Using Field Measurements, Numerical Simulation and Visualization to Improve Utility-Scale Wind Farm Power Forecasts

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Outline

- Overview of the wind energy forecast problem
- Field observations
- Data analysis
- Numerical simulations/forecasts
- Visualization/animation

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Wind Plant Diagnosis and Energy Forecast Improvement

This project recognizes that there are several meteorological factors that are important for developing a day-ahead energy forecast for a wind farm.

1. **Wind Speed. The most important is mean wind speed at hub height**

Wind Plant Diagnosis and Energy Forecast Improvement

2. Wind Speed Shear

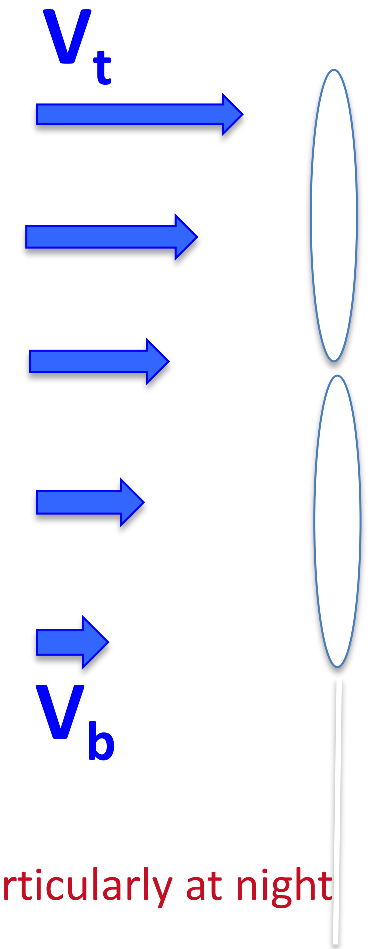
Force on blade:

$$F \sim \rho V^2$$

ρ = air density

$F_t \sim \rho V_t^2$

$F_b \sim \rho V_b^2$

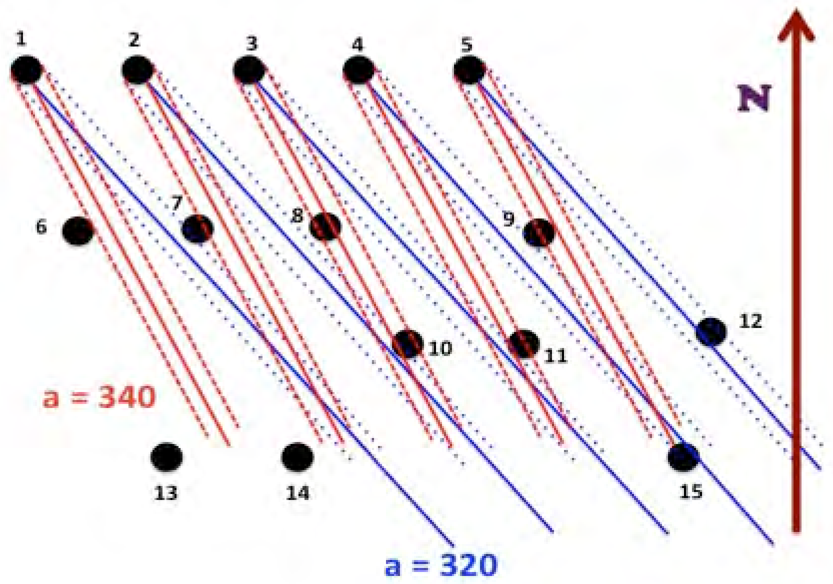


Wind speed much higher at top of blade travel, particularly at night

Wind Plant Diagnosis and Energy Forecast Improvement

3. Wind Direction

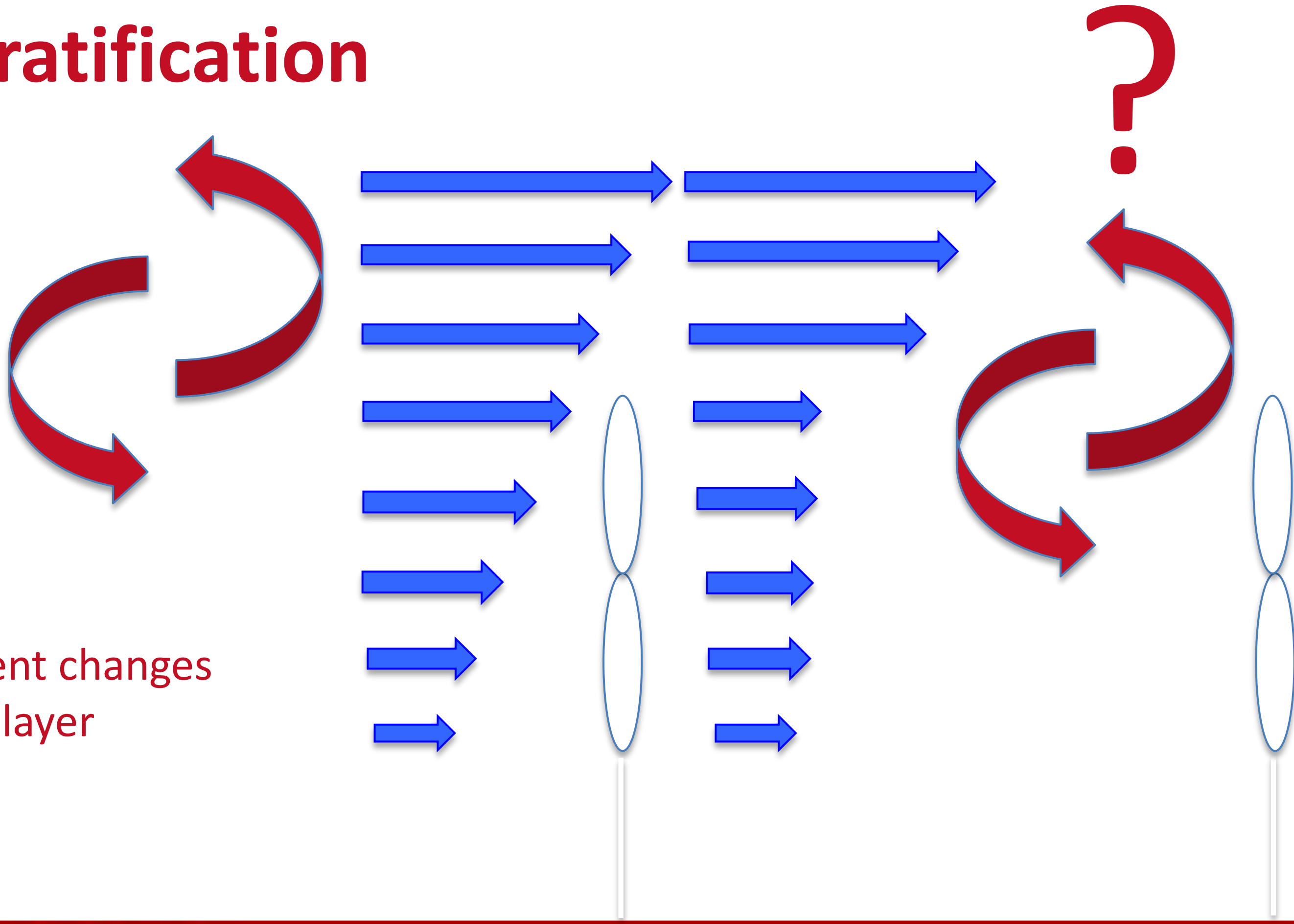
Different wind directions cause different wake losses for downwind turbines



Wind Plant Diagnosis and Energy Forecast Improvement

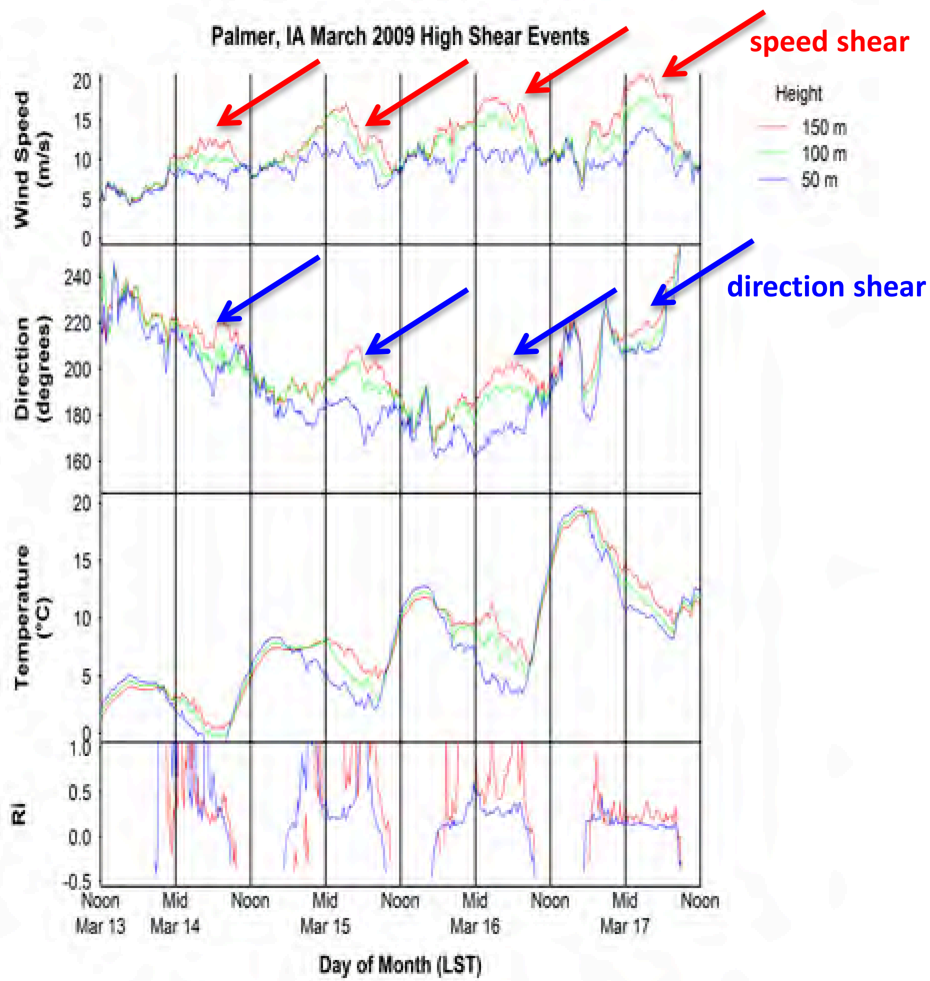
4. Thermal Stratification

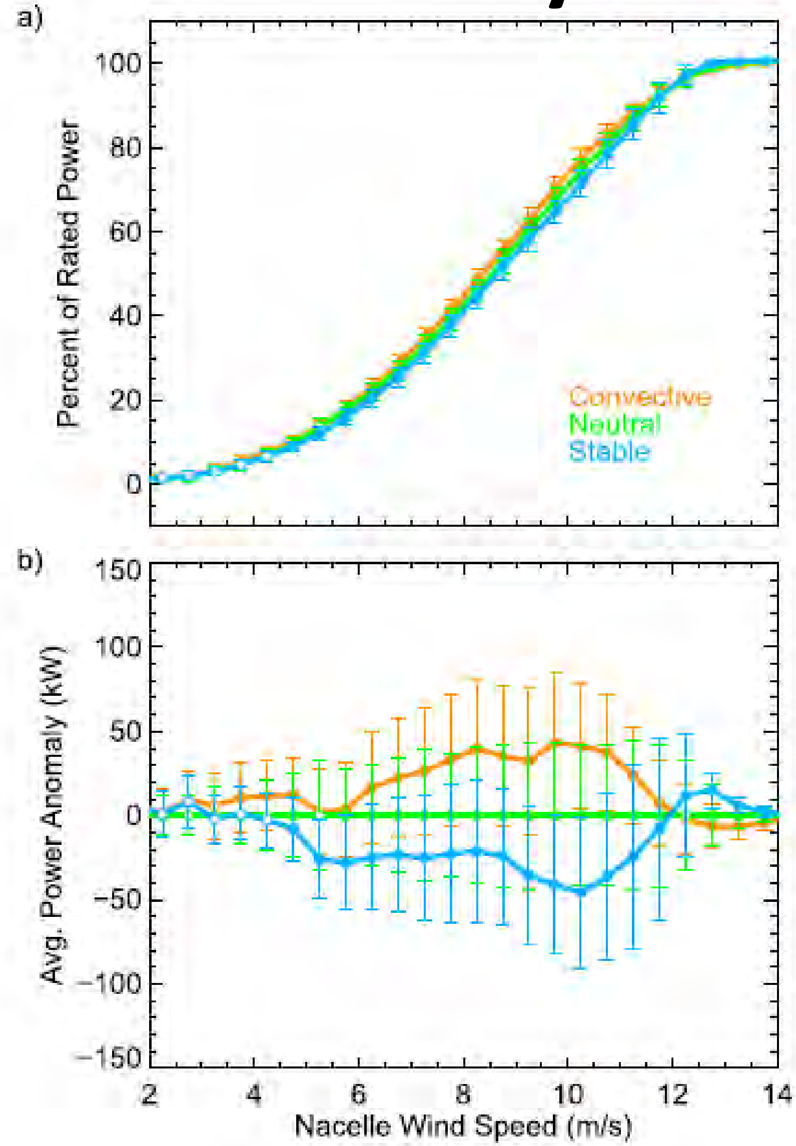
Atmospheric thermal stratification regulates vertical downward mixing of high-speed air from above



Can create large intermittent changes in wind speed in the rotor layer leading to ramp events

Stably Stratified Atmosphere: Higher Power but Lower Efficiency





Vanderwende and Lundquist, 2012

Wind Plant Diagnosis and Energy Forecast Improvement

5. **Wind Ramp Events**

A variety of causes; mostly related to large scale meteorology, but some related to heating/cooling; individual turbines may even ramp in opposite directions

Marquis, M., et al., 2011: Forecasting the wind to reach significant penetration levels of wind energy. *Bulletin of the American Meteorological Society*, *92*(9), 1159–1171.

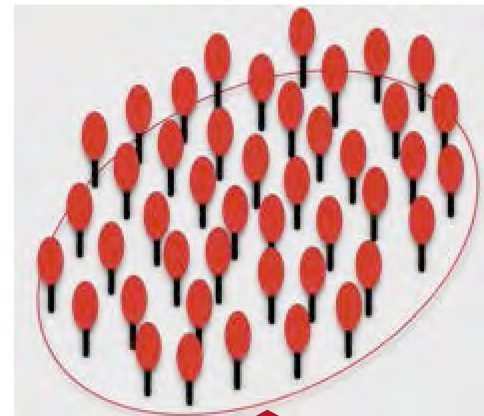
Wind Plant Diagnosis and Energy Forecast Improvement

***Five key ambient wind conditions* of importance to wind energy production:**

1. **Wind speed** (basic variable determining power)
2. **Wind speed shear** (wind speed often much higher at top of the rotor layer compared to bottom)
3. **Wind direction** (creates different wake loss interactions)
4. **Wind vertical mixing** (atmospheric thermal stratification determines vertical mixing of wind)
5. **Wind ramp events** (frontal passage, thunderstorm outflow, surface heating/cooling, wind shear; may be related to 2 or 4)

Wind Plant Diagnosis and Energy Forecast Improvement

Day-Ahead Energy Bid



How much energy to bid on day-ahead market

Use advanced ensemble weather forecast model to predict five key ambient wind conditions 54 hours in advance

Wind speed
Wind direction
Wind vertical mixing
Wind speed shear
Wind ramps

Use probabilistic relations between key ambient wind conditions and individual turbine power levels to determine total wind farm energy production

