The future of weather forecasting: high-resolution ensembles

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The olden days of weather forecasting

PLOTTING UPPER AIR MAPS

http://www.history.noaa.gov/stories_tales/women6.html

Modern weather forecasting

http://www.nextgov.com/emerging-tech/2015/08/video-bringing-together-next-gen-weather-forecasters/119035/

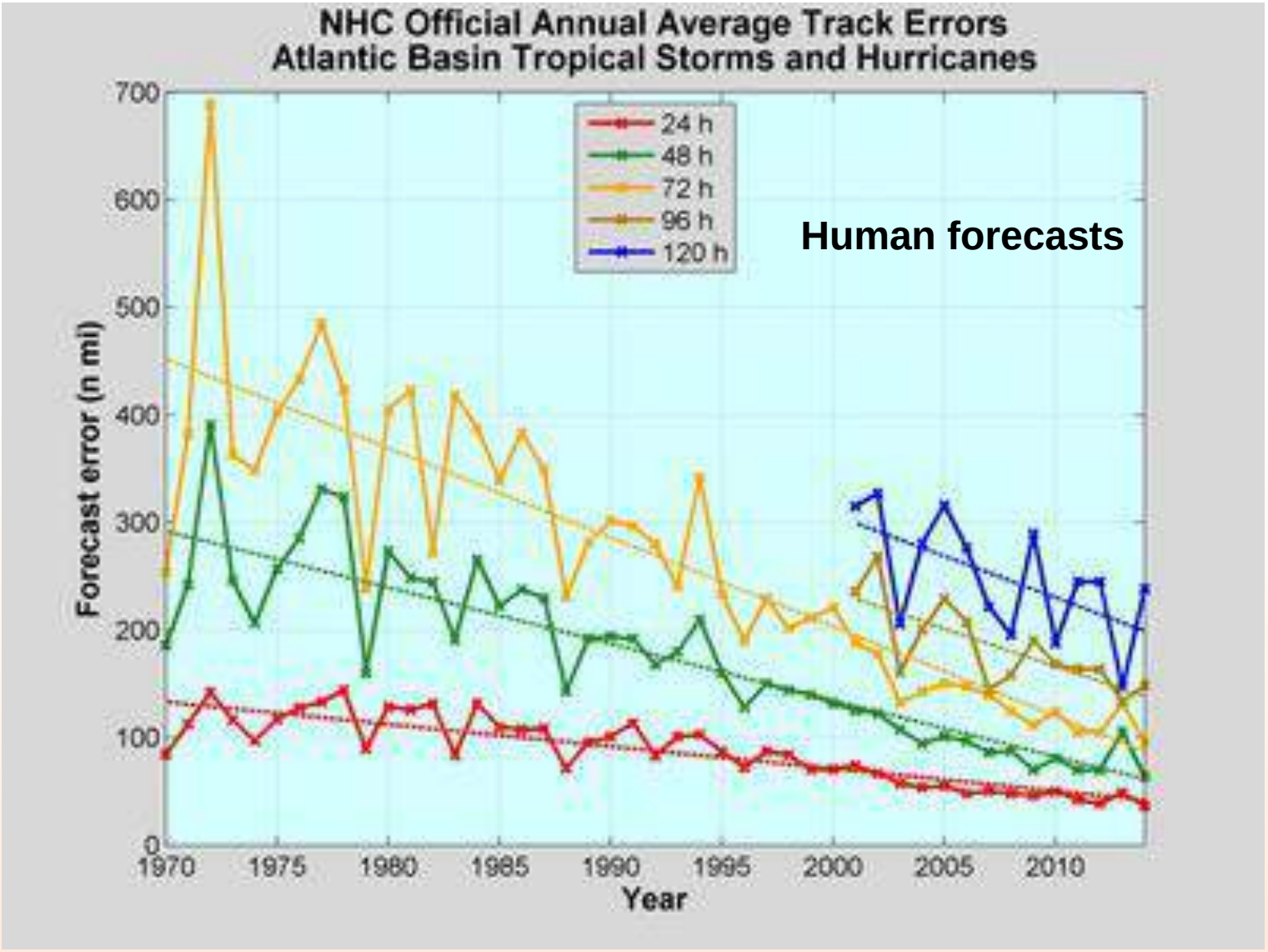
Supercomputer racks

Weather forecasting has improved!

- Partly due to increases in computing, weather forecasting has greatly improved over the past few decades

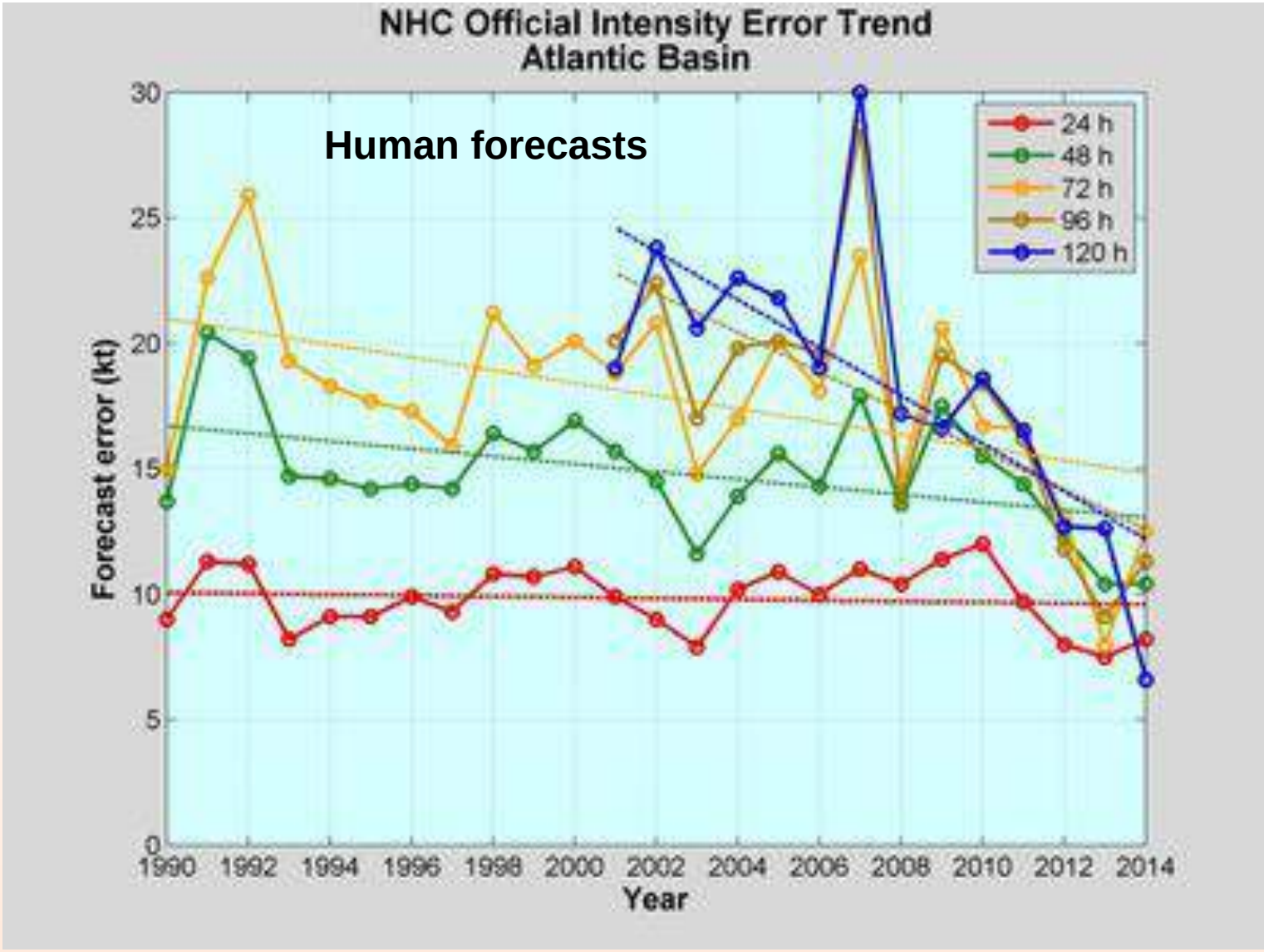
- A happy marriage of computational and scientific progress

Atlantic Basin Hurricane Track Forecasts



http://www.nhc.noaa.gov

Atlantic Basin Hurricane Intensity Forecasts



http://www.nhc.noaa.gov

Components of a numerical weather prediction (NWP) model

- Initialization
  - Data assimilation
- Dynamics
- Physics
- Subjective choices
  - Horizontal resolution

Global Forecast System (GFS) resolution

Steady increase in horizontal resolution with time

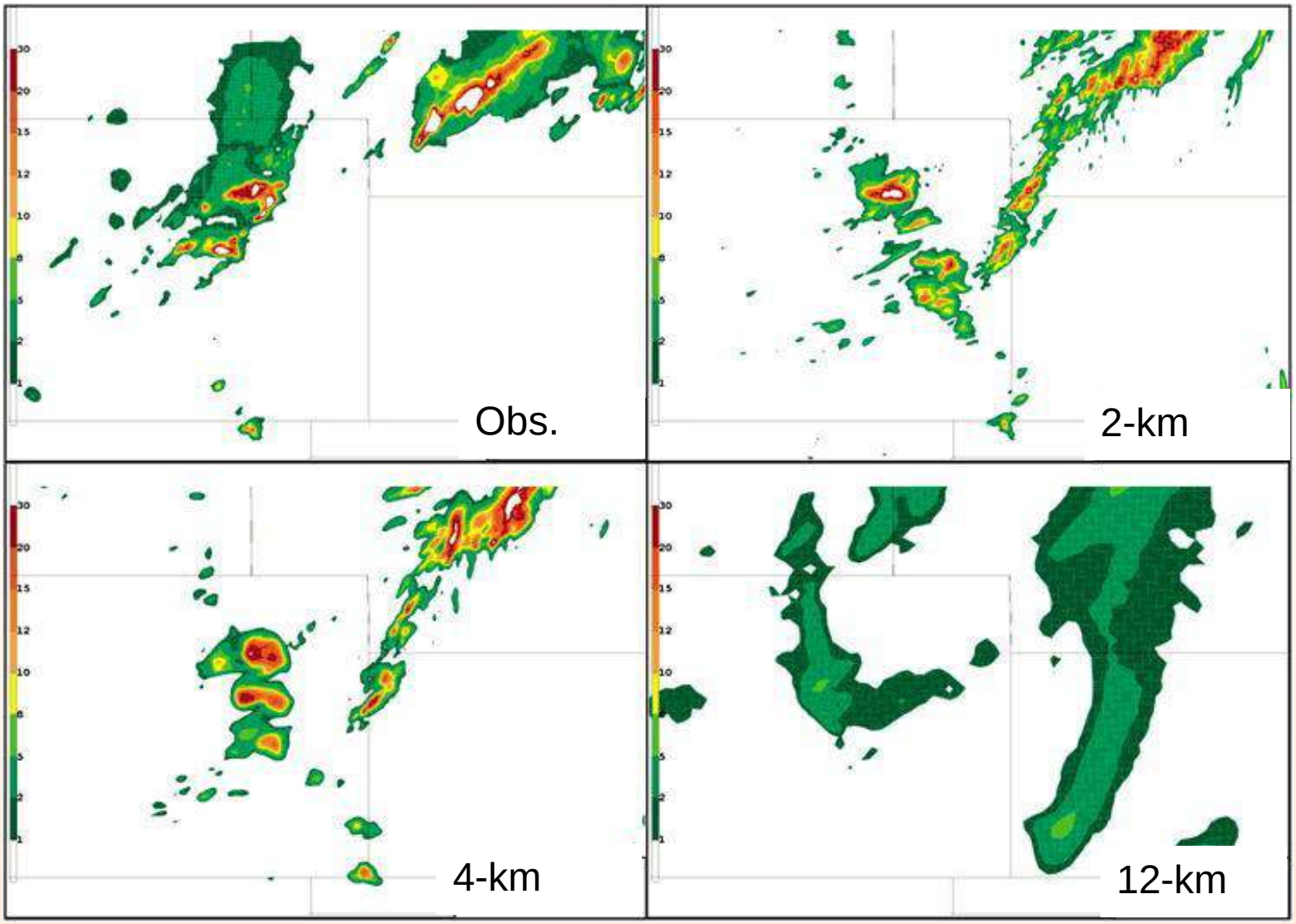
Year	Approximate horizontal grid spacing (km)	Number of vertical levels
1980	375	12
1983	300	18
1987	150	18
1991	105	28
1998	80	42
2002	55	64
2005	35	64
2010	27	64
2015	13	64

Modified from Yang (2015) http://video.ucar.edu/mms/mmm/2015/f_yang.mp4

High-resolution models

- Computer models are pretty good at predicting large-scale systems
- Challenges remain regarding finer-scale details
- To address these challenges, high-resolution models are needed
  - Typically have horizontal grid spacings of 1- to 4-km

