Ensemble forecast system design for high-impact weather prediction applications

Glen Romine
NCAR MMM/IMAGe

Acknowledgements:
NCAR ensemble team: + Craig Schwartz, Ryan Sobash, and Kate Fossell

ICAS 2017 : 9/12/2017

Support: NCAR's MMML and CISL; NCAR Short term explicit prediction program, NOAA: NA15OAR4590191, NA17OAR4590114
Collaborators/contributors: Ryan Torn, Morris Weisman, Dave Ahijevych, Davide Del Vento

Focus is on deep moist convection hazards

e.g., the system design in this talk is geared toward next-day prediction of severe weather hazards (tornadoes, large hail, damaging local winds, and flash flooding), though it can have utility for other weather hazards

Definition + motivation

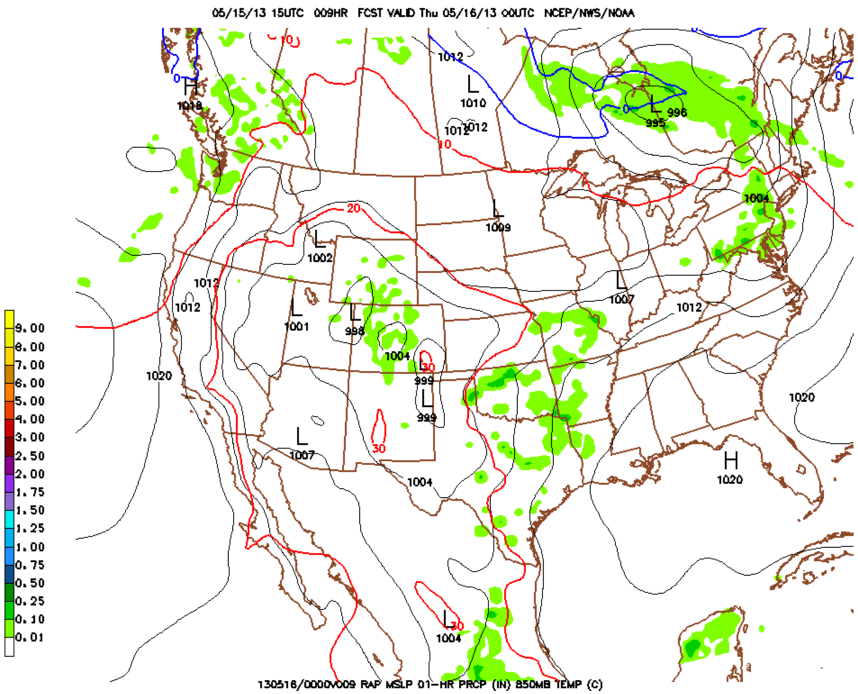
CAM – convection-allowing model

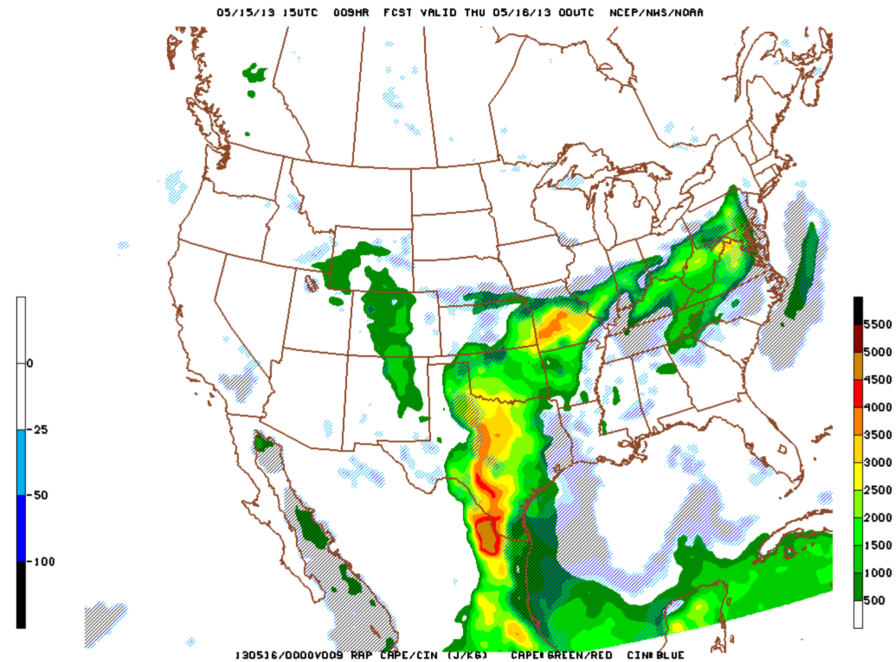
- Model forecast with horizontal spacing between adjacent grid boxes of 3-4 km or less
- Capable of ‘resolving’ individual thunderstorms
- a.k.a. convection-permitting

Why we might want a CAM forecast

- Convective organization informs on primary threats
- A more realistic propagation of weather systems (non-hydrostatic regime)
- **Seeking better guidance on high impact weather hazards**
- Want an ensemble for a probability estimate of threats

Mesoscale model output for convective forecasting





16 May 2013 – 9 h RAP forecast

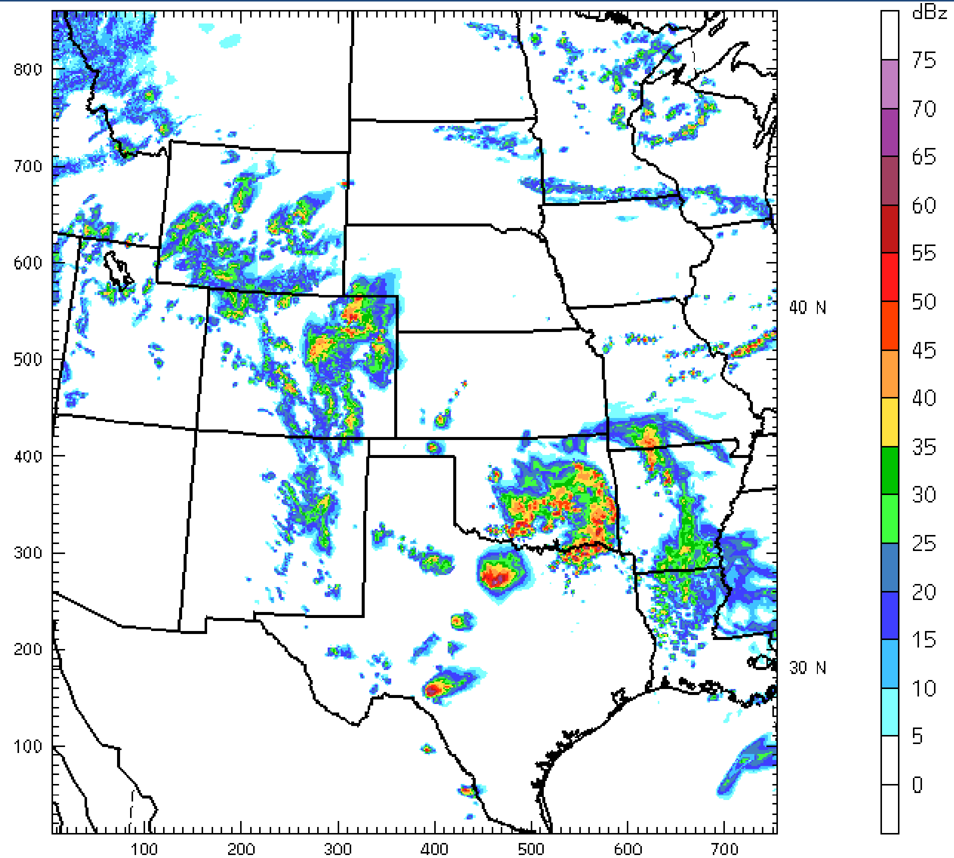
e.g., Stensrud et al. 1997; Ingredients based forecasting of severe storms from mesoscale model output; Co-location of shear, instability and triggered precipitation in a mesoscale model

Benefit – low computational cost

CON – coarse representation of convective events

CAM guidance for convective forecasting

16 May 2013 – 12 h WRF forecast from GFS analysis



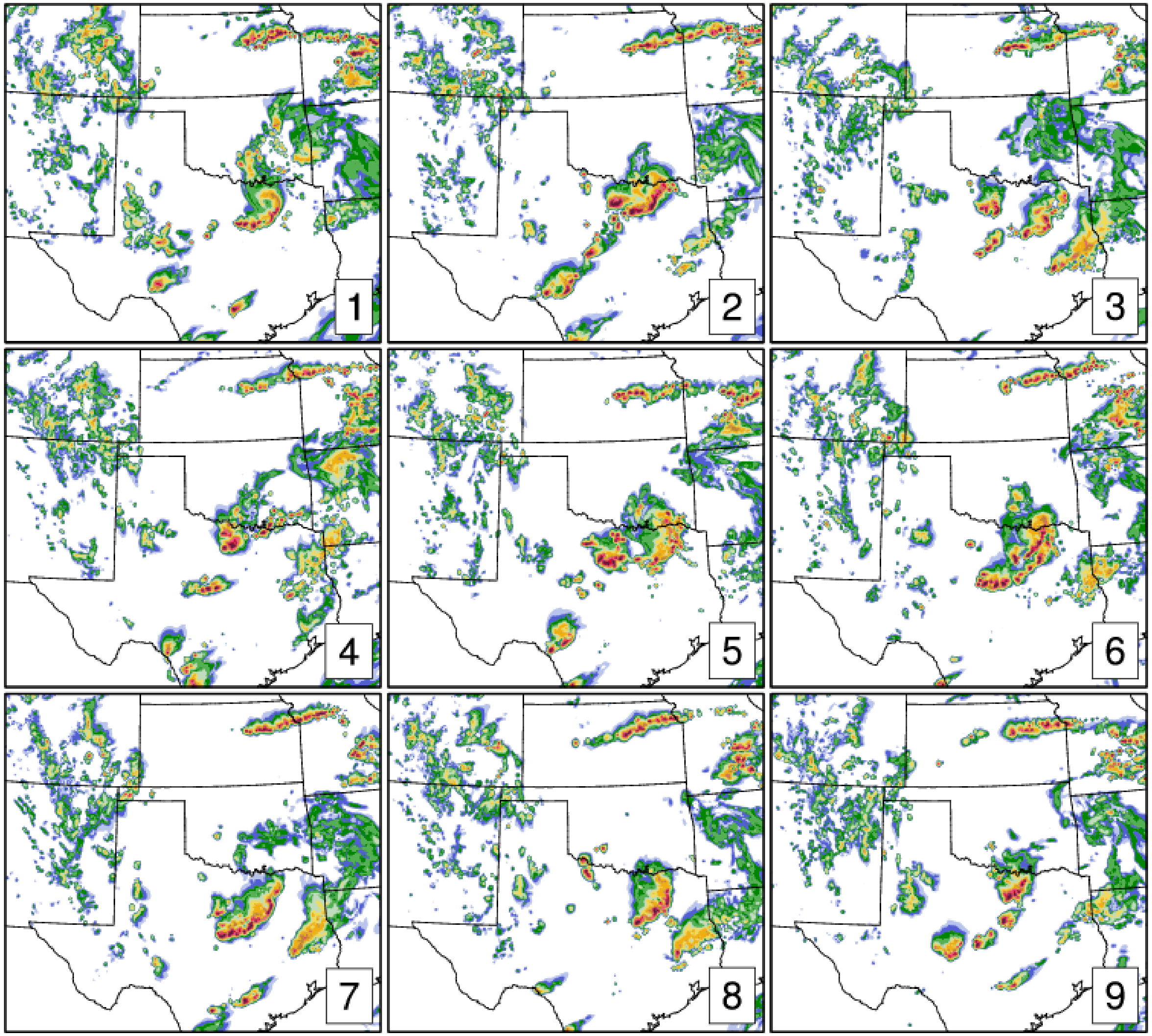
"A shuffling zombie…"
Tom Hammill regarding guidance from deterministic forecasts

Simulated reflectivity – instantaneous precipitation rate, similar to observed weather radar product

Benefit – explicit representation of convection, easy interpretation of forecast mode (e.g., cells, lines, intensity)
CON – more resources, only one representation of event

