NCAR

Probabilistic Forecasting for Weather Prediction

Luca Delle Monache

National Security Applications Program
Research Applications Program
National Center for Atmospheric Research

Software Engineering Assembly
Boulder, CO – 2 April 2018

Acknowledgments

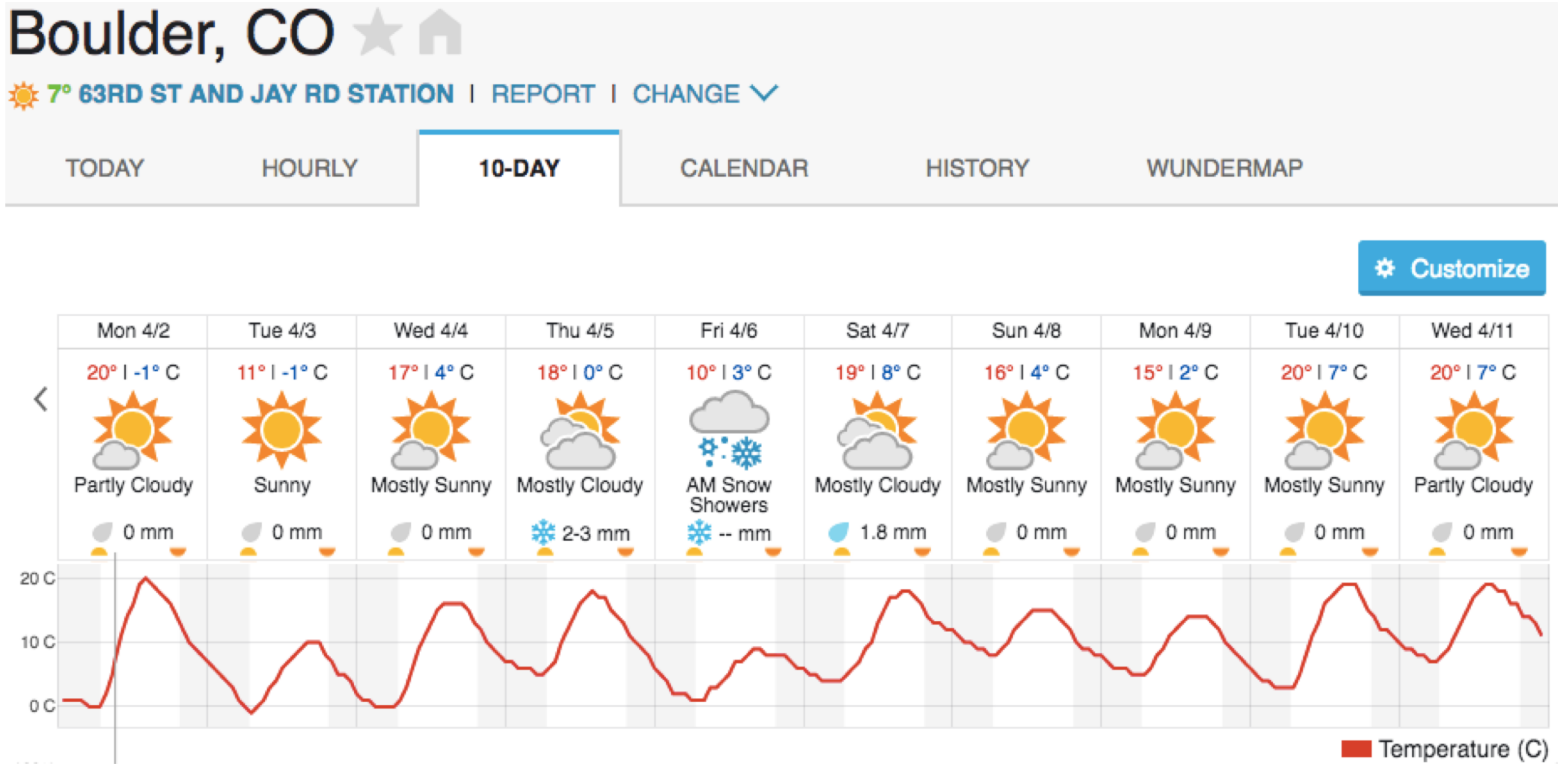
NCAR

- **COLLABORATORS**
  - Stefano Alessandrini, Will Cheng, Sue Haupt, Tom Hopson, Jason Knievel, Chis Rozoff (NCAR, USA)
  - Jan Keller (DWD, Germany)
  - Roland Stull (University of British Columbia, Canada)
  - Constantin Junk, Lueder von Bremen, Detlev Heinemann (ForWind, Carl von Ossietzky University, Germany)
  - Iris Odak, Kristian Horvath (Meteorological and Hydrological Service of Croatia, Croatia)
  - Badrinath Nagarajan (IBM, Australia)
  - Federica Davo', Simone Sperati (RSE, Italy)
  - Caroline Draxl, Bri-Mathias Hodge, Jie Zhang (NREL, USA)
  - Tony Eckel (Climate Corporation, USA)
  - Thomas Nipen (Norwegian Meteorological Institute, Norway)
  - Irina Djalalova, Jim Wilczak (NOAA, USA)
  - Emilie Vanvyve (UK Met Office, UK)
  - Sam Hawkins, Jesper Nielsen Nissen (Vattenfall, UK, Denmark)
  - Jessica Ma, Daran Rife (DNV GL, USA)
  - Martina Calovi, Guido Cervone, Laura Harding, Mehdi Shahriari (Penn State, USA)
  - Will Lewis (University of Wisconsin, Madison, USA)
  - Marina Astitha, Jaemo Yang (University of Connecticut)
  - Min Cheng, Zaiwen Wang (institute of Urban Meteorology, Beijing, China)
  - Sal Candido, Sam Ponda, Bradley Rhodes, Aakanksha Singh (Google X)
- **SPONSORS**
  - U.S. Department of Defense (DOD) Army Test and Evaluation Command (ATEC)
  - U.S. DOD Defense Threat Reduction Agency (DTRA)
  - U.S. Department of Energy (DOE)
  - U.S. National Aeronautics and Space Administration (NASA)
  - U.S. National Renewable Energy Laboratory (NREL)
  - U.S. National Oceanic and Atmospheric Administration (NOAA) Hurricane Forecast Improvement Program (HFIP)
  - Vattenfall, Vestas Wind Systems, Xcel Energy
  - Institute of Urban Meteorology (IUM)
  - Google X

Outline

- Chaos, probabilistic predictions, ensembles
- Analog Ensemble (AnEn) basic idea and algorithm
- AnEn for point-based predictions and downscaling
    - Wind power
- AnEn for 2D/gridded probabilistic predictions
    - 10-m wind speed
- Summary

Traditional forecasting used to (and often still does) consist of one prediction from one model



- Specific… but how likely? Unknown
- Likelihood <100% because the atmosphere is…

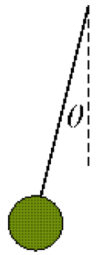
CHAOTIC!

Chaos

NCAR

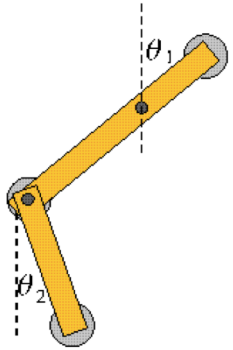
NON-CHAOTIC

Simple pendulum



CHAOTIC

Double Pendulum



The Atmosphere is a Chaotic System

Edward Norton Lorenz

(May 23 1917 - April 16 2008)

"Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?"

The Atmosphere is a Chaotic System

NCAR

- Small differences in the initial conditions between two runs grow in time up to a point when the two simulations look as they were randomly chosen
- The Atmosphere predictability ***is limited***
- Lorenz estimated this limit at ~2 weeks
- Such limit varies with different scales of motion
- Predictability changes with different atmospheric flows, i.e., it is ***flow-dependent***

Prediction Goals

NCAR

- Predict the observed distribution of events and atmospheric states
- Predict uncertainty in the day's prediction
- Predict the extreme events that are possible on a particular day
- Provide a range of possible scenarios for a particular forecast

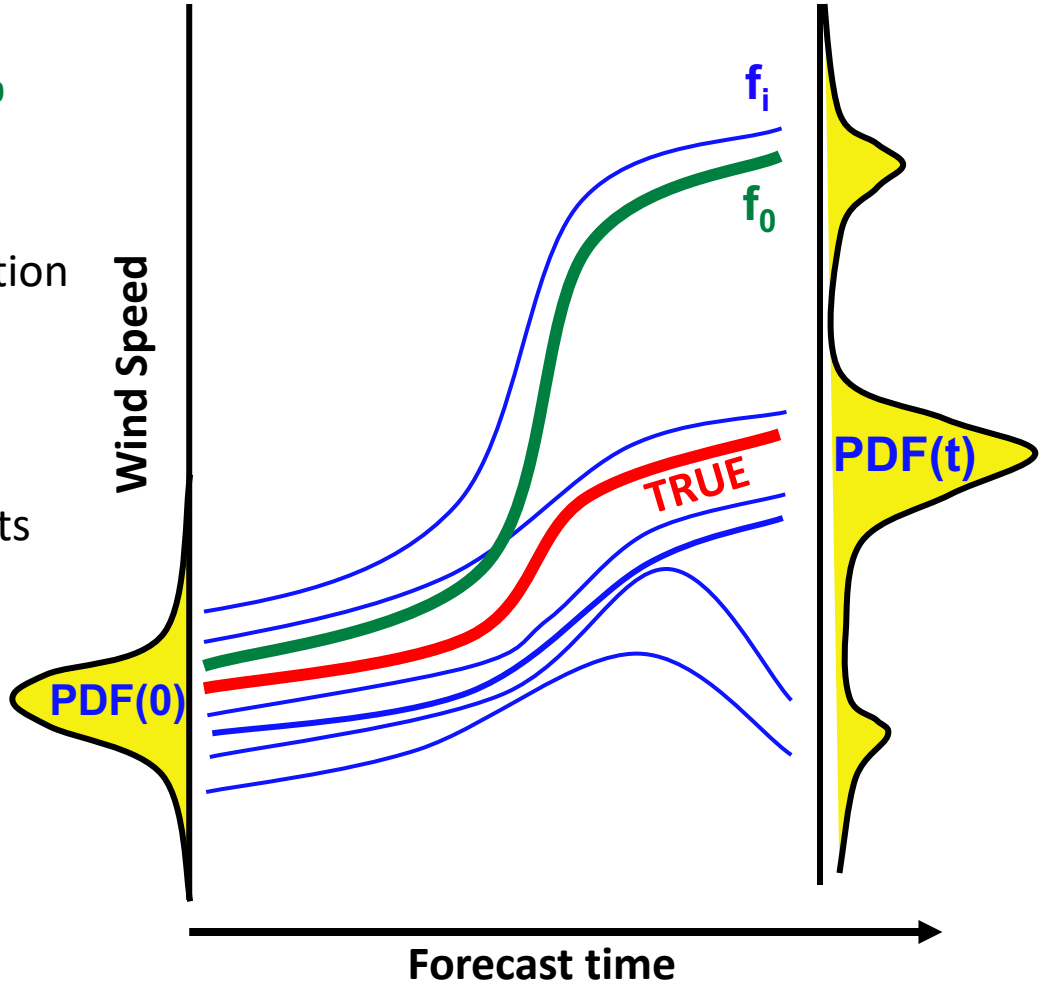
Ensemble Prediction

NCAR

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

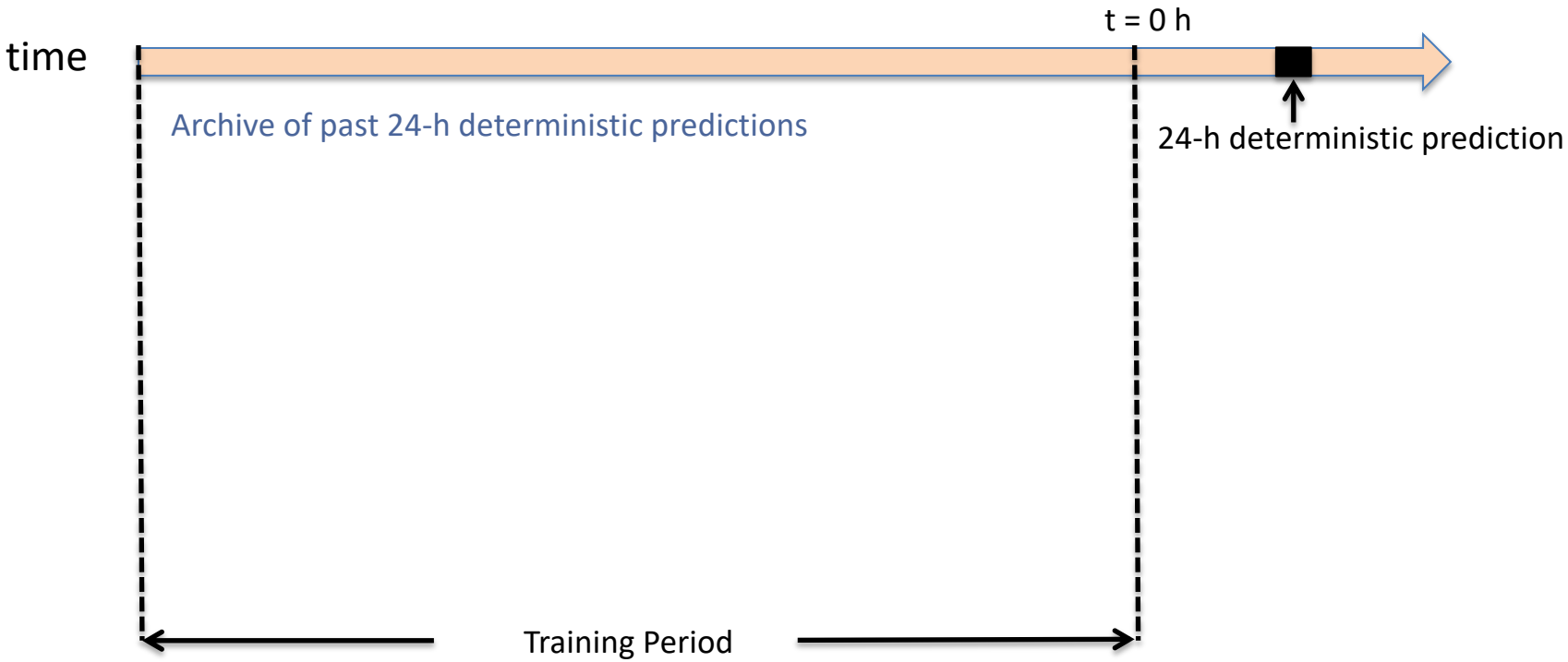
The initial probability density function **PDF(0)** represents the initial uncertainties

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)**



The Analog Ensemble (AnEn)

