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Understanding Mesoscale Influences on Offshore Wind Energy Production:

Case Studies in Ramp Prediction and Resource Assessment

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Center for Ocean Observing Leadership
Department of Marine and Coastal Sciences
School of Environmental and Biological Sciences

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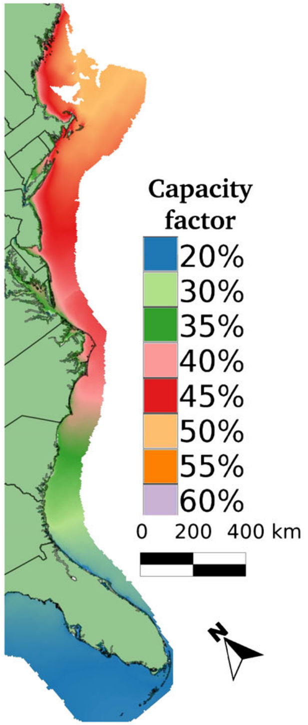
Outline

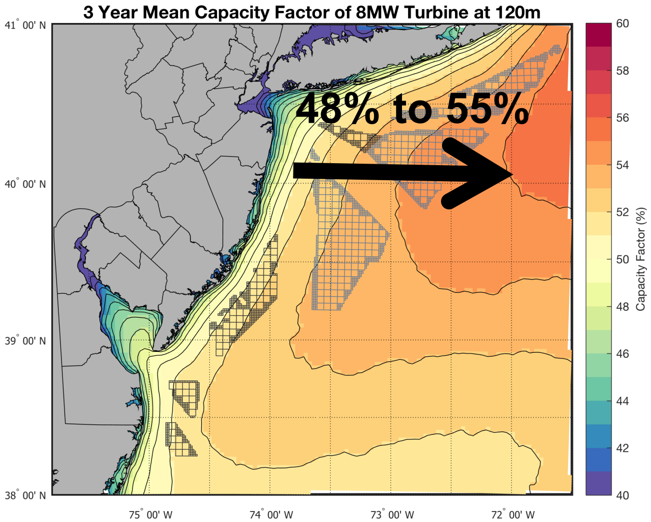
- Introduction
- Wind Farm Layouts and Climatology
- Short-Term Wind Forecasting (Ramp Events)
- Mesoscale Modeling as a Resource Assessment Tool
- What's Next?

Offshore Wind Power

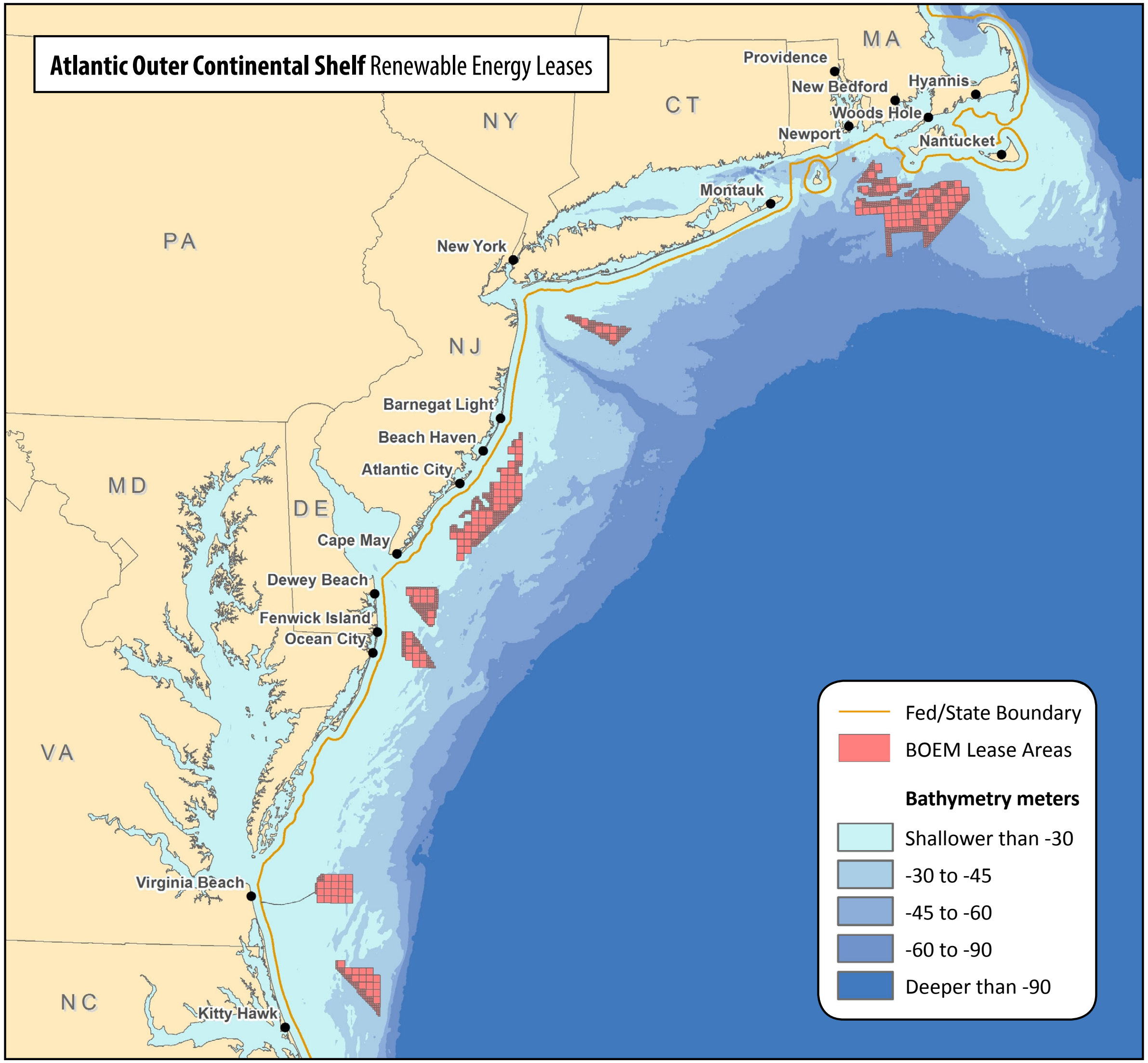
- Various studies have indicated that the eastern United States has a tremendous offshore wind resource, located near a very populated area
- Offshore wind is still in its early stages
  - Only one operating farm in US so far (Block Island Wind Farm, seen here)
- Dynamics of the offshore environment are dramatically different than those onshore



Dvorak et al. 2012



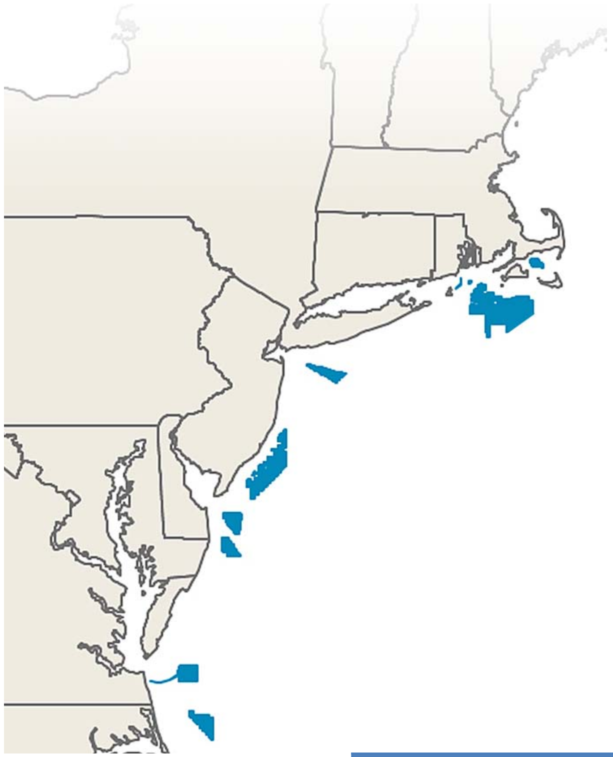
Active Federal Wind Energy Leases



Lease		Year
CVOW	Dominion/Ørsted	2020
Vineyard Wind		2021
South Fork	Deepwater	2022
Ocean Wind	Ørsted	2022
Bay State Wind	Ørsted	2022
US Wind MD		2022
Revolution Wind	Deepwater	2023
Skipjack/GSOE	Deepwater	2023
Dominion		2025
US Wind NJ		2026
Empire Wind	Equinor	2027
Kitty Hawk	Avangrid	2027

Source: BOEM May 2018

State Commitments



State	OSW Goal (MW)	Renewable Goal
Massachusetts	1,600	25% by 2030
Rhode Island	400	38.5% by 2025
Connecticut	250	20% by 2020
New York	2,400	50% by 2030
New Jersey	**3,500**	**50% by 2030**
Maryland	368	25% by 2020
Total	**8,518**	

Source: BOEM Aug 2018

New Jersey Solicitations	Year
1,100 MW	2018 (now!)
1,200 MW	2020
1,200 MW	2022

Challenges: Wind Turbine Wakes

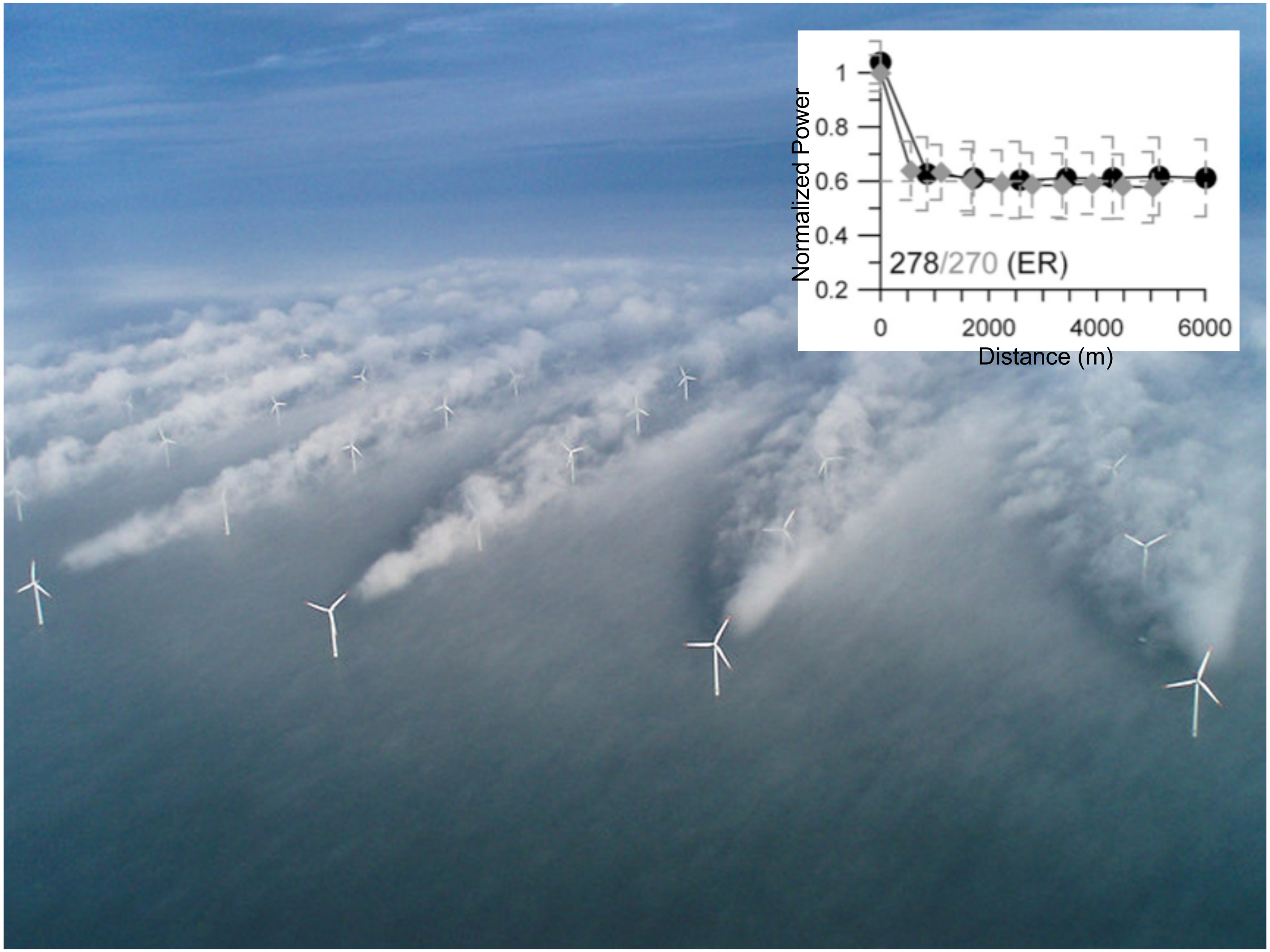
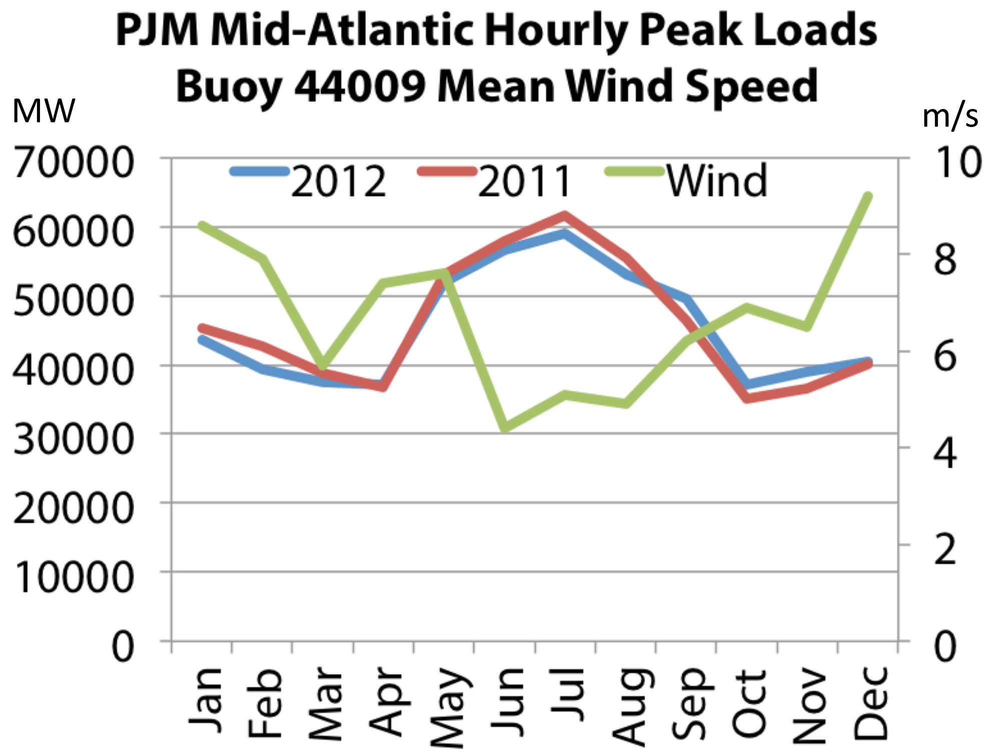


