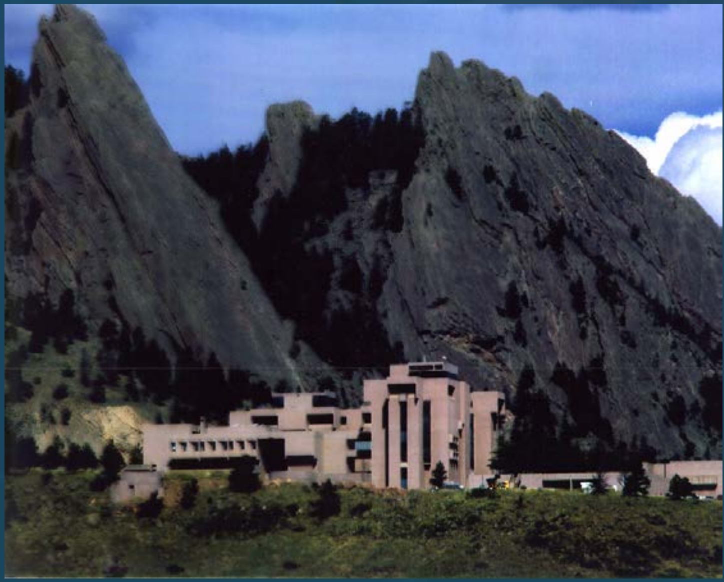
National Center for Atmospheric Research
Research Applications Laboratory

Winter Wind Energy Research at NCAR

Sue Ellen Haupt

What is the US National Center for Atmospheric Research (NCAR)?

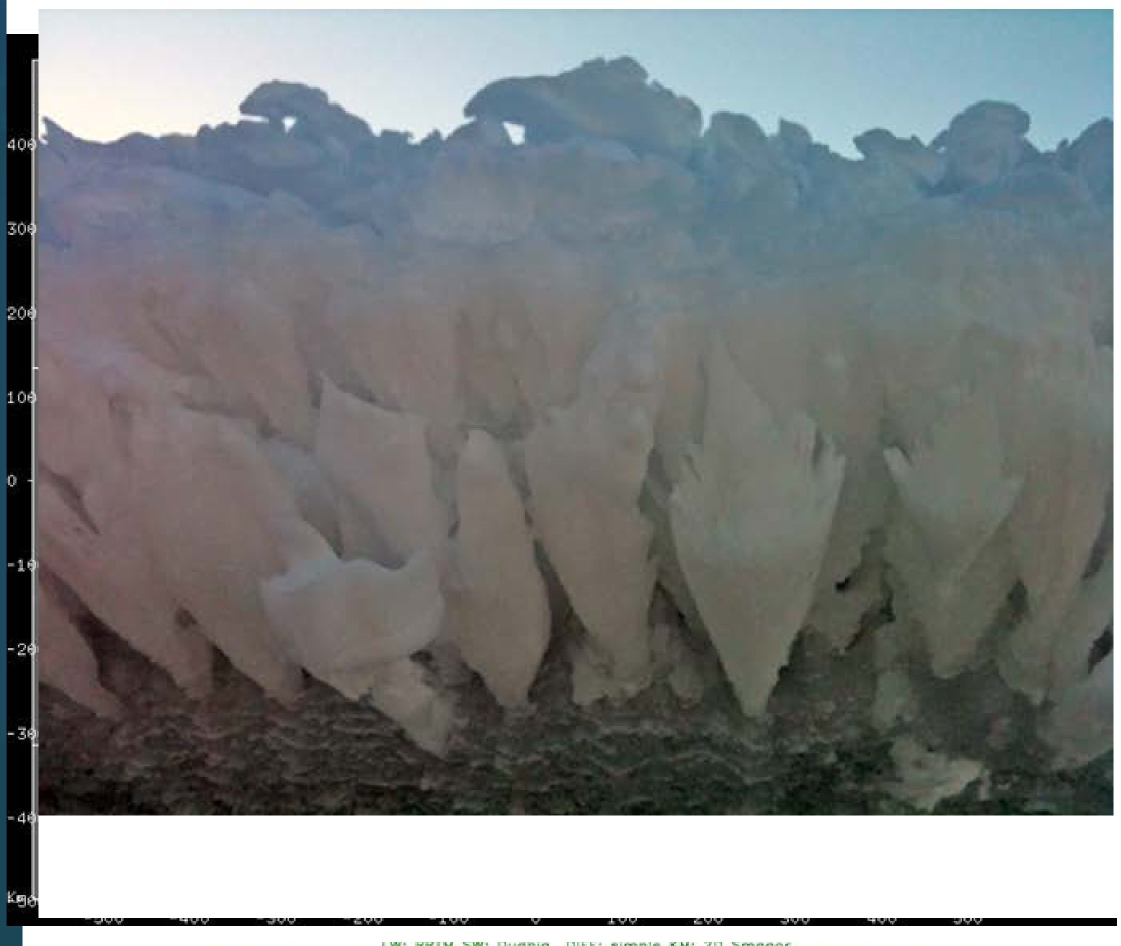
- NCAR is a Federally funded research and development center sponsored by the National Science Foundation.
- NCAR is operated by the University Corporation for Atmospheric Research (UCAR), a non-profit corporation.
- UCAR has 1400 employees and ~$250M budget.
- Research is conducted on weather and climate modeling, renewable energy, thunderstorms, hurricanes, icing, turbulence, societal impacts of weather, air chemistry, solar physics, etc.



NCAR, Boulder, CO

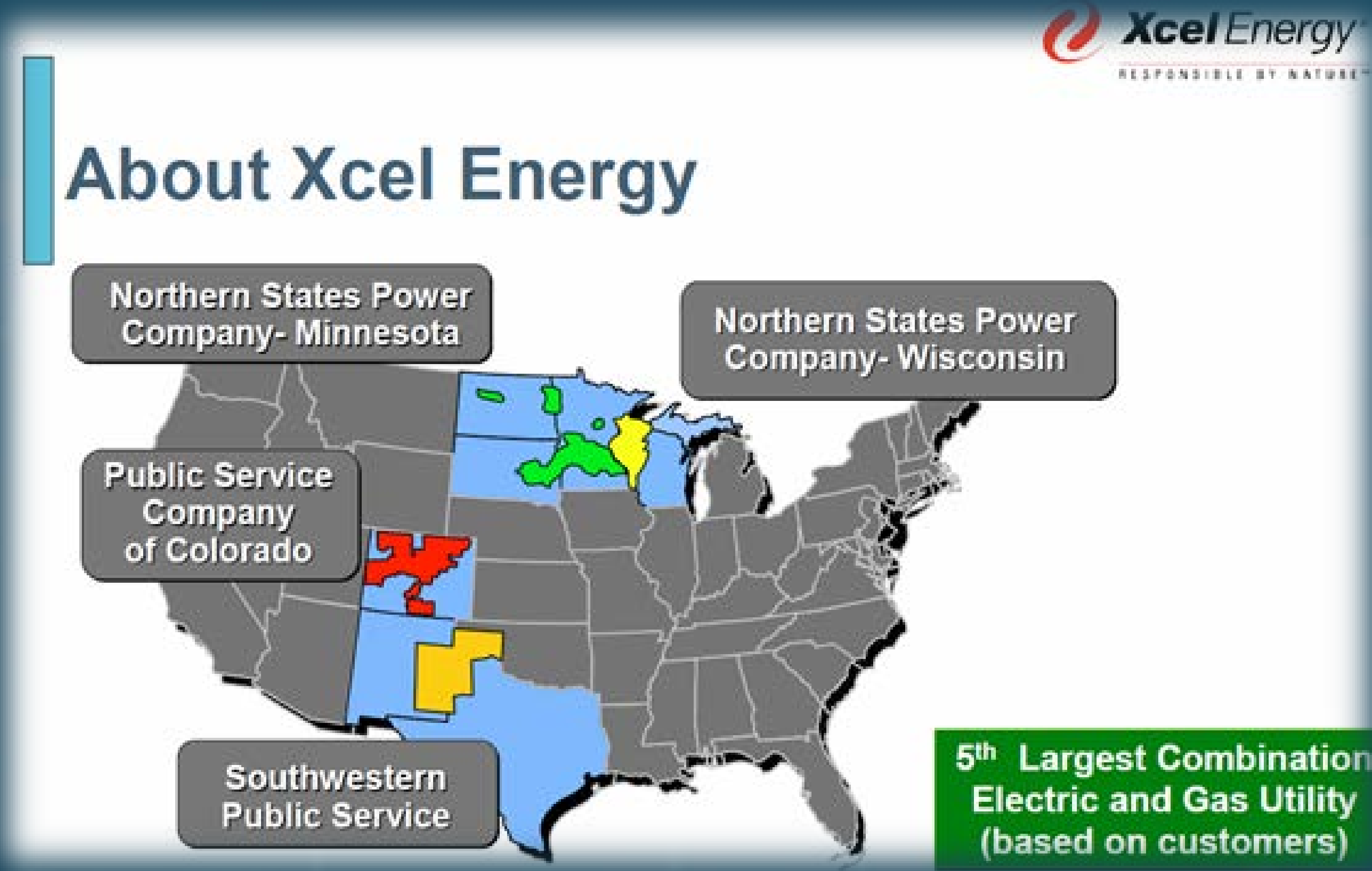
Wind Energy Research

Icing Research



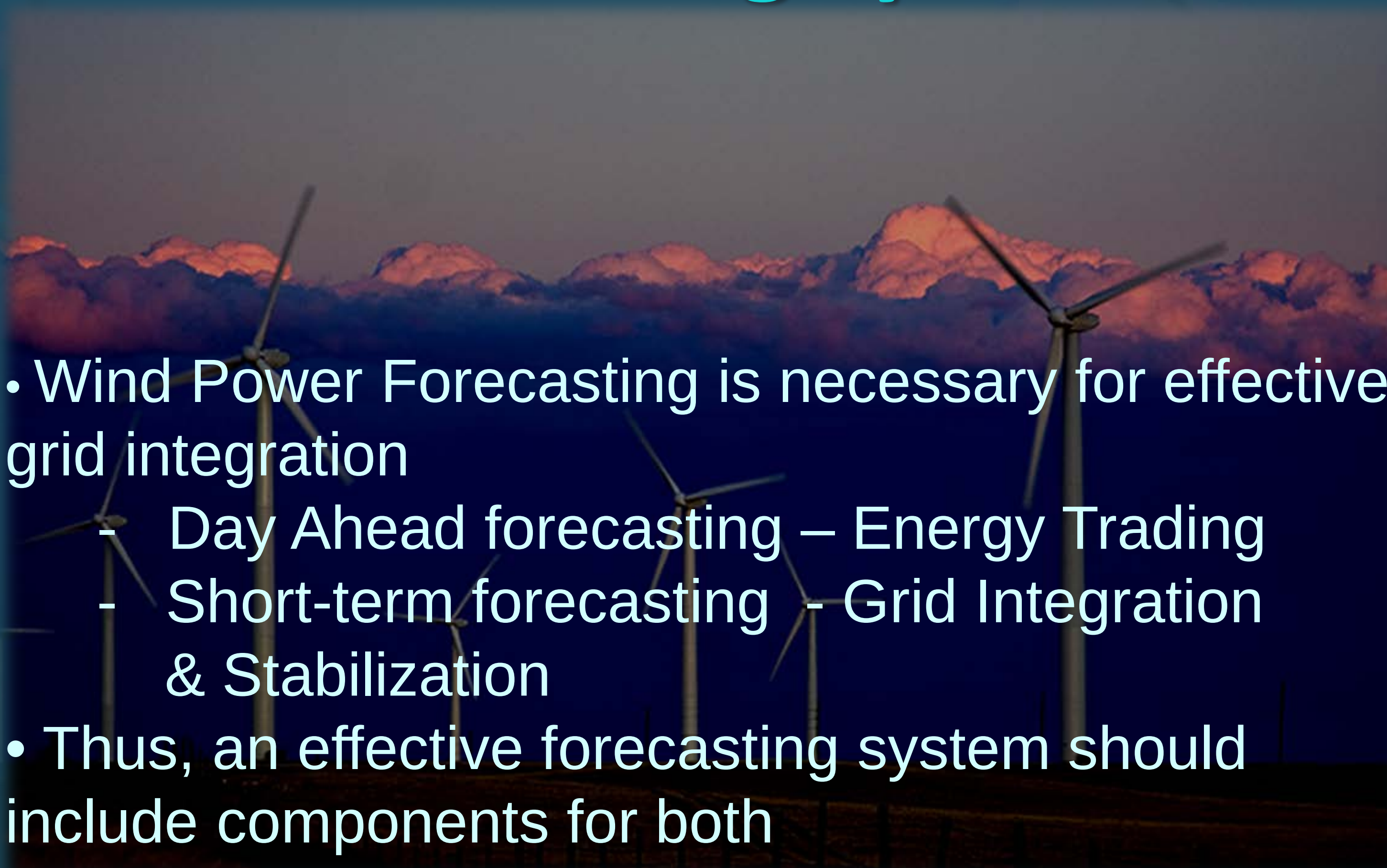
Greg Thompson
Bjorn-Egil Nygaard
(Oslo Univ)
Marcia Politovich
Frank McDonough

Xcel Energy Wind Prediction Project



3.4 million customers annual revenue $11B

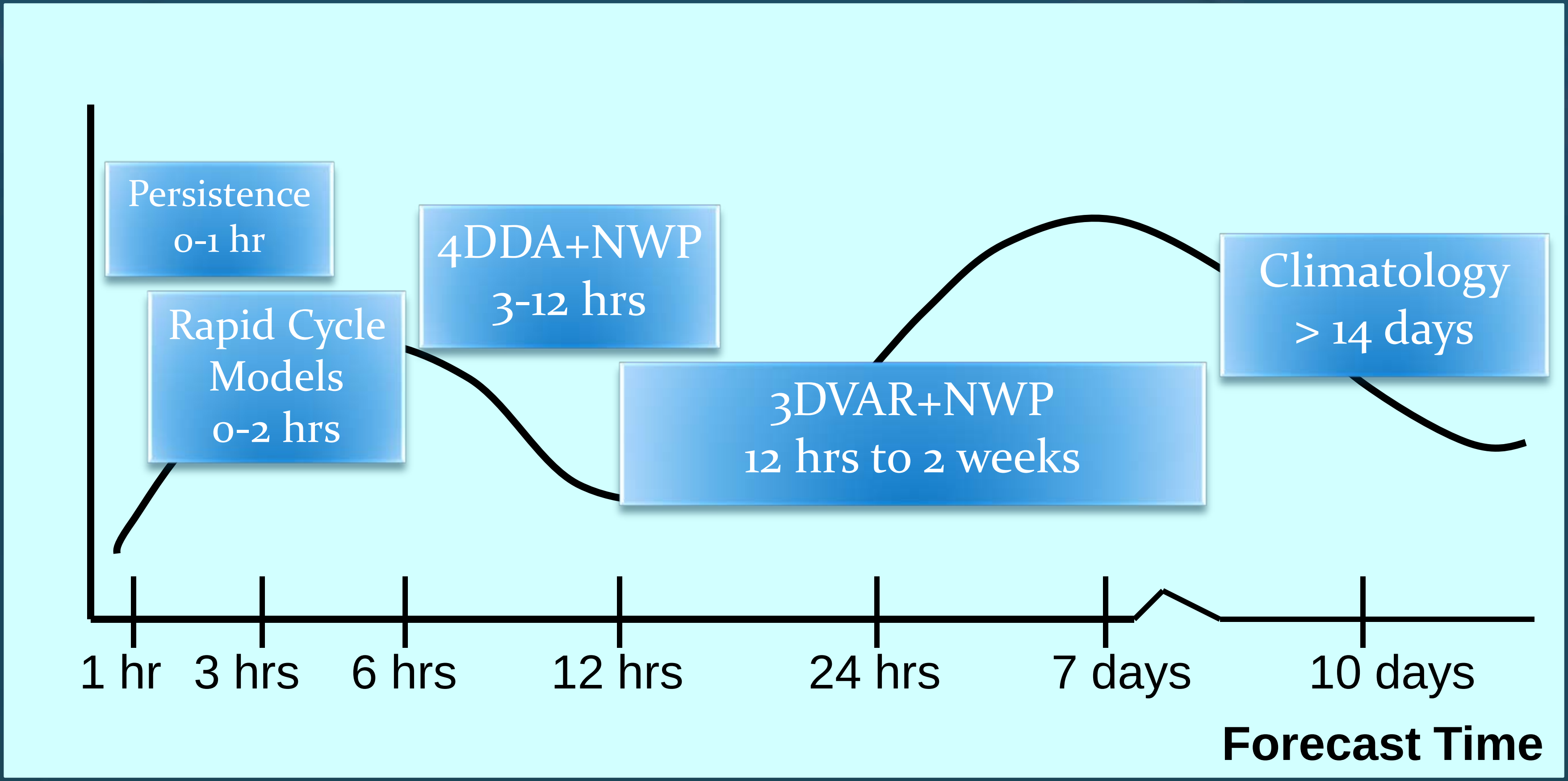
Needs for Wind Power Forecasting Systems