The Analog Ensemble

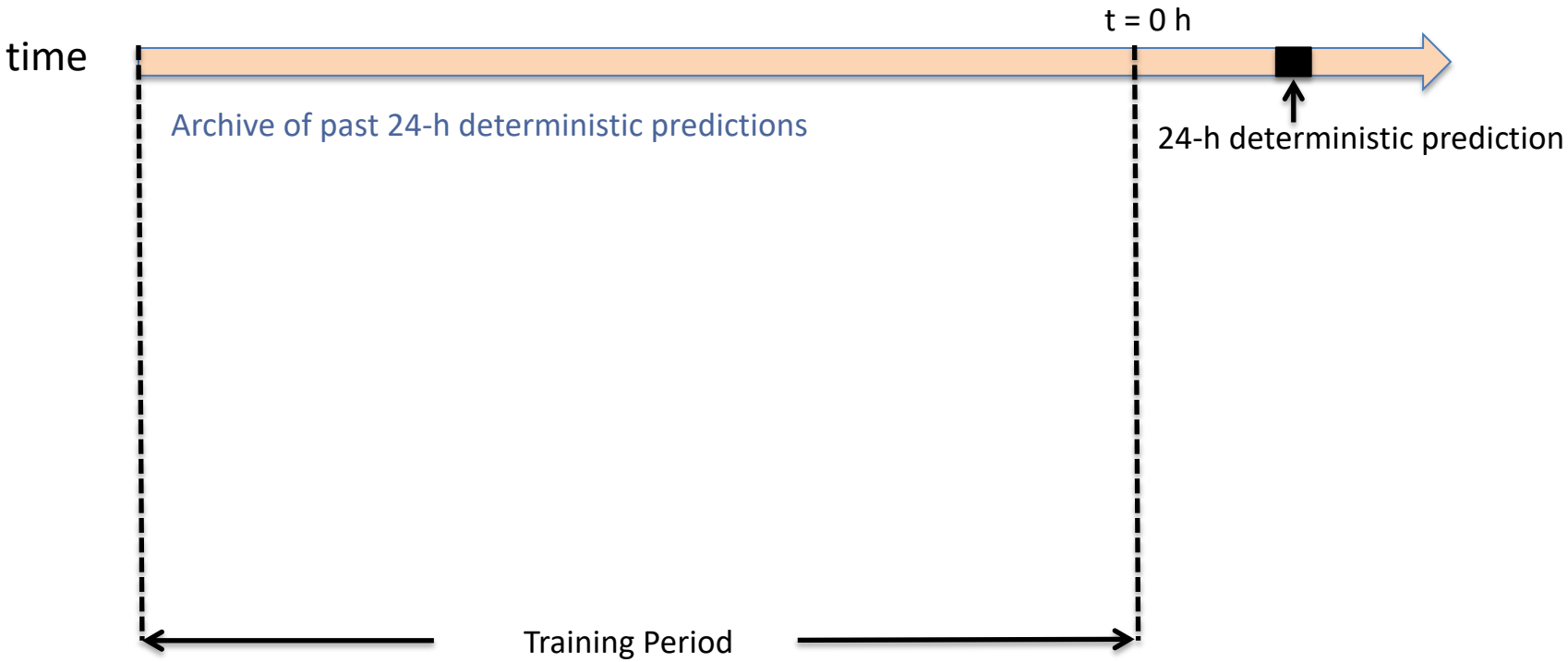


Delle Monache et al. (MWR, 2011, 2013)

The Analog Ensemble

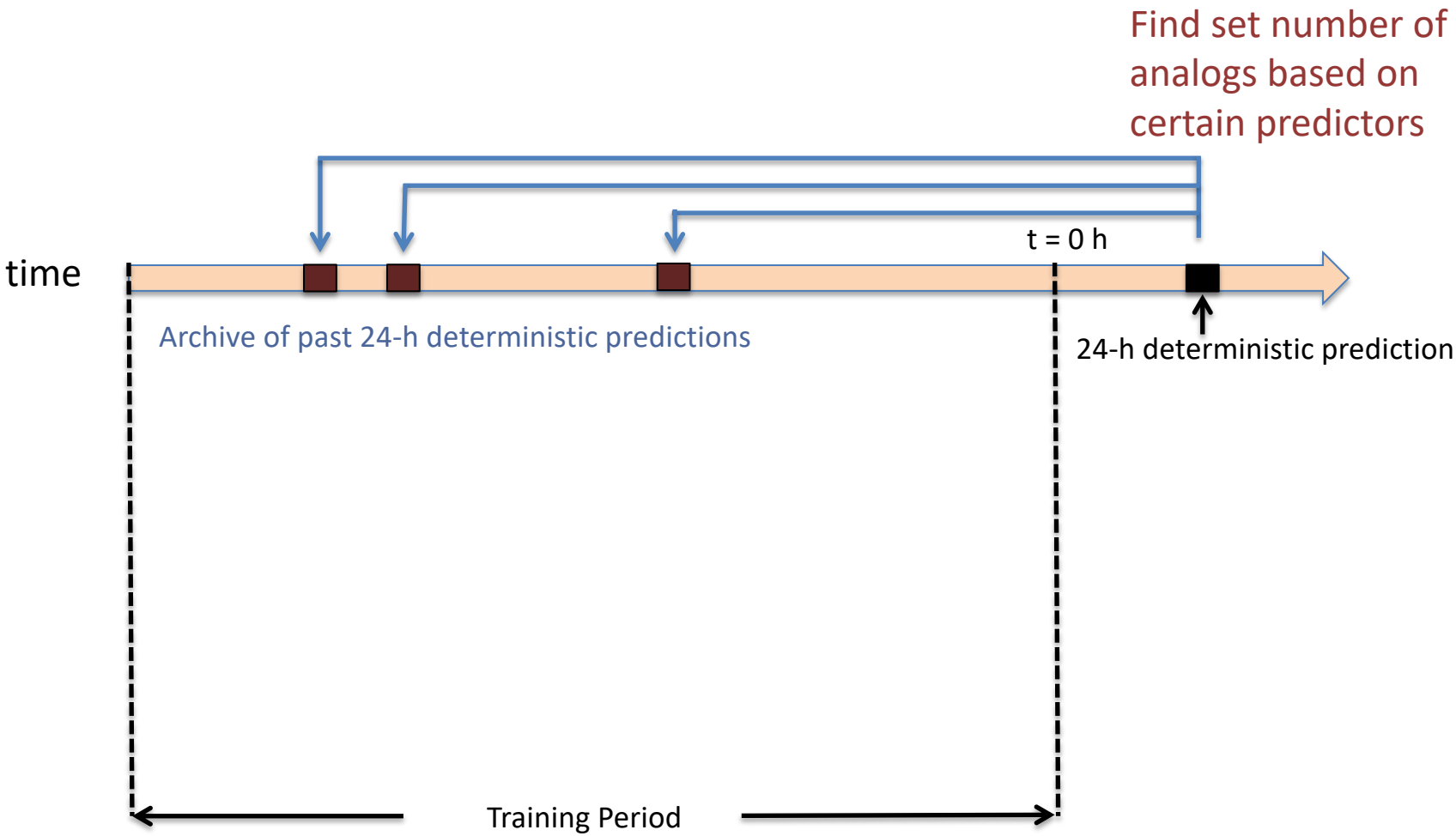
NCAR

Find set number of analogs based on certain predictors



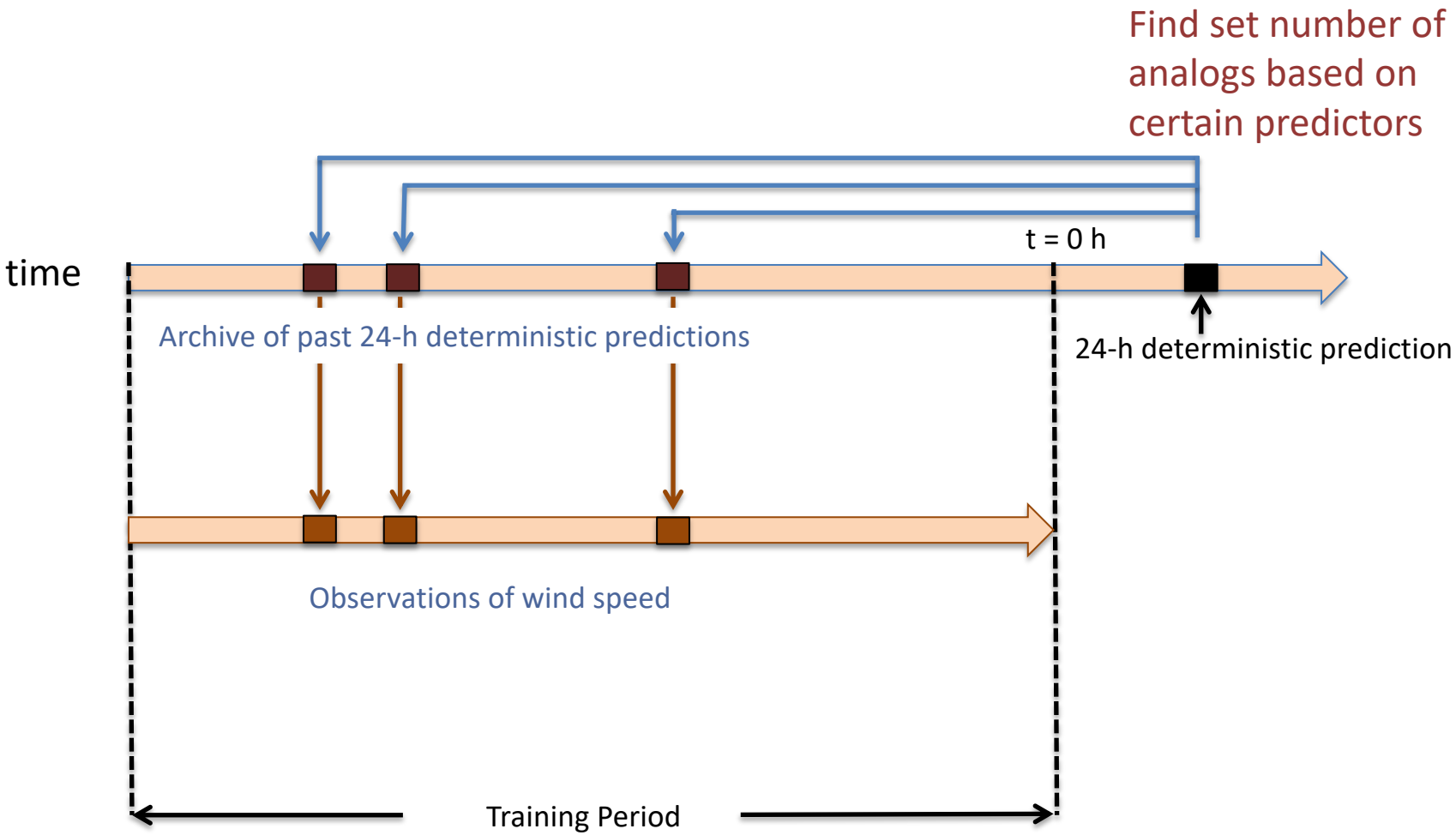
Delle Monache et al. (MWR, 2011, 2013)

The Analog Ensemble



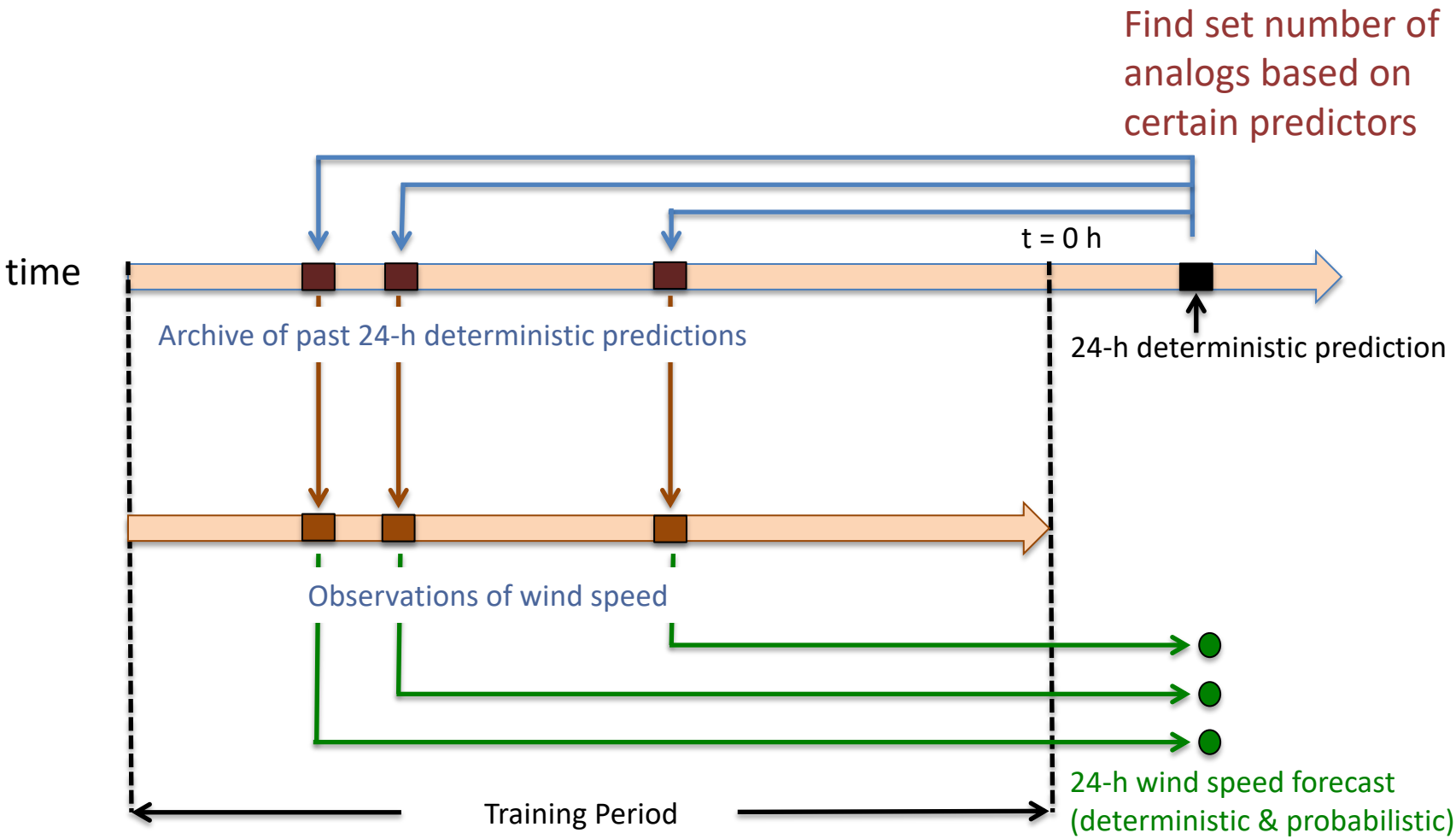
Delle Monache et al. (MWR, 2011, 2013)

The Analog Ensemble



Delle Monache et al. (MWR, 2011, 2013)

The Analog Ensemble



Delle Monache et al. (MWR, 2011, 2013)

AnEn has been successfully applied for:

- Short-term predictions of:
  - 10- and 80-m wind speed, 2-m temperature, etc.
  - Wind and solar power
  - Energy load
  - Air quality predictions (ground level ozone, surface $PM_{2.5}$)
  - Tropical cyclones intensity
  - Gridded/2D probabilistic predictions
- Downscaling, resource assessment:
  - Wind speed, precipitation
  - Computationally efficient dynamical downscaling

AnEn has been successfully applied for:

NCAR

- Short-term predictions of:
  - 10- and 80-m wind speed, 2-m temperature, etc.
    Delle Monache et al. MWR 2011, 2013, Junk et al. MZ 2015
  - Wind and solar power
    Alessandrini et al. RE 2015, AE 2015, Davo et al. SE 2016
  - Energy load
    Alessandrini et al. ICEM 2015
  - Air quality predictions (ground level ozone, surface $PM_{2.5}$)
    Djalalova et al. AE 2015, Delle Monache et al. ACPD 2017
  - Tropical cyclones intensity
    Alessandrini et al. MWR 2017
  - Gridded/2D probabilistic predictions
    Sperati et al. QJRMS 2017
- Downscaling, resource assessment:
  Vanvyve et al. RE 2015, Zhang et al. AE 2015, Keller et al. JAMC 2017
  - Wind speed, precipitation
  - Computationally efficient dynamical downscaling

NCAR

AnEn has been successfully applied for:

- Short-term predictions of:
  - 10- and 80-m wind speed, 2-m temperature, etc.
    Delle Monache et al. MWR 2011, 2013, Junk et al. MZ 2015
  - Wind and solar power
    Alessandrini et al. RE 2015, AE 2015, Davo et al. SE 2016
  - Energy Load
    Alessandrini et al. ICEM 2015
  - Air quality predictions (ground level ozone, surface $PM_{2.5}$)
    Djalalova et al. AE 2015, Delle Monache et al. ACPD 2017
  - Tropical cyclones intensity
    Alessandrini et al. MWR 2017
  - Gridded/2D probabilistic predictions
    Sperati et al. QJRMS 2017
- Downscaling, resource assessment:
  Vanvyve et al. RE 2015, Zhang et al. AE 2015, Keller et al. JAMC 2017
  - Wind speed, precipitation
  - Computationally efficient dynamical downscaling

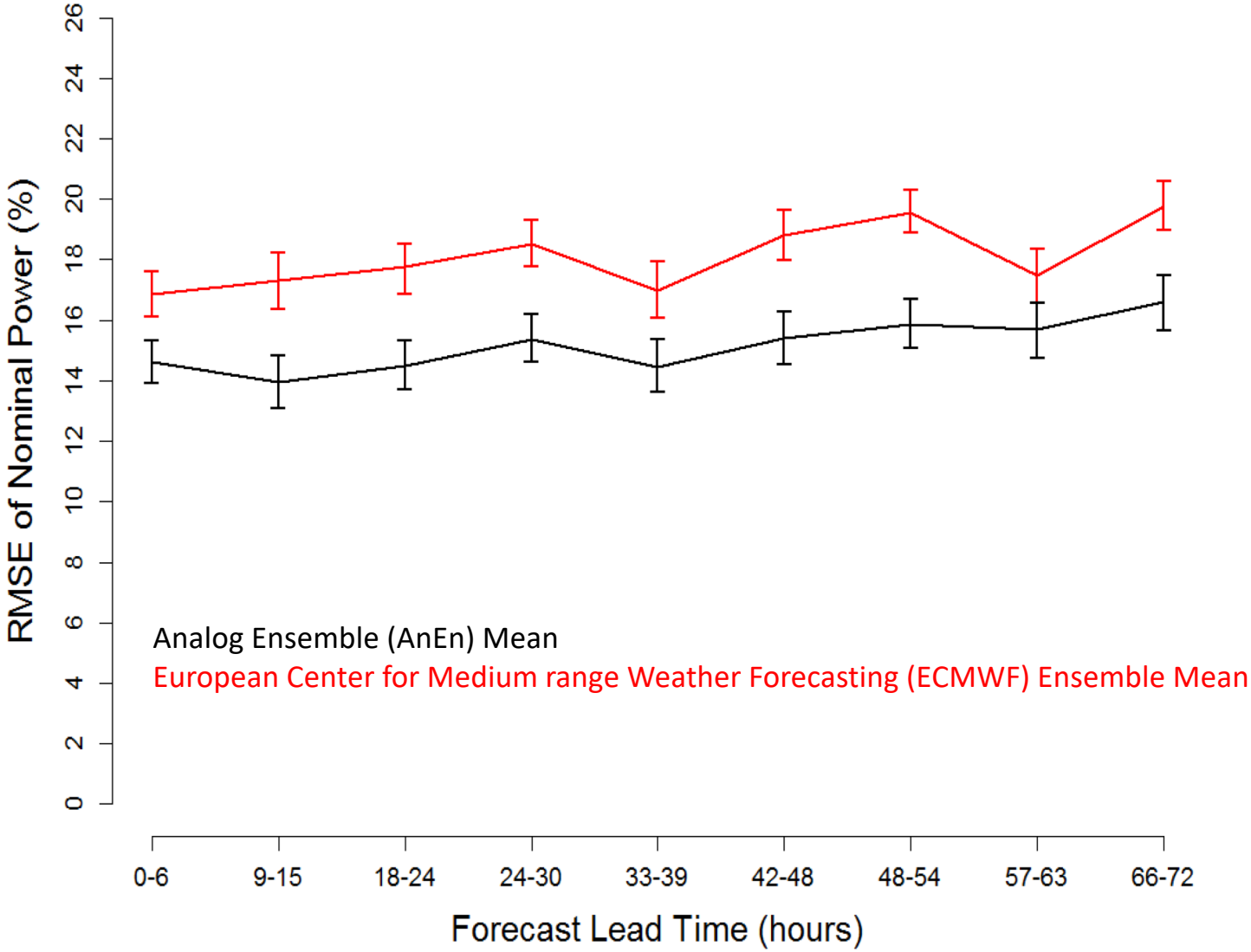
Point-based Probabilistic Predictions with AnEn

Power predictions: Experiment design

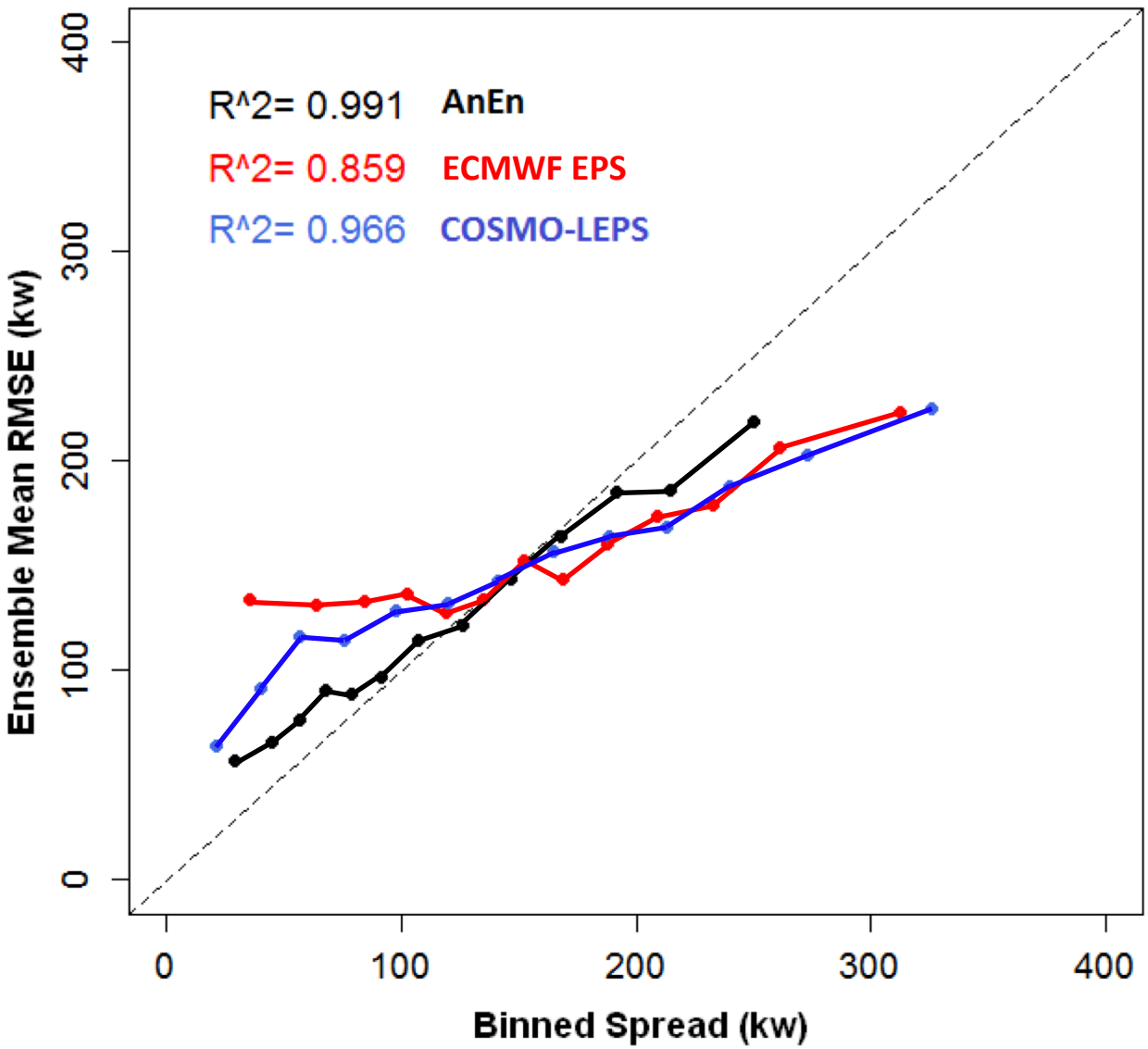
- Test site: Wind farm in northern Sicily − 9 turbines, 850 kW Nominal Power (NP)
- Training period: November 2010 - October 2012
- Verification period: November 2011 – October 2012
- Probabilistic prediction systems: ECMWF EPS, COSMO LEPS, AnEn

Alessandrini et al. (RE, 2015)

RMSE of ensemble means



Spread-skill relathionship

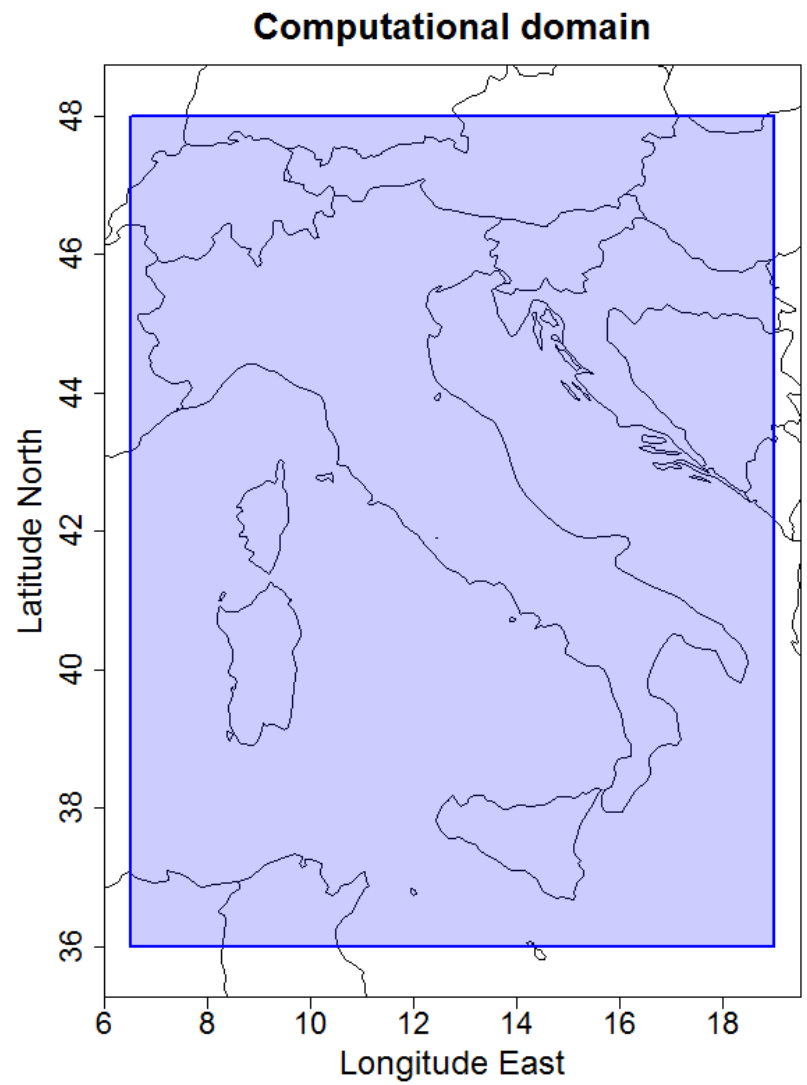


2D/Gridded Probabilistic Predictions with AnEn

Data sets

NCAR

- Predictand variable: 10-m wind speed (WS)
- Predictors: WS, WD, T2M, MSLP, Z500
- Period: January 2013 – December 2015
- Domain (right): Italy, 1000 km x 1300 km (0.25° horizontal resolution, 2499 grid points)
- "Ground-truth": European Centre for Medium-Range Weather Forecasts (ECMWF) Analysis (0.125° horizontal resolution; 0, 6, 12, 18 UTC)
- ECMWF deterministic forecast (HRES) (0.125° horizontal resolution; 0 UTC; +144 h lead time; 3-hourly forecasts)
- ECMWF Ensemble Prediction System (EPS) (0.25° horizontal resolution; 51 members; 0 UTC; +144 h lead time; 3-hourly forecasts)



Sperati et al. (QJRMSE, 2017)

Experiment set-up

NCAR

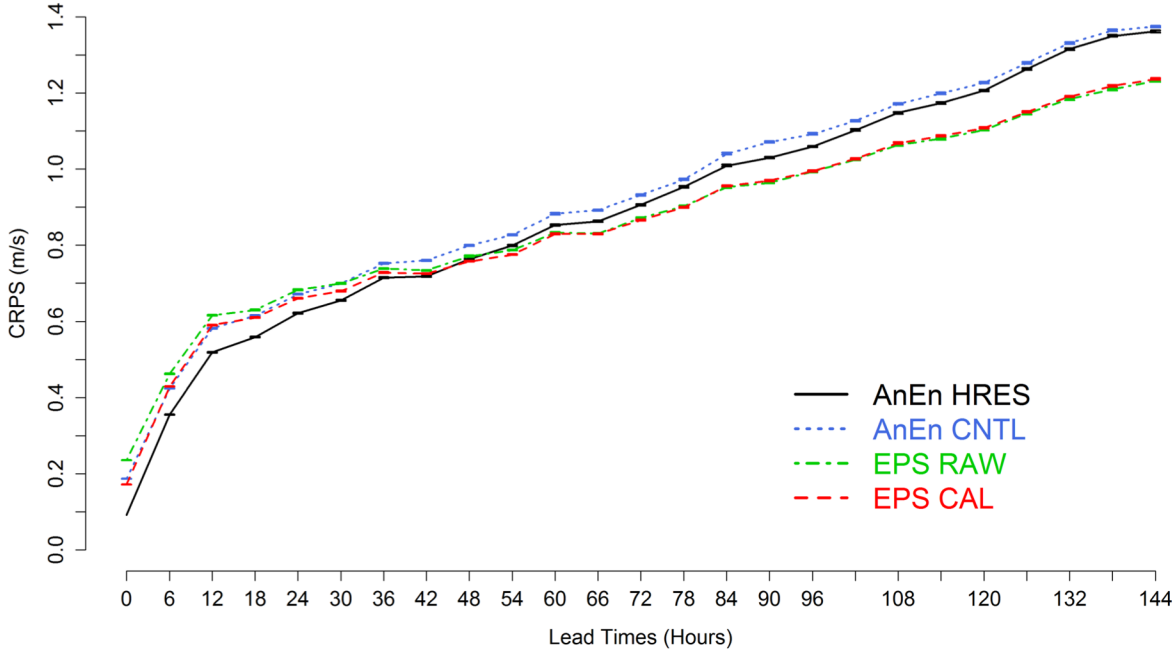
- Methods:
  - **EPS RAW**: ECMWF EP
  - **EPS CAL**: calibrated ECMWF EPS
  - **AnEn HRES**: AnEn generated from ECMWF deterministic run