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Crop/Wind-energy Experiment

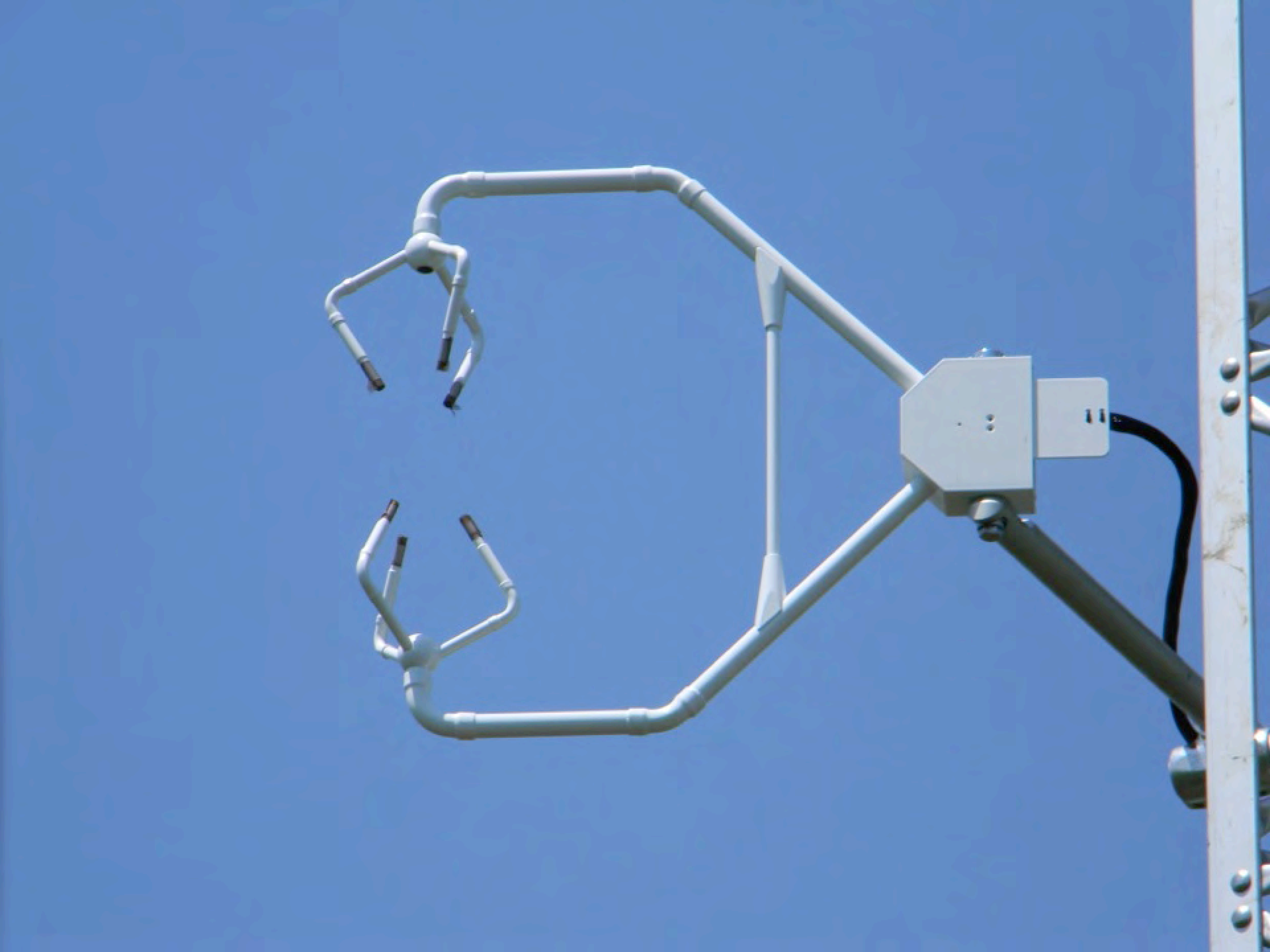
CWEX Science and Engineering Objectives

- Turbine-crop interactions
- Wind-farm internal aerodynamics (pressure forcing, vertical exchange processes, thermal stratification, anisotropic turbulence, vertical shear of speed and direction)
  - Near-turbine flow field environment
  - Individual turbine wakes (elevated, surface based)
  - Multiple turbine wakes (rotor layer vs turbine layer)
- Mesoscale interactions
  - Surface convergence
  - Wind-farm/boundary-layer interactions
  - Vertical velocities
  - Interaction with nocturnal low-level jet
  - Downwind influence (lateral extent of wind farm footprint)
  - Influence on cloud/fog formation

CWEX-10 Flux Tower Measurements

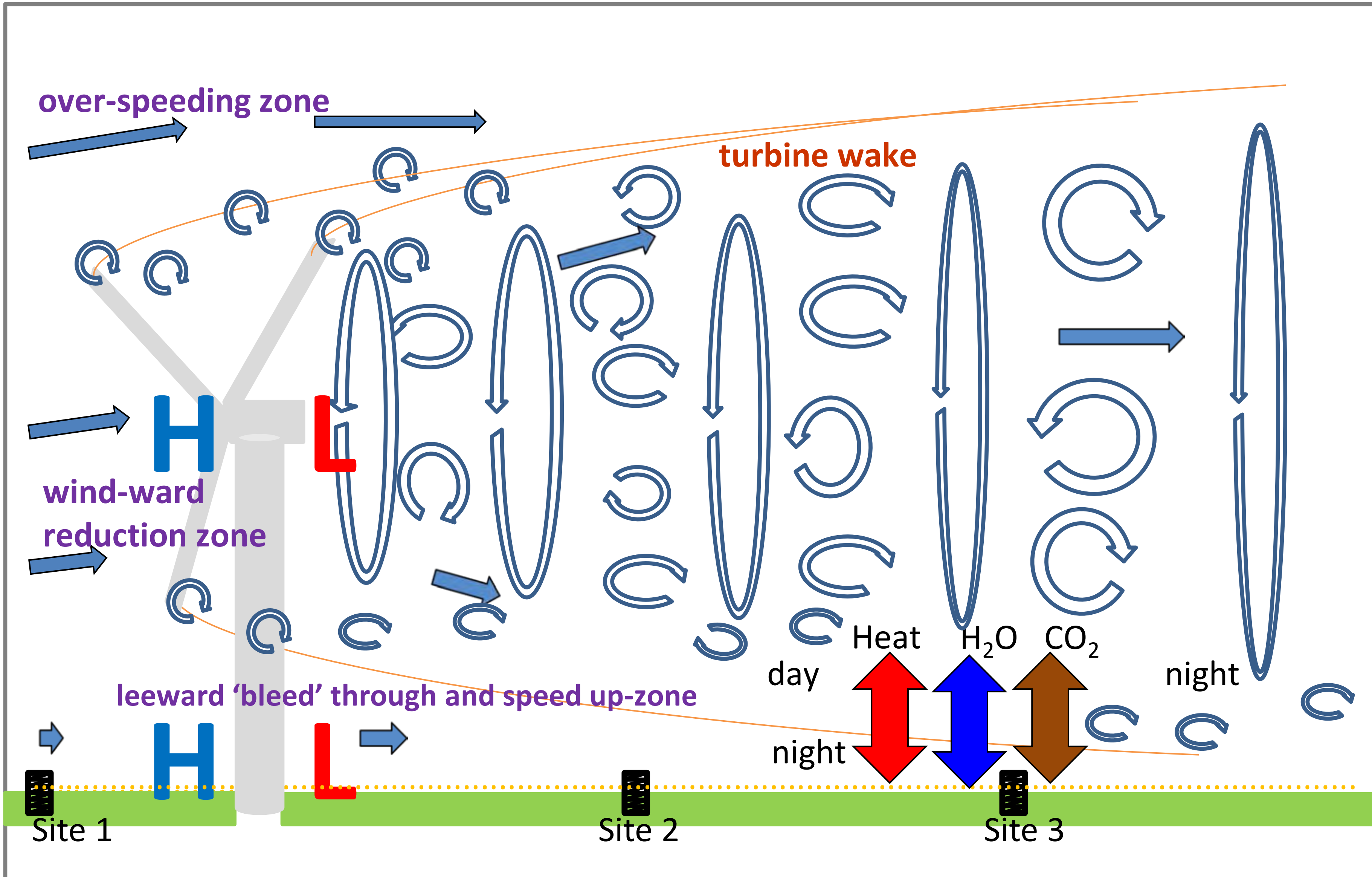
- cup anemometer at 9.1 m
- T & RH at 9.1 m and 5.3 m
- sonic anemometer at 6.45 m
- tipping bucket at 3.75 m
- Two towers (reference and near-wake location) additionally contained
- --Net radiometer (net long wave and short wave radiation) at 5.3 m
- --Open path CO_2/H_20 IRGA LI-7500 gas analyzer
- Sonic anemometer and gas analyzer sampled at 20 Hz w/ 5 min averages
- T, RH, cup anemometer, rain gage output archived at 5 min

All sensors are connected to a data-logger
Systems are powered with solar panels and deep cycle batteries



Conceptual model of turbine-crop Interaction via mean wind, perturbation pressure, and turbulence fields

(based on shelterbelt studies of *Wang and Takle, 1995: JAM*, **34**, 2206-2219)



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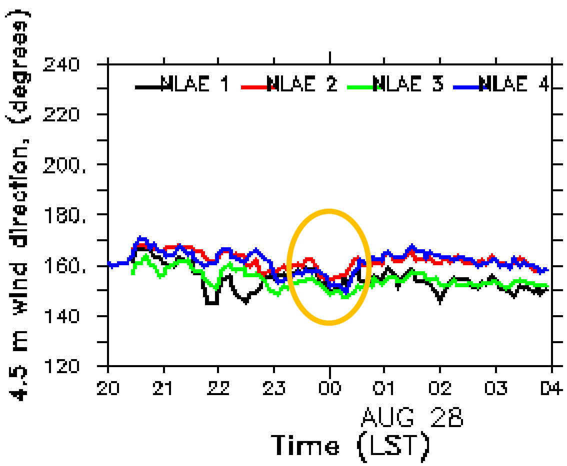
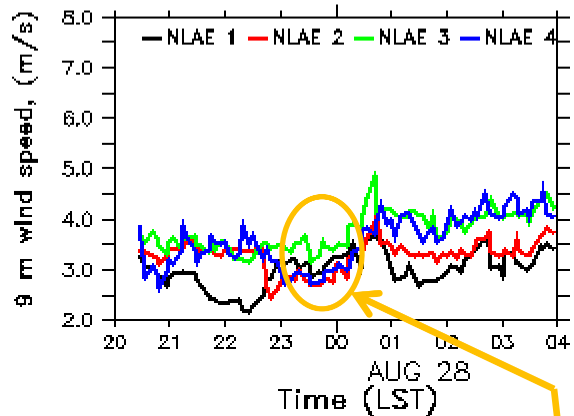
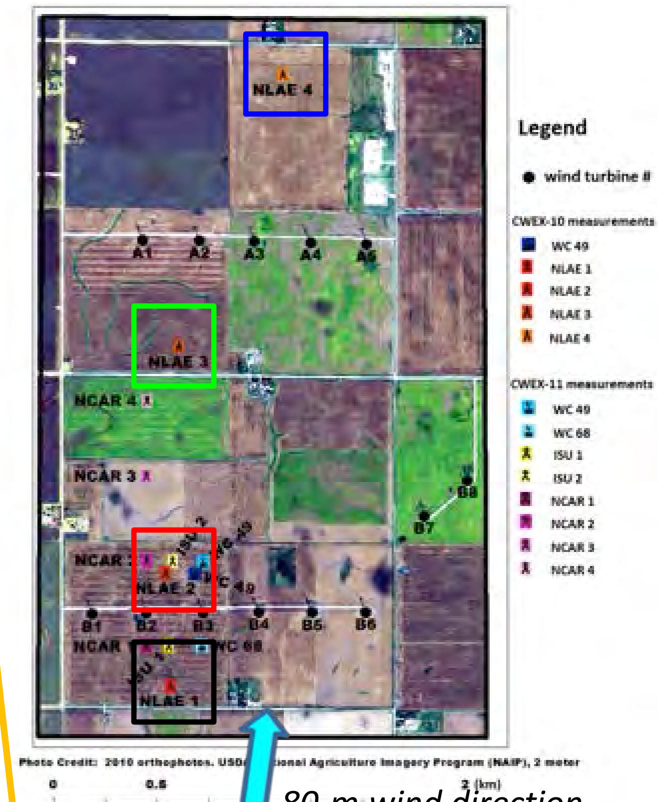
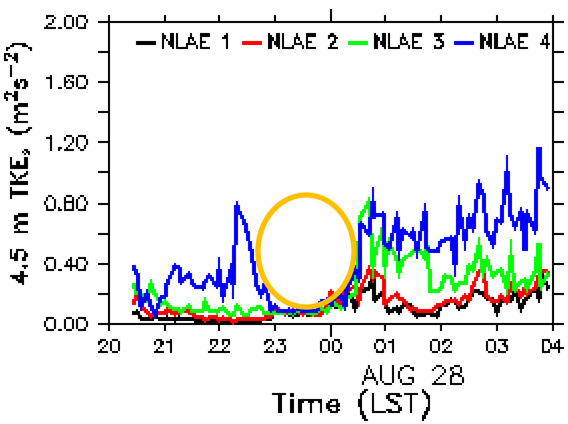
Turbines offline:
August 27, 2010 2300-0000 LST

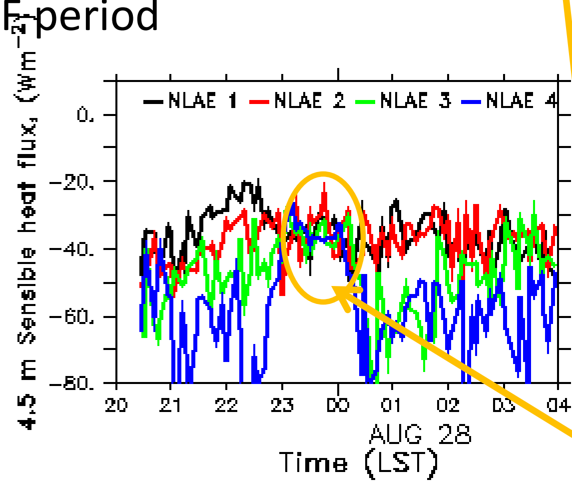






Station north of two turbine lines has 2-3X ambient TKE and Heat flux before/after OFF-period





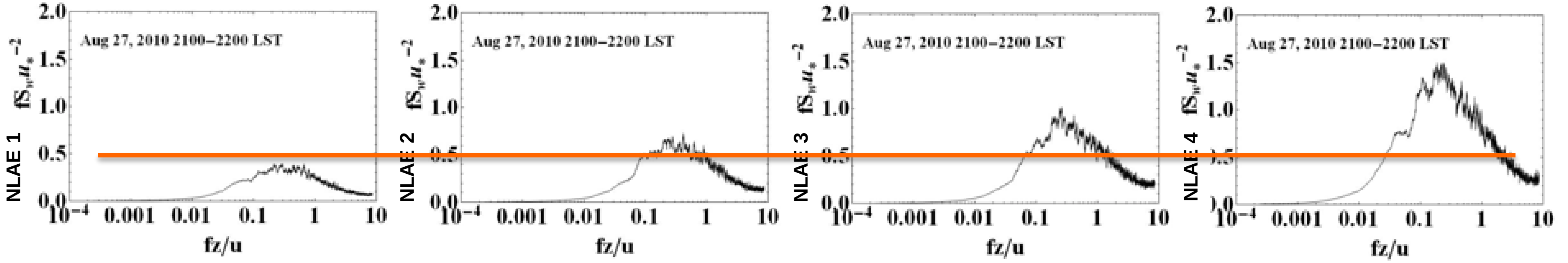
80-m wind direction vector

Return to reference flow conditions during the shut down

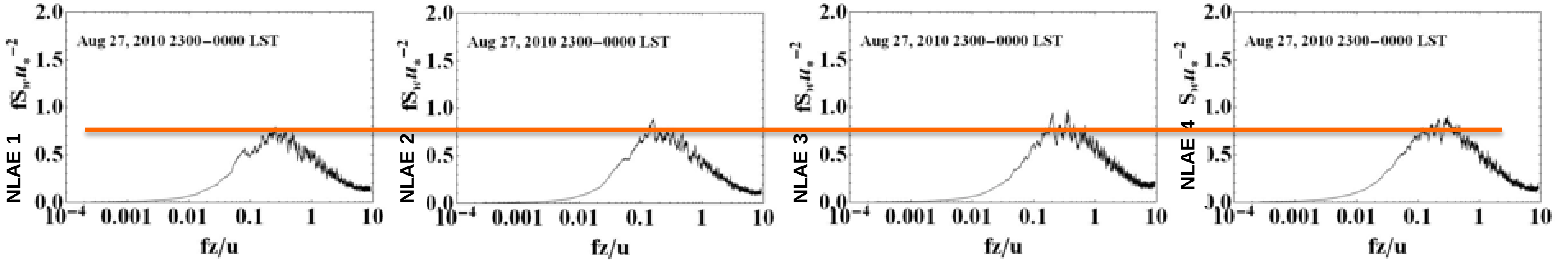
Spectral evidence before and during the shutdown period

W-power spectra

South → North **Turbines ON**



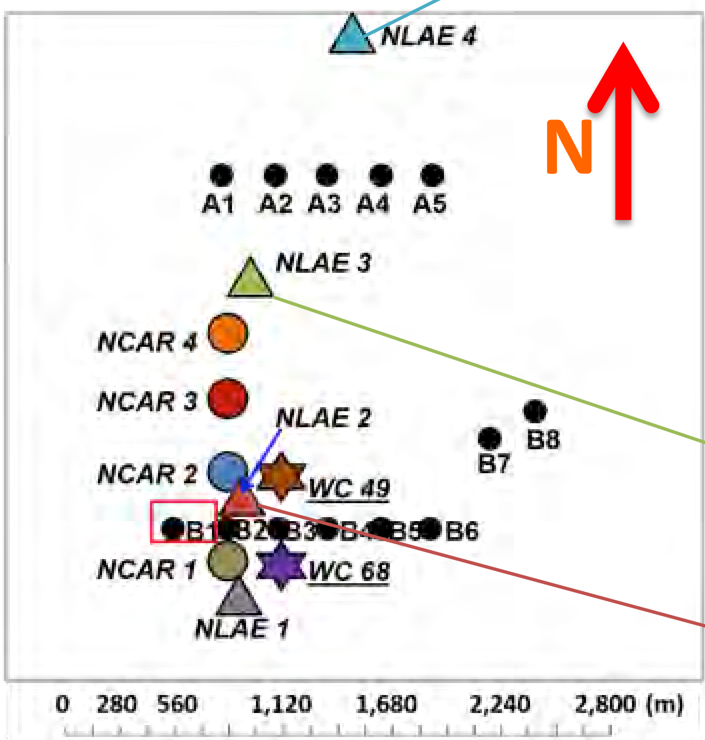
South → North **Turbines OFF**



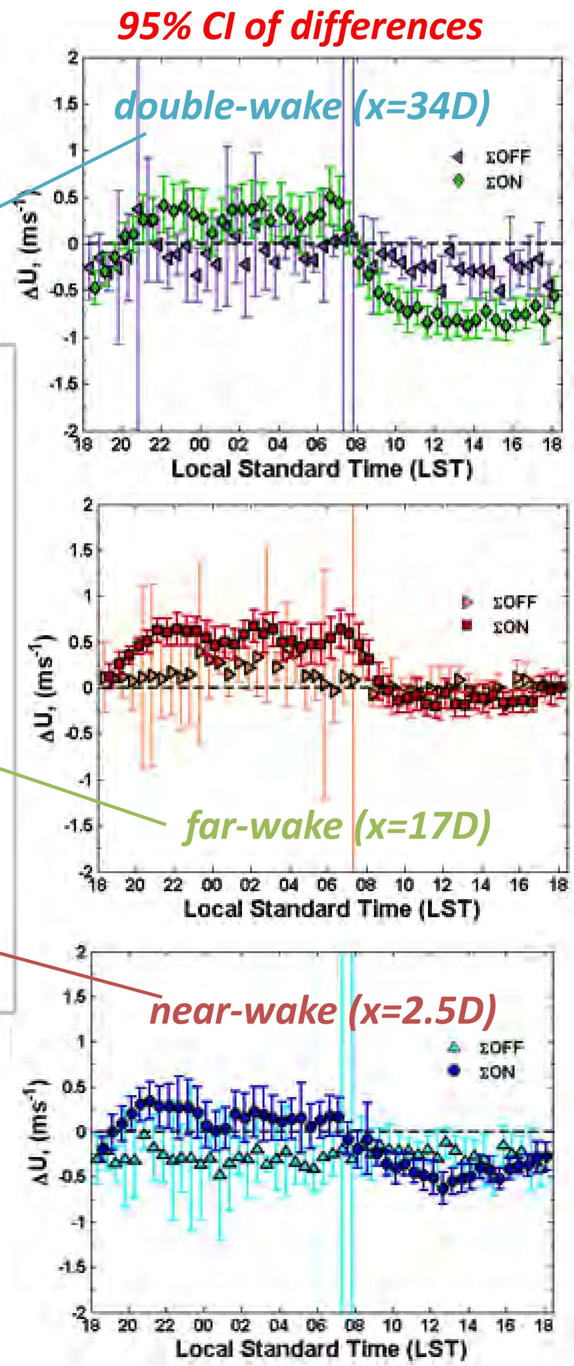
ON: Increase in vertical velocity variance of: 2.0X downwind of first line of turbines
5.0X downwind of two lines of turbines

