# NCAR's Wind Forecasting System

Luca Delle Monache **et al.**

(lucadm@ucar.edu)

National Center for Atmospheric Research (NCAR) – Boulder, CO, USA

Winterwind – International Wind Energy Conference

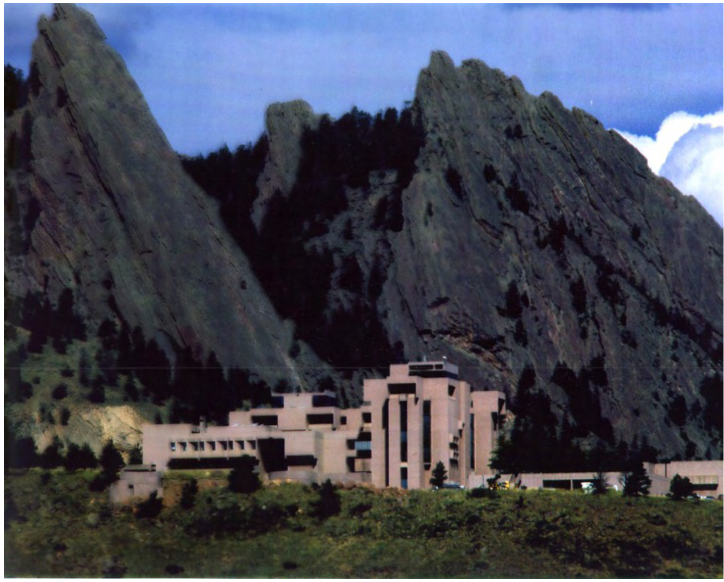
12-13 February, 2013, Östersund, Sweden

# Outline

- The U.S. National Center for Atmospheric Research (NCAR)
- Renewable energy forecasting research and development
- NCAR-Xcel energy project
- Probabilistic power predictions
  - The Analog Ensemble (AnEn)
  - Test cases
- Summary

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

- NCAR is a Federally funded research and development center sponsored by the U.S. 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 climate and weather modeling, air chemistry, thunderstorms, hurricanes, icing, turbulence, societal impacts of weather, energy, solar physics, etc.



NCAR, Boulder, CO

# Power Prediction

**Goal:**

Accurate power forecasts and reliable quantification of forecast uncertainty

**Motivation:**

- 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

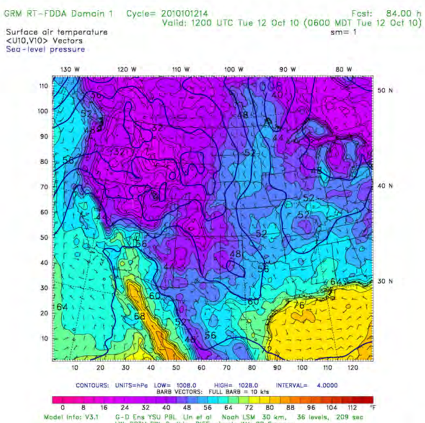
# Renewable Energy Forecasting

NCAR

## Icing Research

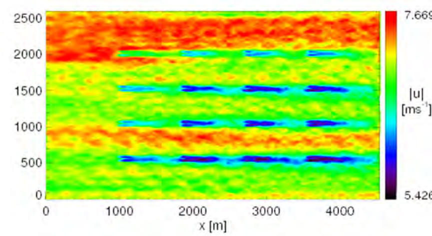
Greg Thompson
Bjorn-Egil Nygaard
(Oslo Univ)
Marcia Politovich
Frank McDonough

## Numerical Weather Prediction



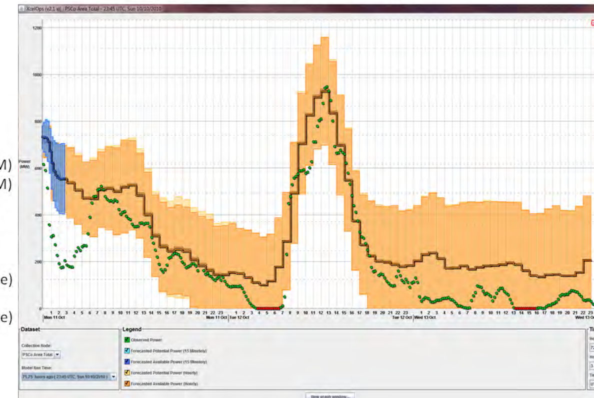
Yubao Liu
Thomas Warner
Will Cheng
Yuwei Liu
Greg Roux
Luca Delle Monache
Tom Hopson
Wanli Wu

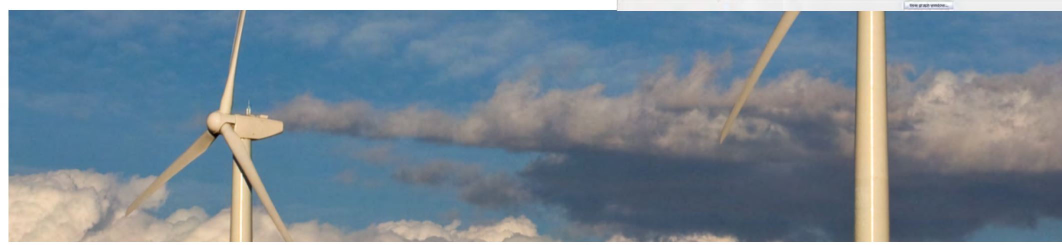
## Fine Scale Modeling & Boundary Layer Meteorology



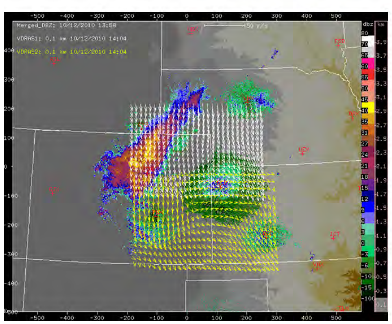

Branko Kosovic
Andrew Annunzio
Ned Patton (MMM)
Peter Sullivan (MMM)
George Bryan (MMM)
Julie Lundquist
(Univ CO)
Sue Haupt
Frank Zajackowski
(Penn State)
Kerrie Long
(Penn State)

## Wind Power Forecasting



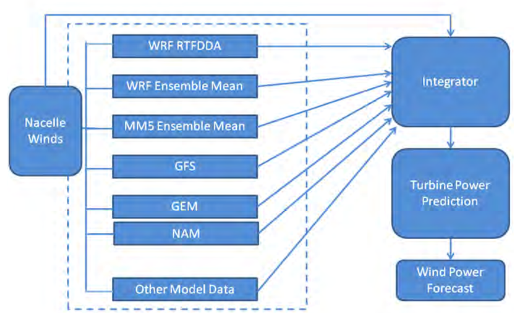


## Variational Nowcasting



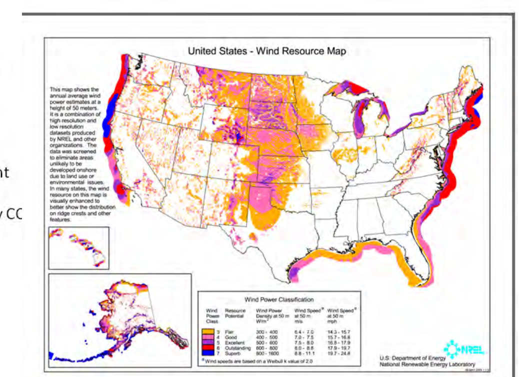
Jenny Sun
Ying Zhang
Niles Oien

## Statistical Learning




Gerry Weiner
Bill Myers
Seth Linden
Julia Pearson
Brice Lambi
Arnaud Dumont
Kent Goodrich
(Univ CC

## Wind Resource Assessment

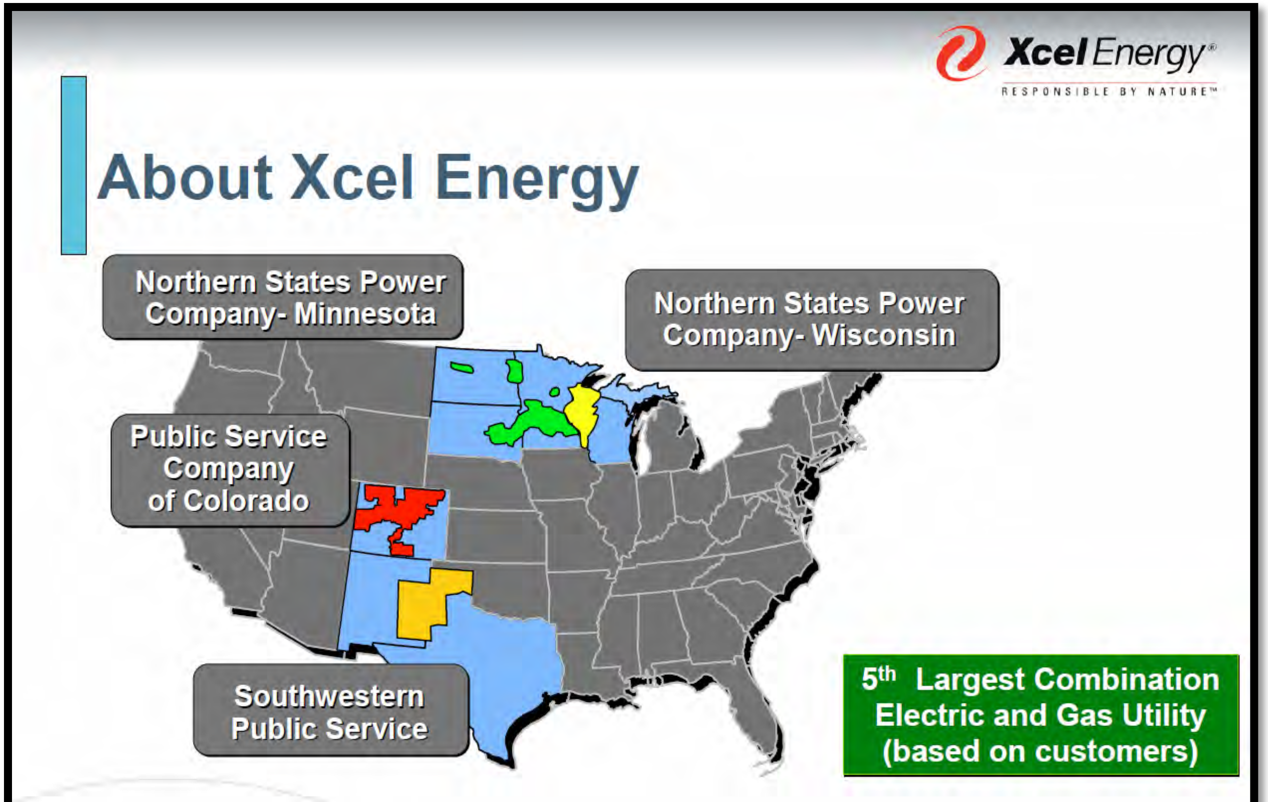



Daran Rife
Andy Monaghan
Francois Vandenberg
James Pinto
Emilie Vanvyve
Chris Davis (MMM)
Thomas Warner
Terri Betancourt
Patrick Sullivan (NREL)
Donna Heimiller
(NREL)