    NOTE: DA + forecast generation ~**6-8 times** cheaper than EPS calibrated
  - **AnEn CNTL**: AnEn generated from ECMWF EPS control run

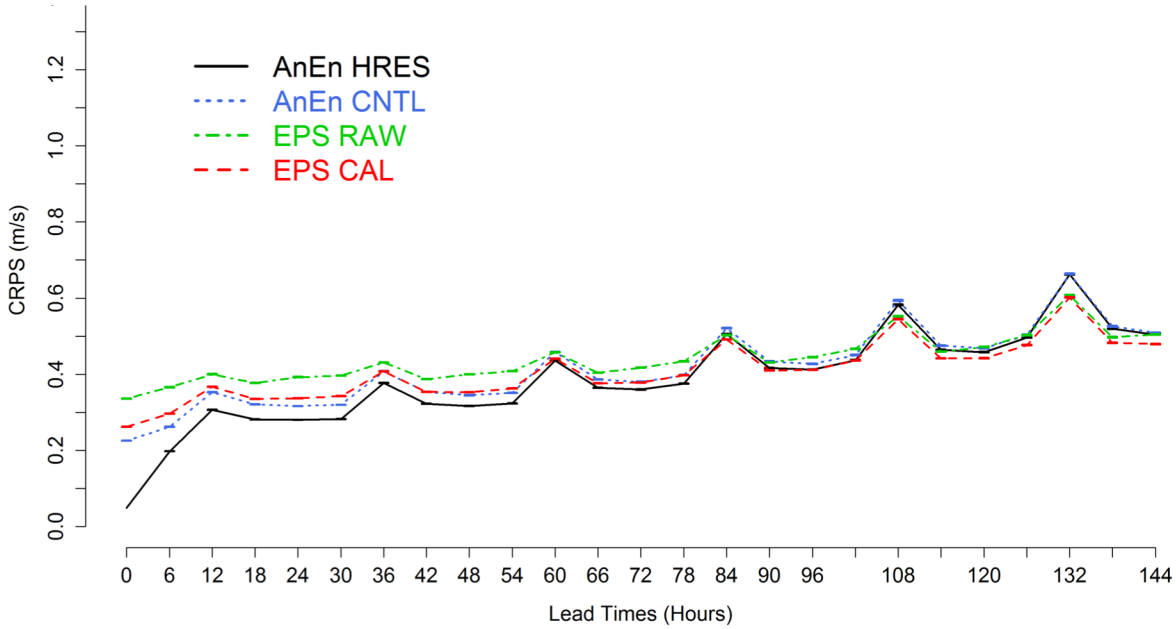
    NOTE: forecast generation **51 times** cheaper than EPS calibrated
- Training: March 2012 – February 2014
  - Search of analogs for AnEn
  - Variance Deficit calibration for ECMWF EPS (Buizza et al. *Q. J. Roy. Meteor. Soc.* 2003; Alessandrini et al. *Appl. Energy* 2013)
- Verification: March 2014 – March 2015
- Several deterministic and probabilistic metrics

Continuous Ranked Probability Score

Grid points
below 100 m asl

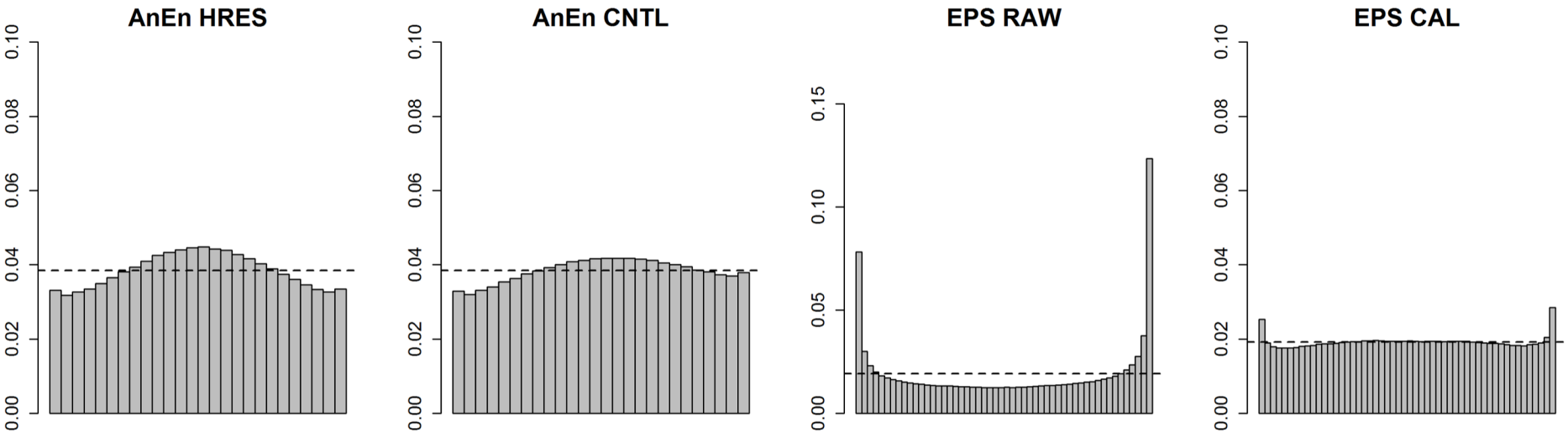


Grid points
above 100 m asl

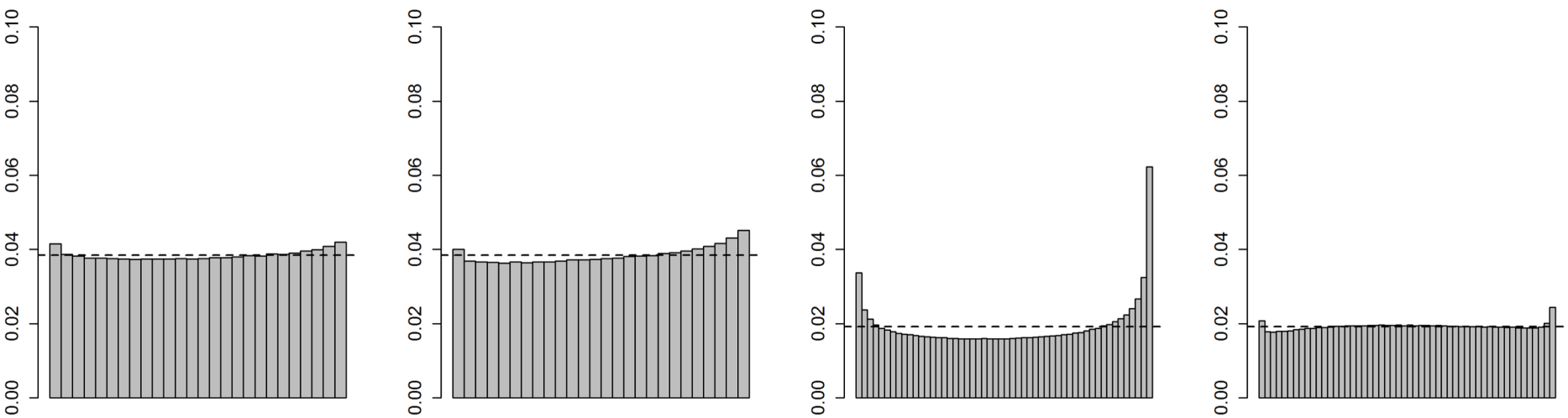


Rank histograms

6-24 h ahead

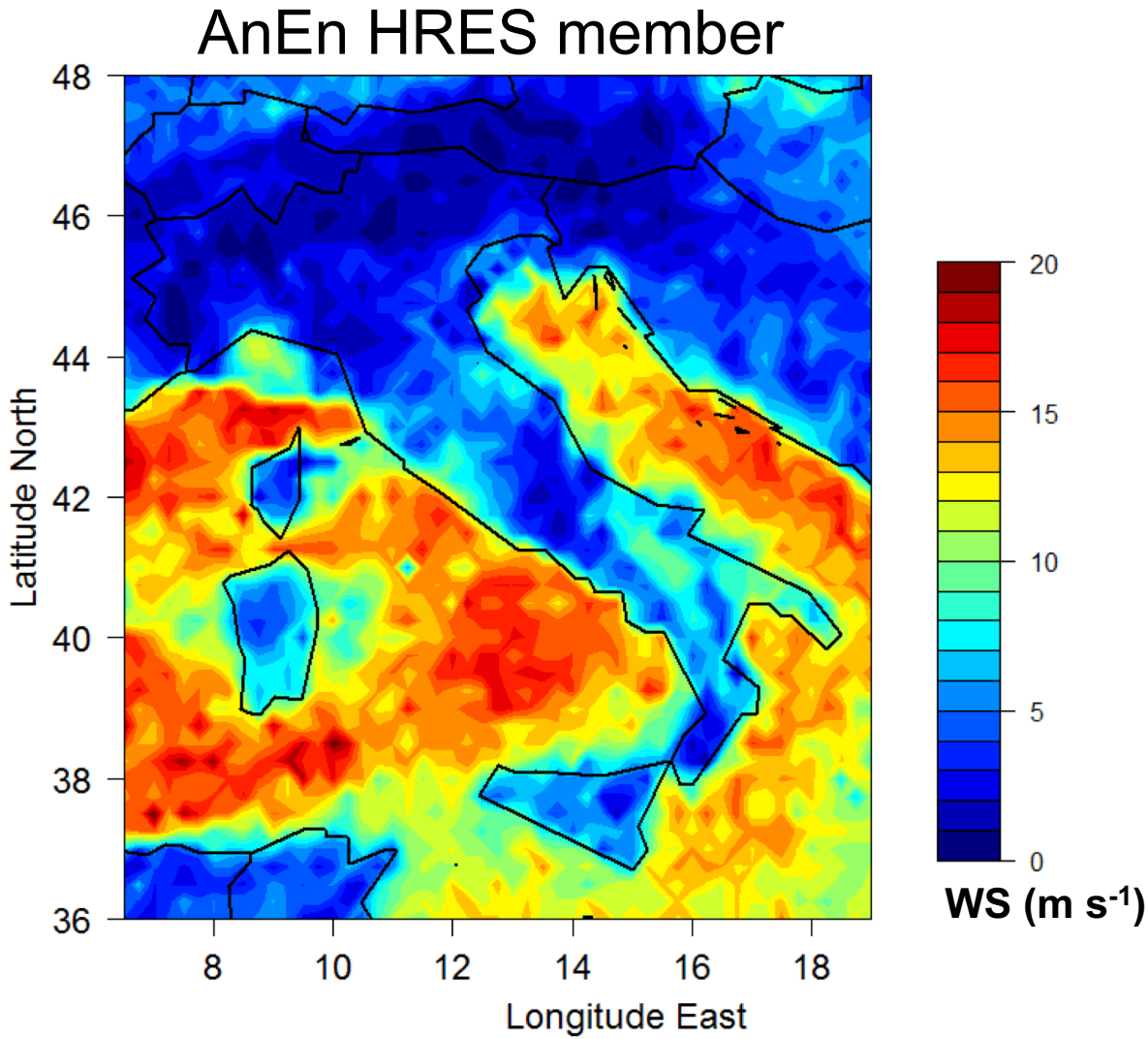


72-96 h ahead



Is spatial/temporal consistency preserved?

NCAR



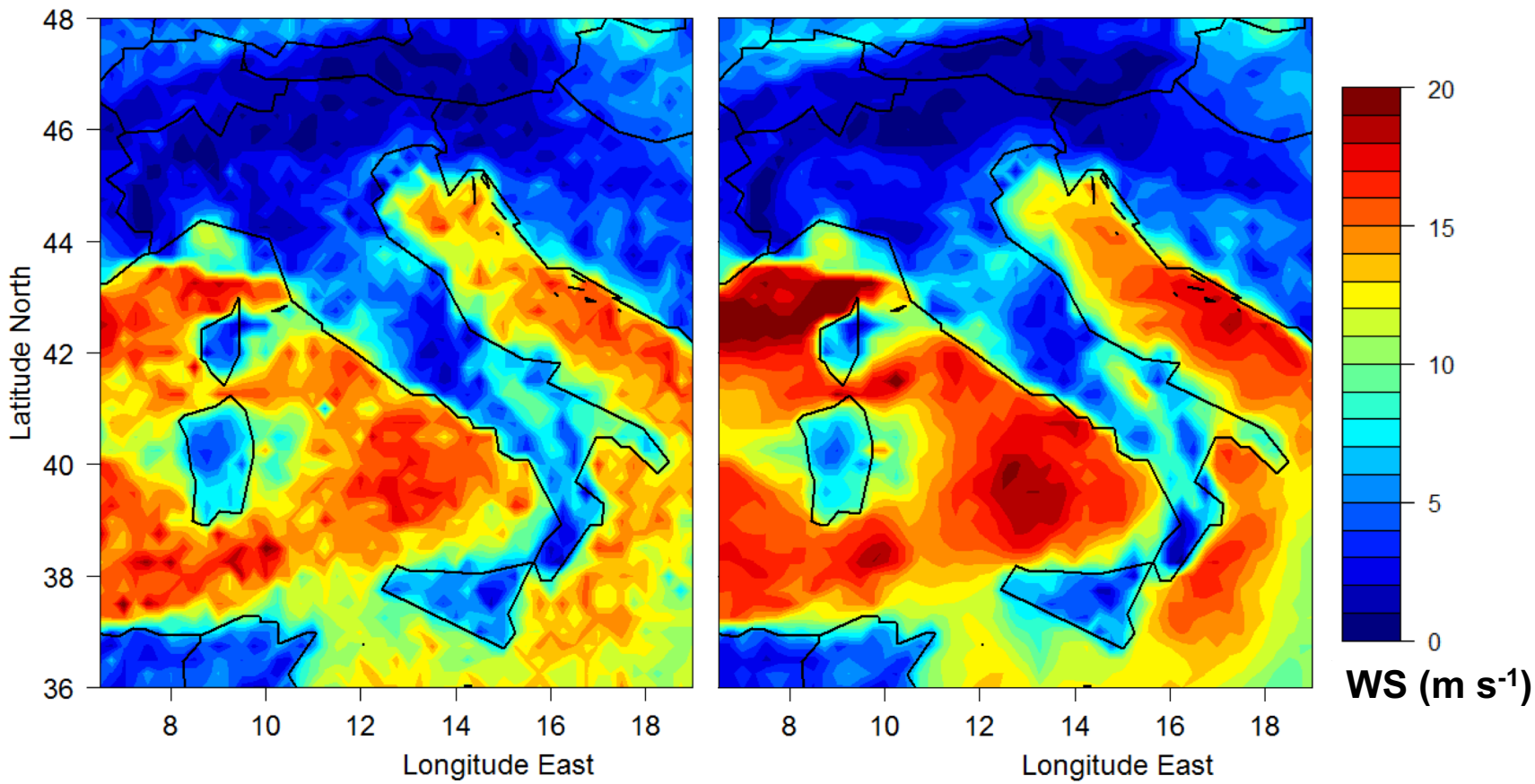
30 Jan 15, 06 UTC, +6 h

Is spatial/temporal consistency preserved?

