Development and Testing of Storm-Scale Radar-Data Assimilation and Forecasting Systems

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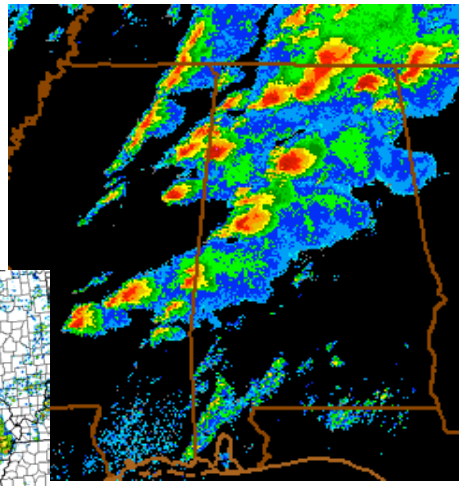

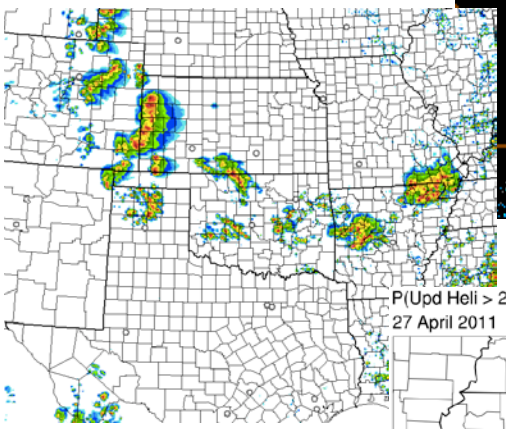

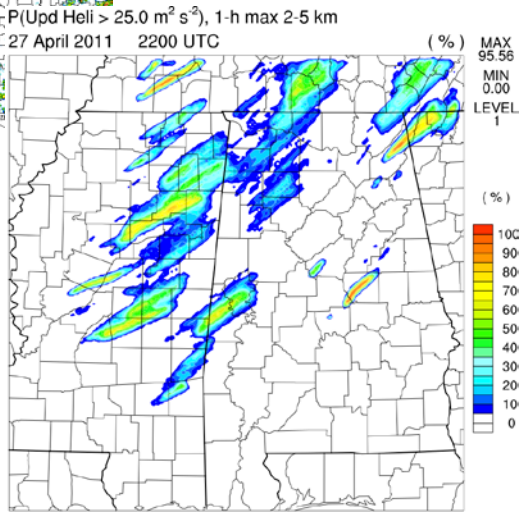

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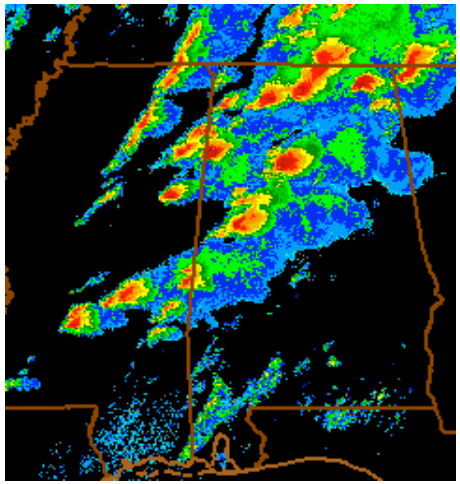
Motivation

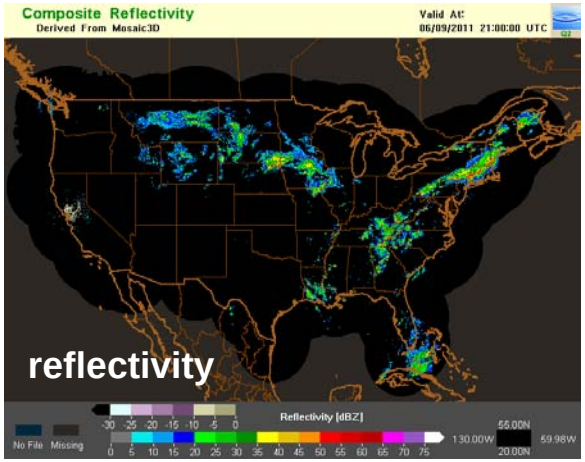
Goal is O(1 h) numerical forecasts of convective storms

Key issues:

1. **Assimilation of radar observations at O(1 km) grid spacing**
2. **Analysis and simulation of mesoscale environment**
3. **Probabilistic ensemble forecasts**
   - **1-h forecast is “medium range” for convective scale.**
   - **Model error must be represented in ensemble design.**



Radar Observations for Storm-Scale DA



Reflectivity: target sizes and number concentrations

- **primary information: presence or absence of hydrometeors**
- **direct assimilation involves multiple bias errors**
  - **model parameterizations, observation operator, radar calibration**
- **CONUS dataset available in near real time (NSSL-NMQ)**
  - **extensive quality control, but with some biased data remaining**

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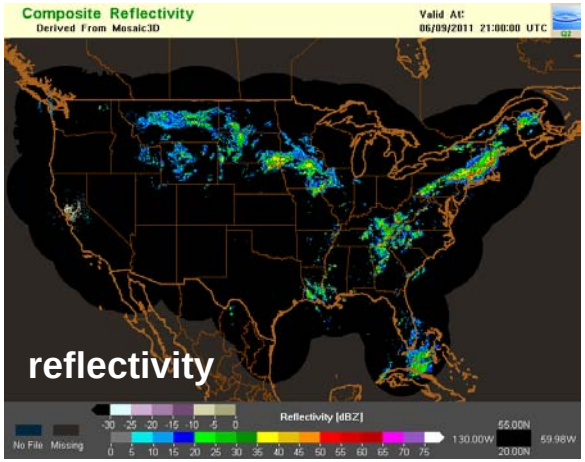

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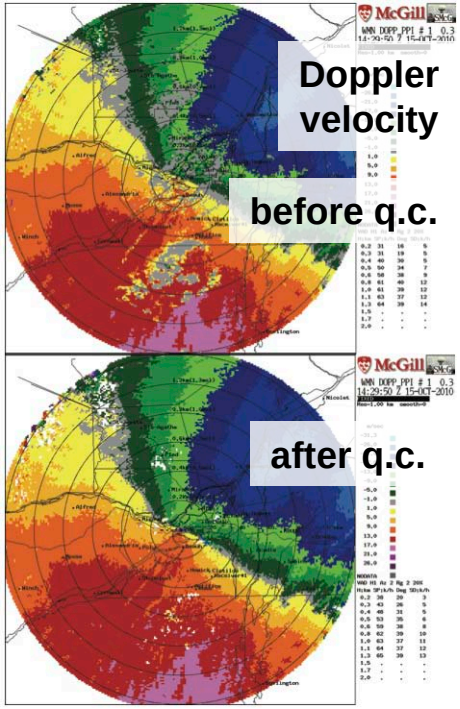
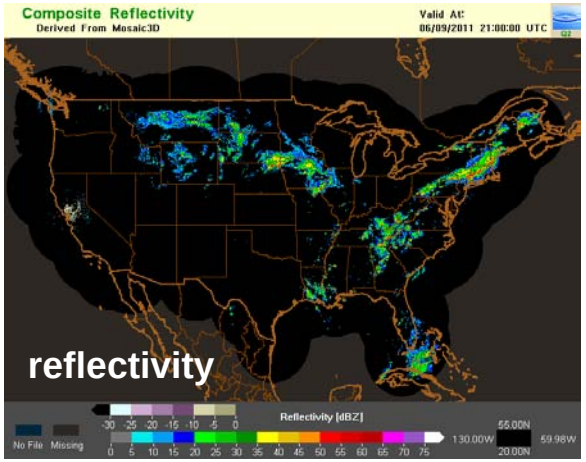
Doppler velocity: **target motion toward / away from radar**

- **most useful ob. type, according to storm-scale DA studies**
- **straightforward relationship with (mostly) prognostic model fields, if radar sampling is properly simulated**
  - **upcoming presentation by Frederic Fabry**
- **qc'd (bias-free) CONUS dataset not yet available in real time**