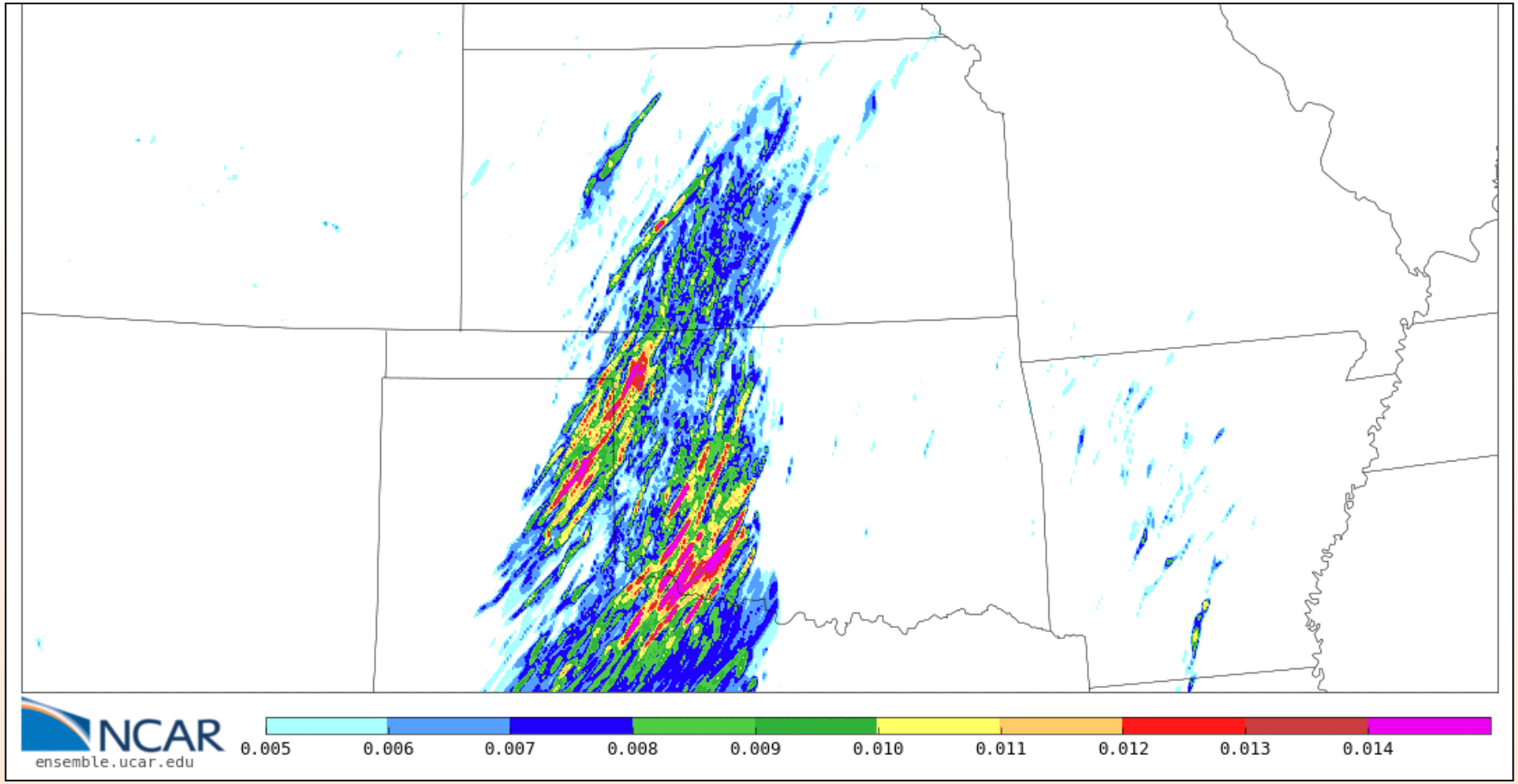
Benefit of high-resolution



Schwartz et al. (2009); *Monthly Weather Review*

Cool high-resolution fields

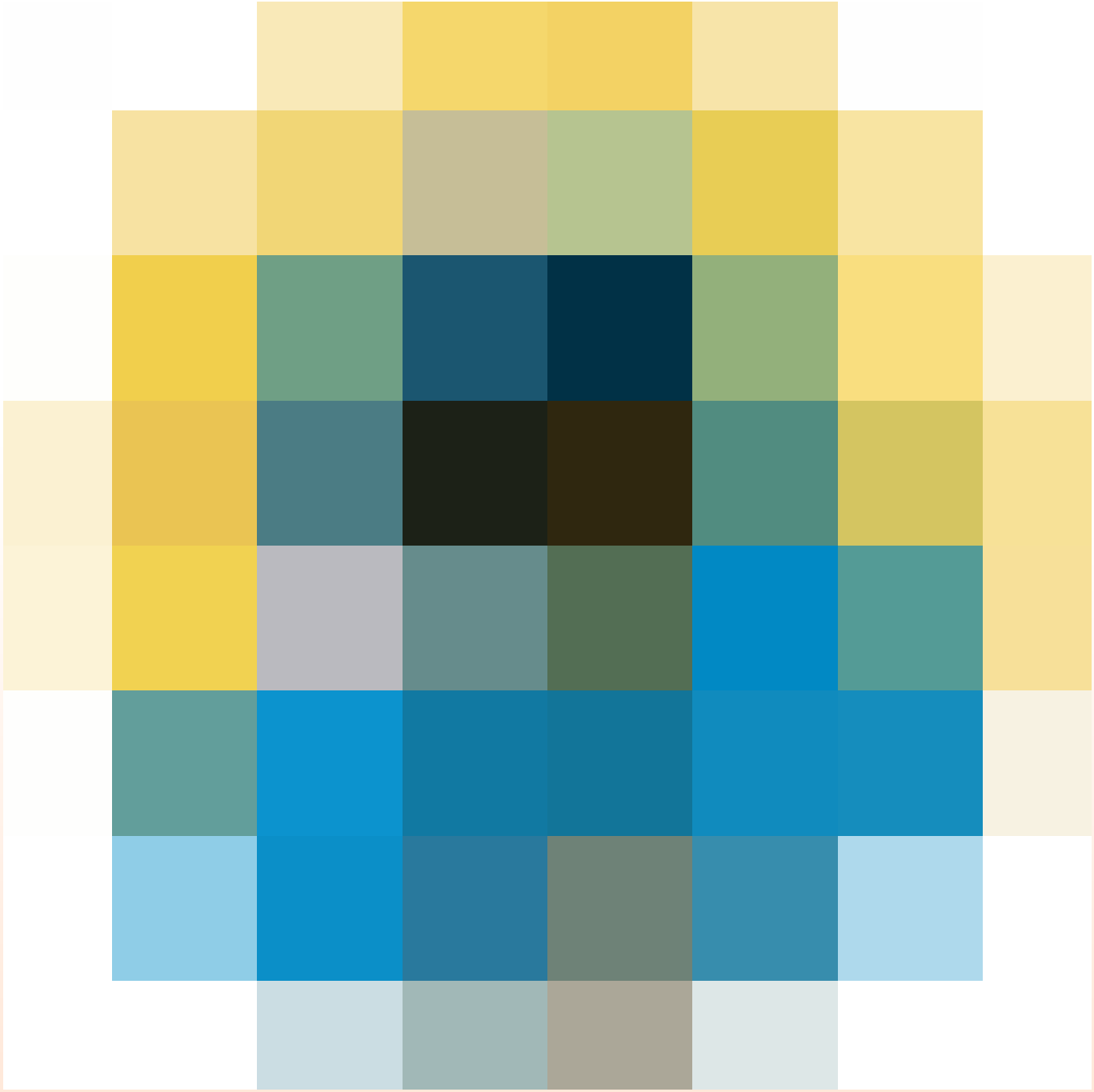
- Maximum 1-km vertical vorticity over 7-hrs
  - Toward tornado prediction

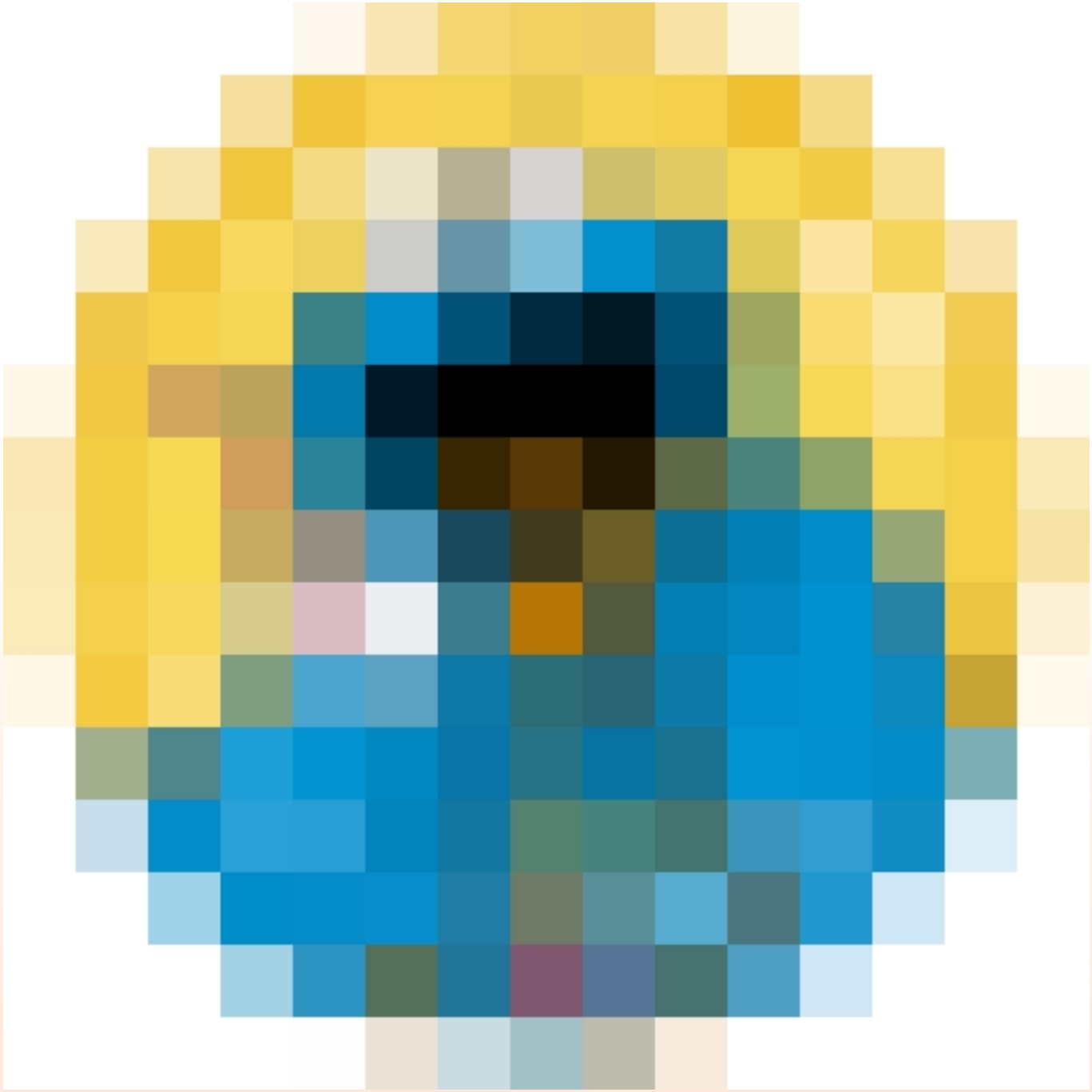


Sensitivity to horizontal grid-spacing

- Within high-resolution model configurations, what resolution is really needed?

- Little dispute that higher-resolution means more realism
  - But does greater realism translate into greater value?
  - If a 4-km model is as useful as 2-km, is it worth the ~8-fold additional cost to have a 2-km model?