NCAR

AnEn + Schaake Shuffle = spatial consistency

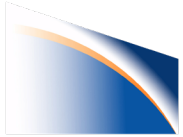
AnEn HRES member AnEn HRES member + SS



30 Jan 15, 06 UTC, +6 h

Clark et al. (2004, JH)

Ensemble mean maps



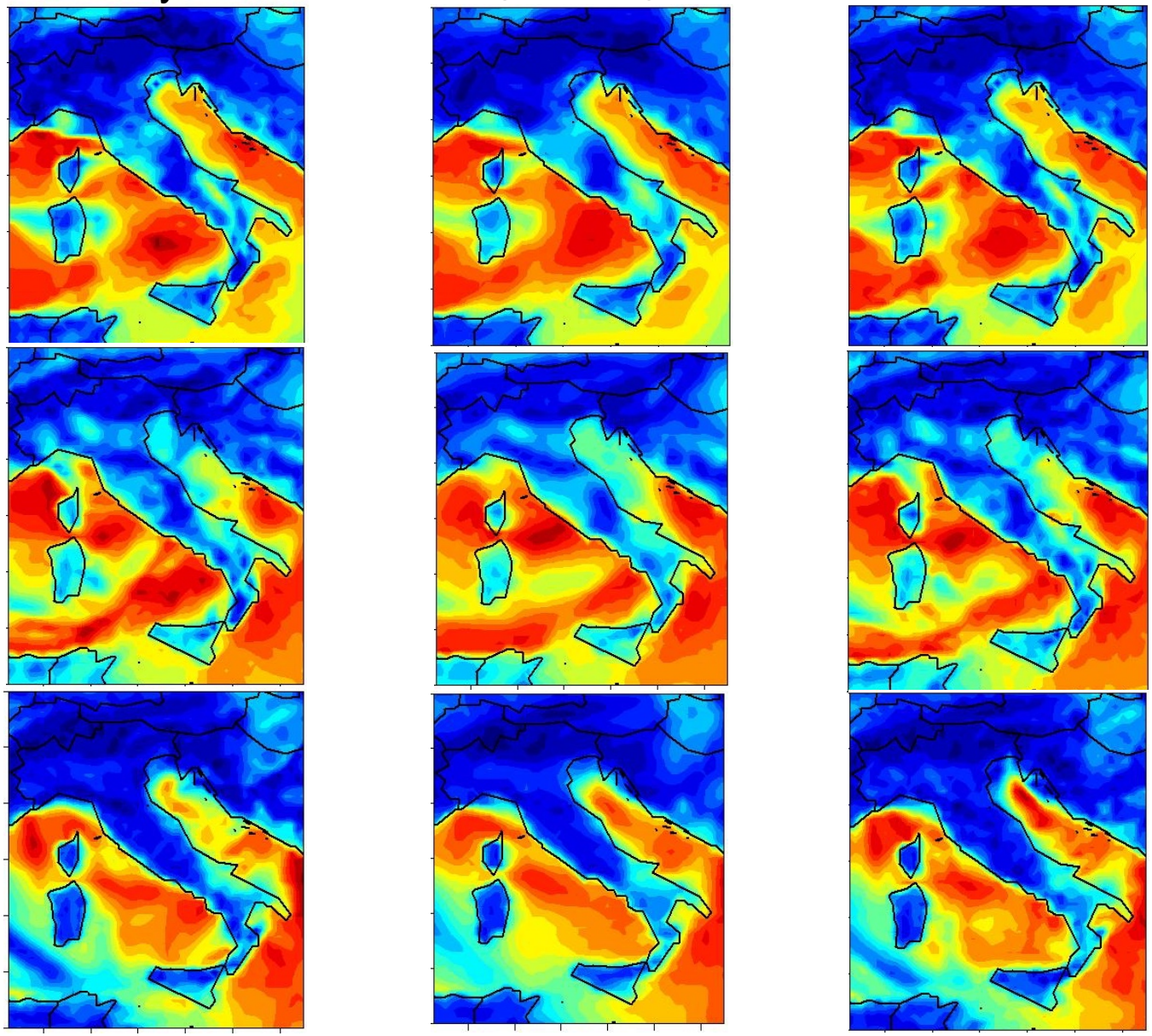
NCAR

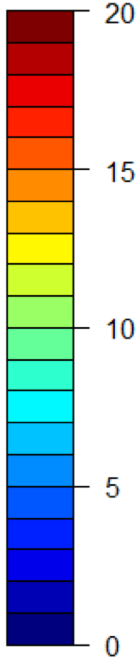
Analysis | EPS (BC+VD) mean | AnEn HRES mean

30 Jan 15
06 UTC
+6 h

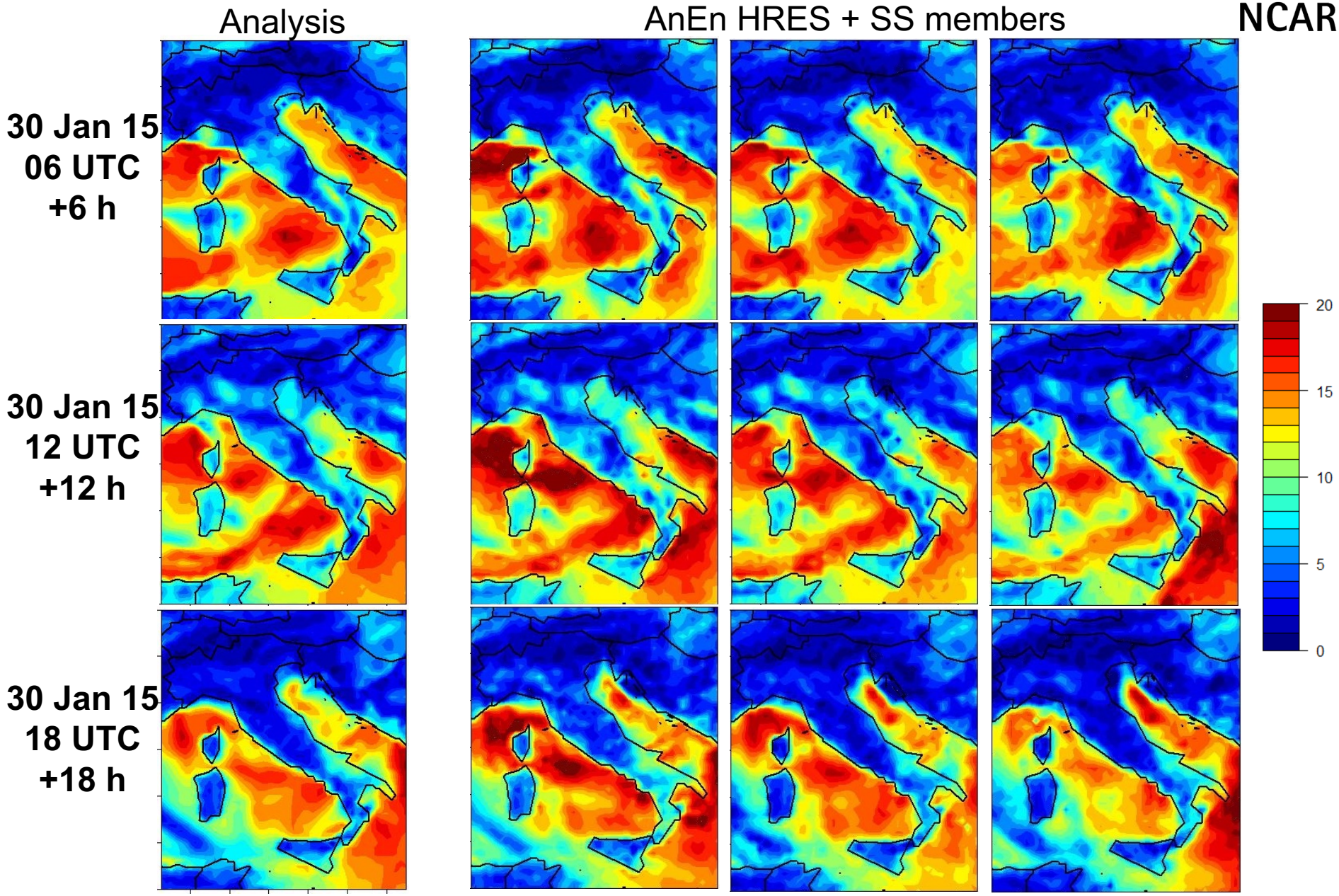
30 Jan 15
12 UTC
+12 h

30 Jan 15
18 UTC
+18 h

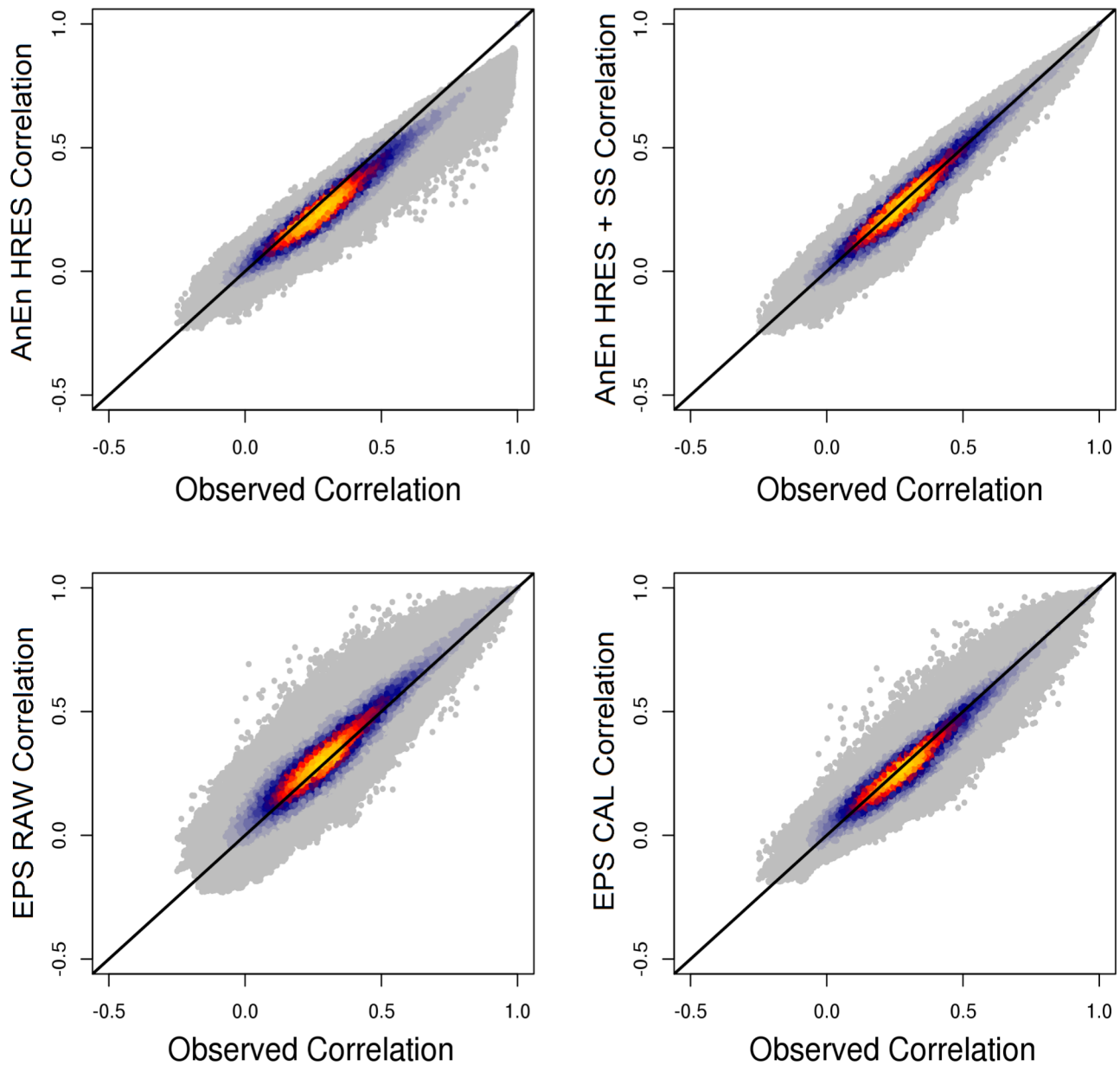




AnEn + SS spatial/temporal consistency



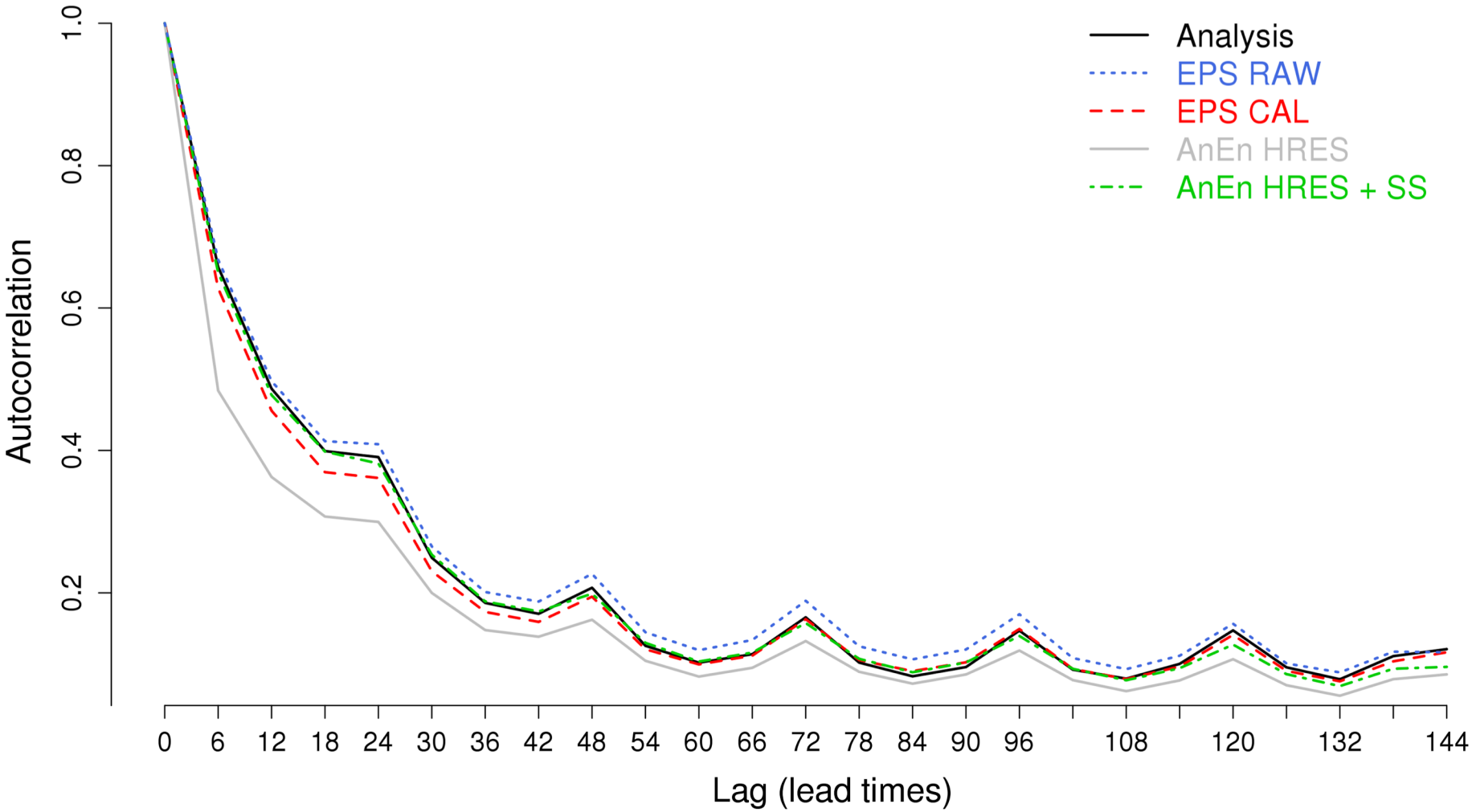
AnEn + SS spatial consistency



Lead time
36 h

X = correlation($A_i(t)$,$A_j(t)$) where i and j are any two points in the map, k are the members
Y = correlation($F_{i,k}(t)$,$F_{i,k}(t)$)

AnEn + SS temporal consistency



Mean autocorrelation across all grid points and ensemble members

Summary

- Need for probabilistic predictions -- we are dealing with a chaotic system!
- AnEn successfully tested point-based probabilistic predictions and downscaling (e.g., wind power)
- AnEn can be used also to generate sharp, reliable, spatially and temporally consistent, and computationally efficient probabilistic predictions over a 2D grid
- AnEn key aspects:
  - Only one real-time deterministic forecast needed to generate
  - probabilistic predictions
  - No need for initial condition and model perturbation strategies to generate an ensemble
  - Improves deterministic forecast as well as provides probabilistic information
  - General algorithm, implemented for several applications
  - Intrinsically parallel algorithm

Thanks!