Fabry and Kilambi 2011

Radar Observations for Storm-Scale DA



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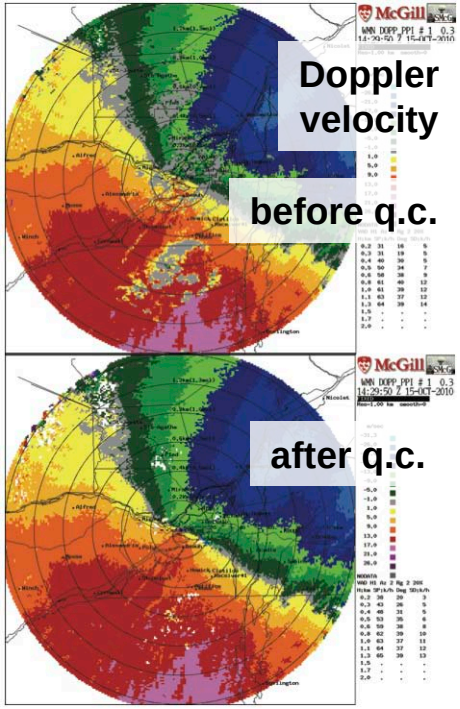


Fabry and Kilambi 2011

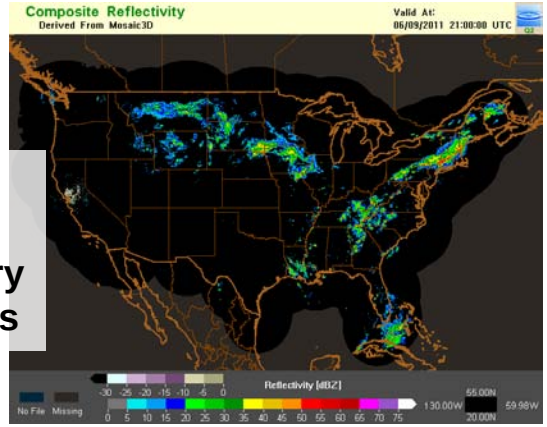
Spectrum width: velocity dispersion within volume

- not typically used for storm-scale DA

Polarimetric variables

- useful for quality control of velocity and reflectivity and for forecast verification (e.g., hydrometeor classifications)
- unclear potential for direct assimilation

Challenges of Storm-Scale DA and NWP



Large radar datasets in need of quality control

190 radars

volumes every 10 min or less

Large model grids

- **1000's of km wide, grid spacing ~1 km**

Model error and predictability

- **unresolved processes: updraft, downdraft, precipitation microphysics, PBL, …**
- **predictability time scale ~10 min for an individual thunderstorm**
- **forecast sensitivity to small changes in initial conditions (e.g., water vapor)**

Flow-dependent background-error covariances

- **no quasi-geostrophic balance on small scales**
- **retrieving unobserved fields**

Verifying forecasts (to improve future ones)

- **unobserved fields, isolated phenomena**

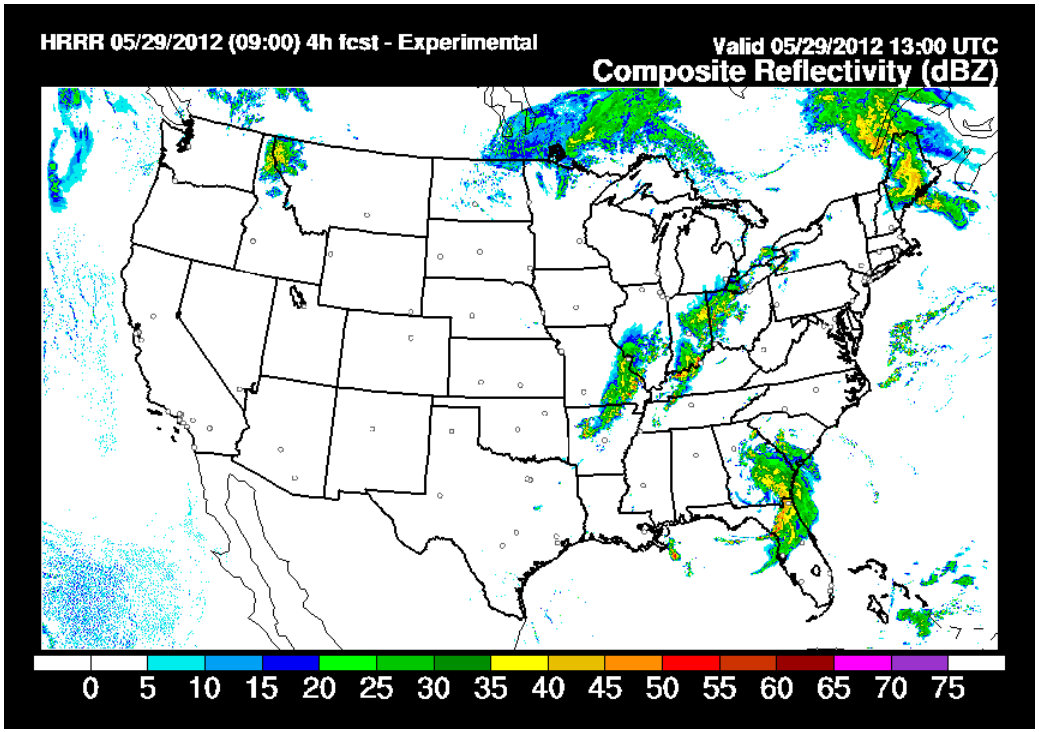
All tasks (preprocessing and assimilating obs, producing forecasts) must occur quickly for the forecast to be useful in real time!

- **within an hour for some applications**
- **within minutes for warning guidance**

Some Ongoing Storm-Scale NWP Projects

High-Resolution Rapid Refresh (HRRR) – NOAA

horizontal grid spacing 3 km ➔ convection allowing
near real time, 15-hour forecast every hour
aviation guidance, severe weather forecasting, etc.