CAM ensemble guidance for convective forecasting

16 May 2013 – 12 h WRF forecast from ensemble EnKF analysis

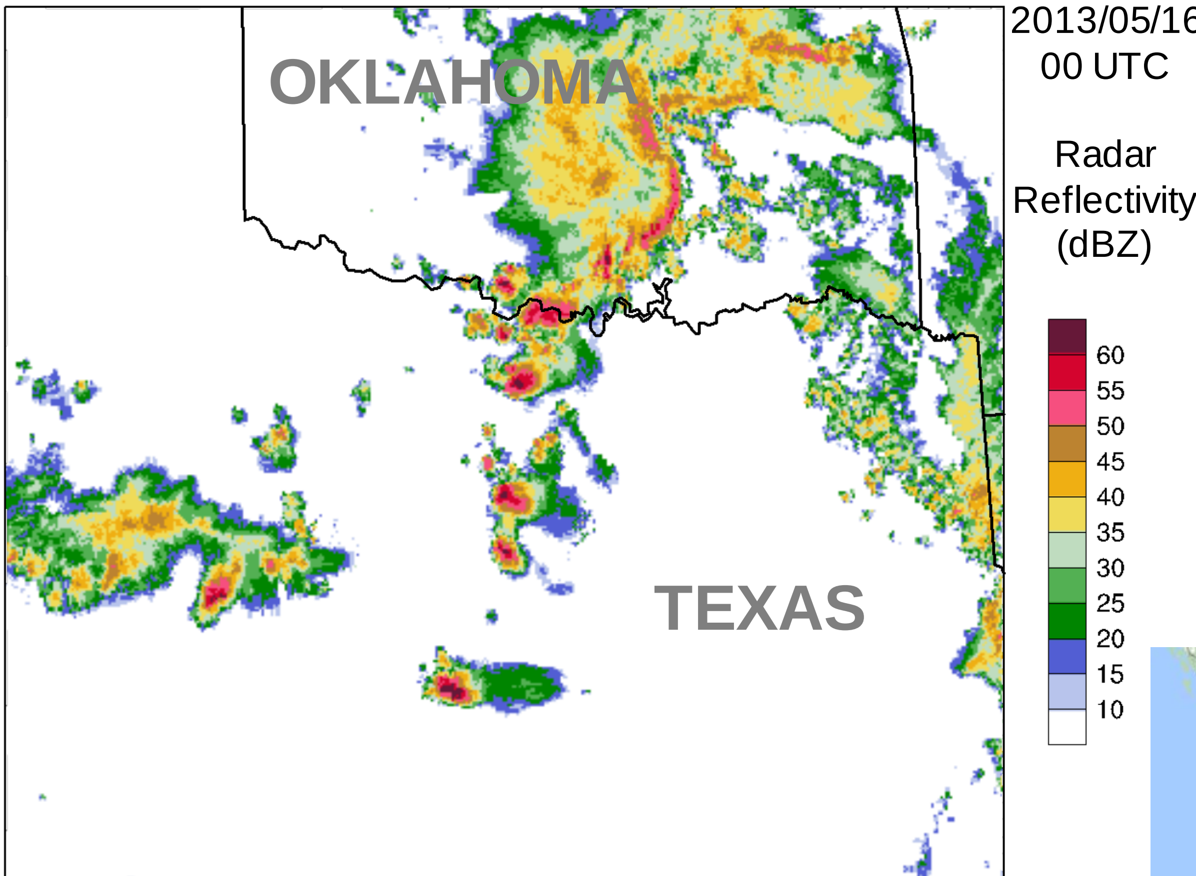


Benefit – information on the likelihood of convective mode and uncertainty in timing, location and intensity

CON – more computing, difficult to look at every solution

CAM ensemble probabilistic guidance

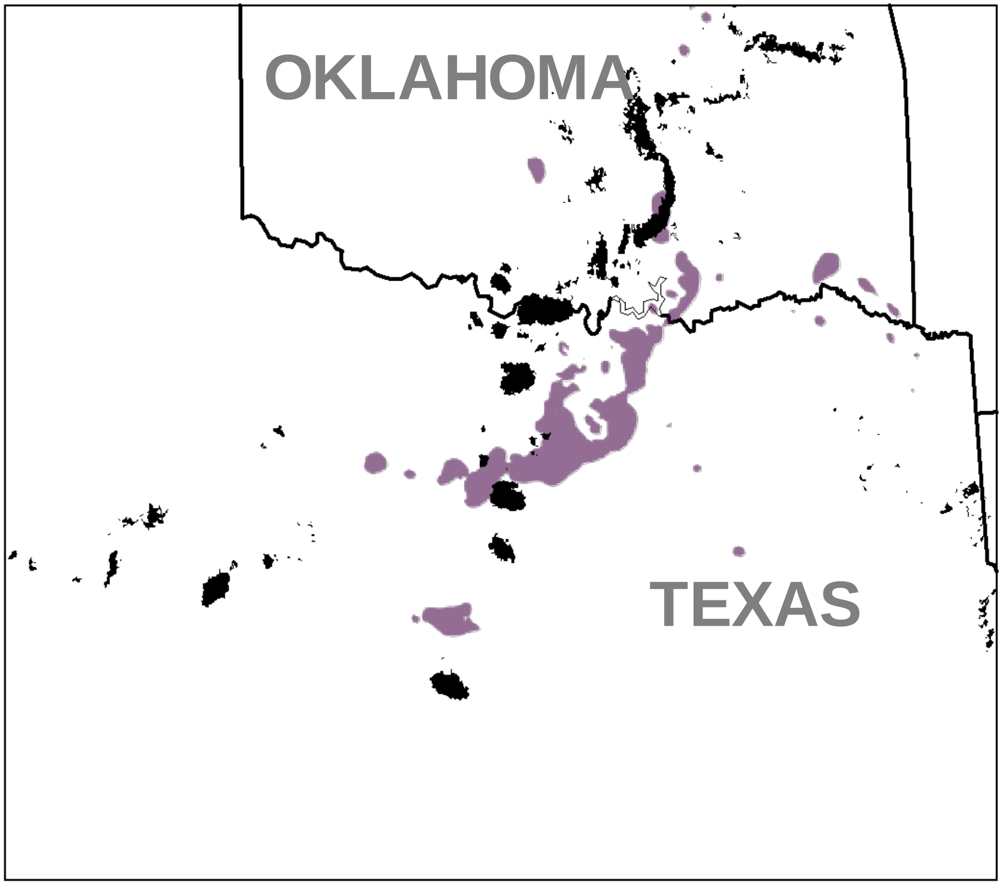
Actual weather radar observations (merged)



CAM ensemble probabilistic guidance

Observed Reflectivity
> 45 dBZ only
(black fill)

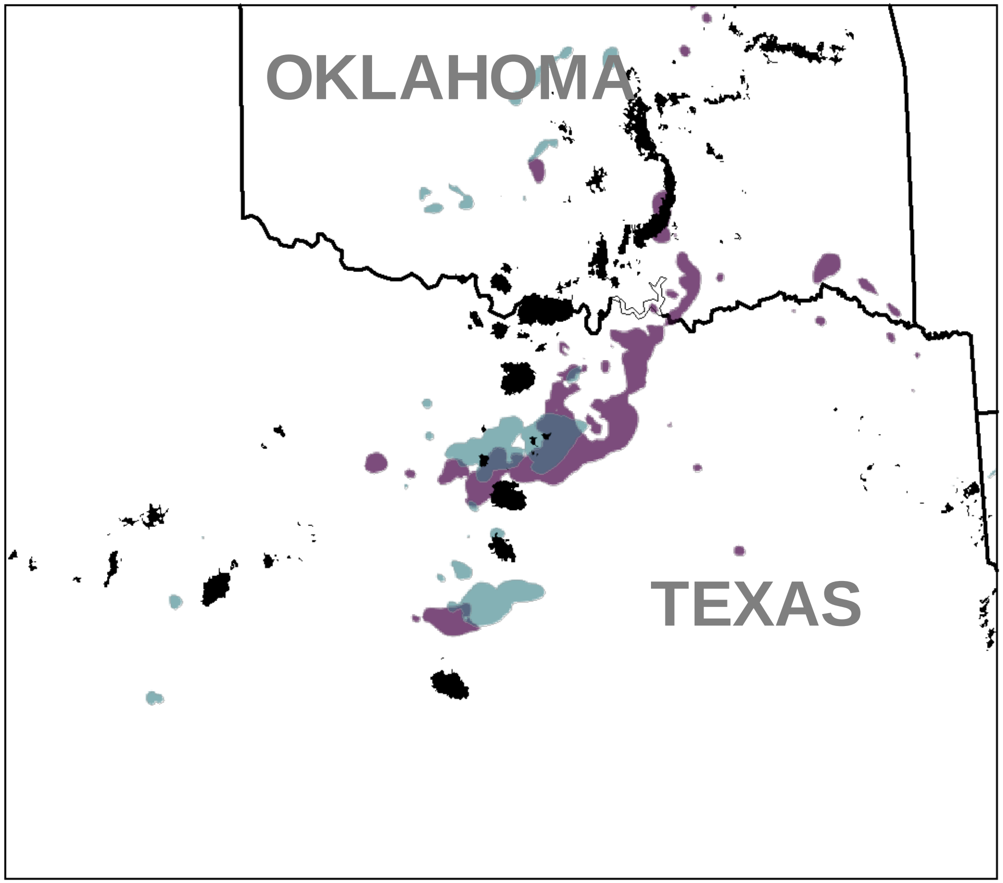
CAM ensemble probabilistic guidance



Observed Reflectivity
> 45 dBZ only
(black fill)

Ensemble member
9-hr forecast
simulated reflectivity
> 45 dBZ only
(1st member lavender)

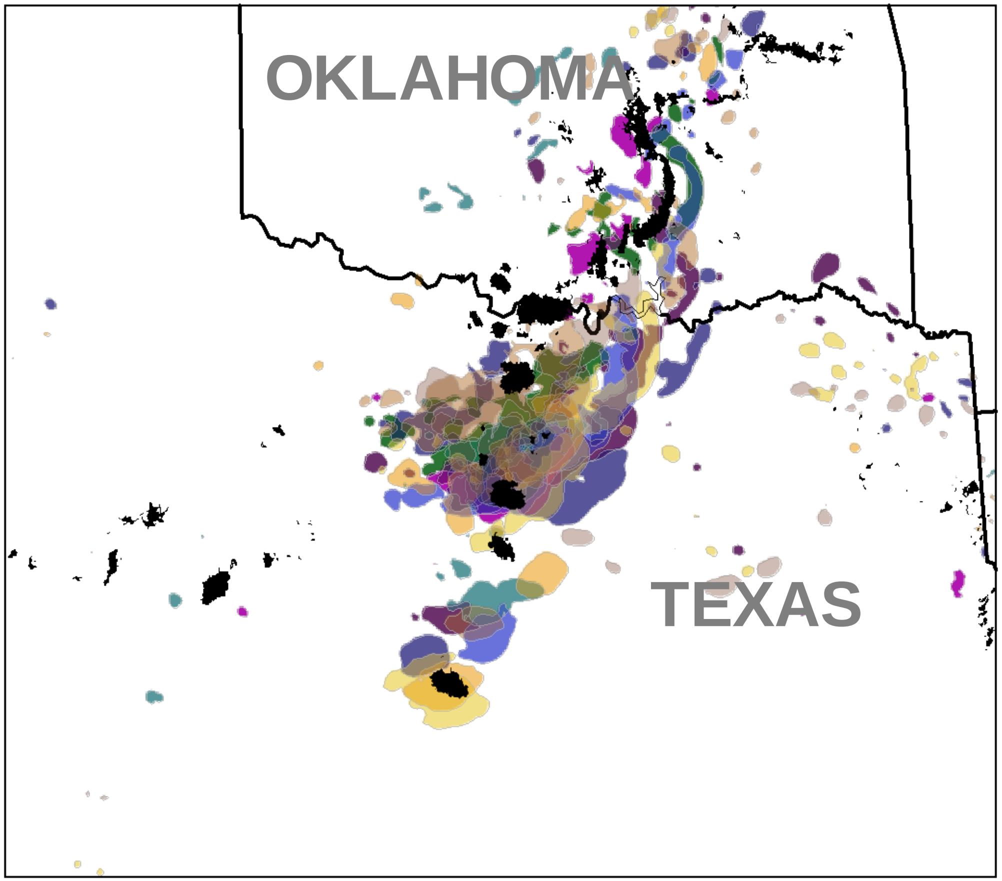
CAM ensemble probabilistic guidance



Observed Reflectivity
> 45 dBZ only
(black fill)

Ensemble member
9-hr forecast
simulated reflectivity
> 45 dBZ only
(1st member lavender)
(2nd member cyan)