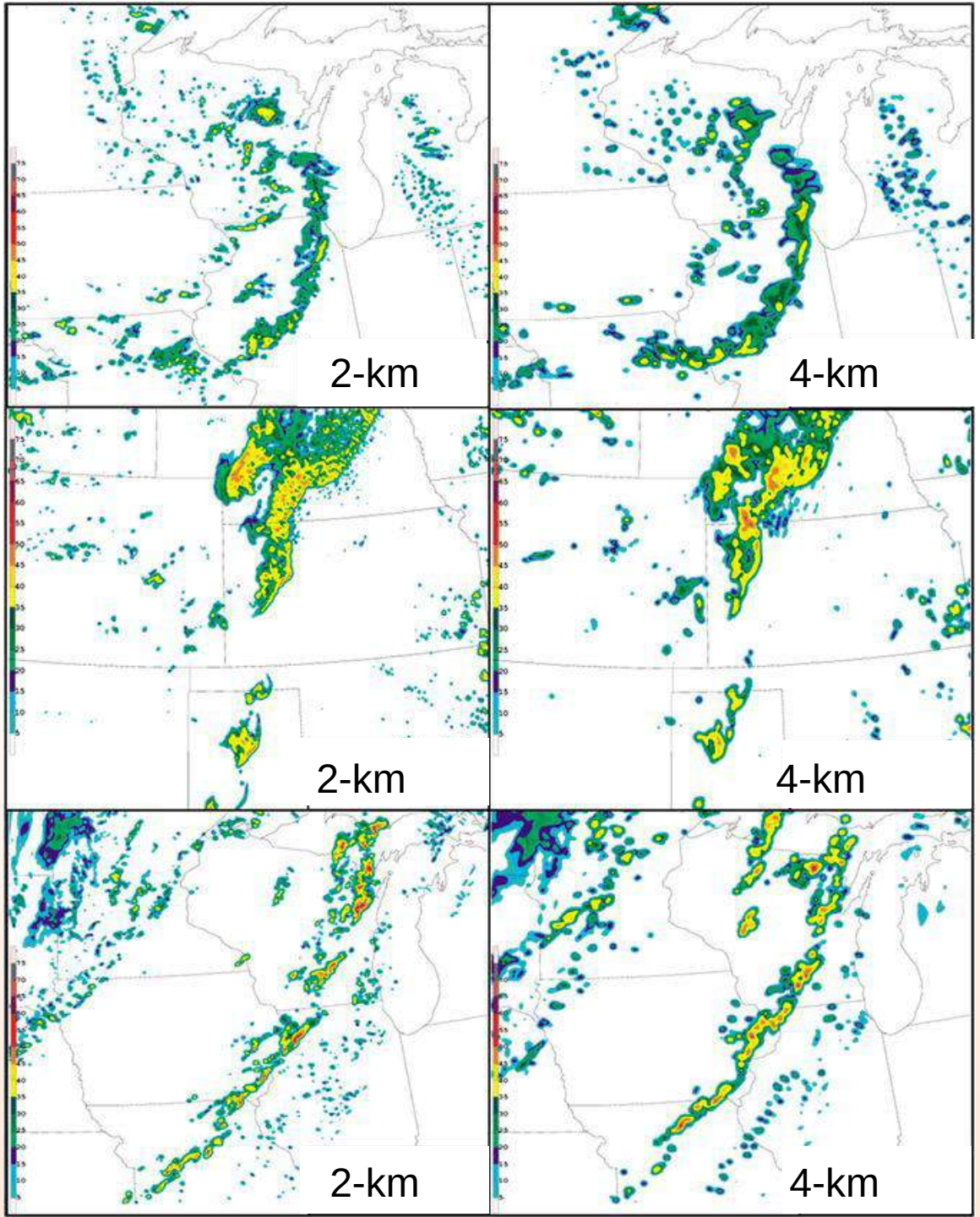





Cookie Monster
Anagram


Cookie Monster
Anagram

Simulated reflectivity snapshots



Schwartz et al. (2009); *Monthly Weather Review*

Convective evolution

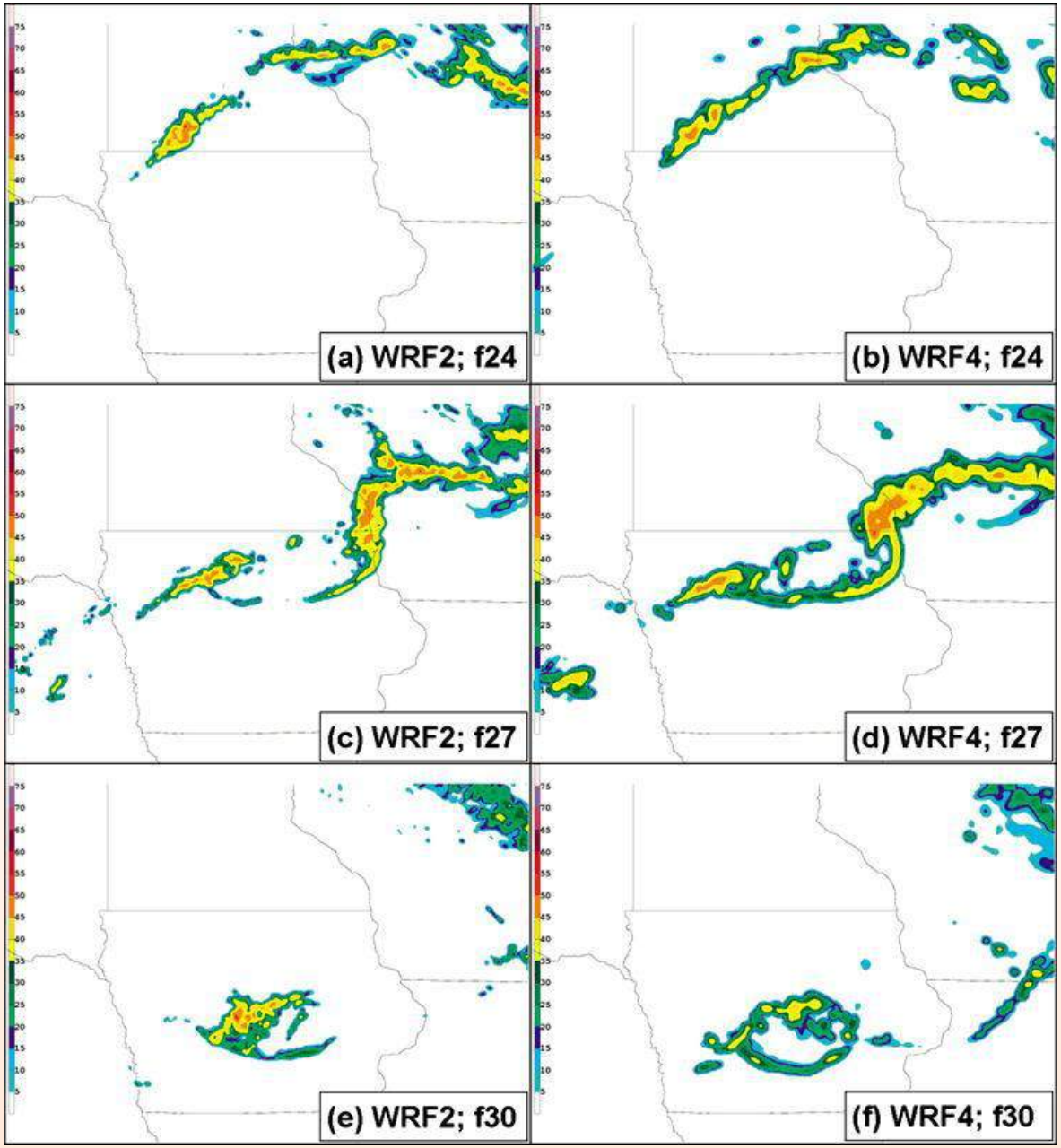
2-km

4-km

24-hr forecast

27-hr forecast

30-hr forecast

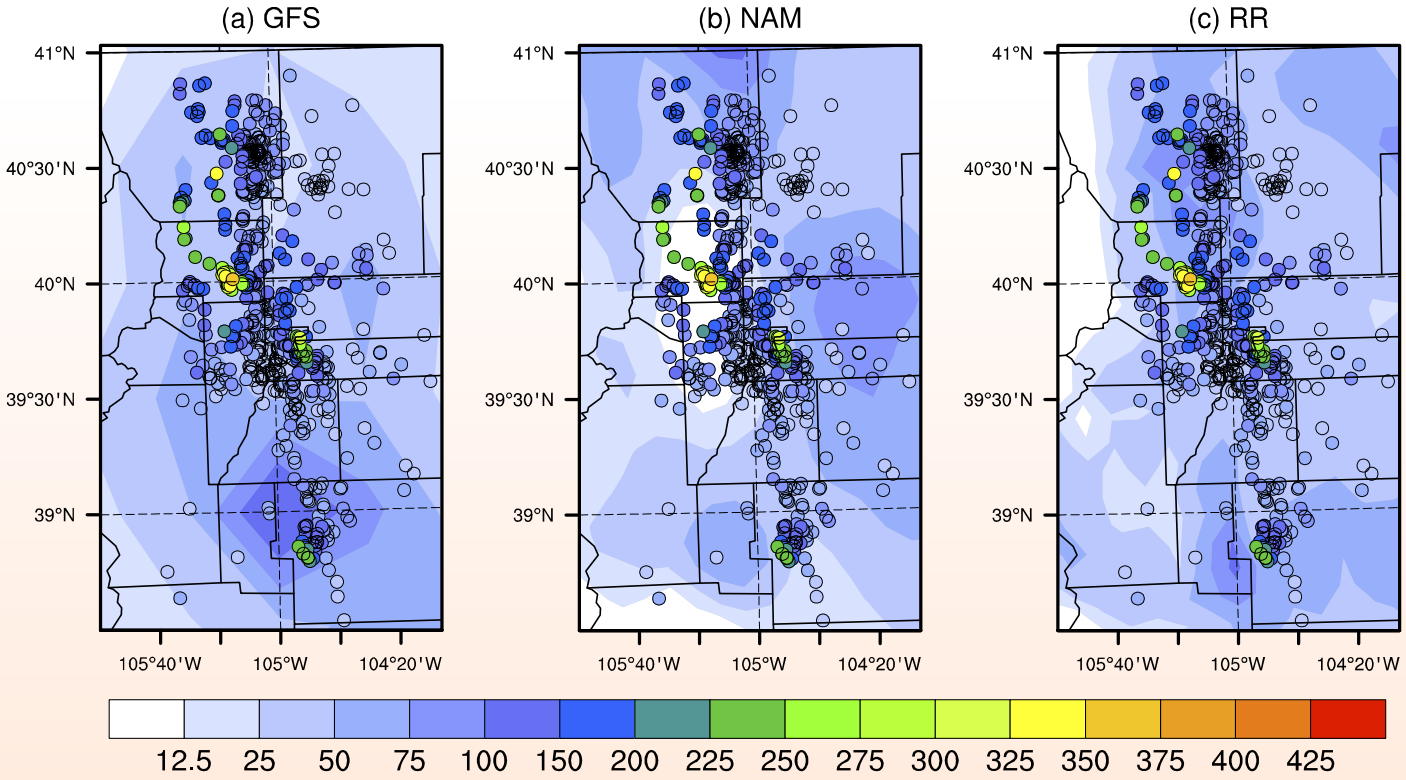


Schwartz et al. (2009); *Monthly Weather Review*

Colorado Front Range floods of 2013

Operational, coarse-resolution forecasts

- 48-hr accumulated precipitation
  - **NAM, GFS, and RR operational models**
- CoCoRaHS gauge measurements overlaid



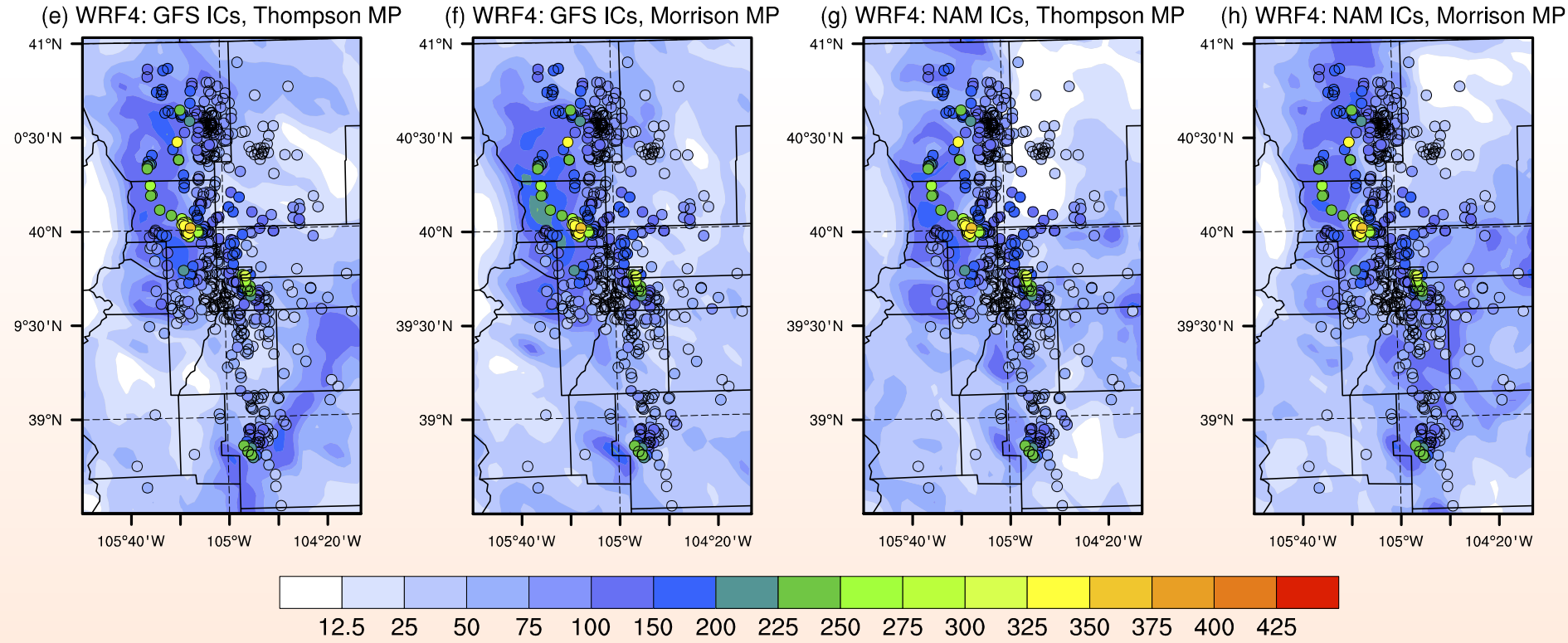
48-hr accumulated precipitation (mm) between 1200 UTC 11 and 1200 UTC 13 September

From Schwartz (2014); *Weather and Forecasting*

4-km WRF model forecasts

- 48-hr accumulated precipitation

- CoCoRaHS gauge measurements overlaid

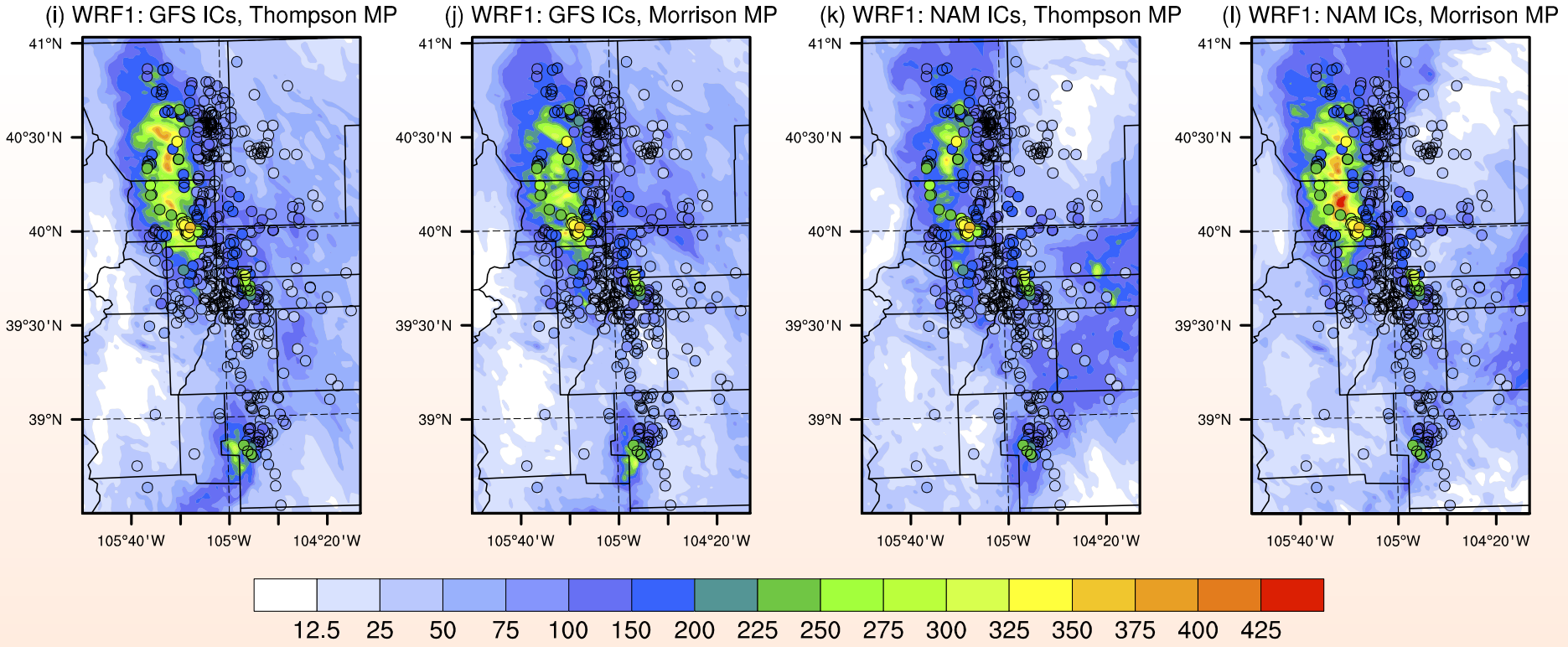


From Schwartz (2014); *Weather and Forecasting*

1-km WRF model forecasts

- 48-hr accumulated precipitation

- CoCoRaHS gauge measurements overlaid



From Schwartz (2014); *Weather and Forecasting*

Objective verification of high-resolution models

Traditional objective verification

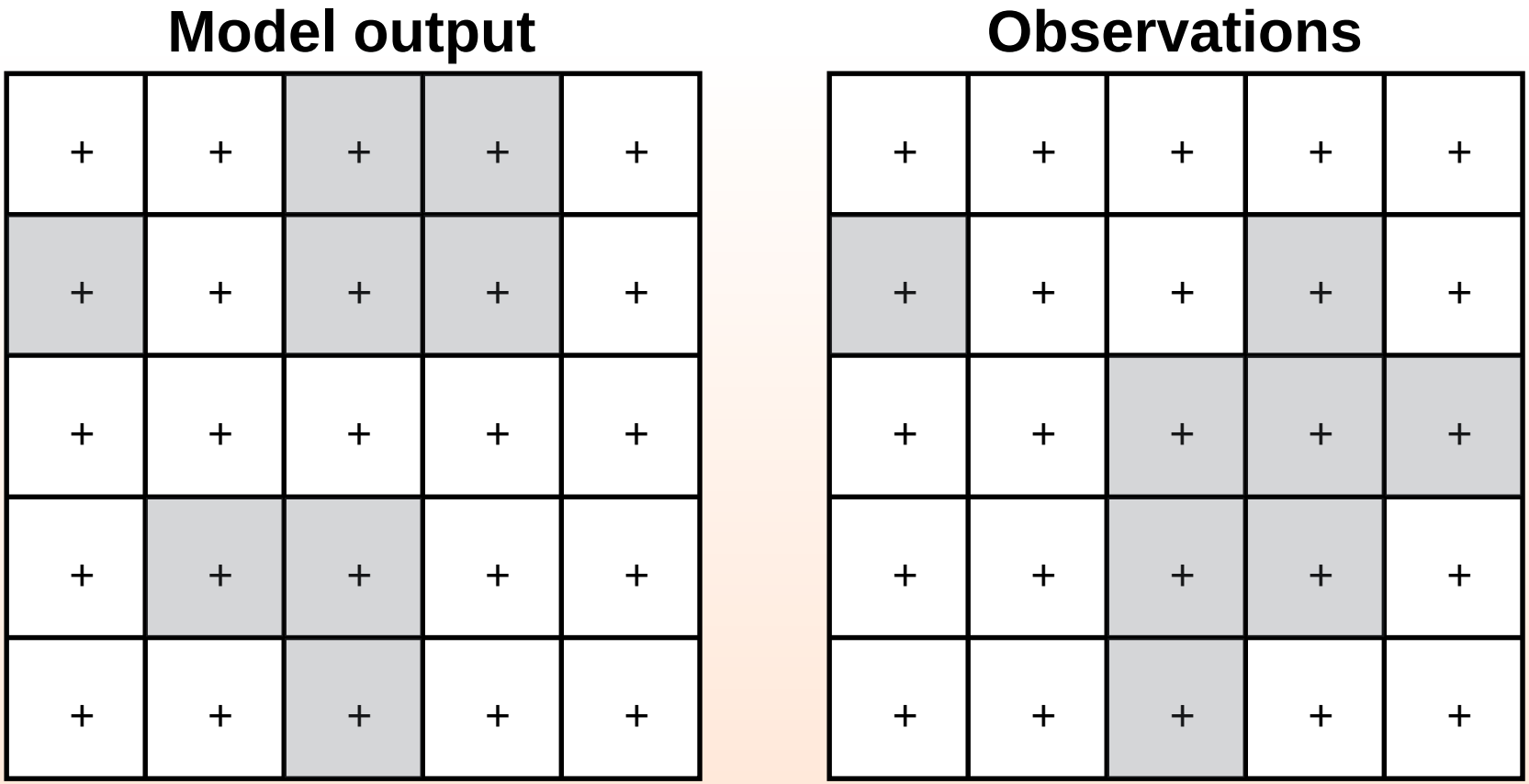
- Verification at the grid-scale
- Pick an event
  - Precipitation exceeding 1.0 mm/hr
- Compare forecast and observations at each grid point