**Future Climate**

Lawrence Buja
Caspar Amman

# Xcel Energy Service Areas

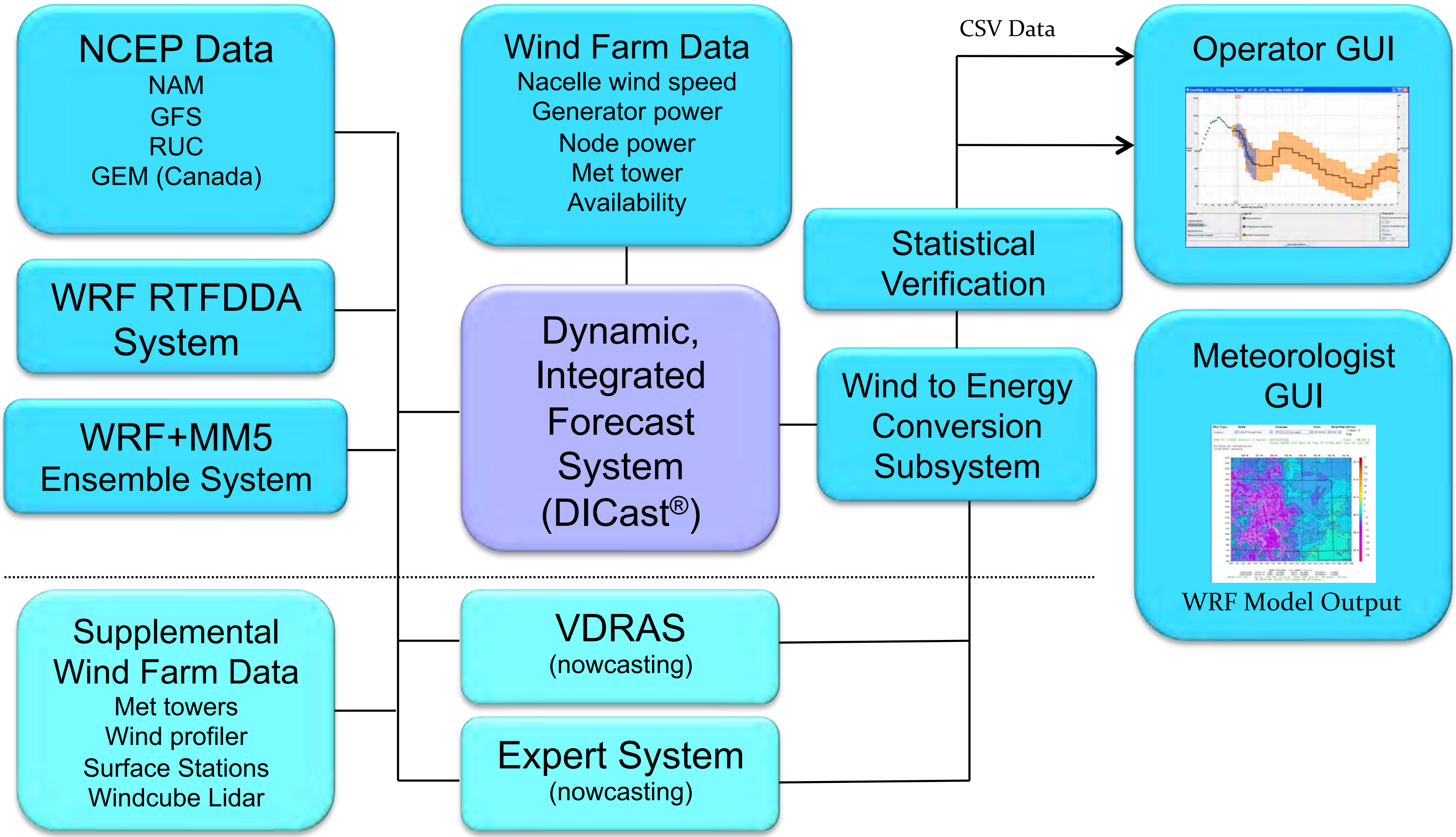



Wind Farms (50+)
3585 Turbines (growing)
4842 MW+ (wind)
~10% Wind
(highest in continental US)

3.4 million customers (electric)
Annual revenue $11B

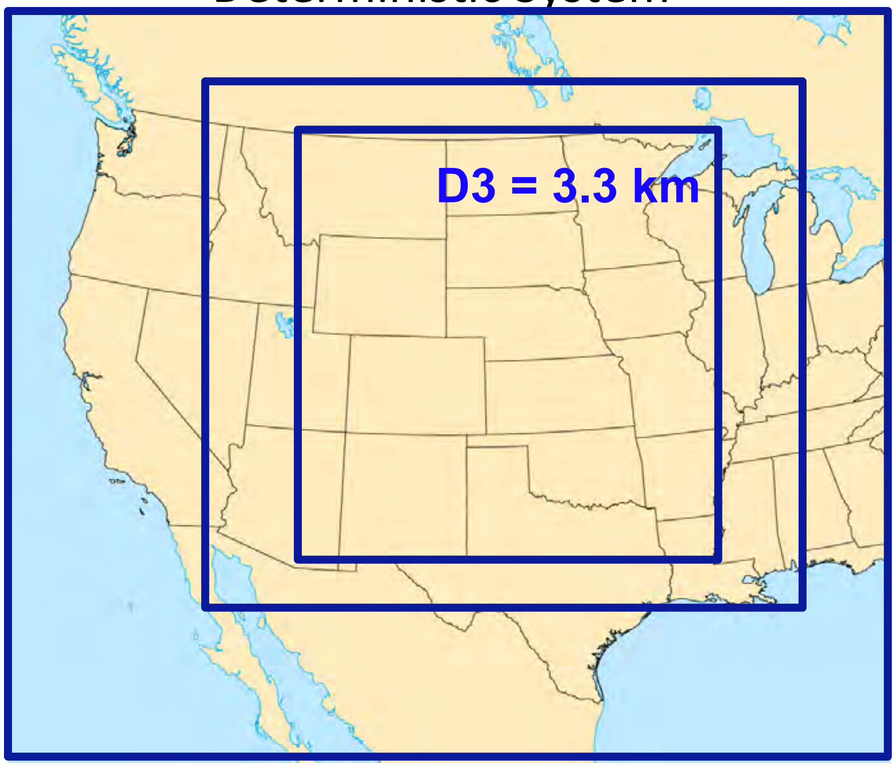
Provides good geographical diversity for research and testing

# NCAR's Wind Energy Prediction System for Xcel Energy



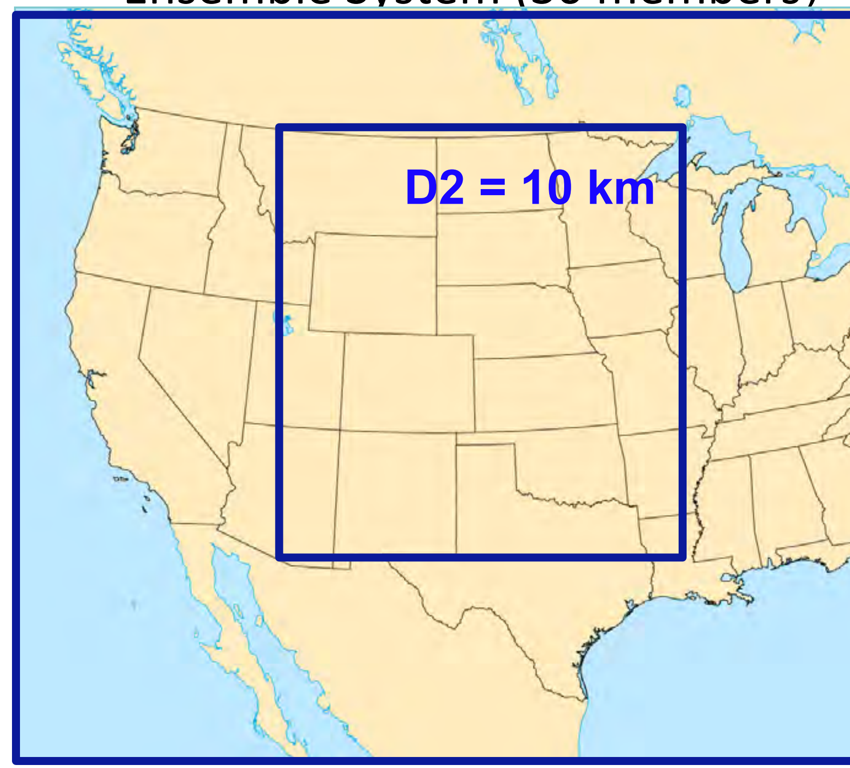
# WRF RTFDDA Model Domains

Deterministic System




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

Ensemble System (30 members)




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

# NCAR-Xcel Energy Project
# Accurate prediction economical benefits

NCAR

**~$1.9M per each percent improvement**

## 2010 Total Benefit

- Error Reduction (expected 2%)
  - PSCo; NSP – much higher than expected
  - SPS – higher than expected
- Rate of Savings
  - PSCo – meets expectations (expected $800k/%MAPE)
  - NSP – higher than expected (expected $500k/%MAPE)
  - SPS – much lower than expected (expected 600k/%MAPE)

| OpCo | 2009 | 2010 | Delta | Rate of Savings | Annualized |
|---|---|---|---|---|---|
| PSCo | 18.07% | 14.25% | -3.81% | $ 850,665 | $ 3,245,102 |
| NSP | 15.66% | 12.20% | -3.47% | $ 748,827 | $ 2,596,873 |
| SPS | 16.26% | 13.86% | -2.39% | $ 175,000 | $ 418,443 |

*Mean Absolute Percent Error

| | |
|---|---|
| **Wind Forecasting Savings** | **$ 6,260,417** |
| **Curtailment Auditing Savings** | **$ 1,260,000** |
| **Grand Total** | **$ 7,520,417** |

Xcel Energy

# NCAR-Xcel Energy Project
# $CO_2$ reduction due to accurate predictions

NCAR

*"The avoided generation occurred when Xcel cycled offline baseload thermal units (coal or natural gas combined cycle) due to extended periods of forecasted low loads and high winds."*

**AVOIDED EMISSIONS DUE TO IMPROVED PREDICTIONS: 238,136 TONS OF $CO_2$**

**MWh's of avoided generation in 2011**

Arapahoe 3 = 317
Arapahoe 4 = 6,941
Cherokee 1 = 11,606
Cherokee 2 = 13,772
Valmont 5 = 10,061
FSV CC = 93,626
RMEC CC = 308,989

# Probabilistic Power Prediction

NCAR

**Goal:**

Accurate power forecasts and reliable quantification of forecast uncertainty

**Motivation:**

- 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

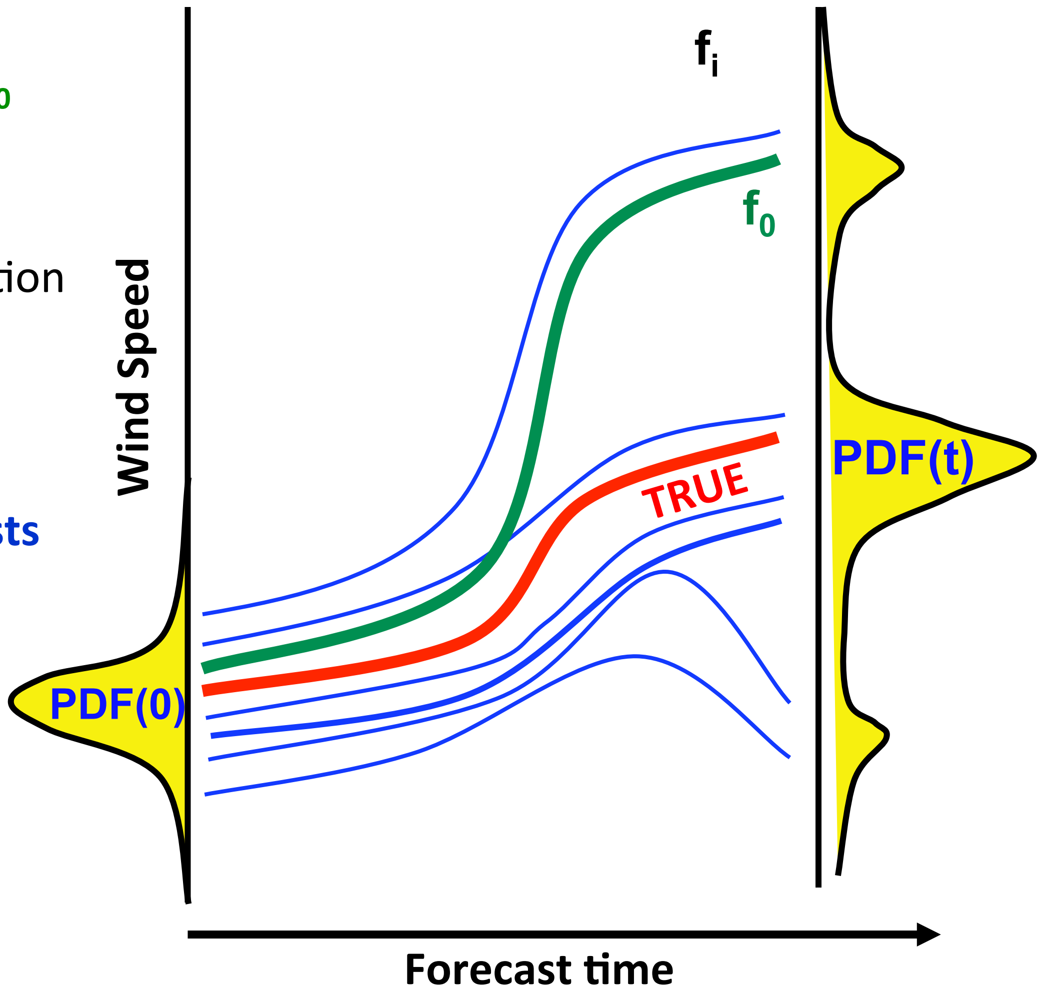
# Ensemble (En) Prediction

NCAR

The single **deterministic forecast $f_0$** fails to predict the **TRUE**

The initial probability density function **PDF(0)** represents the initial uncertainties