OFF: Similar intensity of variance for all flux stations south and north of two turbine lines

9-m wind speed differences ΔU *(downwind-upwind)*



Wind directions from SSE-WSW

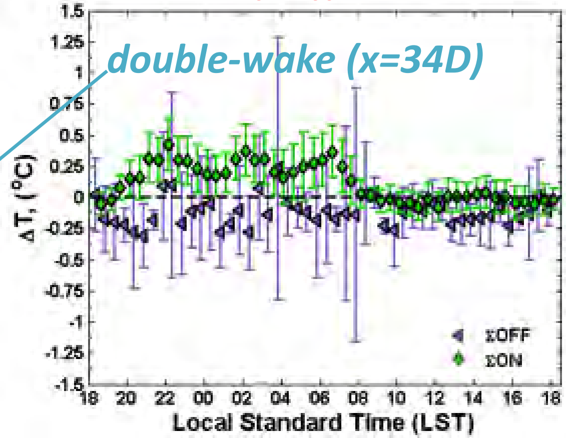


The two stations directly behind the 1st and 2nd turbine line indicate daytime speed reduction of 0.5-1.0 m/s

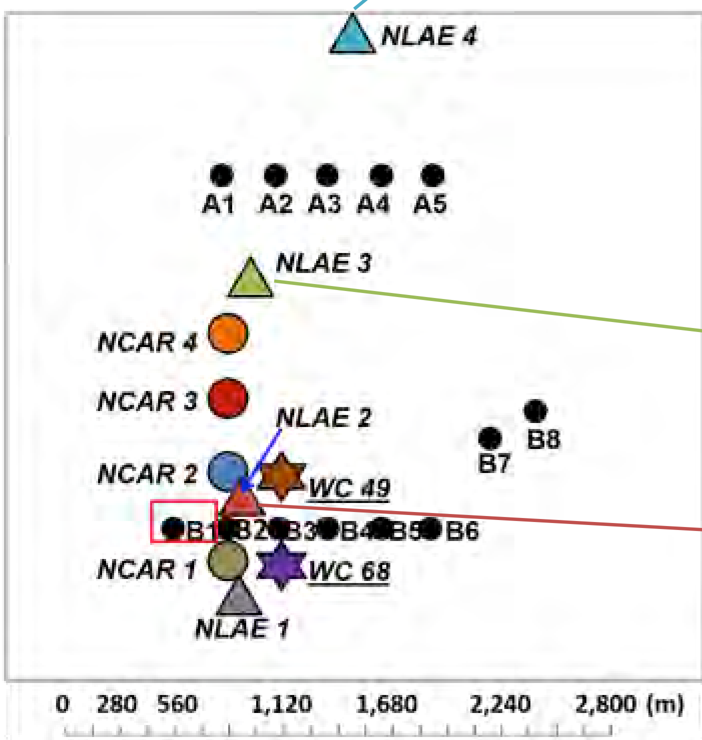
Turbine wakes increase surface speed for multiple hours of the night at the far-wake and double wake location.
Speeds increase at the near-wake location because of flow acceleration underneath the turbine blade

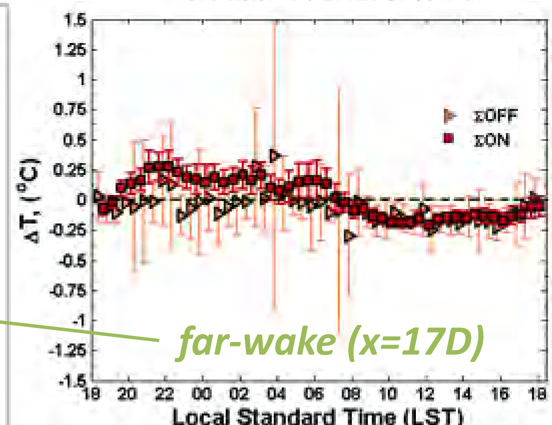
ON vs. OFF 9-m air temperature differences ΔT *(downwind-upwind)*

95% CI of differences

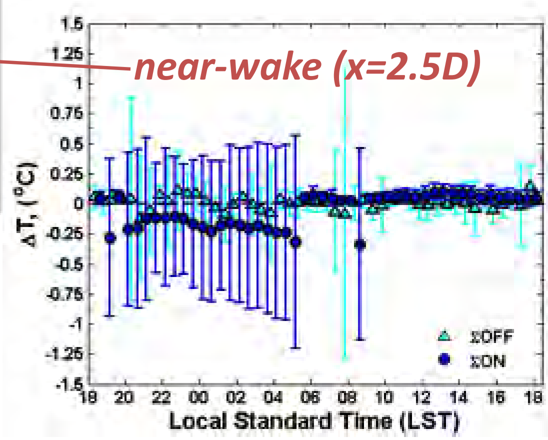


Nighttime temperature warms by 0.25-0.5 °C downwind of the 2nd line of turbines





Weak warming at the Far wake location at night



Weak cooling in the near-wake of turbine caused by decoupled mixing from above the turbine rotor

Wind directions from SSE-WSW

Vertically Pointing Lidar

Vertical profiles of turbulence kinetic energy (TKE)

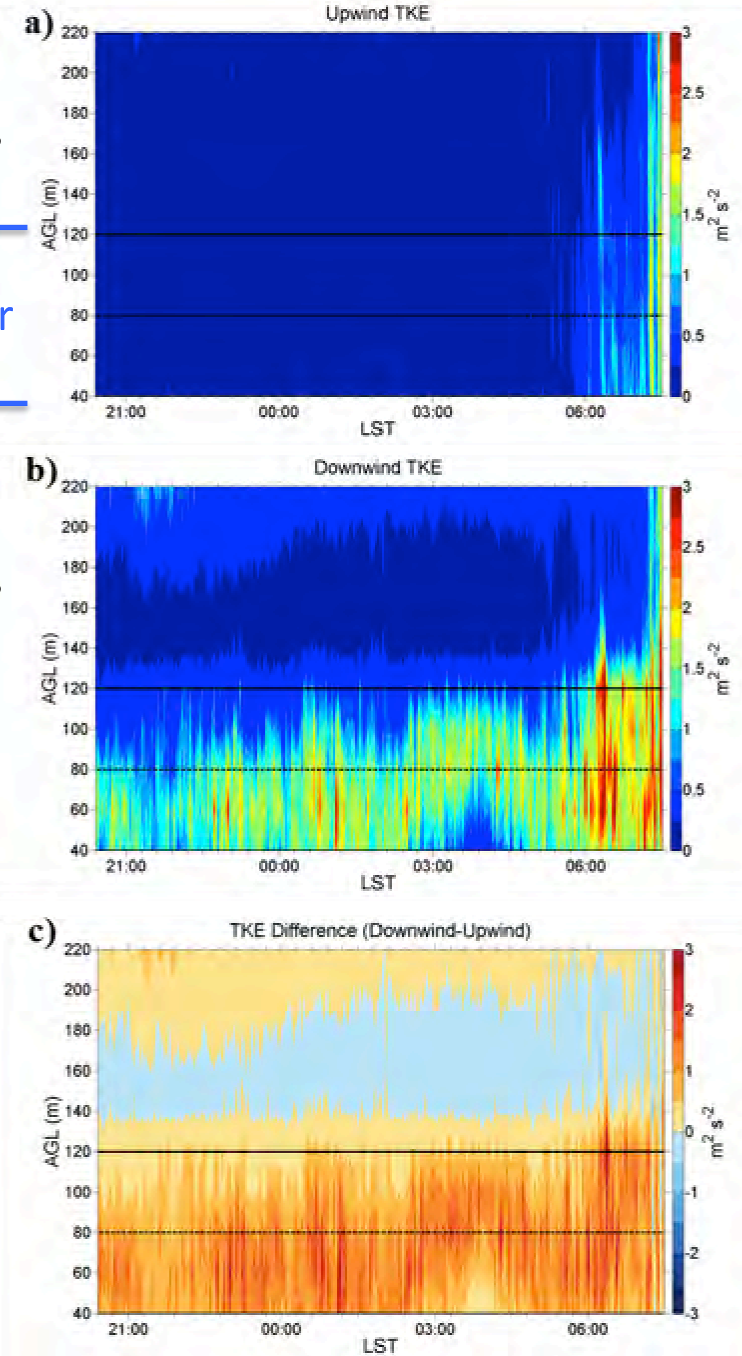
16-17 July 2010

4.5 D South of B-turbines

Rotor Layer

2.0 D North of B-turbines

TKE difference



CU/NREL/ISU Lidar deployment team

Low-Level Jets and wake velocity deficits

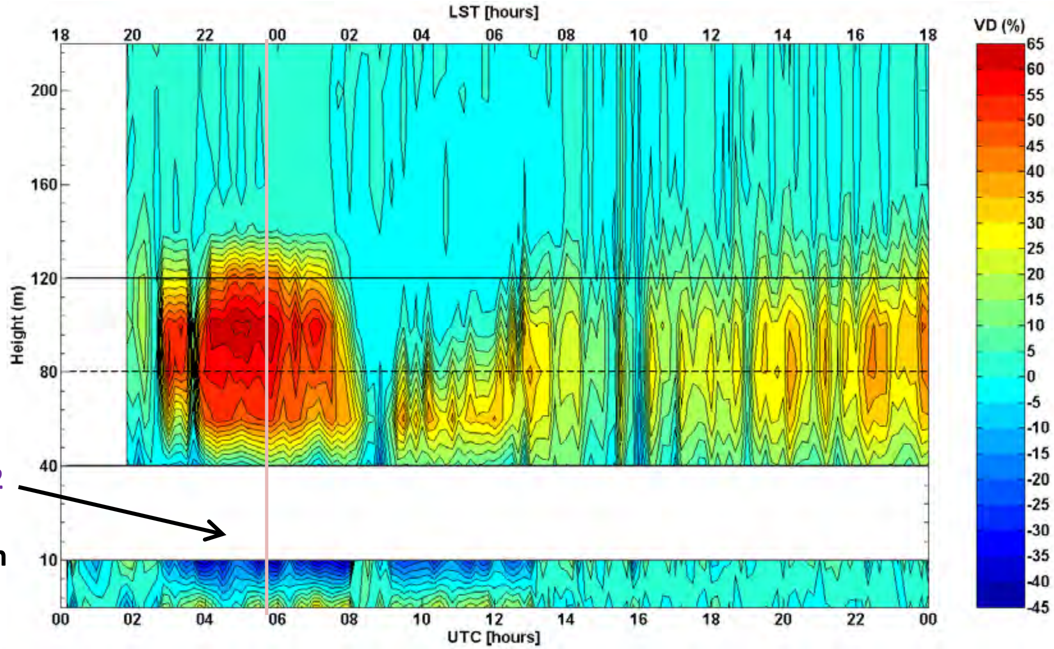
OBSERVED

July 9

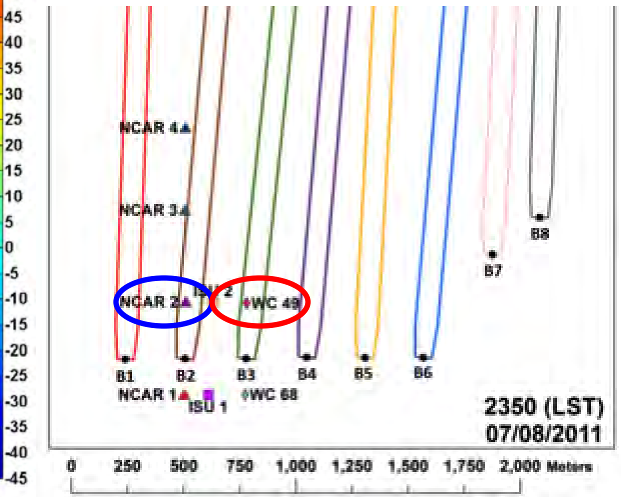
jet max within rotor depth

'non-classical'

over-speeding 30-40% at NCAR 2 underneath the downward branch of the wake swirl



80-m SCADA 'wake lines'