Luca Delle Monache: lucadellemona@gmail.com

NCAR

References

1. Delle Monache, L., T. Nipen, Y. Liu, G. Roux, and R. Stull, 2011: Kalman filter and analog schemes to postprocess numerical weather predictions. *Mon. Wea. Rev.*, 139, 3554–3570
2. Delle Monache, L., T. Eckel, D. Rife, and B. Nagarajan, 2013: Probabilistic weather prediction with an analog ensemble. *Mon. Wea. Rev.*, 141, 3498–3516
3. Mahoney, W.P., K. Parks, G. Wiener, Y. Liu, W.L. Myers, J. Sun, L. Delle Monache, T. Hopson, D. Johnson, S.E. Haupt, 2012: A wind power forecasting system to optimize grid integration. *IEEE Trans. Sustainable Energy*, 3, 670–682
4. Alessandrini, S., Delle Monache, L., Sperati, S., and Nissen, J, 2015. A novel application of an analog ensemble for short-term wind power forecasting. *Renewable Energy*, 76, 768-781
5. Clark, M., Gangopadhyay, S., Hay, L., Rajagopalan, B., Wilby, R., 2004: The Schaake Shuffle: A method for reconstructing space–time variability in forecasted precipitaiton and temperature fields. *J. Hydrometeor.*, 5, 243–262
6. Vanvyve, E., Delle Monache, L., Rife, D., Monaghan, A., Pinto, J., 2015. Wind resource estimates with an analog ensemble approach. *Renewable Energy*, 74, 761-773
7. Nagarajan, B., Delle Monache, L., Hacker, J., Rife, D., Searight, K., Knievel, J., and Nipen, T., 2015. An evaluation of analog-based post-processing methods across several variables and forecast models. *Weather and Forecasting*, 30, 1623–1643
8. Djalalova, I., Delle Monache, L., and Wilczak, J., 2015. PM2.5 analog forecast and Kalman filtering post-processing for the Community Multiscale Air Quality (CMAQ) model. *Atmospheric Environment*, 119, 431–442
9. Junk, C., Delle Monache, L., Alessandrini, S., von Bremen, L., and Cervone, G., 2015. Predictor-weighting strategies for probabilistic wind power forecasting with an analog ensemble. *Meteorologische Zeitschrift*, 24, 361-379
10. Alessandrini, S., Delle Monache, L., Sperati, S., and Cervone, G., 2015. An analog ensemble for short-term probabilistic solar power forecast. Applied *Energy*, 157, 95–110
11. Eckel, T., and Delle Monache, L., 2015. A hybrid, analog-NWP ensemble. *Monthly Weather Review*, 144, 897–911
12. Zhang, J., Draxl, C., Hopson, T., Delle Monache, L., and Hodge, B.-M., 2015. Comparison of deterministic and probabilistic wind resource assessment methods on numerical weather prediction. *Applied Energy*, 156, 528–541
13. Gneiting T, Stanberry LI, Grimit EP, Held L, Johnson NA. 2008. Assessing probabilistic forecasts of multivariate quantities, with an application to ensemble predictions of surface winds. TEST 17: 211-235.
14. Sperati, S., Alessandrini, S., Delle Monache, L., 2017. Conditionally Accepted, *Quarterly Journal of the Royal Meteorological Society*

The metric (1)

NCAR

Analog strength for a particular forecast lead time *t* is measured by the distance between current and past forecast, over a short window, $2\tilde{t}$ wide

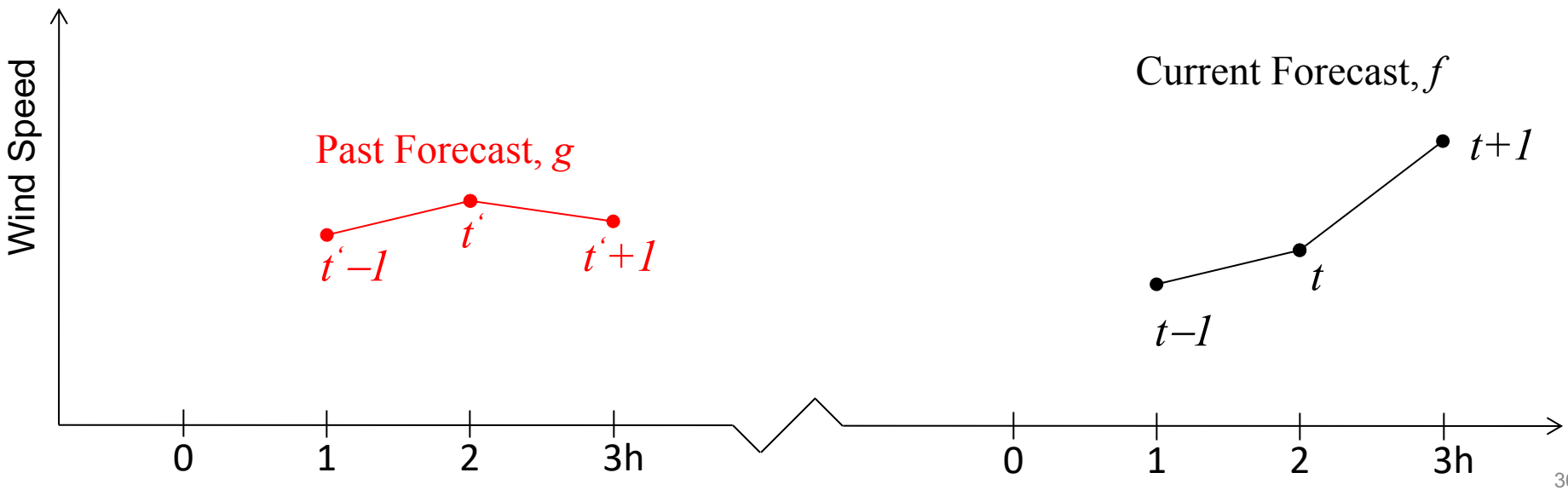
$$\left\| f_t - g_{t'} \right\| = \frac{1}{\sigma_f} \sqrt{\sum_{k=-\tilde{t}}^{+\tilde{t}} \left(f_{t+k} - g_{t'+k} \right)^2}$$

σ_f : Forecasts' standard deviation over entire analog training period

Expanded to multiple predictor variables, but still focused on predictand *f*:
(for wind speed, predictors are speed, direction, sfc. temp., sfp pressure, and PBL depth)

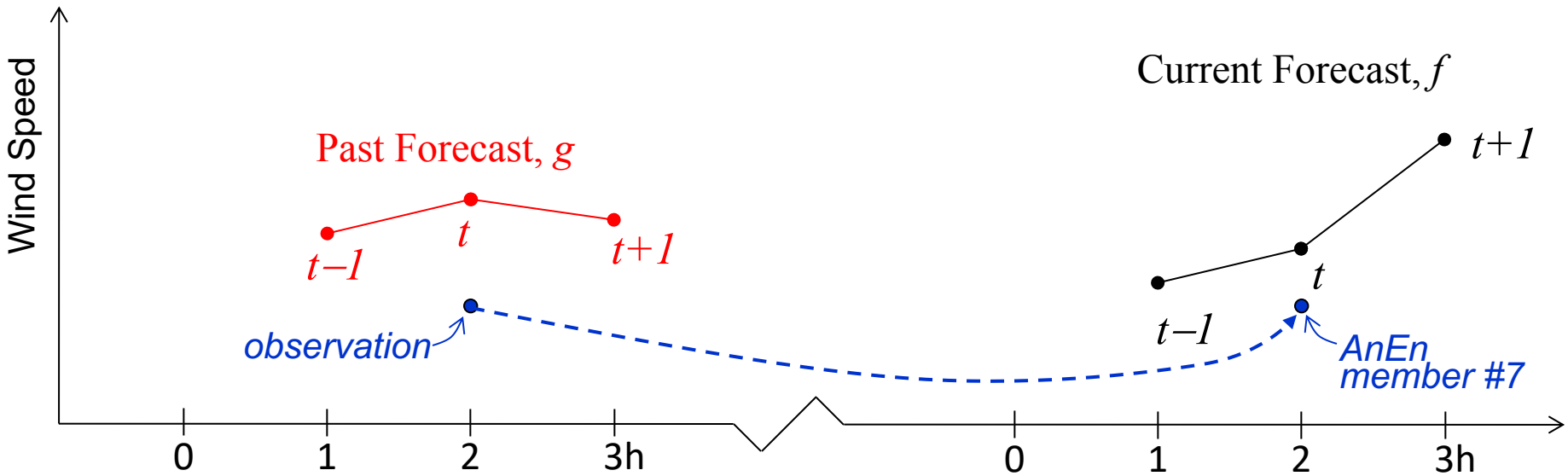
$$\left\| f_t - g_{t'} \right\| = \sum_{v=1}^{N_v} \frac{w_v}{\sigma_{f^v}} \sqrt{\sum_{k=-\tilde{t}}^{+\tilde{t}} \left(f^v_{t+k} - g^v_{t'+k} \right)^2}$$

N_v : Number of predictor variables
w_v : Weight given to each predictor



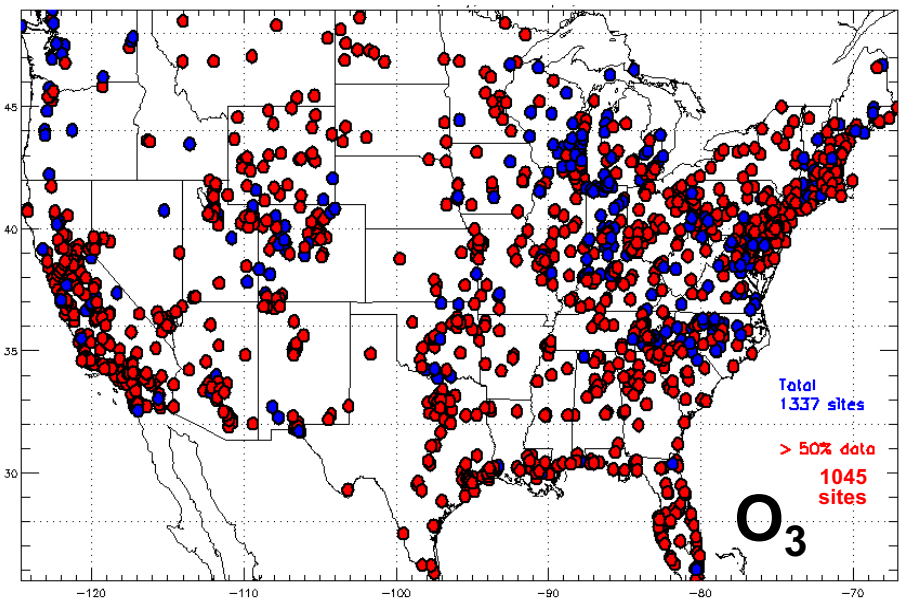
The metric (2)

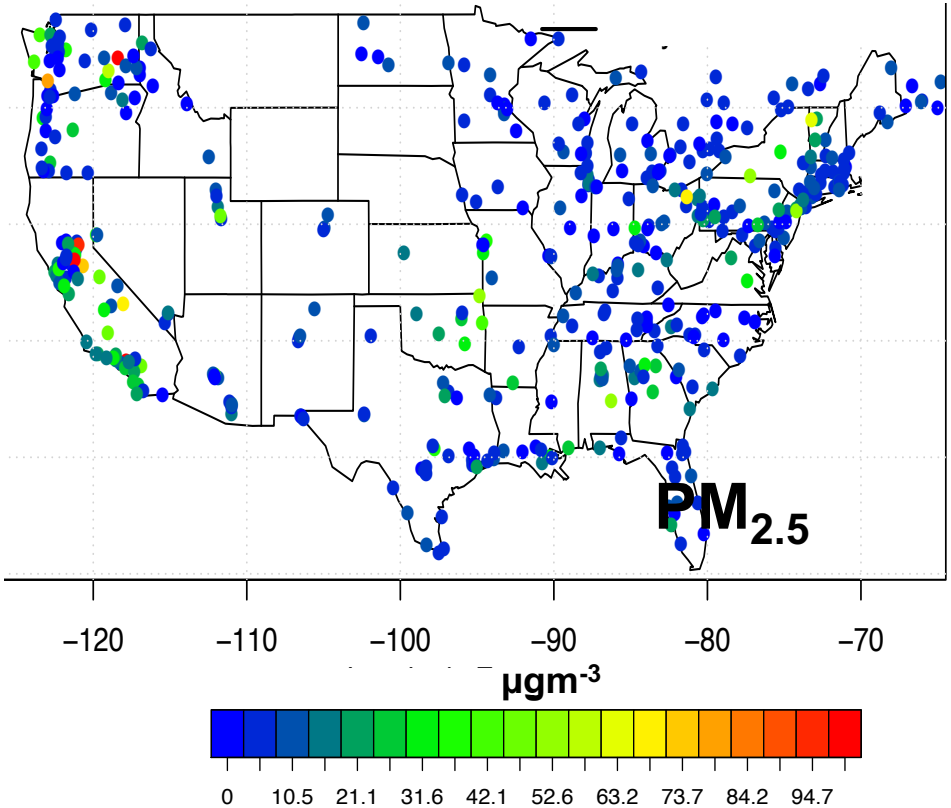
After finding the n strongest analogs, each of the n AnEn members is taken as the verifying observation from each analog.