		Observed		
		Yes	No	
Forecast	Yes	a	b	$a + b$
	No	c	d	$c + d$
		$a + c$	$b + d$	

Standard 2 x 2 contingency table for dichotomous events

Traditional point-by-point methods

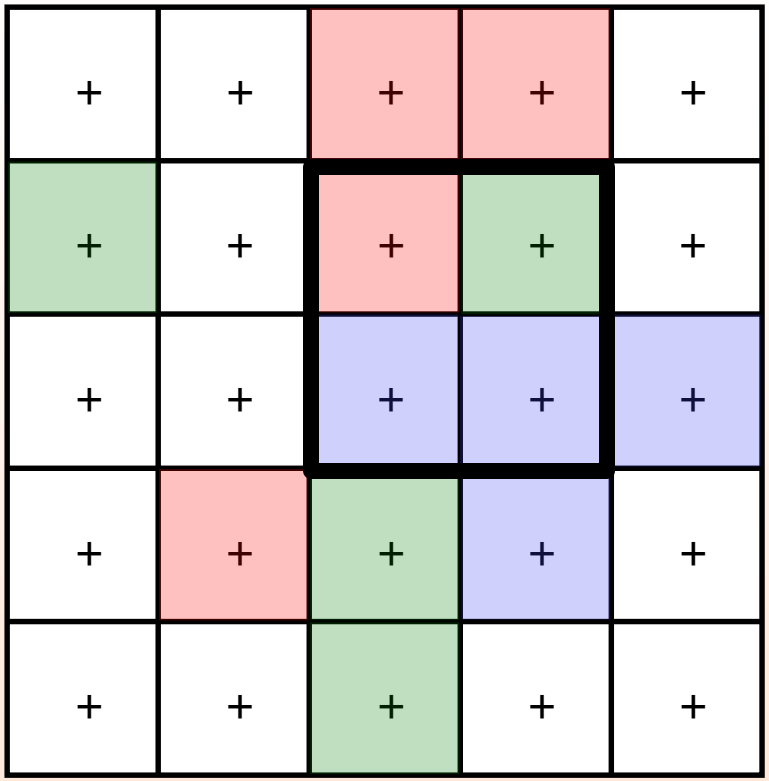
- The event has occurred at the shaded grid points



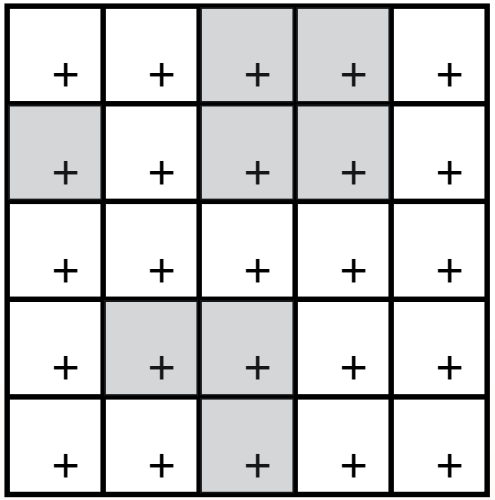
Grid point classification

- Green: “hits”
- Red: “false alarms”
- Blue: “misses”
- White: “correct negatives”

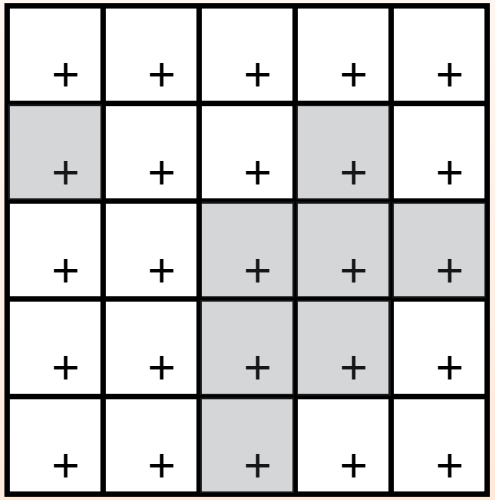
Classification



Model output



Observations



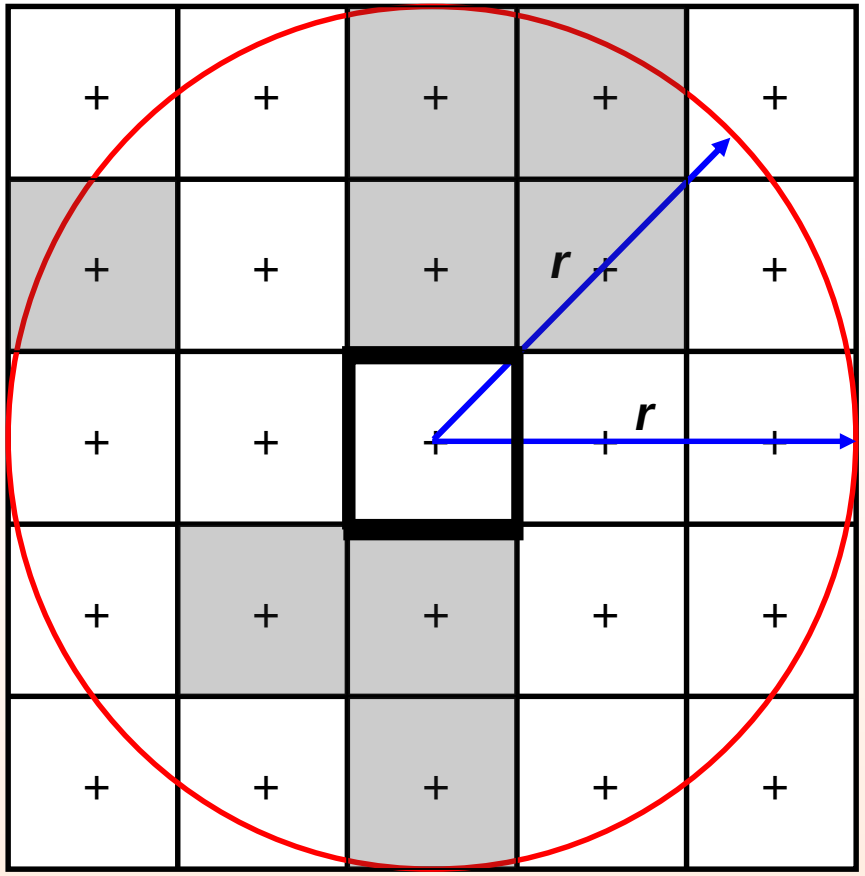
It's a beautiful day in the "neighborhood"

- High-resolution models are not accurate at the grid scale
- To account for spatial displacement errors, specify a radius of influence (r) about each grid point
- Define an event
- Generate a probability at each grid point

Schematic Example

- r = 2.5 times the grid spacing
- The event has occurred in the shaded boxes
- Event occurs in 8 boxes
- 21 total boxes in neighborhood

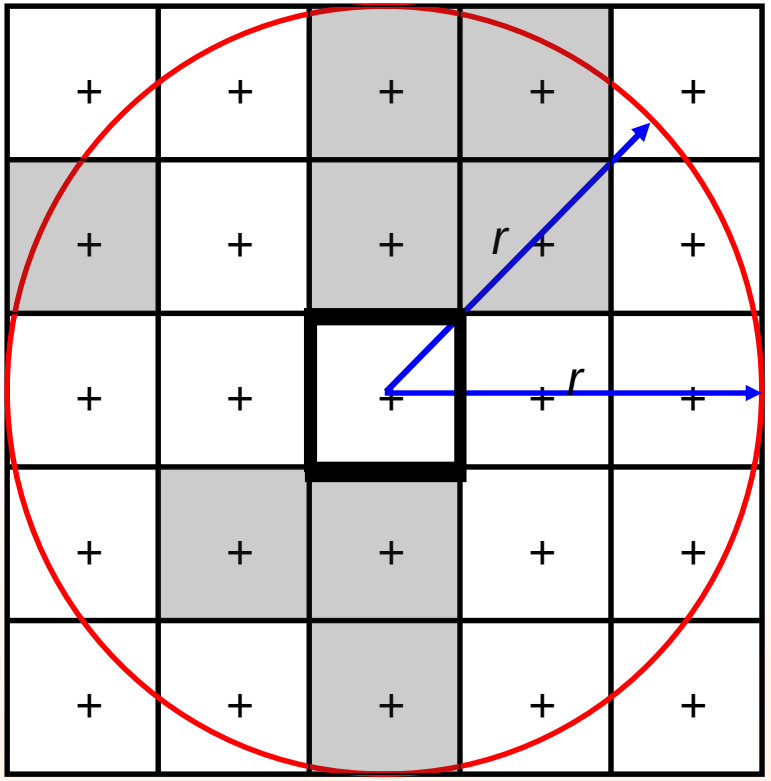
Hypothetical model output



P = 8/21 = 38%

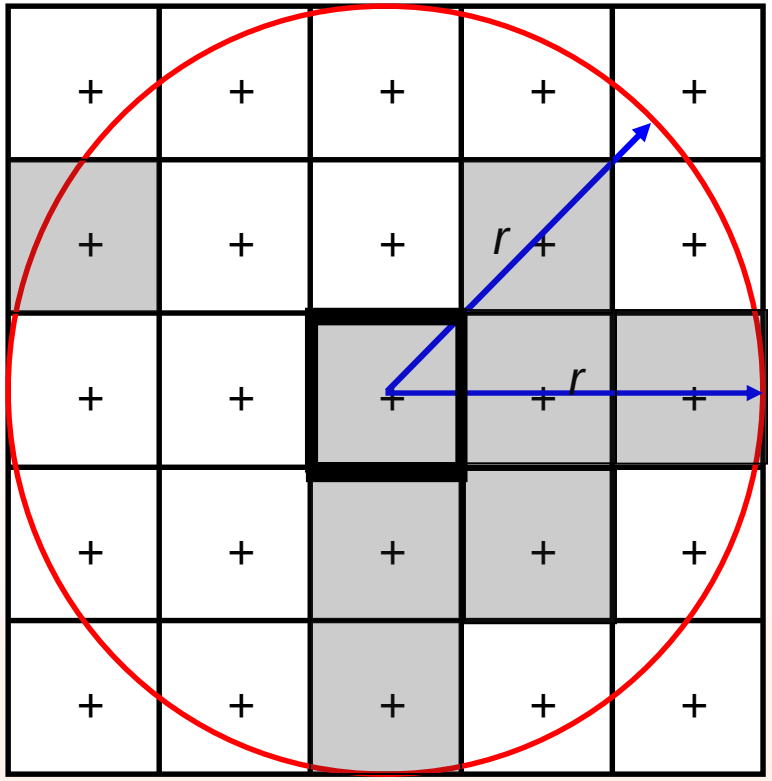
Example Applied to Model and Observations

Model output



P = 8/21 = 38%

Observations



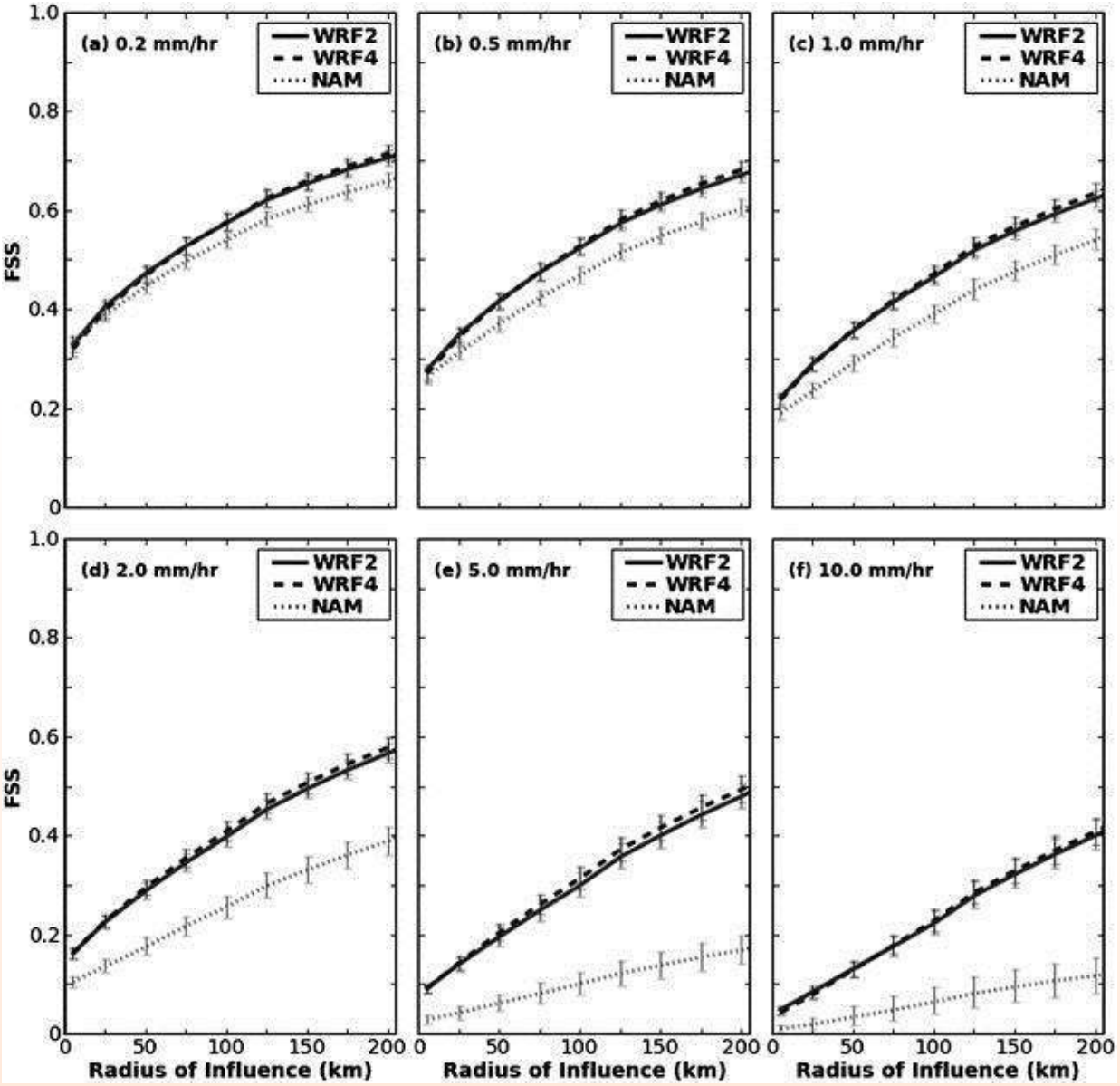
P = 8/21 = 38%

A perfect forecast using this neighborhood approach

Objective benefit of high-resolution

The fractions skill score compares observed and forecast fractions

WRF2: 2-km
WRF4: 4-km
NAM: 12-km



Schwartz et al. (2009); *Monthly Weather Review*

Thoughts about horizontal grid spacing

- It appears that 3- or 4-km horizontal grid spacing provides similar value and accuracy as 1- or 2-km horizontal grid spacing over flat terrain
  - Higher-resolution always provides more realism

- In topographically-diverse areas, higher-resolution (~1-km horizontal grid spacing) is usually better