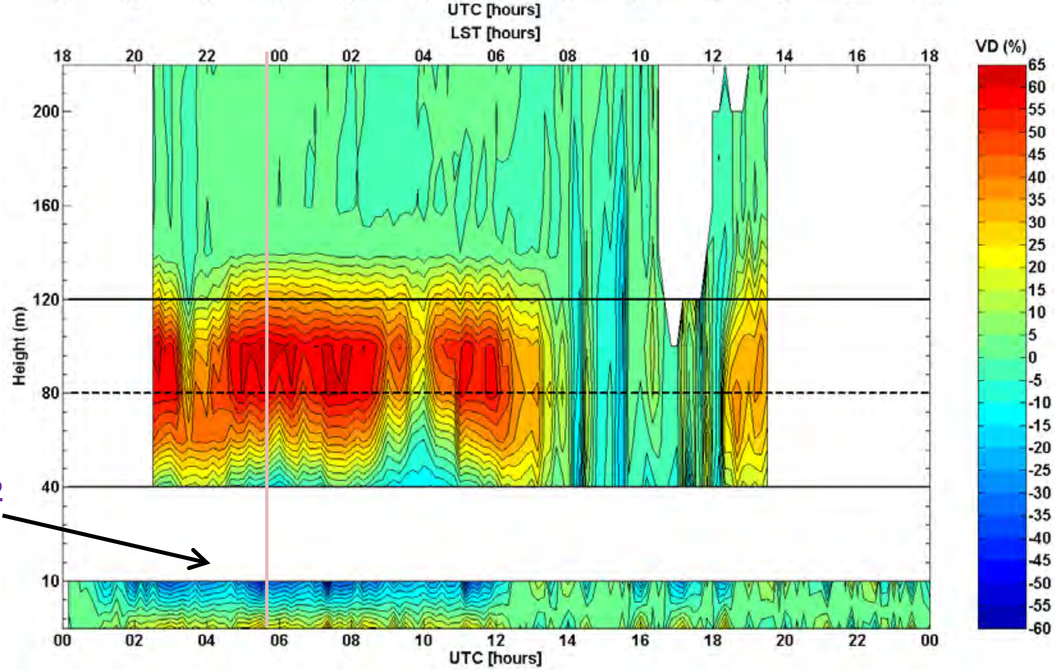


July 17

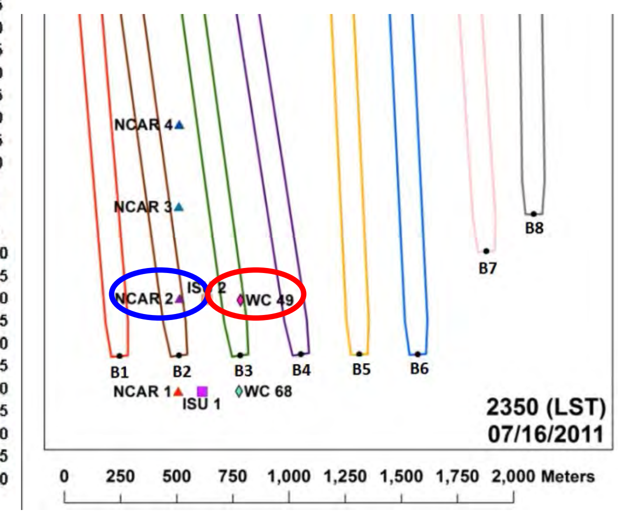
jet max above rotor depth

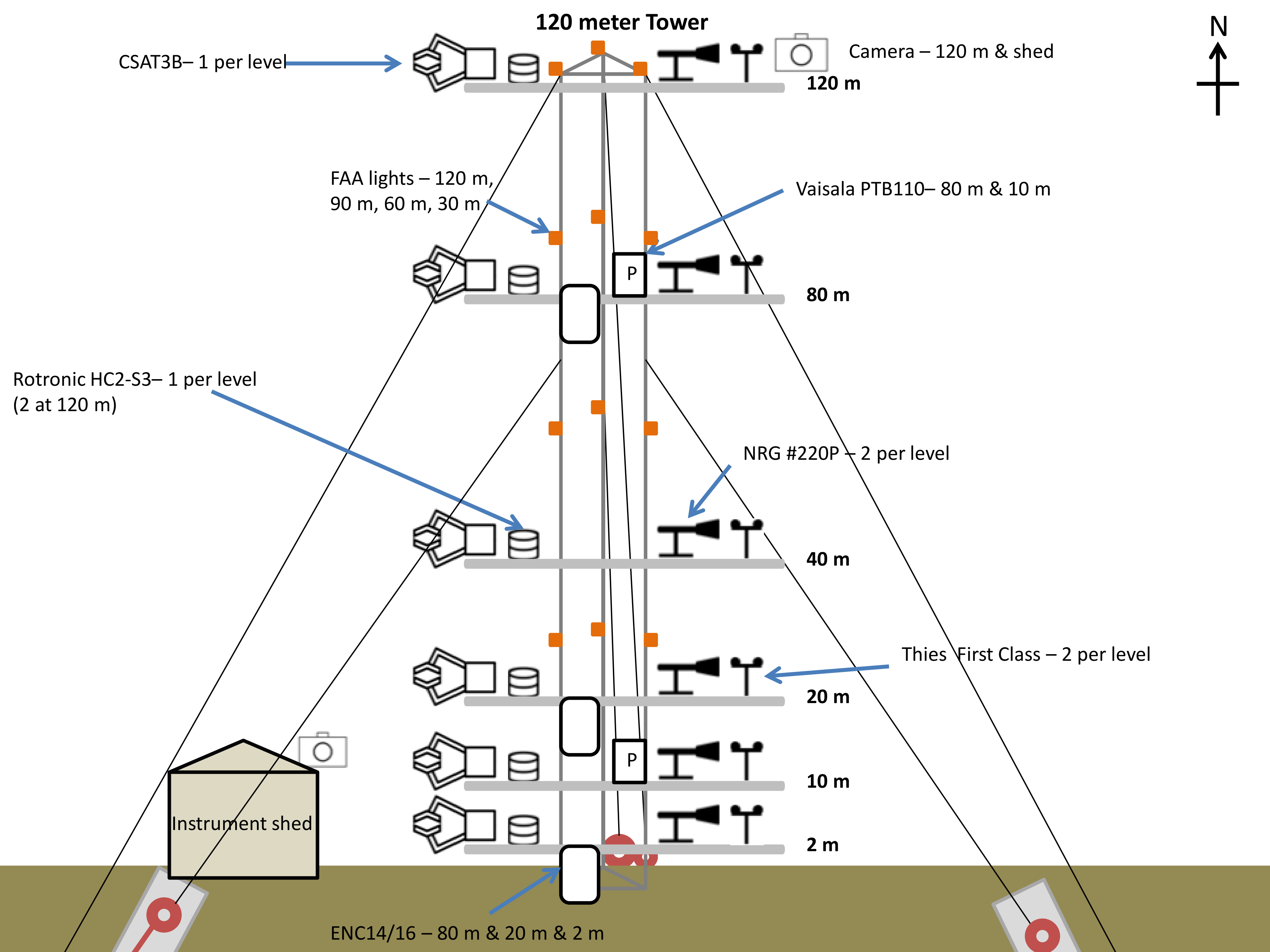
'classical'

over-speeding 20-30% at NCAR 2 underneath the ascending branch of the wake swirl



80-m SCADA 'wake lines'





120 meter Tower
N
CSAT3B– 1 per level
Camera – 120 m & shed
120 m
FAA lights – 120 m,
90 m, 60 m, 30 m
Vaisala PTB110– 80 m & 10 m
P
80 m
Rotronic HC2-S3– 1 per level
(2 at 120 m)
NRG #220P – 2 per level
40 m
Thies First Class – 2 per level
20 m
P
10 m
Instrument shed
2 m
ENC14/16 – 80 m & 20 m & 2 m

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Wind Plant Diagnosis and Energy Forecast Improvement

Our objective is to improve wind-plant day-ahead energy forecasts by use of statistics of past wind-plant power production at the scale of individual turbines and advanced day-ahead "wind-condition" forecasts

Wind Plant Diagnosis and Energy Forecast Improvement

Updated Forecast Skill
(Mean Absolute Error)

	40-m	50-m	80-m	100-m	120-m	150-m
Day-ahead wind speed forecast error (m/s)	1.34	1.51	1.75	1.78	1.82	1.82
Day-2 wind speed forecast error (m/s)	1.56	1.76	1.50	1.68	1.75	1.84
Day-ahead wind direction forecast error (degrees)	23.7	16.8	18.8	17.2	18.0	18.4
Day-2 wind direction forecast error (degrees)	20.2	14.1	18.4	13.9	14.2	15.2

Wind shear forecast error (x 10^{-3} s^{-1})

Day-1: 7.70 Day-2: 9.01

Walton, 2015

Wind Plant Diagnosis and Energy Forecast Improvement

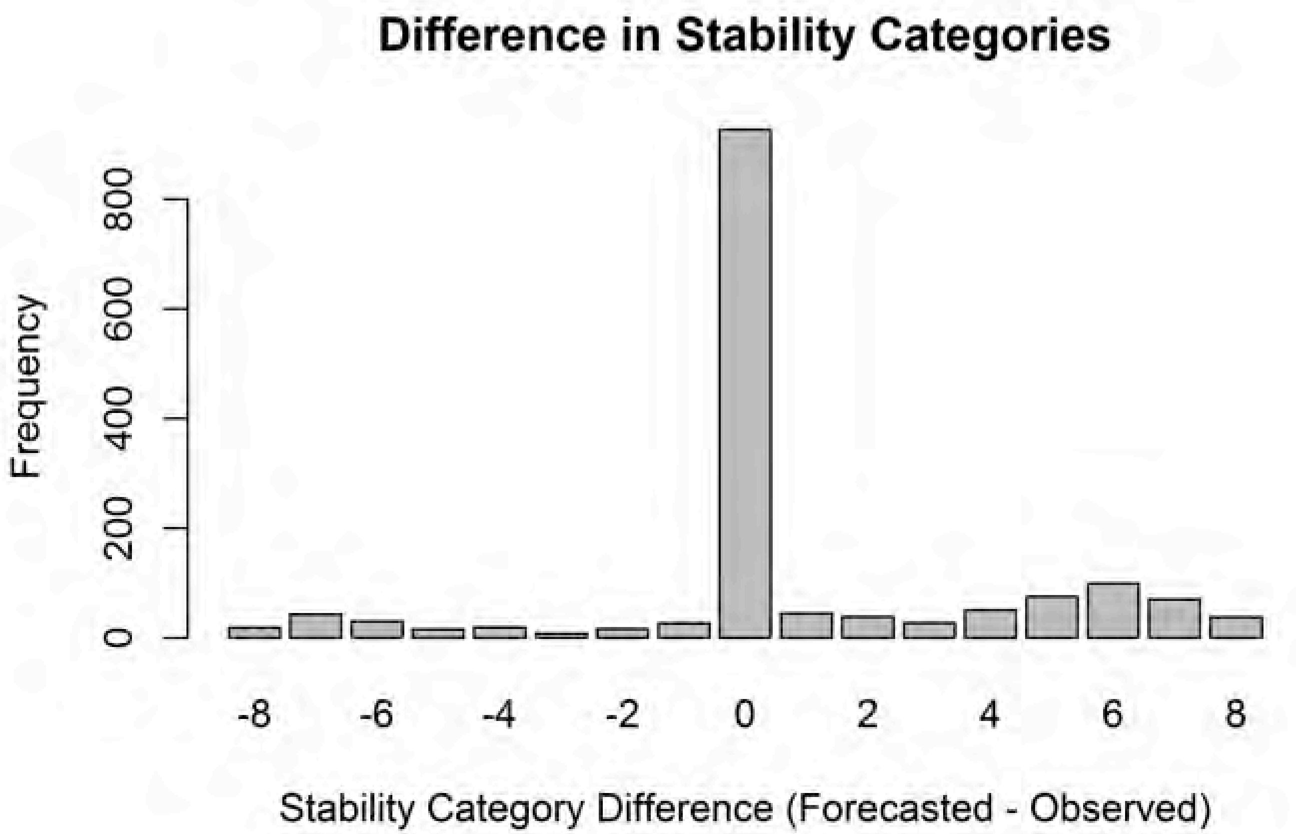
Normalized power is lower for turbine under high shear than low shear

Turbine	High Shear	Low Shear	P-value
A	0.79	0.82	0.038
B	0.69	0.81	0.203
C	0.85	1.07	0.004
D	0.89	1.09	0.005
E	0.85	1.15	1.3×10^{-5}

*** Results are preliminary ***

Lodge, Samantha J., 2014: Determining the effect of wind shear events on power output of individual wind turbines in an Iowa wind farm. Senior Thesis, Meteorology Program, Iowa State University. 8 pp.

Wind Plant Diagnosis and Energy Forecast Improvement



Walton, Renee, 2015: Strong wind shear events and improved numerical prediction of he wind turbine rotor layer in an Iowa tall tower network. MS thesis, Iowa State University. 53 pp.

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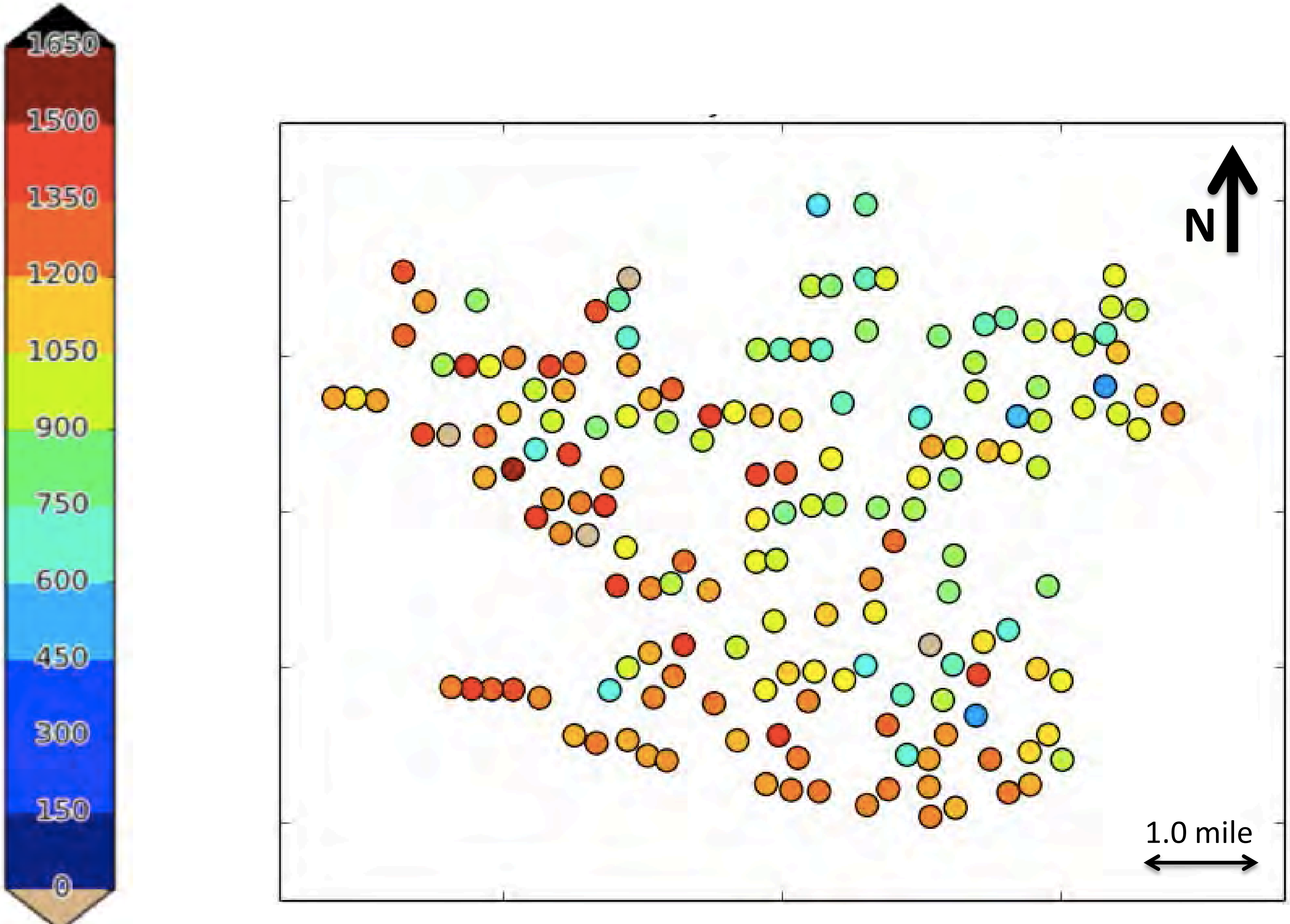
Wind Farm Data Visualization and Animation in Support of Analysis

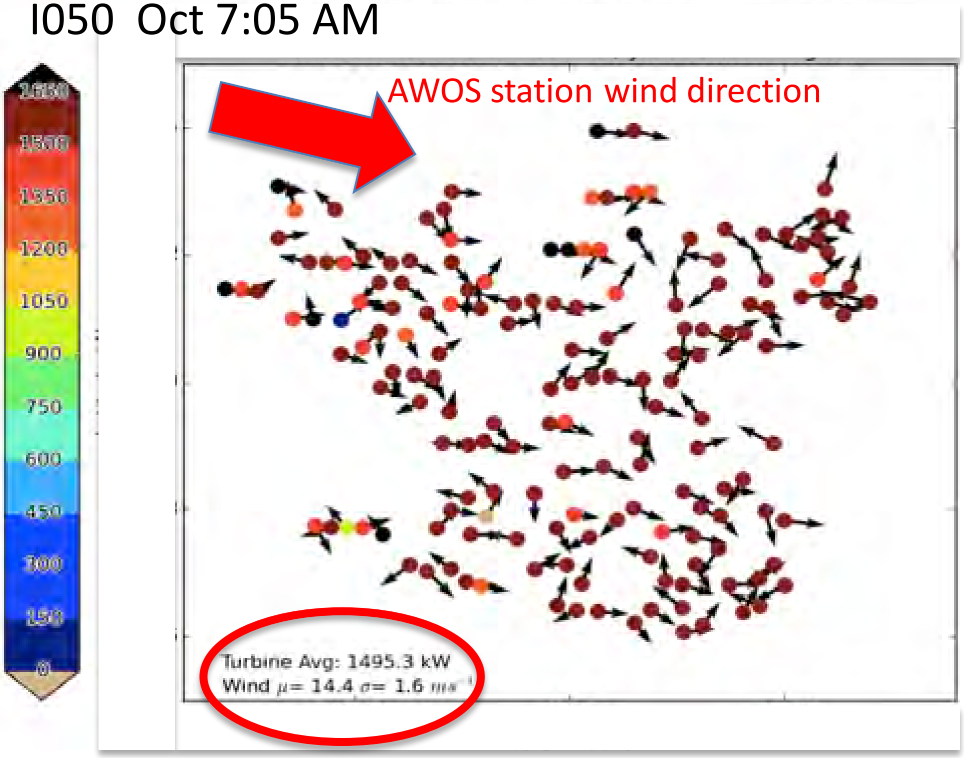
- Supervisory Control and Data Acquisition (SCADA) information for 1.5-MW turbines in an Iowa wind farm (>170 turbines)
- Power, nacelle wind speed, yaw and pitch data at 1-min intervals from each turbine for 3 years
- Data at 10-min intervals from meteorological towers (80-m and a 150-m) nearby