Image: Vattenfall

Barthelmie et al. 2010

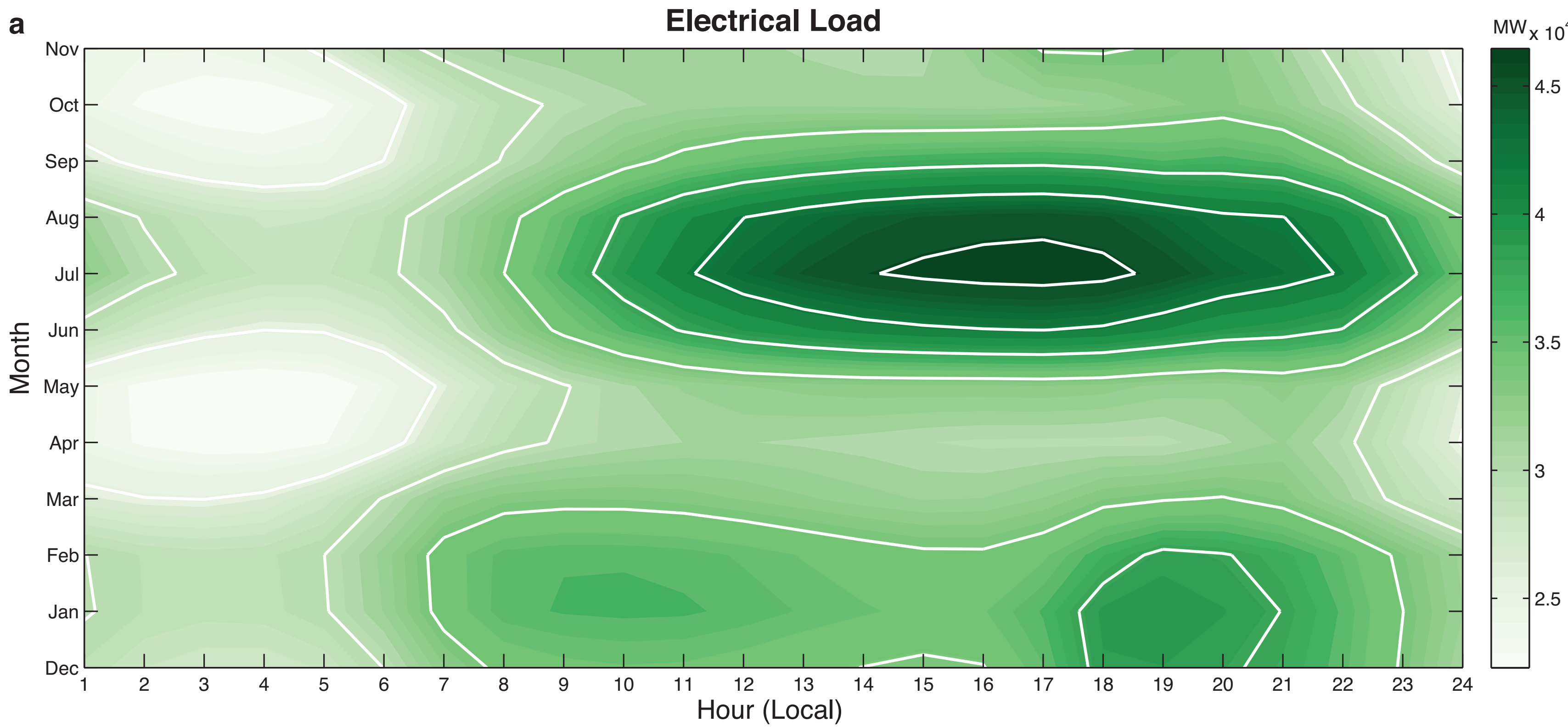
Challenges: Seasonal Load and Wind

- Summer peak in power consumption does not correspond with winter peak in wind power production
- Do we optimize regional farm layouts to give maximum annual power?
- Or is a winter baseline sufficient, seeking to maximize summer production?
- How do various weather phenomena (i.e. sea breezes, storms, ramp events) impact this?



Sources: PJM 2013, Dhanju et al. 2008

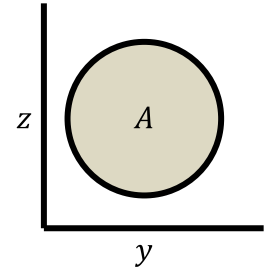
Two Cycles in Electricity Demand



Veron et al. 2018
Source: PJM Load 2005-2011

Weather Research and Forecasting

- WRF is already in widespread use for weather forecasting and research uses
- v. 3.3+ includes a wind farm parameterization (Fitch et al. 2012)
  - Rotor disk extracts KE from atmosphere
  - Some KE converted to electrical energy
  - Remainder dissipated as drag in form of TKE



- Extracted KE results in a change in wind

$$\frac{\partial |\mathbf{V}|_{ijk}}{\partial t} = -\frac{N_t^{ij} C_T |\mathbf{V}|^2_{ijk} A_{ijk}}{2(z_{k+1} - z_k)}$$

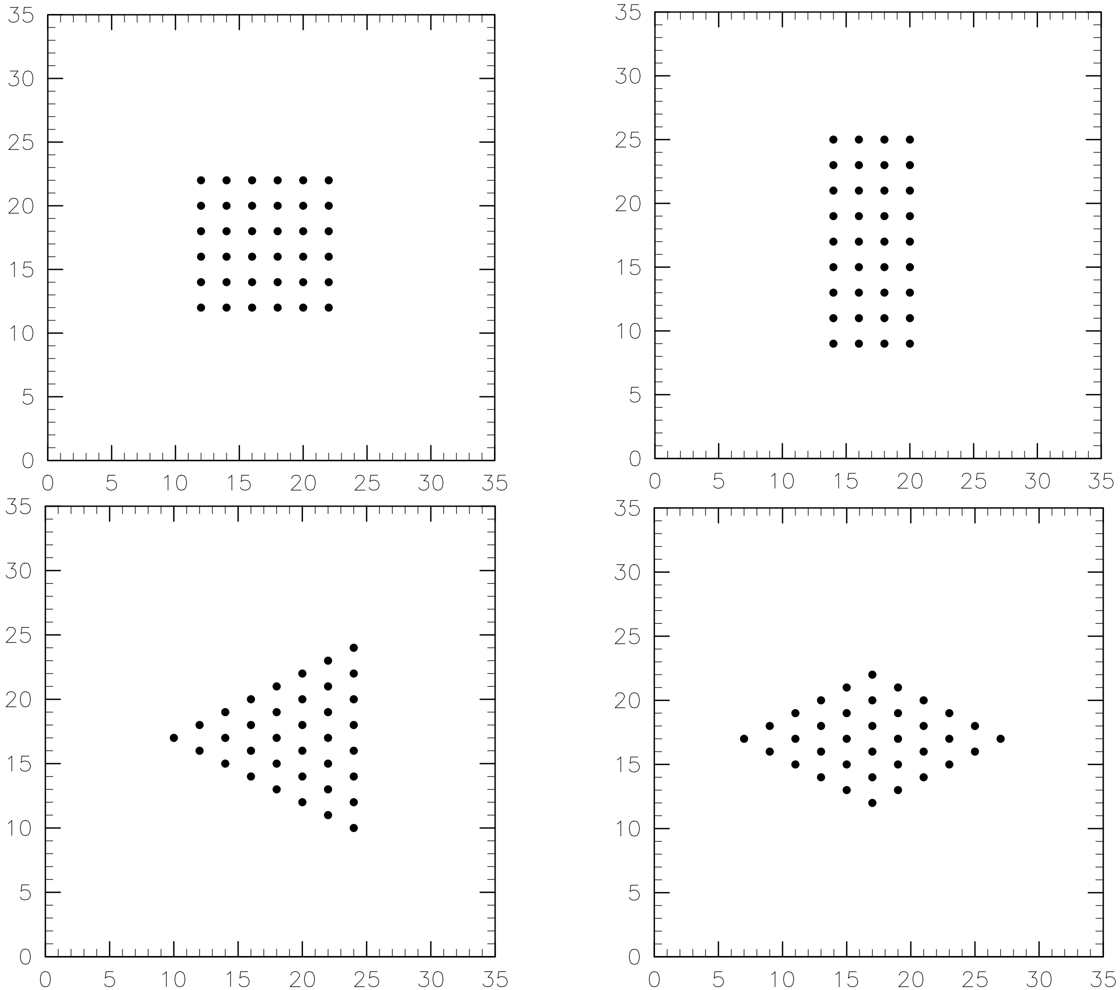
V = Velocity
N_t = Number of turbines
C_T = Thrust coefficient
A = Rotor area
$i, j, k = x, y, z$ grid cell coordinate

The Impacts of Array Losses, Influenced by Climatology

Brodie and Veron 2018 (in final preparation)

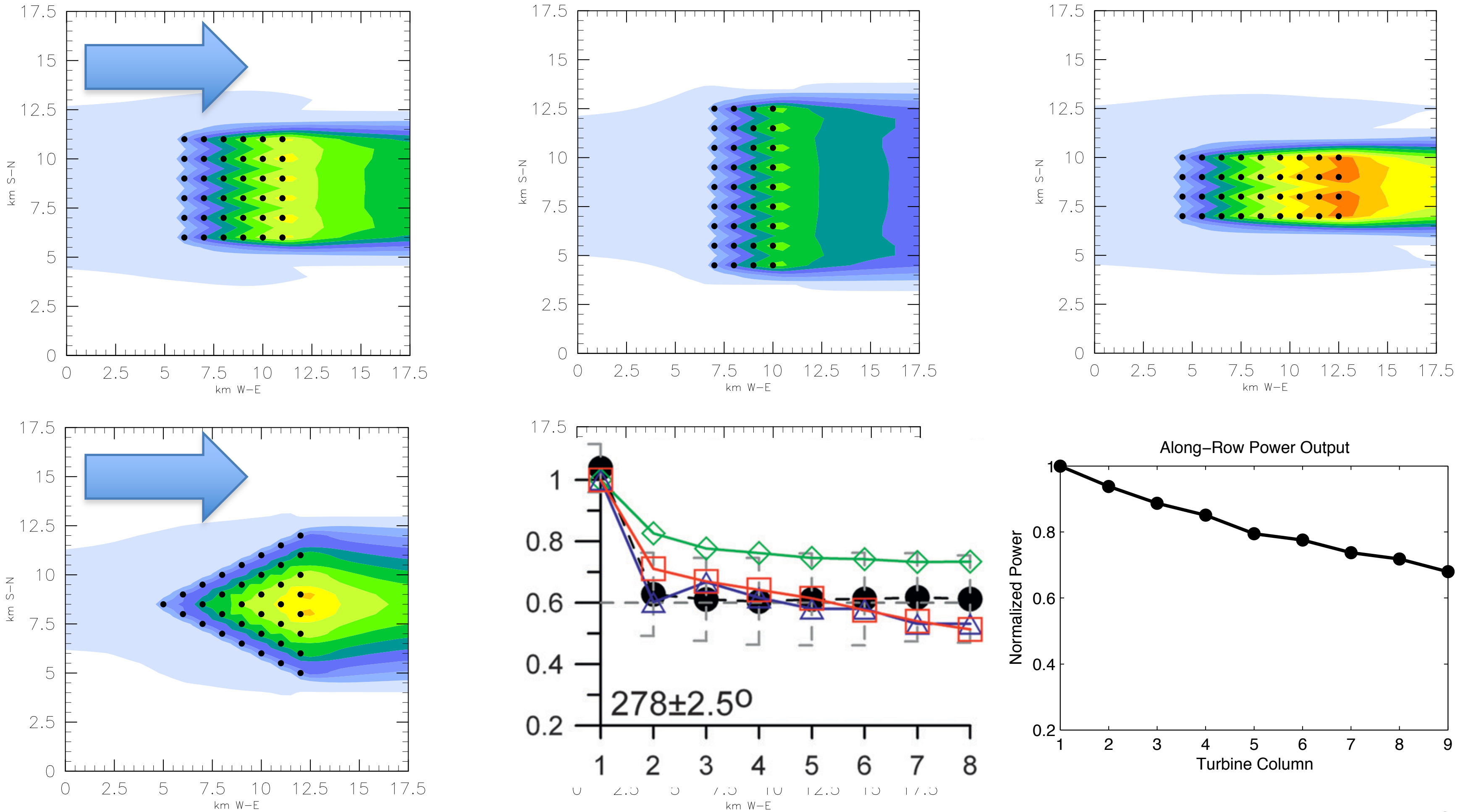
WIND FARM LAYOUTS

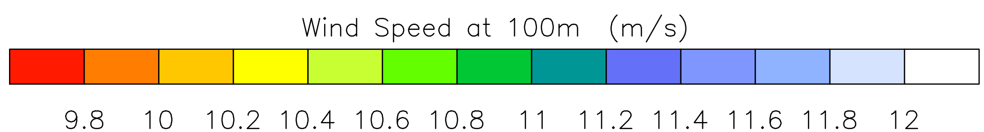
Idealized Wind Farms



- 36 turbines
- 5 MW_c each
- 100 m hub height
- 1 km turbine spacing
- 0.5 km grid spacing
- 13 m/s wind speed
- Neutrally stable atmosphere