- 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



Xcel Energy Variable Energy Forecasting System

Center Data
NAM, GFS, HRR, RAP, ECMWF, GEM

Wind Farm Data
Nacelle wind speed
Generator power
Node power
Met tower
Availability

WRF RTFDDA System

Ensemble System

Solar Energy Forecast

Supplemental Wind Farm Data
Met towers
Wind profiler
Surface Stations
Windcube Lidar

Dynamic, Integrated Forecast System (DICast®)

VDRAS (nowcasting)

Expert System (nowcasting)

Extreme Weather Events

Statistical Verification

Wind to Energy Conversion Subsystem

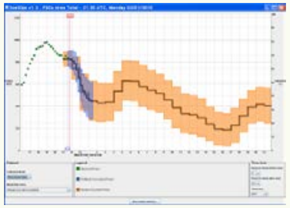
Potential Power Forecasting

Data Mining for Load Estimation

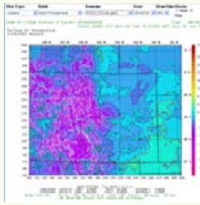
Probabilistic and Analog Forecast

CSV Data

Operator GUI



Meteorologist GUI



WRF Model Output

WRF RTFDDA Model Domains

Deterministic System

Ensemble System (30 members)

D1 = 30 km 0-72 hrs
D2 = 10 km 0-72 hrs
D3 = 3.3 km 0-24 hrs

D1 = 30 km 0-48 hrs
D2 = 10 km 0-48 hrs

Vary:
- Multi-models
- Lateral B.Cs.
- Model Physics
- External forcing

41 vertical levels

Yubao Liu

Real Time Four Dimensional Data Assimilation

DICast Integrator System

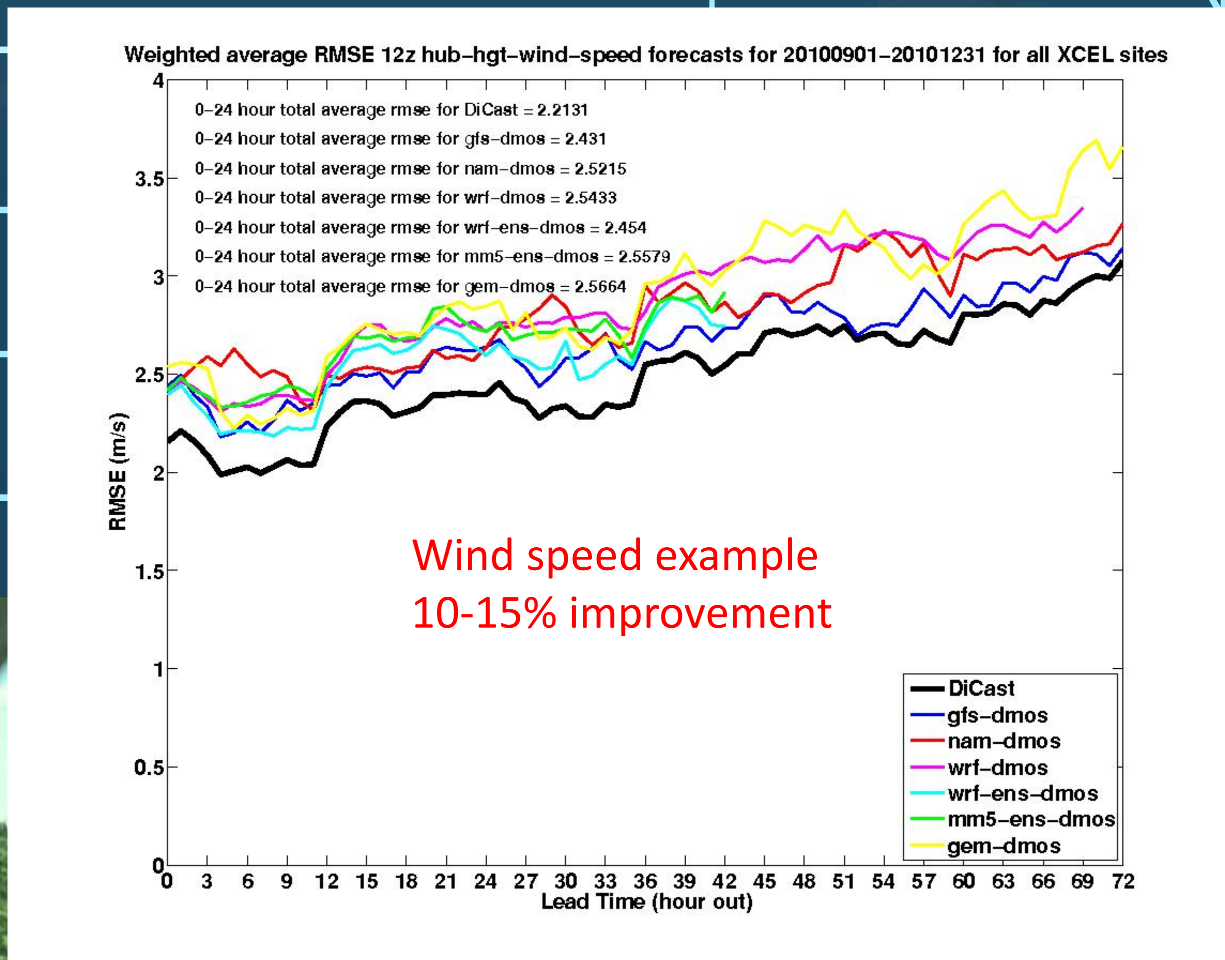
Model Optimization via Dynamic Weighting and Bias Removal

Nacelle Winds

ator

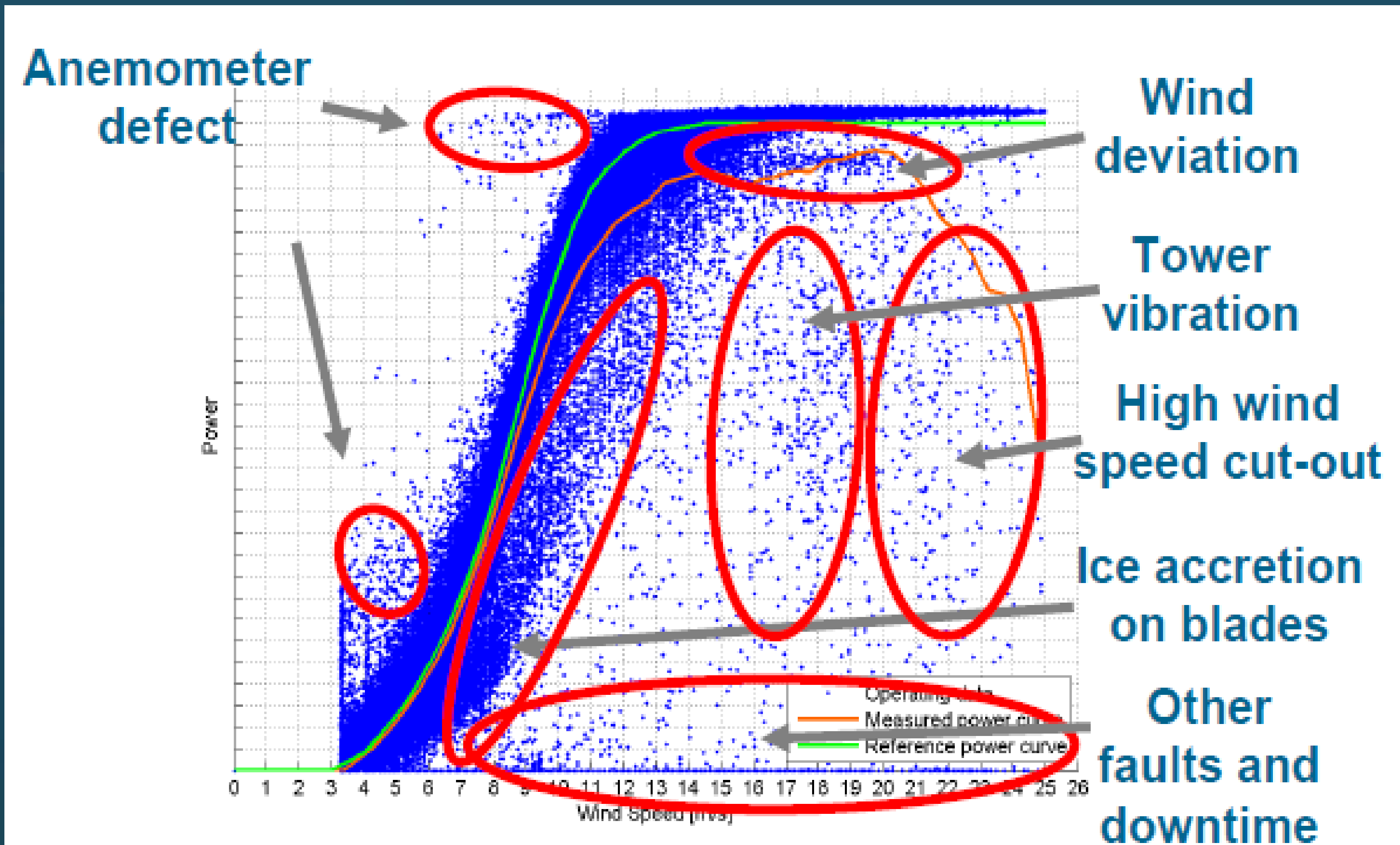
Power
tion

Power
cast



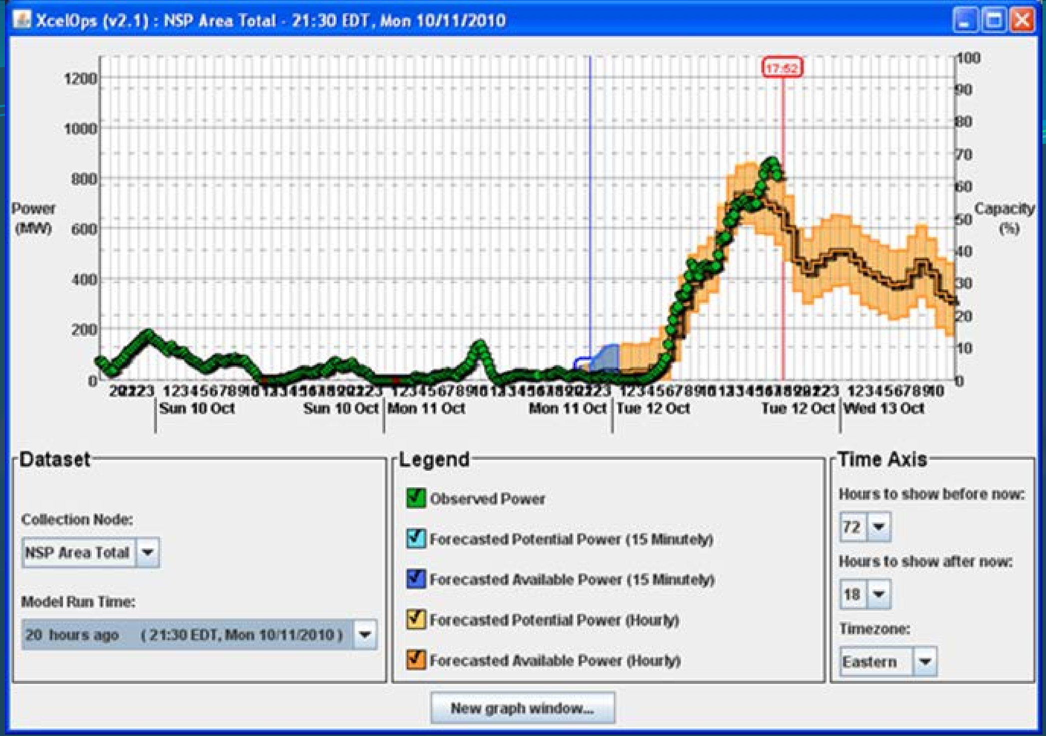
Bill Myers

Empirical Power Conversion Curves



Not Straightforward!