CAM ensemble probabilistic guidance

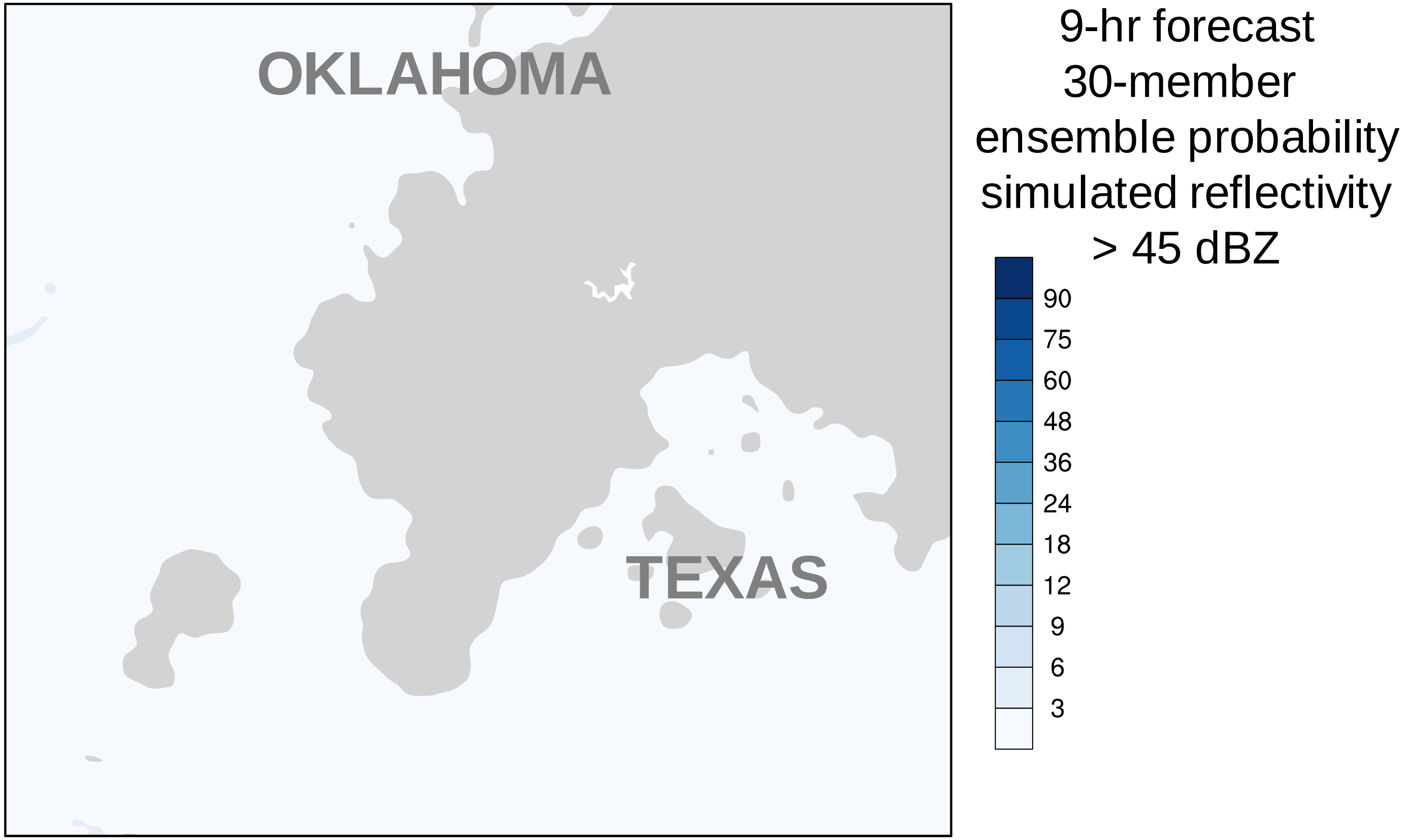


Observed Reflectivity
> 45 dBZ only
(black fill)

10 ensemble members
9-hr forecast
simulated reflectivity
> 45 dBZ only
(color fills)

1 2 3 4 5 6 7 8 9 10 OBS

CAM ensemble probabilistic guidance



Caveat: We cannot verify probabilities (events are binary), only the statistical reliability, so need to consider a large number of events

CAM products for prediction of severe convection

Examples:

Reflectivity – familiar to radar depictions of severe weather

Accumulated precipitation – direct analog to observed event (e.g. flash flooding)

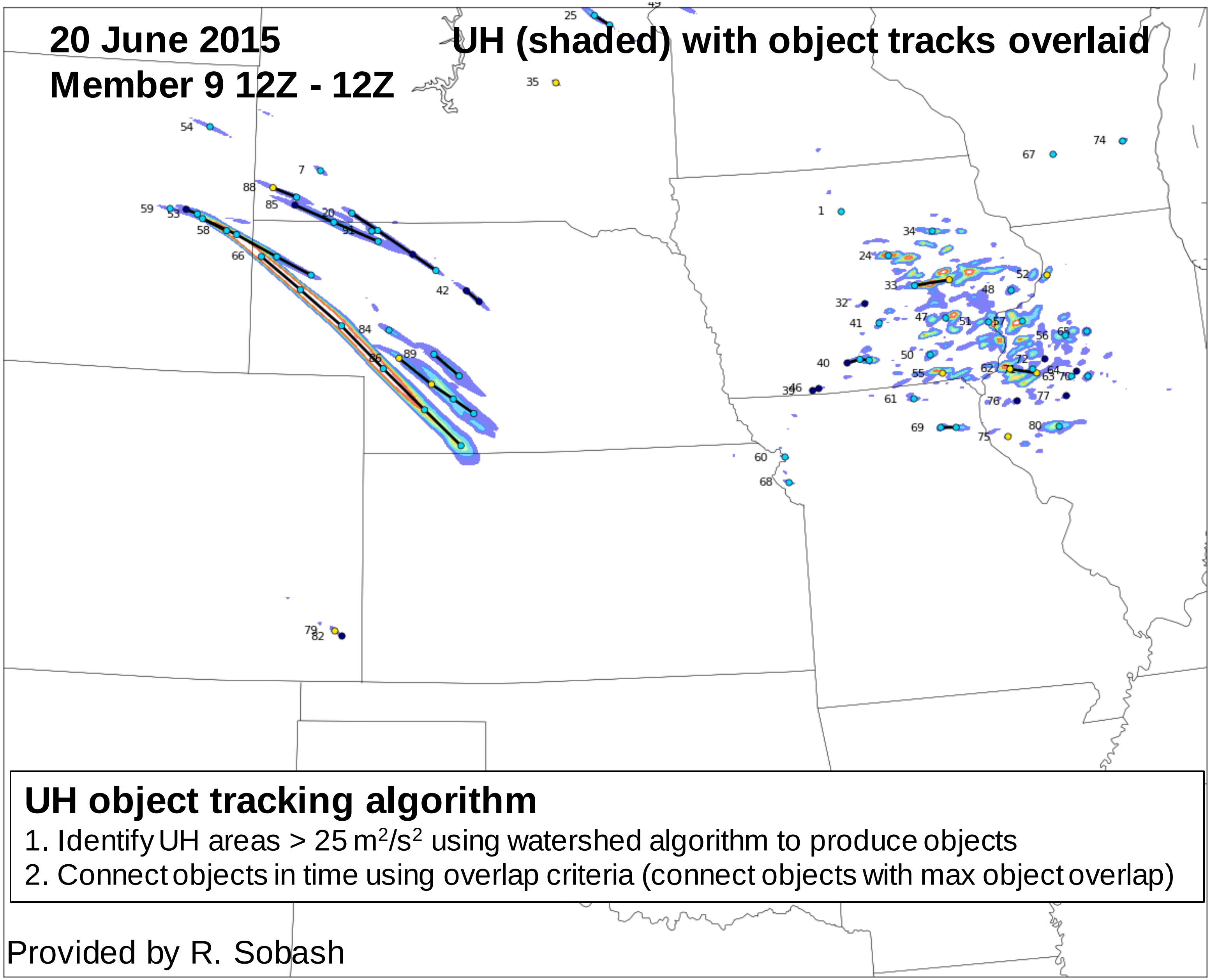
Example storm surrogates – derived information from convective objects in model simulations:

- updraft speed
- maximum hail size estimates
- lightning flash rate
- **updraft helicity – indicates rotating convective storms**
- maximum surface wind speeds
- low-level vorticity

Future: Object-based diagnostics, verification

20 June 2015
Member 9 12Z - 12Z

UH (shaded) with object tracks overlaid

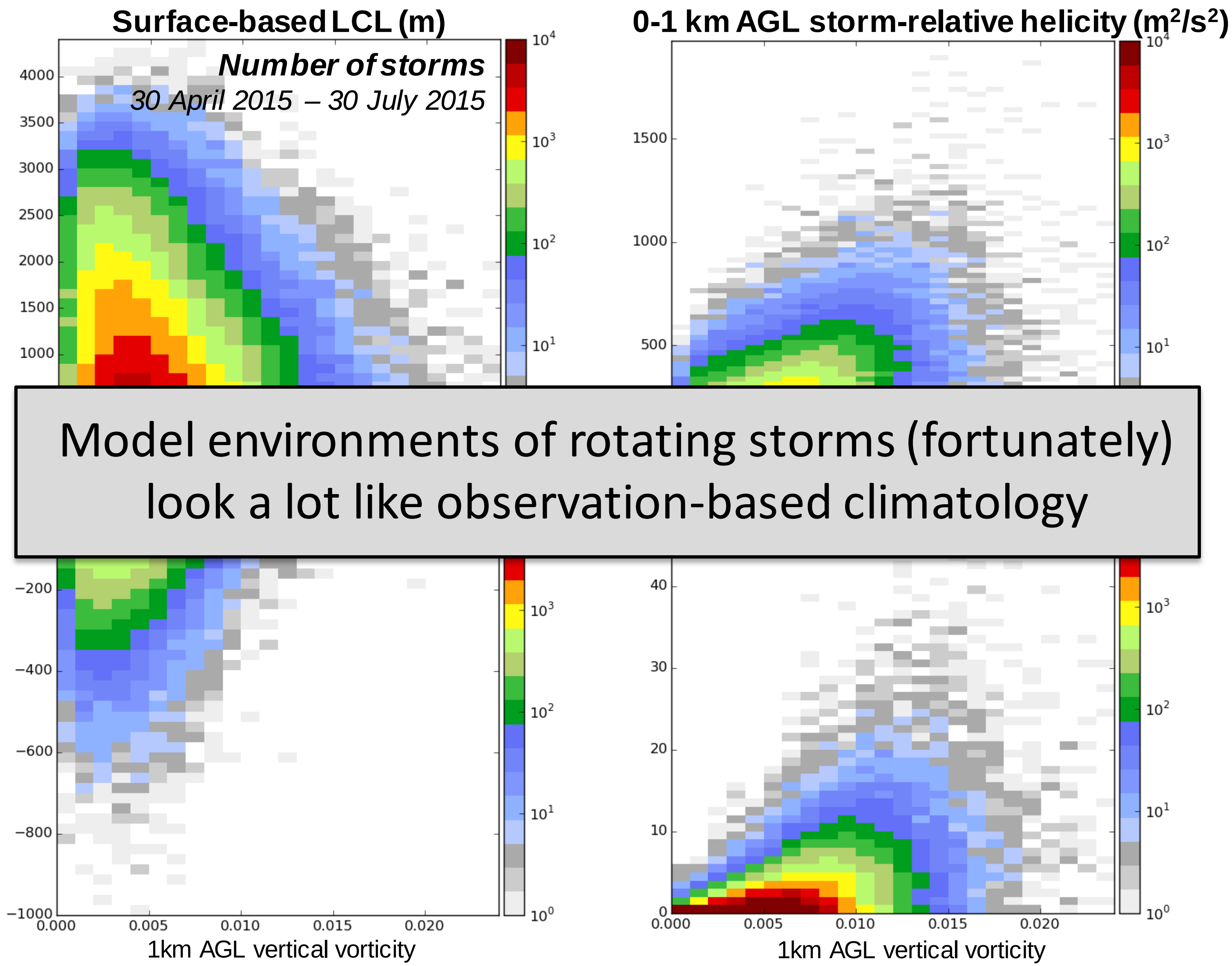


UH object tracking algorithm

1. Identify UH areas > 25 m^2/s^2 using watershed algorithm to produce objects
2. Connect objects in time using overlap criteria (connect objects with max object overlap)