Idealized Productivity

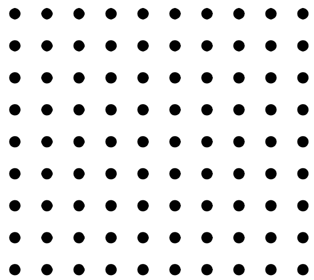




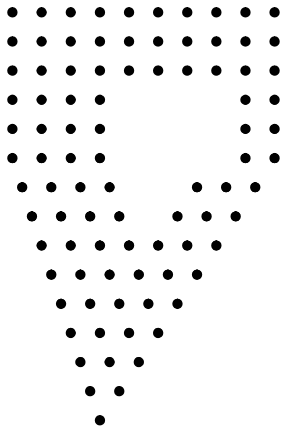
$$P \propto u^3$$

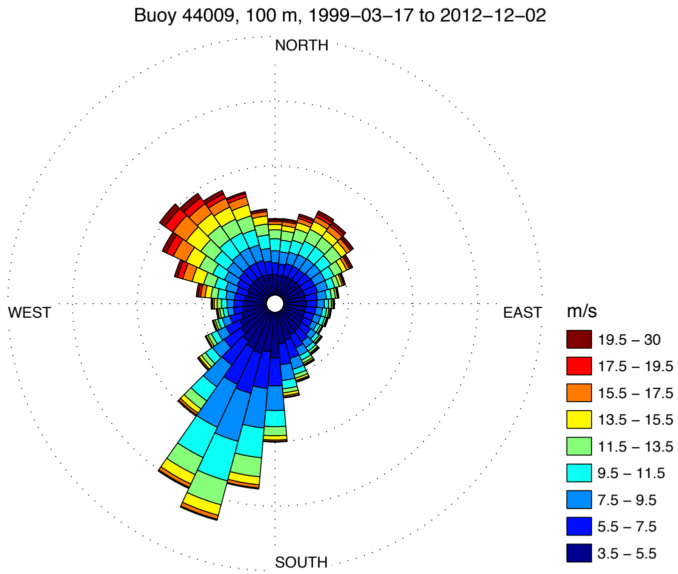
Taking Advantage of Climatology

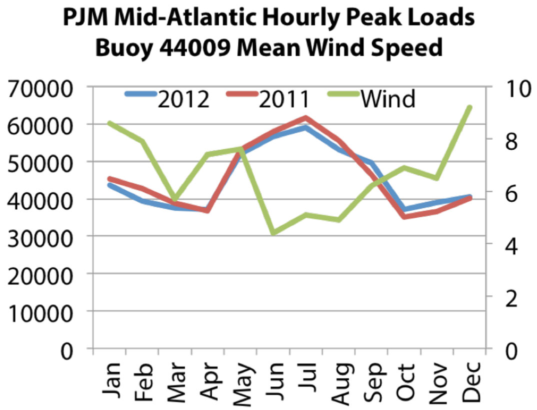
Rectangle



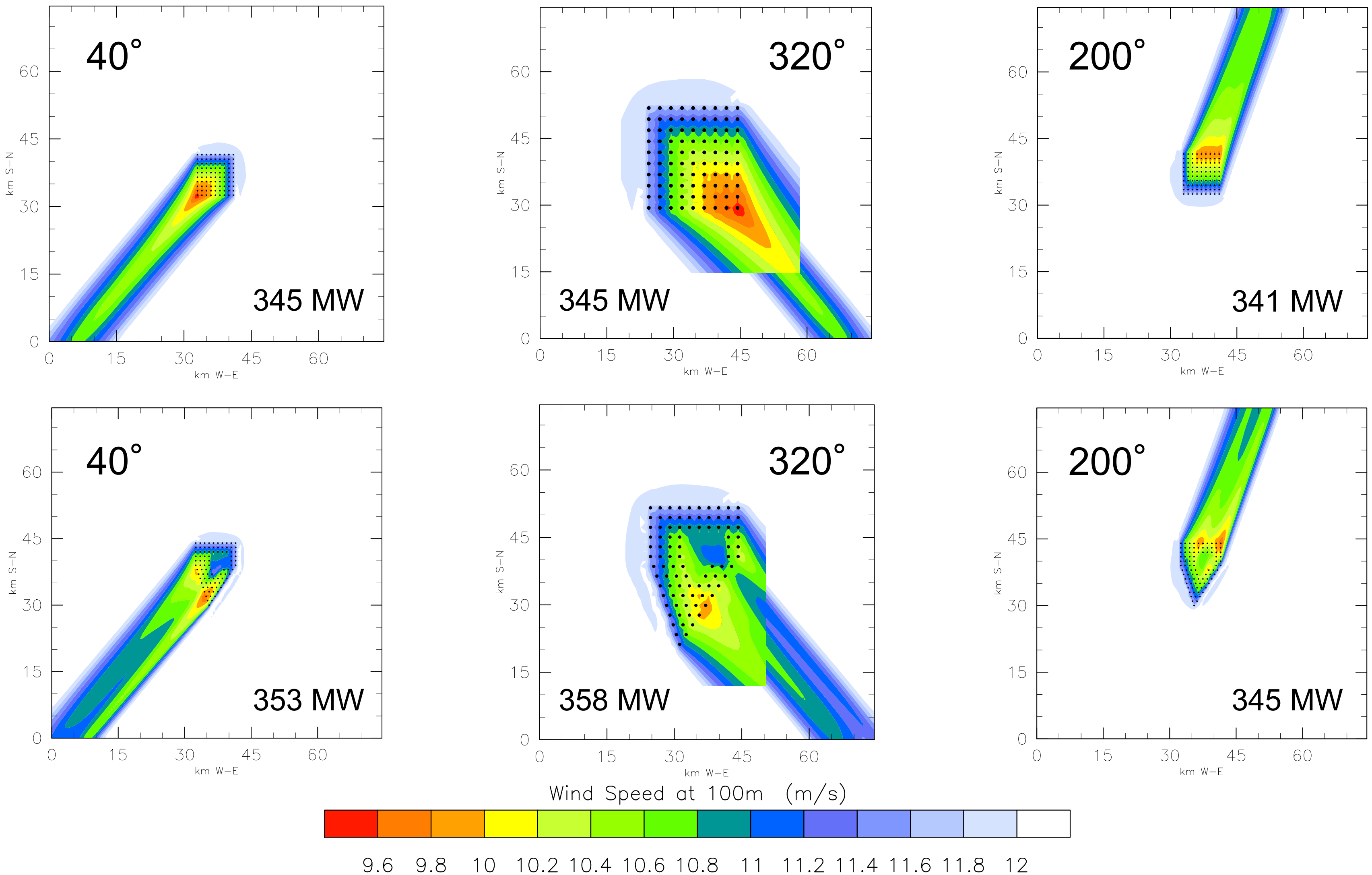
Custom Shape



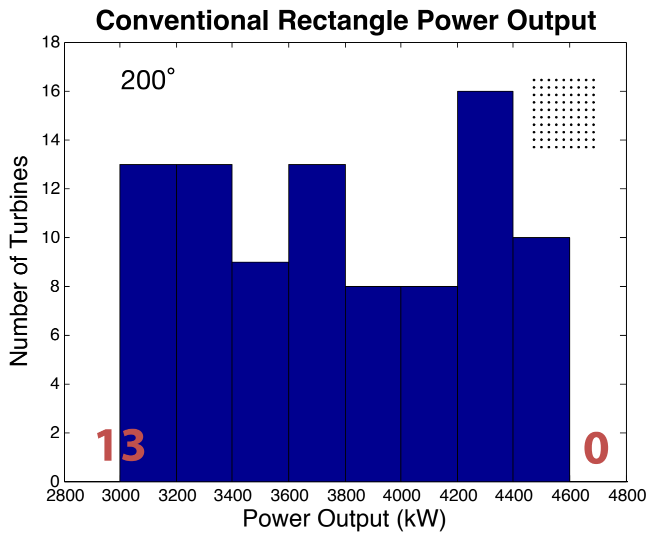


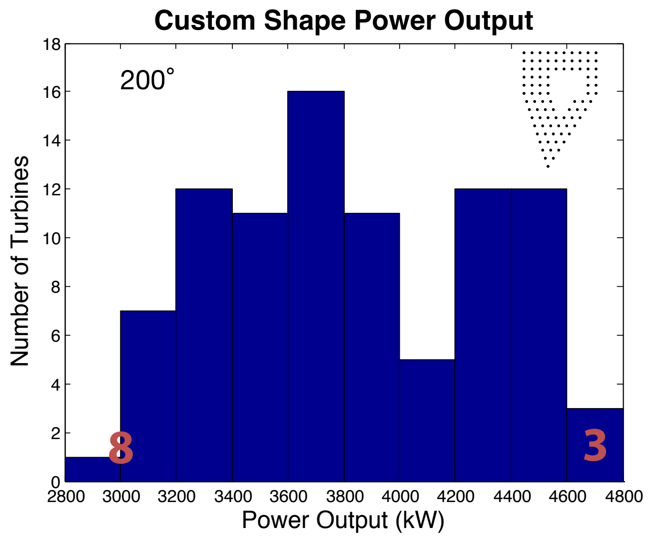


Improved Productivity by Design



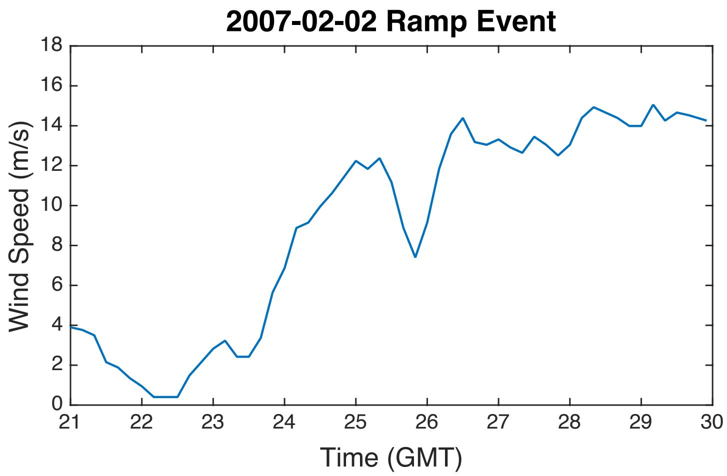
Turbine Output





	Control	Rectangle	Custom
Annual Power (P_{annual}, MWh)	2,141,412	1,630,689	1,666,753
Difference from Rectangle (MWh)	-	-	36,064
Difference from Control (MWh)	-	510,723	474,659
Percent Loss Due to Wakes	0%	23.85%	22.17%

Bottom Line: +$3.8 million annually!



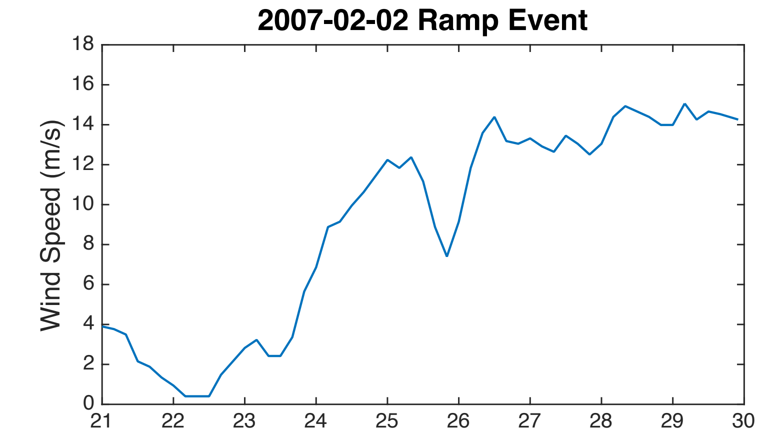
Rapid Wind Changes Influence the Power Grid

Veron, Brodie, Shirazi, & Gilchrist 2018

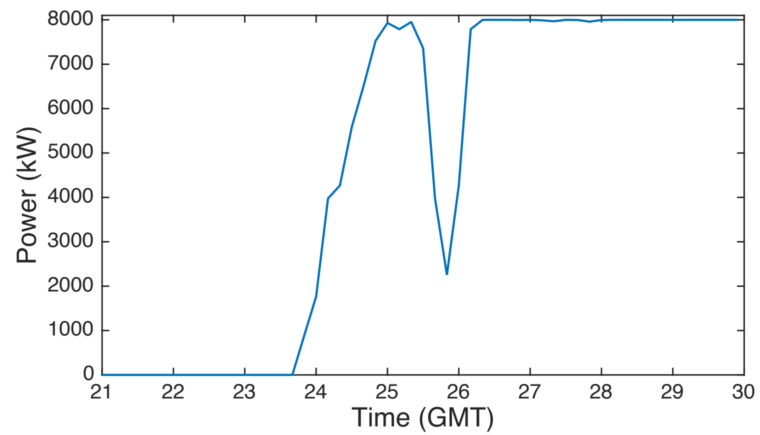
SHORT-TERM WIND FORECASTING

What is a Ramp Event?