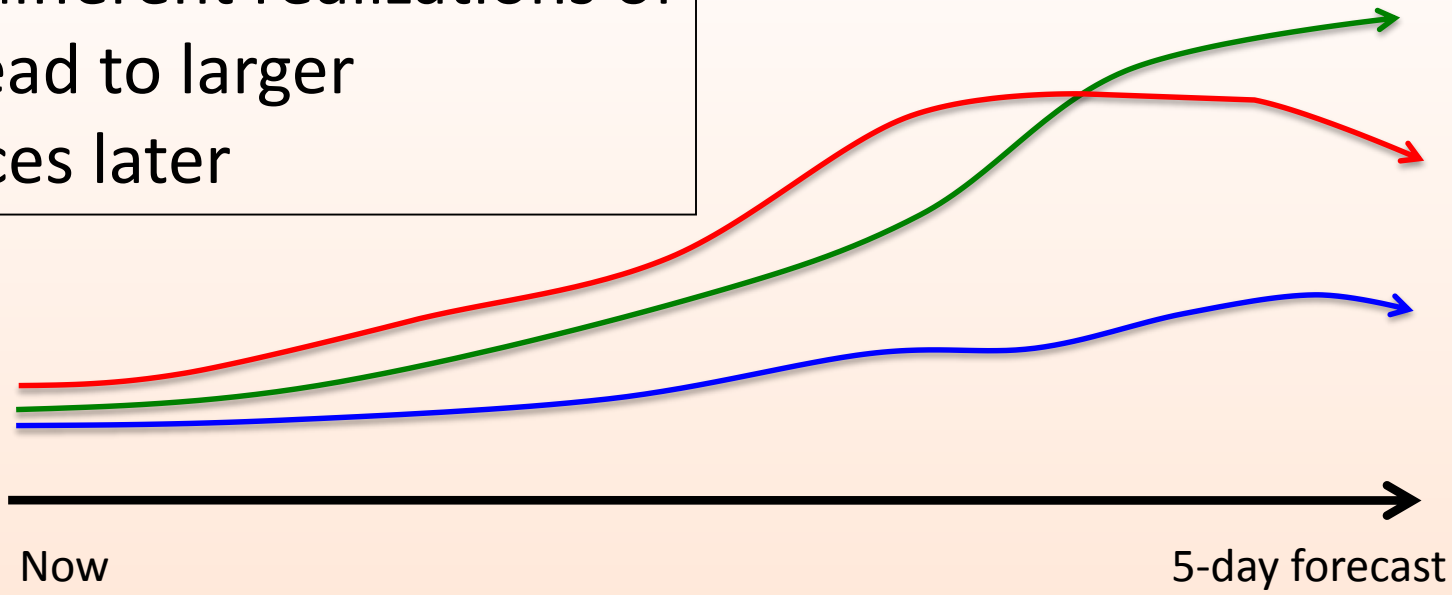
Ensemble prediction systems

Probabilistic predictions

- Probabilistic forecasts are often generated by ensembles of computer models, where variations in model parameters yield different forecast outcomes

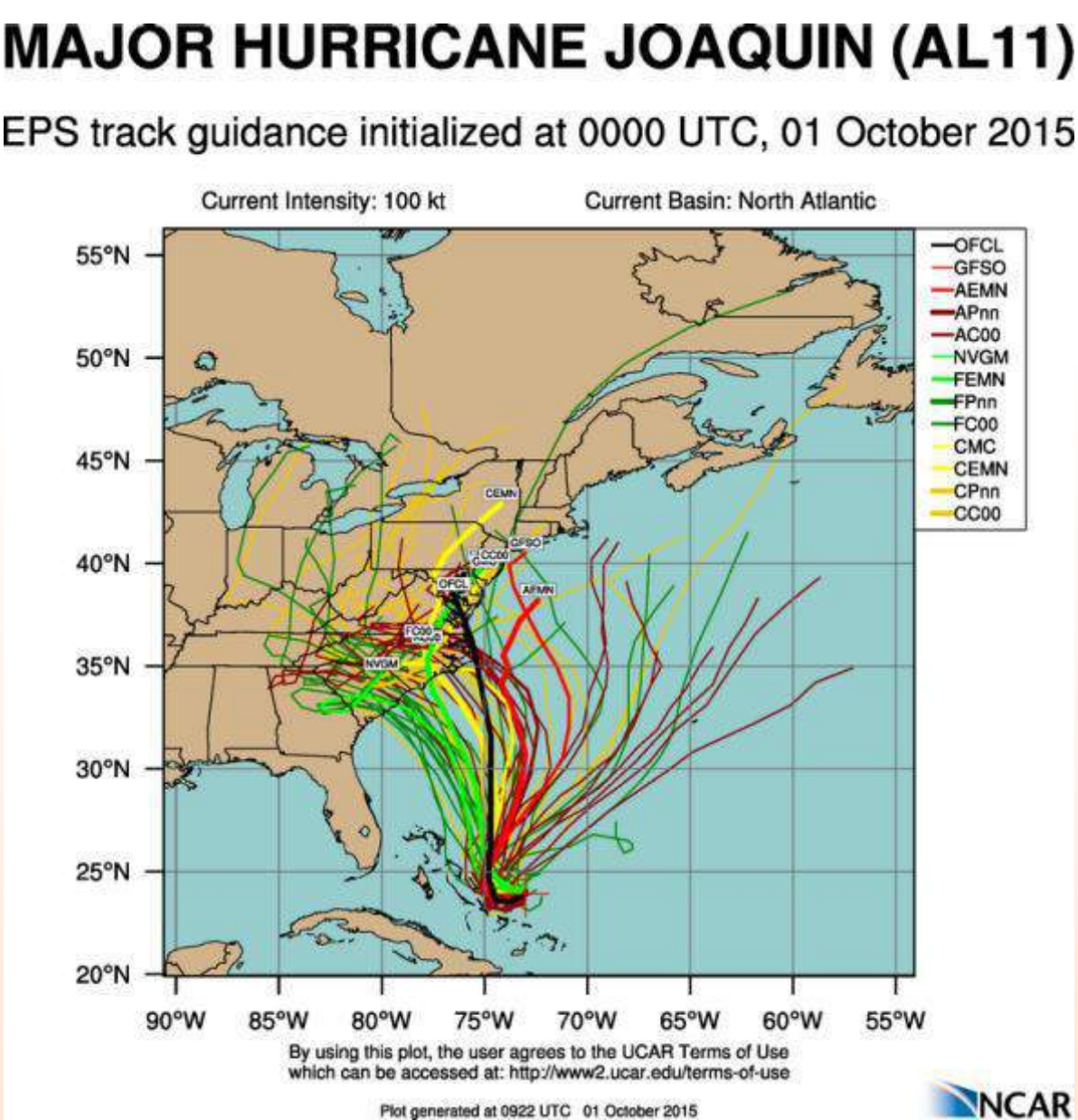
- Different forecasts are called "ensemble members"

Slightly different realizations of "now" lead to larger differences later



Hurricane Joaquin

Hurricane Joaquin had a very uncertain track

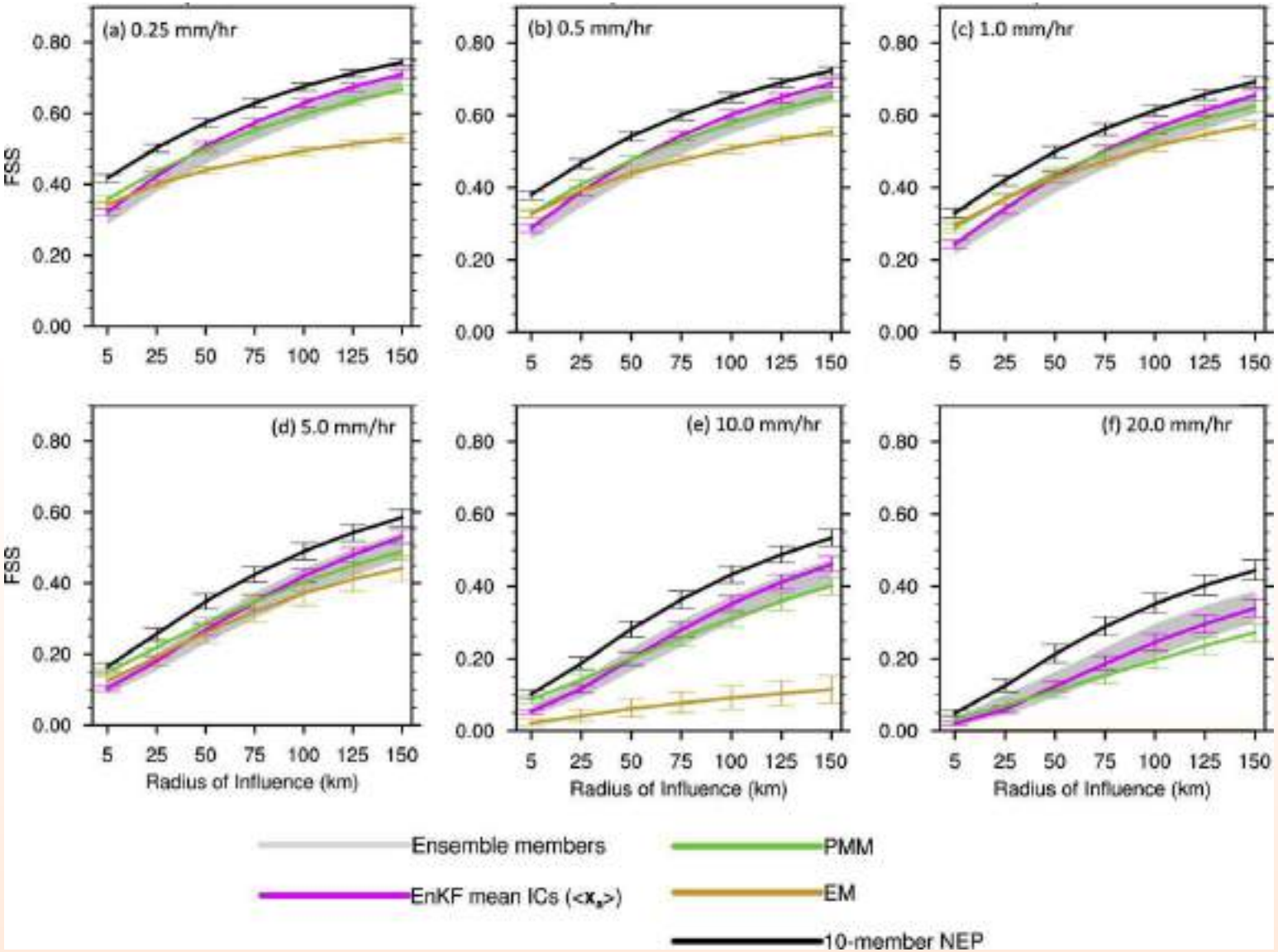


Why ensemble forecasts are desirable

- Quantification of uncertainty
  - Naturally produces probabilities!
  - Allows forecasters to forecast their "true beliefs"
  - Allows users to make decisions based on expected value and cost-loss scenarios

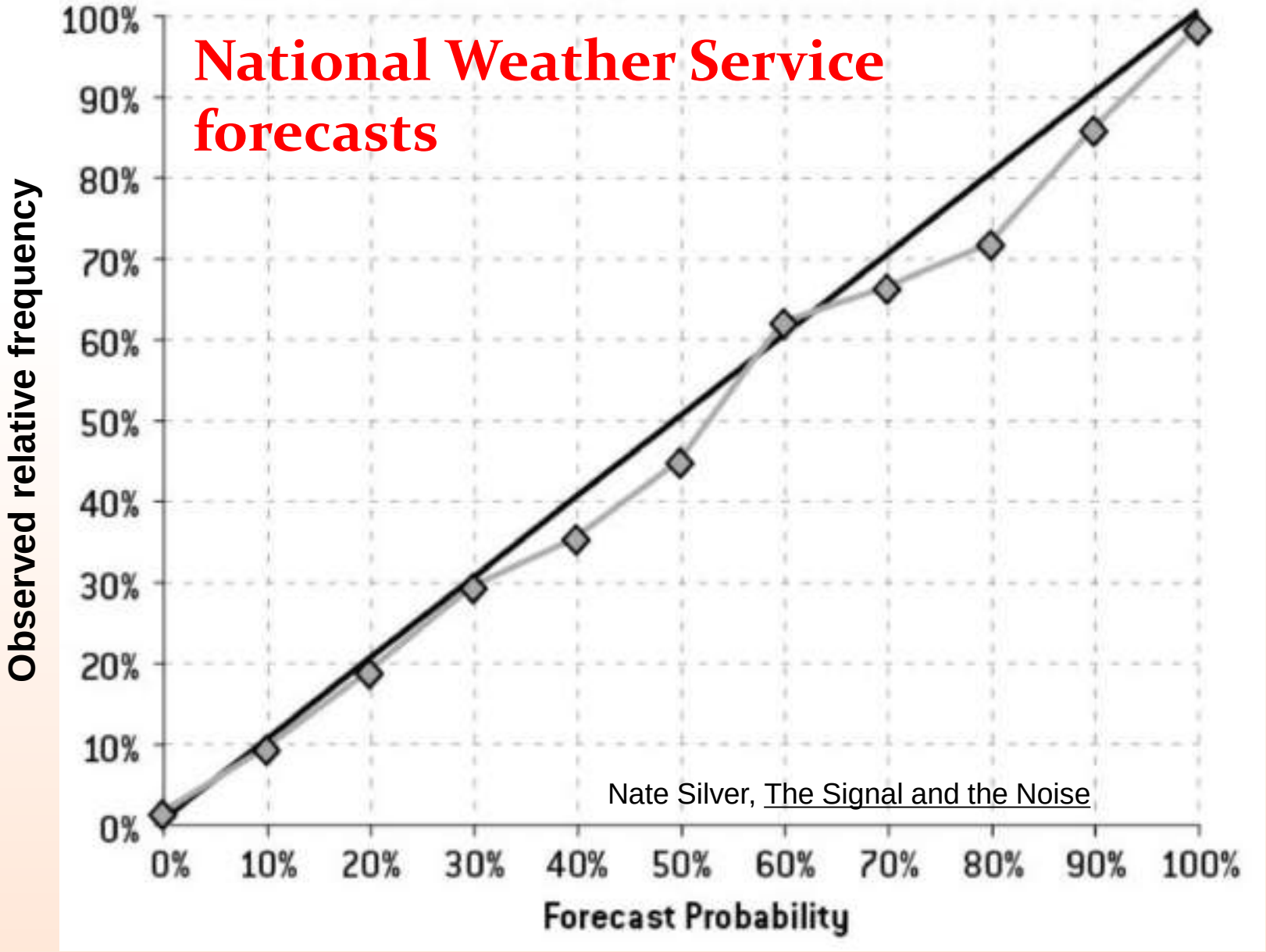
- Errors of different members cancel when combining forecasts across members
  - Forecasts combining information across all members are better than single deterministic forecasts