Provided by R. Sobash

Future: Object-based diagnostics, verification

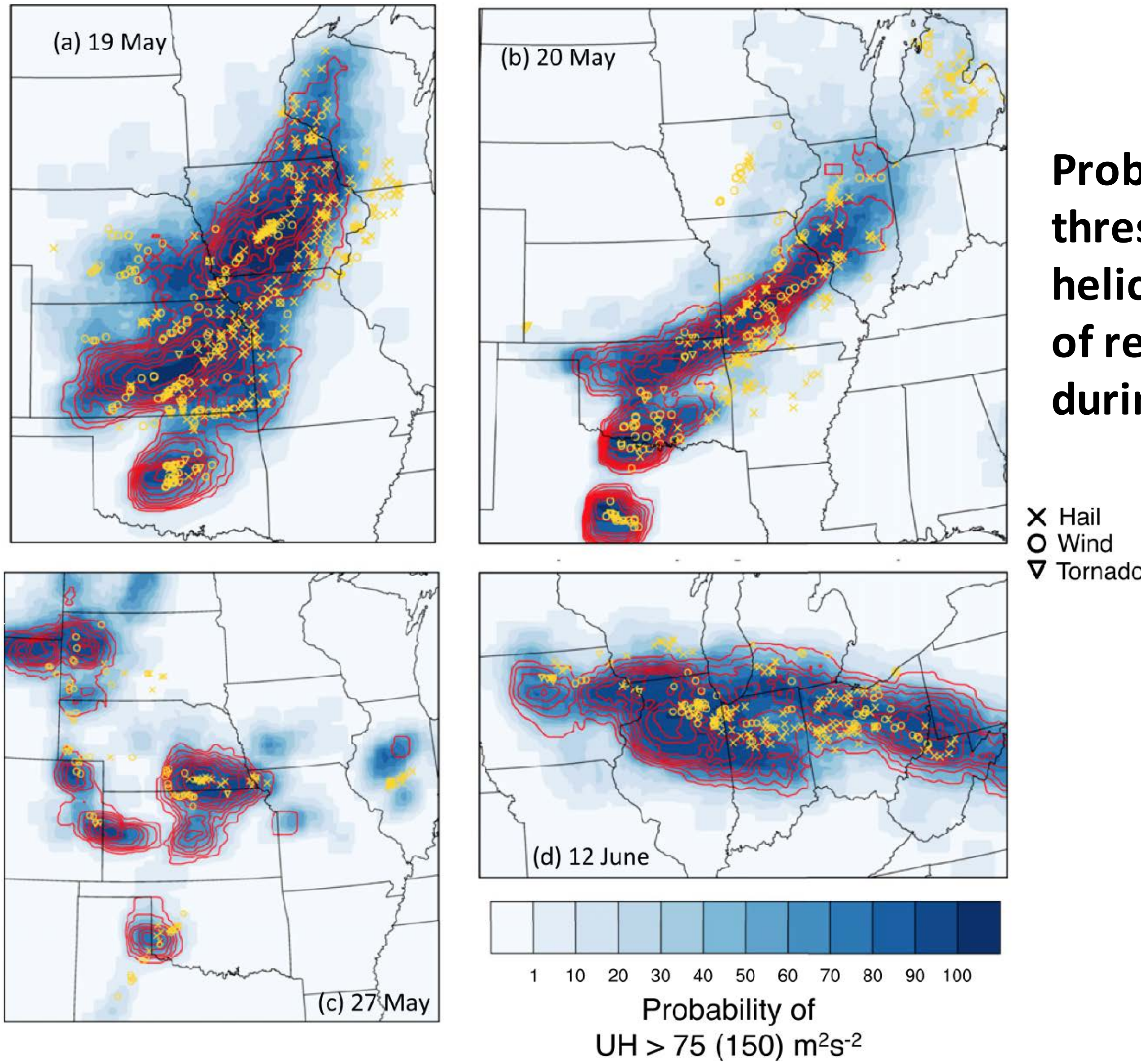


Model environments of rotating storms (fortunately) look a lot like observation-based climatology

Provided by R. Sobash

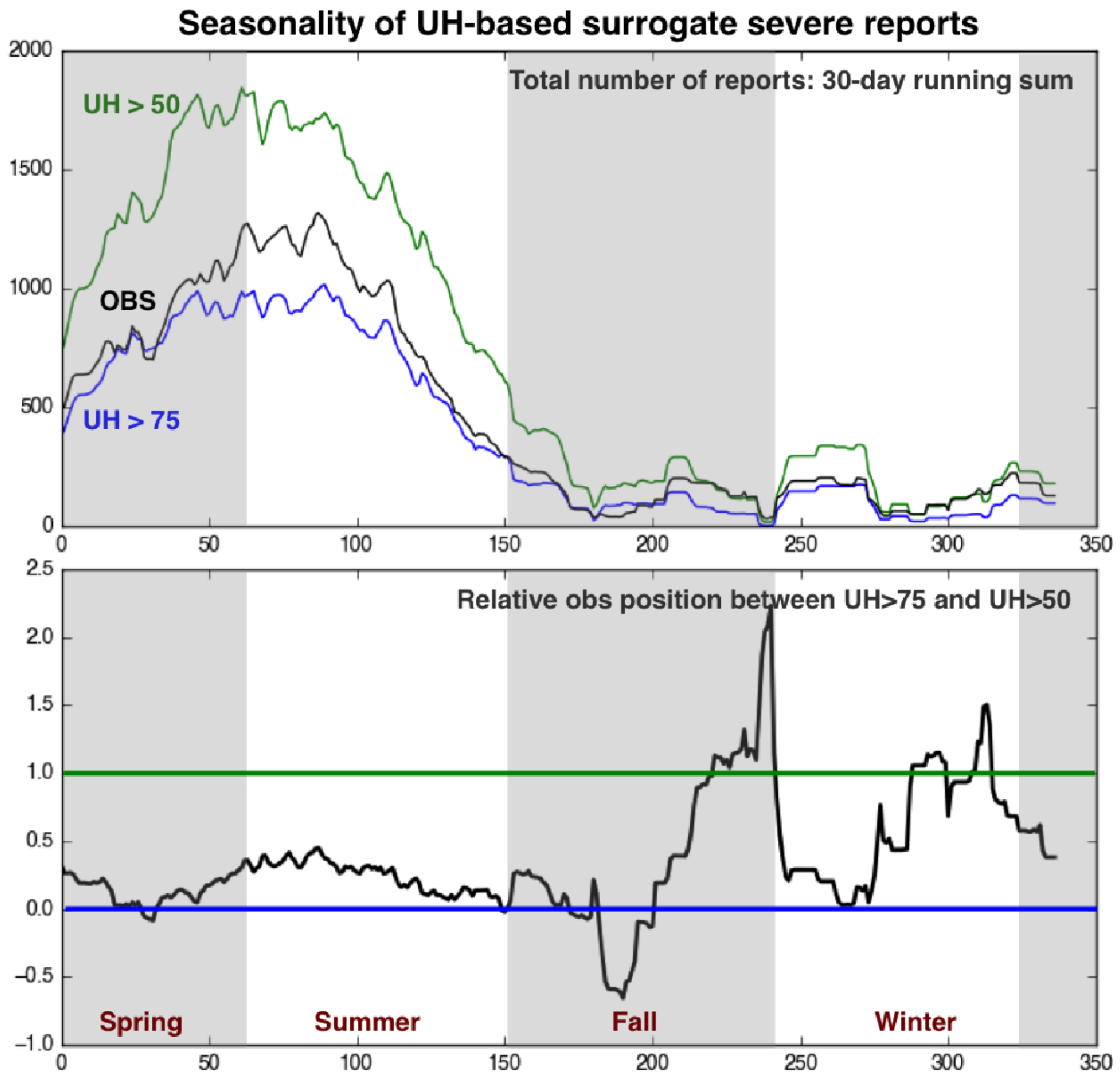
Low-level rotation potential surrogate for tornado prediction

Skill threshold of surrogates varies with time….



Probabilities with a fixed threshold of updraft helicity is a useful predictor of reports of severe weather during <u>springtime</u>

Skill threshold of surrogates varies with time….



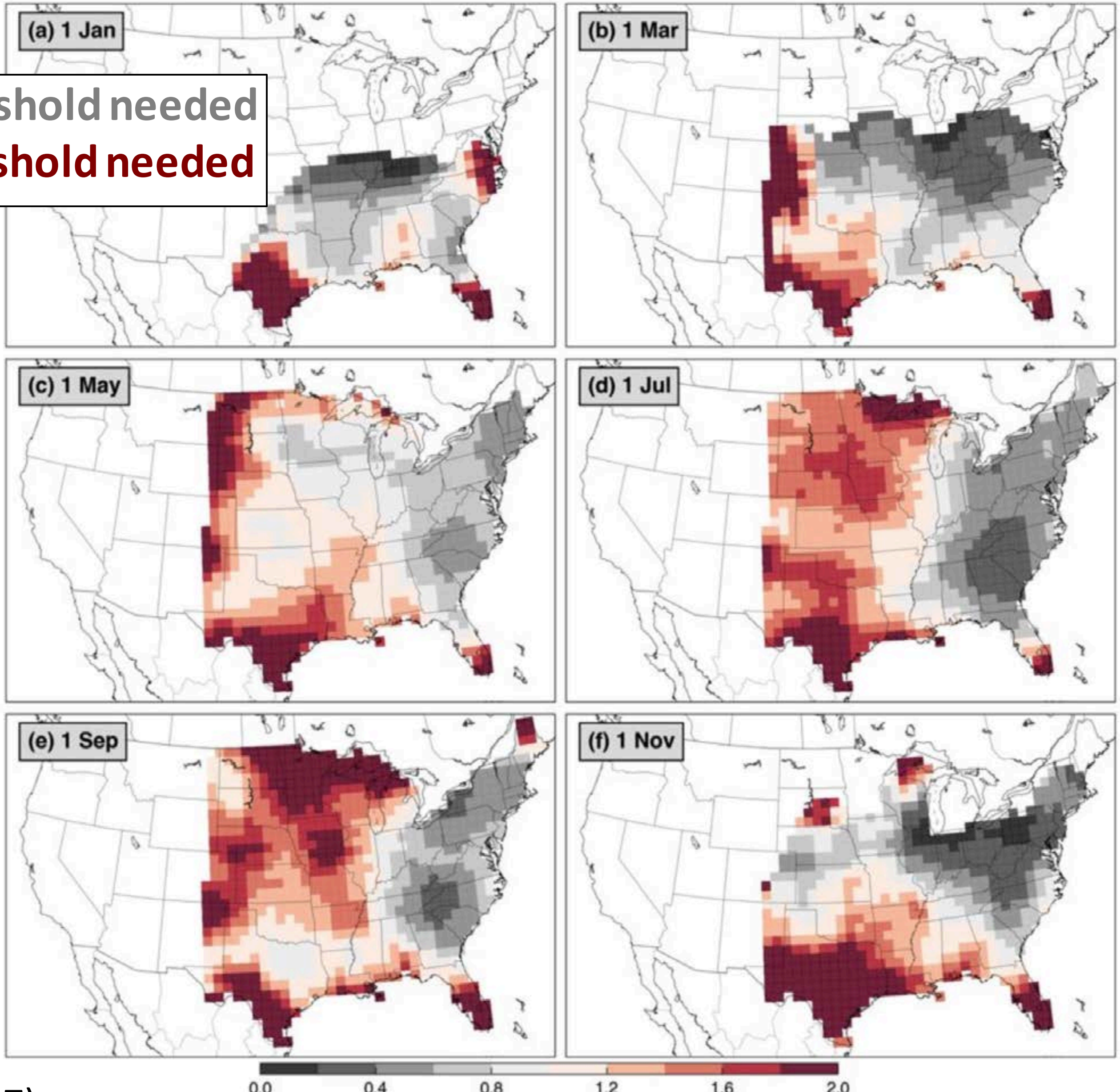
A **lower** threshold would be more skillful during the Fall and winter months

varies in time …. as well as in space

Gray – lower threshold needed
Red – higher threshold needed

Bias from climatological skilled updraft helicity threshold

Caveat – includes regional reporting bias in storm reports



Sobash and Kain (2017)

NCAR's real-time ensemble forecast system

Since April 2015, NCAR ENSEMBLE – http://ensemble.ucar.edu

PRODUCT EXAMPLES

Ensemble mean: average forecast state from all ensemble members
- smooth, 'best forecast'

Probability matched mean: remapping of ensemble mean
- improved magnitudes over ensemble mean, may be unrepresentative

Ensemble spread: variability metric among the member forecasts
- representativeness of the ensemble mean

Ensemble max/min: shows the extreme values at a given location
- quick look for high impact events, little information on likelihood

Paintball (spaghetti) plot: Gives location and structure information
- overlap indicates qualitative agreement, single threshold shown

Postage stamp: small plots with full contour range for each forecast member
- insight on member scenarios

Probability threshold: raw likelihood from ensemble of event occurrence
- summary of ensemble information at a given point, limited skill on grid scale