An **ensemble of perturbed forecasts $f_i$**, starting from perturbed initial conditions designed to sample the initial uncertainties can be used to estimate the probability of future states **PDF(t)**



# Weather analogs: basic idea

NCAR

# Weather analogs: basic idea

**Today**

# Weather analogs: basic idea

**Today**

**One week ago?**

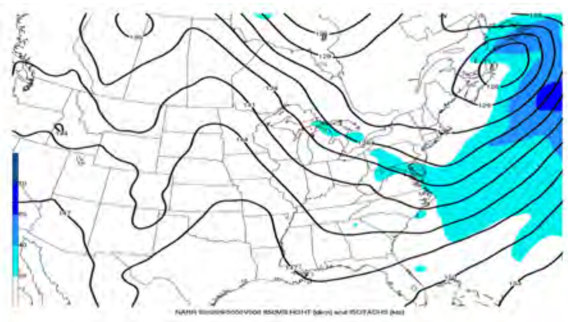
# Weather analogs: basic idea

Today

One week ago?

5 years ago?!?

# Weather analogs: basic idea



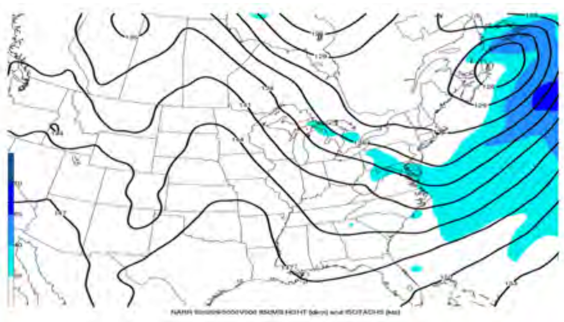
**Today**

**One week ago?**

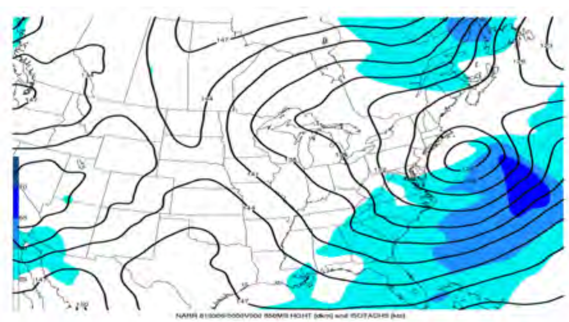
**5 years ago?!?**

# Weather analogs: basic idea

NCAR



**Today**

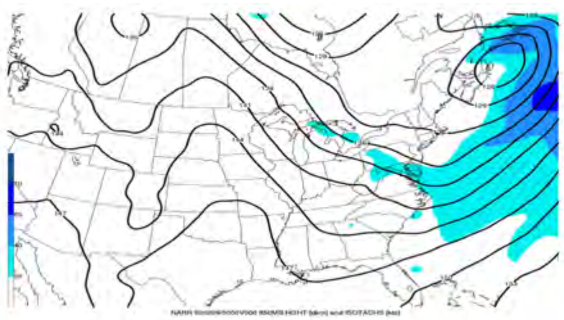


**One week ago?**

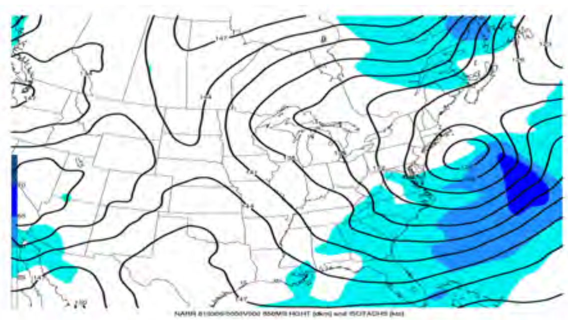
**5 years ago?!?**

# Weather analogs: basic idea

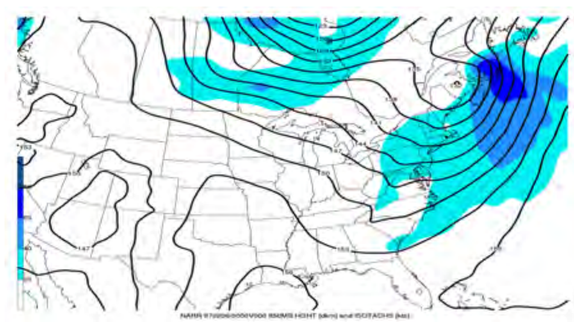
NCAR



**Today**

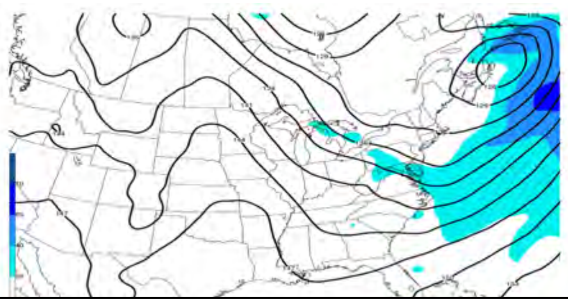


**One week ago?**



**5 years ago?!?**

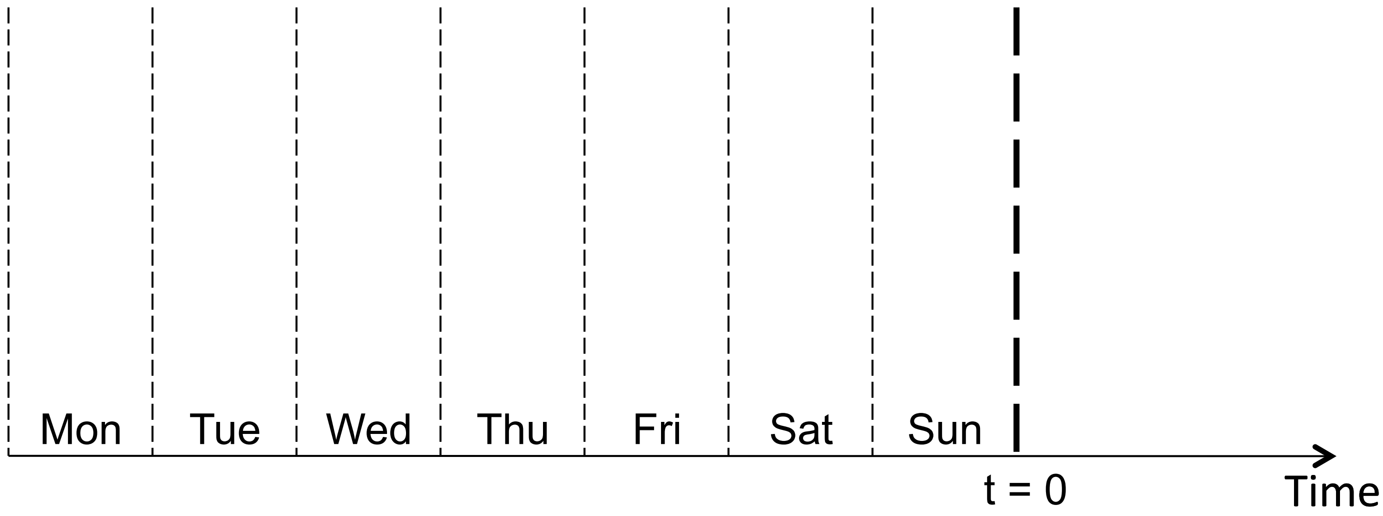
# Weather analogs: basic idea



Can we use this information
(i.e., both obs and re-analysis),
to improve forecasts or resource estimates?

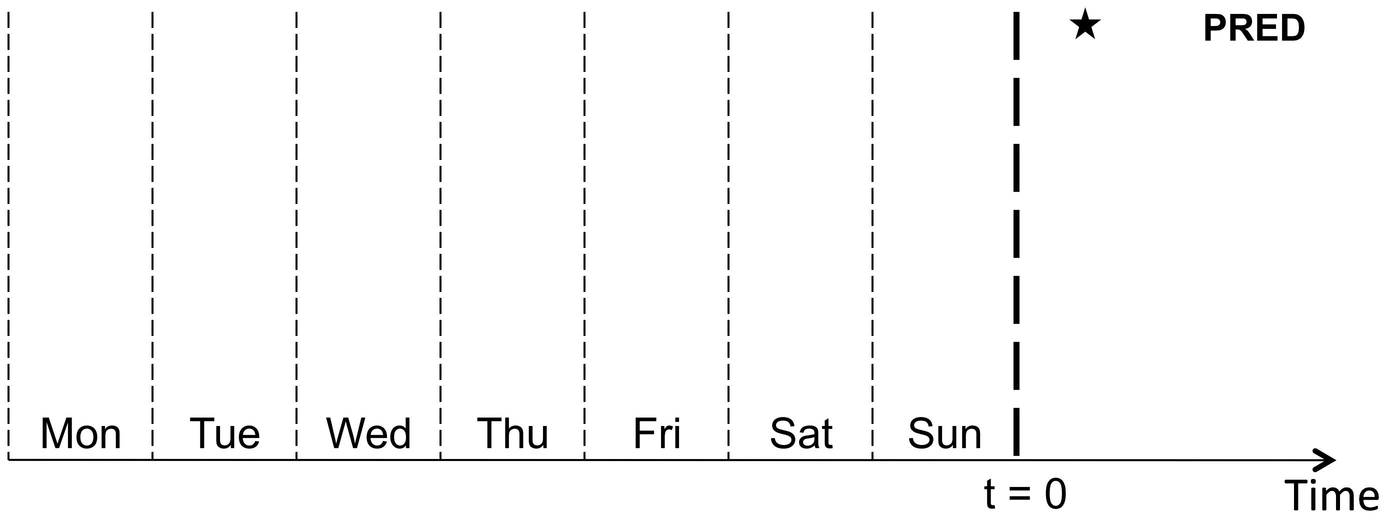
**5 years ago?!?**

# Analog Ensemble (AnEn)




Analog search as in Delle Monache et al. (MWR 2011)