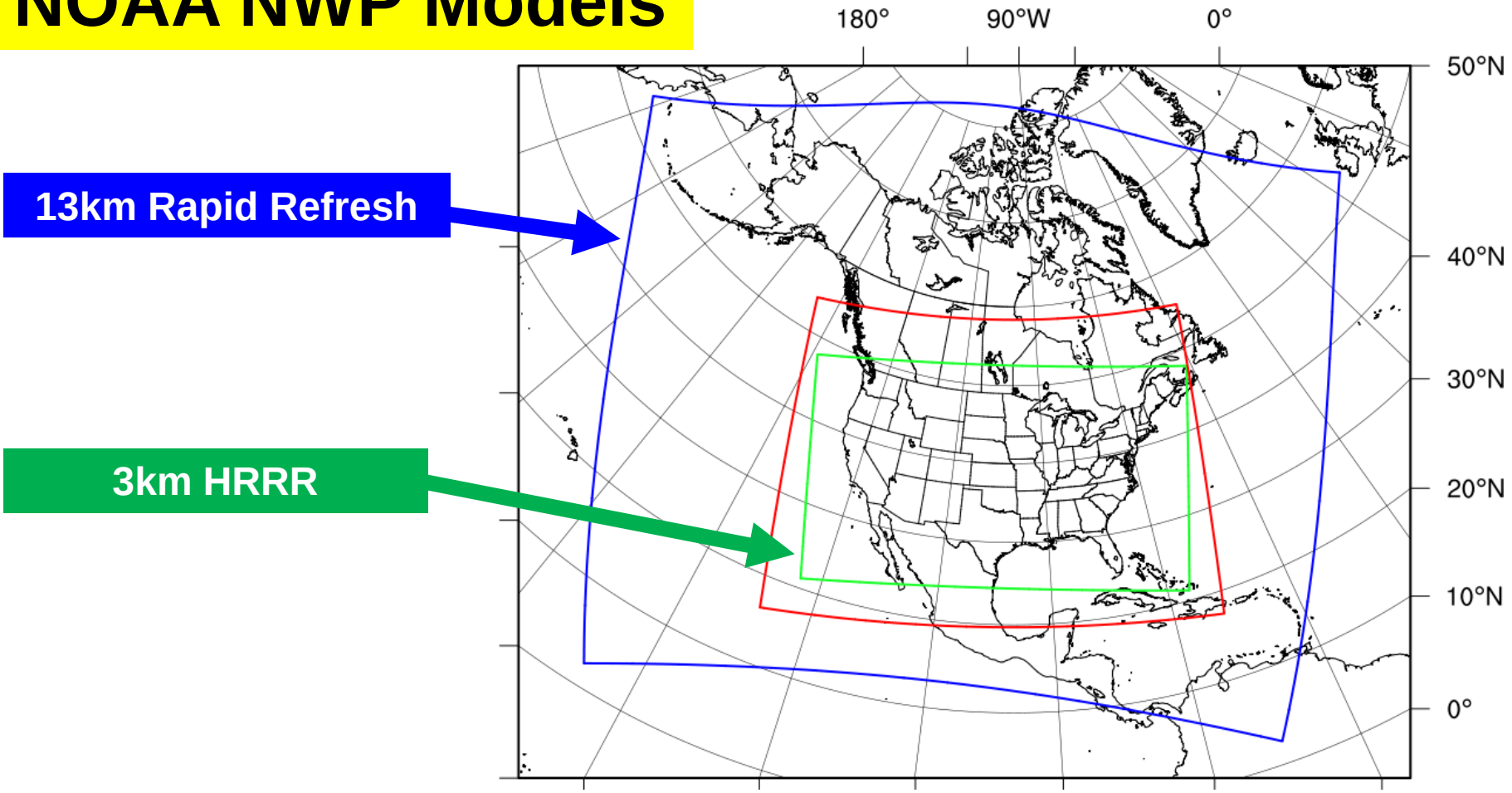


Short-Term Explicit Prediction (STEP) – NCAR

Center for Analysis and Prediction of Storms (CAPS) – Univ. of Oklahoma

Warn on Forecast – NOAA

Hourly Updated NOAA NWP Models

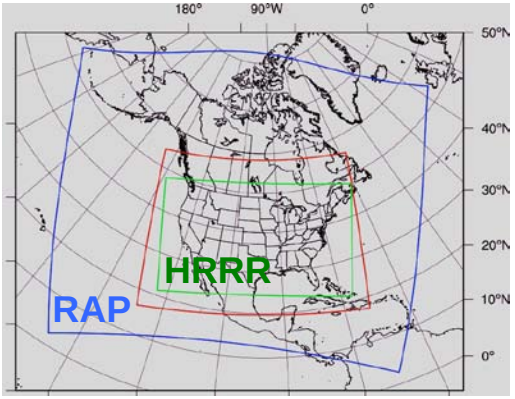


Rapid Refresh (RAP):
WRF-ARW; GSI + RUC-based enhancements; new 18-h fcst every hour

High-Resolution Rapid Refresh (HRRR):
WRF-ARW; experimental 3-km nest inside RAP; new 15-h fcst every hour

RAP and HRRR Model Details

Model	Domain	Grid Points	Grid Spacing	Vertical Levels	Boundary Conditions	Initialized
RAP-ESRL	North America	758 x 567	13 km	50	GFS	Hourly (cycled)
HRRR	CONUS	1799 x 1059	3 km	50	RAP-ESRL	Hourly (no-cycle)

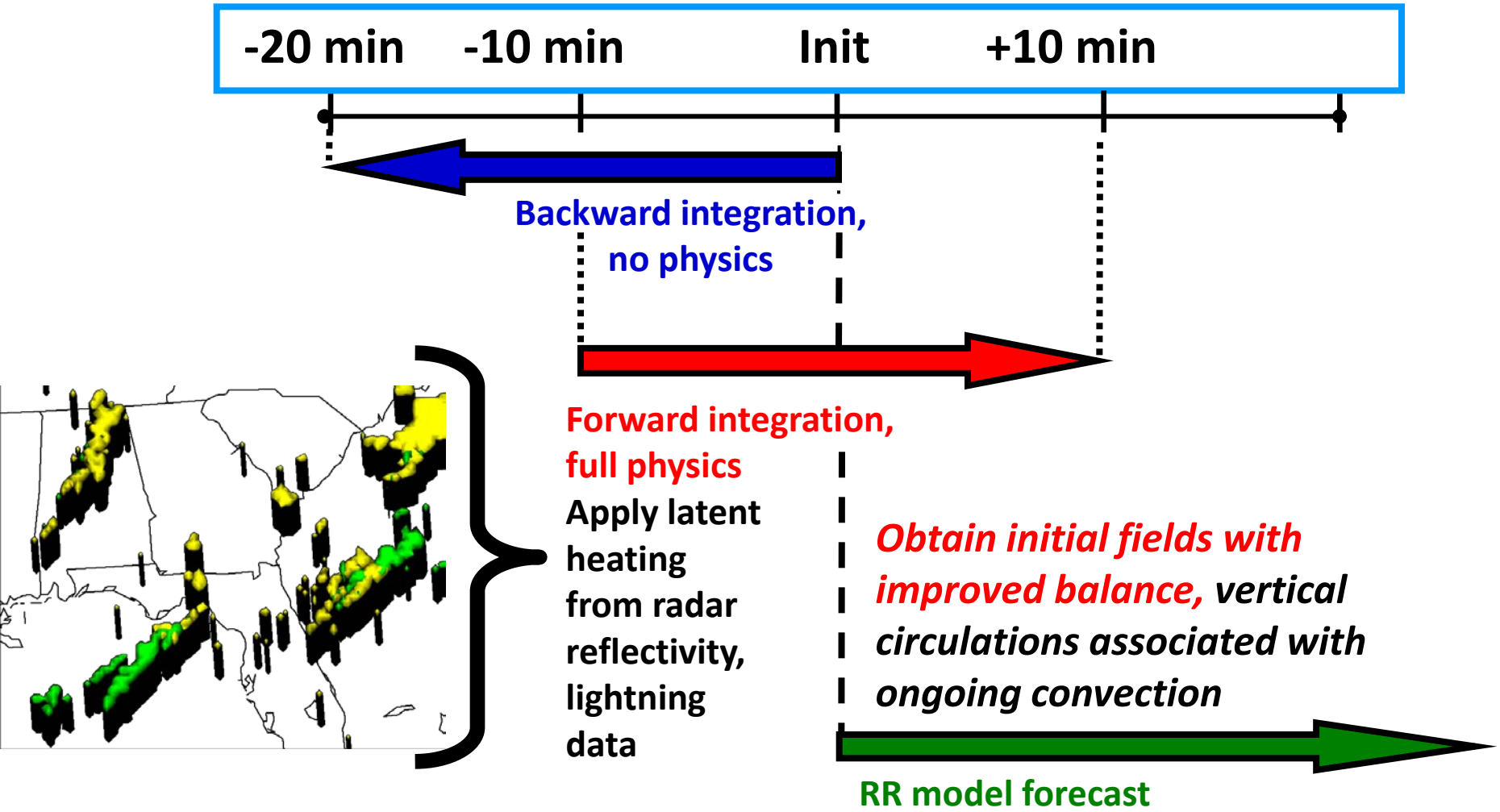


Model	Version	Assimilation	Radar DFI	Radiation	Microphysics	Cum Param	PBL	LSM
RAP-ESRL	WRF-ARW v3.3.1+	GSI-3DVar	Yes	RRTM/Goddard	Thompson v3.3.1	G3 + Shallow	MYJ	RUC v3.3.1
HRRR	WRF-ARW v3.3.1+	None: RAP I.C.	No	RRTM/Goddard	Thompson v3.3.1	None	MYJ	RUC v3.3.1

diabatic digital filter initialization with radar-reflectivity and lightning (proxy refl.) data

observations assimilated with GSI (3DVar) into experimental RAP at ESRL
rawinsonde; profiler; VAD; level-2.5 Doppler velocity; PBL profiler/RASS; aircraft wind, temp, RH; METAR; buoy/ship; GOES cloud winds and cloud-top pres; GPS precip water; mesonet temp, dpt, wind (fall 2012); METAR-cloud-vis-wx; AMSU-A/B/HIRS/etc. radiances; GOES radiances (fall 2012); nacelle/tower/sodar

Diabatic Digital Filter Initialization (DDFI)