Neighborhood probability threshold: relaxes event occurrence to local area
- better representation for extreme events

Forecasts are initialized from our own home-grown ensemble analyses

NCAR’s Data Assimilation Research Testbed (DART)

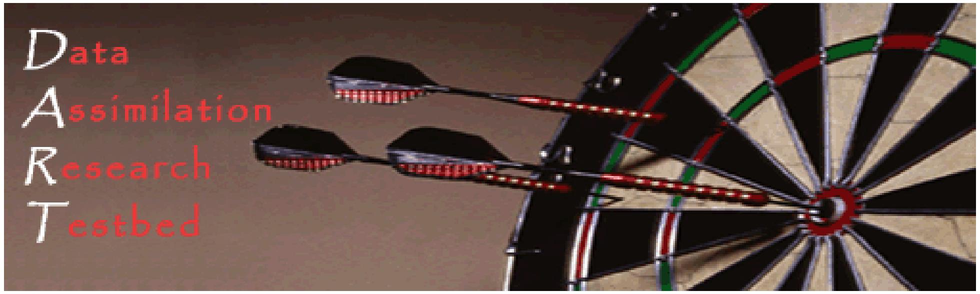
A community facility for ensemble data assimilation

DART is a software environment for exploring ensemble data assimilation (DA) methods across a wide range of models – here we use with NCAR’s Advanced Research **WRF**

DART system provides complete solution to generate <u>ensemble</u> analysis (initial conditions) consistent with forecast model

Confront the (imperfect) model with (imperfect) observations: DART provides rich diagnostics

Ensemble analysis provides a set of <u>equally likely</u> initial conditions



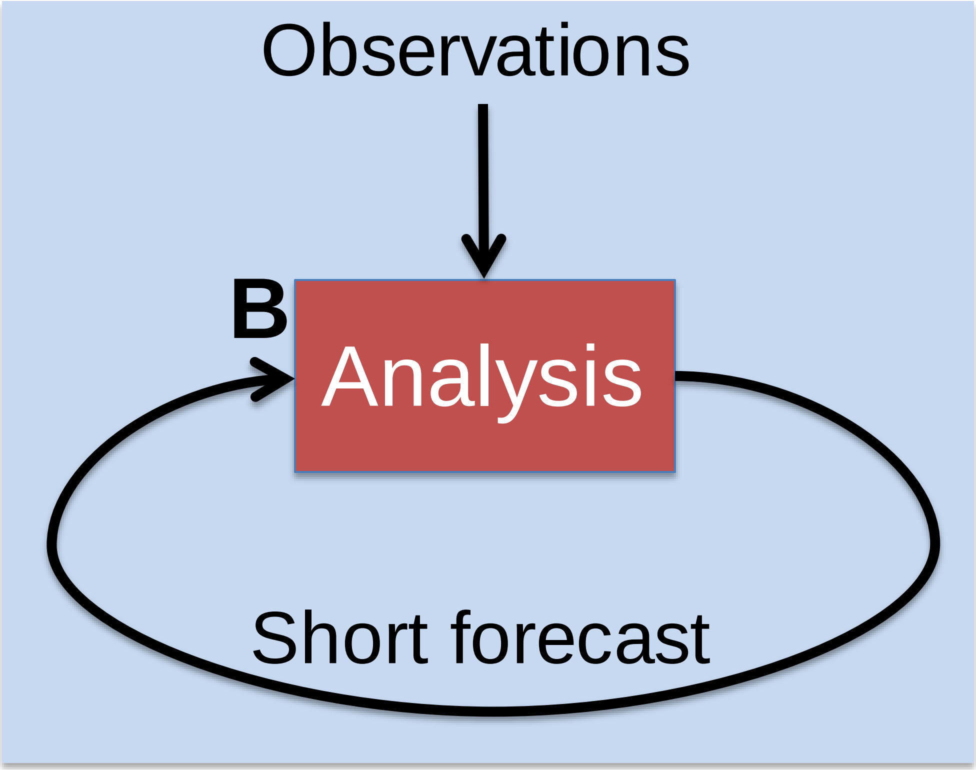
DART team: J. Anderson, N. Collins, T. Hoar, J. Hendricks, and G. Romine

DA primer: continuously cycled analysis

Continuous cycling is ‘best practice’

First guess (**B**) for analysis is short forecast from the prior analysis

No ‘spinup’ needed, on the model attractor

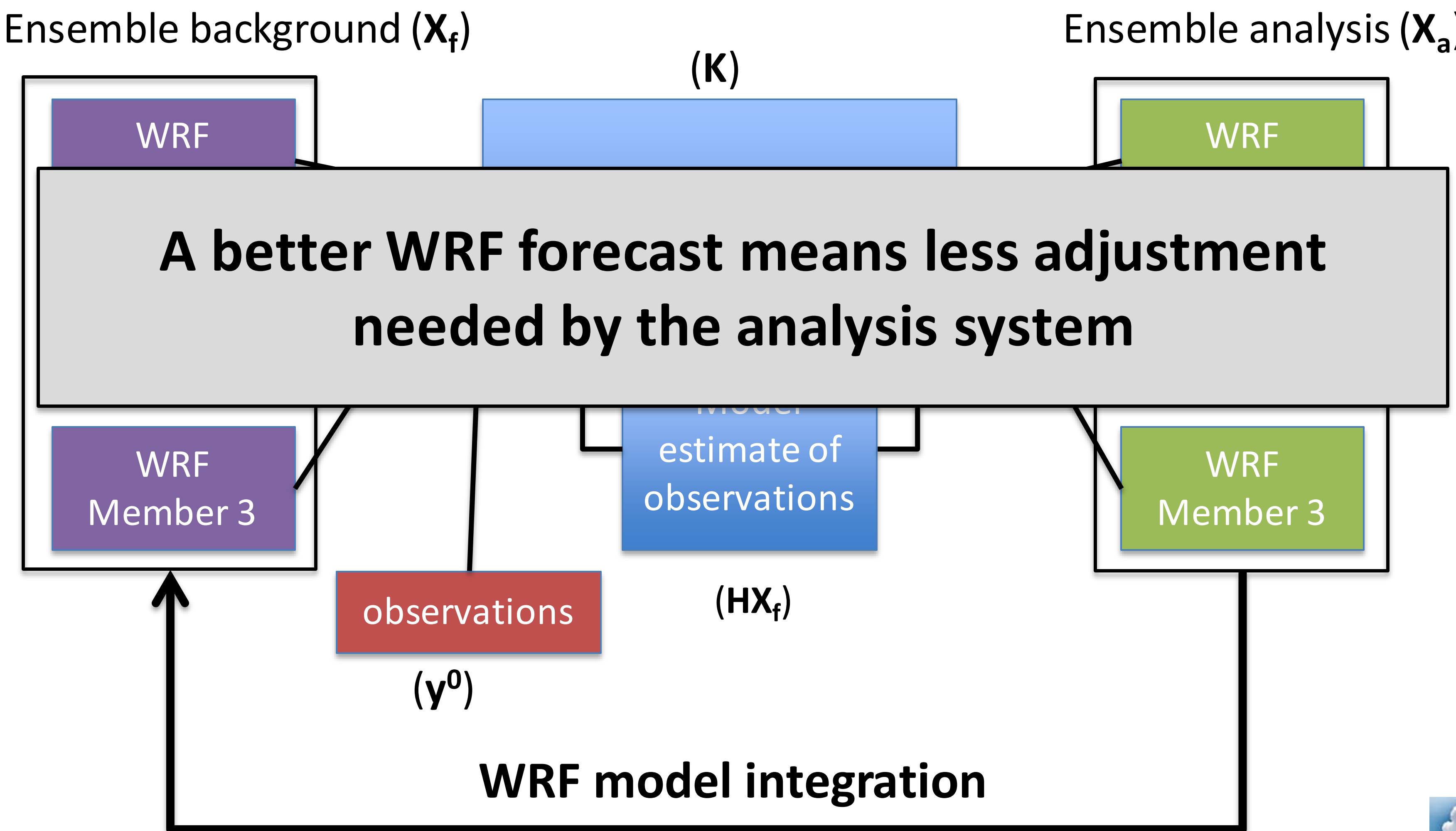


For regional models – nearly all centers use ‘partial’ cycling periodically replacing the background from another (often global) analysis

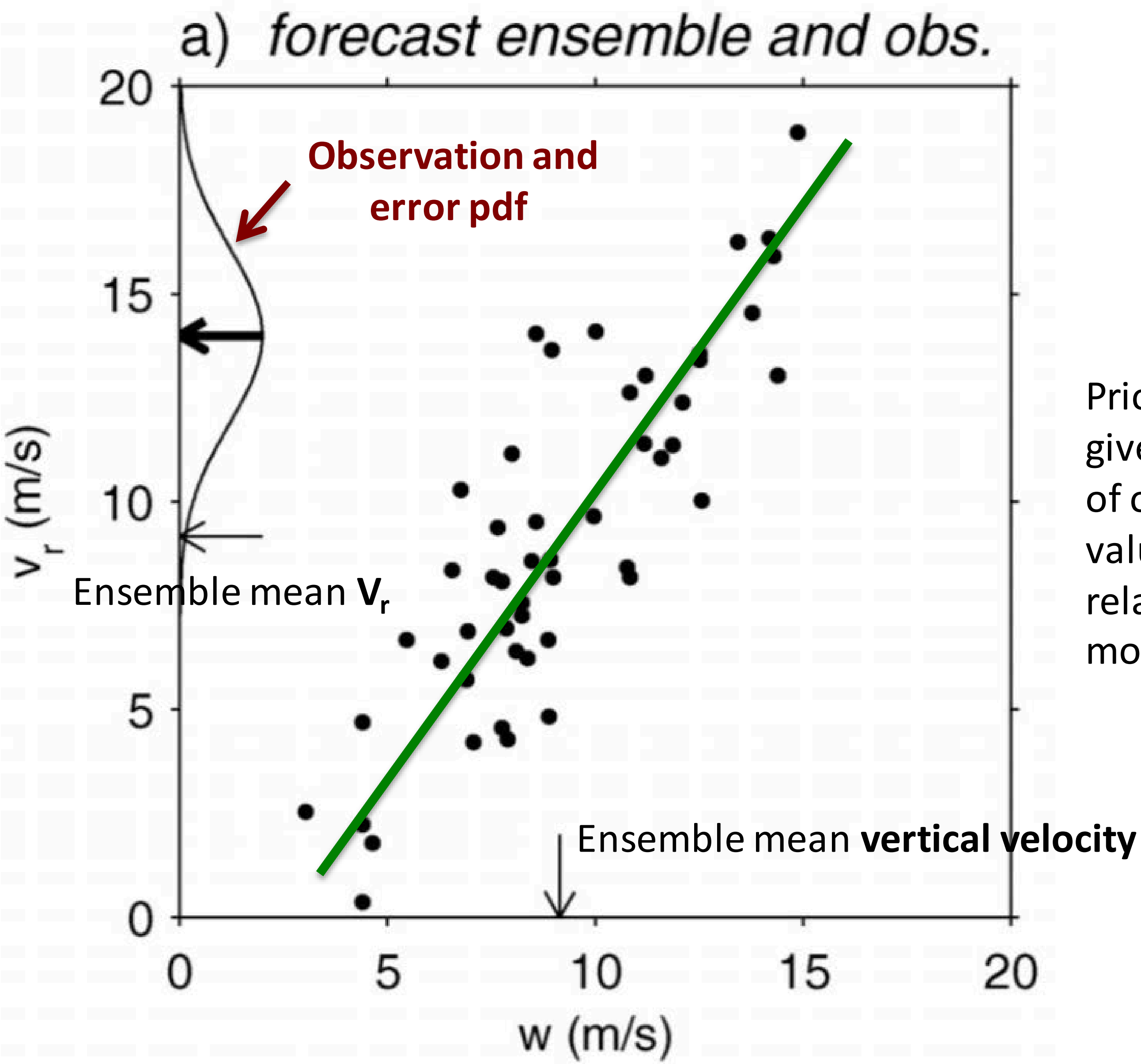
Wiring diagram of ensemble cycled analysis (DART)