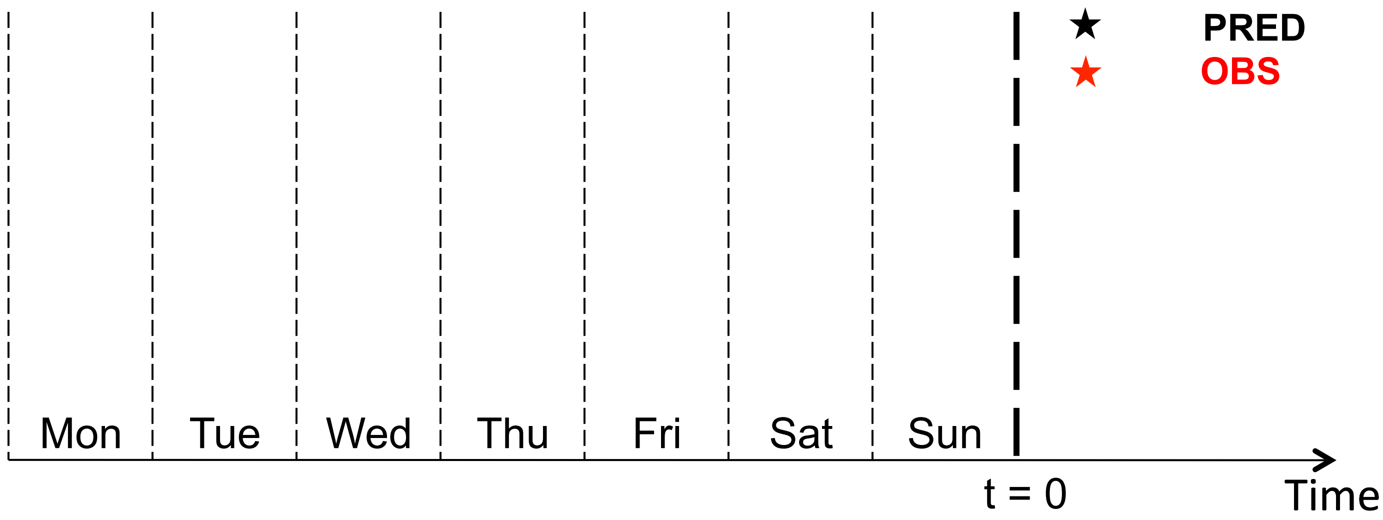
# Analog Ensemble (AnEn)




Analog search as in Delle Monache et al. (MWR 2011)

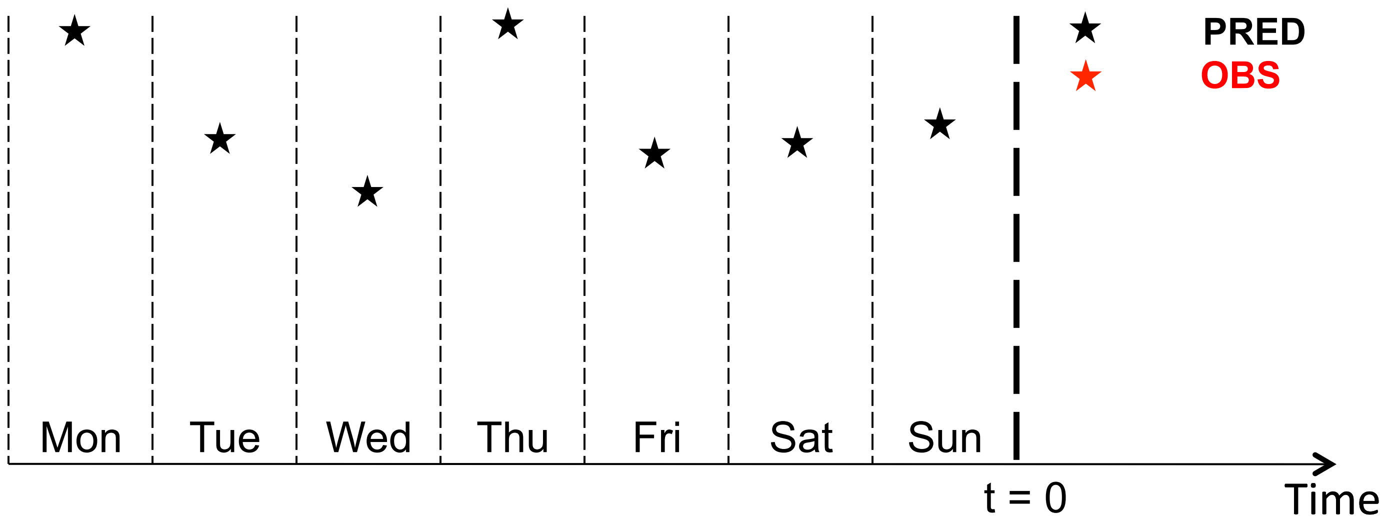
# Analog Ensemble (AnEn)

NCAR



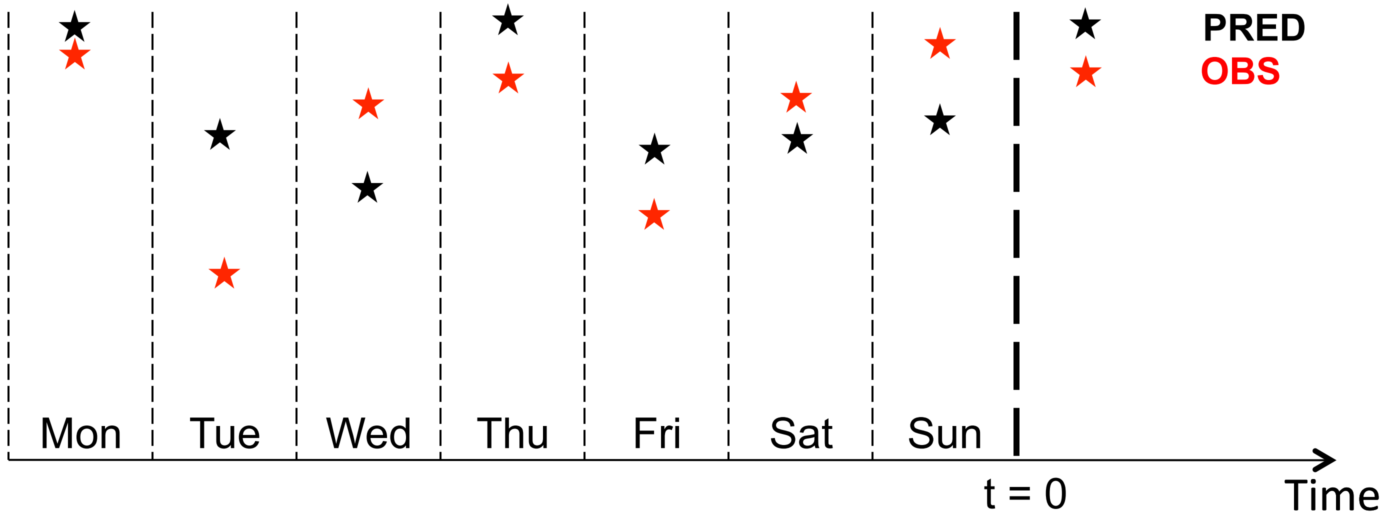

Analog search as in Delle Monache et al. (MWR 2011)

# Analog Ensemble (AnEn)



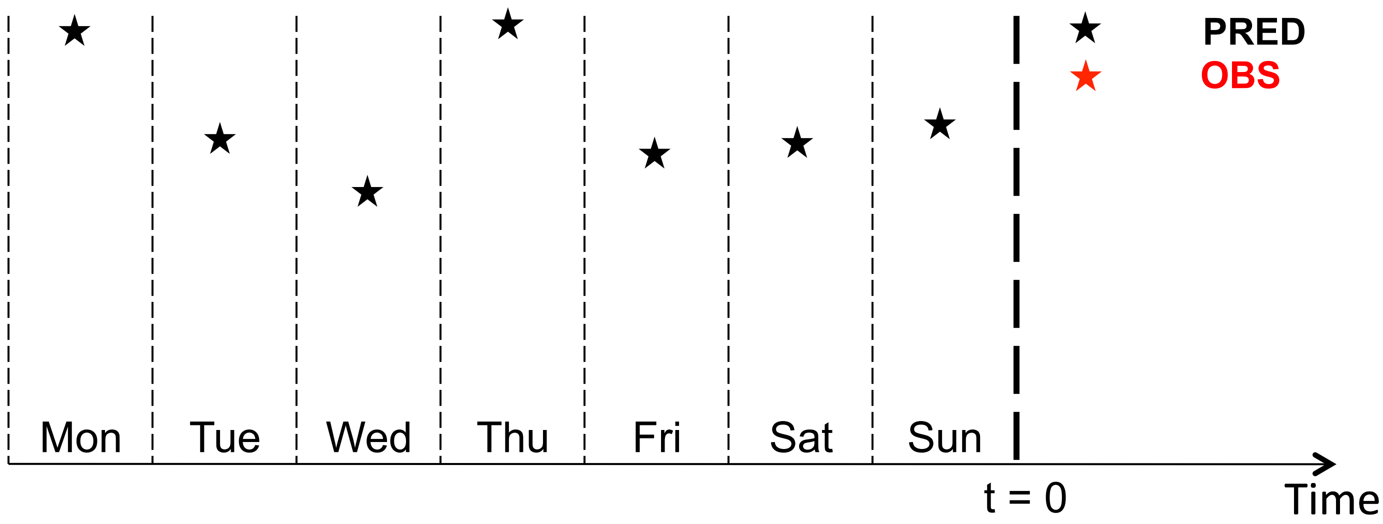

Analog search as in Delle Monache et al. (MWR 2011)

# Analog Ensemble (AnEn)



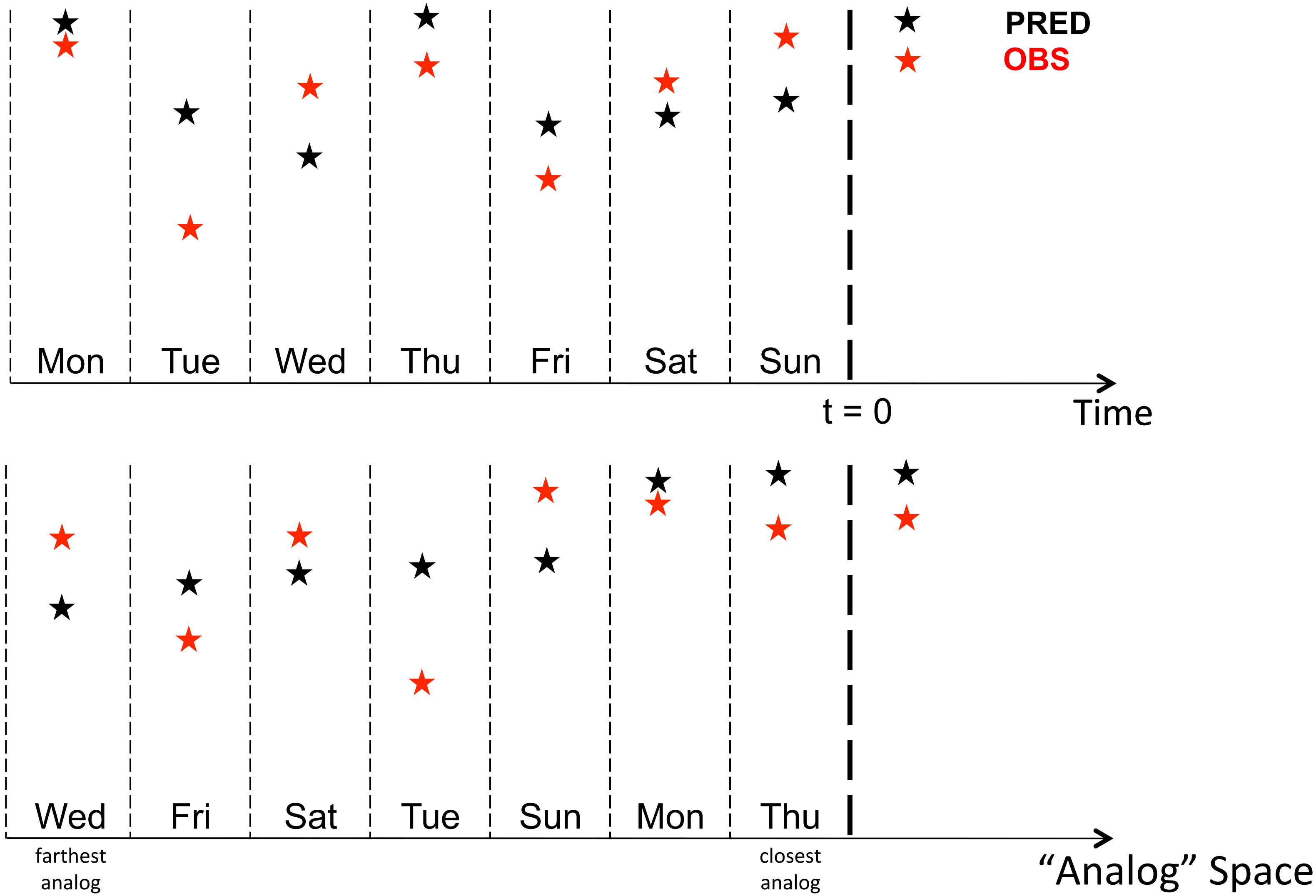

Analog search as in Delle Monache et al. (MWR 2011)