Gerry Wiener

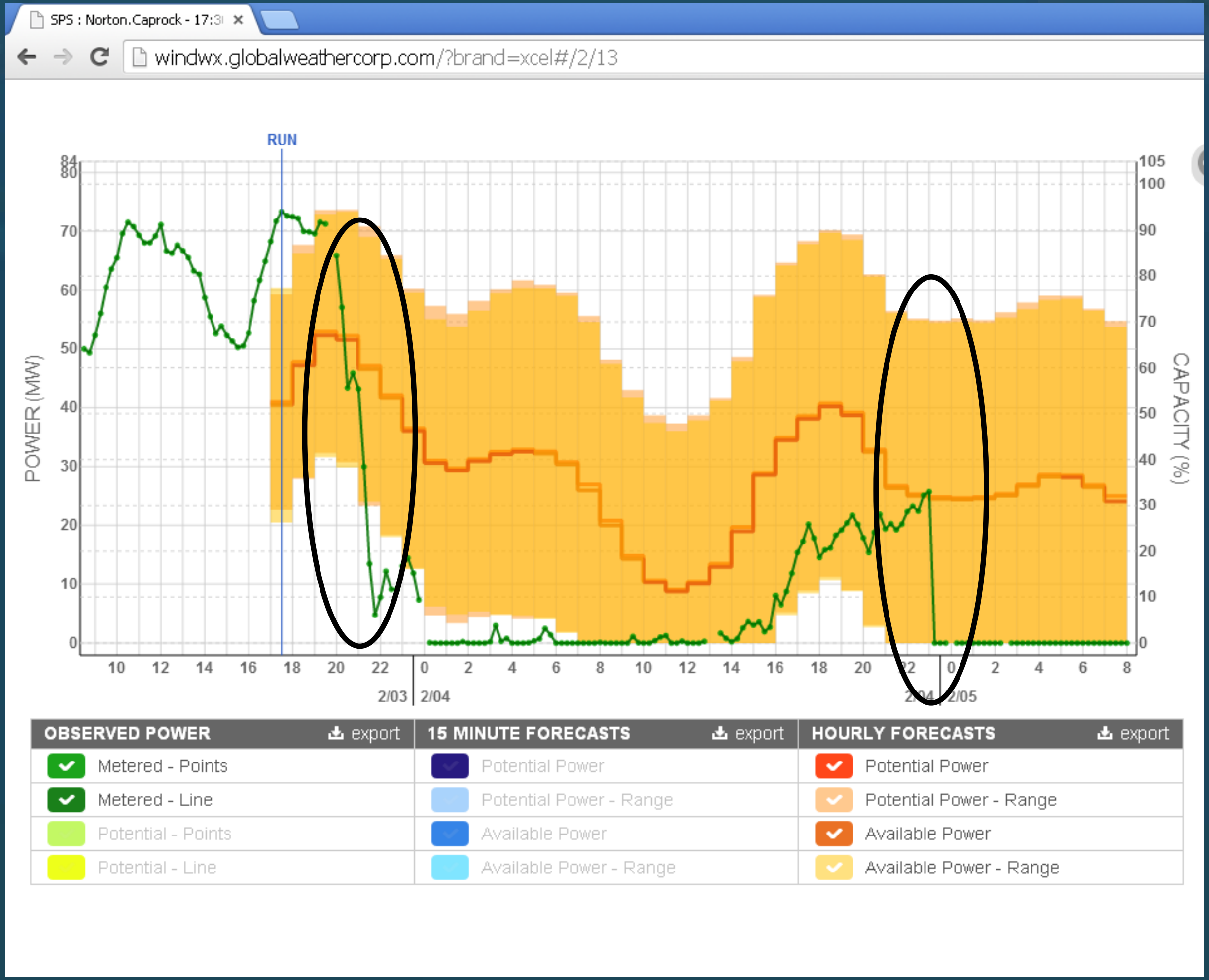


VG Forecast Value for Xcel Energy

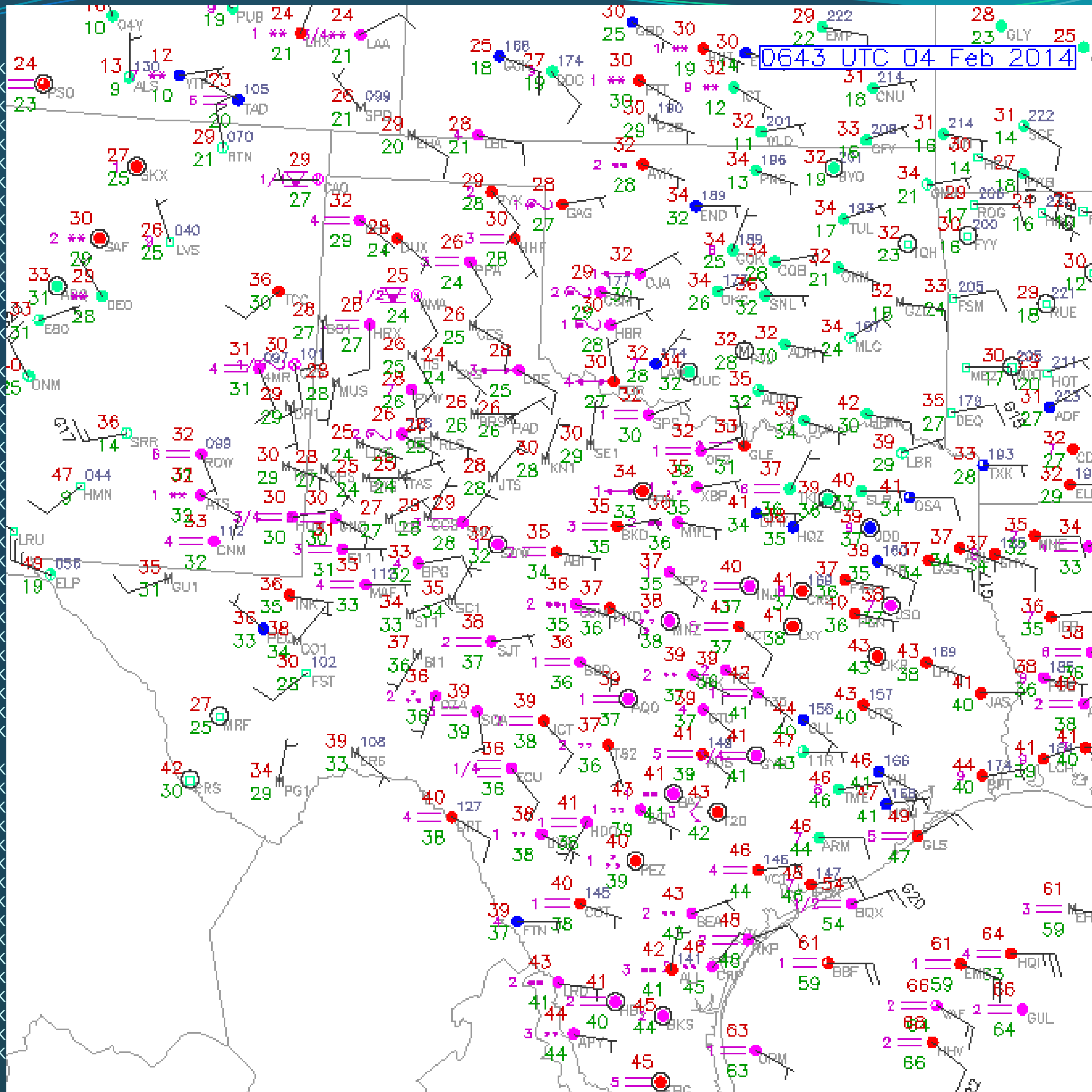
	Forecasted MAE 2009	Forecasted MAE 2012	Total Improvement	Percentage Improvement	Total Savings ($000,000)
PSCo	18.0%	12.2%	5.8%	32.4%	$11.6
NSP	15.7%	9.7%	6.0%	38.1%	$9.0
SPS	16.3%	13.5%	2.9%	17.5%	$1.2
Xcel	**16.8%**	**11.5%**	**5.4%**	**31.9%**	**$21.8**

Drake Bartlett, Xcel

But there can be some interesting occurrences …



48 hr forecast – run Mon 03 Feb 2014



1078 58007

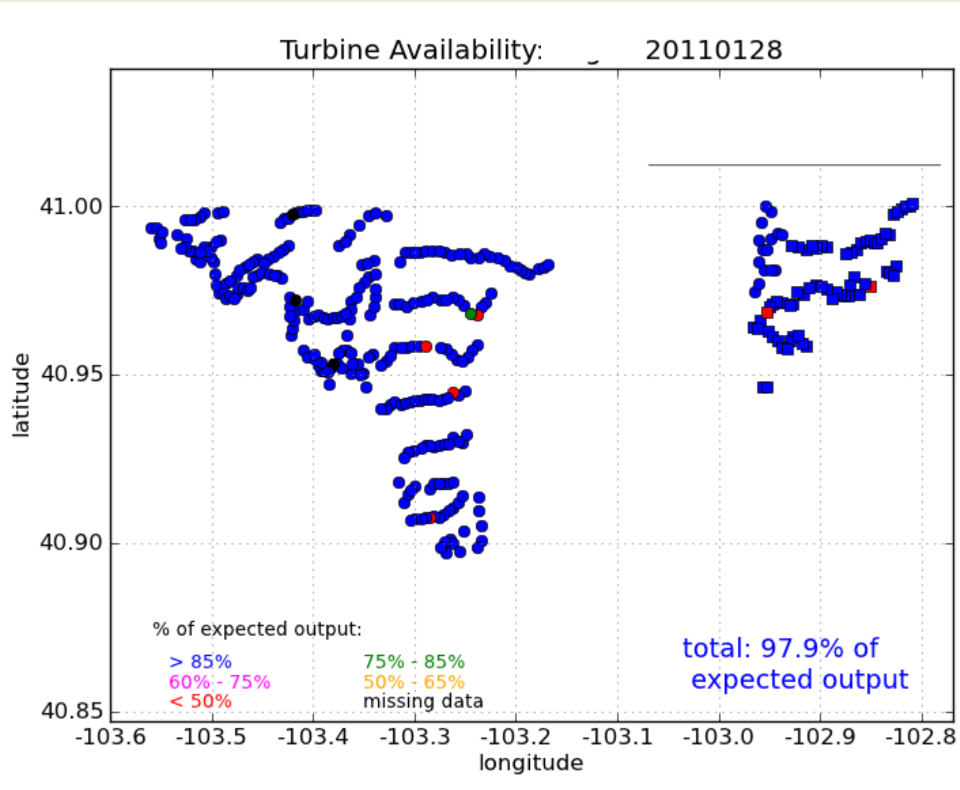
72 58002

A prior Case in Colorado: January 30 – February 2, 2011

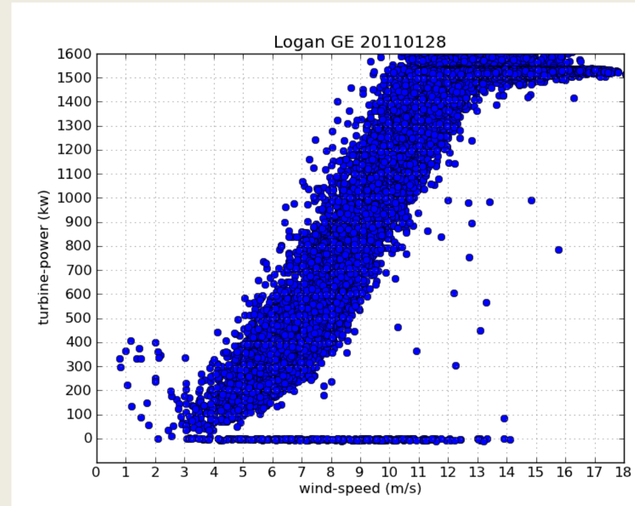
Two Colorado Wind Farms with heavy icing

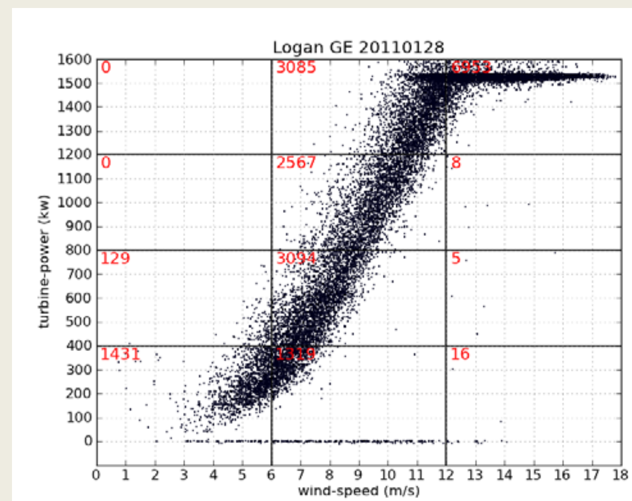
- Can we data mine to see it?
- What caused it?