Analysis = background + analysis increment (Kalman gain x innovation)

$$\mathbf{X_a = X_f + K[y^0 - HX_f]}$$



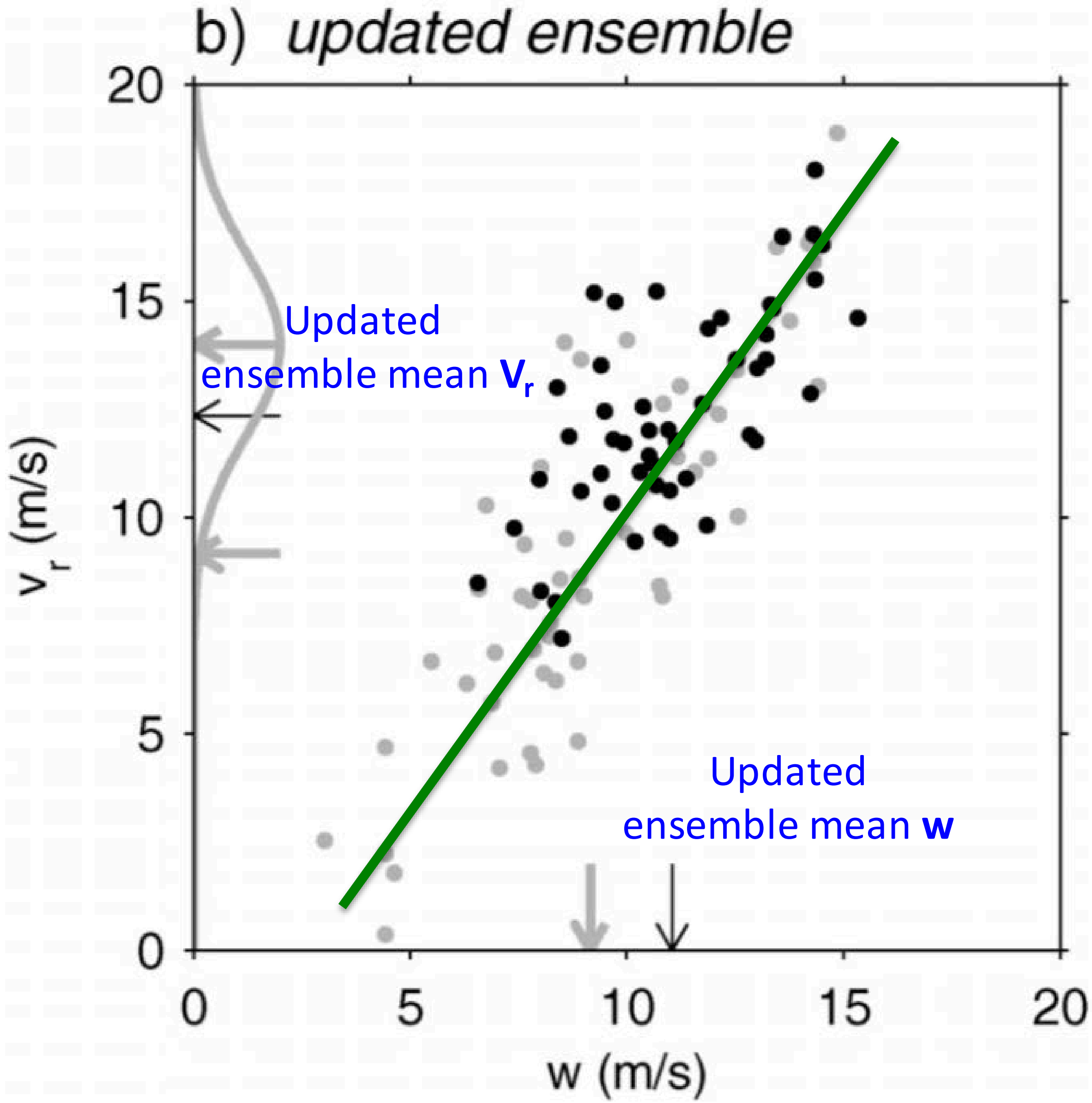
Ensemble analysis state update from an observation



Prior forecast gives first guess of observation values and the relation to the model states

Adapted from Snyder and Zhang (2003)

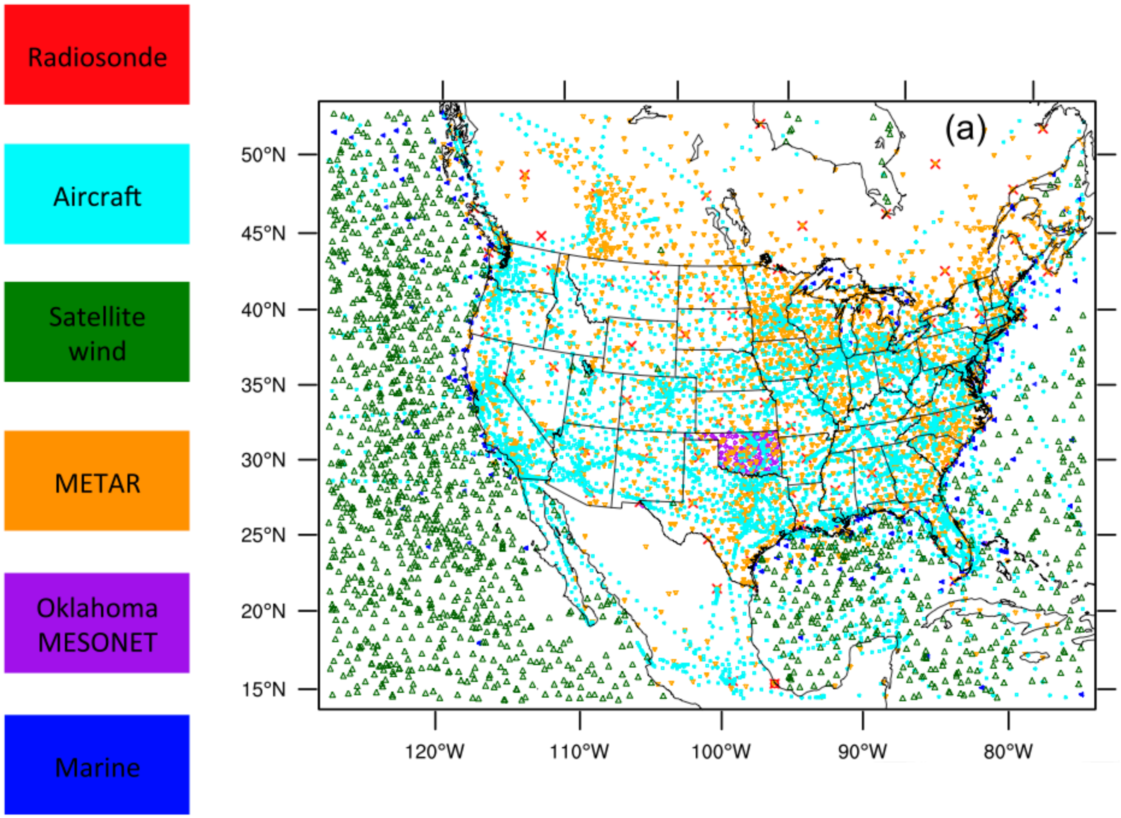
Ensemble analysis state update from an observation



Covariance used to update the analysis from the newest set of observations

New estimate has smaller variance

Assimilation of conventional observations, forecast domain



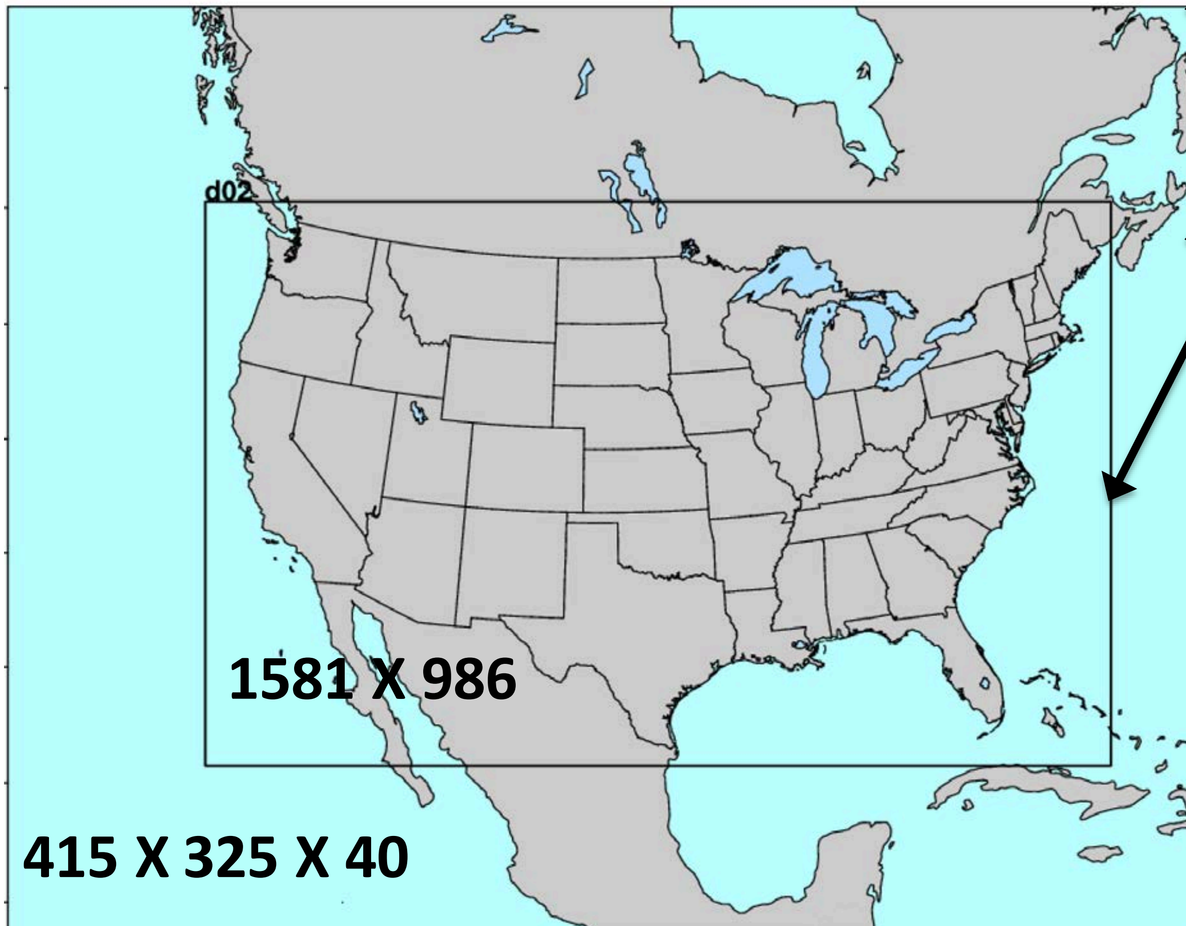
Observations come from a variety of sources, not uniformly distributed in type or time

Each observation platform can have unique bias characteristics

NCAR Ensemble: Domain area

GFS + perturbations

GFS + perturbations



GFS + perturbations

Analysis domain (80 members)

Forecast domains (10 members)