# Analog Ensemble (AnEn)



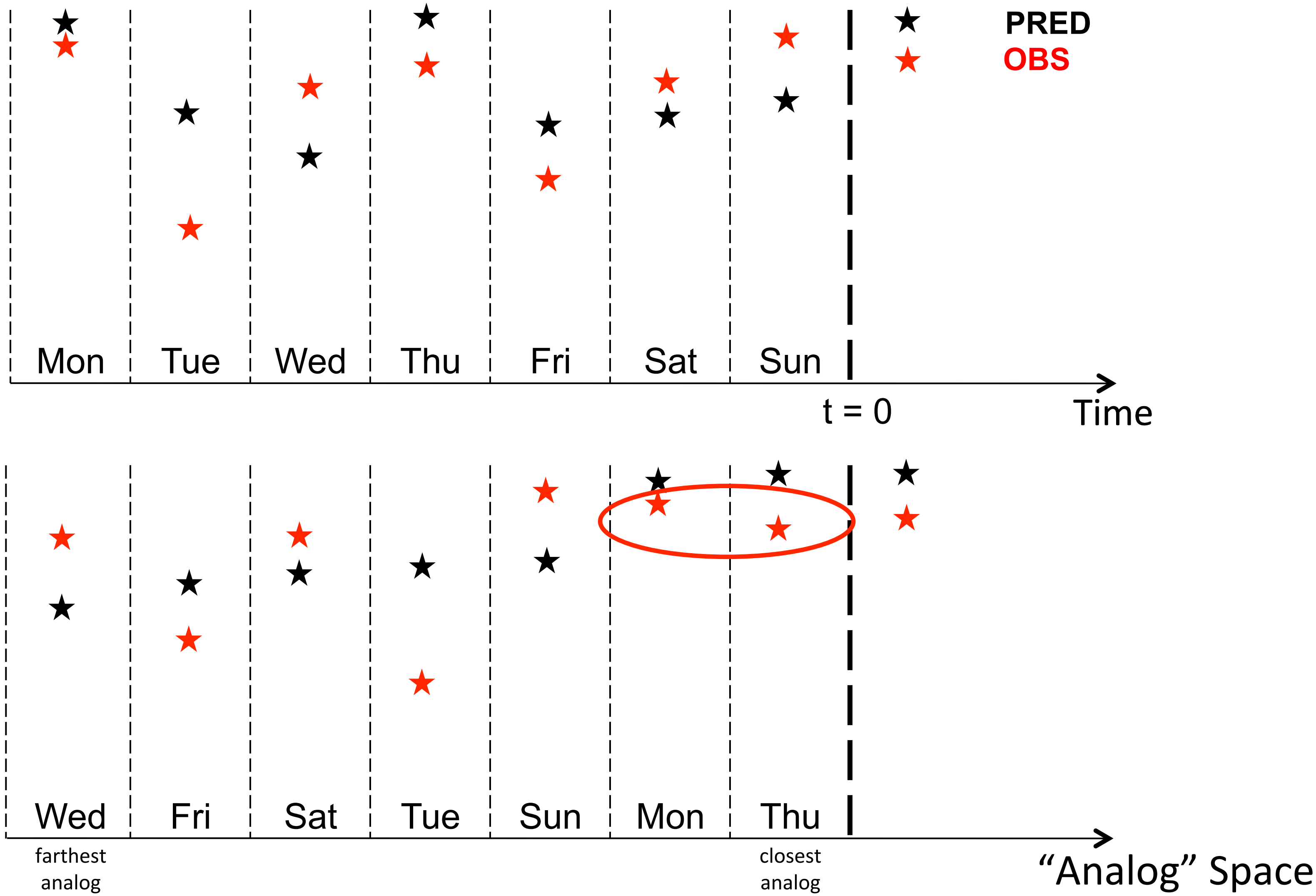

Analog search as in Delle Monache et al. (MWR 2011)

# Analog Ensemble (AnEn)



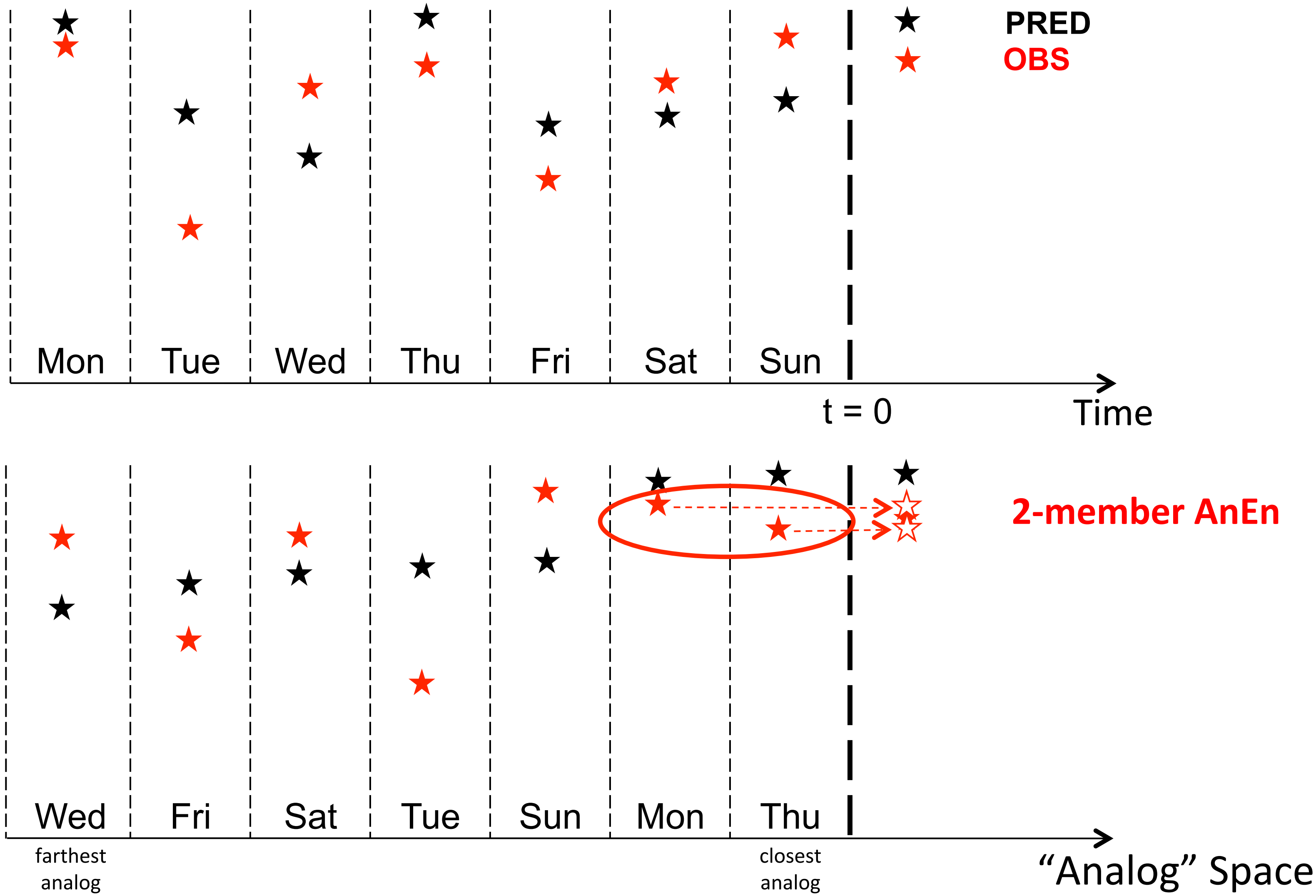

Analog search as in Delle Monache et al. (MWR 2011)

# Analog Ensemble (AnEn)




Analog search as in Delle Monache et al. (MWR 2011)

# Analog Ensemble (AnEn)




Analog search as in Delle Monache et al. (MWR 2011)

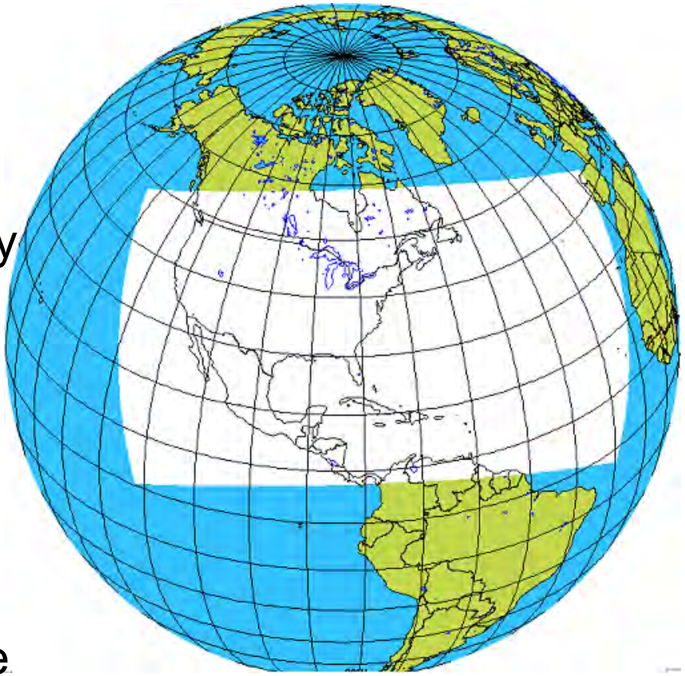
# How skillful is AnEn?