1650
1500
1350
1200
1050
900
750
600
450
300
150
0
N
1.0 mile

Wind Plant Diagnosis and Energy Forecast Improvement

Before **Yaw Correction**

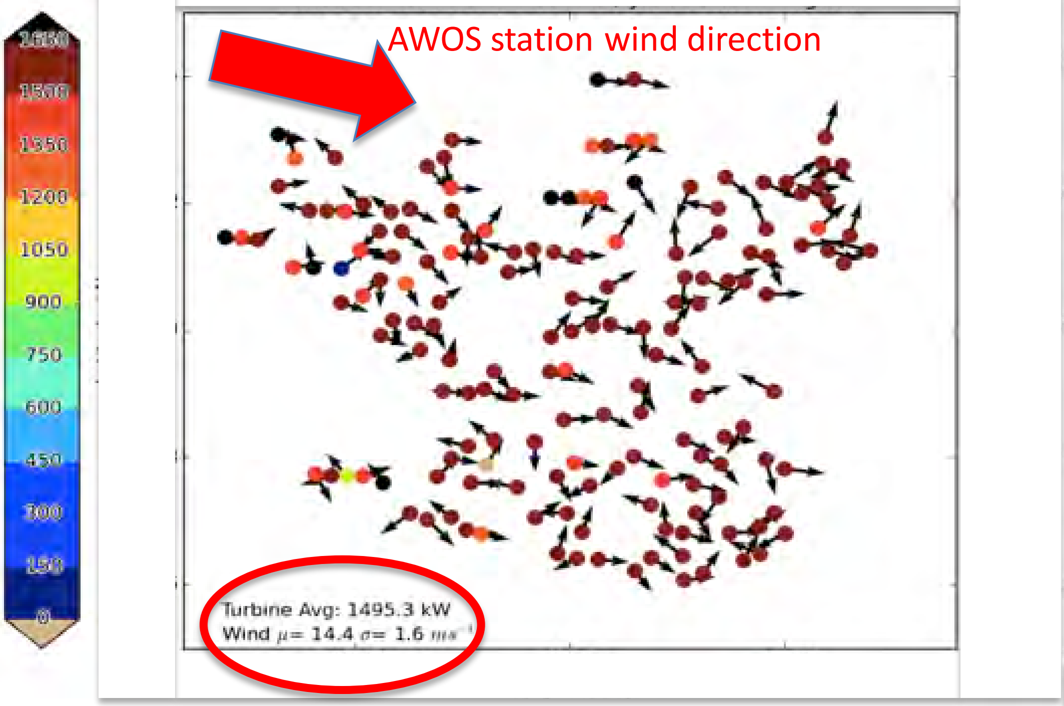
I050 Oct 7:05 AM

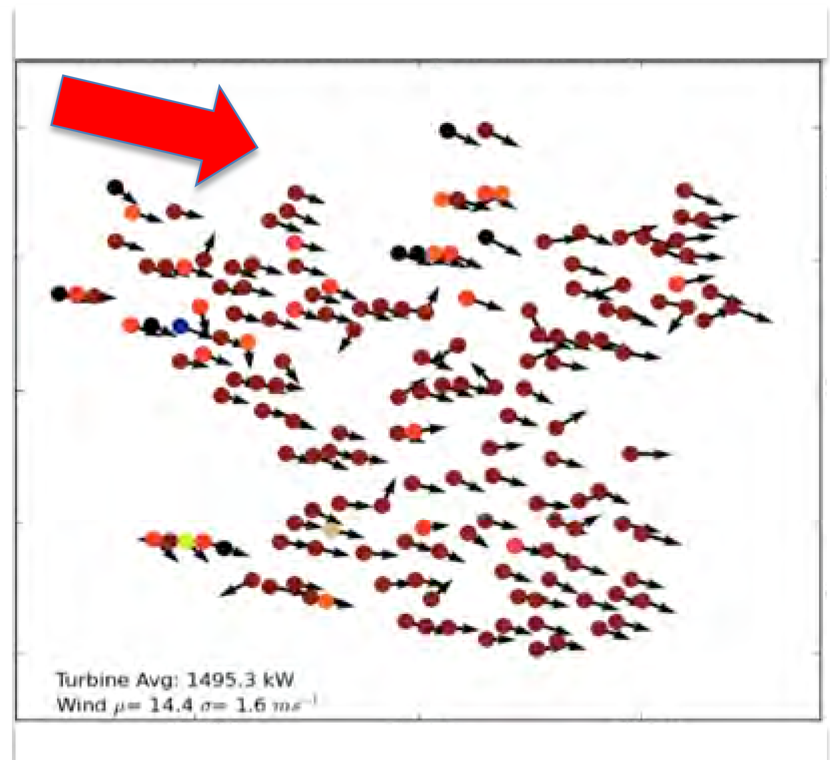


Wind Plant Diagnosis and Energy Forecast Improvement

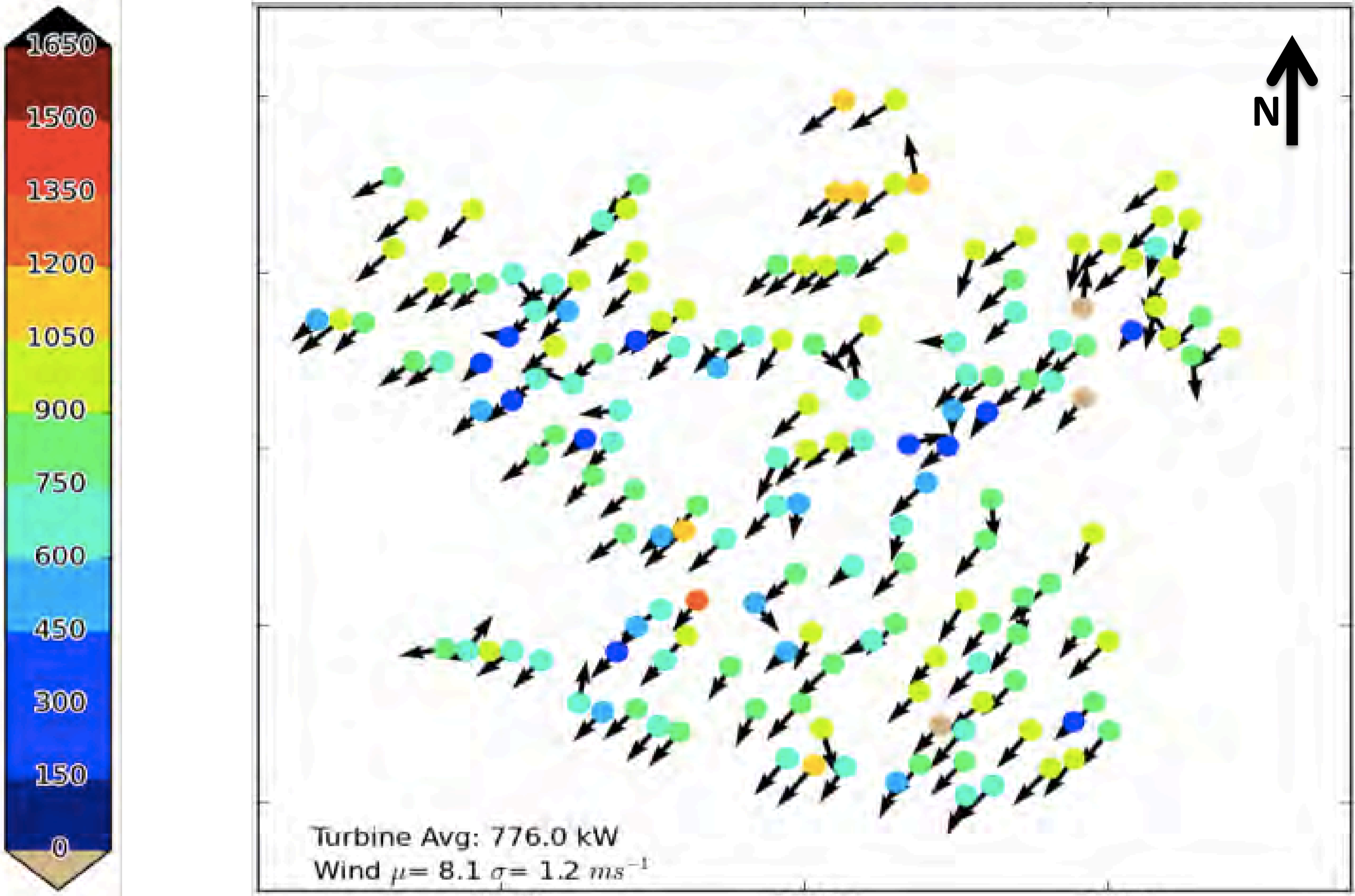
Before **Yaw Correction** **After**

I050 Oct 7:05 AM

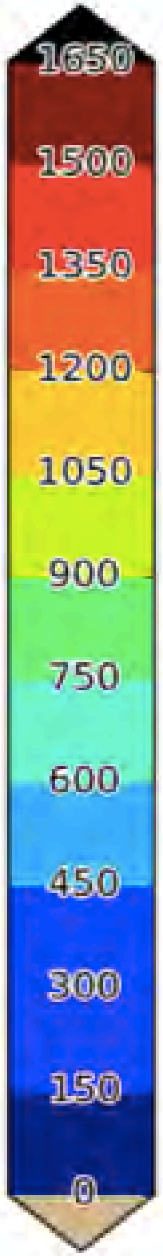


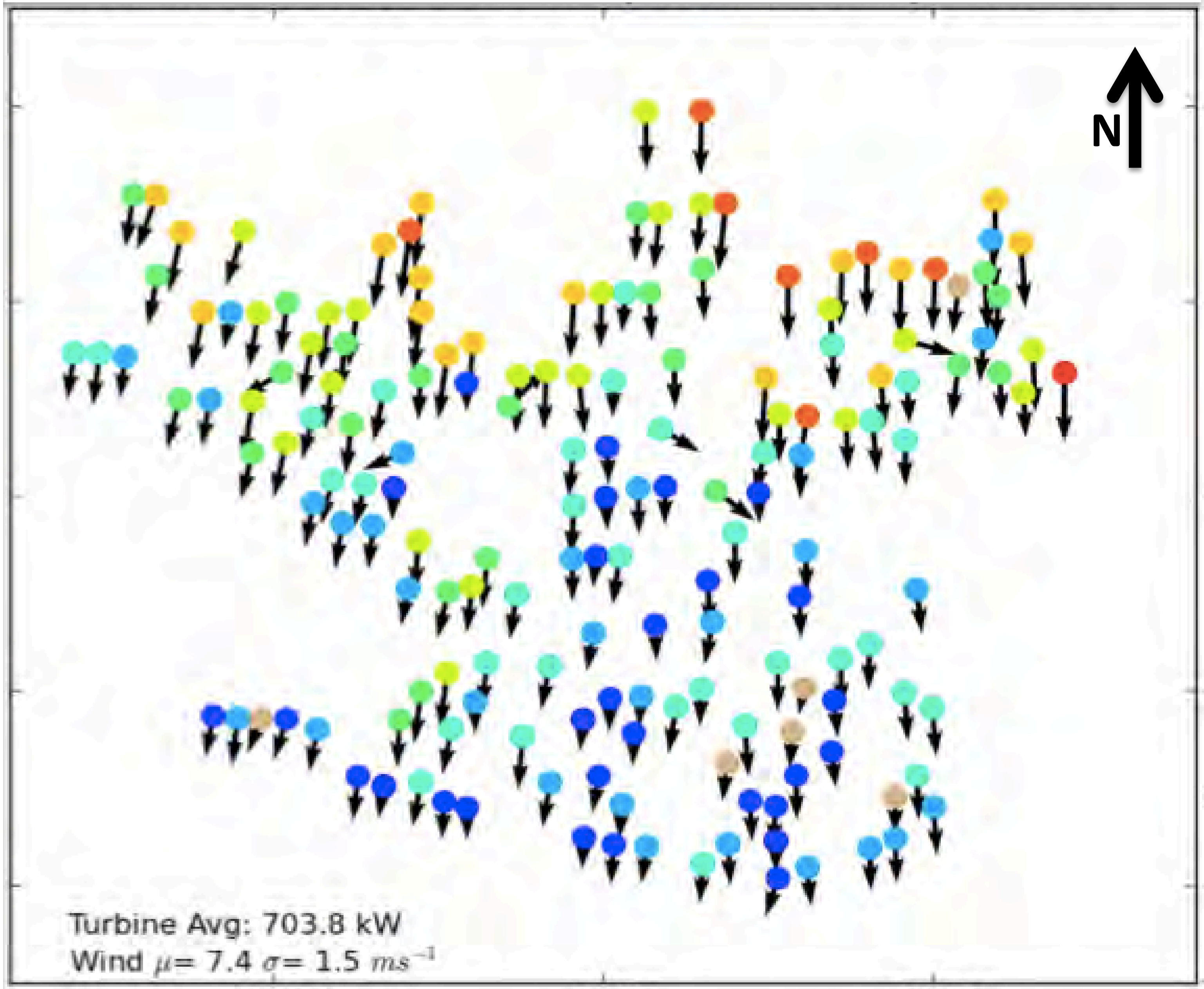


Turbine Interactions