Analysis state size

14 3D variables

14 x 80 x 415 x 325 x 40 =

~ 6 B state elements

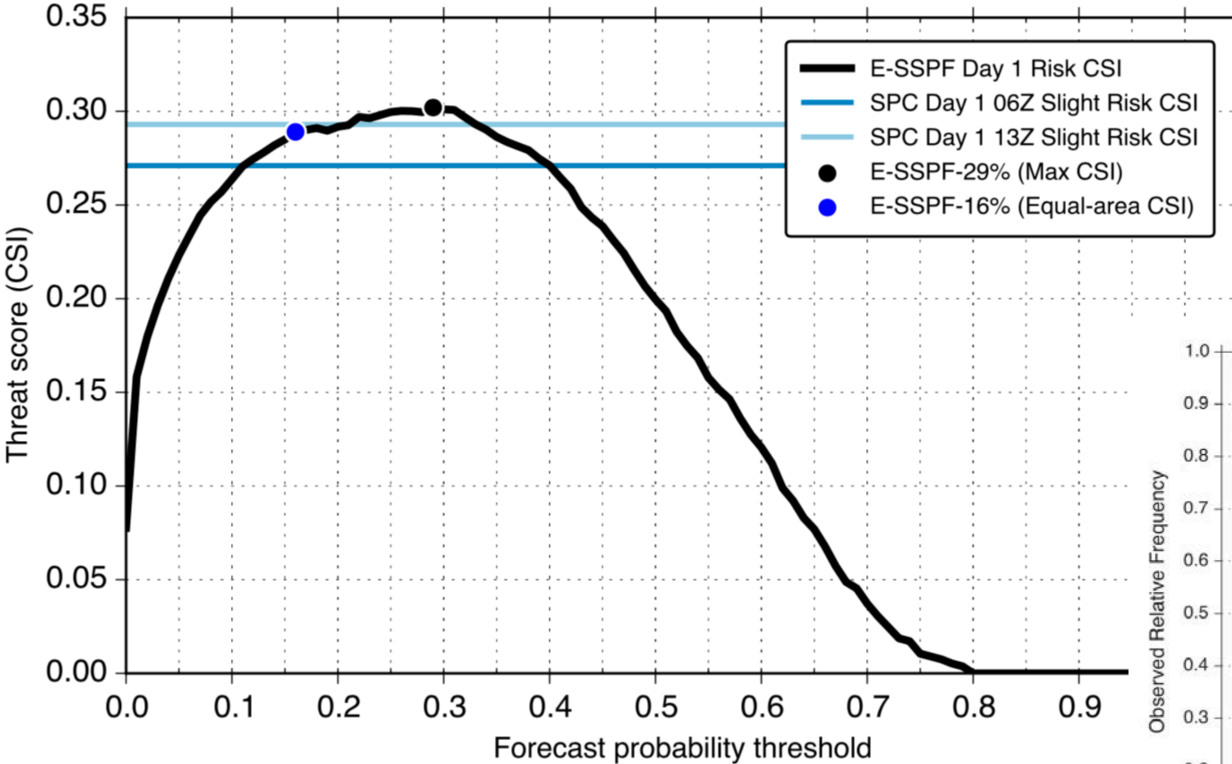
on 15-km domain

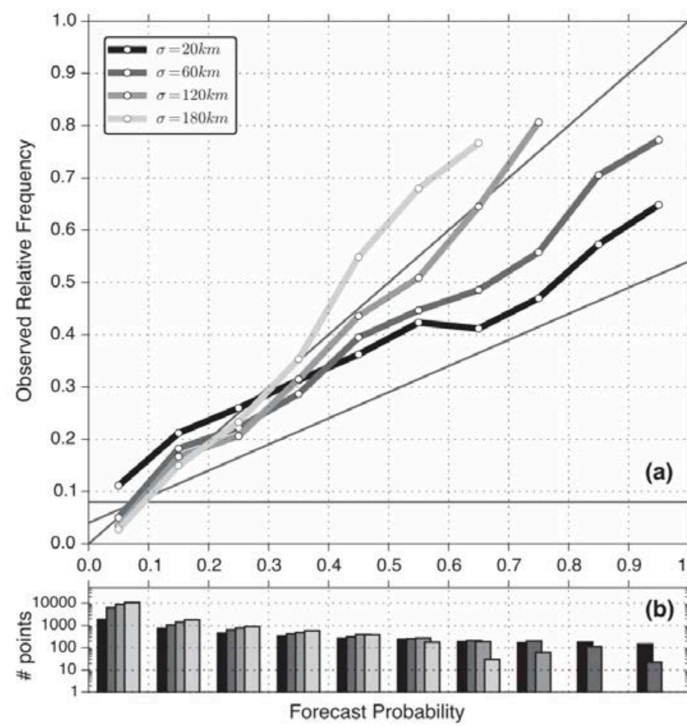
Update every 6 hrs

75k obs, 7 minute wall clock on 512 procs. Fast!

90% of computing is in the analysis state forecasts

NCAR ensemble next day hazard forecast skill

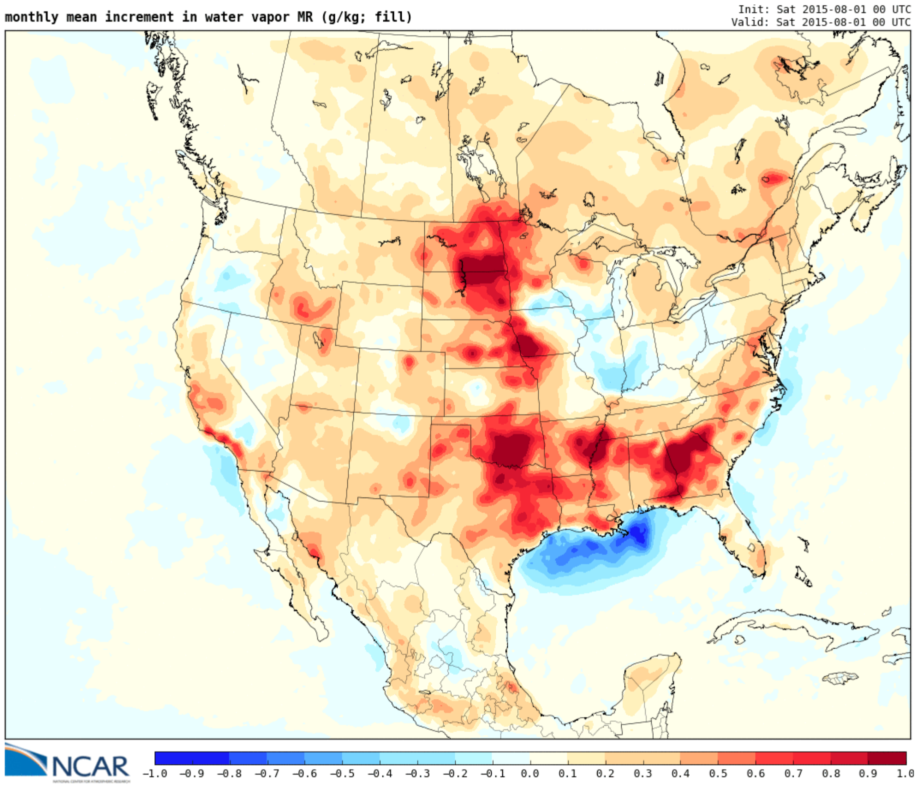




Good skill and reliability for next day severe weather prediction (12-36 h)

Investigating model error with DA

2015 mean analysis innovations for 00 UTC

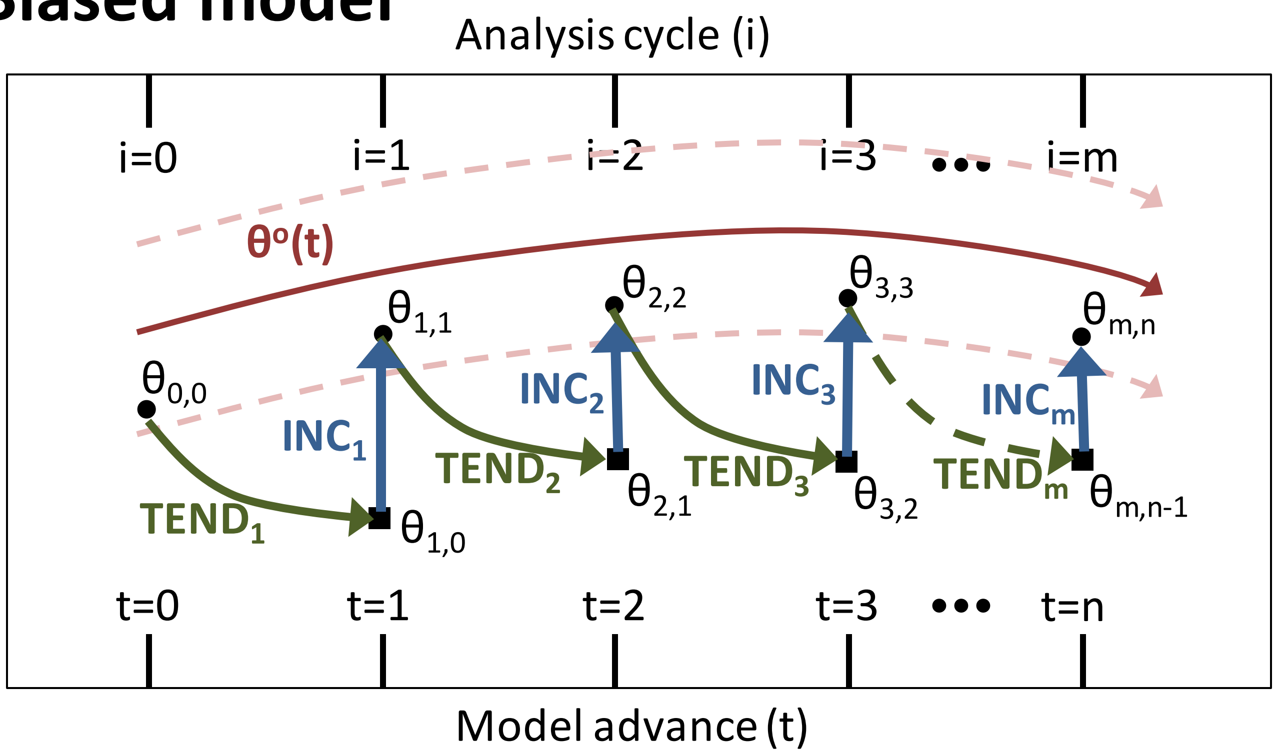


Clear evidence of systematic model bias, though it also has spatial (and diurnal) and seasonal dependence – how can we attribute the source?

Physics tendency tracking for model improvement

A potential means to identify sources of systematic model bias using data assimilation

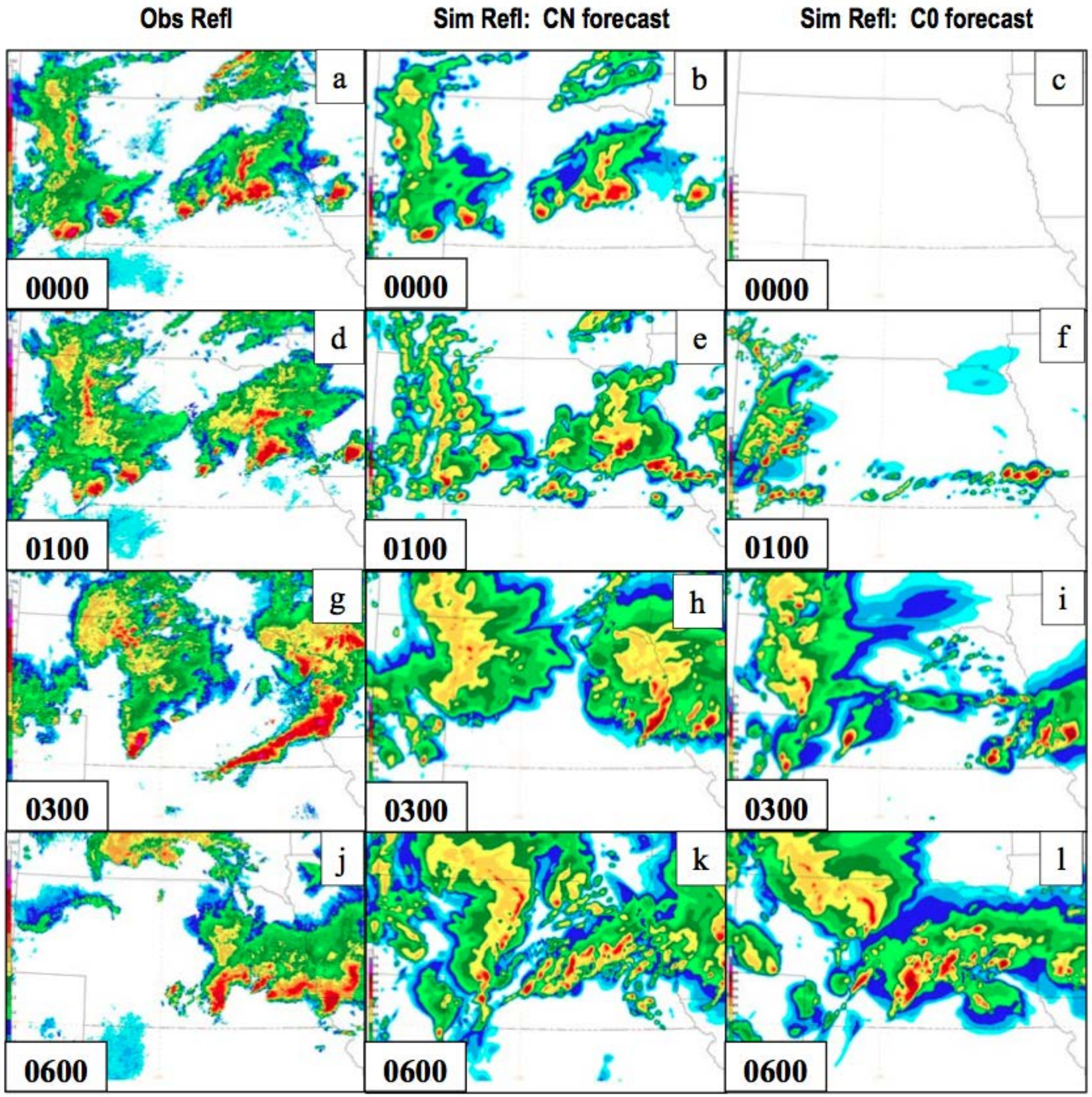
Biased model



$$\frac{1}{n}\sum_{i=1}^{n} INC_i \approx \frac{1}{m}\sum_{t=0}^{m} TEND_t$$

Adapted from Cavallo et al. (2016)