- AnEn generated with Environment Canada GEM (15 km), 0-48 hours
- Comparison with:
  - Environment Canada Regional Ensemble Prediction System (REPS, next slide)
  - Logistic Regression (LR) out of 15-km GEM
  - LR our of REPS, i.e., Ensemble Model Output Statistics (EMOS)
- Period of 15 months (verification over the last 3 months)
- 10-m wind speed
- 550 surface stations over CONUS (in two slides)
- Probabilistic prediction attributes: statistical consistency, reliability, sharpness, resolution, spread-error consistency

# Regional Ensemble Prediction System (REPS)

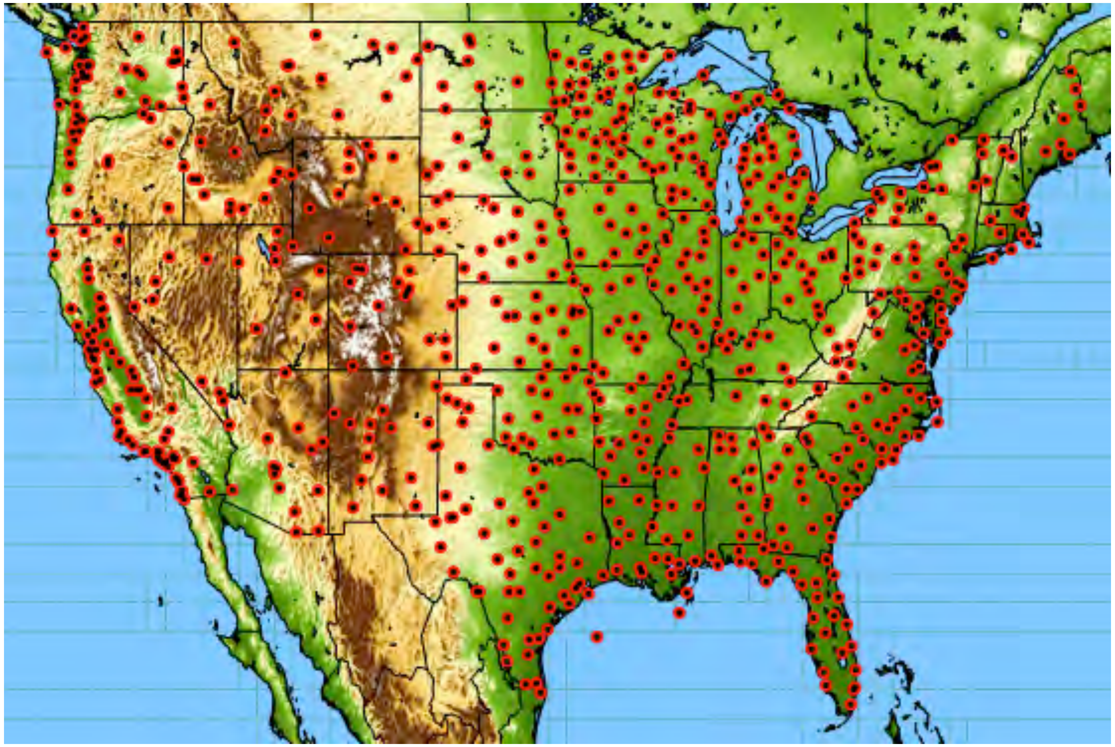
NCAR

- Model:  GEM 4.2.0 (vertical staggering)
- 20 members + 1 control run
- 72 hours forecast lead time
- Resolution:  ~33 km with 28 levels
- Initial conditions (i.e., cold start) and 3-hourly boundary condition updates from GEPS (EnKF + multi-physics)
- Physics:
    - Kain et Fritsch (1993) for deep convection
    - Li et Barker (2005) for the radiation
    - ISBA scheme (Noilhan et Planton, 1989) for surface
- Stochastic Physics:  Markov Chains on physical tendencies



# Ground truth dataset

- 550 hourly METAR Surface Observations
- 1 May 2010 – 31 July 2011, for a total of 457 days
- 10-m wind speed



# Probabilistic forecast attributes: Reliability

Example:

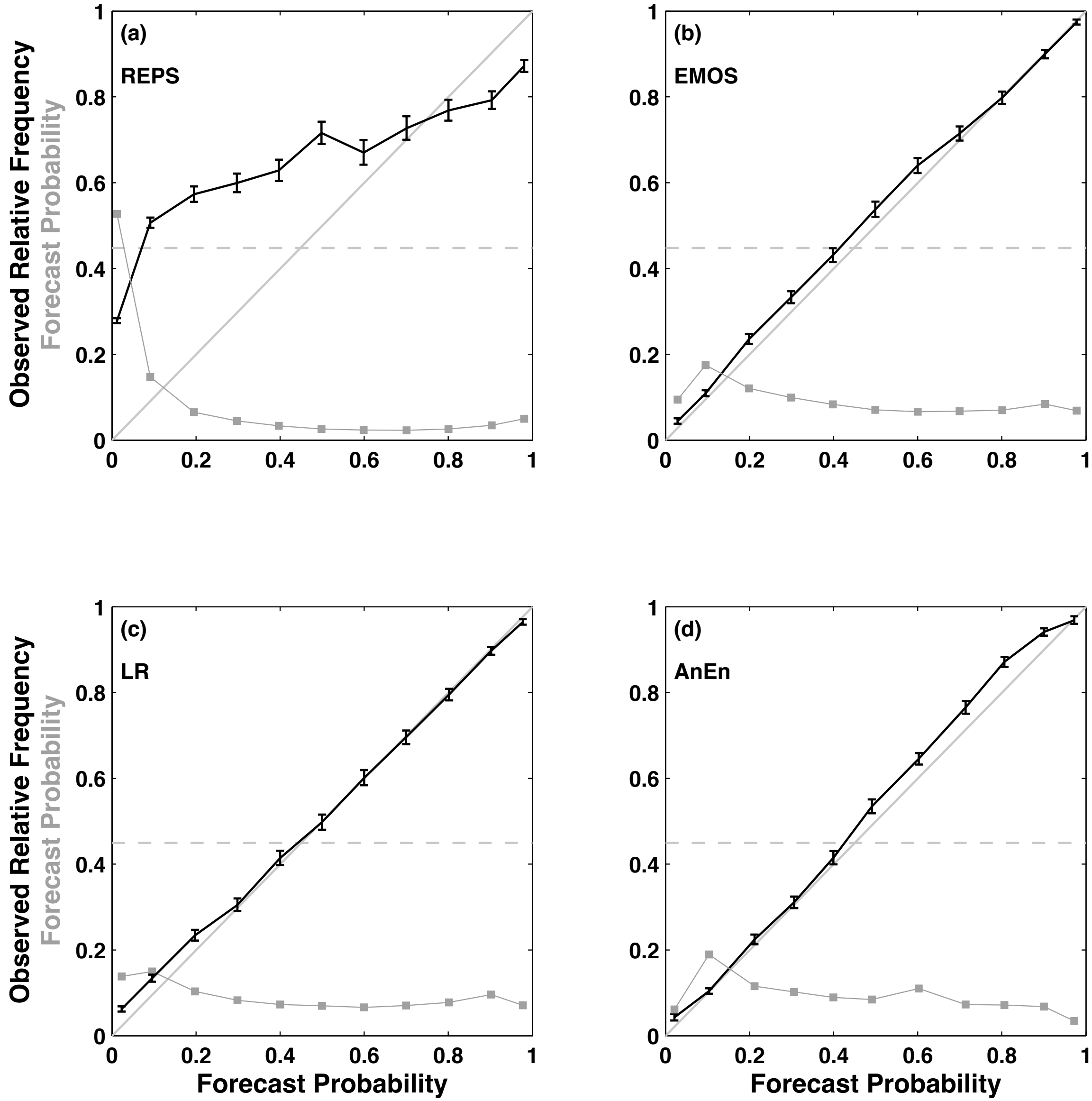
① An event (e.g., wind speed > 5 m/s) is predicted to happen with a 30% probability

② We collect the observations that verified every time we made the prediction in ①

③ If the frequency of the event in the observation collected is 30%, then the forecast is perfectly *RELIABLE*

# Analysis of reliability & sharpness

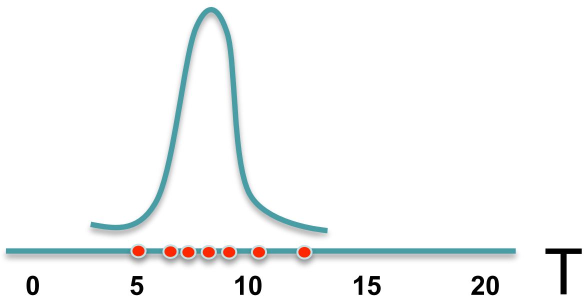
Reliability and sharpness diagram: 10-m wind speed > 5 m s$^{-1}$, 9-h fcst



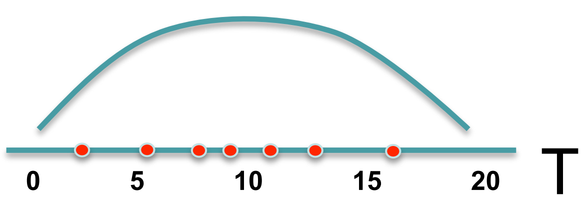
# Probabilistic forecast attributes: Sharpness

Sharpness refers to the degree of concentration of a forecast PDF's probability density, and is a property of the forecasts only.

Ideally, we want the forecast system, while mainly reliable, with as many forecasts as possible close to 0% and 100%, corresponding to a perfect deterministic forecast system. However, an improvement in sharpness does not necessarily mean that the forecast system has improved.