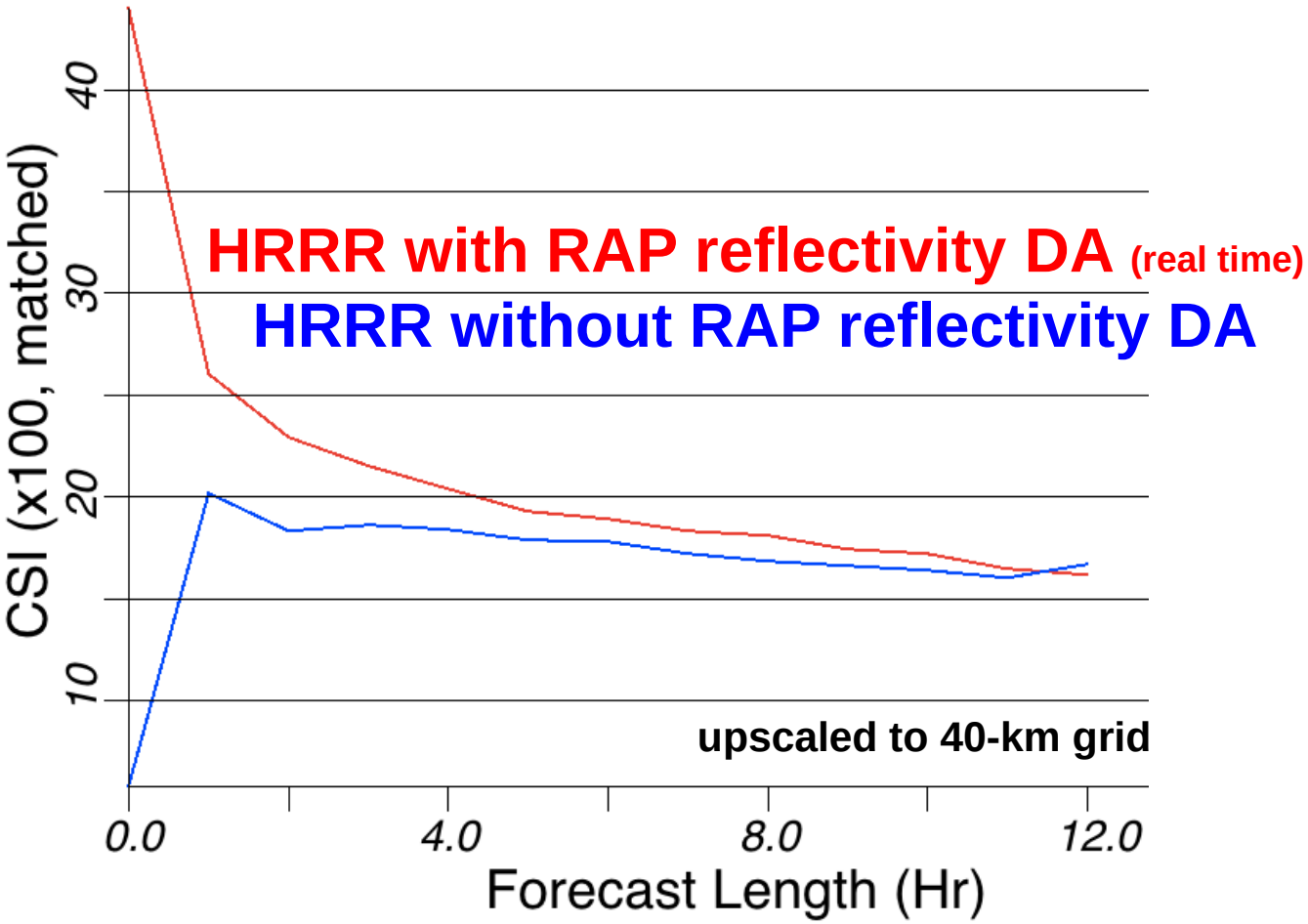


The model microphysics temperature tendency is replaced with a reflectivity-based temperature tendency. Dynamics respond to forcing.

Analysis noise is reduced by digital filtering.

Positive Contribution to HRRR (3-km) Forecasts from Reflectivity DA (DDFI) in Parent (13-km) RAP

Critical Success Index (CSI) for 25-dBZ Composite Reflectivity



11-20 August 2011 retrospective period
verification over eastern half of US (widespread convective storms)

Anticipated Progression of RAP and HRRR Radar DA

now: **radar DA in RAP (13 km) only**

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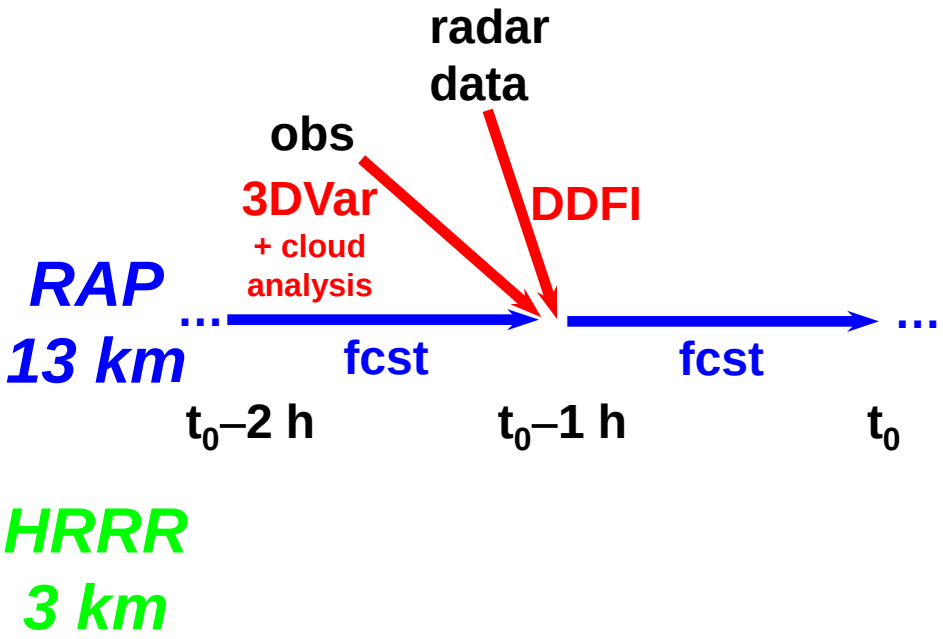
near future (proposed): **continued radar DA in RAP (13 km);**
short period of radar DA in HRRR (3 km) before HRRR forecast begins



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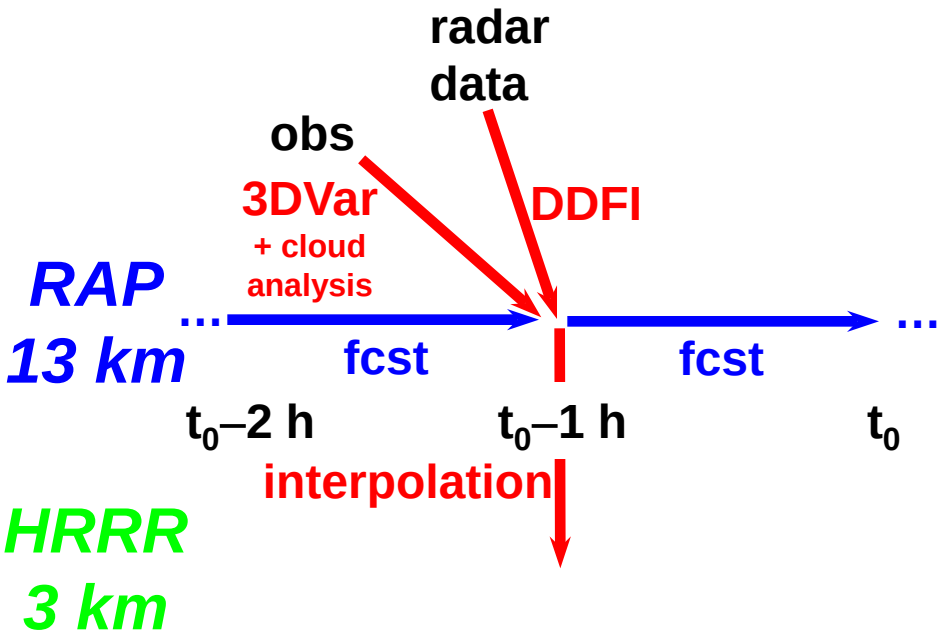