Model physics spinup – large scale forcing dominates



From Kain et al. (2010) – precipitation areas needs to be dynamically consistent with ICs

Next-generation ensemble analysis and forecast system

Development plans in Ensemble DA

- Leverage both DART (NCAR ensemble DA), GSI (U.S. operational DA)
- GSI for forward observation operators
- Will monitor physics tendencies to reduce systematic bias
- Full conterminous U.S. 3-km analysis
- **Analysis on convection-allowing grid** (a.k.a. multi-scale initial conditions)
- About 26X more computation needed

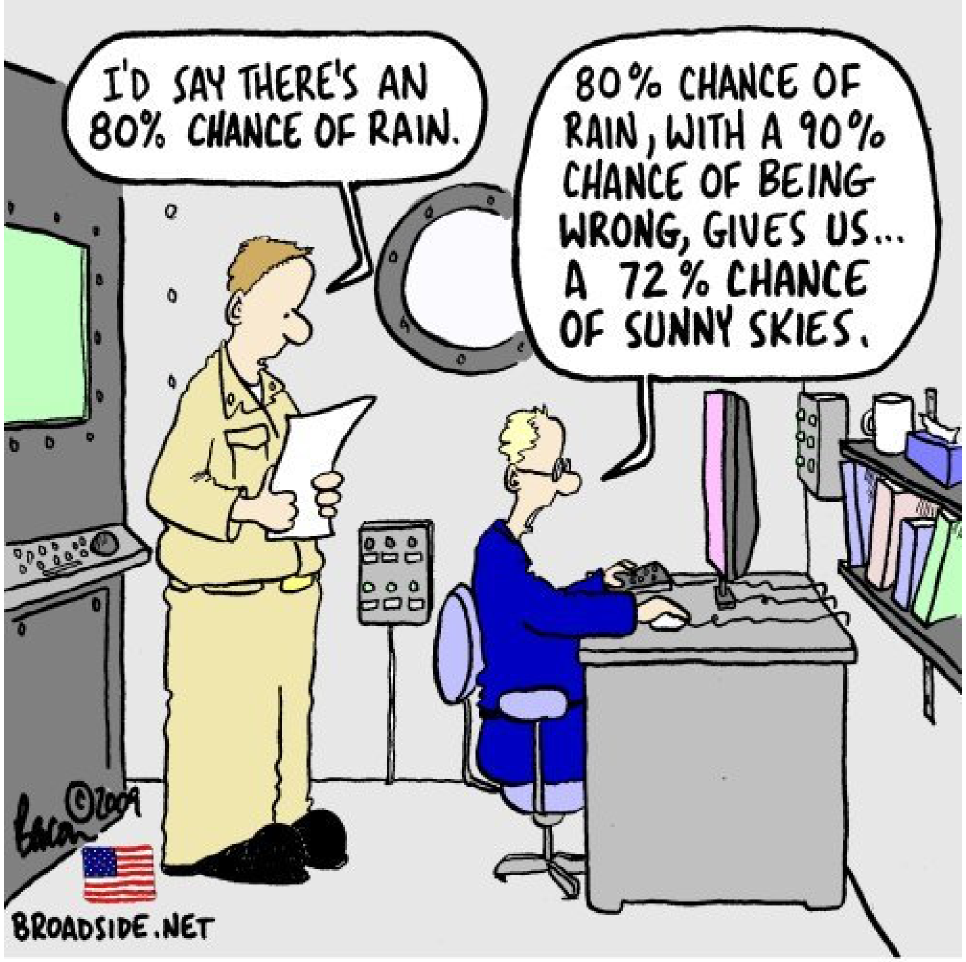
Reduction in spin-up errors

- Assimilation of radar observations
- More frequent cycling (hourly or more frequent updates)
- Looking at GOES-16 – much larger data set!

Analysis state size
14 3D variables
14 x 80 x
415 x 325 x 40 +
16 x 80 x
1581 x 986 x 40 =
~ 86 B state points
For both 15- and 3-km domains
> **14x increase in size**!

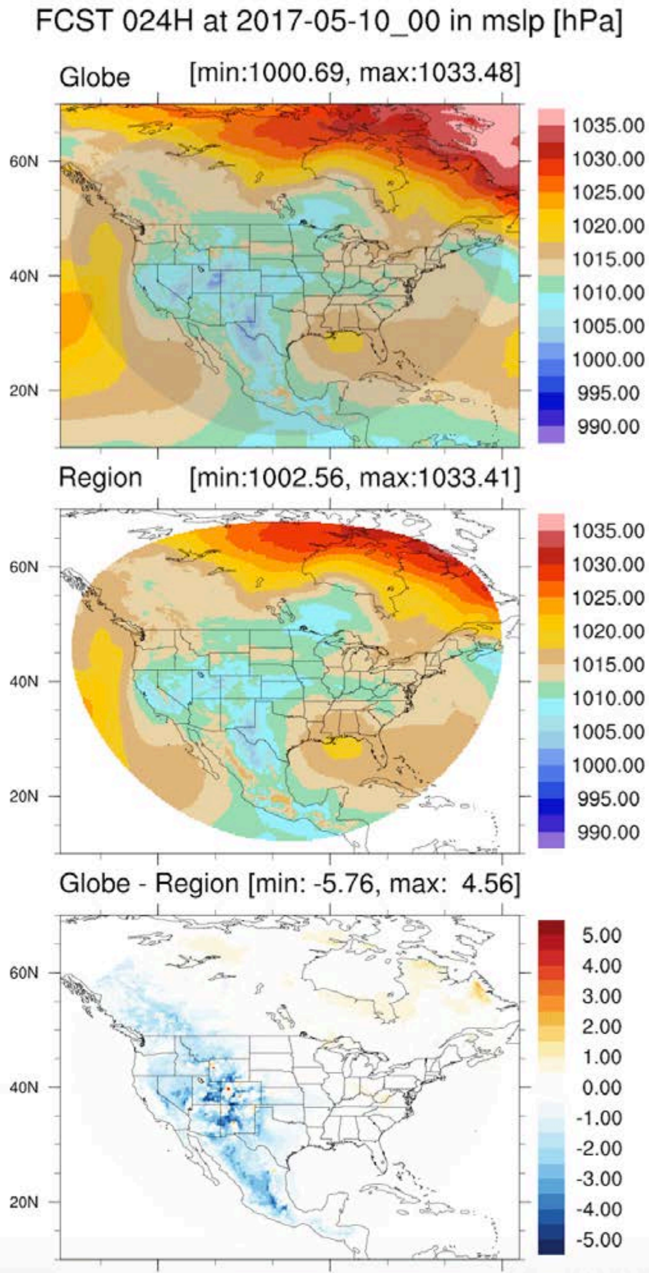
The End!

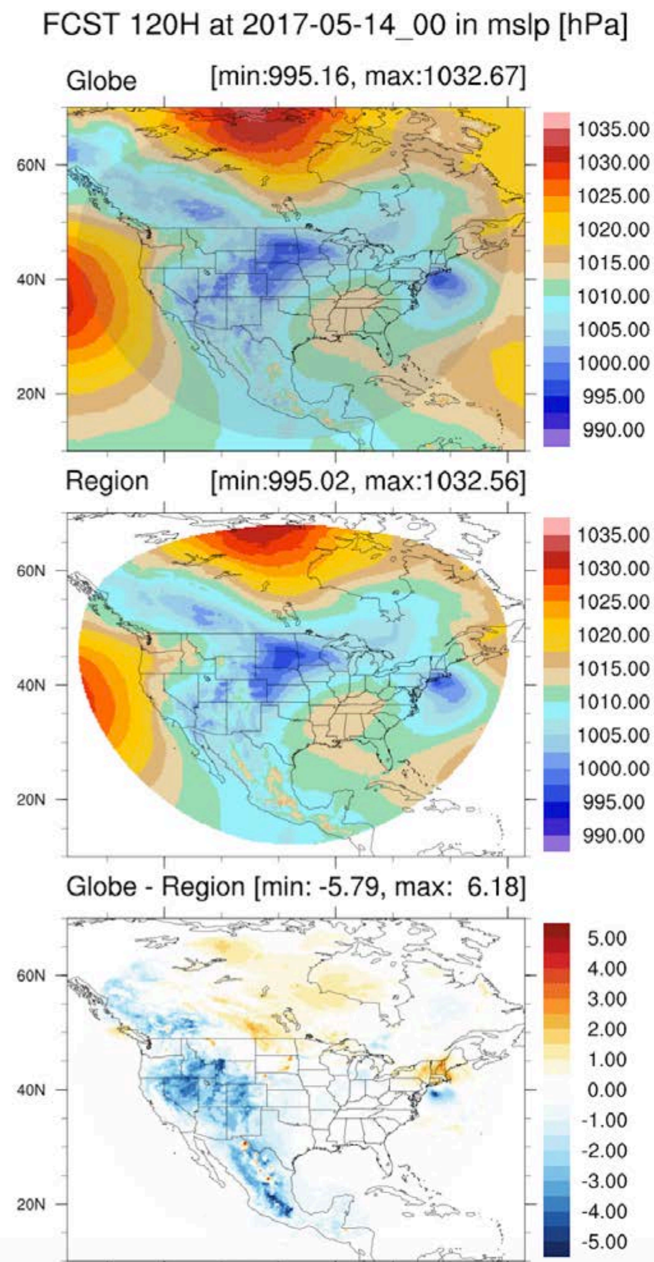
Thank you for your attention



How forecasts are made

Regional model lateral boundary errors – via MPAS

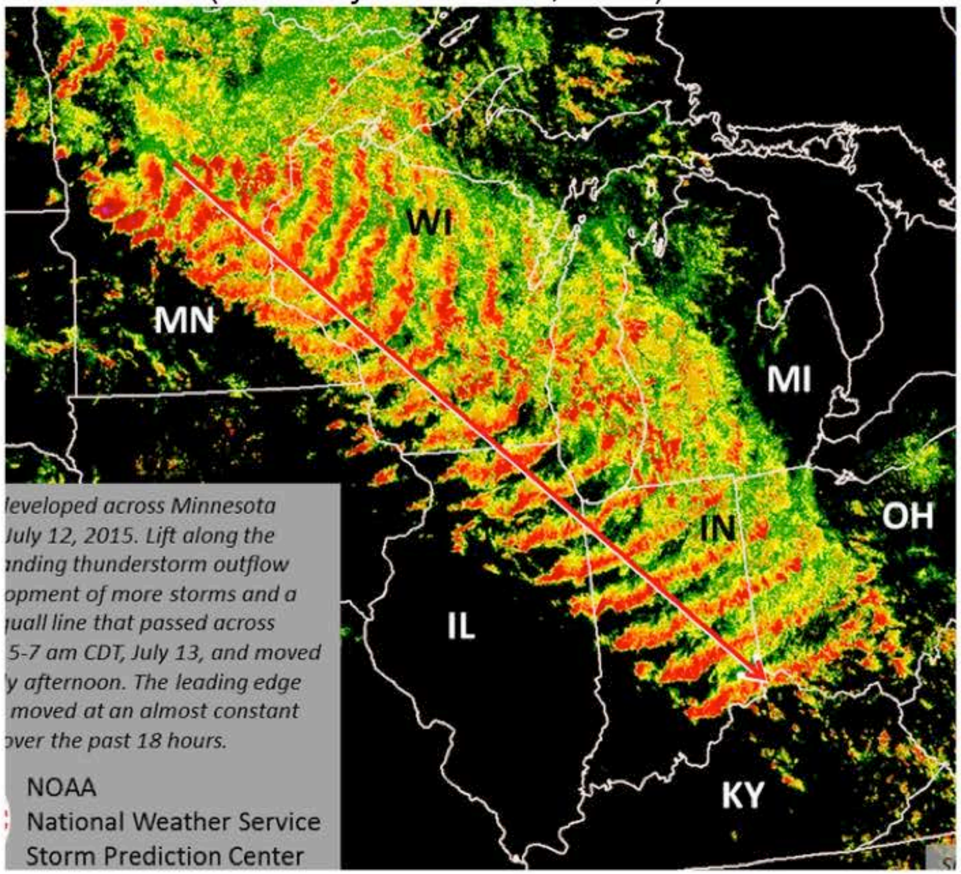




Courtesy S. Ha

CAM forecasts are sometimes very useful….

Observed (courtesy G. Carbin, SPC)



NCAR Ensemble Member (26 – 45 hr fcst)