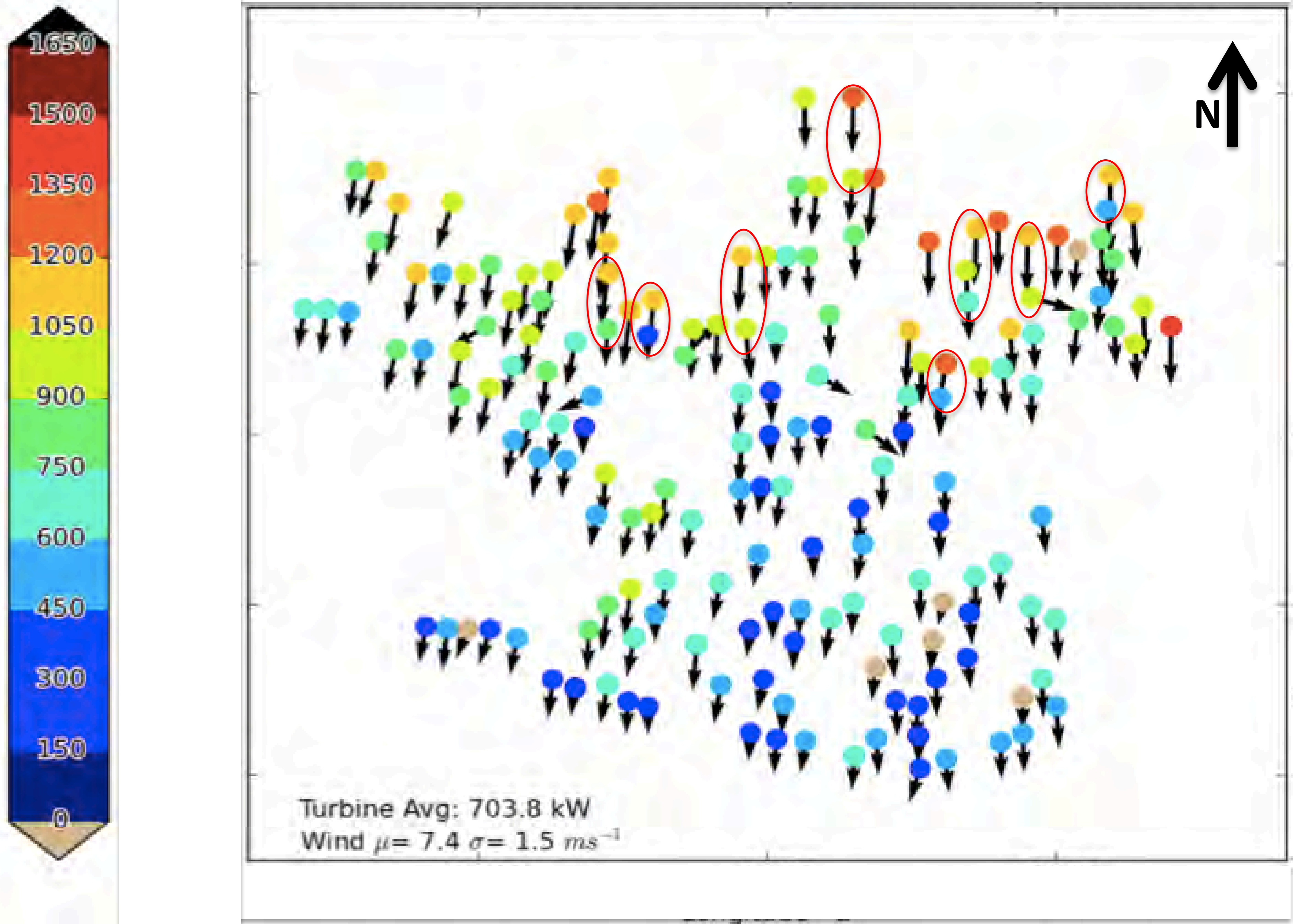


Turbine Interactions



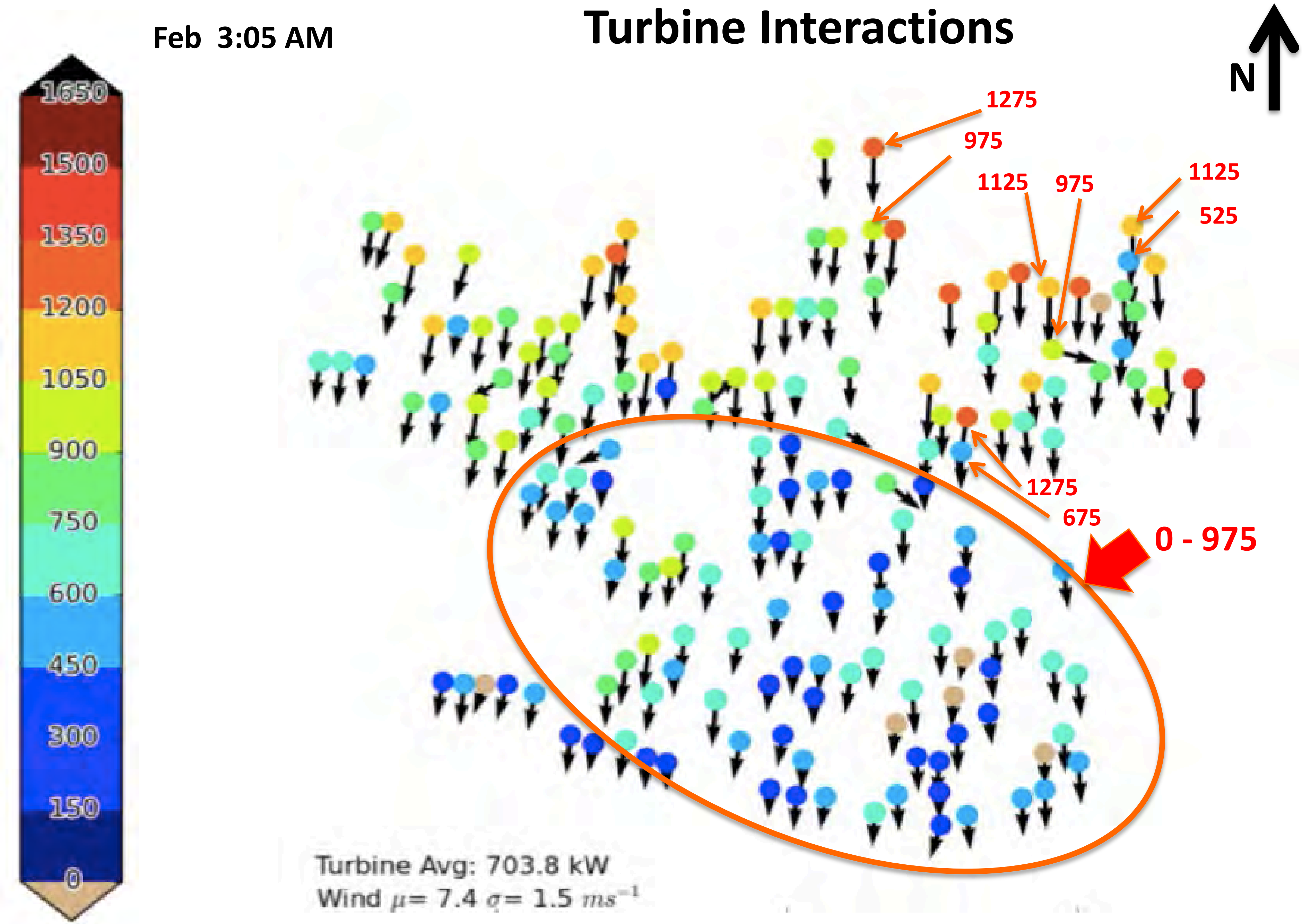


Turbine Interactions

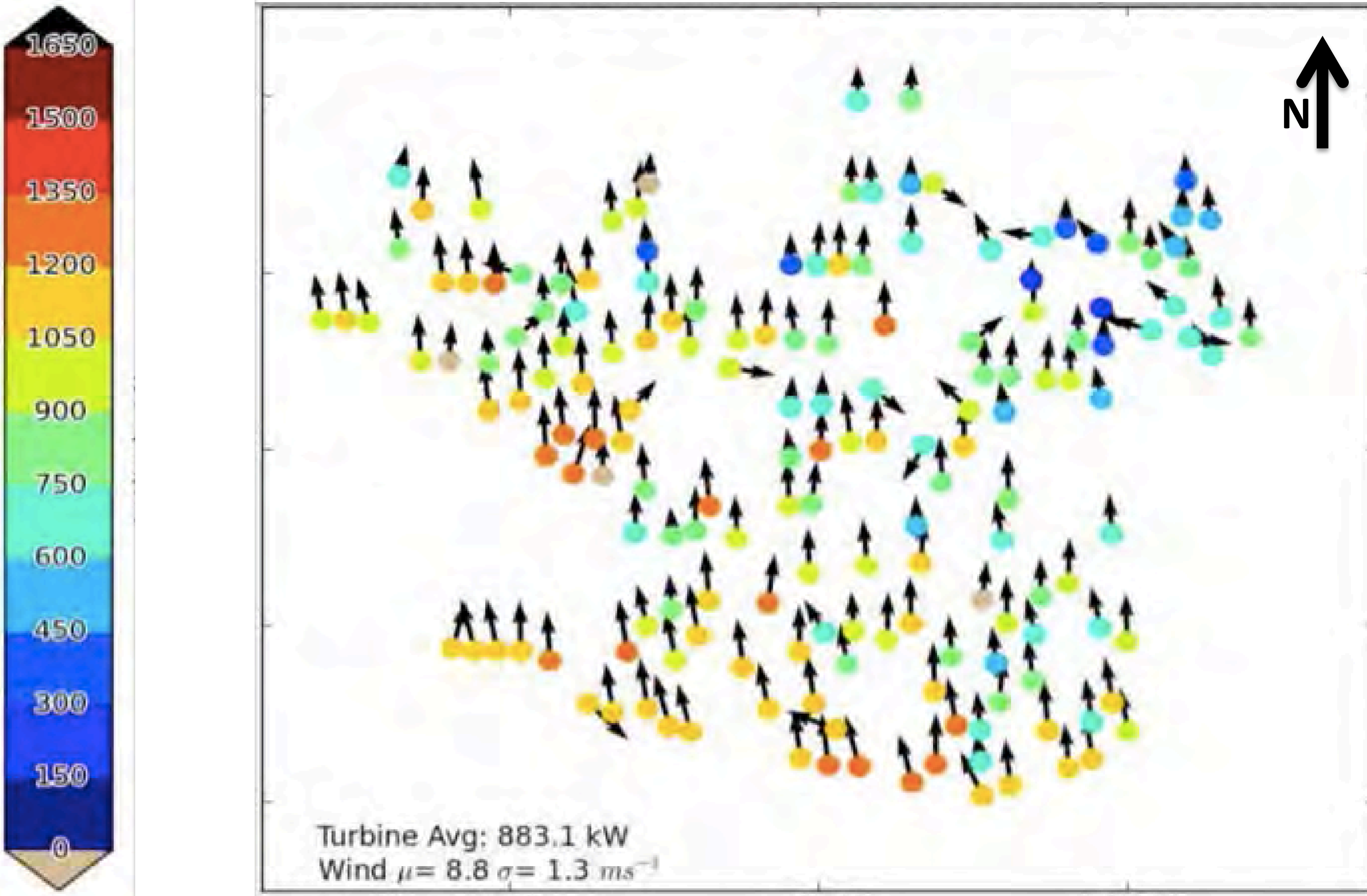


Turbine Interactions

Feb 3:05 AM



Turbine Interactions

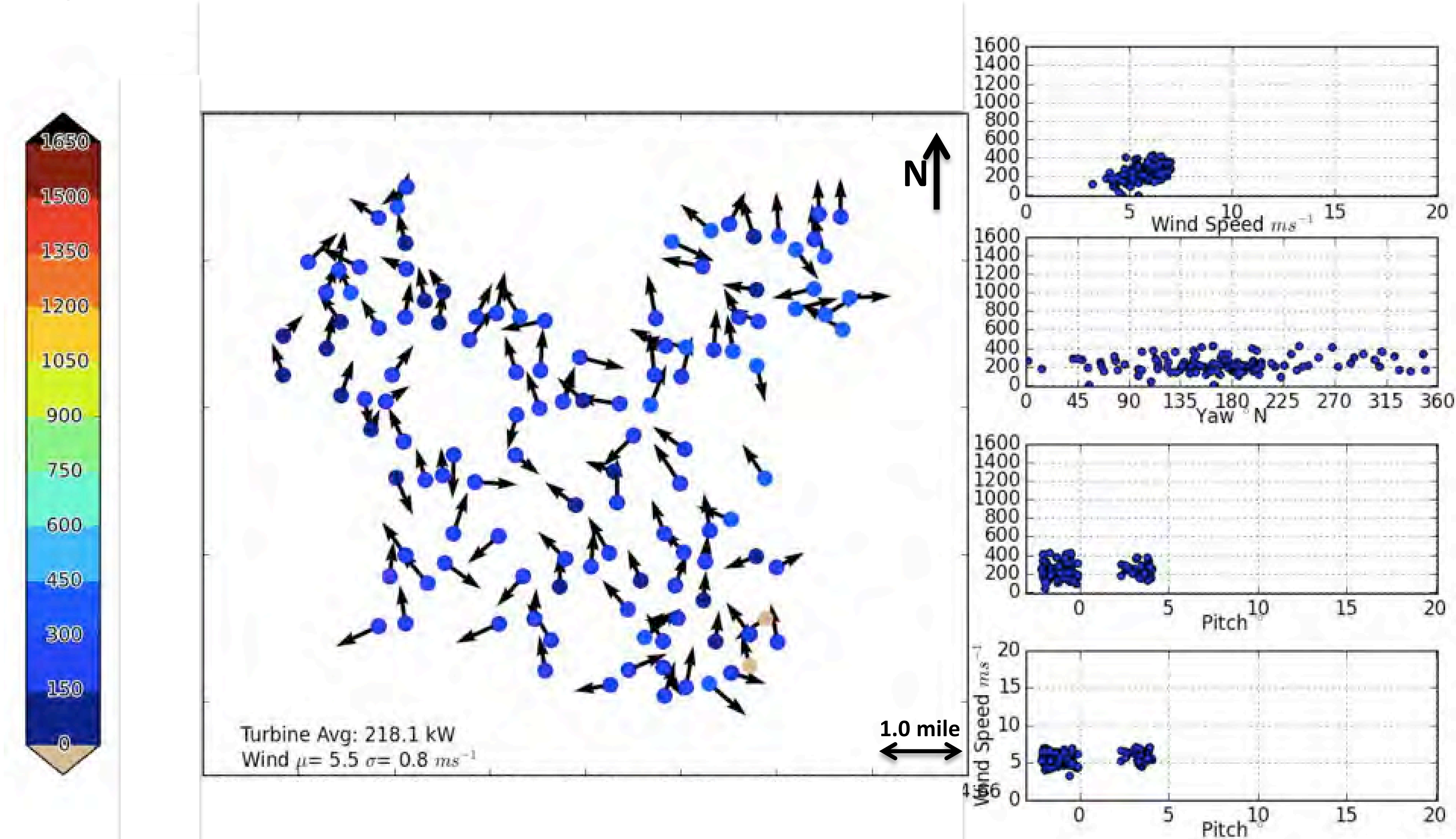


Ramp Event

- Iowa wind farm
- August 2008
- Early morning

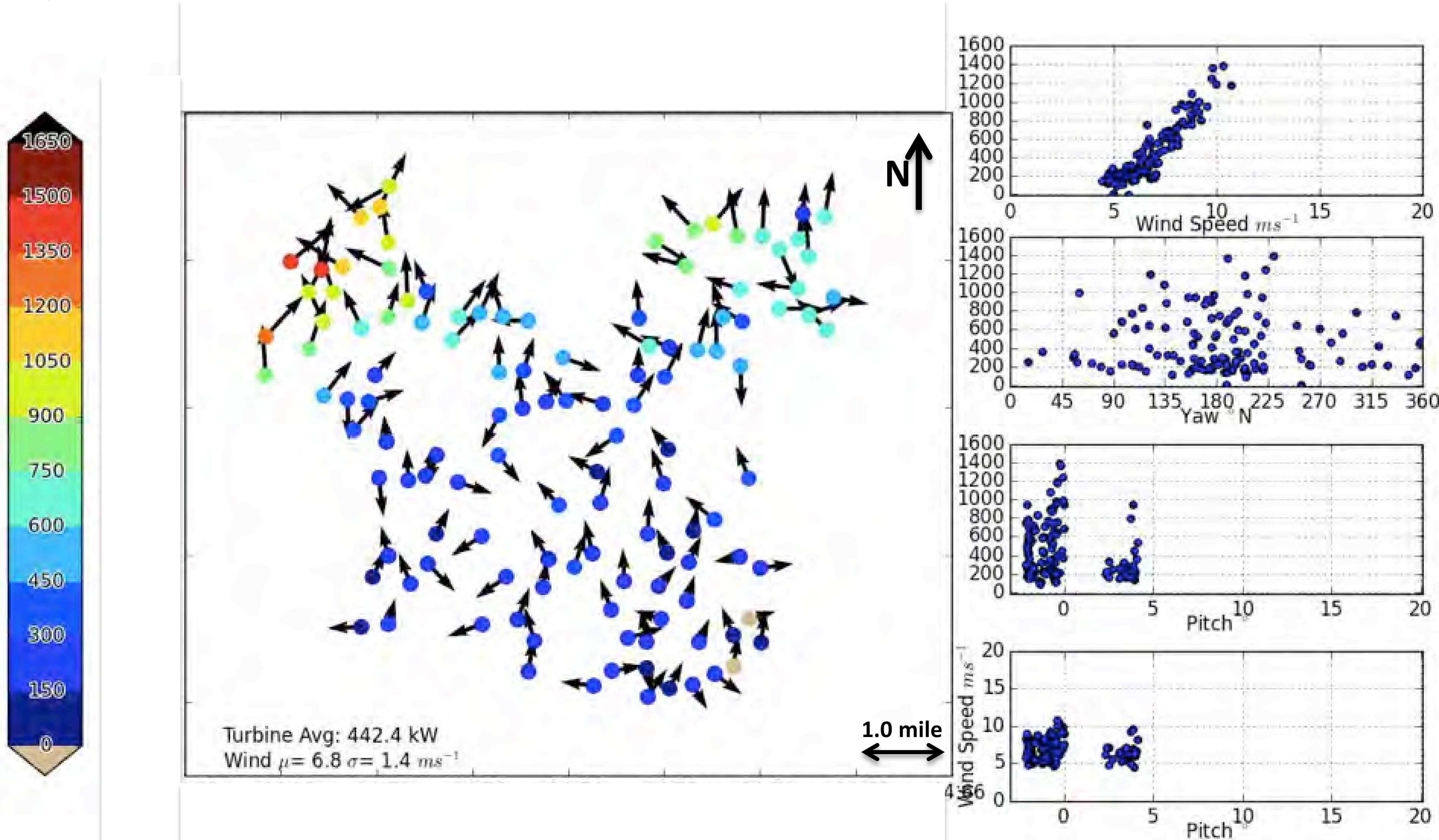
Ramp Event   Iowa Wind Farm   August 2008

Aug 4:35 AM



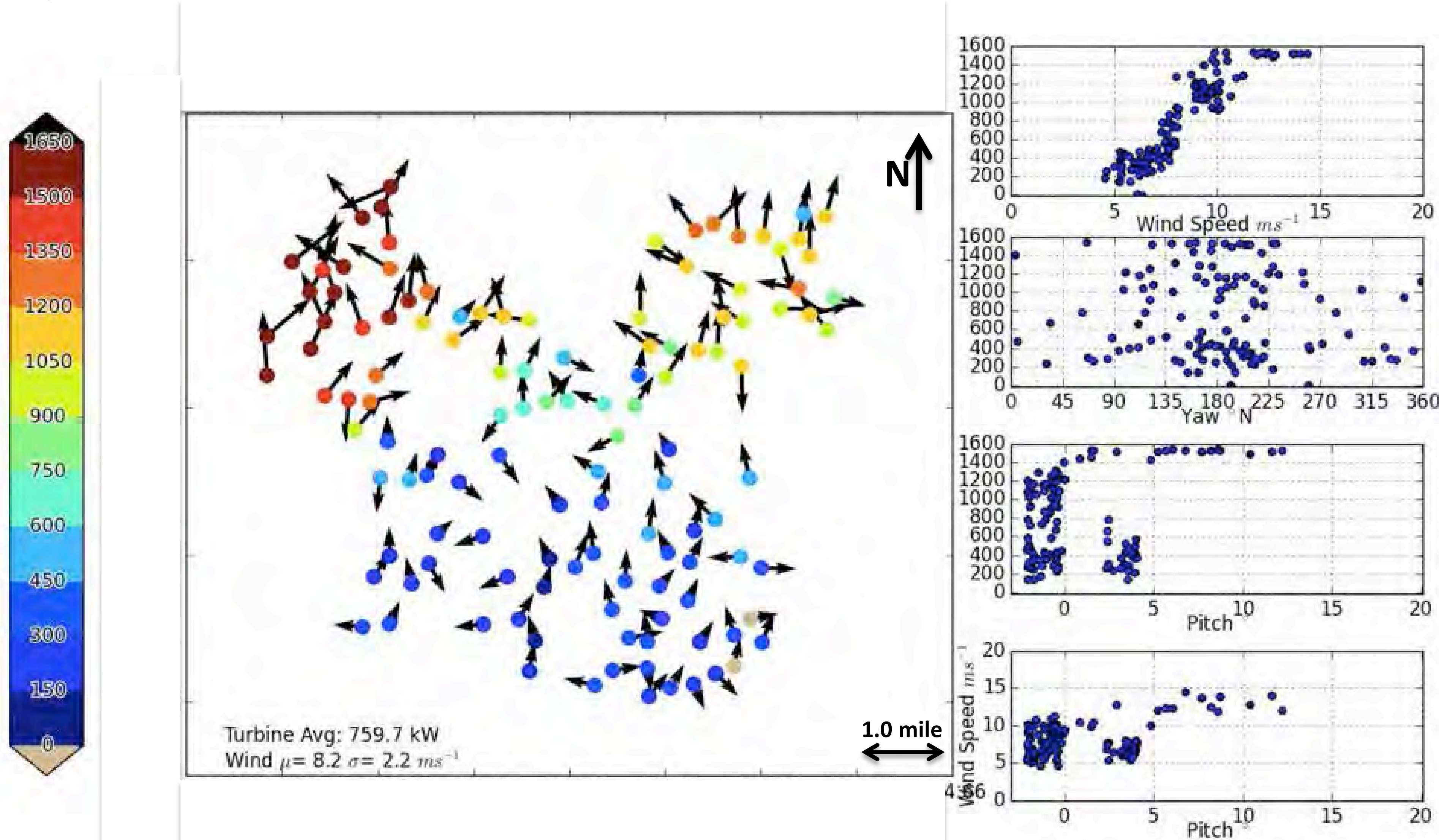
Ramp Event   Iowa Wind Farm   August 2008