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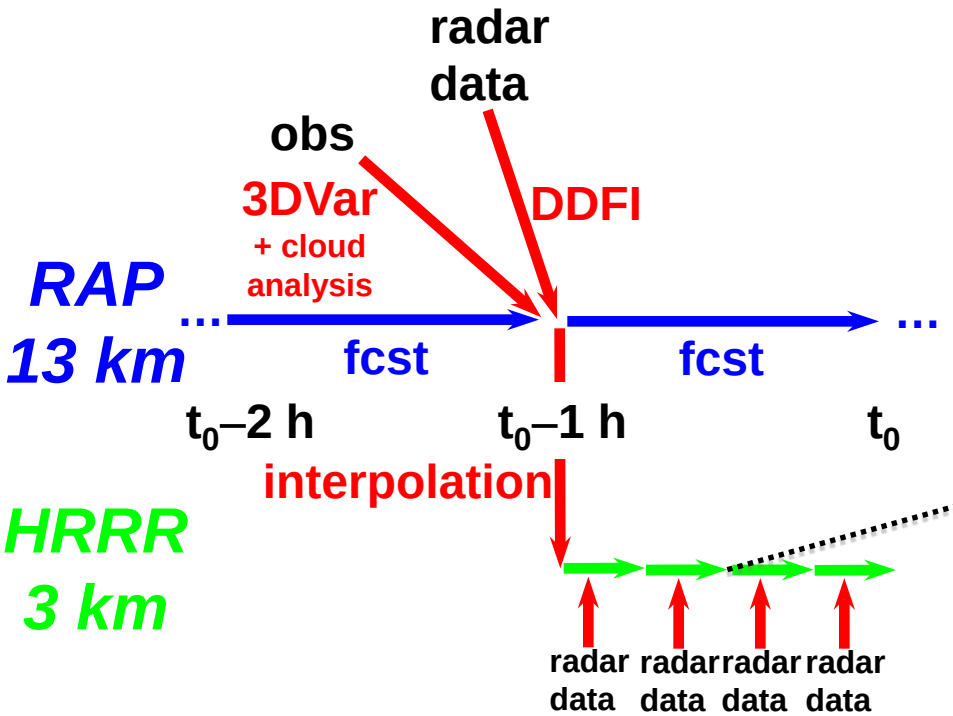

HRRR reflectivity DA

- same formulation of **reflectivity-based temperature tendency** as in RAP
- **no digital filter**

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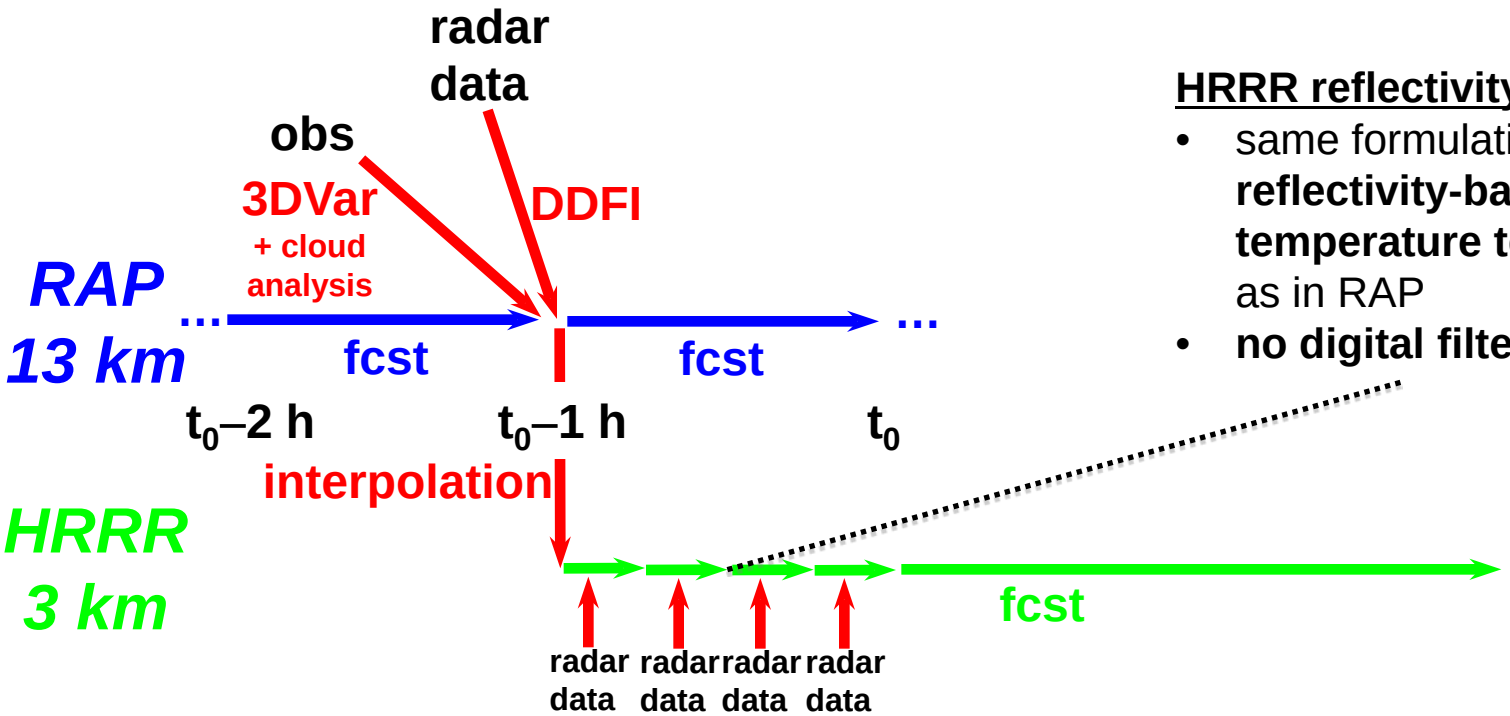

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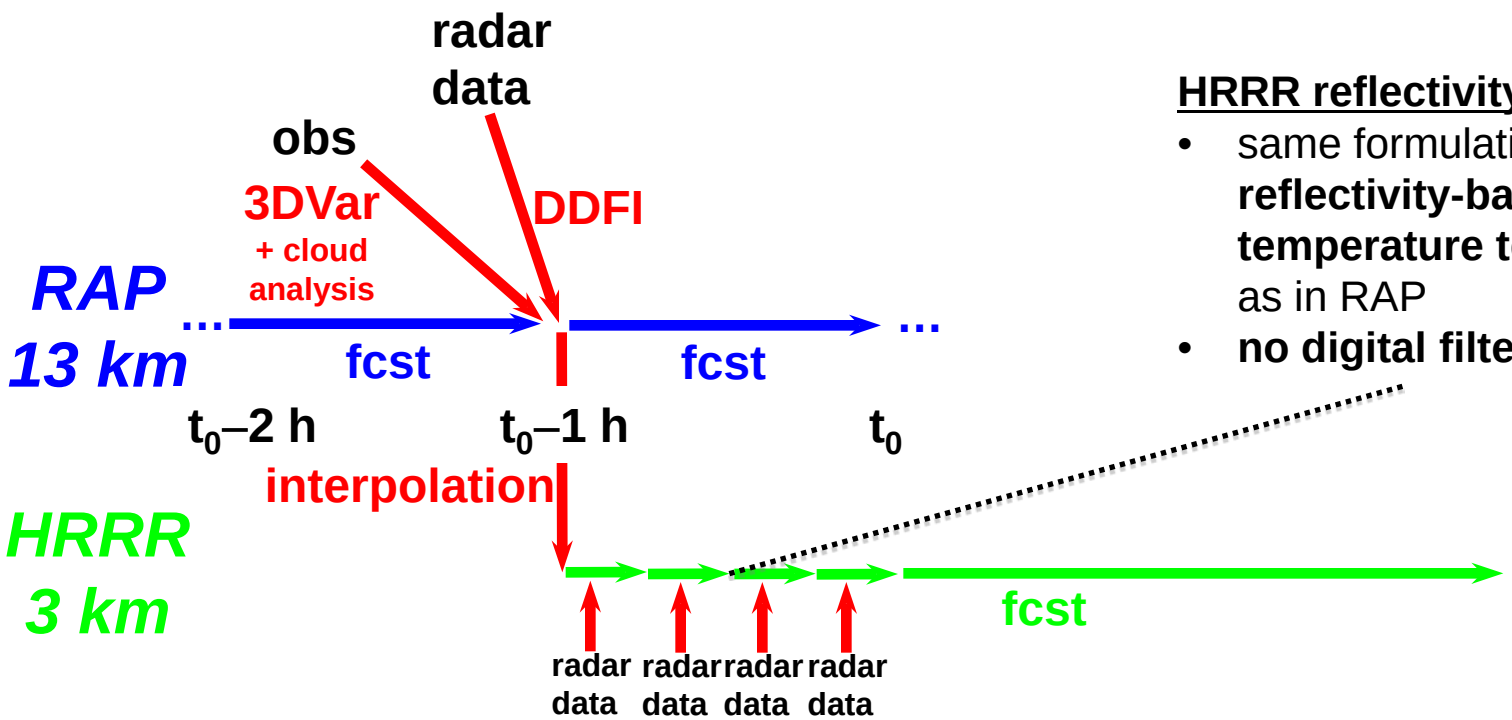