- Sudden and rapid change in wind speed
- Results in rapid change to power output
- Tricky to forecast
  - Timing error
  - Intensity error
  - Shape error
- NWP advances have improved forecasting, but not sufficiently for wind industry (i.e. Marquis et al. 2011)

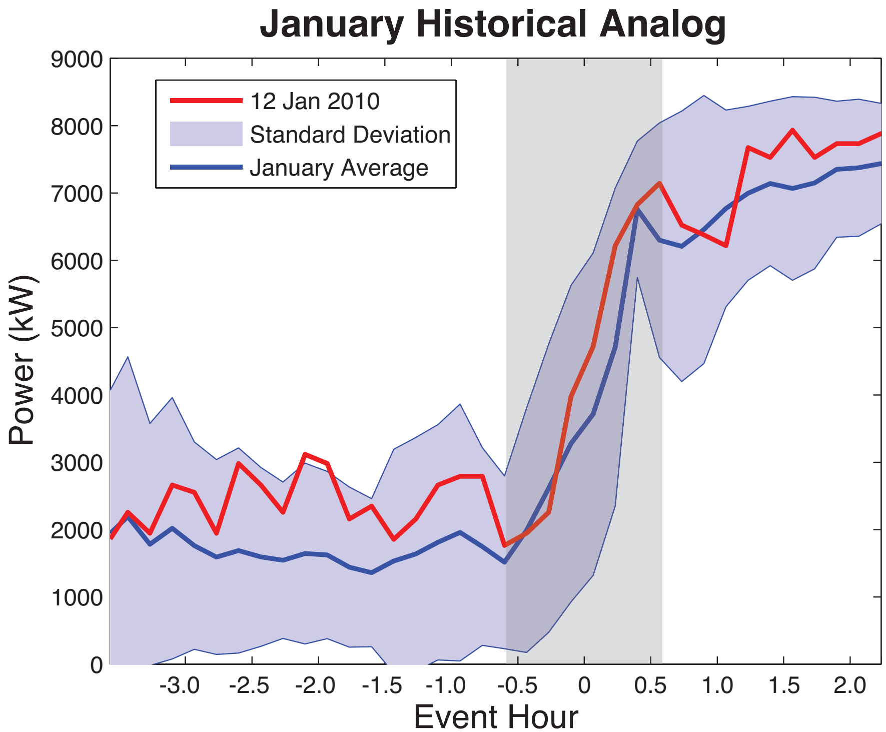


$$P \propto u^3$$



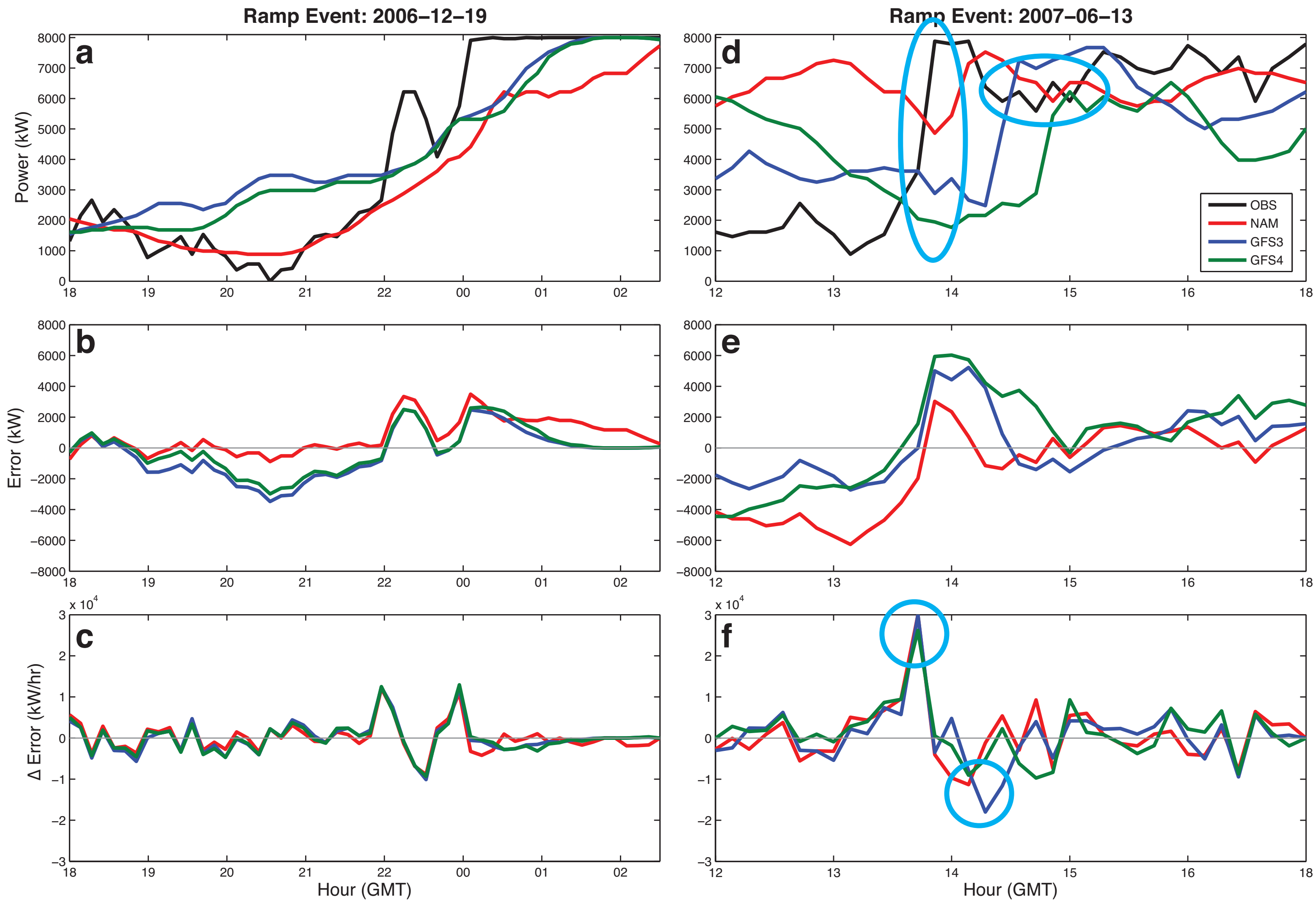
Detecting Ramp Events

- 50% increase in power output in 1 hour or less
- 428 ramp up events between 1 Mar 2005 and 31 Dec 2012
- Selected 12 monthly analogs to represent "average" events
- Selected 12 "extreme" events based on ramp magnitude and potential grid impacts



Veron et al. 2018

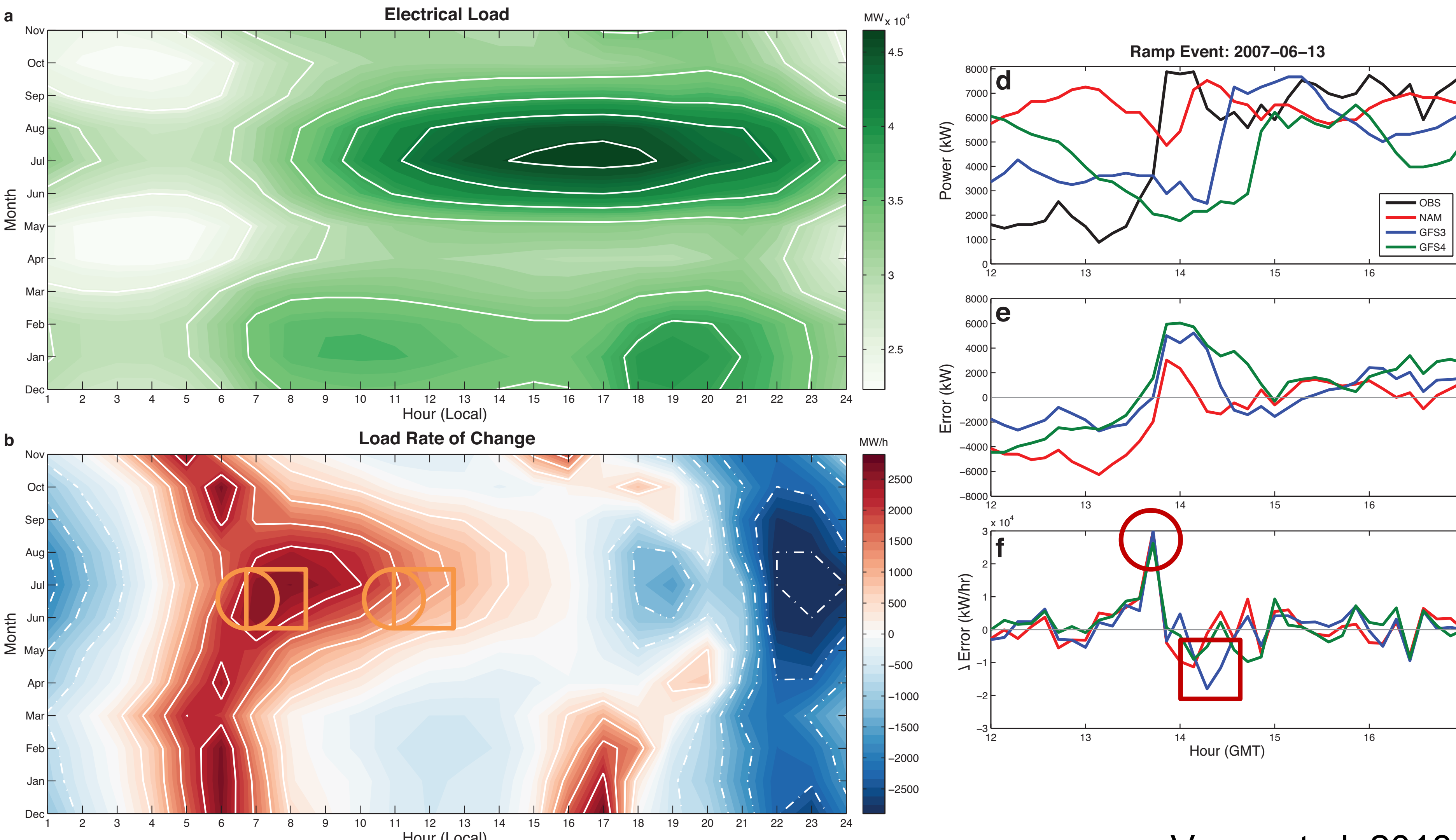
Model Performance is Variable



Overall Model Performance

- Timing Error
  - Model may predict ramp several hours early or late
  - WRF more likely to predict ramps to occur too early
- Intensity Error
  - Modeled wind speed tended to be too high prior to ramp (9 extreme, 5 analog)
  - 2 extreme events, 1 analog event entirely missed
- Shape Error
  - WRF tended to predict ramps to be more gradual
  - Often sustained wind speed too high after the ramp
- Serves to demonstrate the challenge of predicting ramps

It's More Than Just Winds



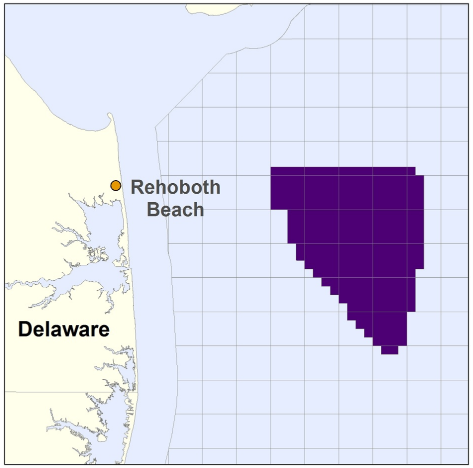
Veron et al. 2018

Ramps Can Have Significant Grid Impacts

- Three types of ramp errors
  1. Large change in forecasting error
  2. Large change in net load
  3. Modest change in forecasting error, high load demand
- Two variants for each
  - (+) : power surplus
  - (–) : power deficit
- (–) events are more challenging

	Type 1^-	Type 1^+	Type 2^-	Type 2^+	Type 3^-	Type 3^+
Analogs	1	3	7	15	5	2
Extremes	6	13	23	17	7	2

Improved model performance in summer morning and winter evening would be most beneficial

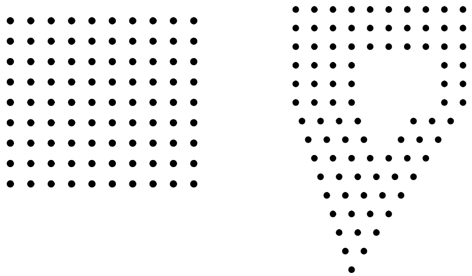


Connecting the Dots to Improve Resource Assessments

MESOSCALE MODELING AS A TOOL

Regional Modeling Design

- Capture variability with limited time and computational resources
- How does power output respond to real weather systems?



