Atmospheric science challenges related to large-scale deployment of weather-dependent renewable energy

Part I: Jim Wilczak/NOAA
Part II: Sue Ellen Haupt/NCAR
Outlines

**Part I:**
- Economics
- Instrumentation
- PBL processes
  - diurnal cycle, LLJ, shear, stability, waves
- Wake effects
- Offshore
- Forecasting/data assimilation
  - Ramp events
  - Thunderstorms

**Part II:**
- Spatial/Temporal Variability
- Interannual variability
- Terrain effects
- Turbulence
- Models
- Terra incognita
- Wave-wind interaction
- Extreme events
- Forecasting
Grid Balancing

Grid operators keep demand (load) and generation closely balanced.

Because of start-up costs and technical limits, can’t/don’t want to turn off plants for short periods of time: Nuclear: weeks; Coal and Steam Gas: ~6-24 h; CC ~hours, GT: minutes.

Plants operating at reduced capacity are less efficient (~30 % lower efficiency for CC, 15 % for coal)
Levelized Cost of Wind Energy versus Fossil Fuels

Figure 8. Estimated LCOE for wind energy from 1980 to 2009 for the United States and Europe (excluding incentives)

IEA Wind Task 26 Report (Lantz et al., 2012)
DOE/EIA Annual Energy Outlook 2012
Potential Savings

Savings between a (State-of-the-Art) SOA next-day wind forecast and a perfect forecast for a national 20% wind in 2030 scenario

Savings sensitivity to % forecast improvement

Lew et al., 2010
Determining cost savings from better met info can be complicated, requires understanding of met and engineering/systems analysis

- Dollar savings are potentially large
- Dollar savings increase with wind penetration level
- Modest improvements in meteorological information can produce large savings
- Better met info is not an absolute necessity for WE, but it makes it cheaper!
- Useful to view all met challenges/research/information through the financial prism
Instrumentation

wind profiling lidar detects wind, turbulence profiles. Pros: low 1st gate, high vertical resolution. Cons: No signal in extremely clean (aerosol-free) air, during precipitation and fog. Restricted range. Frequent loss of data.
Radar wind profiler/RASS delivers wind and temperature profiles.
Pros: deep layer for data assimilation, both winds and temperature.
Cons: high 1st range gate, coarse vertical resolution. Improvements to data qc needed.

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Scanning Doppler lidar detects wind and turbulence fields.
Pros: spatial wind variations as well as vertical profile, turbulence.
Cons: No signal in extremely clean air, precip, fog. High cost. Restricted vertical range.
SODAR detects wind, turbulence profiles.
Pros: High vertical resolution, low 1st gate, low cost.
Cons: Does not work well with very high wind speeds, and during stronger precipitation events. Restricted range. Noise contamination.
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Radiometers detects temperature profiles.
Pros: provides temperature and moisture profiles.
Cons: No wind information. Accuracy depends on nearby sounding.

Courtesy Katja Friedrich

Wind profiling lidar detects wind, turbulence profiles. Pros: low 1st gate, high vertical resolution Cons: No signal in extremely clean (aerosol-free) air, during precipitation and fog. Restricted range. Frequent loss of data.


Industry tall towers/nacelles wind, turbulence, temperature 1 or more levels. Pros: provides information at or near hub height. Already exist. Cons: Difficult to obtain. Loss of data due to icing. No data in upper half of rotor plane or above.
Instrumentation

Key Challenges

• Higher accuracy/cheaper/more easily deployed instrumentation is needed!
• Better automated QC needed especially for data assimilation
• Maintaining national networks in times of shrinking federal budgets.
PBL Processes
Diurnal cycle
LLJ
Shear
Stability
Waves
Composite PBL – Wind Profiling Radar

Vertical Wind Variance

August 12 – September 30, 2006
AVRG level > 50%

m²/s²

SR

SS

Low Level Jet

7 sites
50 days
no rain
Lidar Observations of LLJ

- **Sunset**
- **Midnight**

![Graphs showing LLJ observations with height, jet speed, and radial velocity over time.](image)
- LLJ speed $U_j$, and height $Z_j$ - key velocity and length scales for the SBL
- Constant shear of $0.1 \text{ s}^{-1}$ below jet

LLJ Geographic Variation

Radiosonde network

Frequency of LLJ occurrence

Bonner, 1968
What is geographical variation of $U_j$, $Z_j$? Time of onset, cessation?

Walters et al., 2008
TexAQS 2006 wind profiler network

Composite of 17 LLJ days, all sites

Wilczak et al., 2009
California Profiler Sites 2008

[Map of California with profiler sites marked, including locations such as CCD, SAC, LVR, CCL, and LHS.]
- Stability affects PBL growth of PBL
- PBL depth affects LLJ
- Large spatial variability of stability in complex terrain
- Models have greater difficulty on simulating climatology of stability, PBL, LLJ
Power production by the leading turbine varies with atmospheric stability.

Based on SCADA and SODAR data from an operating wind farm, West Coast North America.