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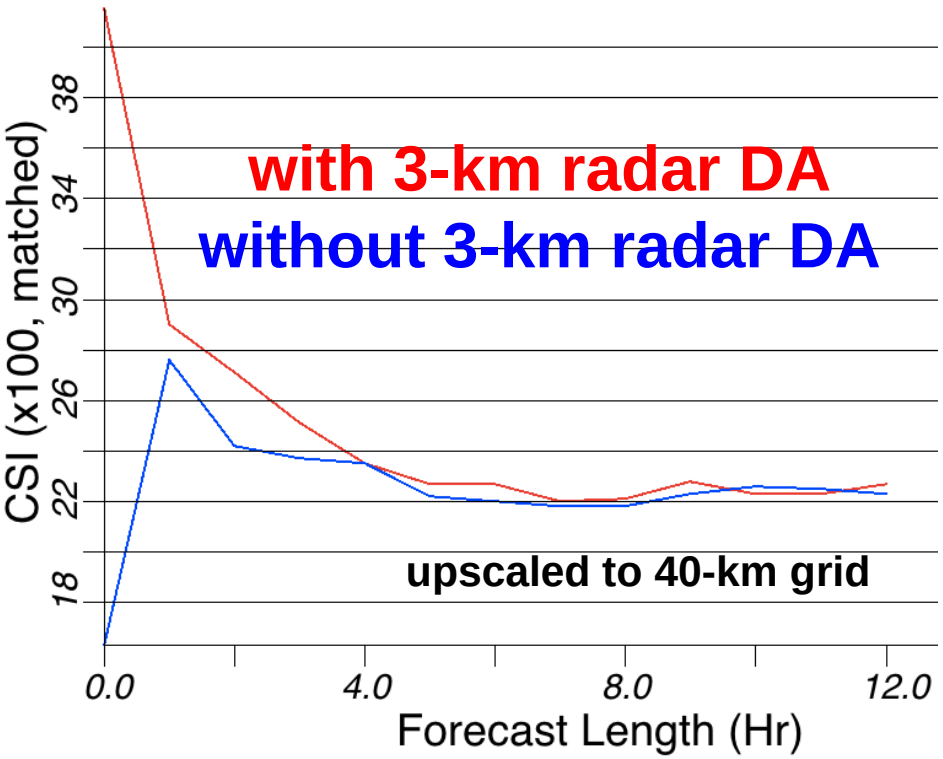
future: **cycling with all obs (including radar) on HRRR (3-km) grid**

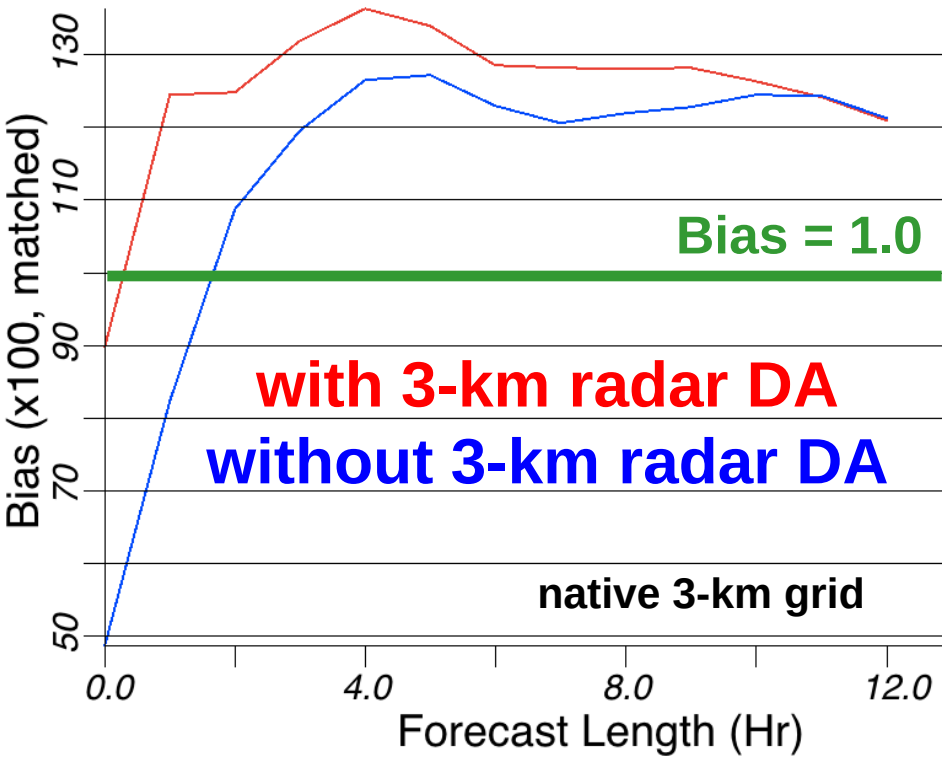
3DVar and reflectivity-based temperature tendency
hybrid / ensemble DA and forecasting

HRRR Skill: 20 dBZ threshold

Critical Success Index (CSI)