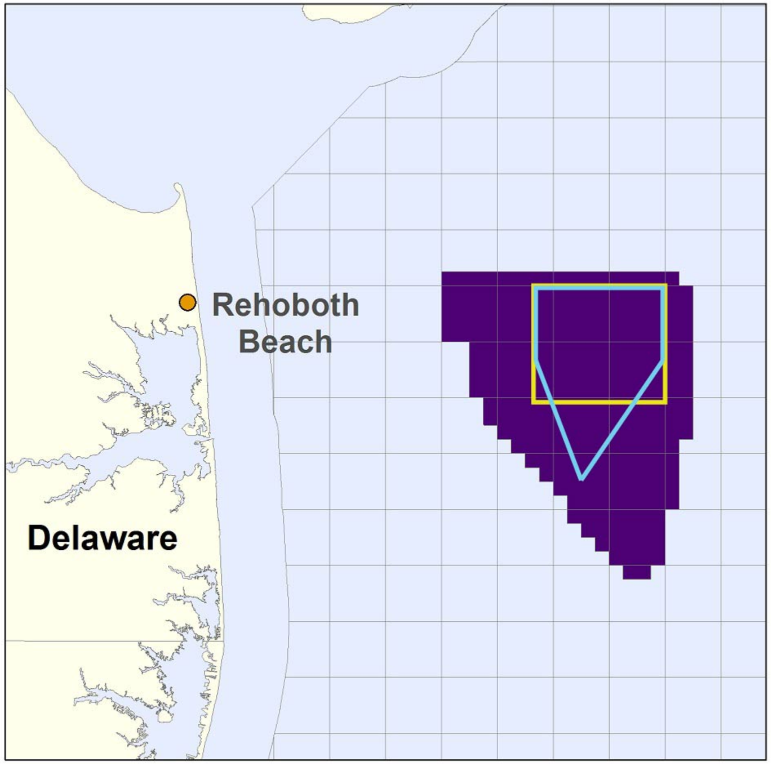


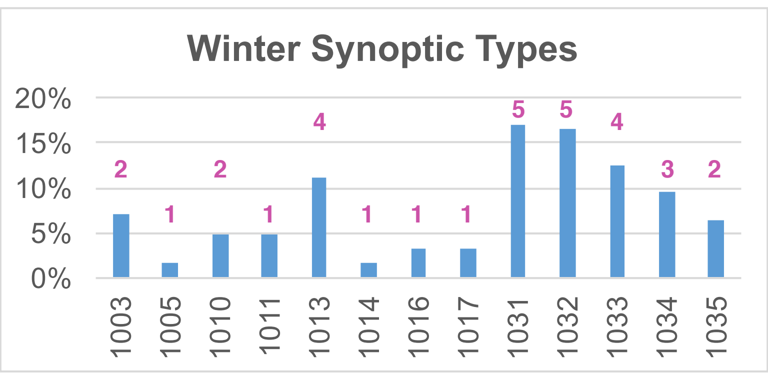
Image adapted from BOEM

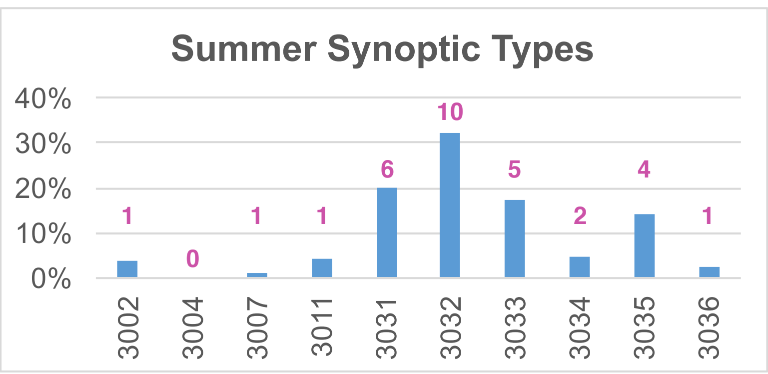
Atmospheric Stability

- Offshore during the day, generally well-mixed and unstable
  - Increased ambient turbulence improves wake recovery
- Offshore during the night, generally stable
  - Can lead to reduced wake recovery, and longer wakes
- Stable conditions often lead to a low-level jet
- LLJ frequently occurs at heights within turbine rotors
- Case-study selection must include:
  - Variety of stability conditions
  - Diurnal cycles

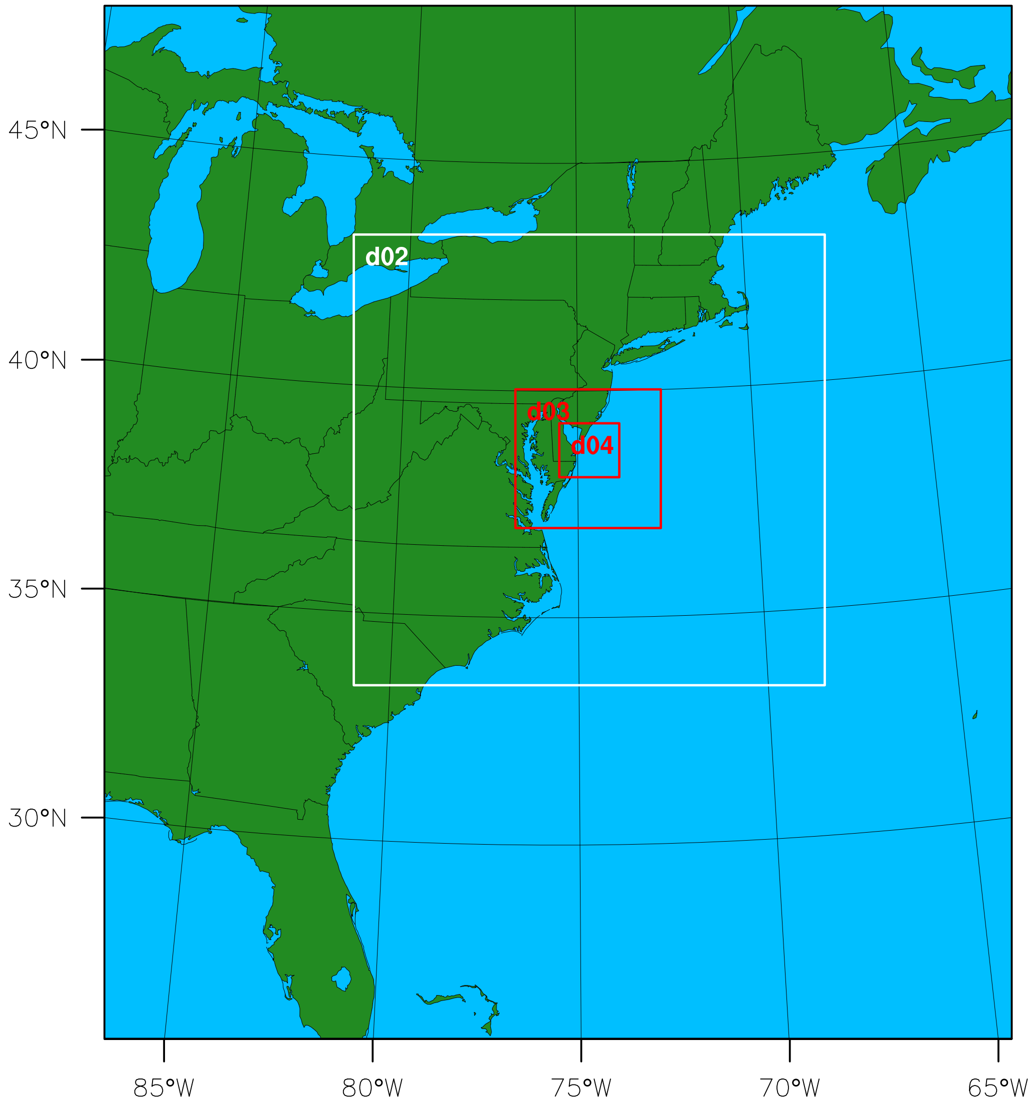
Accounting for Variability

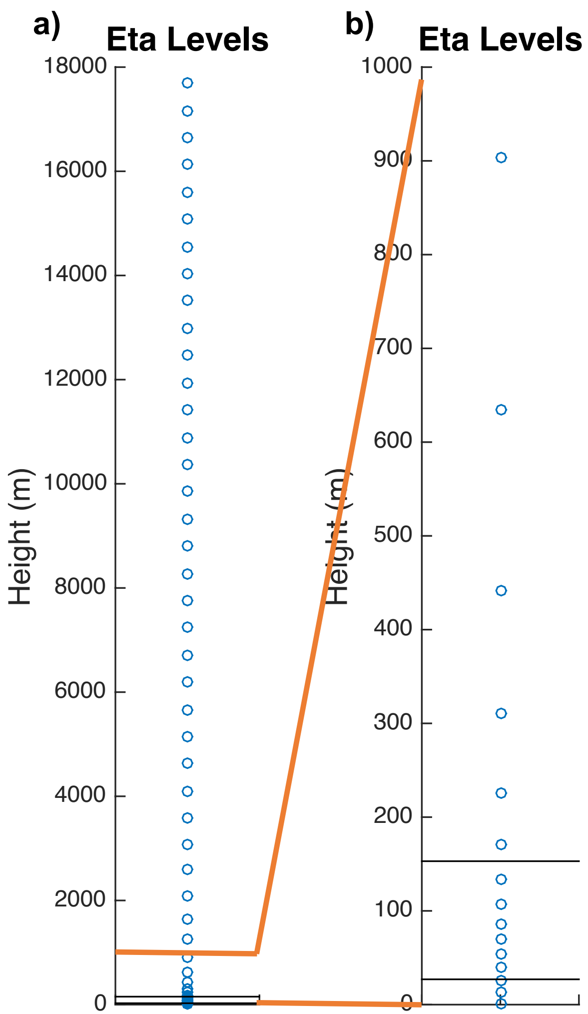
- Synoptic Typing (Suriano and Leathers 2017)
  - PCA using surface weather observations
  - Describes the overarching synoptic weather conditions
  - Used in various other climatological studies (hydroclimatology, lake effect snowfall, ramp events, ozone pollution, coastal storms)
- 13 winter types; 10 summer types