Stability stratification by SODAR $I_U$
Waves

Turbulence measurements usually do not separate wave motions

PBL Processes
Diurnal cycle
LLJ
Shear
Stability
Waves

Key Challenges
• Improve model climatology of LLJ $U_j$ and $Z_j$ (mostly model physics)
• Improve forecast skill of LLJ’s (Mostly initial conditions?)
• Understand links between stability and LLJ’s
• Improve model forecast skill of stability
• Understand impacts of waves on turbines and turbine power curves
Wake effects
Velocity deficit

\[ VD(R) = \left( \frac{U(R)-U_{IN}}{U_{IN}} \right) \times 100\% \]
Horizontal extend, length, and meandering of wakes
Wake effects

Key Challenges
• Understand wakes dependency on atmospheric state: stability, shear, turbulence and PBL depth
• Determine optimal turbine deployment strategy
Offshore
• sea-breeze circulations
• summer strongly stable boundary layers with large shear
• winter cold-air outbreaks (icing conditions, extreme turbulence)
• coastal frontogenesis (Nor’ easters)
DOE Reference Facility for Offshore Renewable Energy (RFORE)

Slide courtesy of Will Shaw/DOE PNNL
Extrapolation of offshore near surface winds to hub-height using logarithmic wind profile

\[ U(z) = \frac{u_*}{K} \left( \log \left( \frac{z}{z_o} \right) - \Psi_m \left( \frac{z}{L} \right) \right) \]

- \( u_* \) = friction velocity, \( L \) = Monin-Obukhov length,
- \( z_o \) = roughness: all 3 computed using COARE3.0 bulk flux algorithm.

Inputs: \( U(18m) \), SST, Tair, pressure, RH, SW and LW radiative fluxes, time of day.
Motion compensation

- Stabilize the pointing of the beam
- Remove platform motion from LOS velocity measurements
- Measure instantaneous pointing angles
- Calculate mean wind profile by averaging beams pointing at different (but known) angles
Offshore

Key challenges
• Deploy hub-height wind measurements in US Atlantic waters
• Coastal boundary effects larger for Atlantic US wind farms than for Europe
• Effects include:
  • sea-breeze circulations
  • summer strongly stable boundary layers with large shear
  • winter cold-air outbreaks (icing conditions, extreme turbulence)
  • coastal frontogenesis (Nor’ easters)
Forecasting
Wind Ramps

![Graph showing wind speed and power output over time.](image-url)

- 90%
- 10%
The Wind Forecast Improvement Project (WFIP)
New Instrumentation

915 MHz radar profiler
0.1-4km

Sodar
40-200m

Lidar
40-200m

Tower
50-80m

449 MHz ¼ scale radar profiler
0.2-8km

Nacelle anemometers
85m

Surface Flux
10m
Southern Study Area

3 profilers
7 sodars
### Hourly Updated NOAA NWP Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RUC</strong></td>
<td>older oper model - 13km</td>
</tr>
<tr>
<td><strong>Rapid Refresh (RR)</strong></td>
<td>new WRF-based oper model in May 2012 - 13 km</td>
</tr>
<tr>
<td><strong>HRRR - Hi-Res Rapid Refresh</strong></td>
<td>Experimental 3km 15h fcst updated every hour - Initialized from RUC/RR</td>
</tr>
</tbody>
</table>

All models re-initialized and run every hour, run to at least 15 hs, 3D var data assimilation
Model comparisons

<table>
<thead>
<tr>
<th>OPERATIONAL (NWS)</th>
<th>RESEARCH (ESRL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HRRR (w/ assimilation of WFIP obs)</td>
</tr>
<tr>
<td>Rapid Refresh (RR)</td>
<td>RR (w/ assimilation of WFIP obs)</td>
</tr>
<tr>
<td>Rapid Update Cycle (RUC)</td>
<td>RUC (w/ assimilation of WFIP obs)</td>
</tr>
</tbody>
</table>

- Same grids, same dynamical core, same physical parameterizations
- Different computers, minor differences in implementation

- Exercise of opportunity – models are similar but not identical. Not ideal!
- Data Denial Experiment for 30-40 days at end of field program

New data assimilation:
- Radar wind profilers: 27 August 2011
- RASS and sodars: 23 December 2011
- Towers and nacelles: 14 March 2012
Impact of data on models:
Vertically averaged radar wind profiler vector wind RMSE, w/wo WFIP data, RR and RUC models
Model evaluation using tall tower observations

RMSE
% Improvement
Vector wind
Preliminary Economic Results—Southern Region

• Analyses performed for “shoulder” month – October 2011 when load is low and wind speeds are higher

• Operational Cost Savings are dependent on natural gas prices – average actual price of 3.44 $/MMBtu used for October in Texas

• Preliminary results show both environmental and cost benefits as a result of improved forecasts

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Benefit (Savings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production Cost ($)</td>
<td>(1,086,000)</td>
</tr>
<tr>
<td>Cost to Serve Load ($)</td>
<td>(5,752,123)</td>
</tr>
<tr>
<td>Conventional Units - Number of Starts</td>
<td>(49)</td>
</tr>
<tr>
<td>Emissions (NOx Tons)</td>
<td>(4)</td>
</tr>
<tr>
<td>Reduction in Wind Generation Curtailment (GWh)</td>
<td>(22)</td>
</tr>
<tr>
<td>~ Energy Imbalance Costs paid by Wind Generators ($)</td>
<td>(1,500,000)</td>
</tr>
</tbody>
</table>
3 hour cloud reflectivity forecasts, valid 19 UTC 06 August 2012

NWS operational RAP model
13km resolution, parameterized convection

ESRL experimental HRRR model
3km resolution, explicit convection
Forecasting

Key Challenges

• Relatively minor changes in wind speed result in large changes in power (ramps)
• Insufficient obs to capture relevant atmospheric scales
• Assimilation of current obs needs to be improved
• Operational models need to be run at storm resolving scales
• Thunderstorm initiation is a major problem
Summary

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• Offshore
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Contributions from

Laura Bianco
Irina Djalalova
Katja Freidrich
Julie Lundquist
Bob Banta
Yelena Pichugina
Stan Benjamin
Spatial and temporal variability of winds

ERCOT:
9.8 GW installed capacity
Max generation:
18 March 2012
7.9GW, 24% load