Jan 28: two days prior



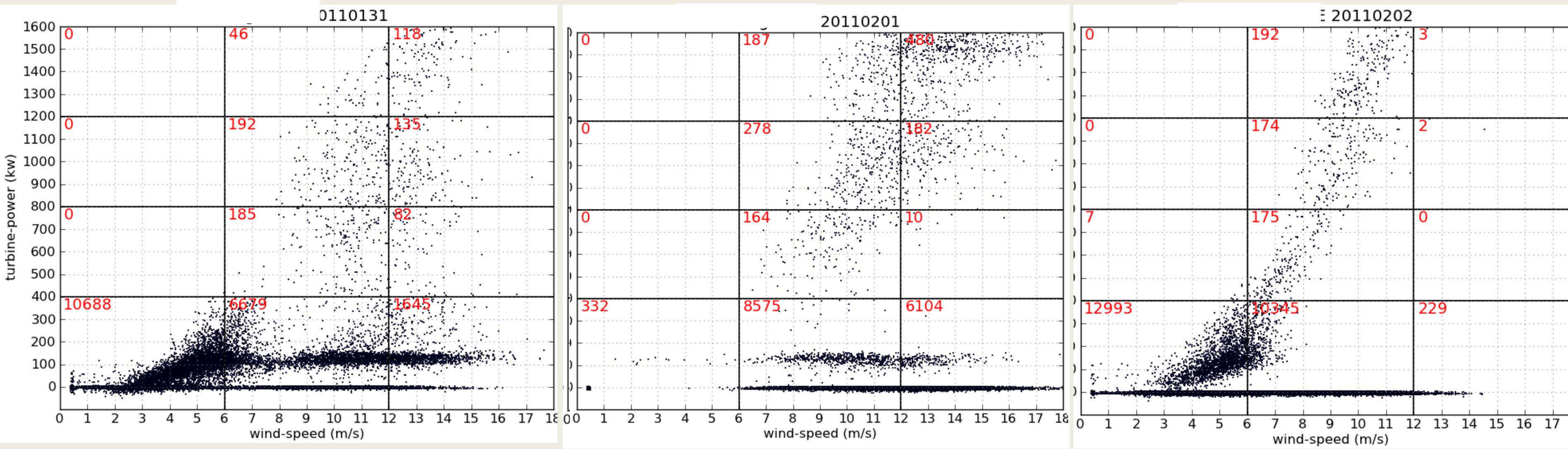
Turbine type 1



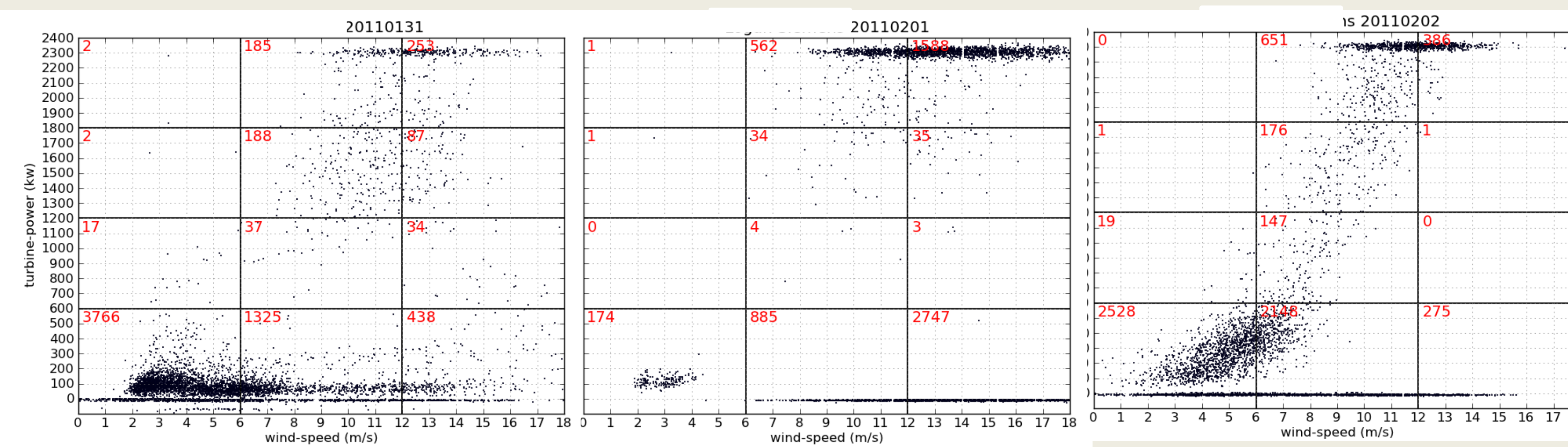


31 Jan 2011 | 1 Feb 2011 | 2 Feb 2011

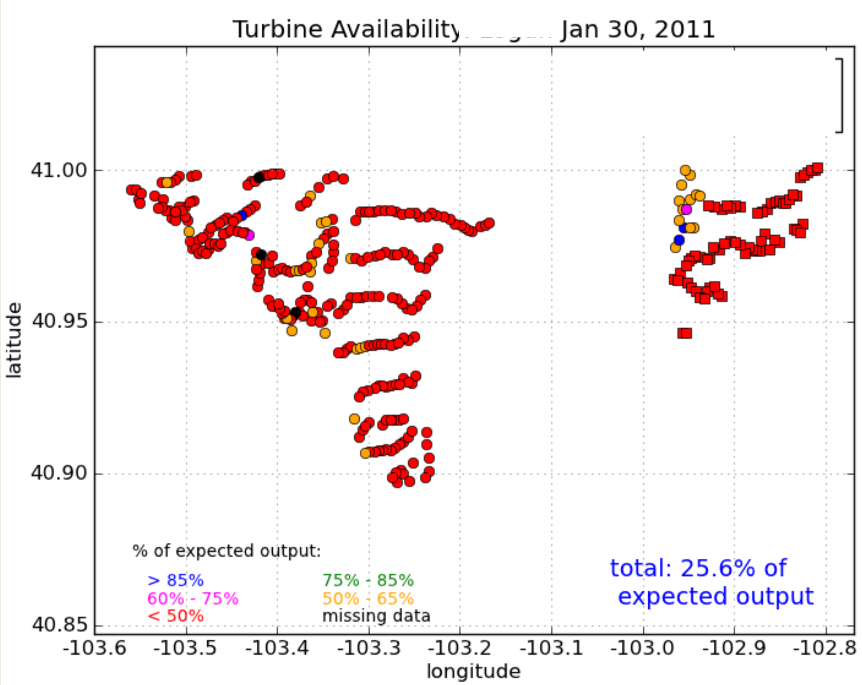
Turbine Type 1

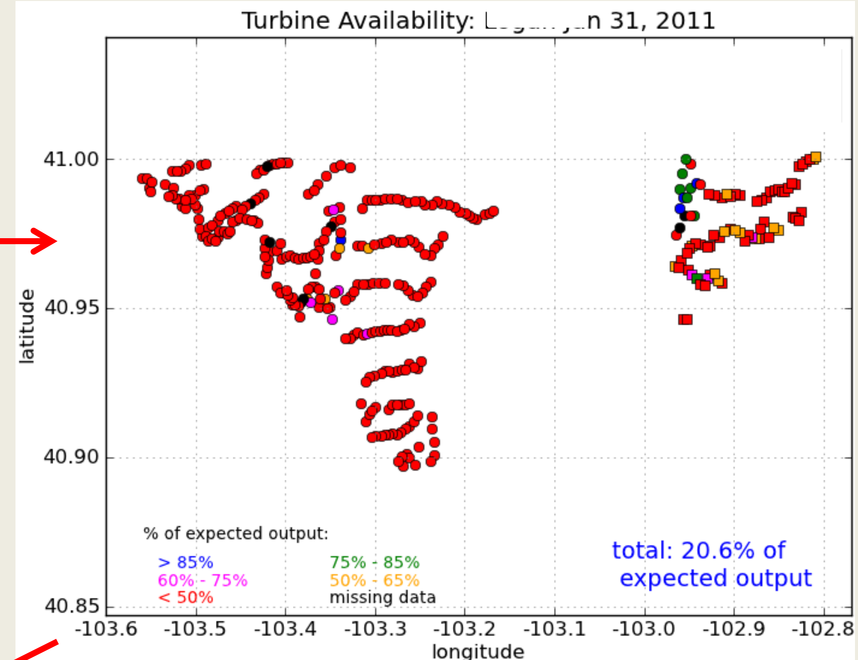


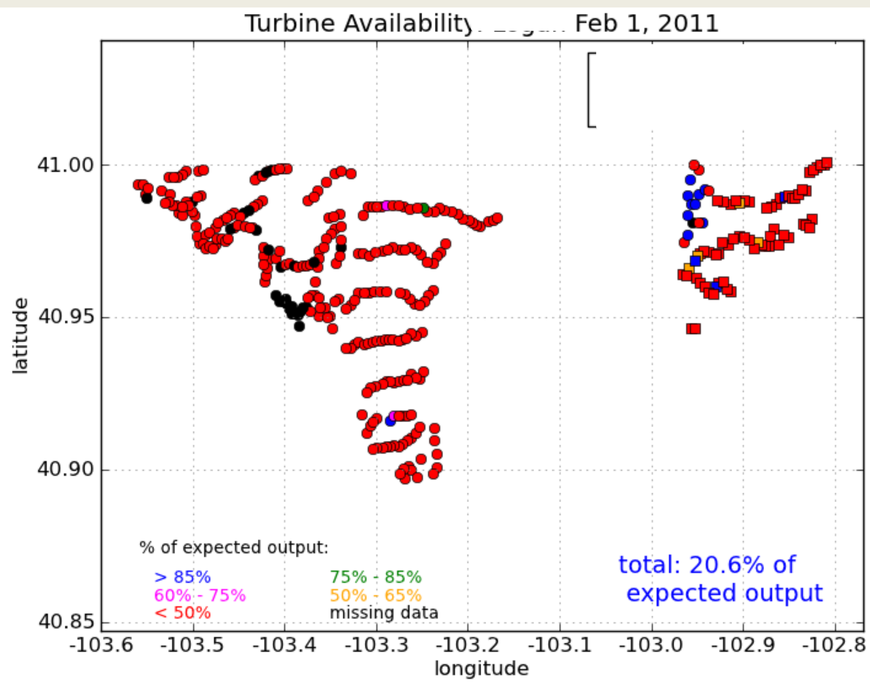
Turbine Type 2

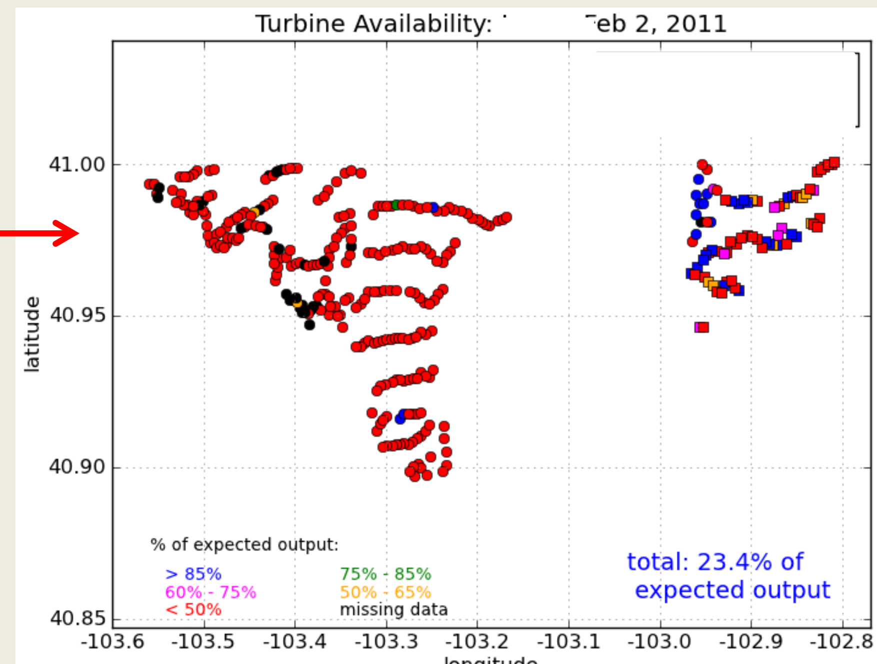


* Numbers in red represent the number of data points in each rectangle

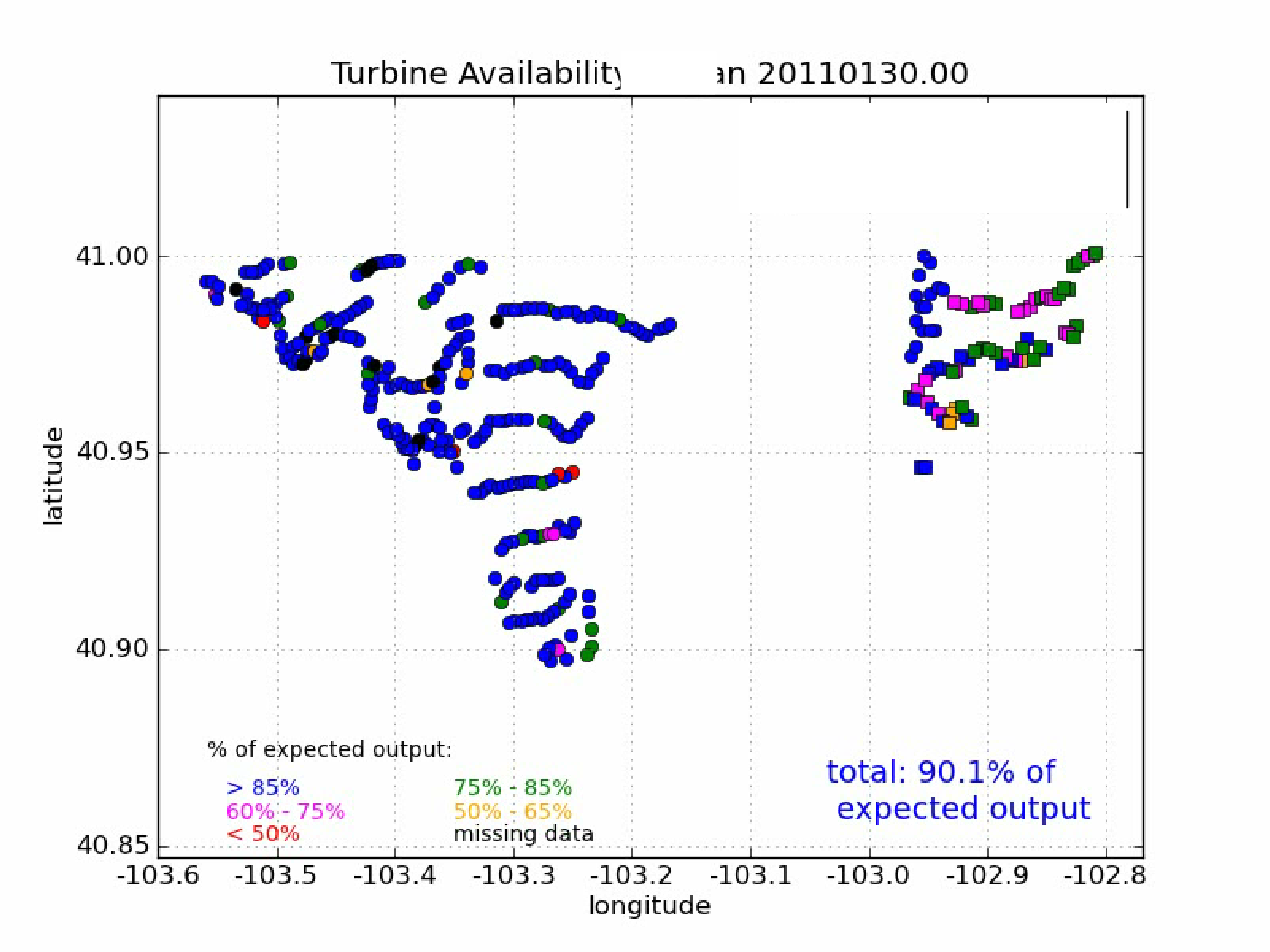

Turbine Availability Jan 30, 2011
latitude
longitude
41.00
40.95
40.90
40.85
-103.6 -103.5 -103.4 -103.3 -103.2 -103.1 -103.0 -102.9 -102.8
% of expected output:
> 85%
75% - 85%
60% - 75%
50% - 65%
< 50%
missing data
total: 25.6% of expected output


Turbine Availability: n 31, 2011
latitude
longitude
41.00
40.95
40.90
40.85
-103.6 -103.5 -103.4 -103.3 -103.2 -103.1 -103.0 -102.9 -102.8
% of expected output:
> 85%
75% - 85%
60% - 75%
50% - 65%
< 50%
missing data
total: 20.6% of expected output

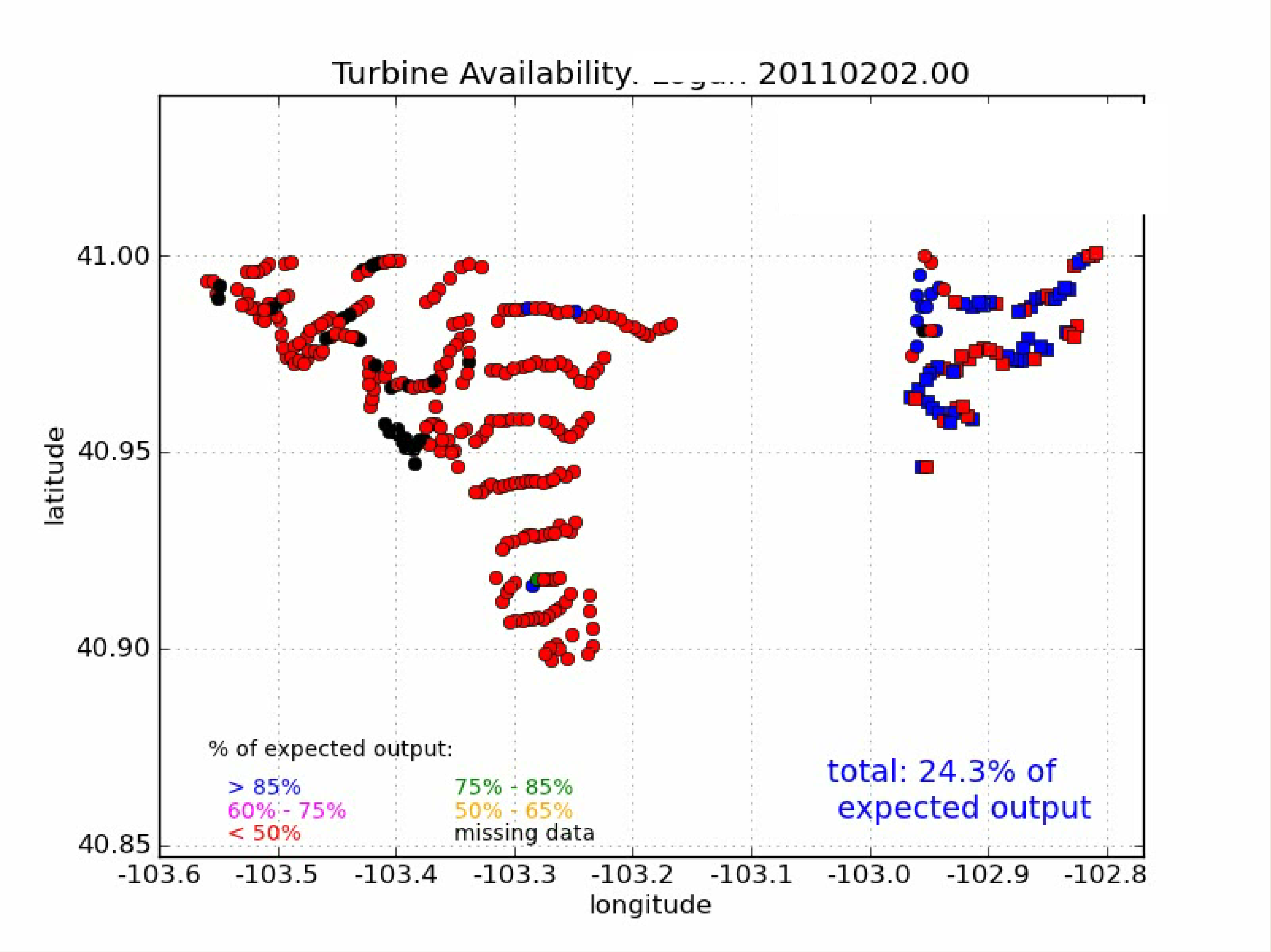

Turbine Availability Feb 1, 2011
latitude
longitude
41.00
40.95
40.90
40.85
-103.6 -103.5 -103.4 -103.3 -103.2 -103.1 -103.0 -102.9 -102.8
% of expected output:
> 85%
75% - 85%
60% - 75%
50% - 65%
< 50%
missing data
total: 20.6% of expected output


Turbine Availability: eb 2, 2011
latitude
longitude
41.00
40.95
40.90
40.85
-103.6 -103.5 -103.4 -103.3 -103.2 -103.1 -103.0 -102.9 -102.8
% of expected output:
> 85%
75% - 85%
60% - 75%
50% - 65%
< 50%
missing data
total: 23.4% of expected output

Jan 30


Turbine Availabilit an 20110130.00
41.00
40.95
40.90
40.85
latitude
-103.6
-103.5
-103.4
-103.3
-103.2
-103.1
-103.0
-102.9
-102.8
longitude
% of expected output:
> 85%
75% - 85%
60% - 75%
50% - 65%
< 50%
missing data
total: 90.1% of
expected output