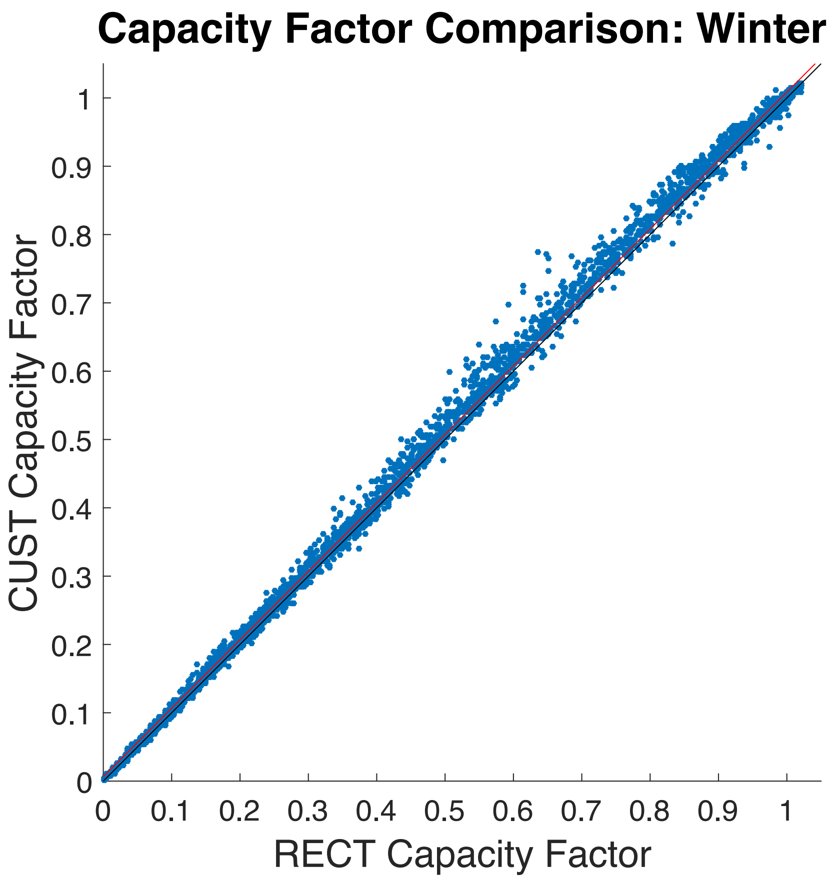


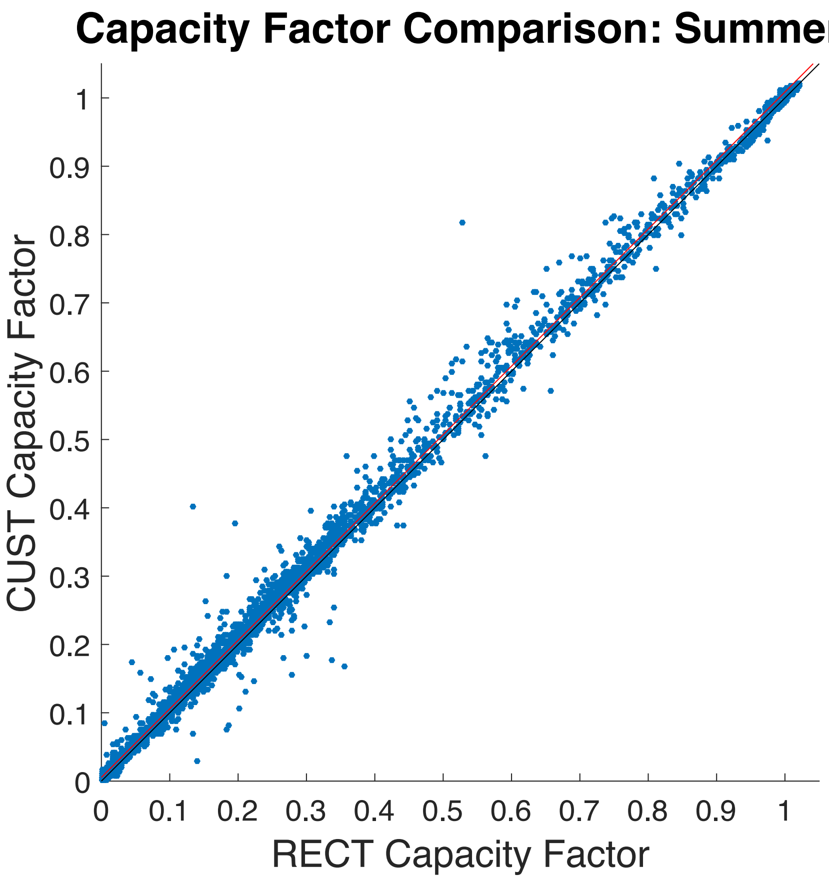
Domains and Vertical Structure



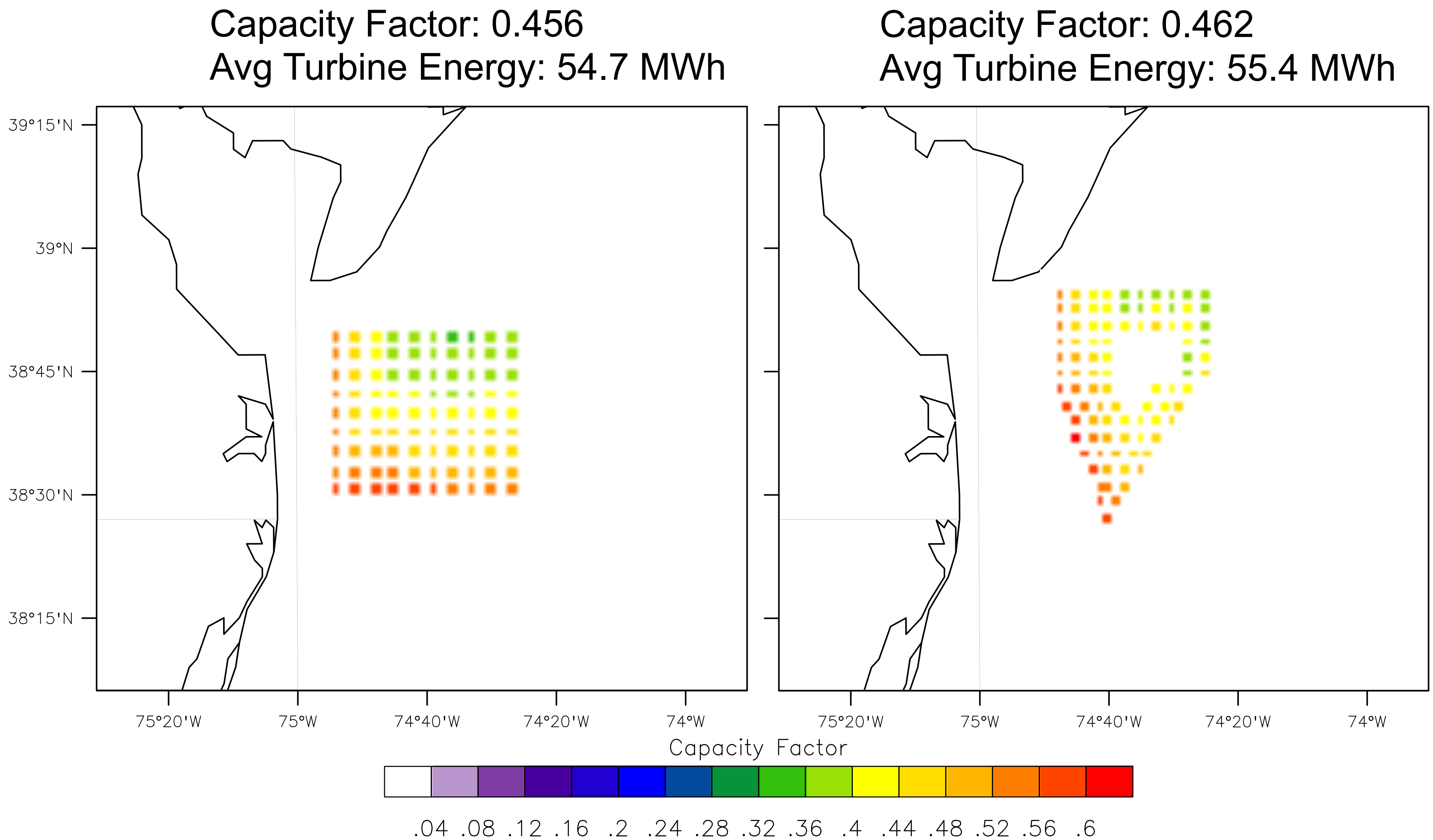


Custom Shape Performs Better

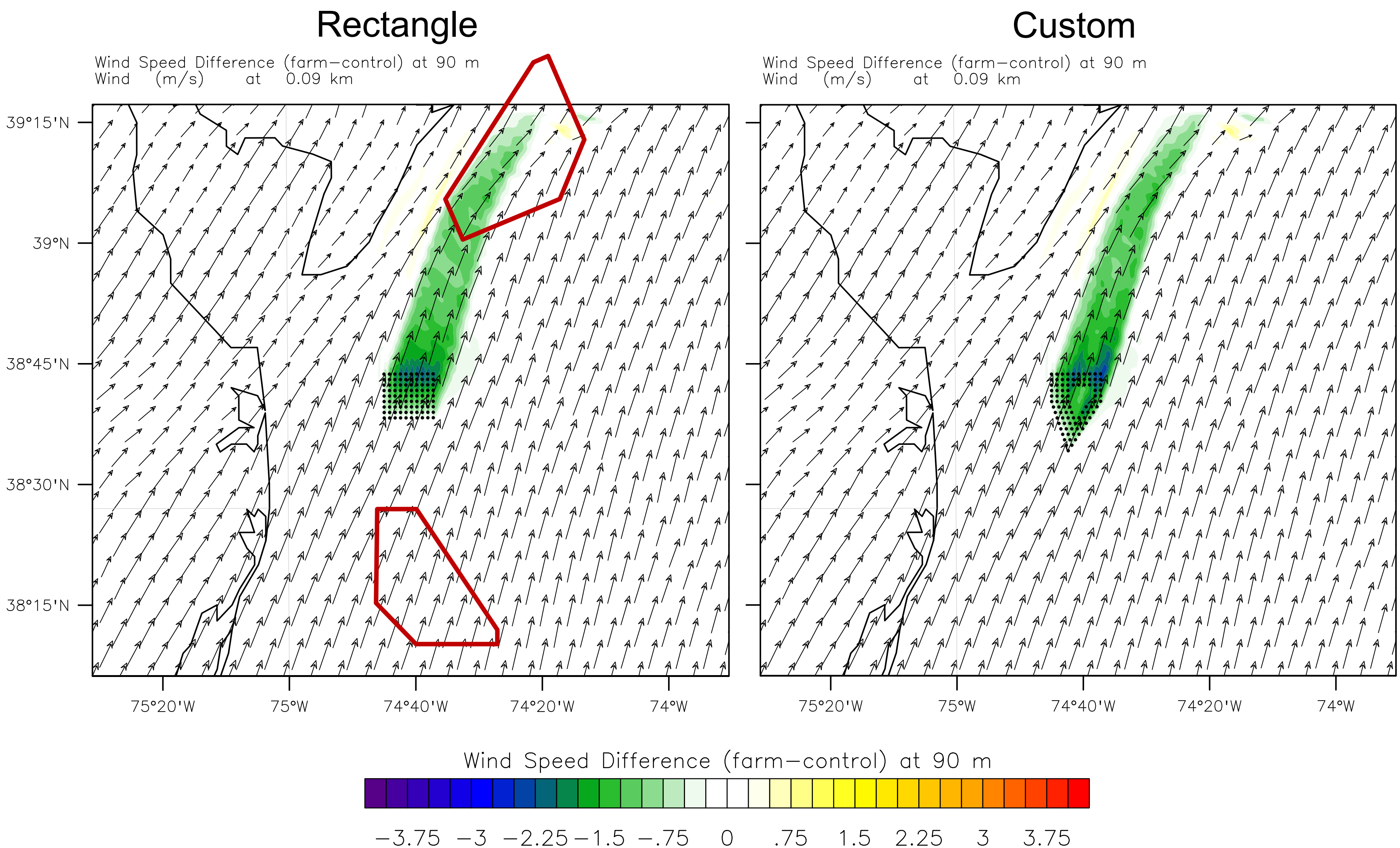




"Productive" Summer Day: 2010-08-17



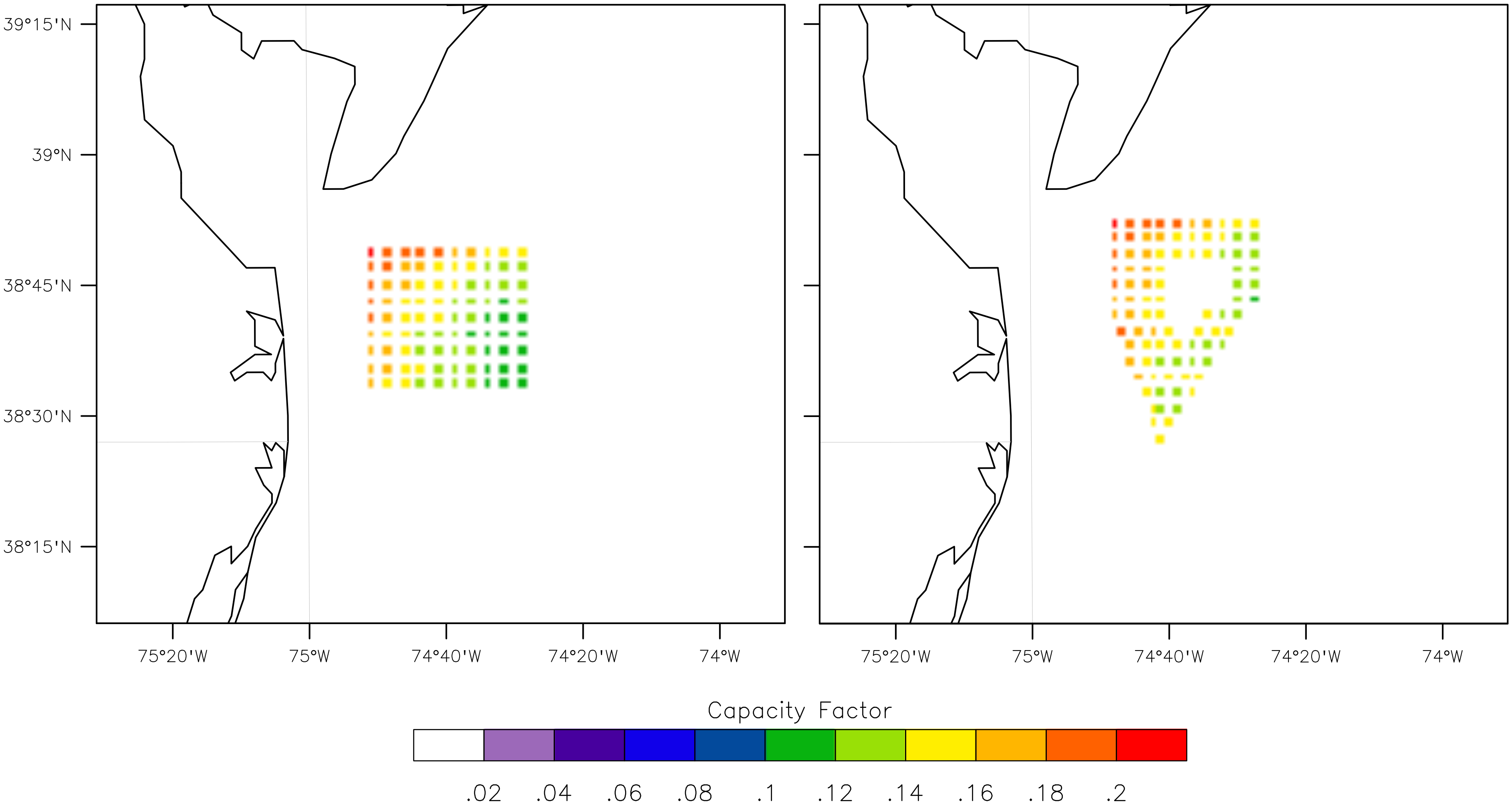
Wake Effects in Action (05GMT)



"Calm" Summer Day: 2008-08-03

Capacity Factor: 0.145
Avg Turbine Energy: 17.4 MWh

Capacity Factor: 0.154
Avg Turbine Energy: 18.5 MWh



How Much Does Layout Matter?