Ensembles are better

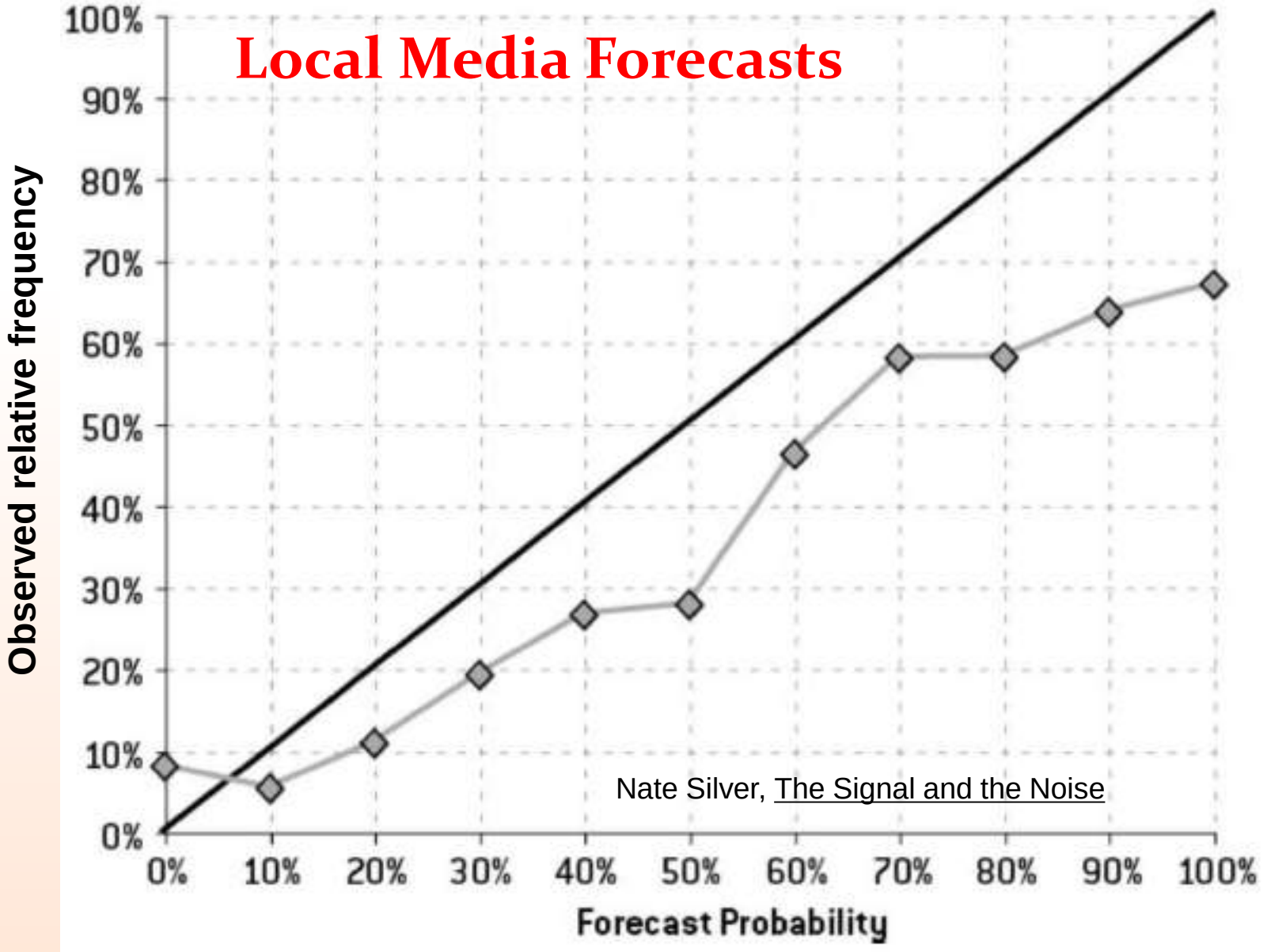


From Schwartz et al. (2014); *Weather and Forecasting*

Ensemble verification: Calibration



Calibration



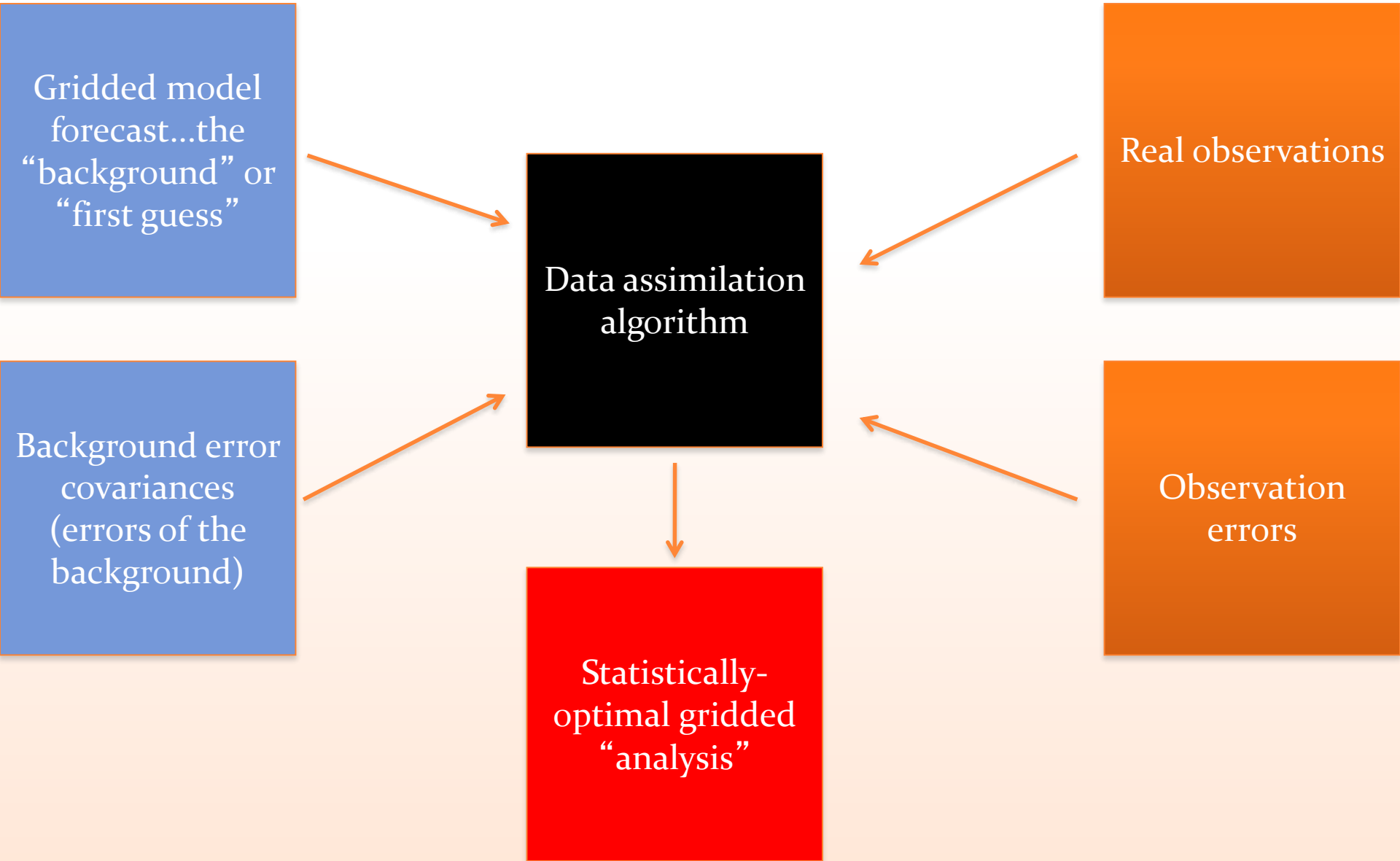
Challenge with high-resolution ensembles

- One of the forefronts of NWP model research is how to design high-resolution ensembles
  - Vary just initial conditions?
  - Configure different members with different physics or dynamics?
- Each method has advantages and disadvantages
- General goal is to improve calibration

How to initialize high-resolution ensembles?

- Use existing operational ensembles
  - Cheap and easy but potential for mismatches
- Add random noise to a single field
  - A bit ad hoc
- Use ensemble data assimilation

What is data assimilation?



Two (of many) data assimilation approaches

- Three-dimensional variational (3DVAR)
  - Background error covariances (BECs) typically fixed/time-invariant
  - May yield poor results when actual flow differs from that encapsulated within the fixed "climatology"

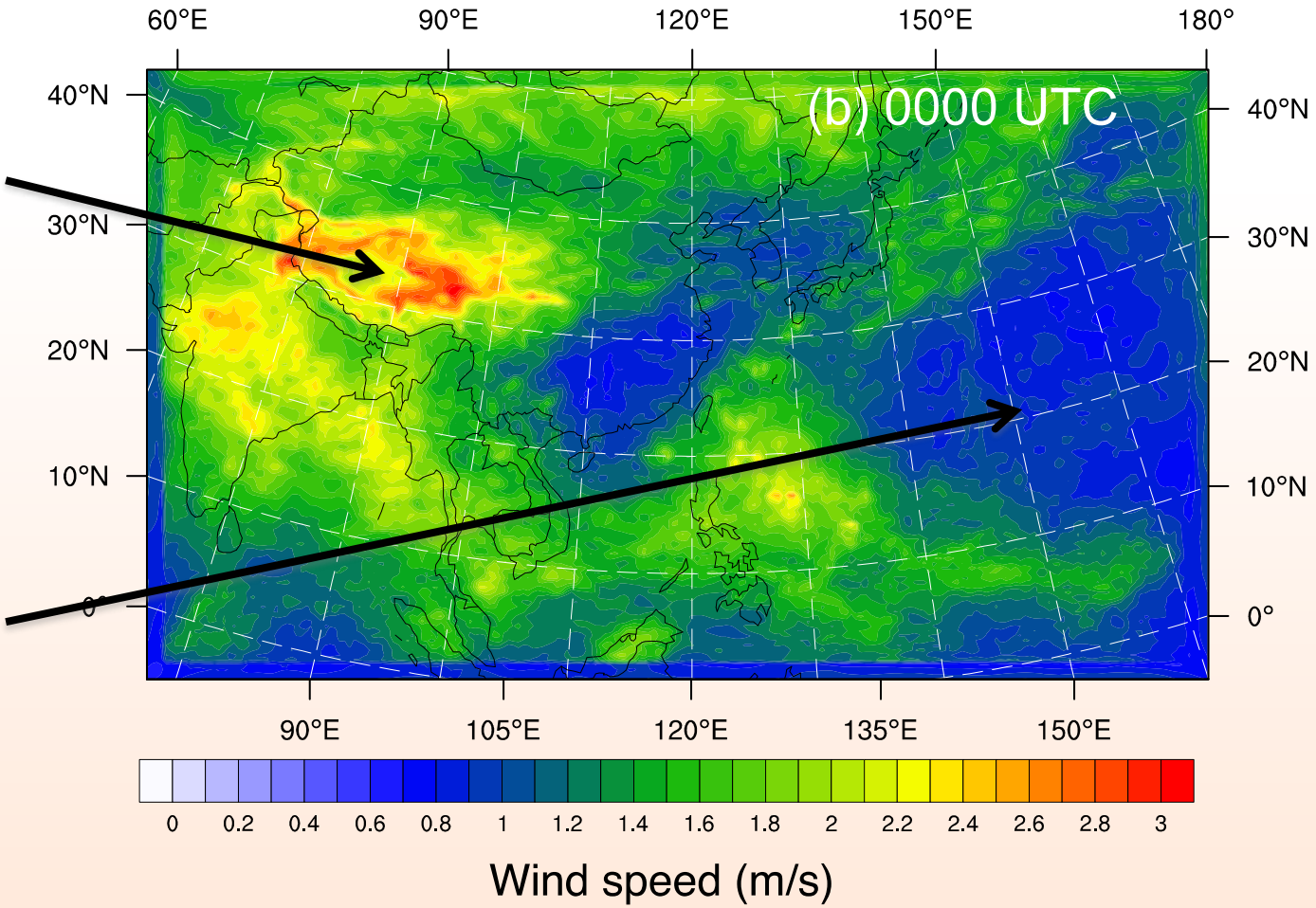
- Ensemble Kalman filter (EnKF)
  - Time-evolving, "flow-dependent" BECs estimated from a short-term ensemble forecast

Background errors and observations

- Ensemble spread (standard deviation) of wind speed

More model uncertainty: give observations more weight

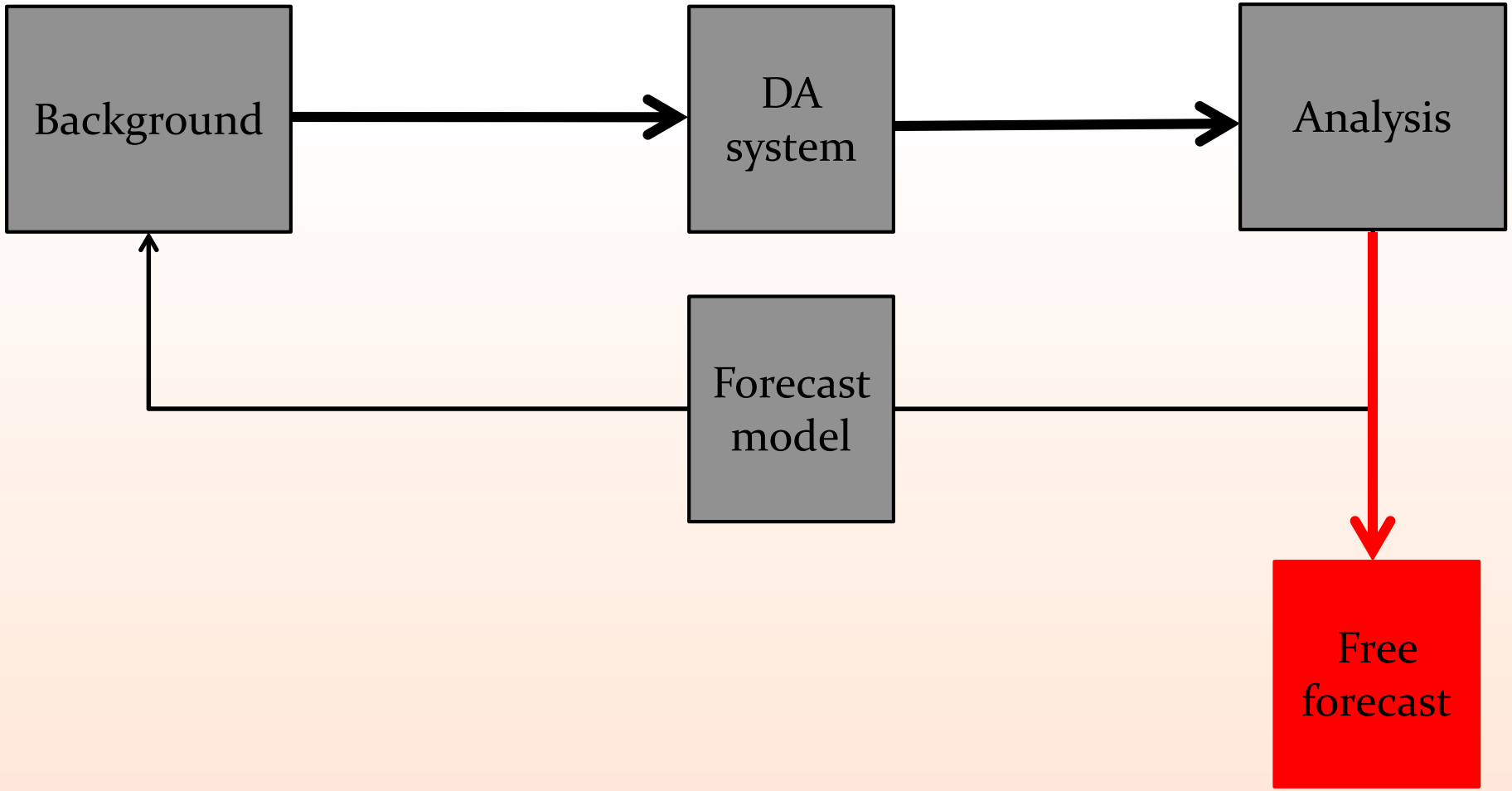
Less model uncertainty: give observations less weight