Feb 02



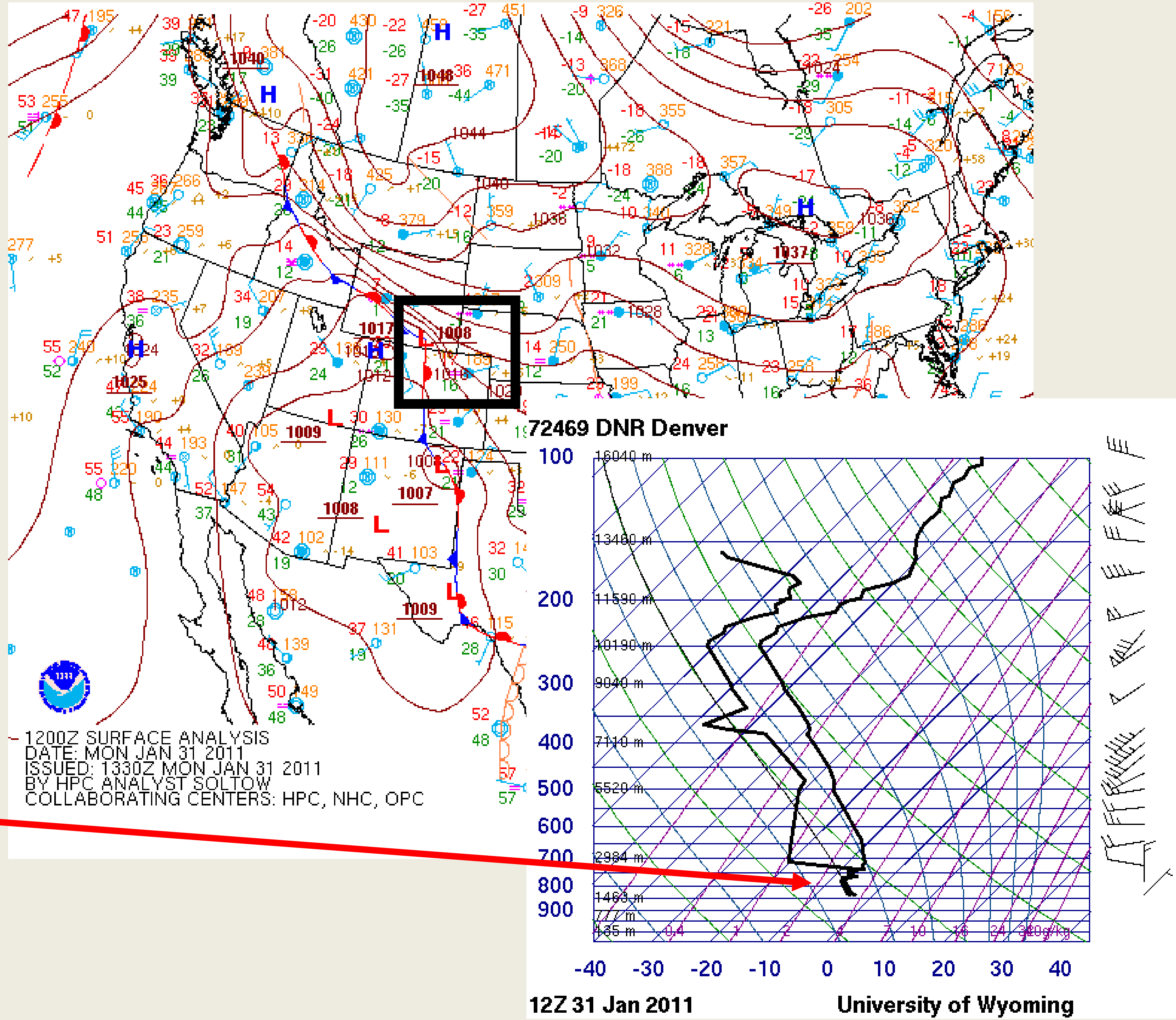
Turbine Availability. 20110202.00
latitude
longitude
41.00
40.95
40.90
40.85
-103.6
-103.5
-103.4
-103.3
-103.2
-103.1
-103.0
-102.9
-102.8
% of expected output:
> 85%
75% - 85%
60% - 75%
50% - 65%
< 50%
missing data
total: 24.3% of expected output

Case study: Freezing drizzle icing Jan 31, 2011

Arctic high moving south

Upslope flow across the western High Plains leading to freezing drizzle

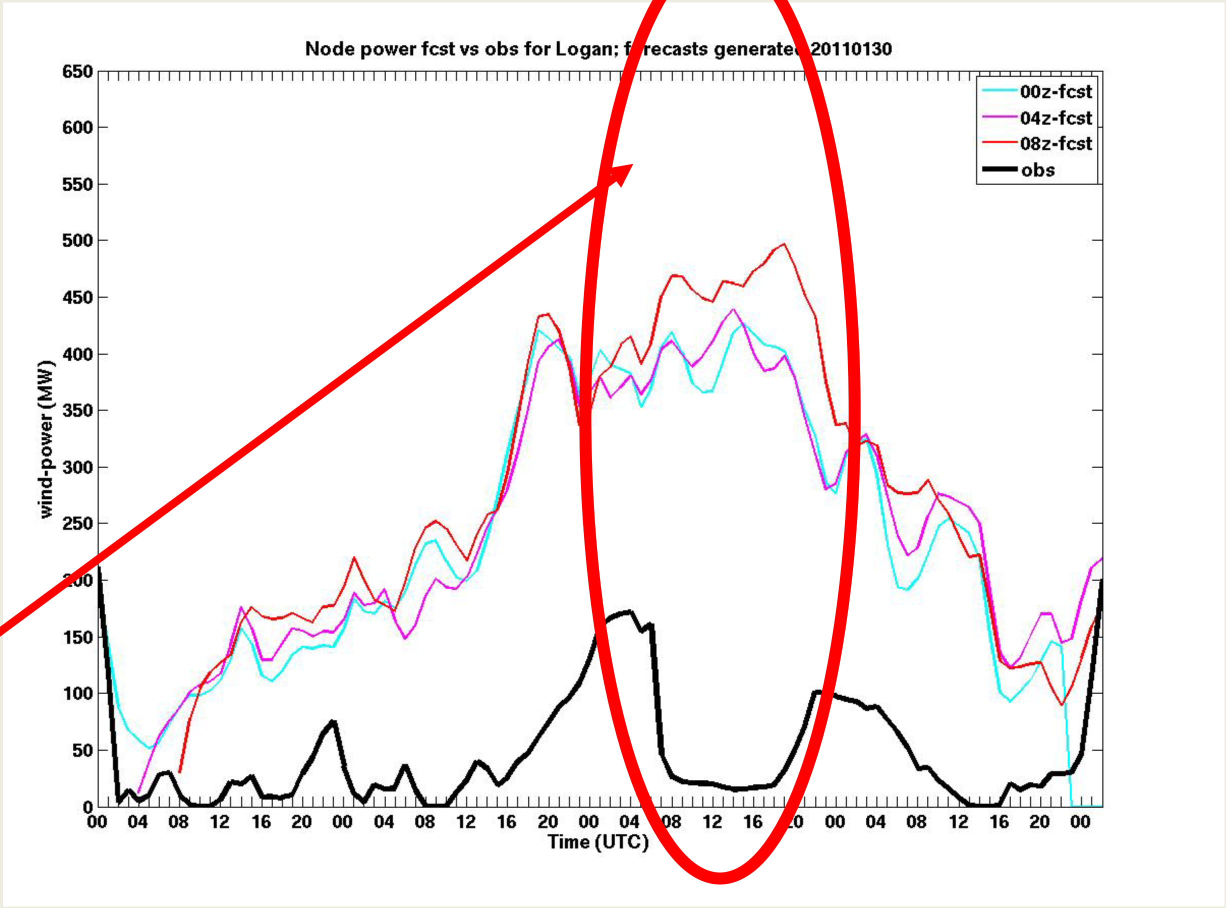
2 layer cloud present, CTT of both layers ~ -8C



Case study: Freezing drizzle icing Jan 31, 2011

Forecast and observed power radically different, goes to zero at 12-UTC on Jan 31, 2011

Freezing drizzle observed in area at 12-UTC



WRF Enhancements

- Thompson & Eidhammer (2013) aerosol-aware microphysics (in Spring 2014 release)
  - explicit CCN activation
  - predicted cloud droplet concentration
- 3D prognostic aerosols from GOGART 7-yr simulation

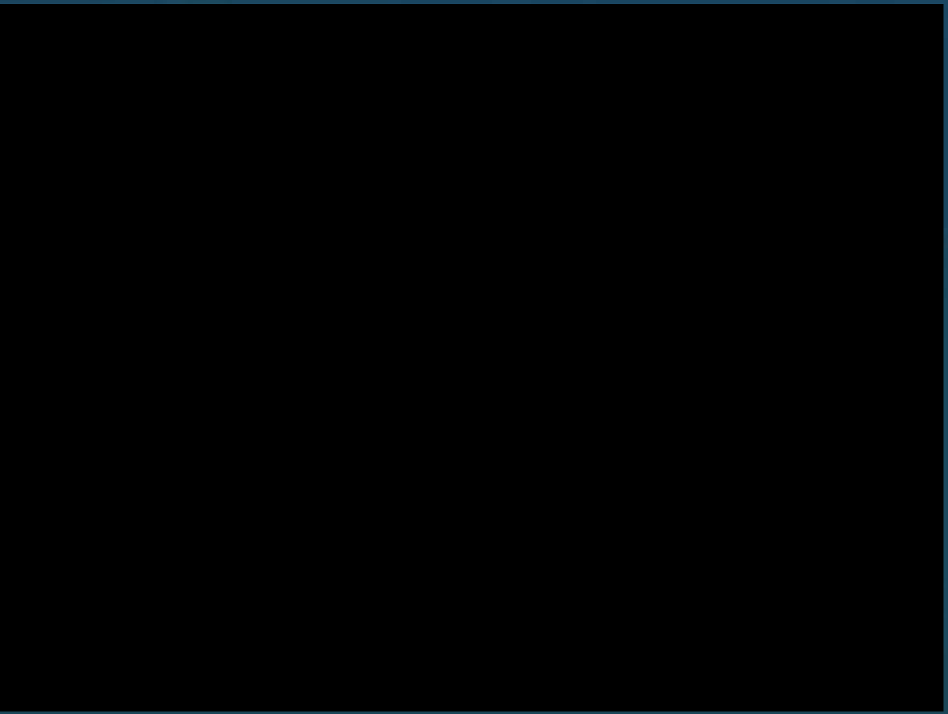
Icing diagnosis – Makkonen, 2000

- Ground/structural icing
  - LWC = cloud + rain
  - Joint distribution MVD -> Efficiency
  - dM/dt = E * LWC*V*A
  - Use max dM/dt at any level < 200m
- Wind turbine icing
  - As above, but V is speed of turbine blade at 75% length
- Wet snow accumulation
  - As above, but
    - LWC = snow content
    - V = 1 m/s (veloc of falling snow)
    - E = f(T_wet, wind speed)

