Lower Atmosphere Spectra Under Stably-Stratified Conditions Display Discontinuity But Not A Gap
Blending Mesoscale Data into CFD for Turbine Design

1. Prescribe WRF inflow
2. Assimilate WRF flow at gridlines
3. Apply spreading
4. Run CFD

Haupt with Frank Zajaczkowski & Kerrie Schmehl at Penn State University
Flow over Terrain

Courtesy Ned Patton
Additional Offshore Challenges:

Wave Generated Winds

Waves Generate their Own Wind Field that Persists to Hub Height

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Courtesy Peter Sullivan
Finer Scale Variations

Pressure Contours and Flow Vectors

smooth

rough

Flow separation

Courtesy Peter Sullivan
PRESSURE FLUCTUATIONS IN XZ PLANES NEAR THE WATER SURFACE (note different scales)

Ug = 5 m/s
Wave age ~ 5.8

Ug = 20 m/s
Wave age ~ 1.8

Courtesy Peter Sullivan
Impact of Extreme Events

When Turbine Meets Typhoon...

Turbine Design Criteria

Wind Characteristics of Typhoons
Extreme Conditions & Hurricane Models

62 m Large Eddy Simulations

Can integrate modeled hurricane forces models with turbine design models

Turbulence kinetic energy

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Wind Power Forecasting

George Young
Needs for Wind Power Forecasting Systems

• Wind Power Forecasting is necessary for effective grid integration
  - Day Ahead forecasting – Energy Trading
  - Short-term forecasting – Grid Integration & Stabilization
• Thus, an effective forecasting system should include components for both

Cedar Creek Wind Farm, Northeast Colorado
Photo by Carlye Calvin, UCAR
Optimizing Prediction Methods by Blending Technologies

Forecast Time

- Persistence: 0-1 hr
- Rapid Cycle Models: 0-2 hrs
- 4DDA+NWP: 3-12 hrs
- 3DVAR+NWP: 12 hrs to 2 weeks
- Climatology: > 14 days

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DICast Integrator System

Model Optimization via Dynamic Weighting and Bias Removal

Nacelle Winds

Wind speed example 10-15% improvement
Empirical Power Conversion Curves

Not Straightforward!

Anemometer defect

Wind deviation

Tower vibration

High wind speed cut-out

Ice accretion on blades

Other faults and downtime

Gerry Wiener
8/03/09 771mw up-ramp from 20:10 - 22:10 followed by a 738mw down-ramp from 22:40 - 00:50

800 MW increase then decrease over 4 hrs!
Wind Energy Ramp Event Nowcasting

- **Causes of Wind Ramp Events**
  - Cold Fronts
  - Warm Fronts
  - Thunderstorm Outflows
  - Low Level Jets
  - Sea Breezes
  - Microbursts
  - Gravity Waves
  - Eroding Surface Inversion
  - Momentum mixing

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Bill Mahoney
Thunderstorm gust fronts cause rapid increase in energy output.

Rapid cycle cloud-scale model

Gust front analyzed with the Variational Doppler Radar Assimilation System (VDRAS) - NCAR

Courtesy: Jenny Sun
Doppler Radar Retrieval

10/12/2010 Wind Energy Ramp Case

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Uncertainty in Meteorological Flow

- Atmospheric flows display sensitivity to initial & boundary conditions and to physics parameterization

  → Chaos

- Meteorologists address this by modeling ensembles of realizations

  → Uncertainty Quantification
Xcel Energy Wind Forecasting

2010 Total Benefit

- Error Reduction (expected 2%)
  - PSCo; NSP – much higher than expected
  - SPS – higher than expected
- Rate of Savings
  - PSCo – meets expectations (expected $800k/%MAPE)
  - NSP – higher than expected (expected $500k/%MAPE)
  - SPS – much lower than expected (expected 600k/%MAPE)

<table>
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<th>Delta</th>
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*Mean Absolute Percent Error

Wind Forecasting Savings: $6,260,417
Curtailment Auditing Savings: $1,260,000
Grand Total: $7,520,417

Also: saved > 238,000 tons CO2 (2011)

~$1.9M per each percent improvement
NEW YORK (CNNMoney) -- During the early morning hours of April 15, with a steady breeze blowing down Colorado's Front Range, the state's biggest utility set a U.S. record -- nearly 57% of the electricity being generated was coming from wind power.
Conclusions

- Understanding atmospheric variability is critical to optimizing power production.
- Meteorological modeling is needed to help deal with the issues:
  - Turbine viability
  - Siting
  - Real-time forecasts
Thank You!

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Julie Lundquist
Greg Thompson
Seth Linden
Julia Pearson
Frank McDonough

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