Delle Monache et al. (MWR, 2011, 2013)

AnEn for air quality: available obs





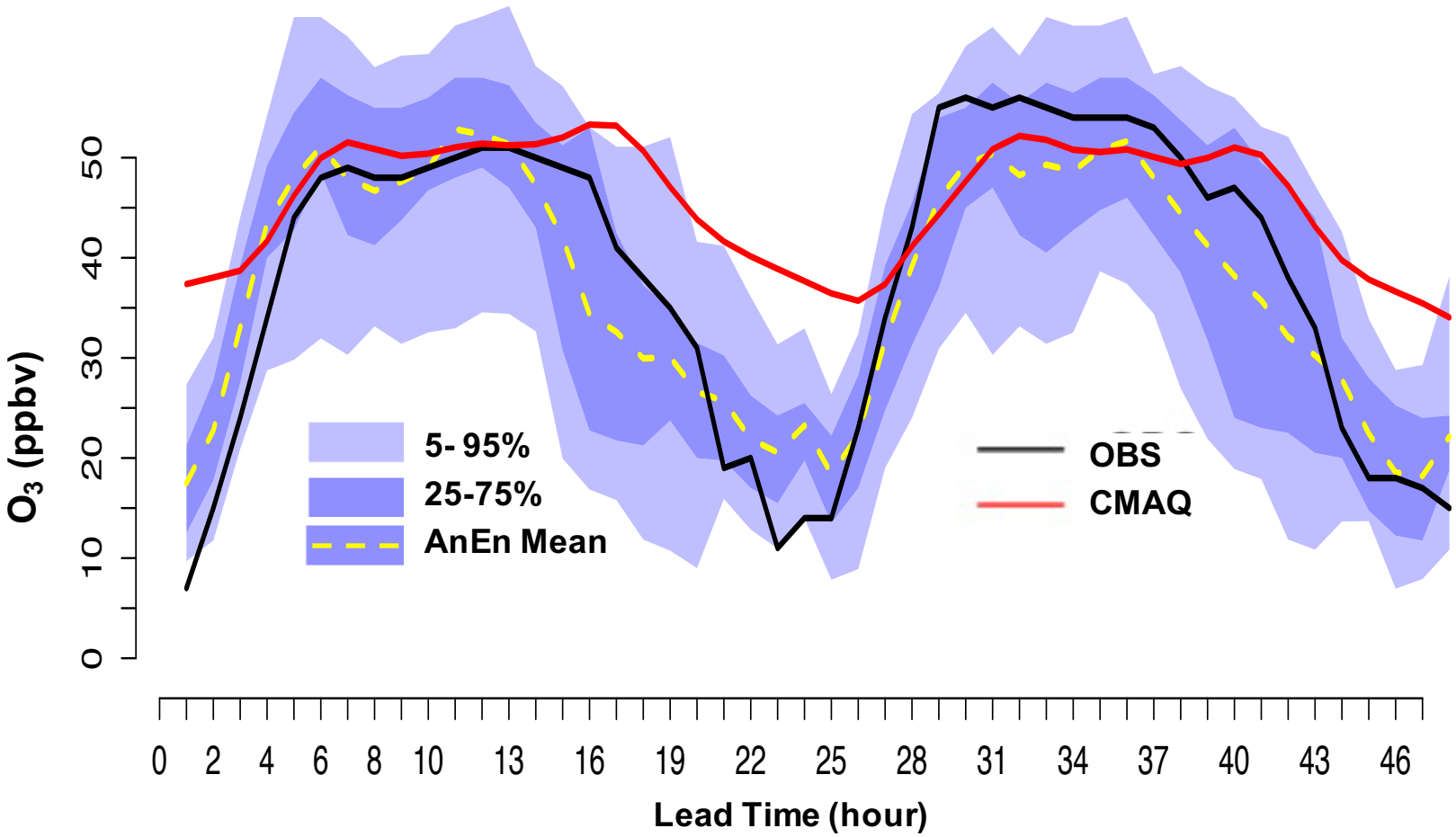
- 1337 AirNow stations
- Training: 15 months, Jul 2014 − Sept 2015
- Verification: May – Sept 2015
- Data availability: 1045 stations with more than 50% of valid data

- 564 AirNow stations
- Training: 13 months, July 2014 − July 2015
- Verification: Dec 2014, Jan 2015
- Data availability: 465 stations with more than 50% of valid data

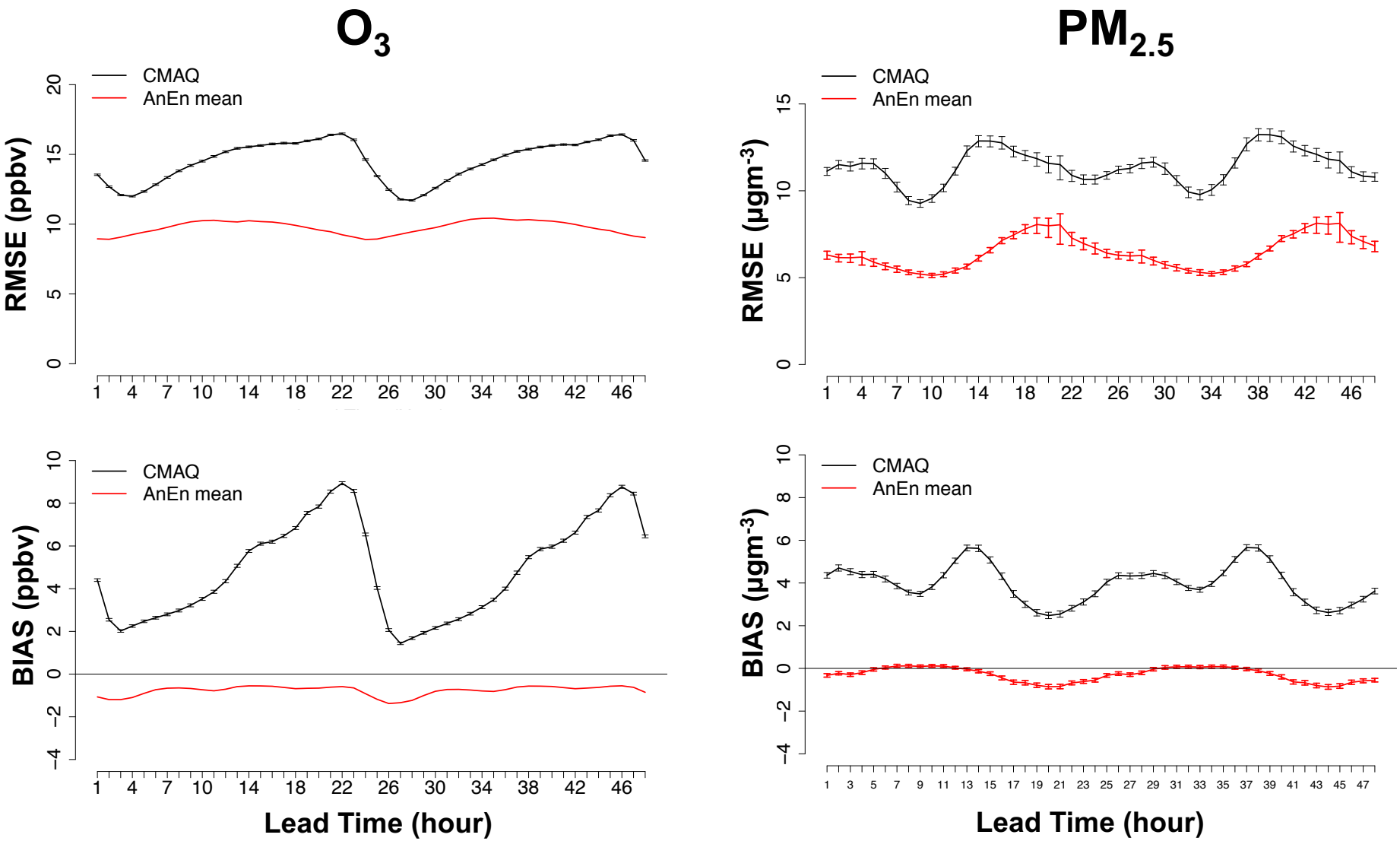
Deterministic prediction to build AnEn: Community Multi-scale Air Quality Model (CMAQ)

AnEn for air quality: example

NCAR



Drastic reduction of CMAQ errors



AnEn error reductions with respect to CMAQ (O_3 and $PM_{2.5}$):
~35-50% RMSE, ~85-95% BIAS

Schaake Shuffle (SS) (1)

Choose N Past Dates, where N = n. of AnEn members

same dates for every grid point (00 UTC)

Dates = (18 Dec, 10 Dec, 8 Nov, 5 Nov, 25 Nov)

⇩

Corresponding Observations =(13., 7., 18., 5., 11.)

⇩

Sorted Observations = (5., 7. ,11. ,13. ,18.)

⇩

Establishing function (B) linking positions of observations before and after sorting

B (1, 2, 3, 4, 5) = (4, 2, 5, 1, 3)

Clark et al. *JH* (2004)

Schaake Shuffle (SS) (2)

NCAR

Raw ensemble forecast (AnEn) at any given grid point

e.g., first available lead time 00 UTC, 15 Dec 2015

⇩

AnEn = (15., 3. ,17. ,12. ,9.)

⇩

Sorted AnEn members

⇩

AnEn Sorted = (3., 9., 12., 15., 17.)

⇩

B(AnEn sorted) = (**15, 9, 17, 3, 12**)

IMPORTANT

(1) past selected dates must remain the same for consecutive lead times

(2) B function is location and lead time dependent

(3) For spatial consistency, past selected dates must be the same across multiple locations

Clark et al. *JH* (2004)

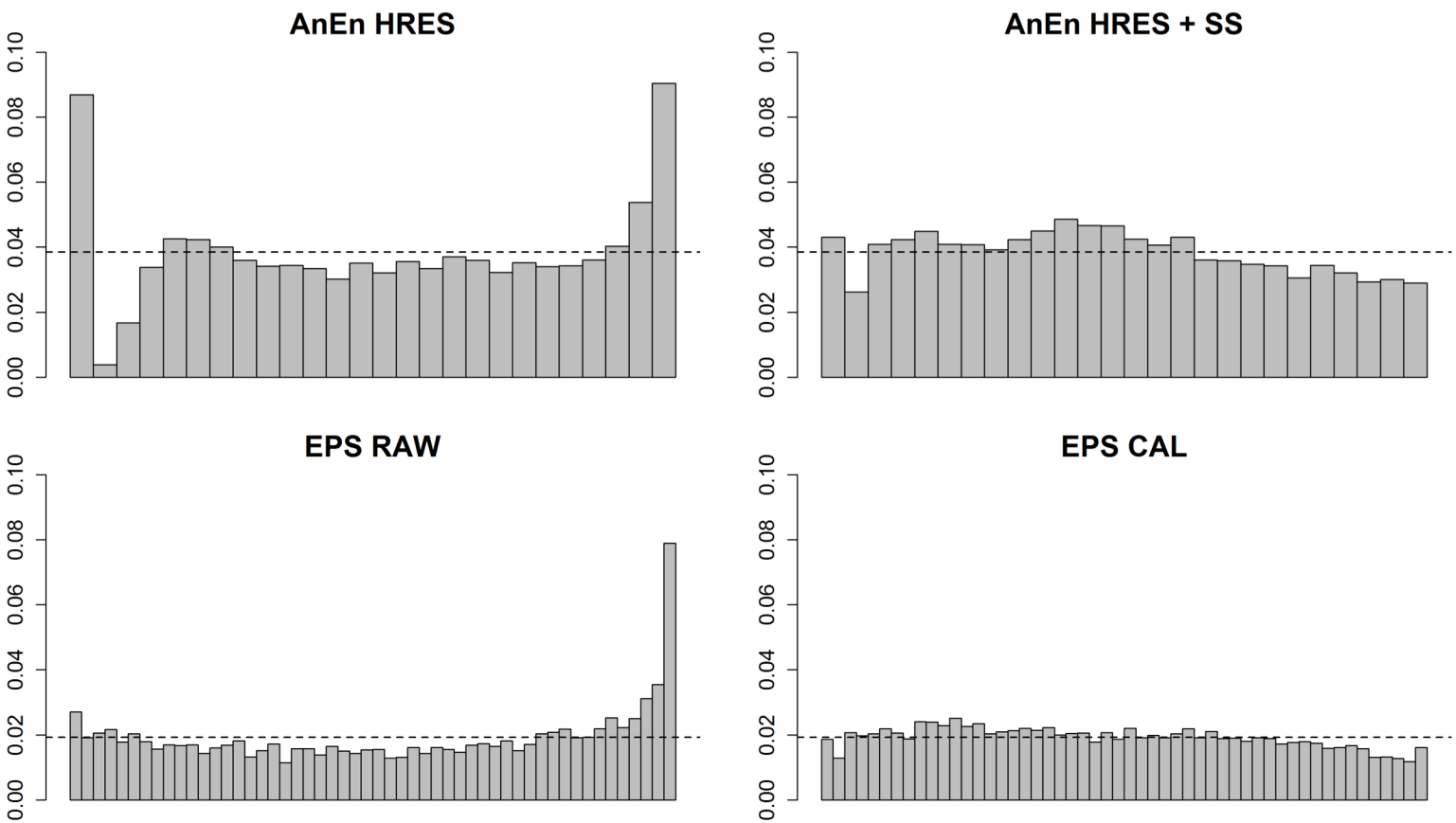
Multivariate forecast performance

NCAR

Multivariate rank histograms (Gneiting *et al.*, 2008)

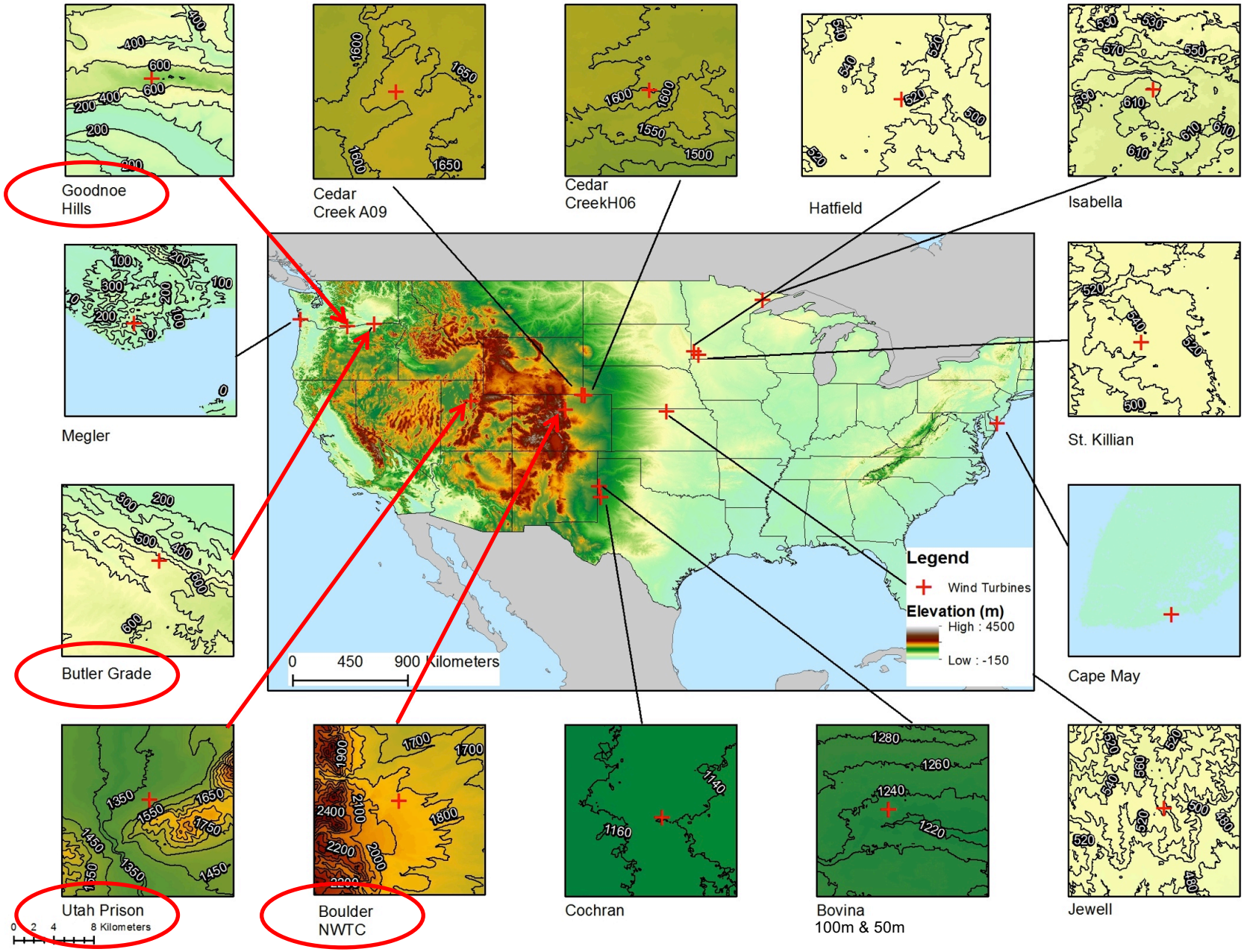
Assign pre-ranks to the ensemble forecast: $\rho_j = \sum_{k=0}^{m} I(x_k \leq x_j)$