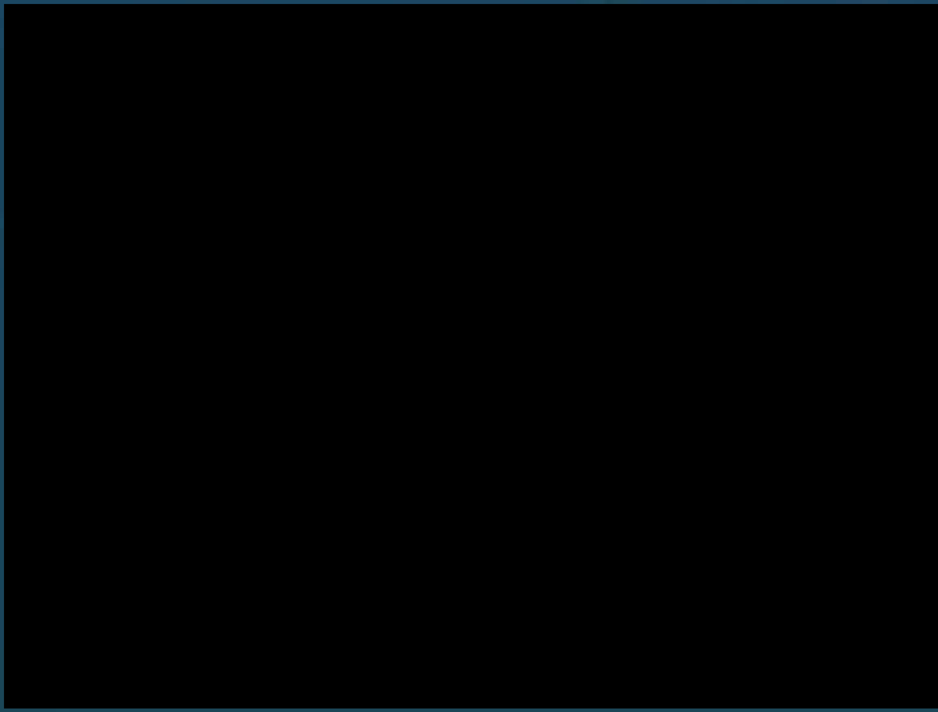
WRF Icing

31 Jan – 2 Feb, 2011

Ground Structures



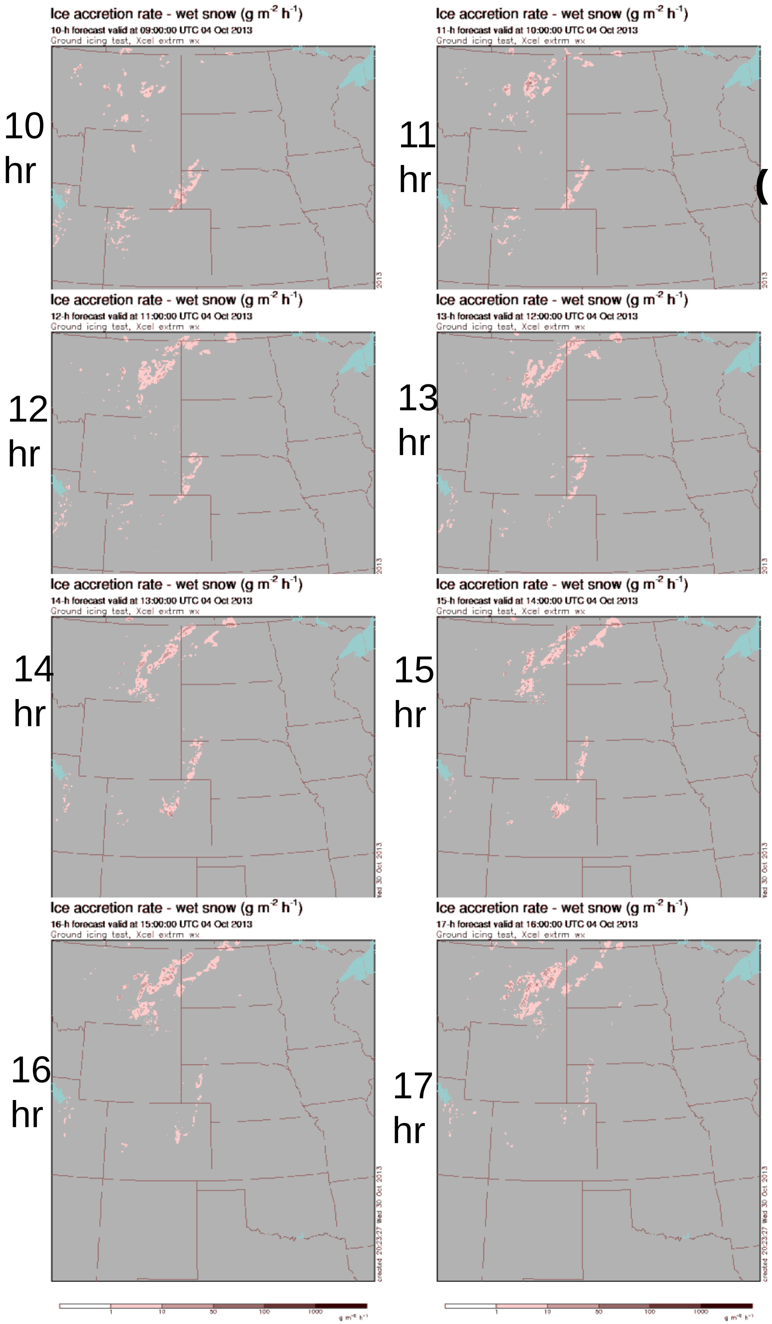
Wind Turbines



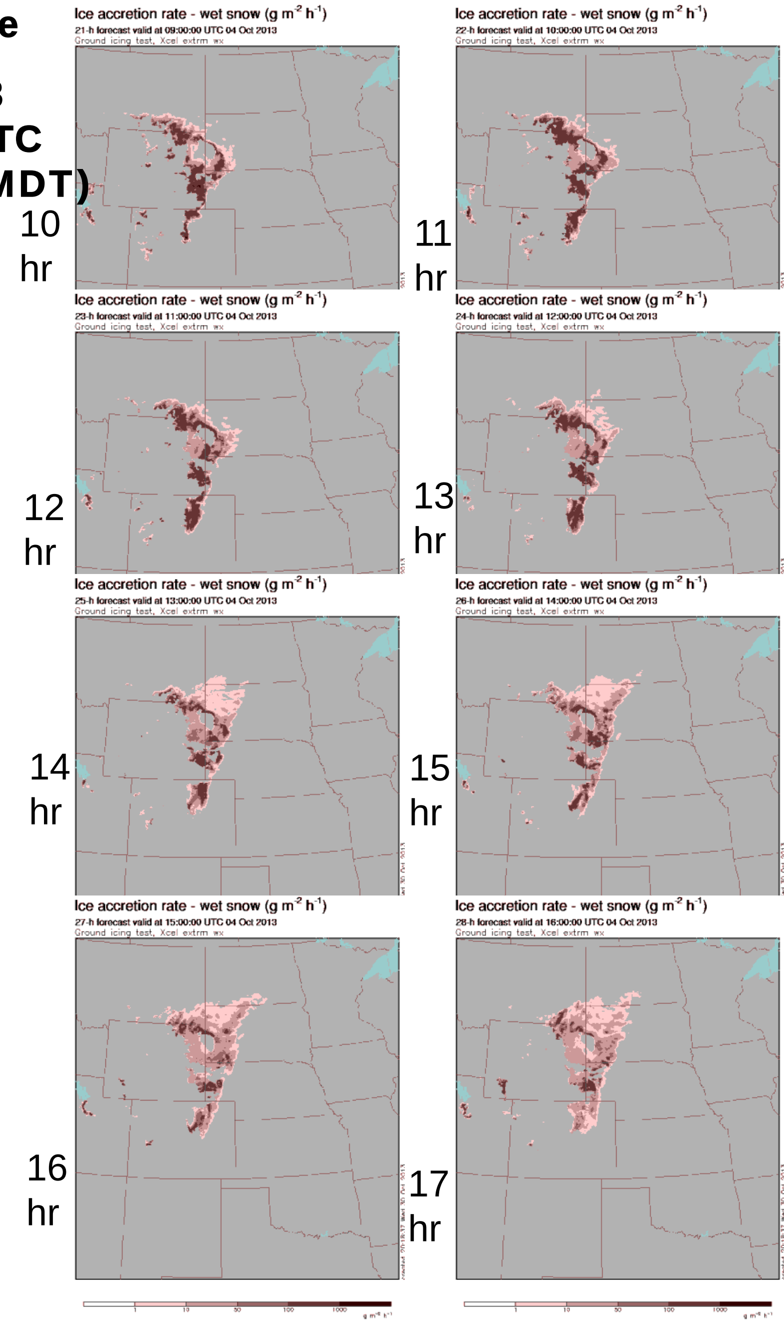
Explicit wet snow accretion rate

04 Oct 2013 0900-1600 UTC (2:00-9:00 AM MDT)

Real-time run with Purdue-Lin microphysics

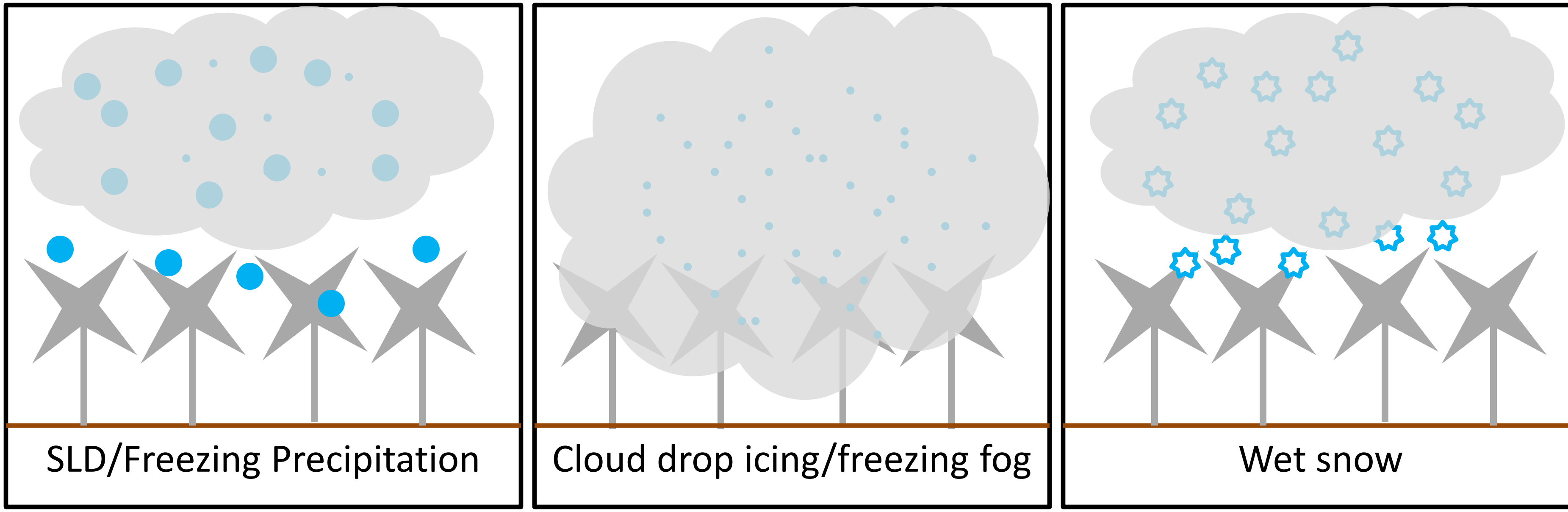


Thompson microphysics



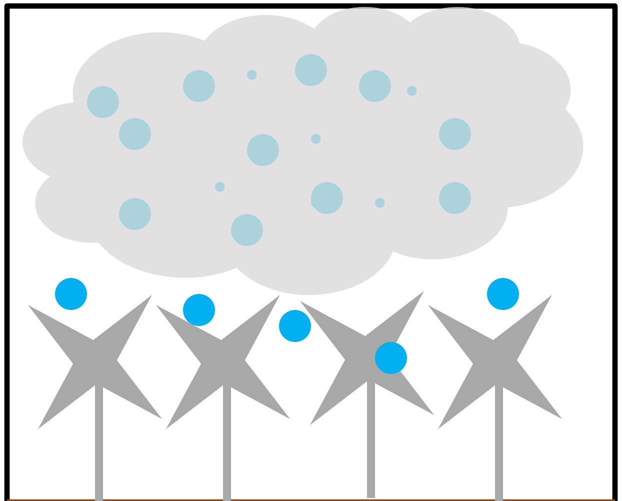
NCAR's Icing/snow system

Scientists: Dan Adriaansen/Marcia Politovich
Engineer: Paul Prestopnik

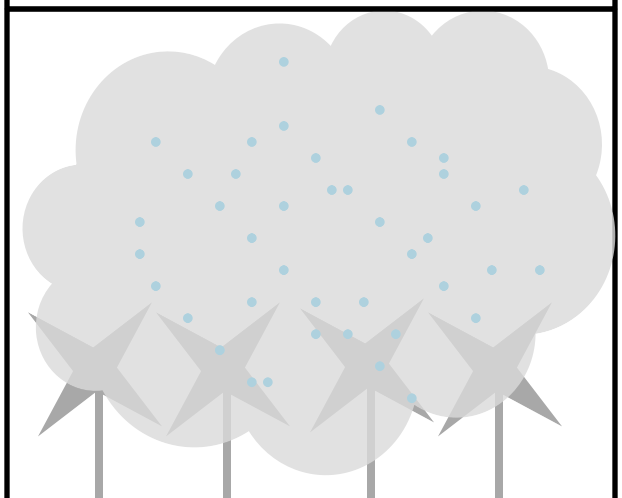


Three major impacts

Icing/freezing precip & fog



SLD/Freezing Precipitation

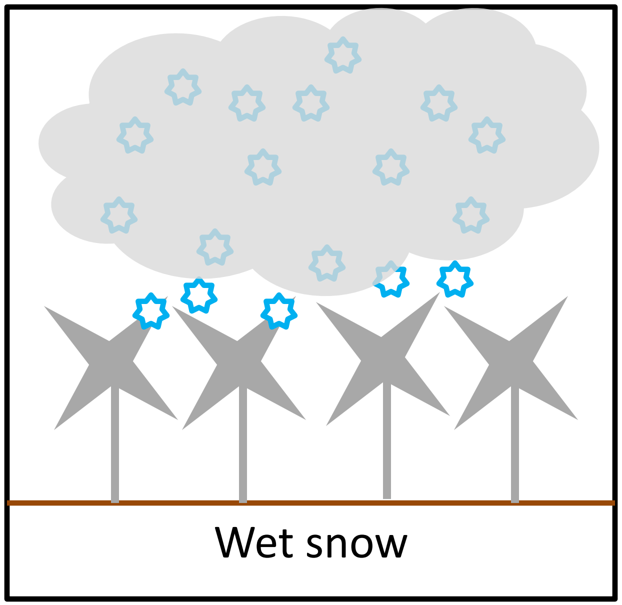


Cloud drop icing/freezing fog

Modified FIP - Forecast Icing Potential

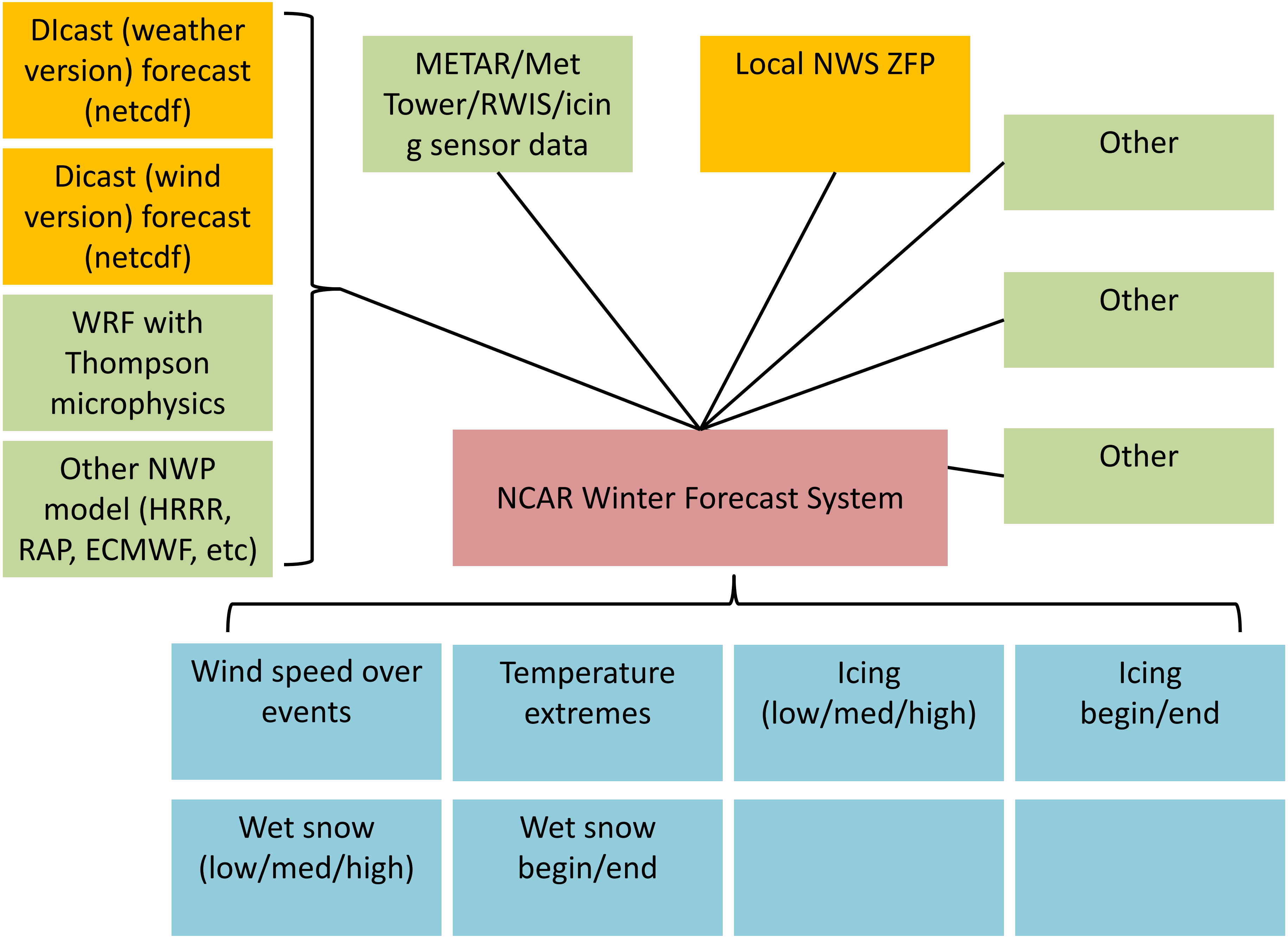
- What is the approximate size of the drops?
  - Difficult
- How much LWC is present?
  - Modified adiabatic assumption
- Is there a warm nose present? How deep?
  - T profile
- What is the temperature at the top of the cloud layer?
  - T profile
- How deep is the cloud layer?
  - Model RH
- What is the cloud base height?
  - Model RH/other