	RECT CF	CUST CF	Add'l Energy	Improvement
Winter	0.5322	0.5399	7132 MWh	1.4%
Summer	0.2491	0.2654	6224 MWh	2.4%

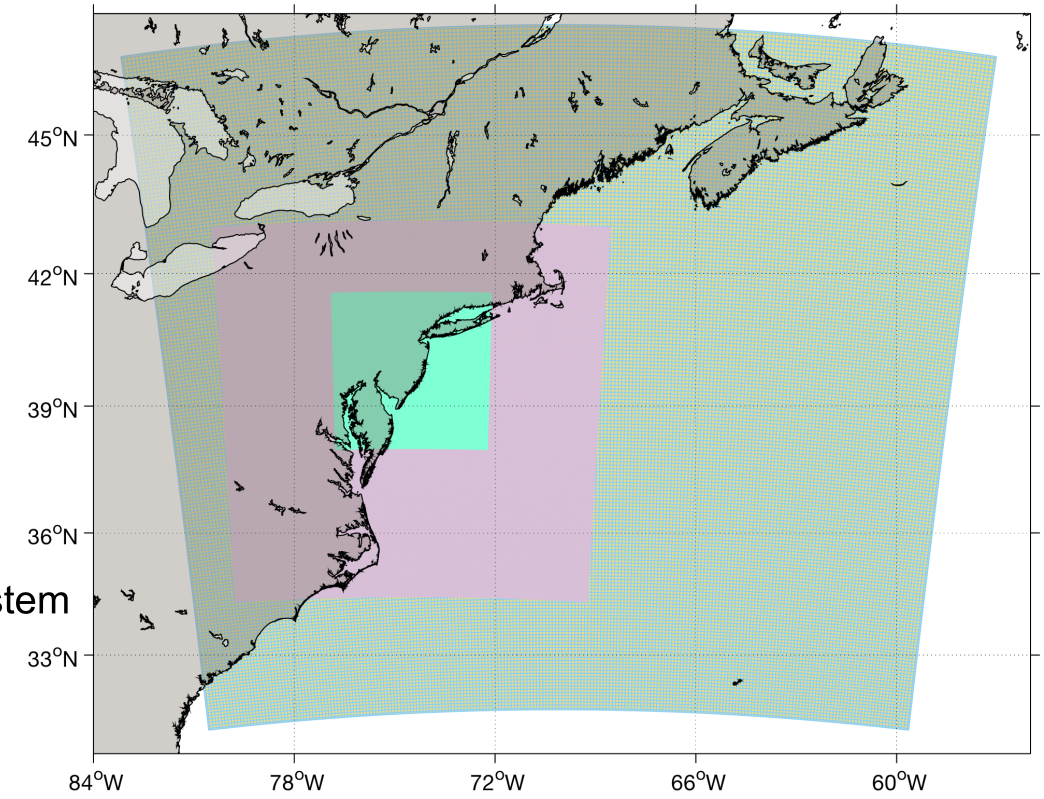
- The additional 13.4 GWh of electricity generated by CUST in these two seasons provide enough power for more than 1200 additional homes
- But, energy production isn't the only factor in deciding wind farm layouts
  - Land (ocean) lease area
  - Cabling and platform costs
  - Geological considerations
- ***Need to evaluate regional interactions***

Real-Time WRF Forecasting as a Wind Energy Resource and Operations Tool

WHAT’S NEXT?

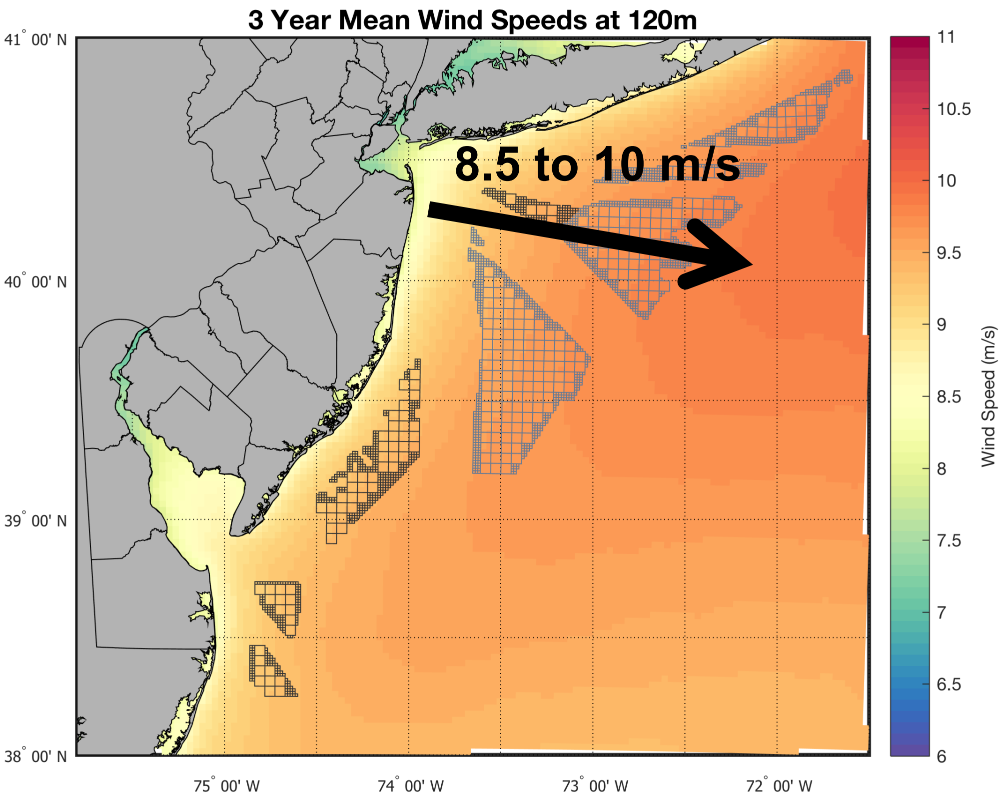
Real-Time Weather Modeling with RU-WRF

- Run Continuously 2011 – Present
- Triple nested: 9km-3km-1km
  - 9km: 0, 6, 12, 18Z cycles
  - 3km: 0, 12Z cycles
  - 1km: 0Z cycle (Research Mode)
- Hourly forecast:
  - 9km: out 5 days
  - 3km: out 2 days
  - 1km: out 1 days
- Lateral Boundary Conditions:
  - 9km: 0.25 degree Global Forecast System
  - 3km: RU-WRF 9km
  - 1km: RU-WRF 3km
- Vertical Levels:
  - 40 levels more tightly packed near the surface.
- Surface Boundary Condition:
  - RUCOOL Coldest Dark Pixel Composite