Given $s^{<} = \sum_{j=0}^{m} I(\rho_j - \rho_0)$ and $s^{=} = \sum_{j=0}^{m} I(\rho_j - \rho_0)$ the multivariate rank r is chosen from a discrete uniform distribution on the set on $\{s^{<} + 1, \ldots, s^{<} + s^{=}\}$

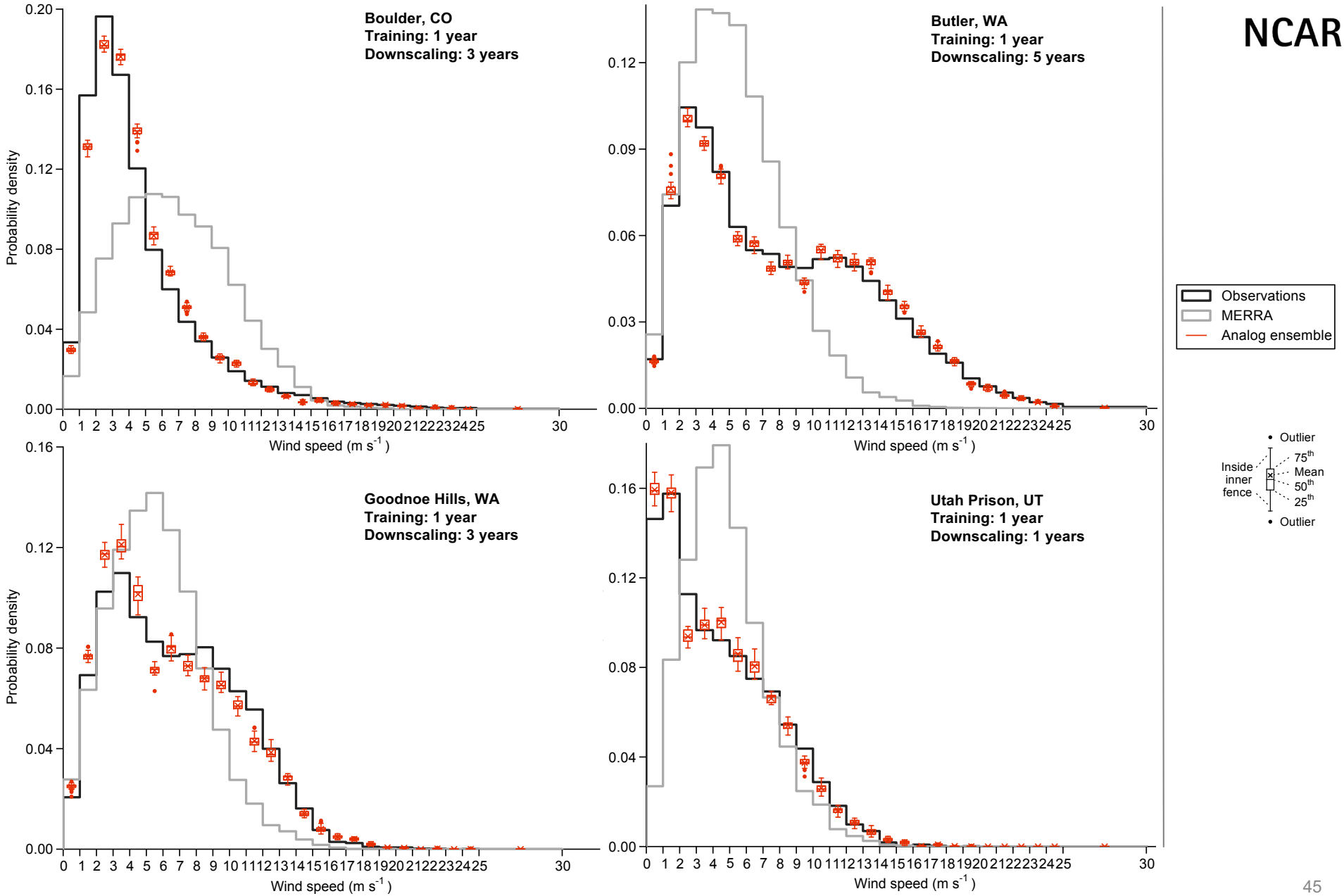


2 adjacent grid points

Downscaled wind tower locations

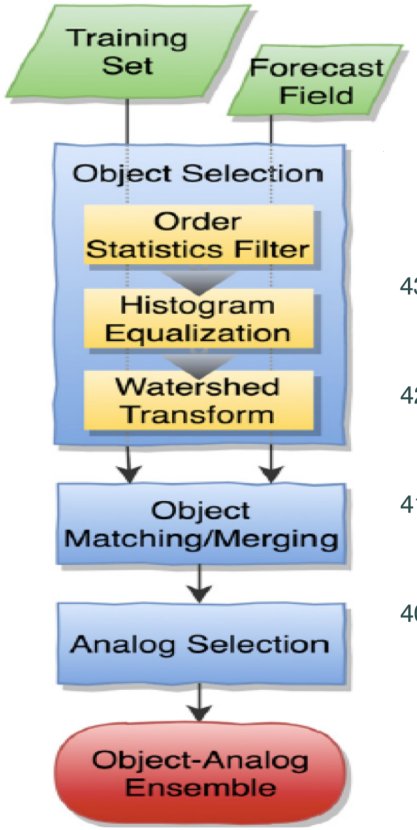


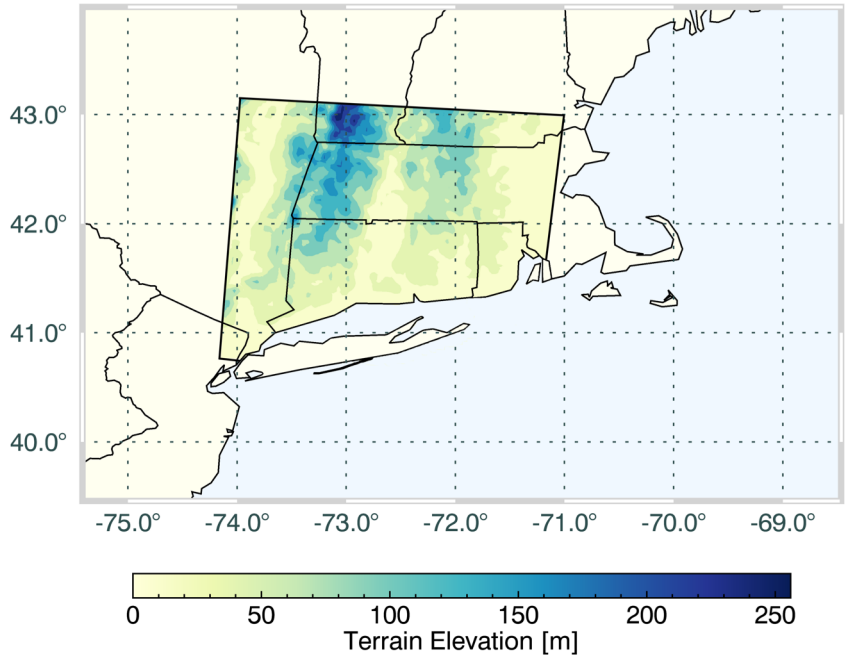
Wind distributions comparison



Object-based Probabilistic Predictions with AnEn

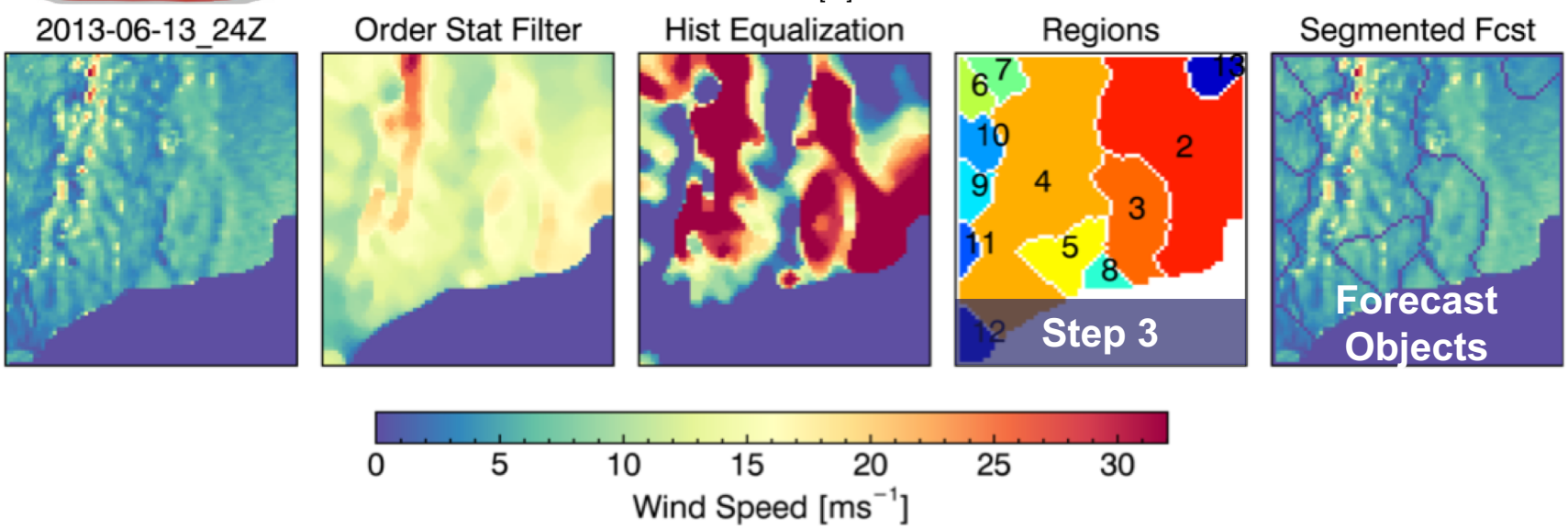
Object-based Analog Ensemble





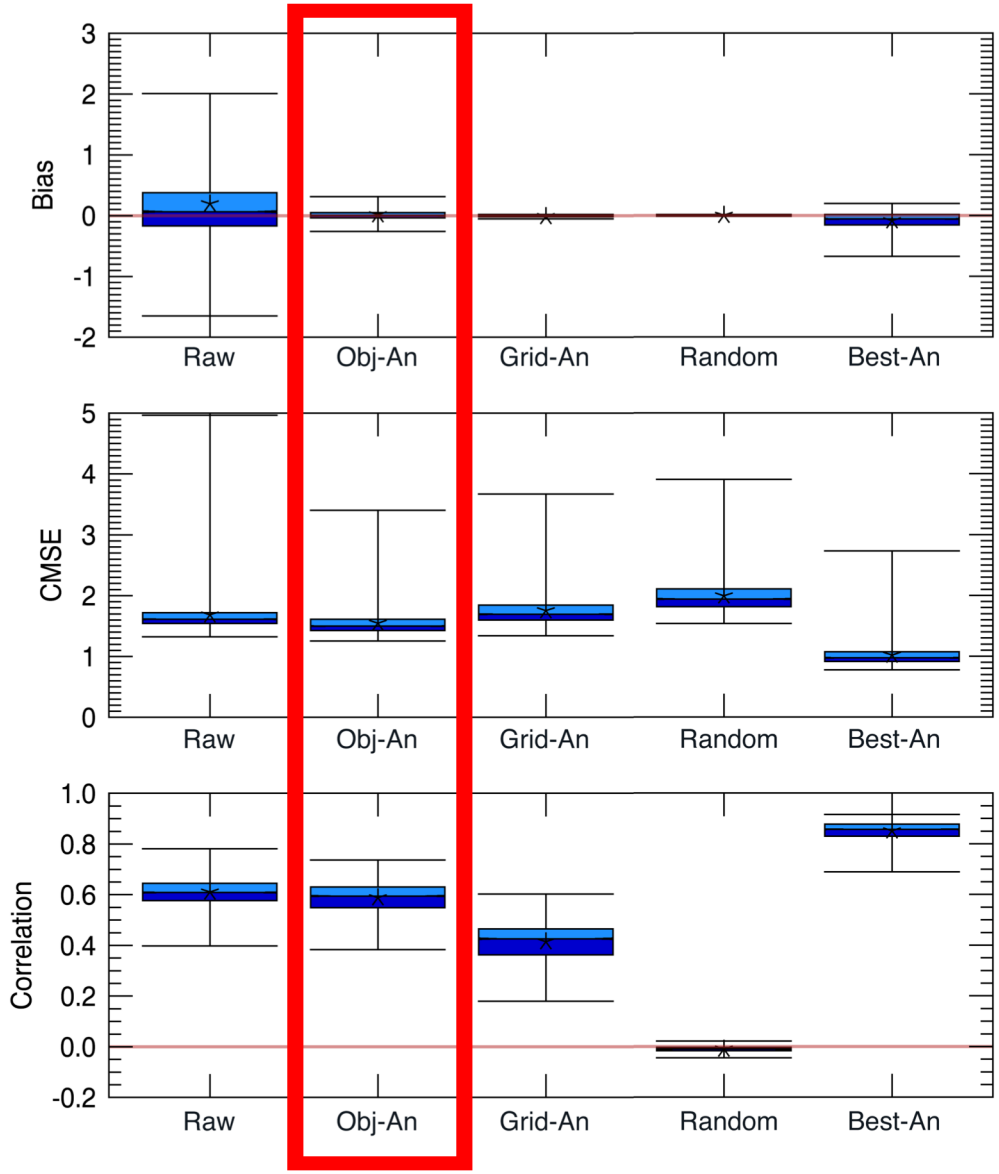
Frediani et al. (2017)

- Forecasts: WRF
- Ground-truth: CFSR
- 89 storms
- ~6000 fcst hours



Object-based Analog Ensemble: Results

NCAR



Frediani et al. (MWR, 2017)