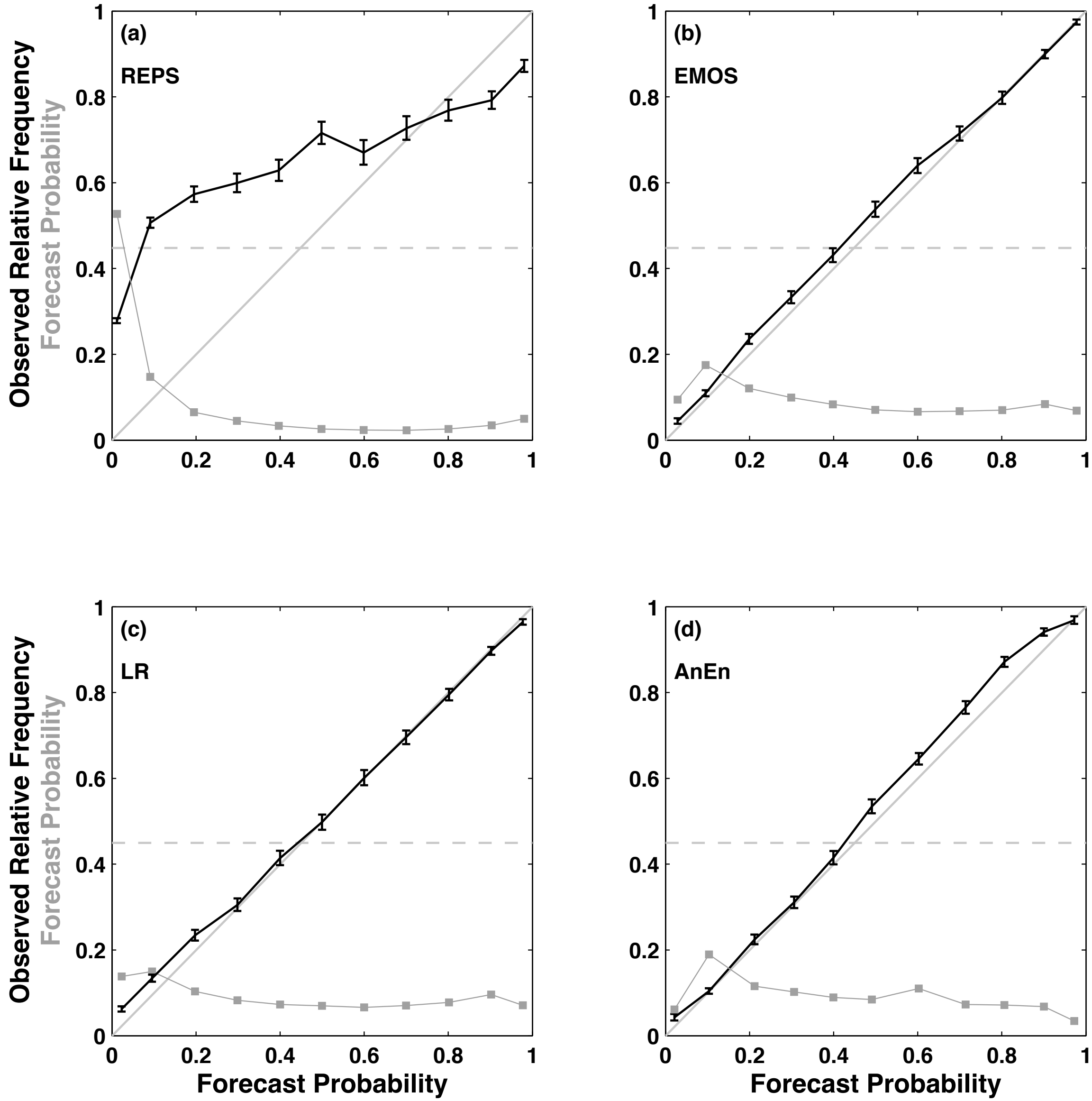

**Sharper Forecast**



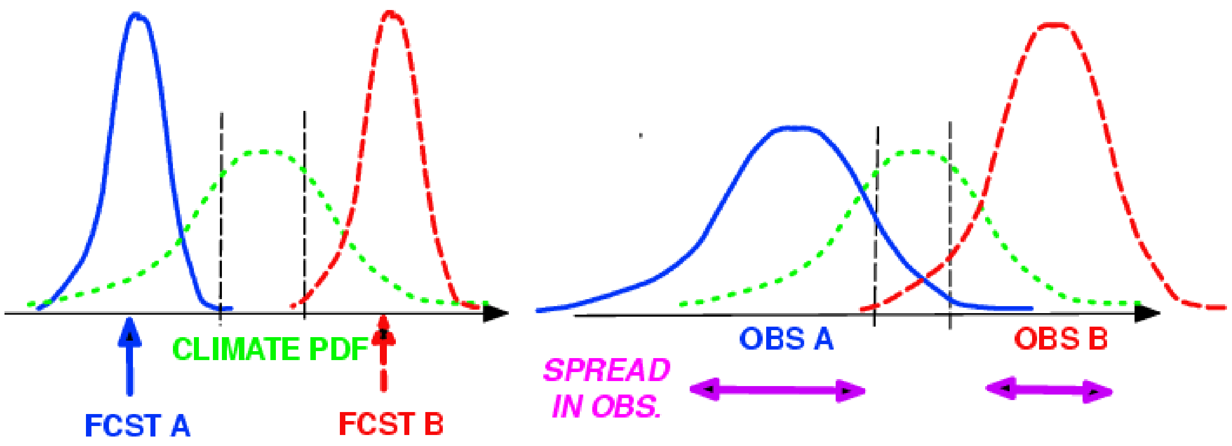

**Less Sharp Forecast**

# Analysis of reliability & sharpness

Reliability and sharpness diagram: 10-m wind speed > 5 m $s^{-1}$, 9-h fcst



# Probabilistic forecast attributes: Resolution



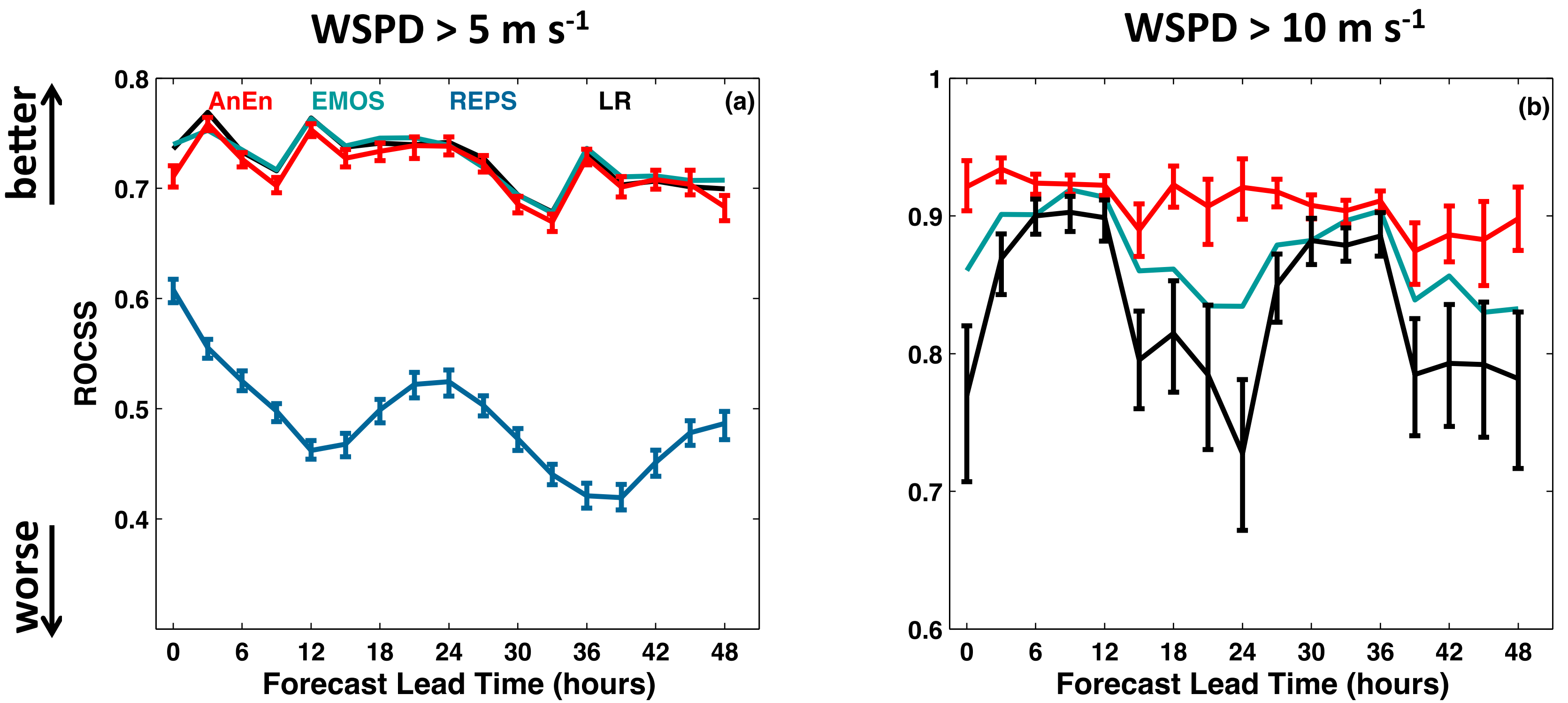

Consider different classes of forecast events.

If all observed classes corresponds to different forecast classes, then the probabilistic forecast has perfect *RESOLUTION*.

# Analysis of Resolution (1)

NCAR

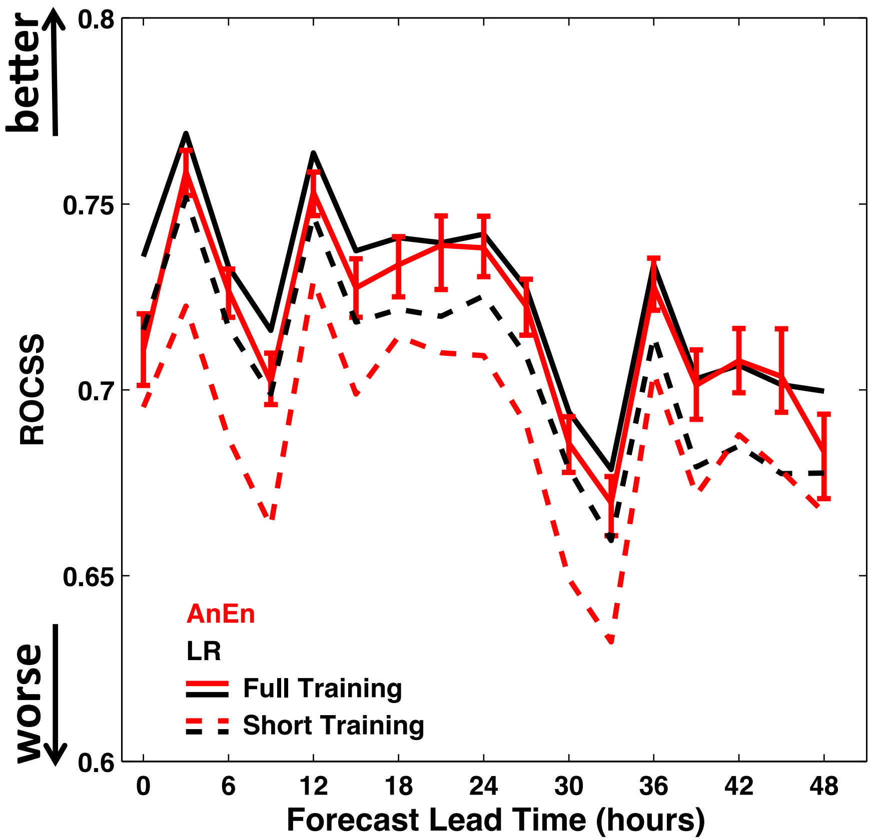
Relative Operating Characteristics skill score, 10-m wind speed ≥ 5, 10 m $s^{-1}$



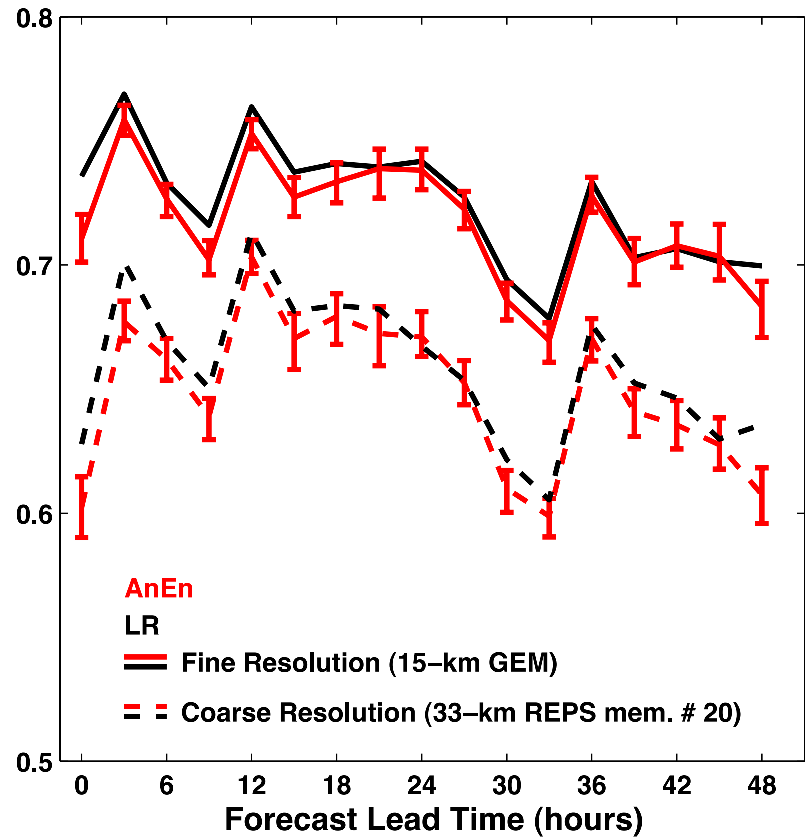
# AnEn sensitivity

Relative Operating Characteristics skill score, 10-m wind speed ≥ 5 m $s^{-1}$

AnEn with a shorter training data set (15 → 9 months)