From Schwartz et al. (2013); *Monthly Weather Review*

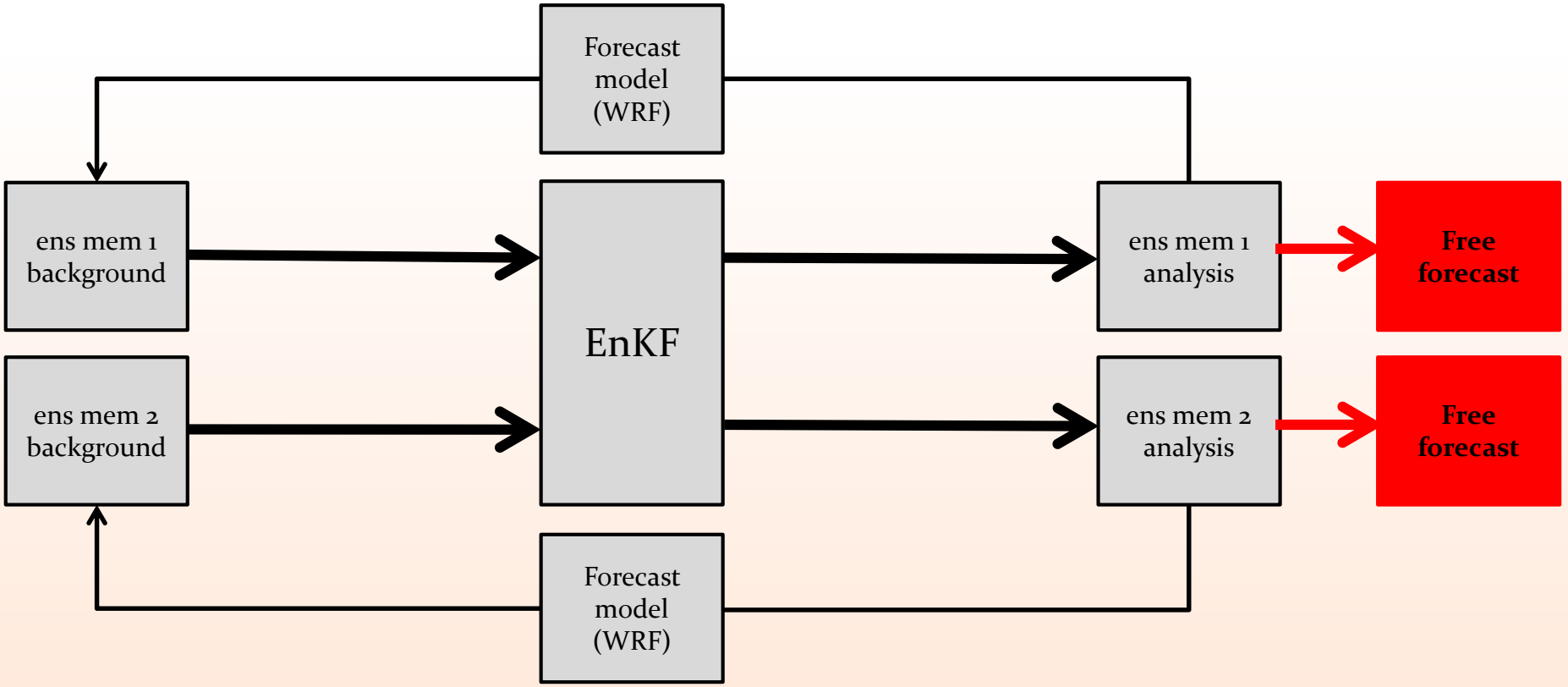
Continuously cycling data assimilation

- Usually 1- to 6-hrs between each analysis



Continuously cycling EnKF

- Initial conditions for all ensemble members are dynamically consistent
  - No ad hoc assumptions or use of external models



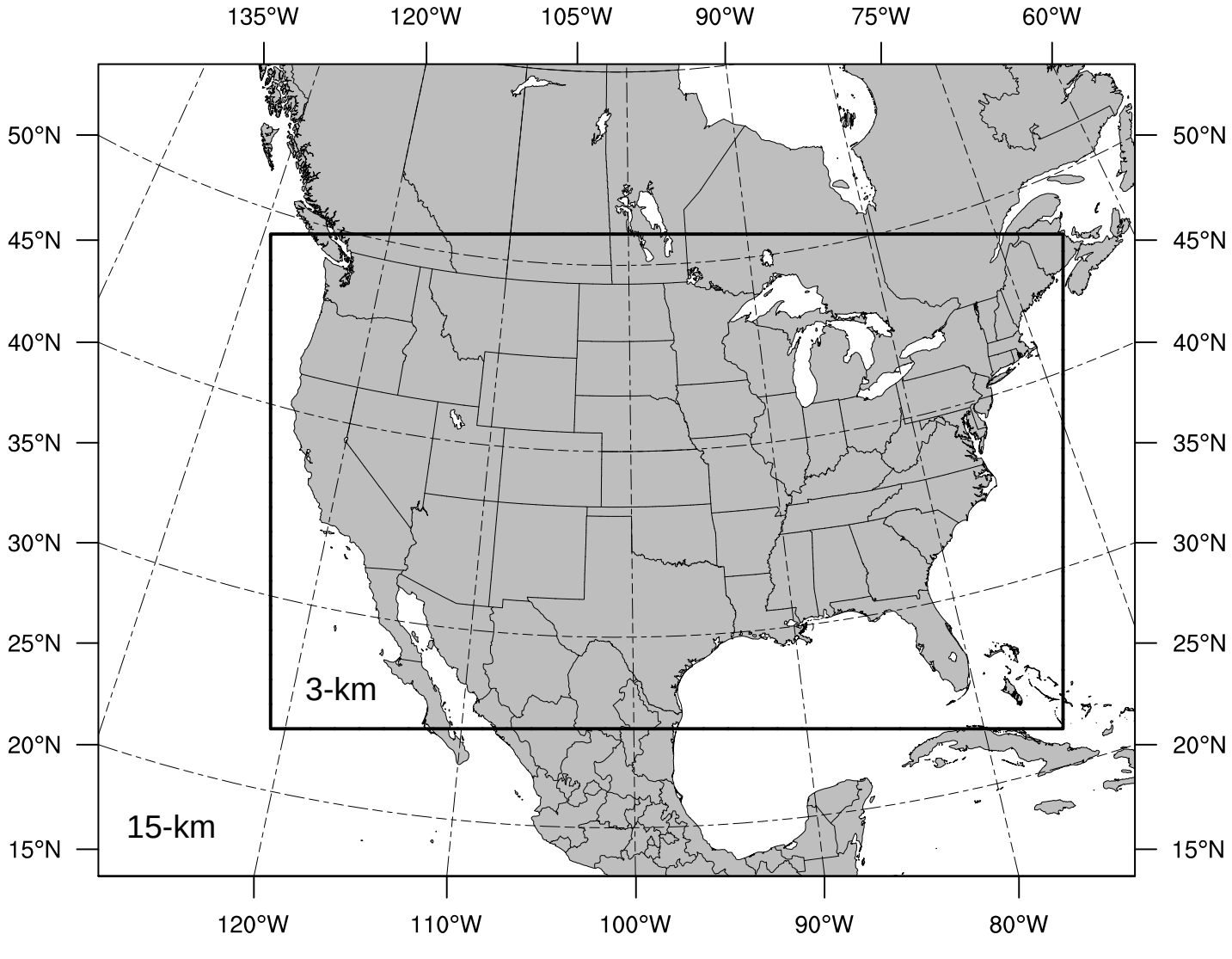
What we're doing at NCAR/MMM

- Since April 7, 2015, we have been producing real-time, 10-member ensemble forecasts
  - 3-km horizontal grid spacing

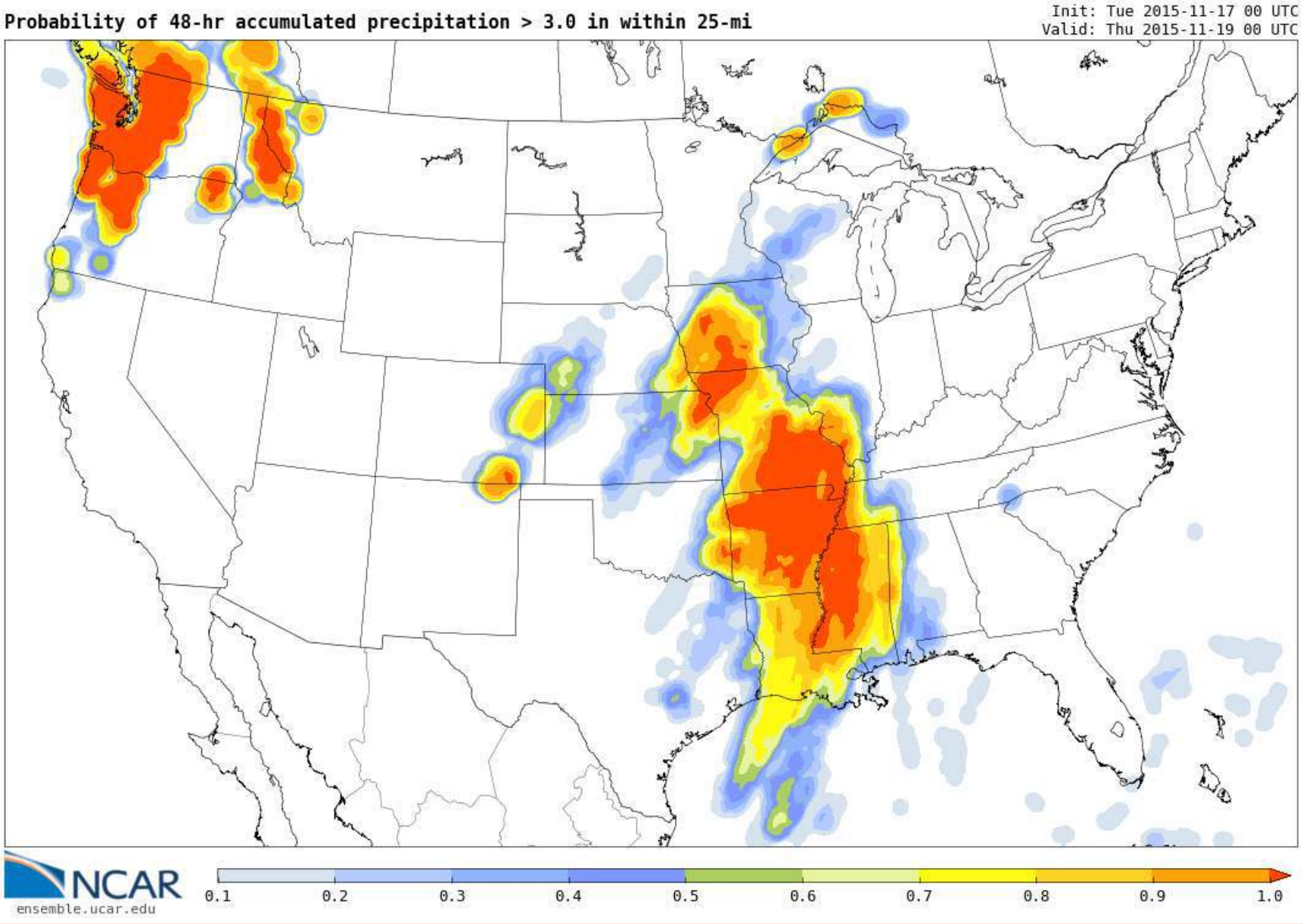
- 50-member continuously cycling EnKF
  - 15-km horizontal grid spacing
  - New analysis every 6-hrs
  - Initializes the 10-member, 3-km ensemble forecasts
  - Use of EnKF to initialize high-resolution ensembles is unique