Icing/snow system

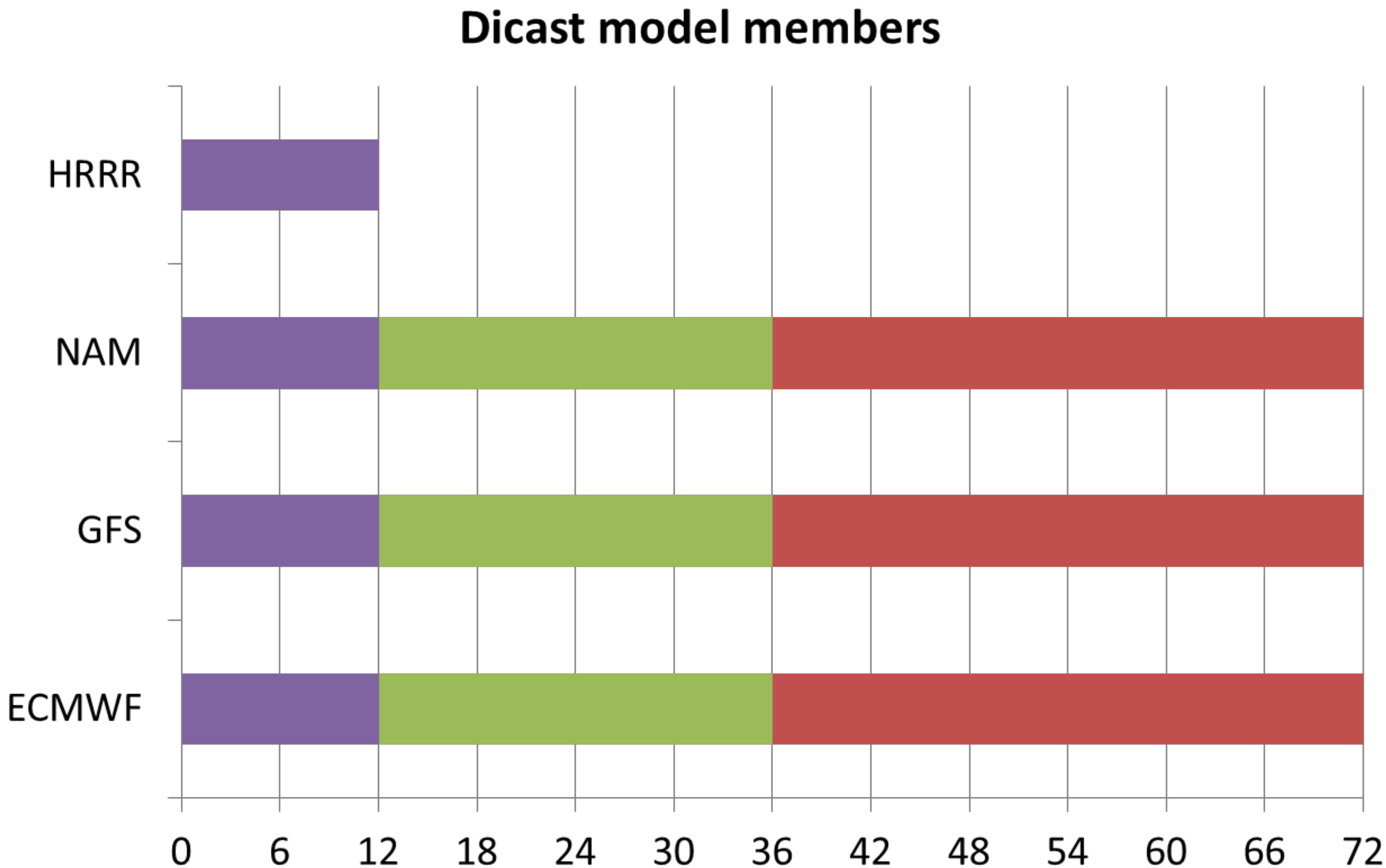


Based on new Thompson WRF wet snow algorithm

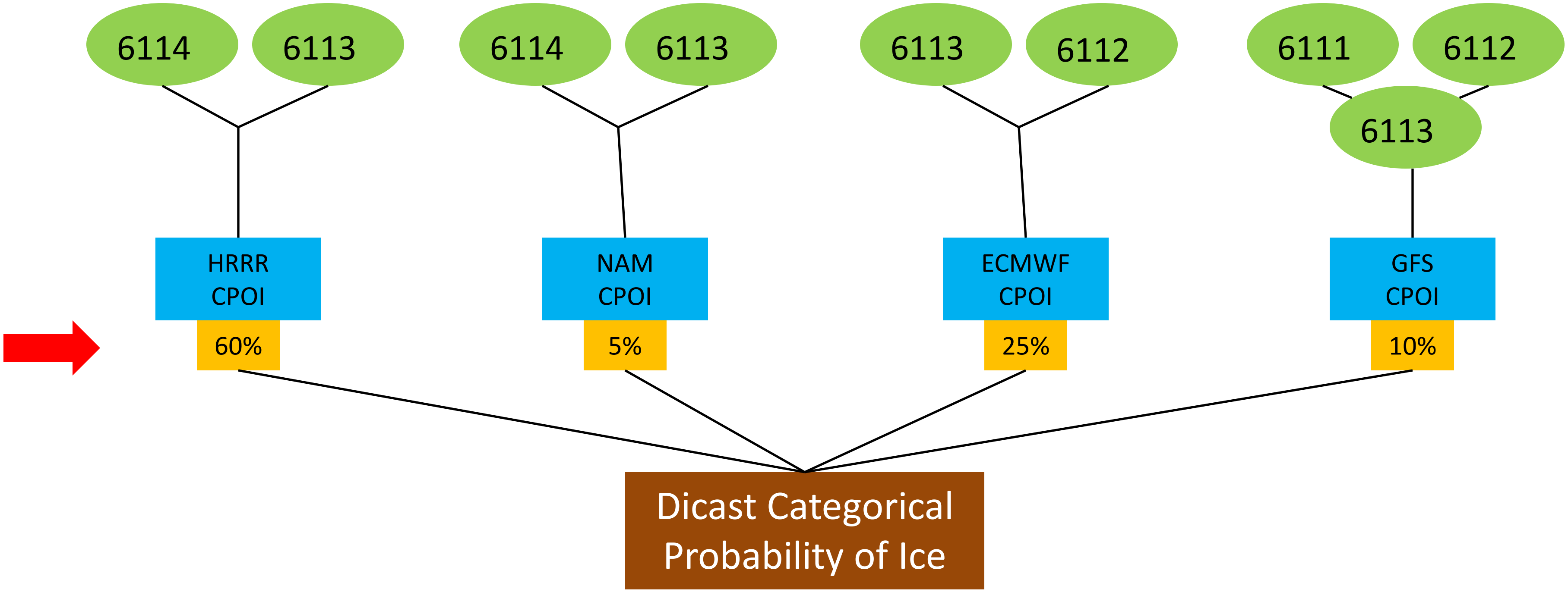
- Examine antecedent T at hub height
- Assess probability of snow
- Tw


DIcast (weather version) forecast (netcdf)
Dicast (wind version) forecast (netcdf)
WRF with Thompson microphysics
Other NWP model (HRRR, RAP, ECMWF, etc)
METAR/Met Tower/RWIS/icing sensor data
Local NWS ZFP
Other
Other
Other
NCAR Winter Forecast System
Wind speed over events
Temperature extremes
Icing (low/med/high)
Icing begin/end
Wet snow (low/med/high)
Wet snow begin/end

DICast: model data

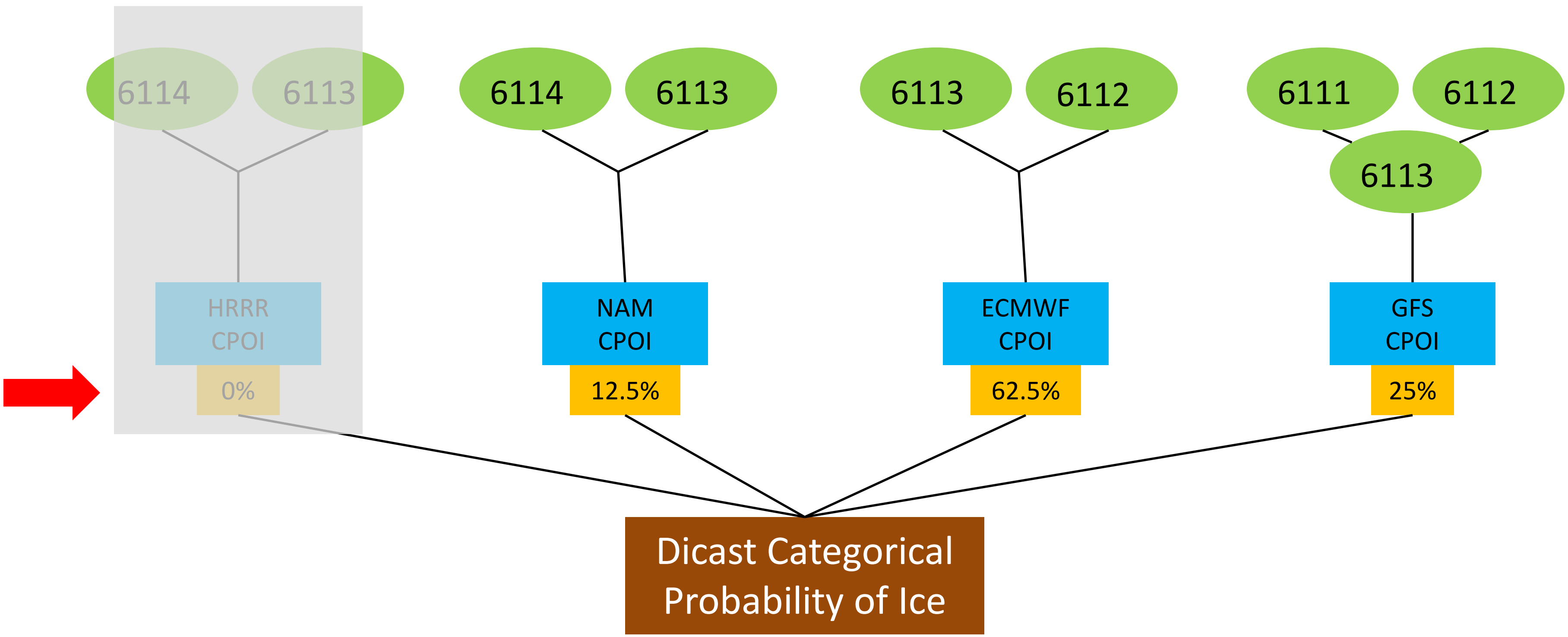


Dicast: 0-12 hr



- 6111 = [Twet MaxT @ sfc] [hourly Twet] [Low cloud (layer?) CTT]
- 6112 = [Twet corrected for station pressure/elevation]
- 6113 = Temperature only
- 6114 = Combination of the categorical prob of FZRA @ sfc and IP @ sfc

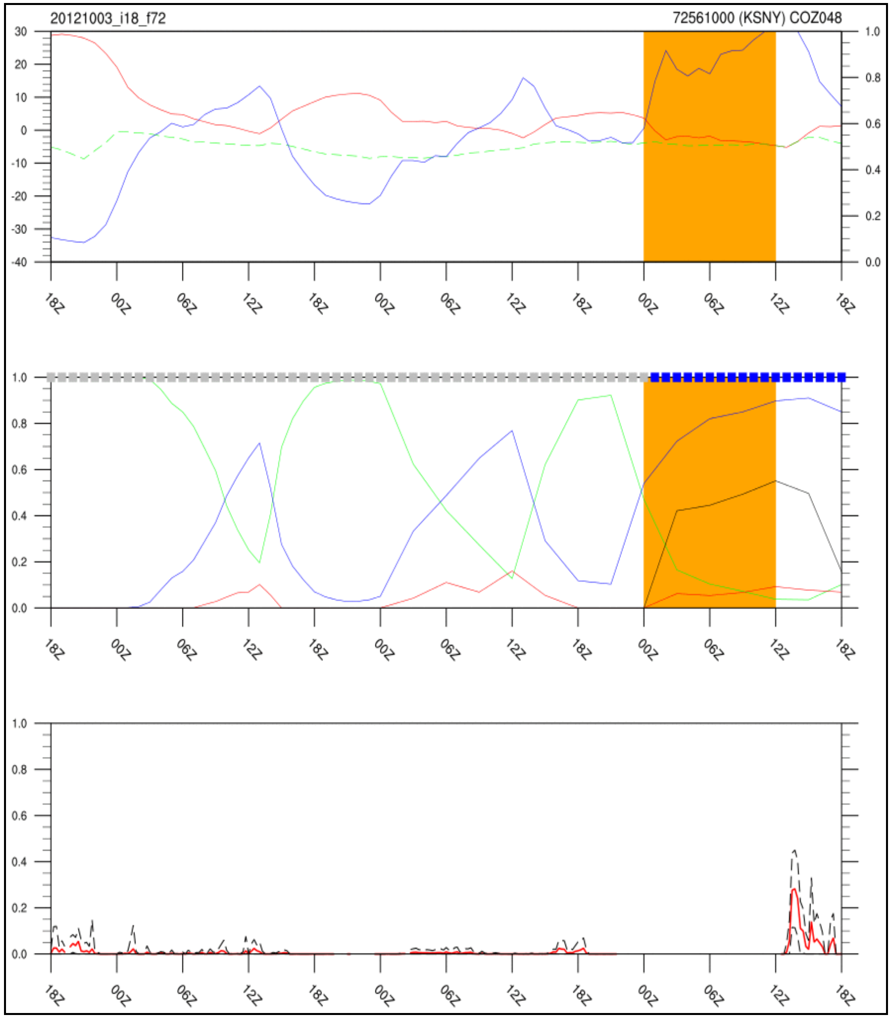
Dicast: 12-72 hr



- 6111 = [Twet MaxT @ sfc] [hourly Twet] [Low cloud (layer?) CTT]
- 6112 = [Twet corrected for station pressure/elevation]
- 6113 = Temperature only
- 6114 = Combination of the categorical prob of FZRA @ sfc and IP @ sfc

Hazard: Turbine icing 06 Oct 2012

18Z 03 October 2012 - 18Z 06 October 2012



DiCast site: KSNY (Sidney, NE METAR station), NWS forecast zone: Colorado zone 48

PANEL 1 (TOP):

- Red = DiCast temperature forecast (C)
- Green = DiCast T_D forecast (C)
- Blue = DiCast RH forecast (right axis, %)
- Orange shading: 12 hour period indicating mention of FREEZING DRIZZLE by NWS

PANEL 2 (MID):

- Lines = DiCast categorical probability of precipitation forecast (%). Red = ice, green = rain, blue = snow, black = fog
- Orange shading: 12 hour period indicating mention of FREEZING DRIZZLE by NWS

PANEL 3 (BOT):

- Red line = Icing event metric.
- Combines observed power, expected power based on the wind speed (from manufacturer power curve), and wind speed at each turbine to assess likelihood of icing . farm average.
- Black dashed lines = standard deviation of icing event metric. Farm average.

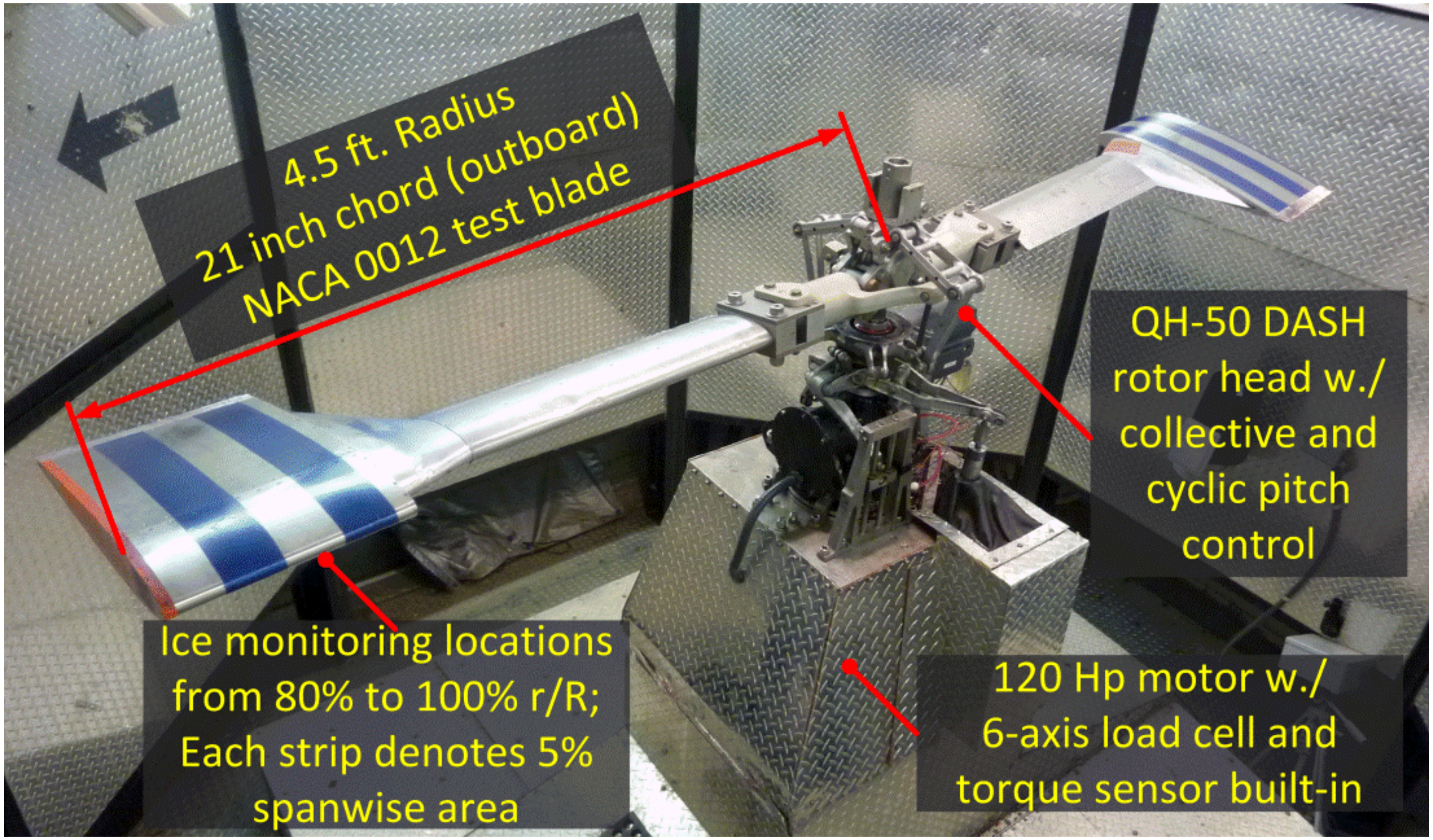
Wind Turbine Performance Degradation Due To Atmospheric Icing

Sven Schmitz, Assistant Professor
Jose Palacios, Assistant Associate
sus52@engr.psu.edu and jlp324@engr.psu.edu