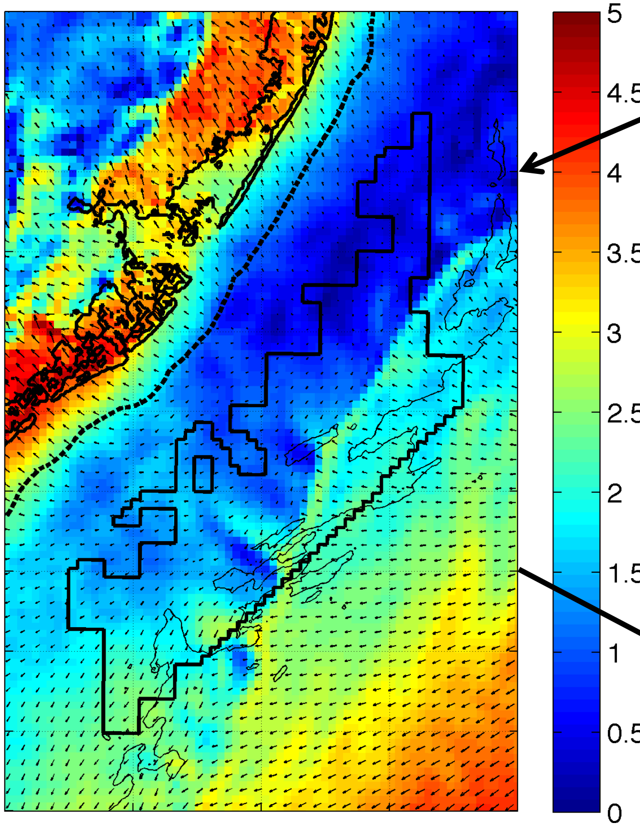


RU-WRF Wind Resource

3 Year Mean



One Hour Sample

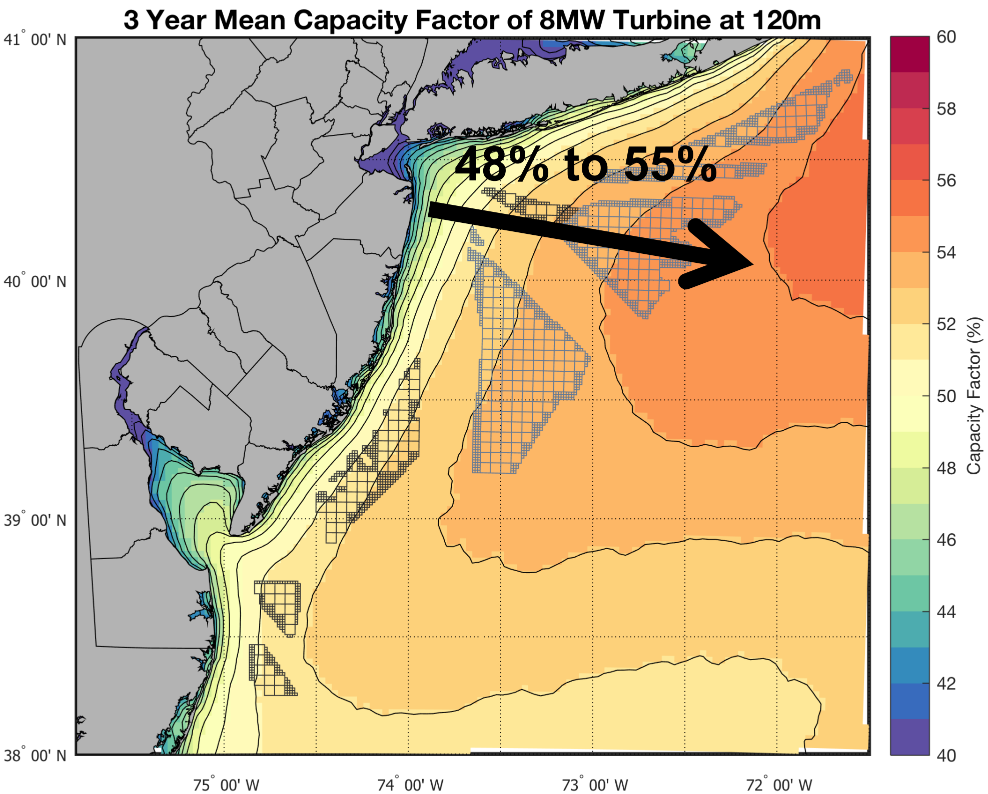


Modeling at 3km grid spacing, 10m height

Hourly winds

RU-WRF Wind Resource

3 Year Mean



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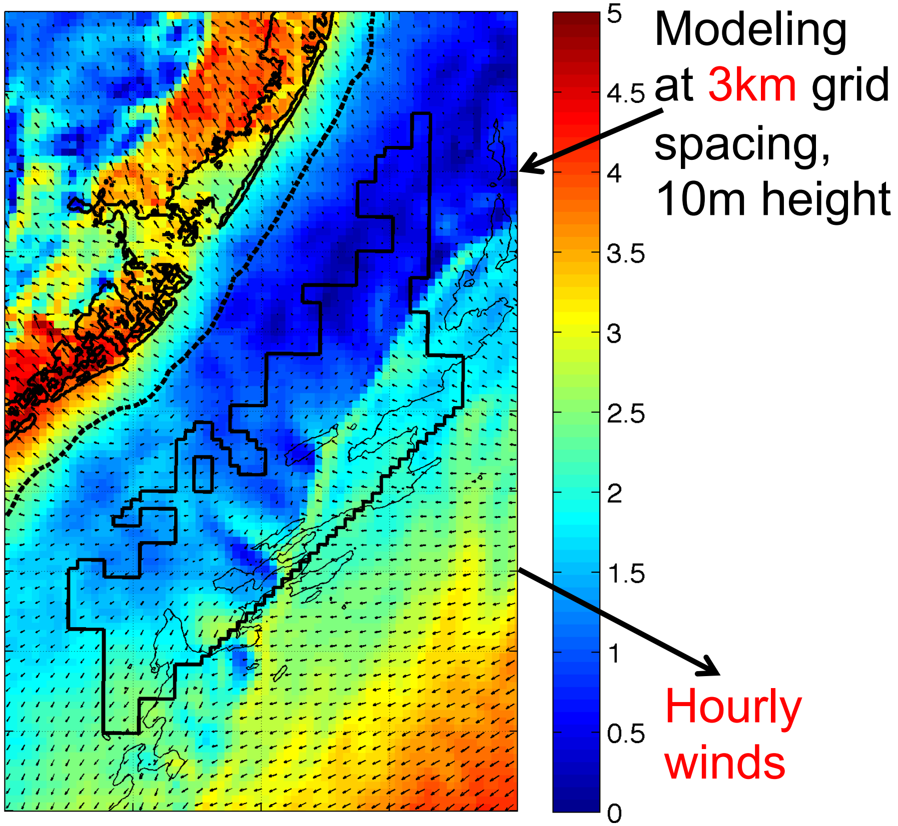
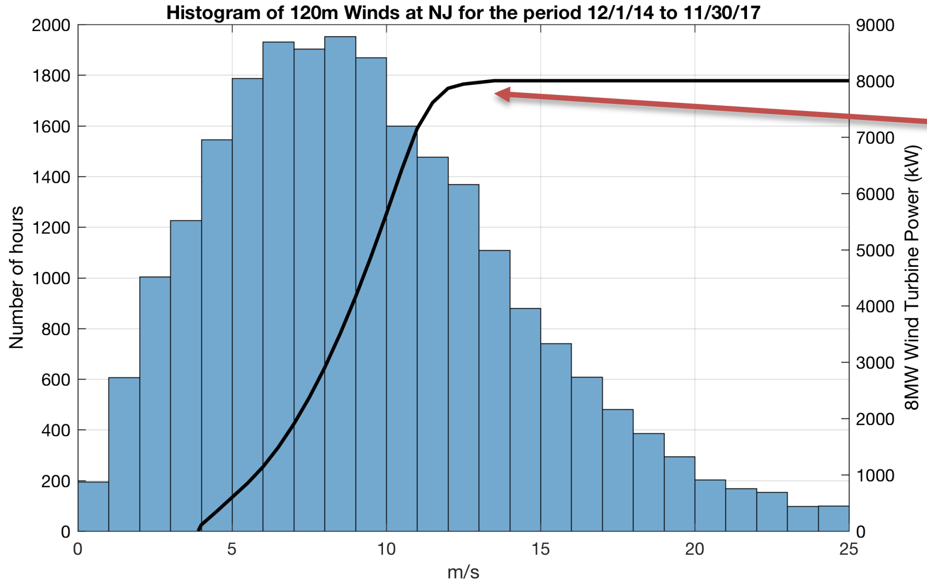


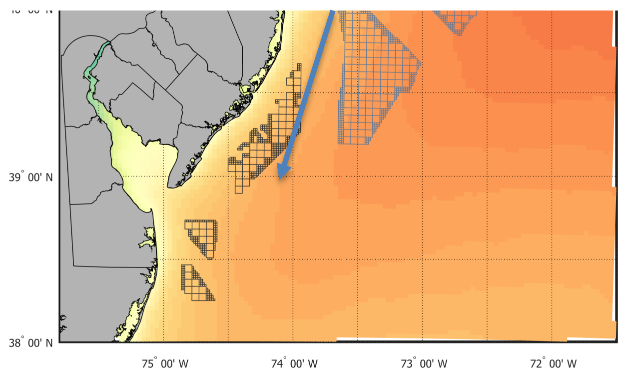
RU-WRF Wind Resource

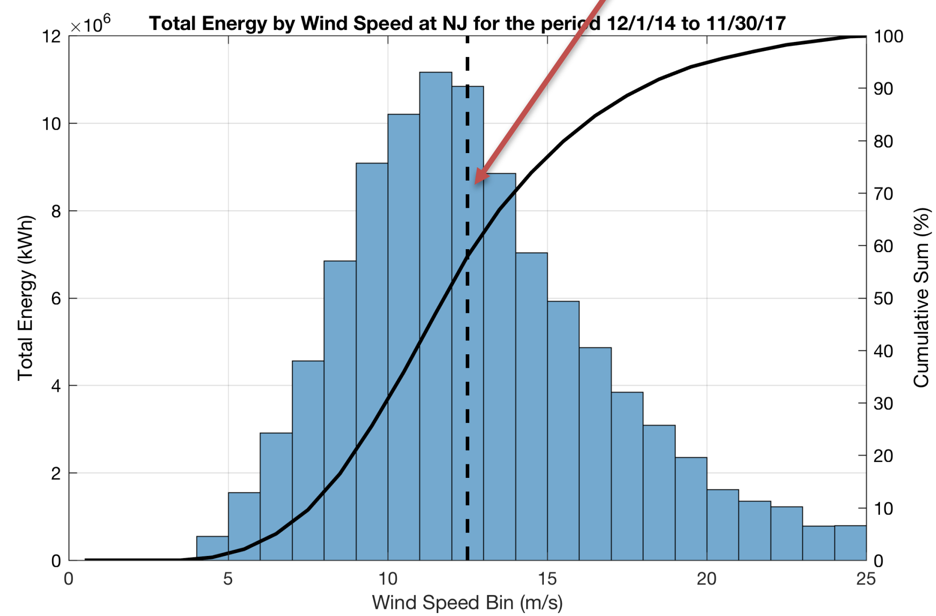


8 MW wind turbine
12.5 m/s rated speed

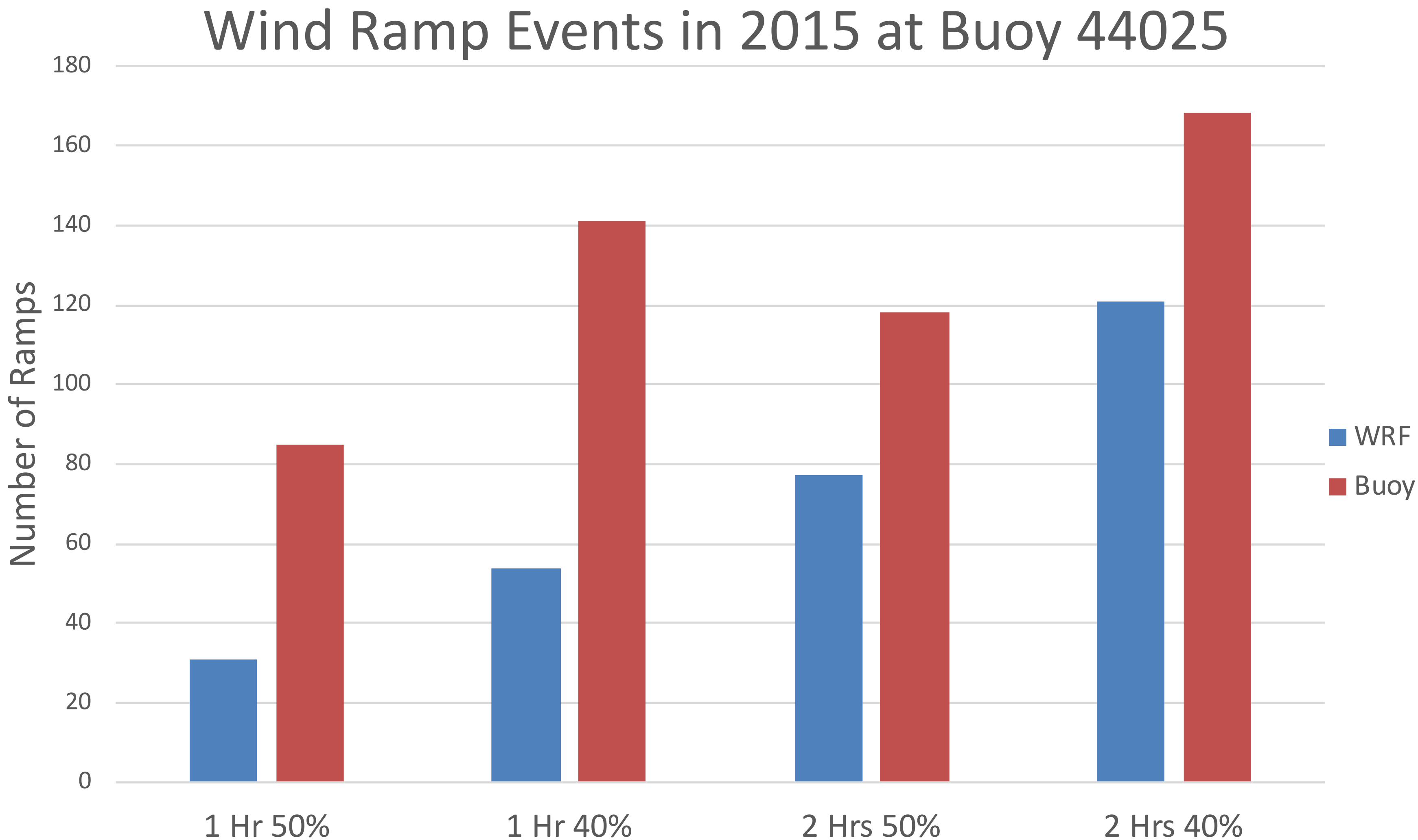
60% of energy extracted
below turbine rated speed

Virtual Met Tower





RU-WRF and Ramp Events



Improving Wind Predictions

- Evaluate the synoptic conditions where the model does well, and where it doesn't
- Other factors: sea surface temperature, ocean heat content/upwelling, waves
- The land is not the ocean! Better observations of the atmospheric boundary layer over the ocean can lead to dramatic improvements in our ability to model it accurately

To Bring it All Together:

- Considering wind climatology is an important factor in wind farm layouts
- Wake effects on a regional scale are important when considering multiple farms, and new lease locations
- Wind ramp events remain an important area of research for wind forecasting improvement
- Mesoscale atmospheric (and better yet, coupled) models are an ideal tool for exploring these issues, and more

Rutgers Energy Institute – Wind Working Group: "Triple-E" Multidisciplinary Expertise

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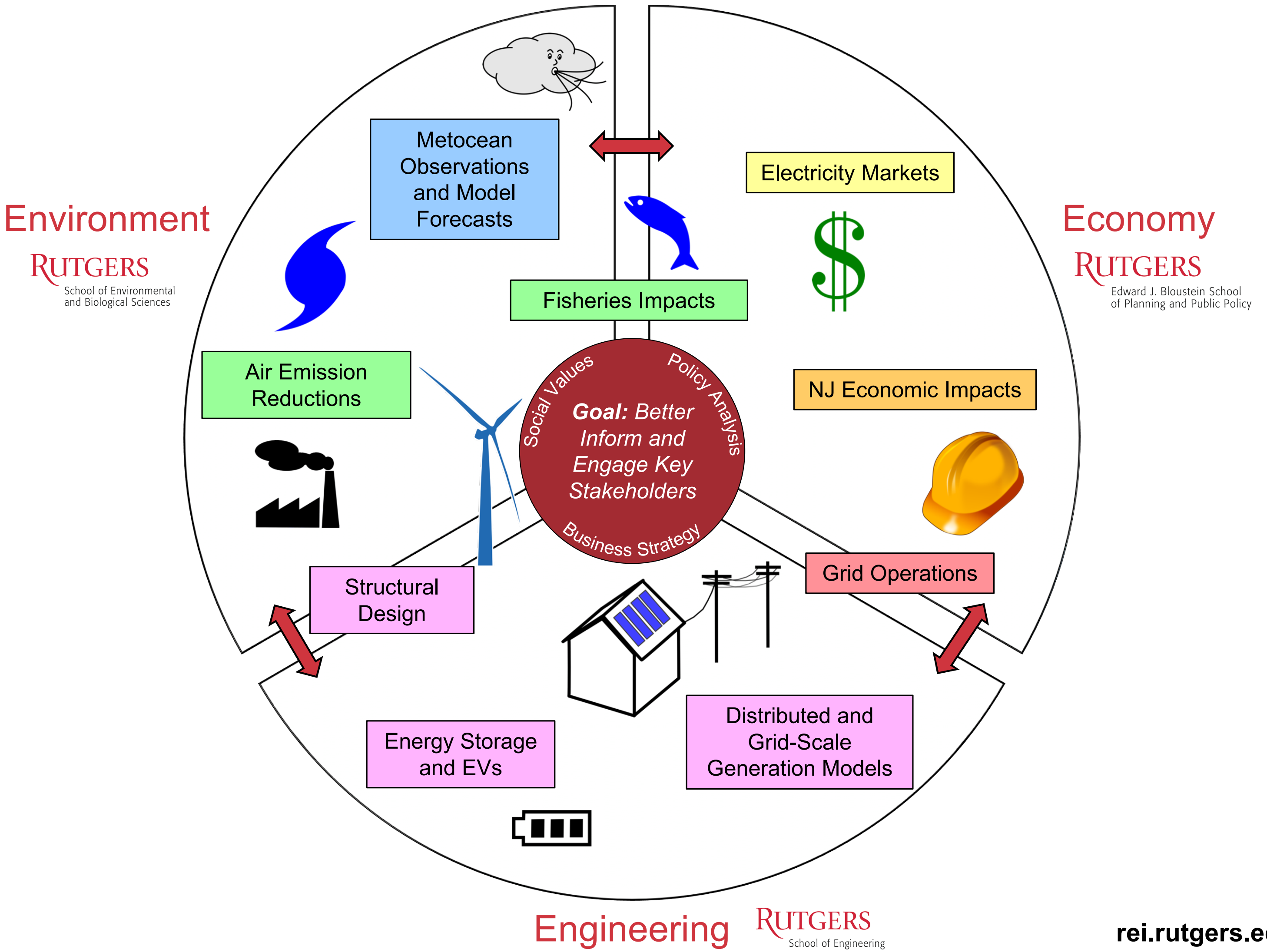

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Thank you!

Questions?

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Image: Vattenfall