On the interaction of wind energy with climate and weather

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Thesis committee:
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Wind energy

Climate + weather

Climate
Medici: “Wind turbine wakes – control and vortex shading”, 2004
Vermeer et al.: “Wind turbine wake aerodynamics”, 2003
Calaf et al.: “Large eddy simulation of fully developed wind-turbine array boundary layers”, 2010
Christiansen and Hasager: "Wake effects of large offshore wind farms identified from satellite SAR", 2005
Annual and Cumulative Growth in U.S. Wind Power Capacity

Source: AWEA project database

Nameplate Resource Capacity in 33 Selected Interconnection Queues

Source: Exeter Associates review of interconnection queues

Part I:
Weather response to a large wind turbine array
Model description

Model: Community Atmosphere Model, version 3.0, Eulerian spectral core

Resolution: T42 ~ 2.81°, 26 vertical levels

Ocean component: Climatological sea surface temperatures

Wind farm representation: Heightened surface roughness
Surface roughness estimation via Lettau (1969)

\[ z_o = \frac{1}{2} h^* \frac{s_s}{S_L} \]

\( z_o \) = surface roughness
\( h^* \) = average vertical extent
\( s_s \) = object surface area
\( S_L \) = object footprint

\[ z_o = \frac{1}{2} (100m) \cdot \frac{\pi \cdot (56.3m)^2}{(771m)^2} = 0.837m \]
Surface roughness estimation via Lettau (1969)

Stull: “An introduction to boundary layer meteorology”, 1988
Barrie and Kirk-Davidoff: “Weather response to a large wind turbine array”, 2010
Model experiments

Control run: 6 years, 72 case studies (1 per month) with wind farm

Case studies: Branch run of each case study without wind farm
Barrie and Kirk-Davidoff: “Weather response to a large wind turbine array”, 2010
Ensemble average geopotential height anomaly at 510mb (4.5 days)

Standard deviation across ensemble members is contoured

Barrie and Kirk-Davidoff: “Weather response to a large wind turbine array”, 2010
Part II:
Wind farm parameters: studies with a simplified model
Model description

Model: Weather Research and Forecasting model, Held-Suarez configuration (Newtonian cooling, Rayleigh damping)

Resolution: 2.8125° x 2.5°, 40 vertical levels

Simplifications: No topography or water

Initial condition: Isothermal atmosphere at rest

Wind farm representation: Heightened Rayleigh damping in the lowest model layer
\[ T_{eq} = \max \left\{ 200, \left[ 315 - (\Delta T) \sin^2 \phi - (\Delta \theta) \log \left( \frac{p}{p_o} \right) \cos^2 \phi \left( \frac{p}{p_o} \right)^k \right] \right\} \]
Model experiments

Five wind farm parameters were altered:
  Size
  Position
  Magnitude of damping
  Atmospheric static stability
  Jet stream strength

Model spin-up : >200 days

Model runs : 14 days for each parameter value initialized with identical initial conditions

Static stability/jet ensembles : 7 member ensemble, each member initialized with initial conditions separated by 40 days
Size – streamwise
Size – streamwise
Position – streamwise
Position – streamwise
Damping
Damping

$z_0$ vs. damping coefficient

avg. and std. dev. from Calaf et al. (2010) shown

$z_0$ (m)

Damping coefficient (times normal)
Static stability experiment

Static stability (vertical temperature gradient) controlled by term 2 in the equilibrium temperature profile equation:

\[ T_{eq} = \max \left\{ 200, \left[ 315 - (\Delta T)_y \sin^2 \phi - (\Delta \theta)_z \log \left( \frac{p}{p_o} \right) \cos^2 \phi \right] \left( \frac{p}{p_o} \right)^k \right\} \]

Term 2: Release of latent heat in convective processes

Manipulate \((\Delta \theta)_z\) to control static stability
- Default value = 10
- Large values = increased static stability

Side effect: Jet strength altered
Static stability experiment (continued)

Procedure to conserve jet strength:

Derive geostrophic wind field from equilibrium temperature profile using thermal wind:

\[
V_r = \frac{R}{f} \ln \left( \frac{p_1}{p_2} \right) \times \nabla T
\]

For a given value of \((\Delta \theta)_z\), find corresponding value of \((\Delta T)_y\) that preserves jet strength, using iterative process

<table>
<thead>
<tr>
<th>Test</th>
<th>((\Delta \theta)_z)</th>
<th>((\Delta T)_y)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>62.88</td>
<td>Decreased stability</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>60</td>
<td>Default stability</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>53.84</td>
<td>Increased Stability</td>
</tr>
</tbody>
</table>
Static stability
Static stability
Static stability
Jet experiment

Jet strength controlled by term 1 in the equilibrium temperature profile equation:

\[ T_{eq} = \max \left\{ 200, \left[ 315 - (\Delta T)_y \sin^2 \phi - (\Delta \theta)_z \log \left( \frac{P}{P_o} \right) \cos^2 \phi \right] \left( \frac{P}{P_o} \right)^k \right\} \]

Term 1: Meridional temperature gradient

Manipulate \((\Delta T)_y\) to control jet
- Default value = 60
- Large values = increased jet strength
Jet
Part III:
The impact of climate change on the United States wind resource
Data

13 Coupled Model Intercomparison Project, Phase 3 model datasets

SRES A2 emissions pathway: higher than average emissions growth, lower than recent actual emissions

10 m daily zonal and meridional wind speed fields

Intermodel resolution range: 45x72 to 160x320

Time periods analyzed: 1990-2000, 2050-2060, 2090-2100
Models showing a 1990-2050 wind speed increase

1990-2090

# of models
CMIP3

1990-2050 multimodel wind speed anomaly

AVERAGE

1990-2090 multimodel wind speed anomaly

AVERAGE

STANDARD DEVIATION

STANDARD DEVIATION
Wind power

Power is proportional to speed cubed:

\[ P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot c_B \cdot c_g \]

Total speed:

\[ V = \left[ \sqrt{(u)^2 + (v)^2} \right] \]

Stationary component of speed:

\[ V_s = \left[ \sqrt{\left( \frac{u}{v} \right)^2 + (v)^2} \right] \]

Transient component of speed:

\[ V_t = V - V_s \]
CMIP3

1990s – 2050s total power anomaly
CMIP3

1990s – 2050s transient power anomaly
CMIP3

1990s – 2050s stationary power anomaly
Data

3 North American Regional Climate Change Assessment Program model datasets

SRES A2 emissions pathway

10 m 3-hour zonal and meridional wind speed fields

Model resolution : 50 km

Time periods analyzed : 1990-2000, 2040-2050, 2060-2070

Validation of 1990-2000 against North American Regional Reanalysis data
NARCCAP
Conclusions

• Atmospheric perturbations generated by central United States wind farm grow over North Atlantic

• Wind farm impacts could rival forecast uncertainty in magnitude; impacts may be forecastable

• Downstream impacts increase as wind farm size increases

• Increased static stability suppresses near-farm impacts, encourages remote impacts

• Stronger jet increases downstream range of impacts
Conclusions (continued)

- Climate change due to anthropogenic global warming is projected to enhance central United States wind power resource

- High variability in the intermodel projections
Future work

• Apply fundamental modeling conclusions to detailed weather impacts studies

• Formulate a dynamical framework that describes the transient atmospheric response to the wind farm

• Study CMIP3 and NARCCAP wind speed frequency distributions in greater detail

• Continued study of the NARCCAP data set, which is in nascent stages.
Thank you