Aug 4:45 AM



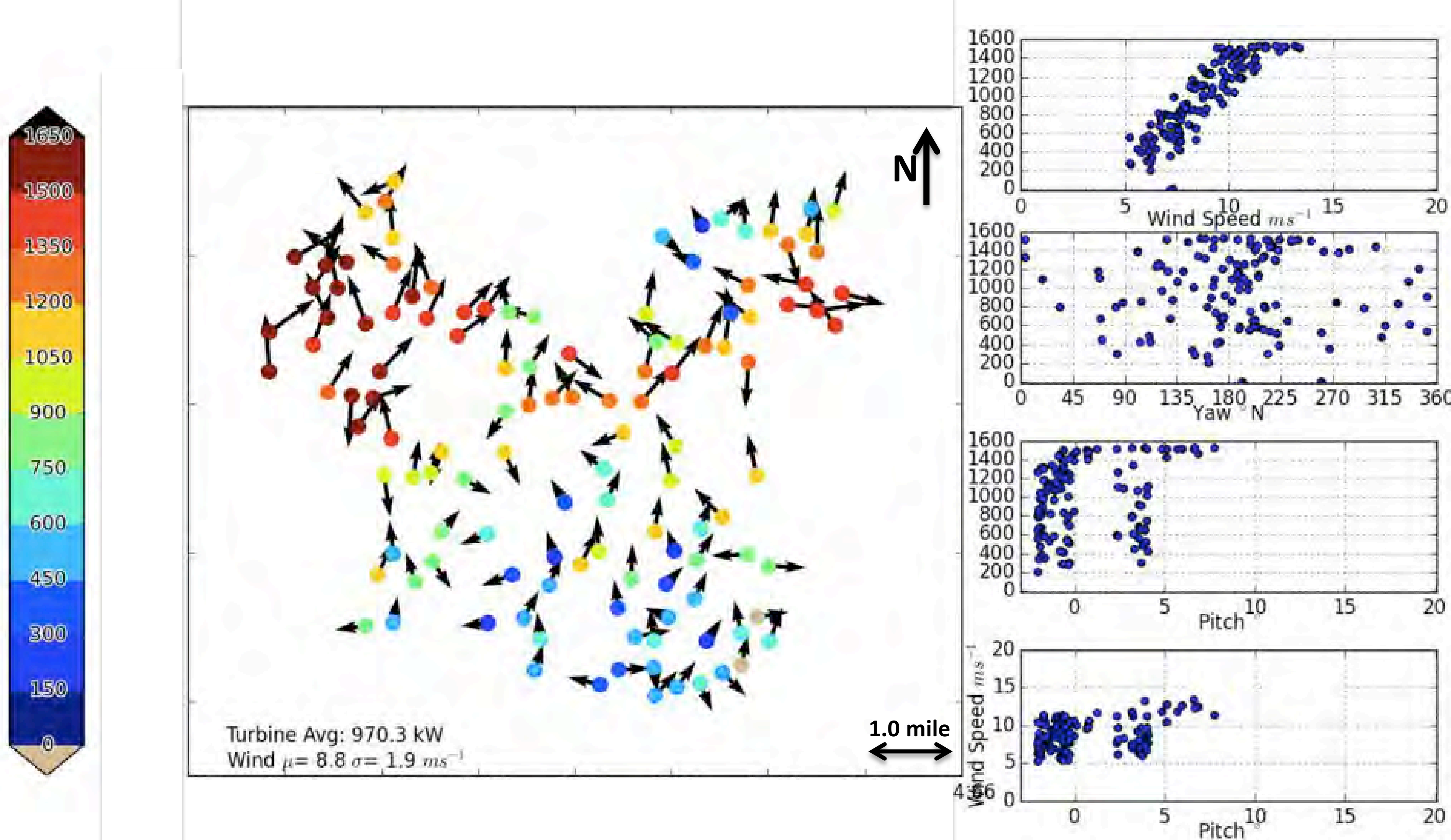
Ramp Event   Iowa Wind Farm   August 2008

Aug 4:50 AM



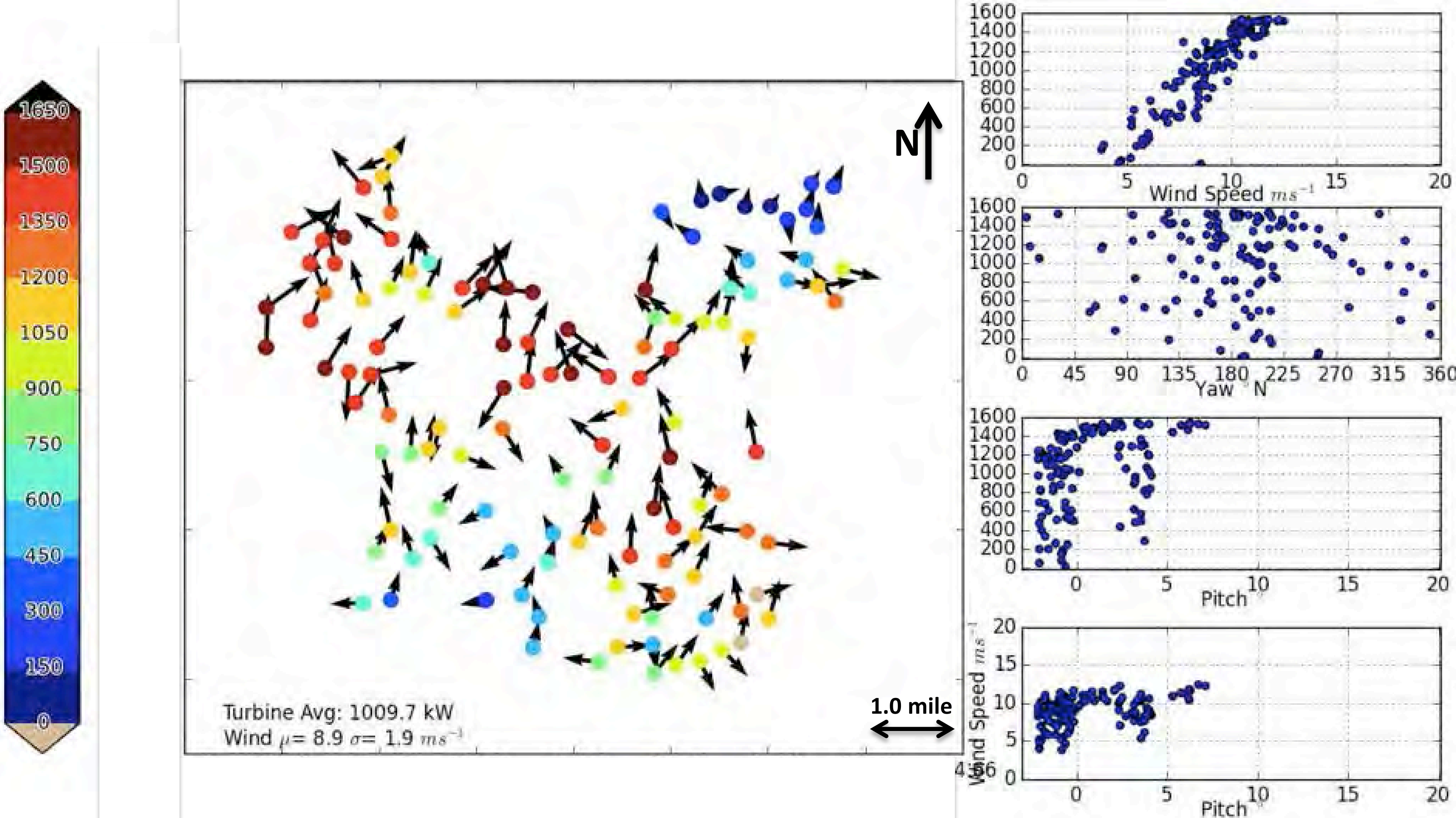
Ramp Event   Iowa Wind Farm   August 2008

Aug 4:55 AM



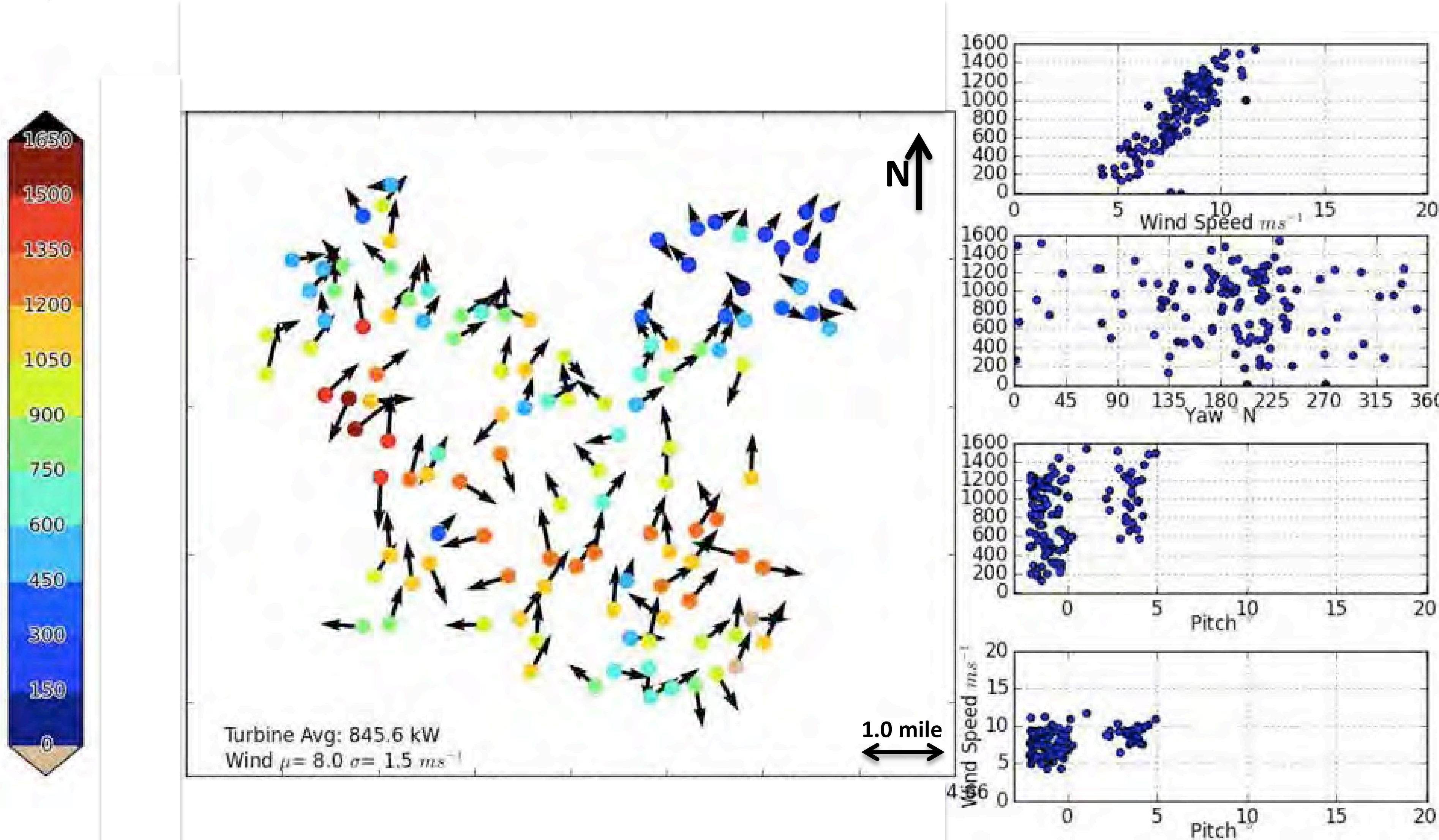
Ramp Event Iowa Wind Farm August 2008

Aug 5:00 AM



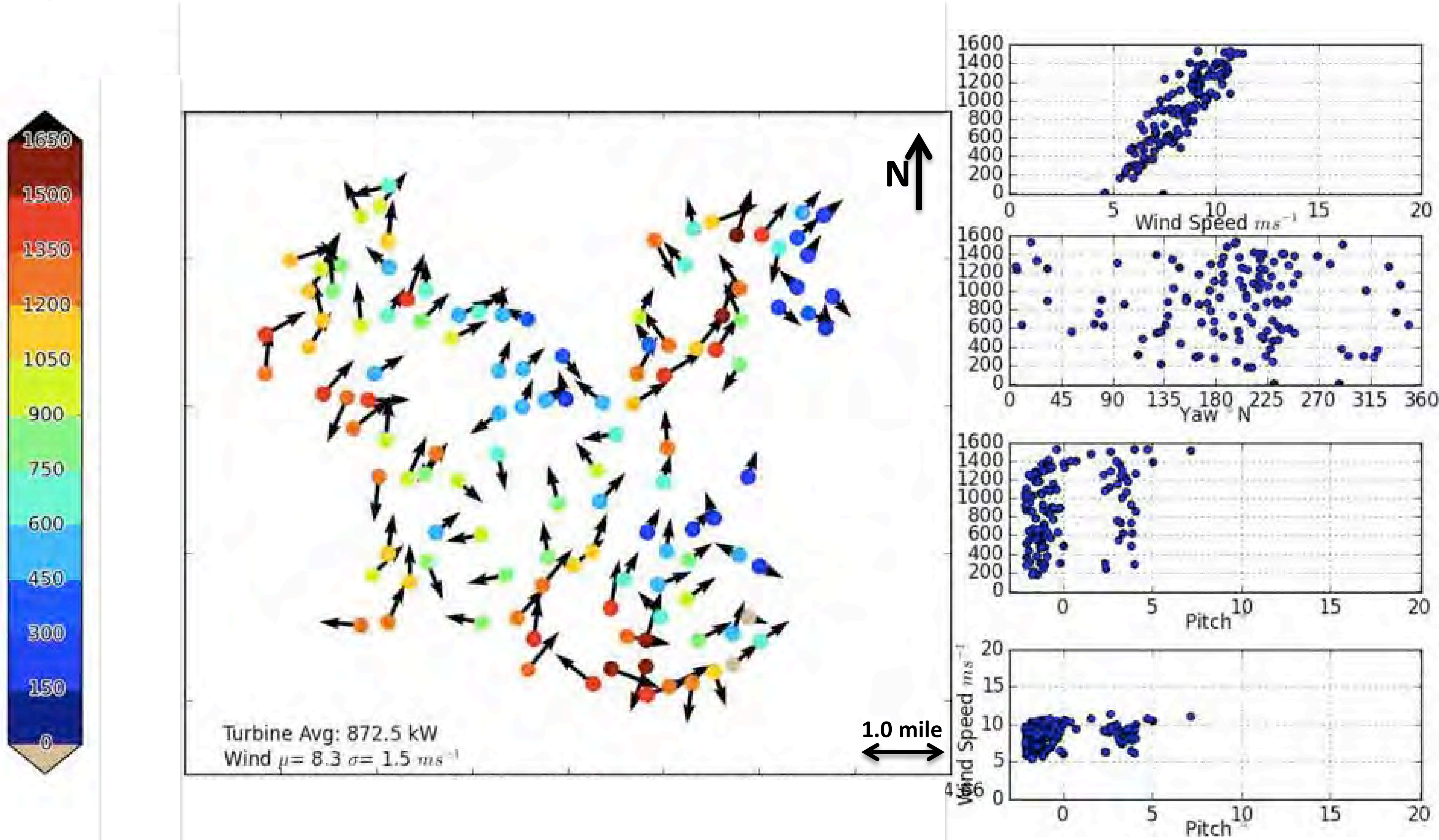
Ramp Event Iowa Wind Farm August 2008

Aug 5:10 AM



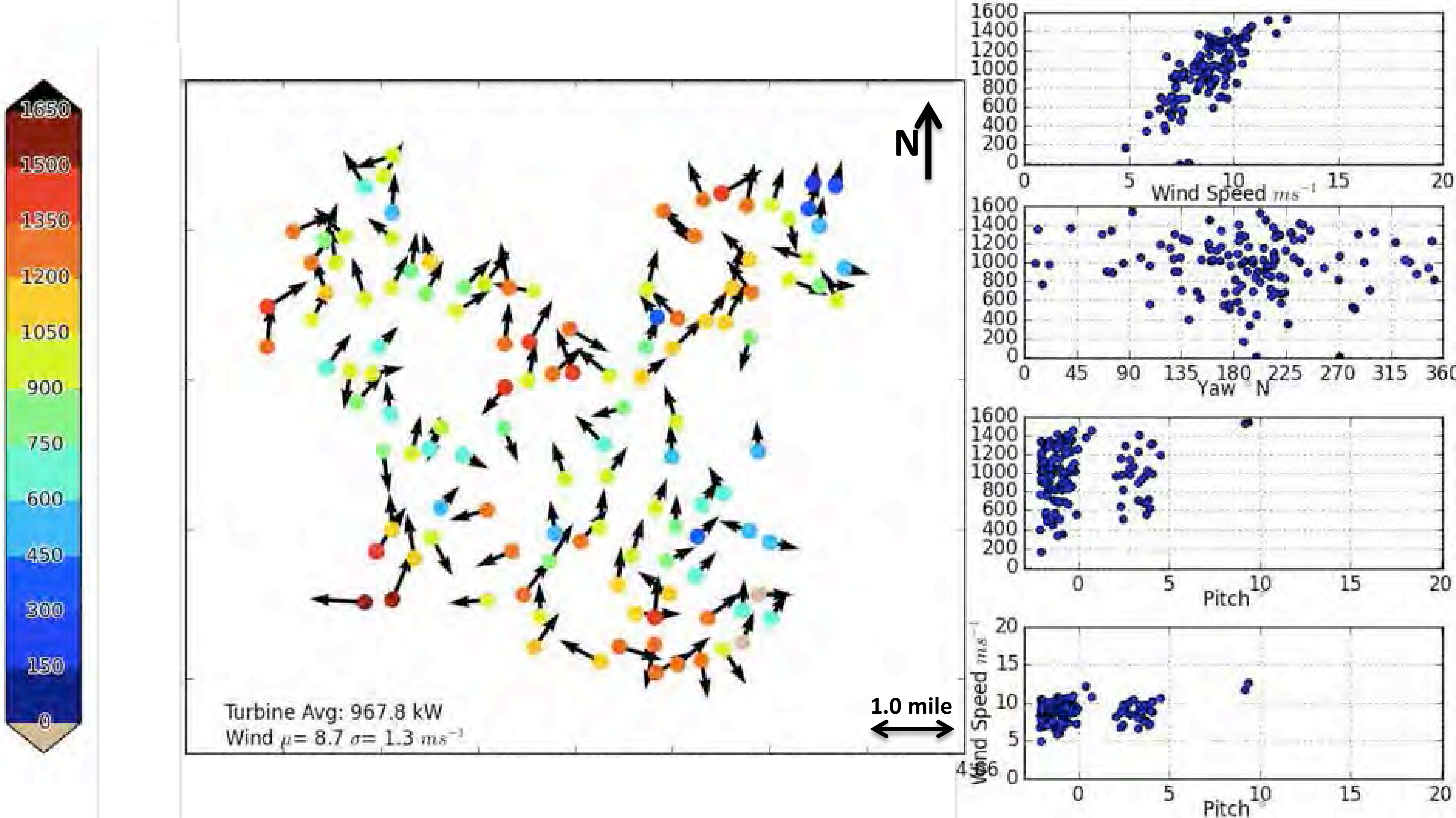
Ramp Event   Iowa Wind Farm   August 2008

