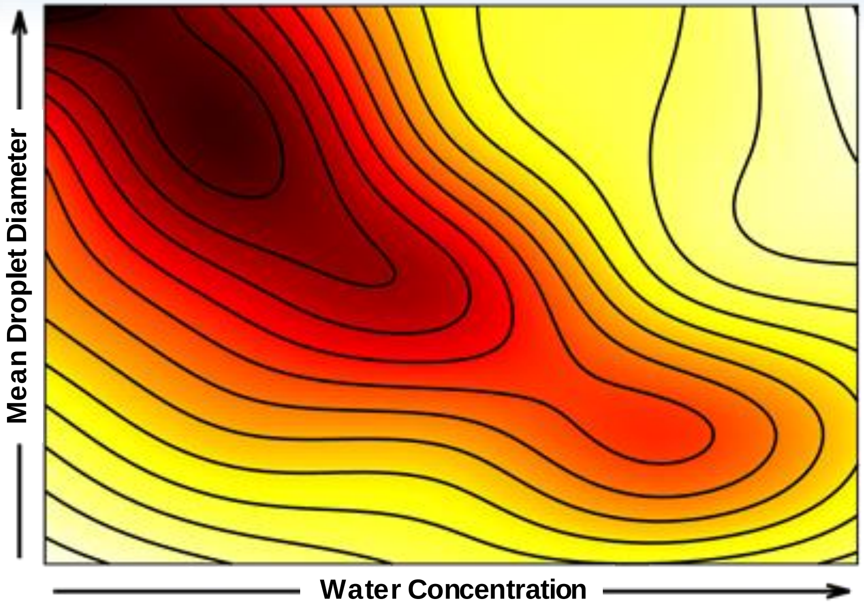
Performance Degradation: Variability

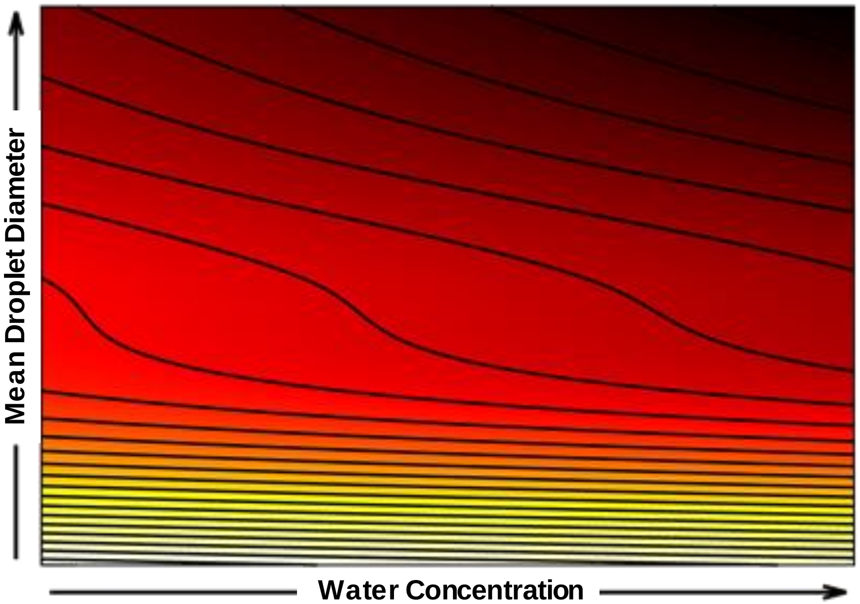
- NREL Phase VI IPS power requirements map



Performance Degradation: Variability

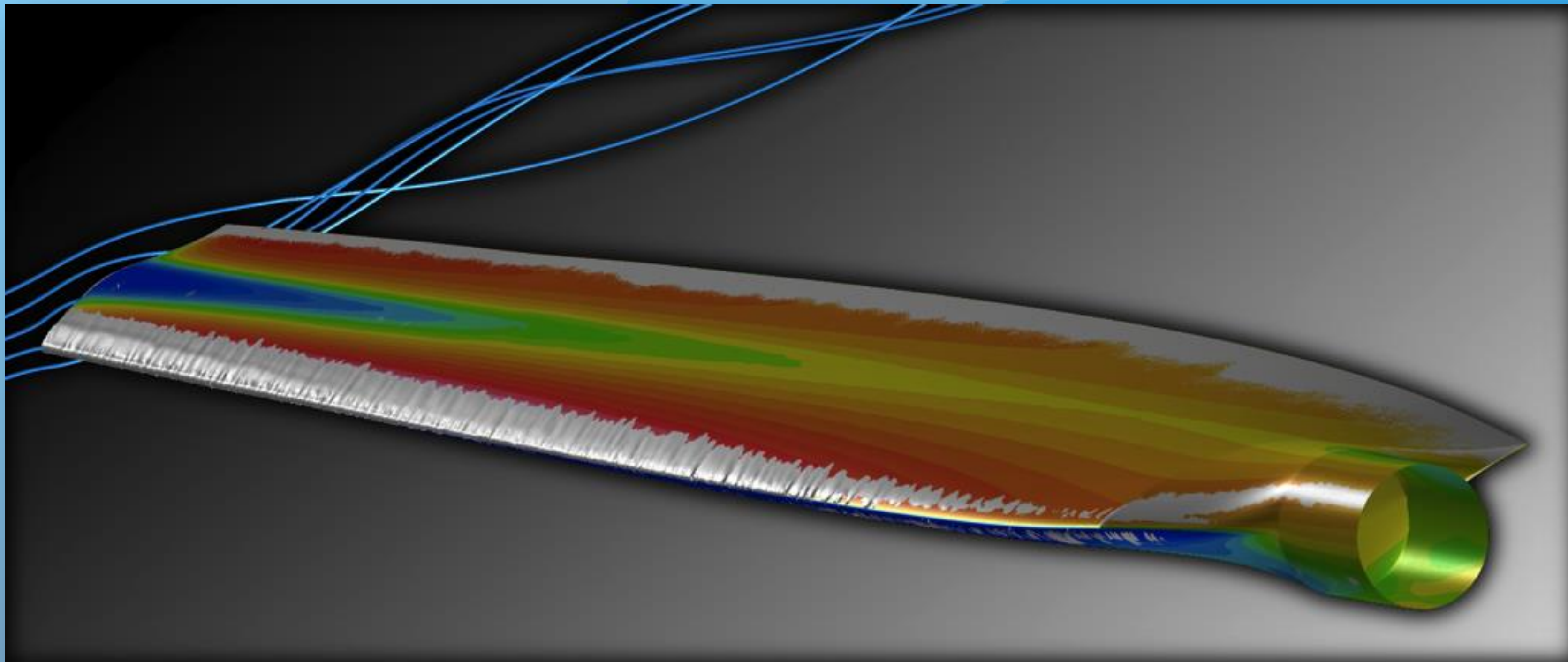
- Efficient IPS cost/benefit analysis





Towards Winterwind 2014…

- CFD can yield **extensive** performance datasets
- Techniques like ROM allow extremely **fast predictions** (once the snapshots are calculated)
- **Many possibilities** beyond wind resource assessment:
  - Icing protection system cost-benefit analysis
  - Optimal operation control during icing events
  - Enrich on-site measurements
- CFD can play a **significant role** in tackling wind turbine icing issues



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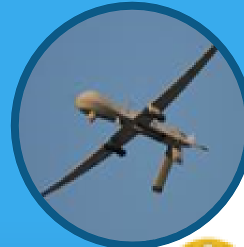

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