NCAR-XCEL-PSU

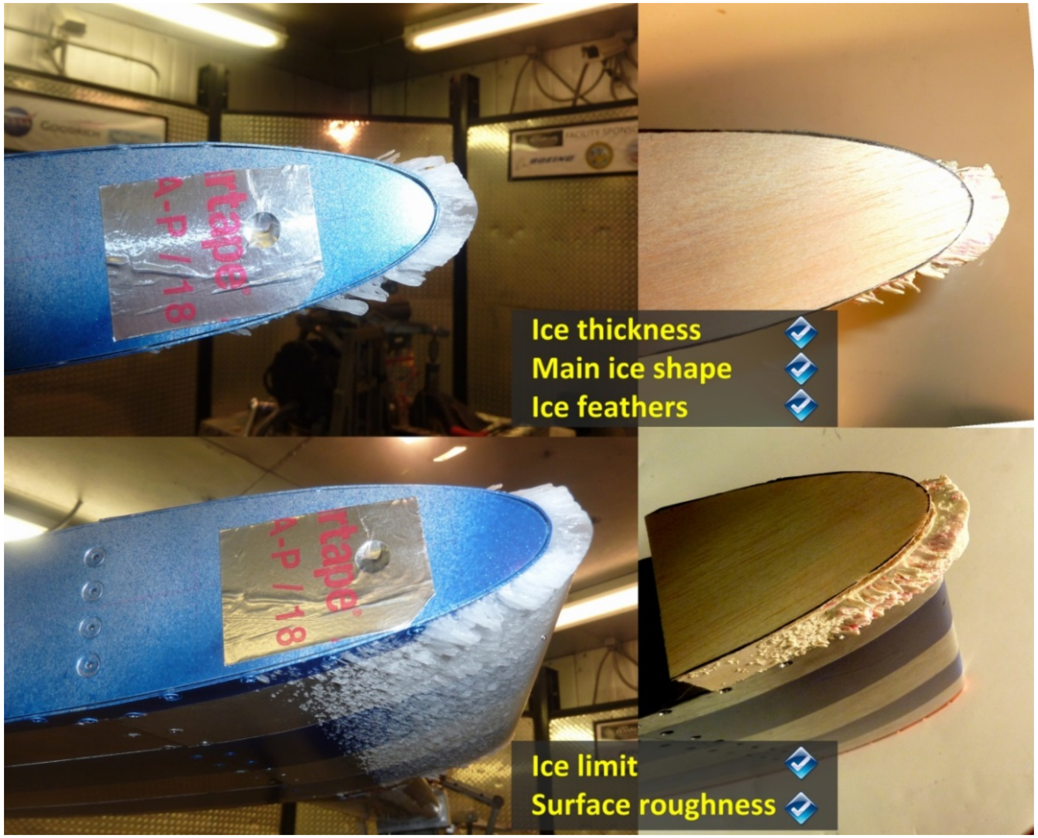
Adverse Environment Rotor Test Stand (AERTS) Facility

– $Re_{Icing} = 1.5 – 2.4 \times 10^6$



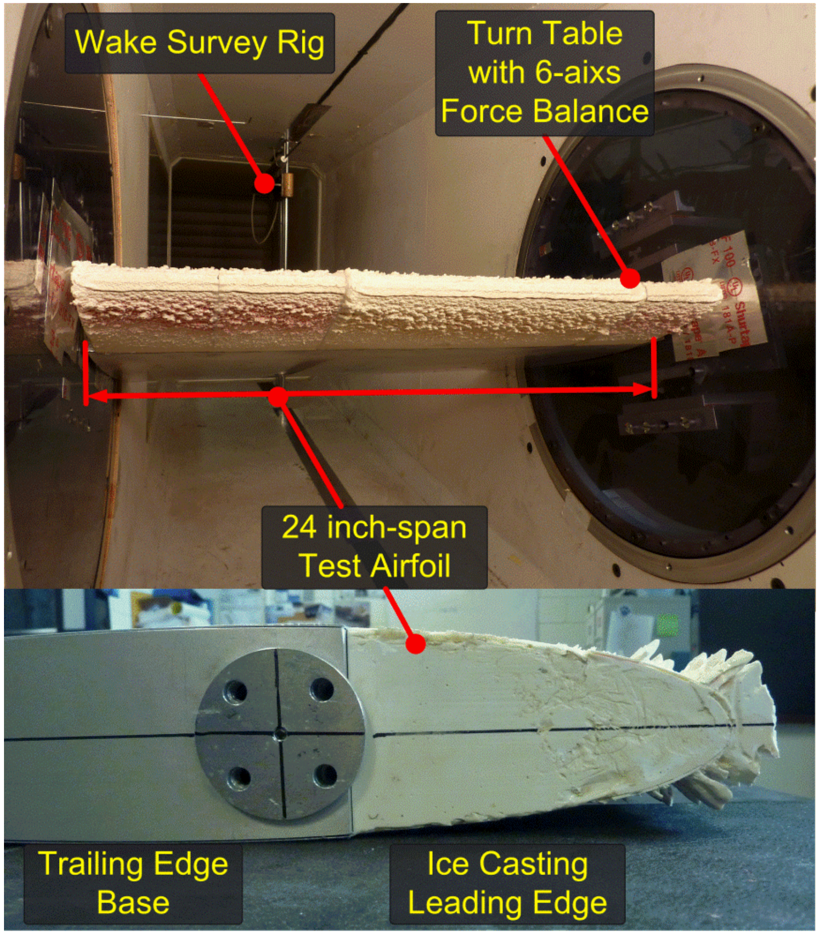
Ice Molding and Casting Techniques

- Material: RTV silicone rubber and Urethane liquid plastic
- Curing time: 24hr (Molding) / 15 min. (Casting)



Wind Tunnel Testing Configuration

- **PSU Low-speed Wind Tunnel**
  - Test section size: 36 in. (h) × 24 in. (w)
  - Max. Speed 150 ft/s;
  - Test speed 130 ft/s;
  - Turbulence Intensity (Ti) 0.22%;
- **Wind Tunnel Measurement**
  - Wake survey using hot wire probe: *Cd*
  - 6-axis external force balance: *Cd, Cl, Cm*
- **Testing Airfoil**
  - Airfoil size: 24 in. (span) × 21 in. (chord)
  - Re = 1.4 ×10^6
  - Multiple pieces of ice casting models from the same icing condition



Scaling Conditions – DU-93-210 Test Blade

- The experimental blade chord is 1:2 scale
- Results when scaling icing conditions from *real to experimental*:
  - Roughly 1:2 scale for MVD
  - A small increase in LWC
  - A large increase in local blade velocity
  - A large decrease in icing event time
- Scaling Conditions represented on the next page

PENNSTATE

1 8 5 5

Scaling Test Points

Real Test Points

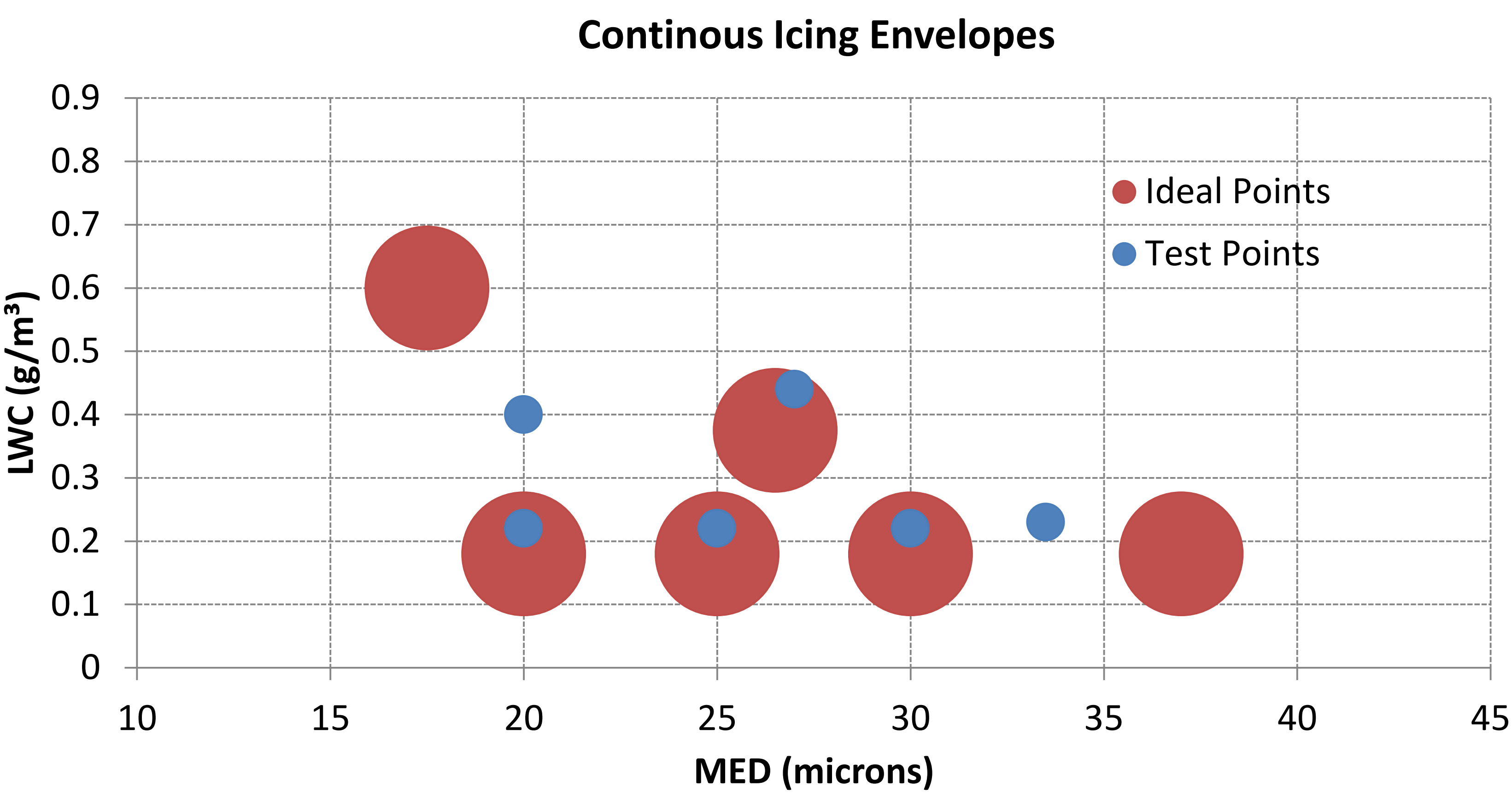
LWC (g/m³)	MVD	T (°C)	Velocity (m/s)	Time (min)	Chord (cm)
0.44	27	-3	41.4	45	145
0.22	20	-15	41.4	45	145
0.22	25	-12	41.4	45	145
0.22	30	-10	41.4	45	145
0.23	33.5	-5	41.4	45	145
0.4	20	-10	41.4	45	145

Scaled Test Points

LWC (g/m³)	MVD	T (°C)	Velocity (m/s)	Time (min)	Chord (cm)
0.449	15.4	-3.2	58.55	15.6	72.5
0.255	11.4	-15.2	58.55	13.73	72.5
0.253	14.2	-12.2	58.55	13.88	72.5
0.25	17.1	-10.2	58.55	14	72.5
0.251	19.1	-5.2	58.55	14.61	72.5
0.458	11.4	-10.2	58.55	13.9	72.5

Icing Envelope and Test Points

- Display of suggested and actual test points



Testing Process

1. LWC measurements taken and validated for various conditions in the AERTS facility
2. Ice shapes generated using scaled test conditions
3. Ice shapes molded for preservation
4. Molded ice shapes mounted to “carrier airfoil”
5. Lift and drag coefficients of accreted ice shapes measured in the wind tunnel

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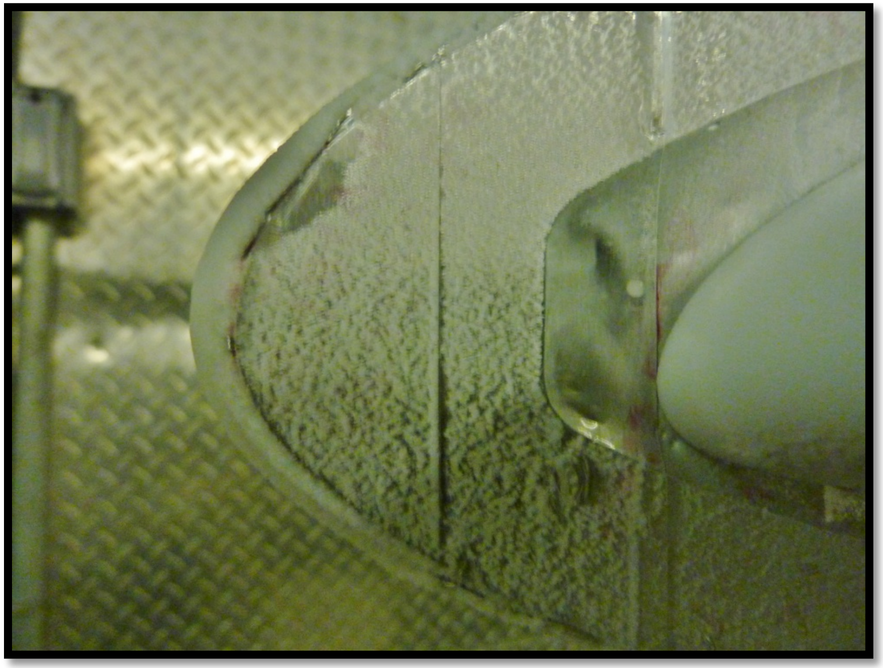
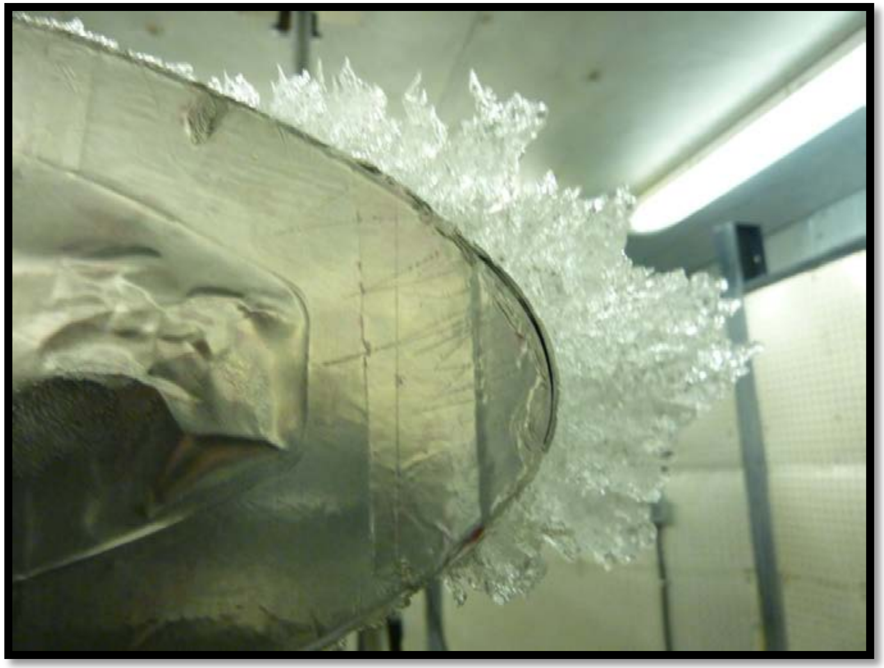
Testing Photos

- Ice Shapes are compared to LEWICE predictions for validation
- Ability to create large variations in ice shapes





Testing Photos

- Glaze Ice – 0.45 LWC, 18 MVD, -3° C

Testing Photos

- Rime Ice – 0.21 LWC, 17 MVD, -11° C

Molding Photos

- Ice Shapes molded to preserve shape for wind tunnel testing

Example Wind Tunnel Expt

http://www.youtube.com/watch?v=BZ2k01BR_z8

Summary

- Xcel Energy has seen power loss due to icing and wet snow in all systems
- Data Mining can distinguish events
- Experiments can provide insight
- New systems to forecast events
  - WRF w/ new Thompson microphysics
  - Modified FIP
  - Real-time forecasting

NCAR

Thank You !

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