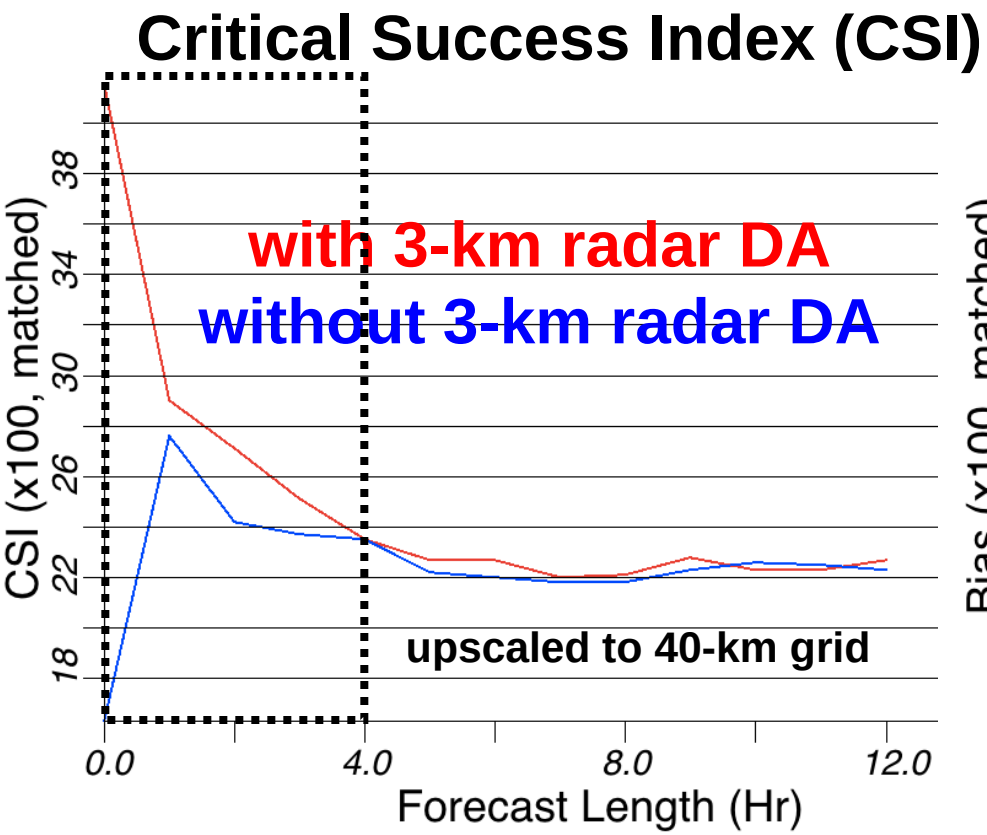


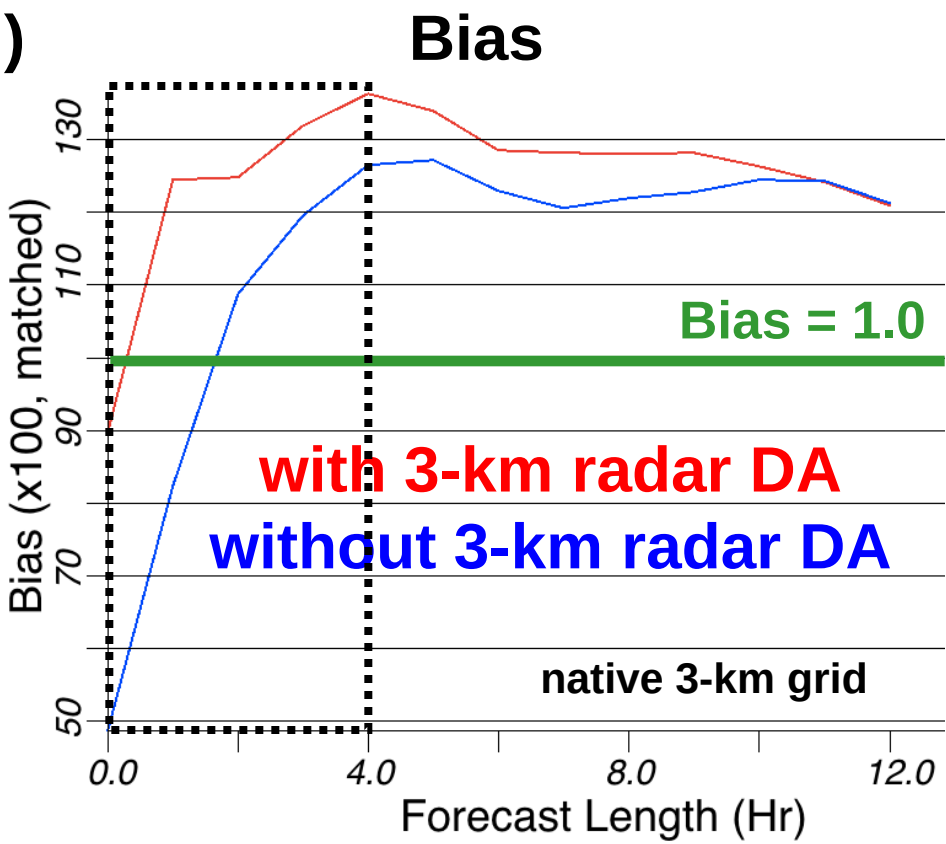
Bias



3-day retrospective period June 2011, forecasts every 2 hours
composite reflectivity
verification over eastern half of US (widespread convective storms)

HRRR Skill: 20 dBZ threshold





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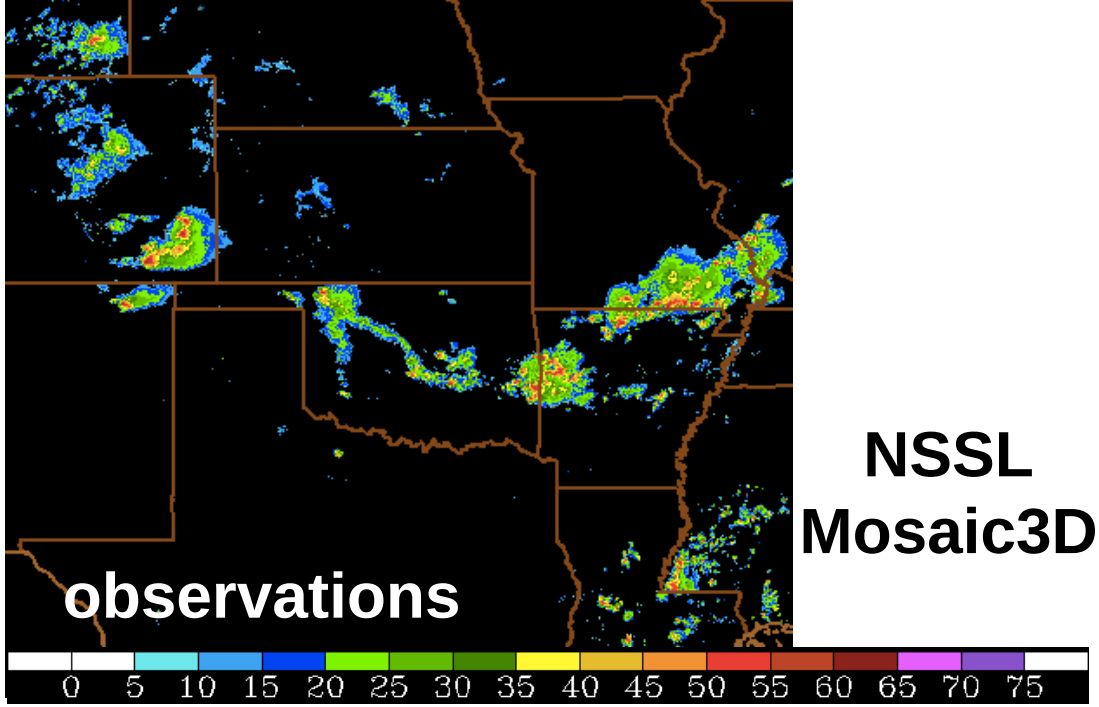
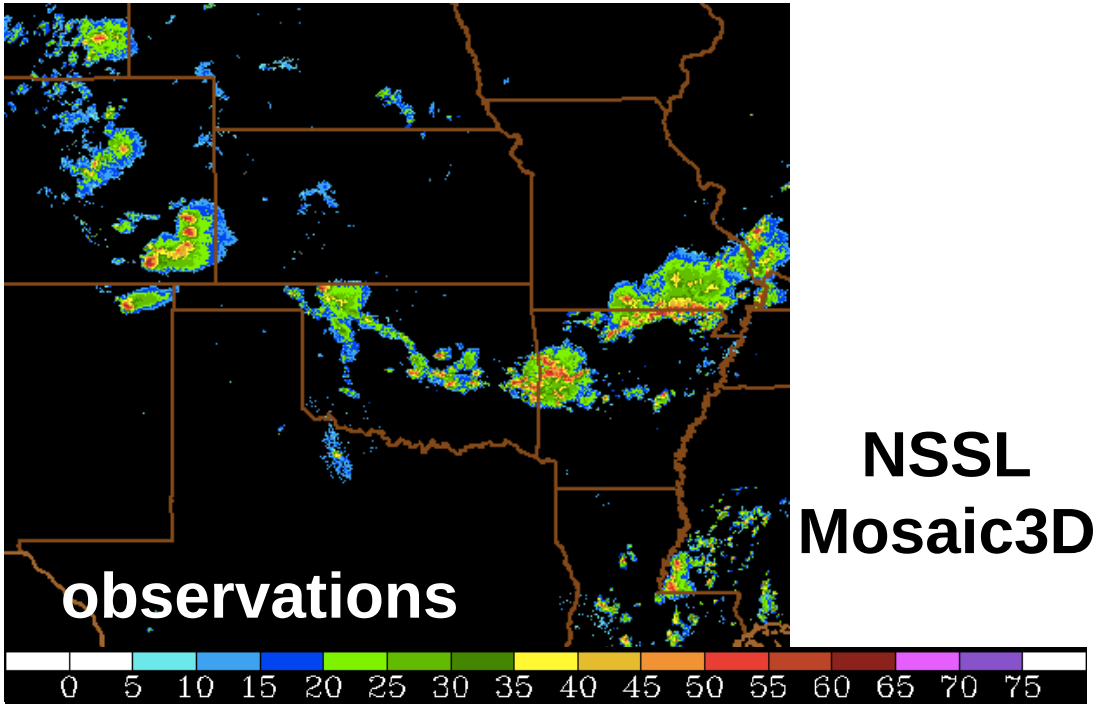
Composite Reflectivity 2100 UTC 11 June 2011