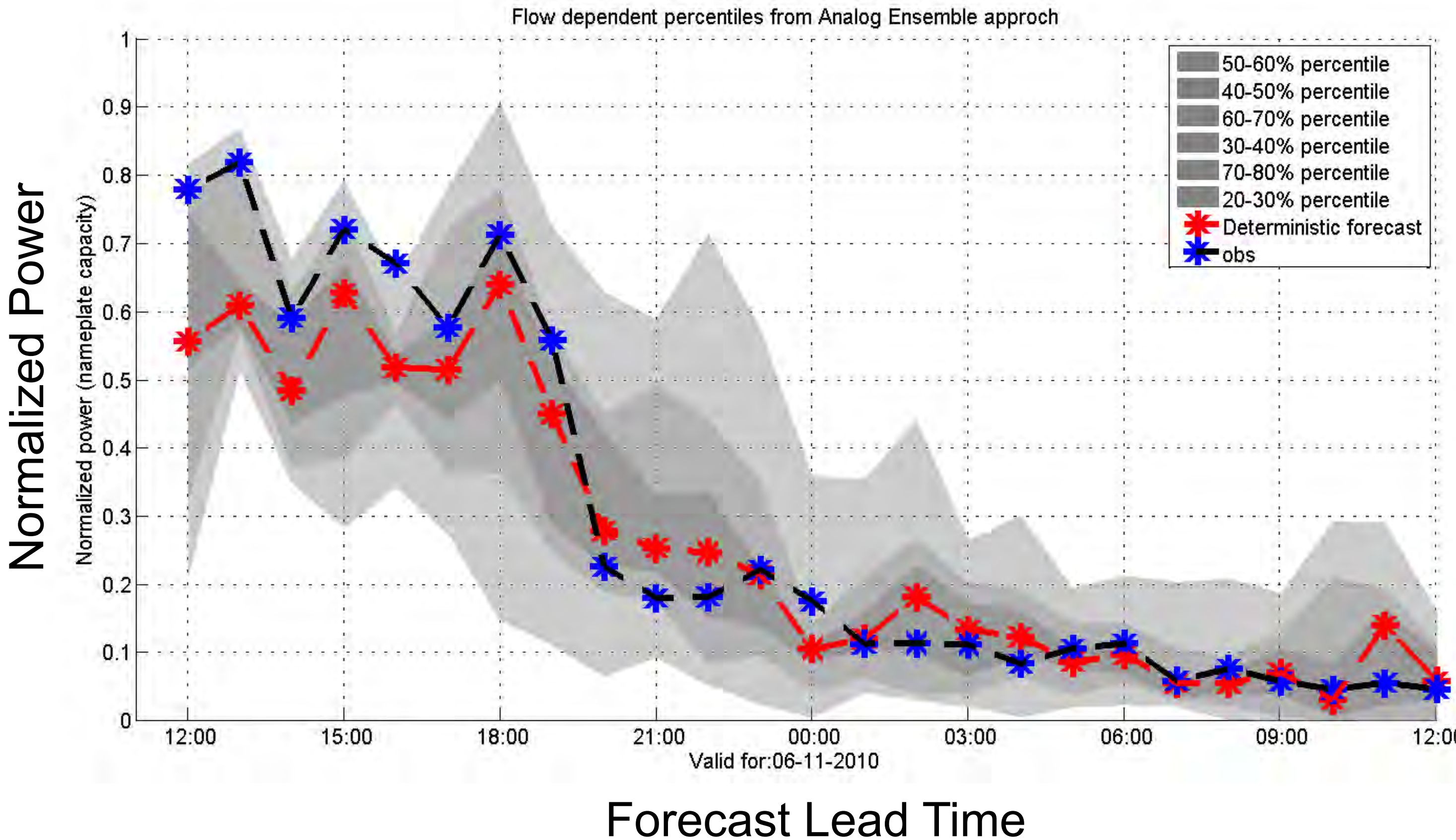

AnEn built with a coarser dynamical model (15 → 33 km)



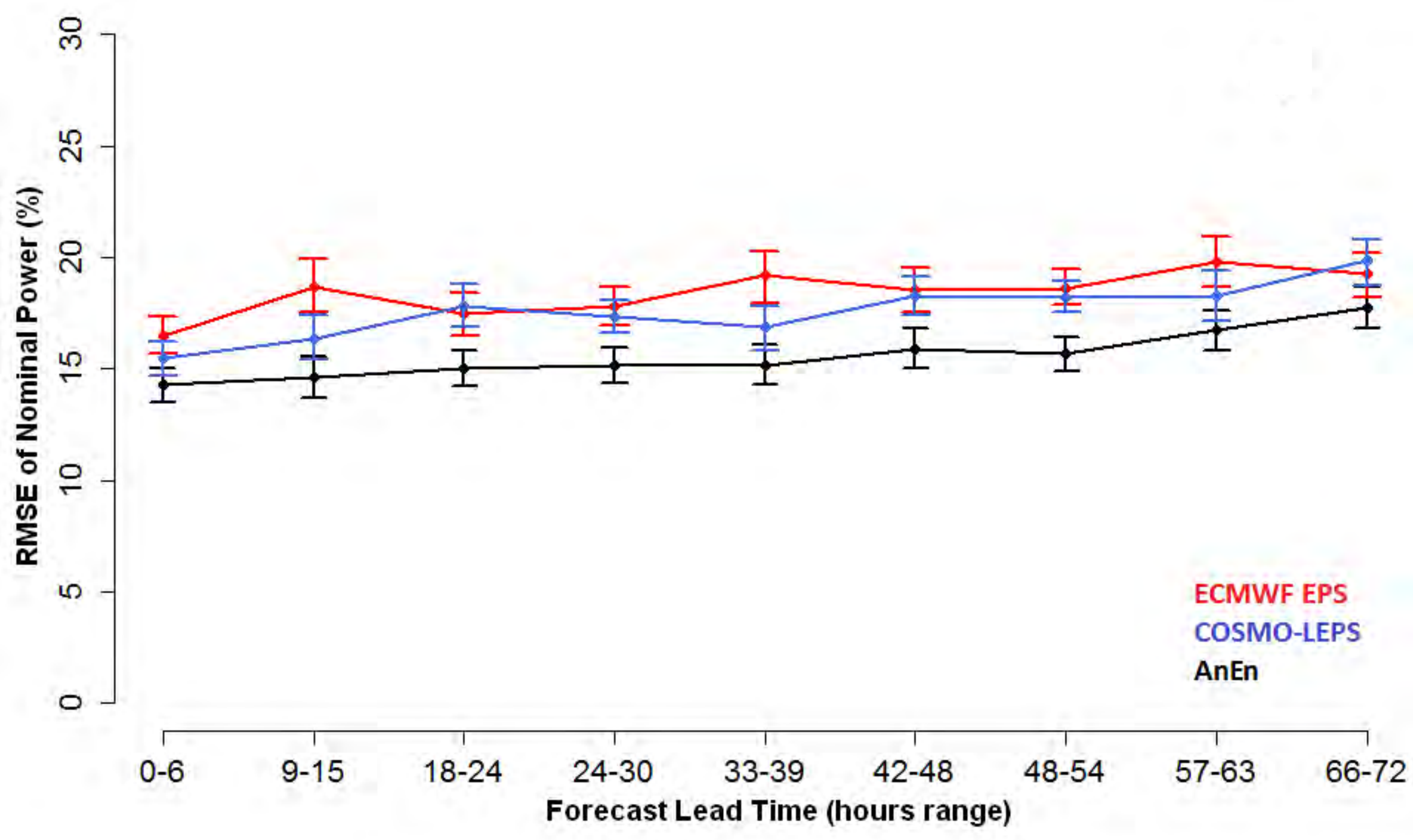
# Power predictions: Experiment design

- Test site: Wind farm in northern Sicily − 9 turbines, 850 kW Nominal Power (NP)
- Training period: November 2010 - October 2012
- Verification period: November 2011 – October 2012
- Probabilistic prediction systems: ECMWF EPS, COSMO LEPS, AnEn

# Power predictions



# RMSE of ensemble means



# Probabilistic forecast attributes: Statistical and spread-error consistency

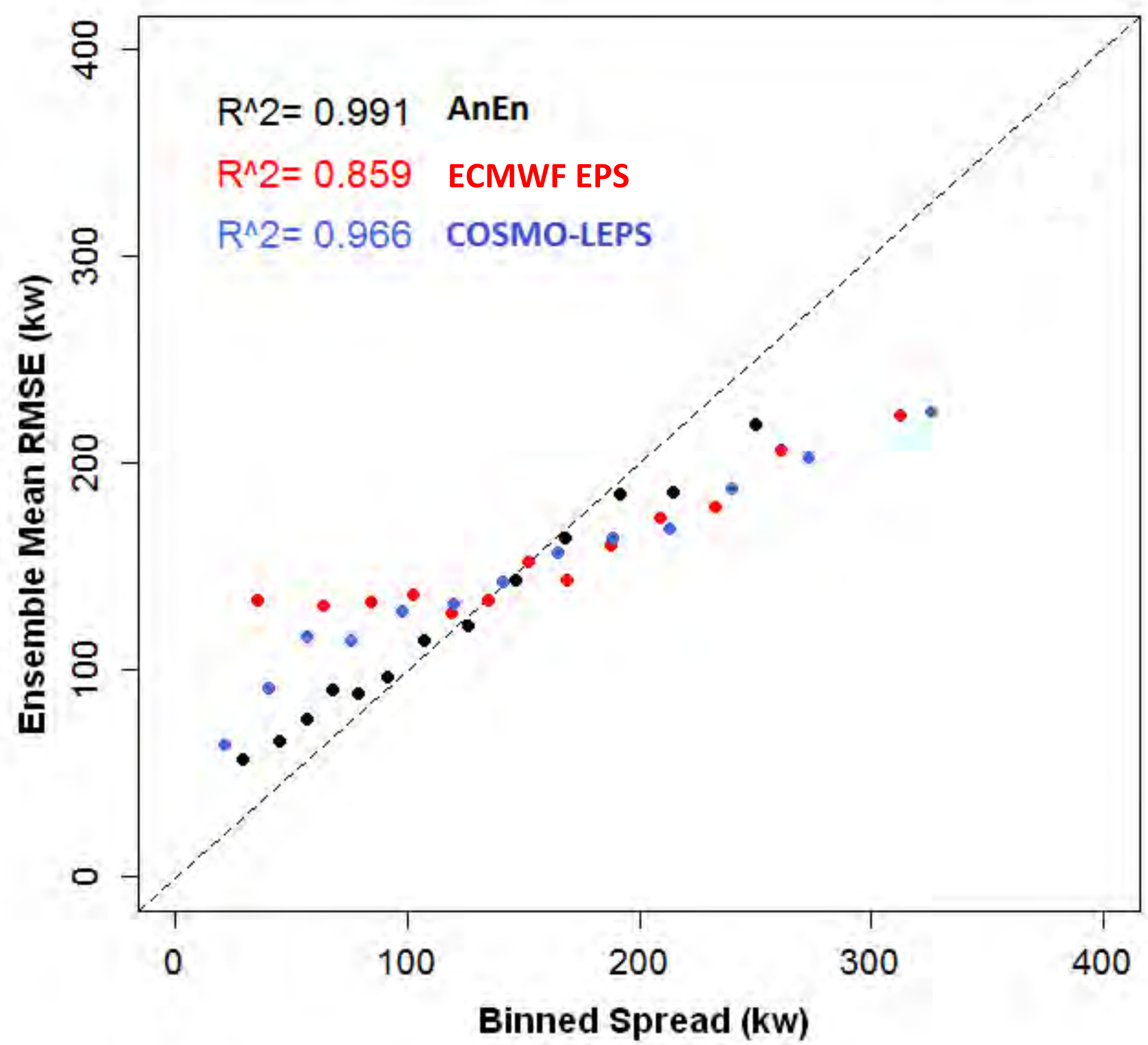
NCAR

① The ensemble spread tell us how uncertain a forecast is. Ideally, large spread should be associate with larger uncertainties, low spread should indicate higher accuracy

② If an ensemble is perfect, than the observations are indistinguishable from the ensemble members

# Spread-skill relathionship

NCAR



# Summary

- NCAR's wind energy research and development
  - Icing, fine-scale & boundary layer meteorology research
  - Data assimilation, statistical learning
  - Wind & power predictions, wind resource assessment
- The NCAR-Xcel Project, a successful story
- The analog ensemble provides accurate predictions/estimates and reliable uncertainty quantification (at a lower computational cost)
- The analog ensemble can be used for dynamical downscaling and wind resource assessment

# THANKS!

(lucadm@ucar.edu)

**Collaborators include**:
Bill Mahoney, Sue Haupt, Greg Thompson, Gerry Wiener, Bill Myers, David Johnson, Yubao Liu, Jenny Sun, Tom Hopson, Branko Kosovic, Julie Lundquist, Stefano Alessandrini, Seth Linden, Julia Pearson, Frank McDonough, …

## References

- Delle Monache et al., 2011: Kalman filter and analog schemes to postprocess numerical weather predictions. *Monthly Weather Review*, **139**, 3554–3570.
- Delle Monache et al., 2013: Probabilistic weather predictions with an analog ensemble. *Mon. Weather Review*, sub.
- Vanvyve and Delle Monache, 2013: Wind resource assessment with an analog ensemble. *Journal of Applied Meteorology*, in preparation.