Aug 5:20 AM



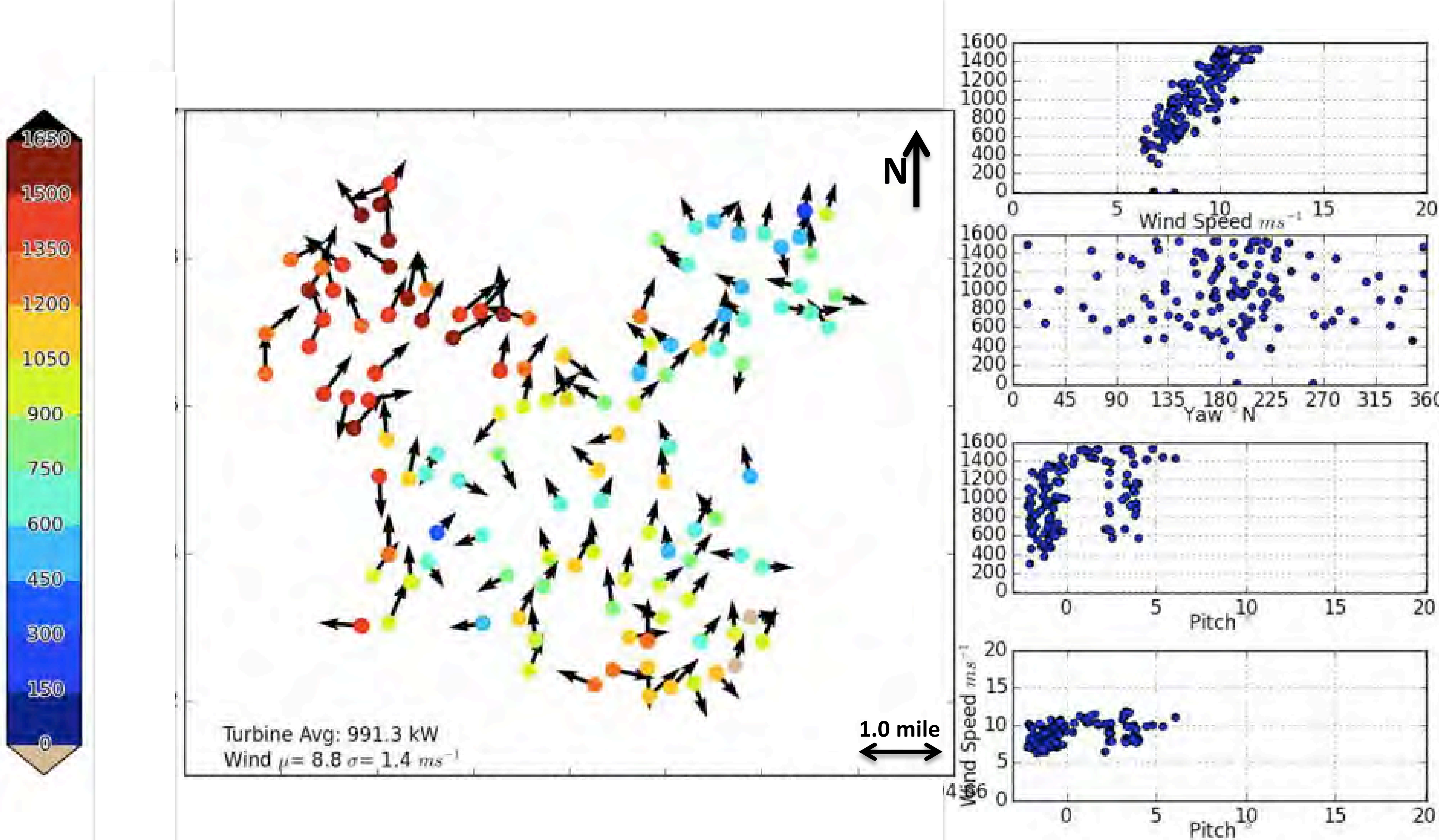
Ramp Event   Iowa Wind Farm   August 2008

Aug 5:30 AM



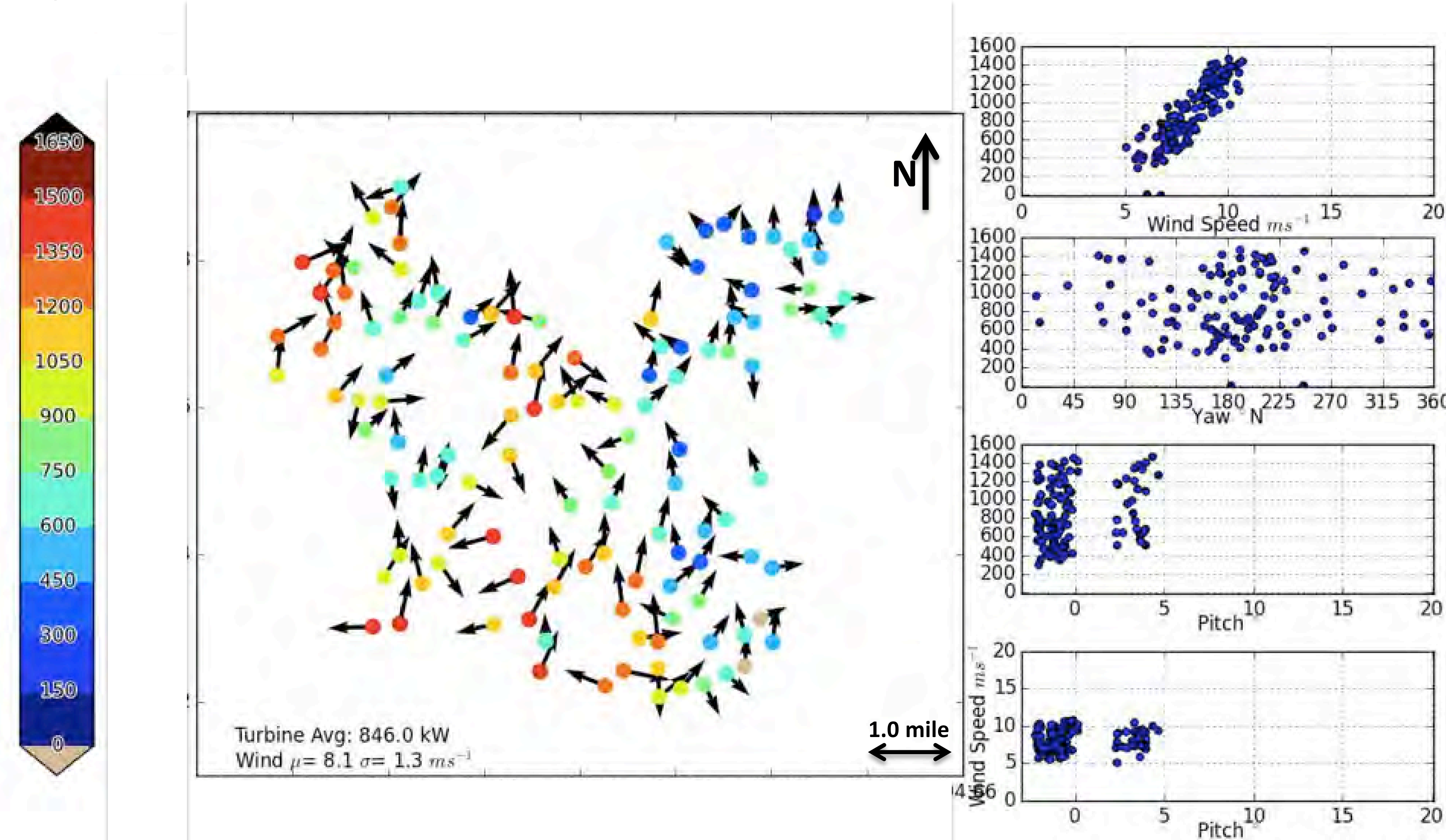
Ramp Event Iowa Wind Farm August 2008

Aug 5:40 AM



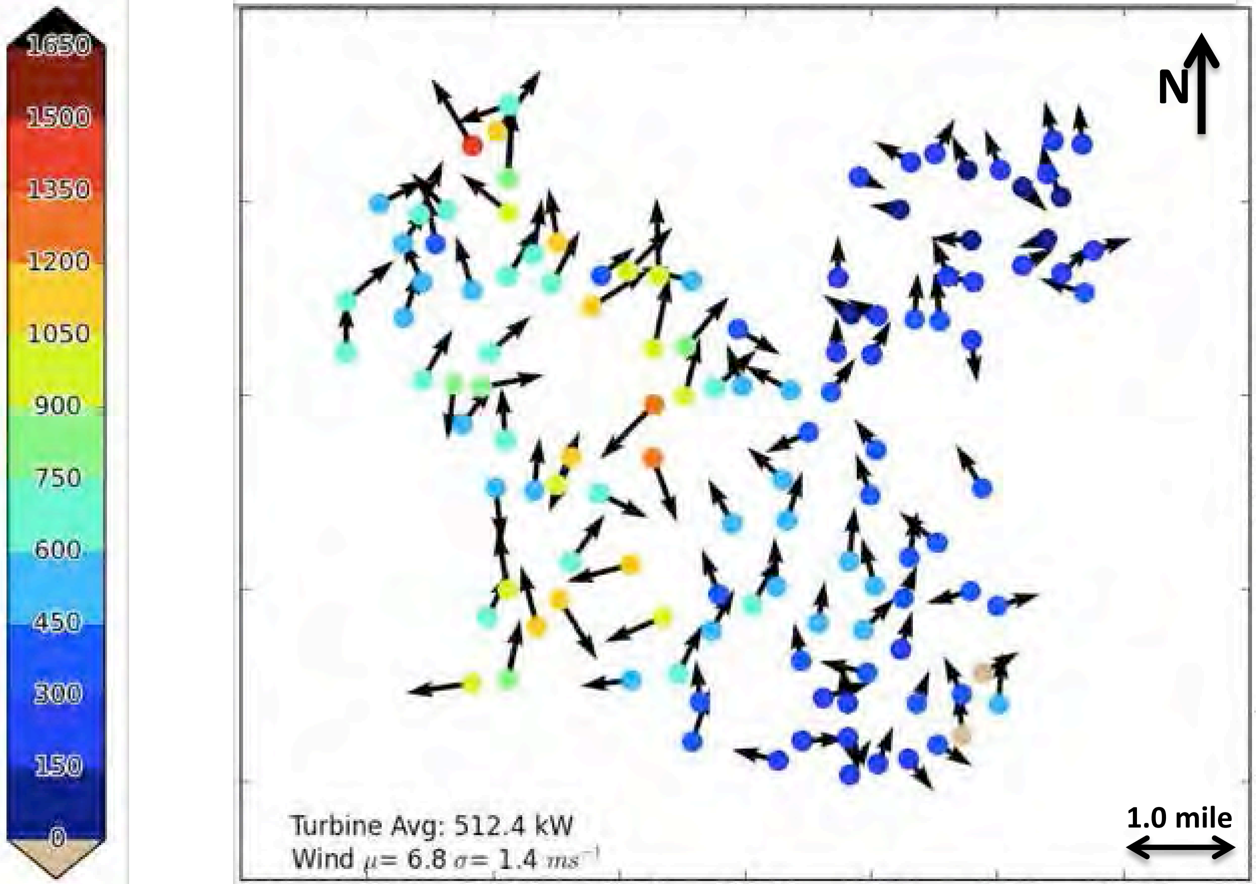
Ramp Event Iowa Wind Farm August 2008

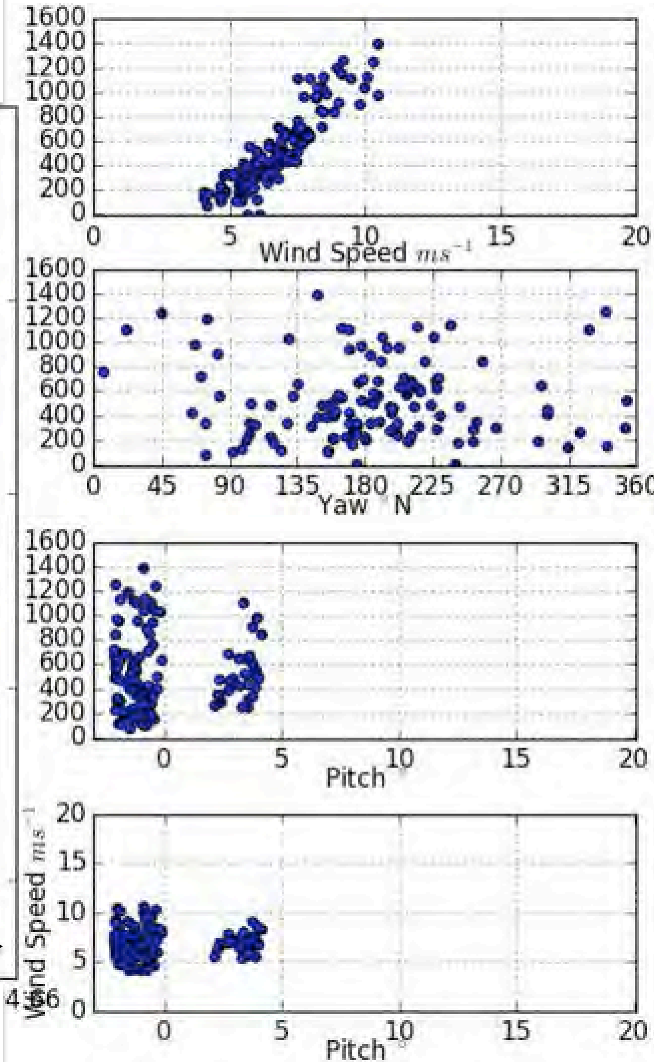
Aug 5:50 AM



Ramp Event Iowa Wind Farm August 2008

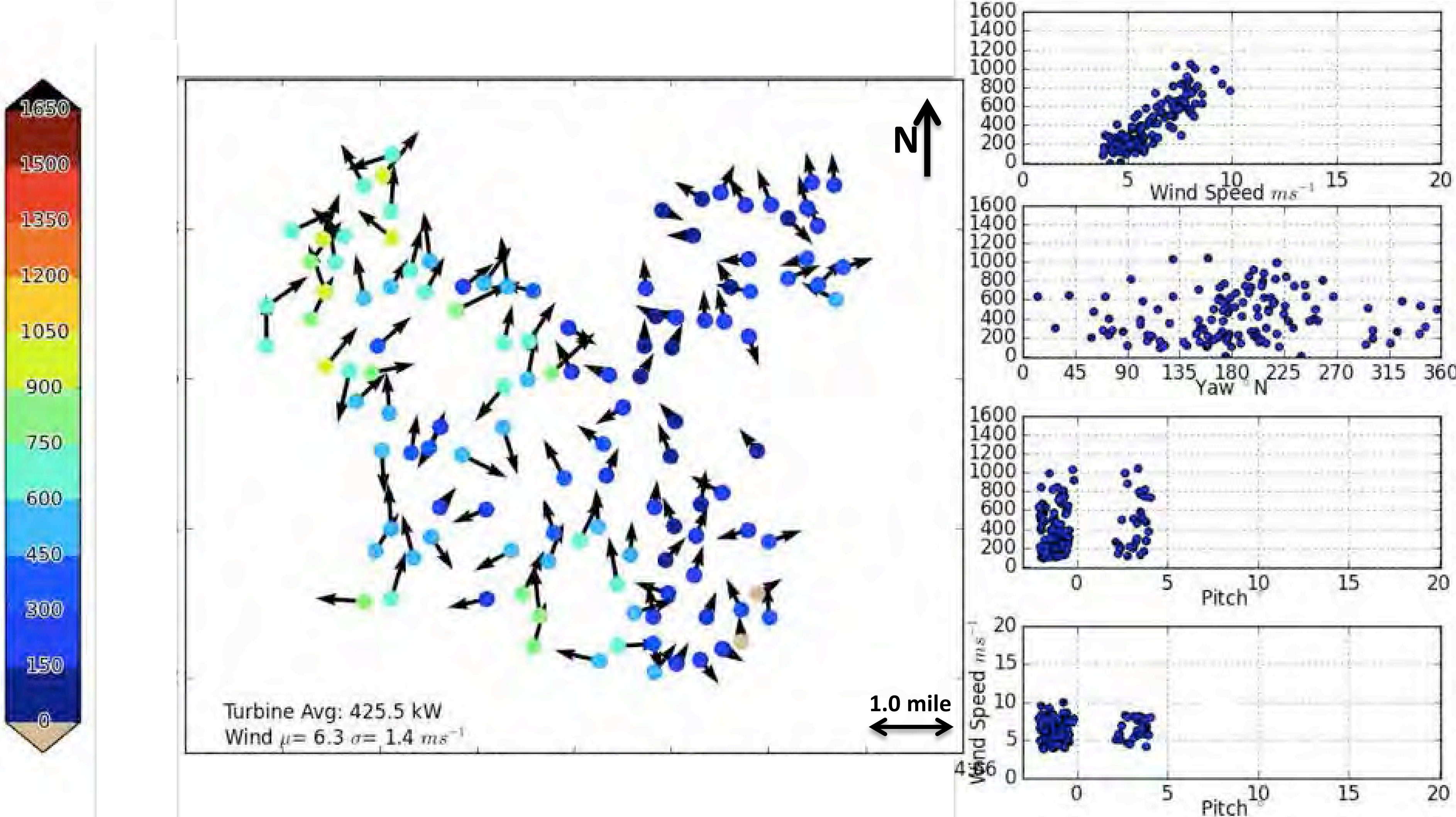
Aug 6:00 AM





Ramp Event   Iowa Wind Farm   August 2008

Aug 6:10 AM



Summary

- Power forecasting for wind farms involves wind direction, wind shear, stability, and ramps in addition to wind speed
- Measurements in operating wind farms help us understand wake structure, evolution and interaction with downwind turbines
- Visualization and animation of wind farm performance offers new understanding of wind farm power production

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Photo courtesy of Lisa H Brasche