http://www.ensemble.ucar.edu

NCAR ensemble domain

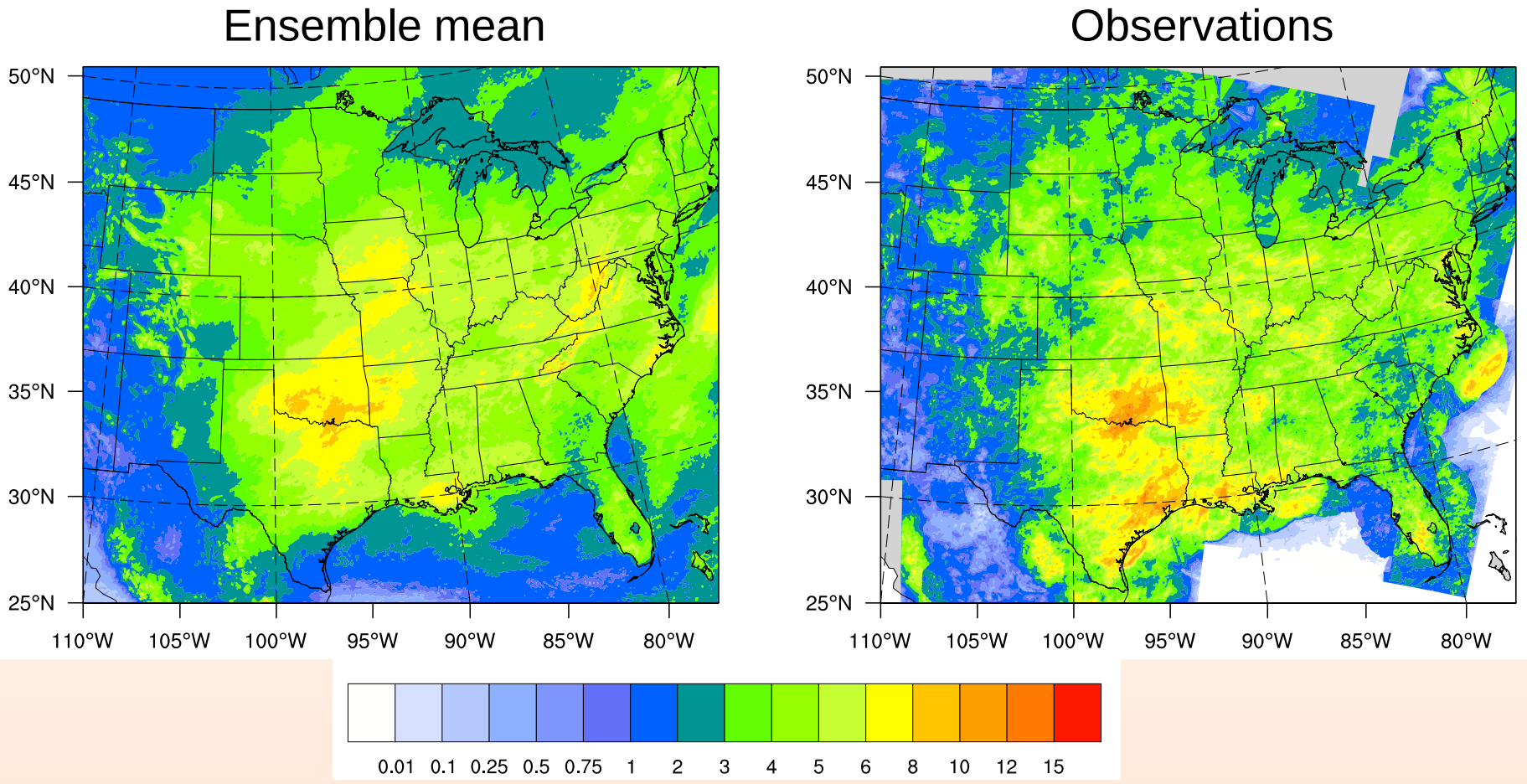


Heavy precipitation probabilities



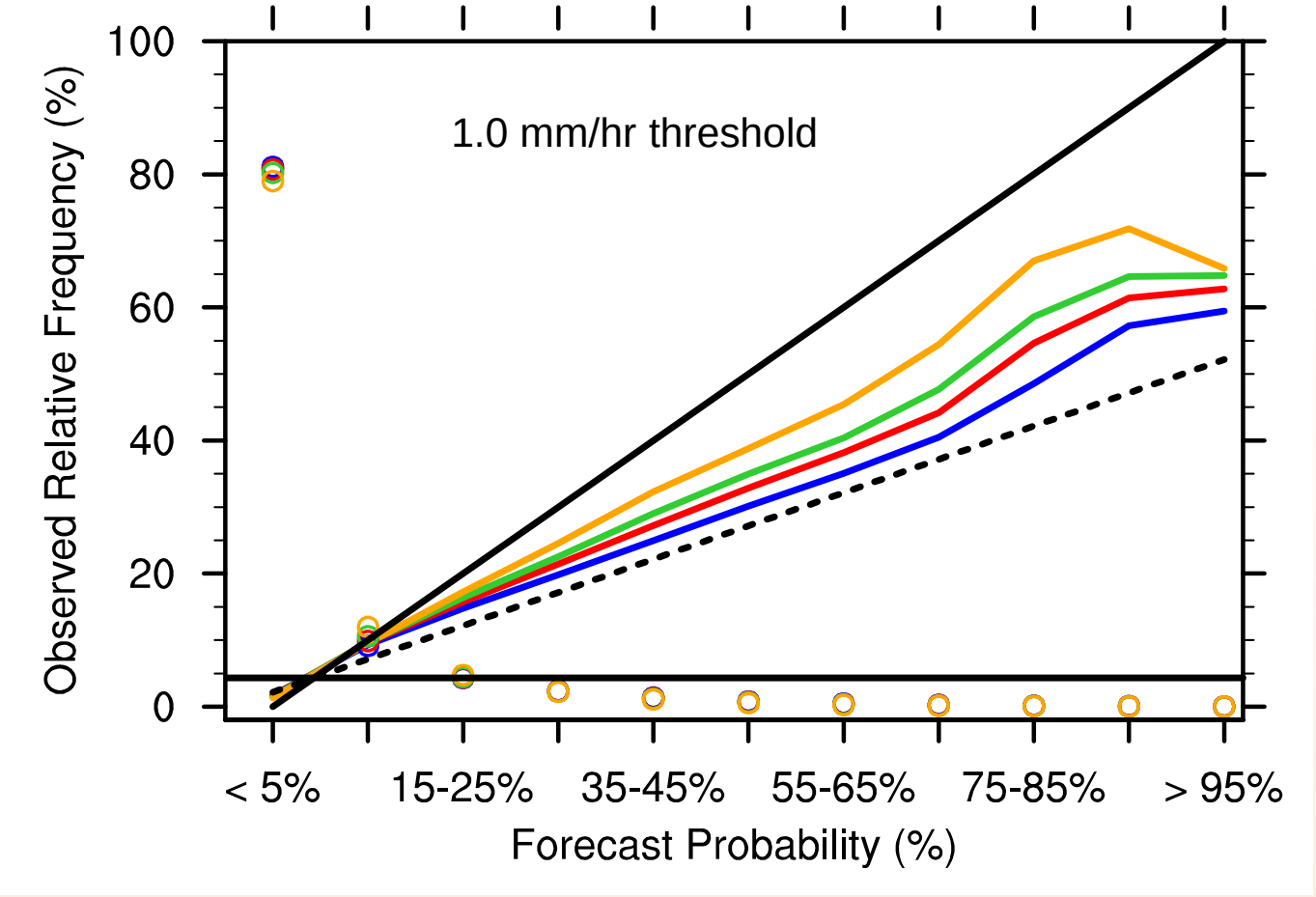
General precipitation placement

- Average 12-36-hr ensemble mean precipitation between April 7 and July 5, 2015



NCAR ensemble calibration

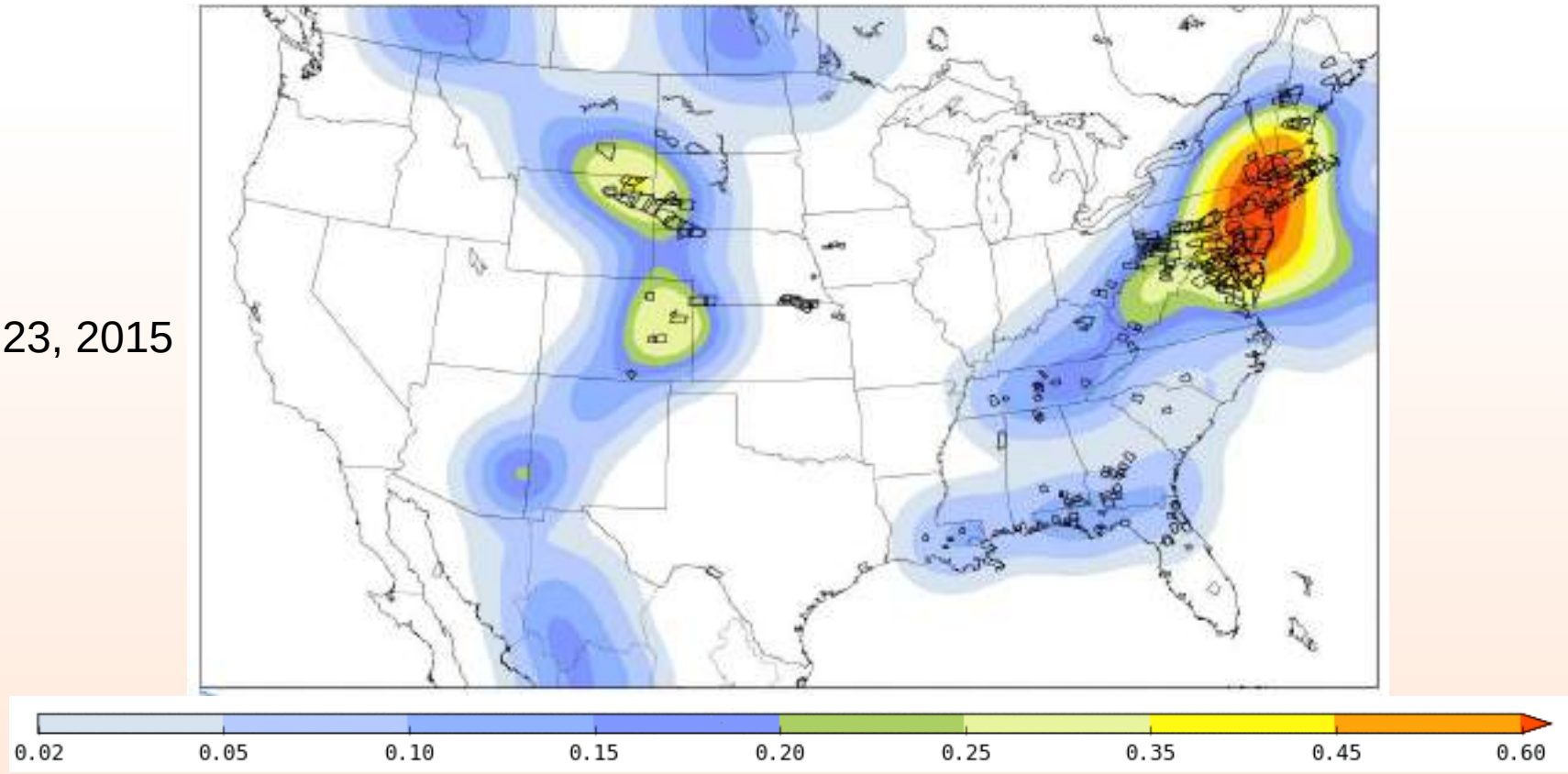
- Attributes diagrams for 18-36-hr precipitation over ~90 forecasts



Severe weather guidance

- Smoothed probabilities of the *union* of hail > 1 inch, wind exceeding 25 m/s, and intense mid-level rotation within 25 miles of a point within a 24-hr period

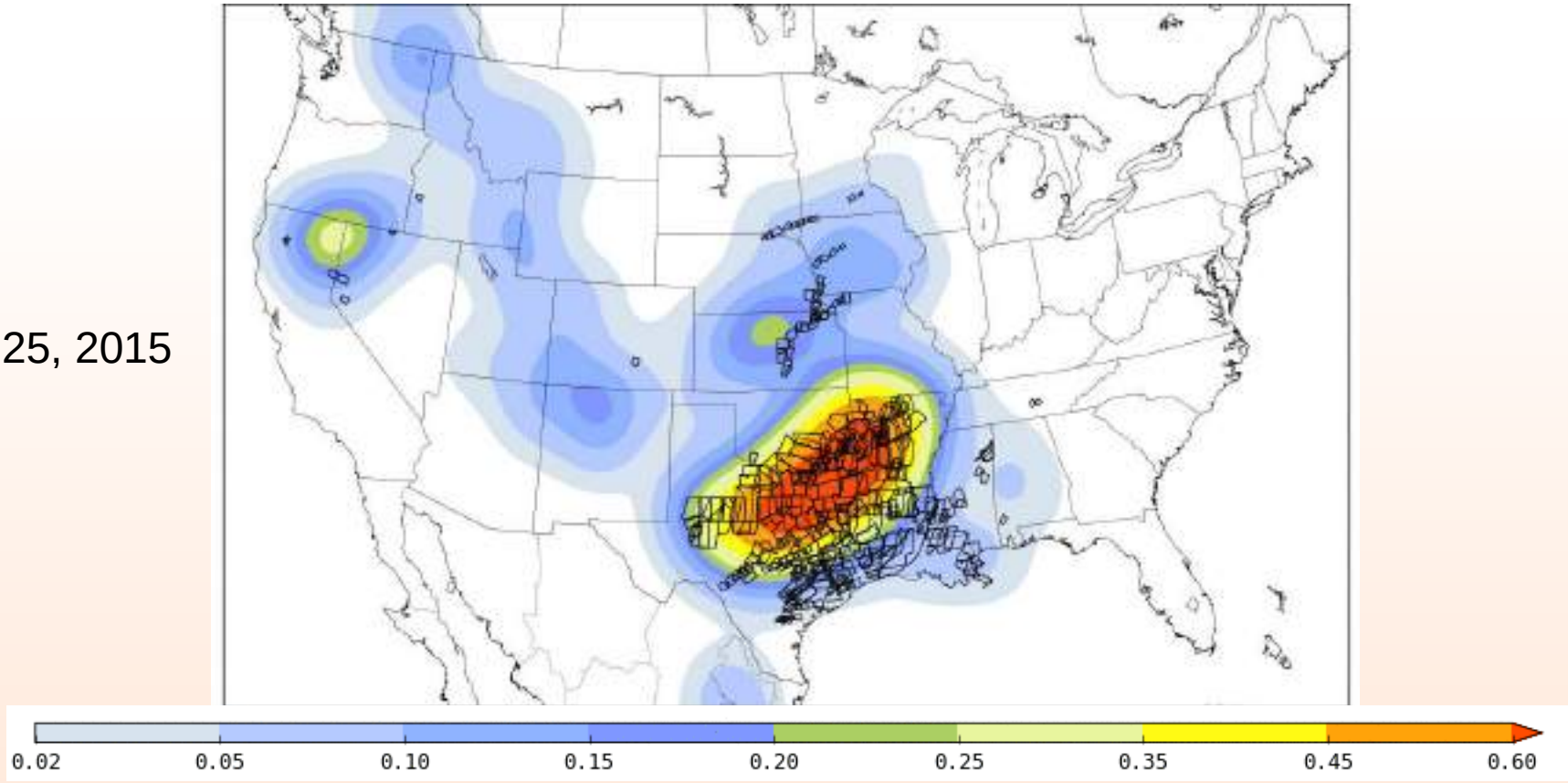
June 23, 2015



Severe weather guidance

- Smoothed probabilities of the *union* of hail > 1 inch, wind exceeding 25 m/s, and intense mid-level rotation within 25 miles of a point within a 24-hr period

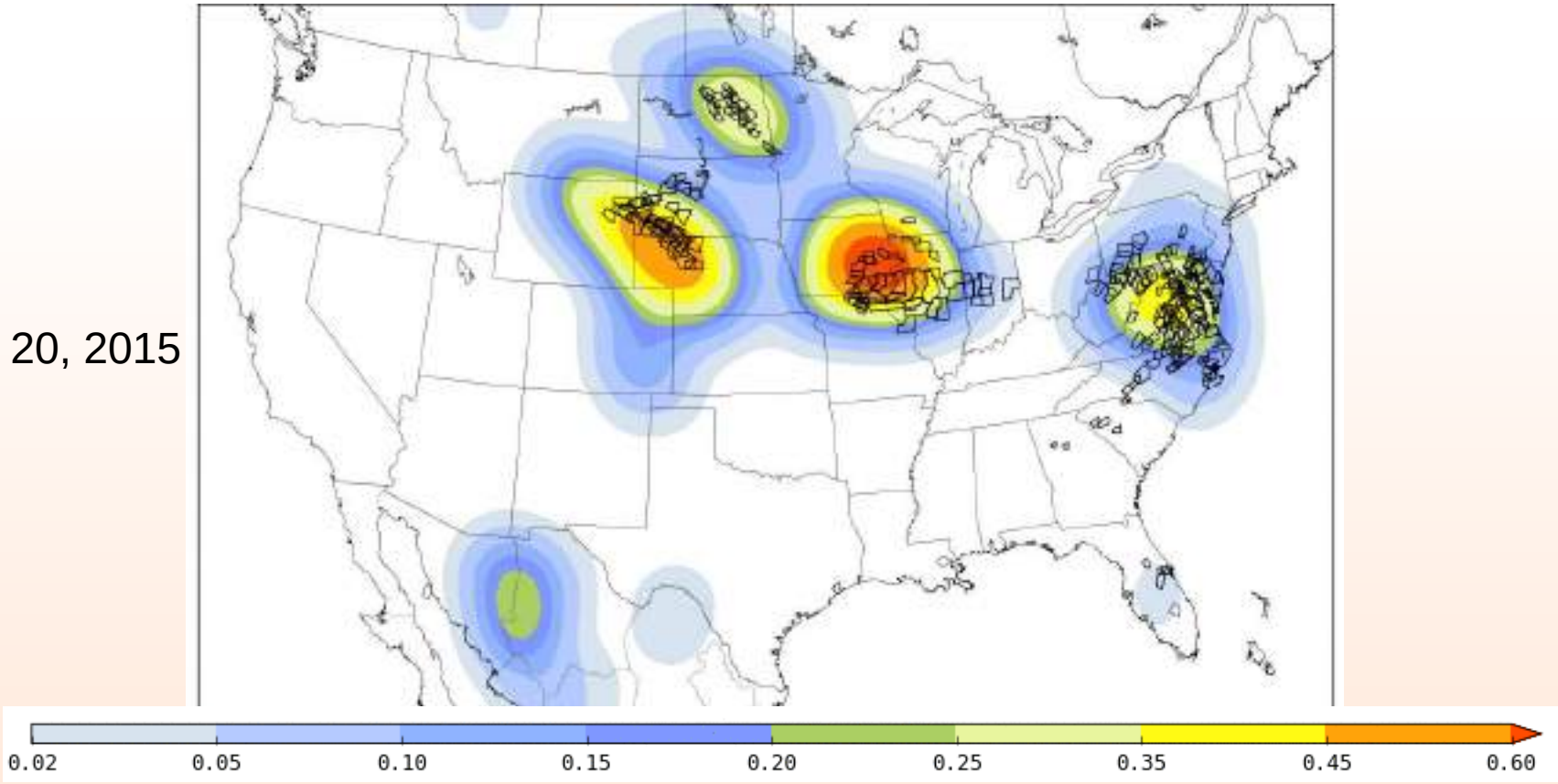
May 25, 2015



Severe weather guidance

- Smoothed probabilities of the *union* of hail > 1 inch, wind exceeding 25 m/s, and intense mid-level rotation within 25 miles of a point within a 24-hr period

June 20, 2015



Closing thoughts

- High-resolution ensembles are the future
- Development at operational centers worldwide
- Challenges
  - Optimal ensemble design?
  - How to get well-calibrated forecasts?
  - How to best use the ensemble output?
  - How many members are necessary?
- Expect much effort on these topics in upcoming years