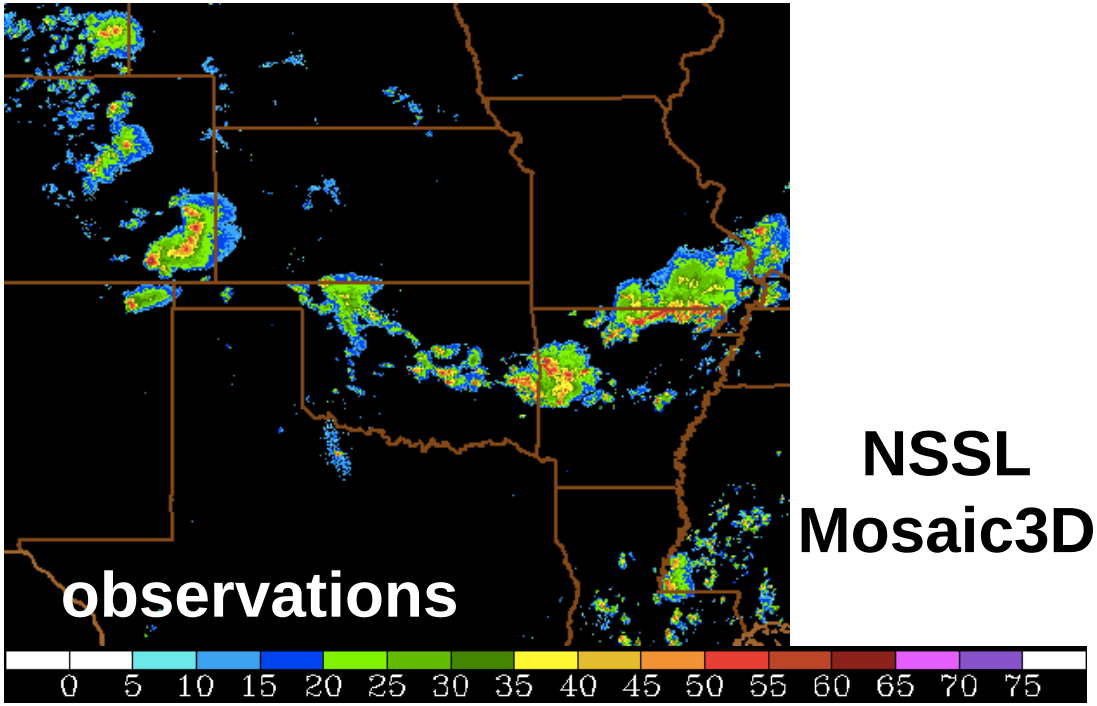
NSSL Mosaic3D

Composite Reflectivity 2115 UTC 11 June 2011



NSSL Mosaic3D

Composite Reflectivity 2130 UTC 11 June 2011



NSSL Mosaic3D

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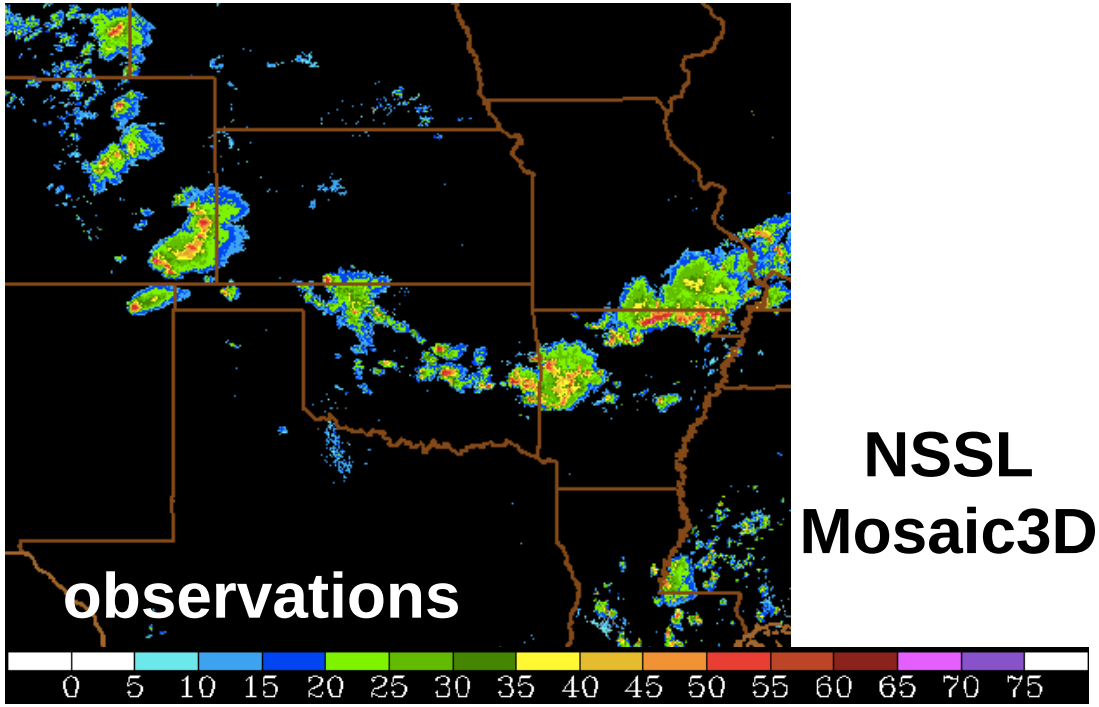
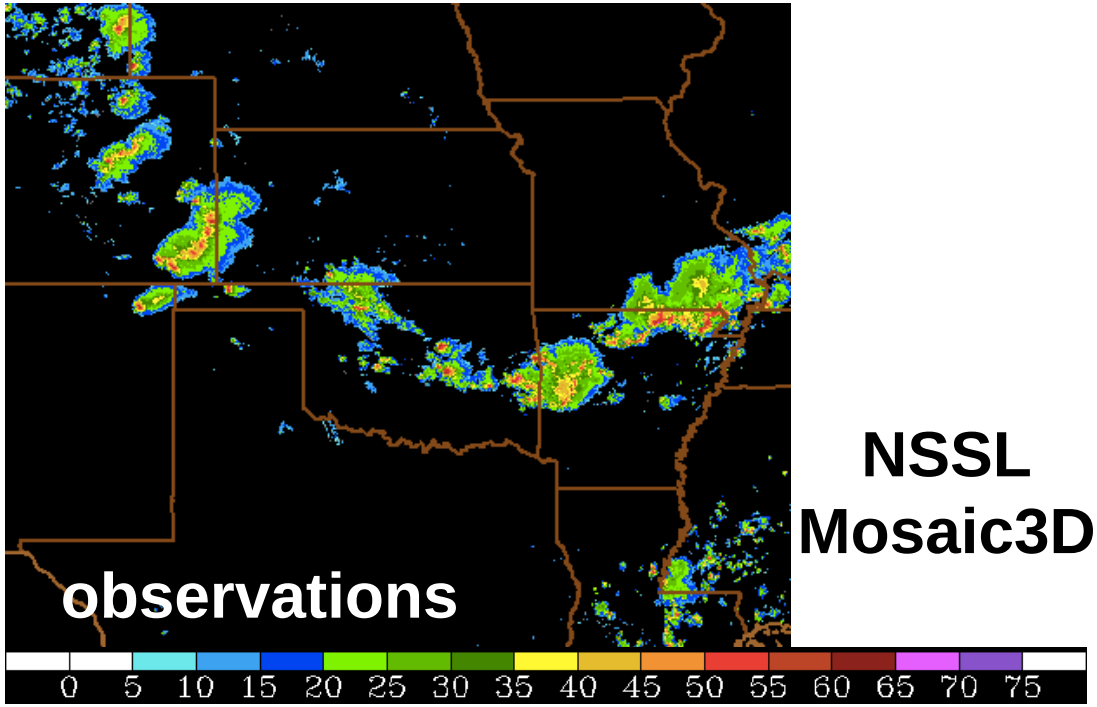


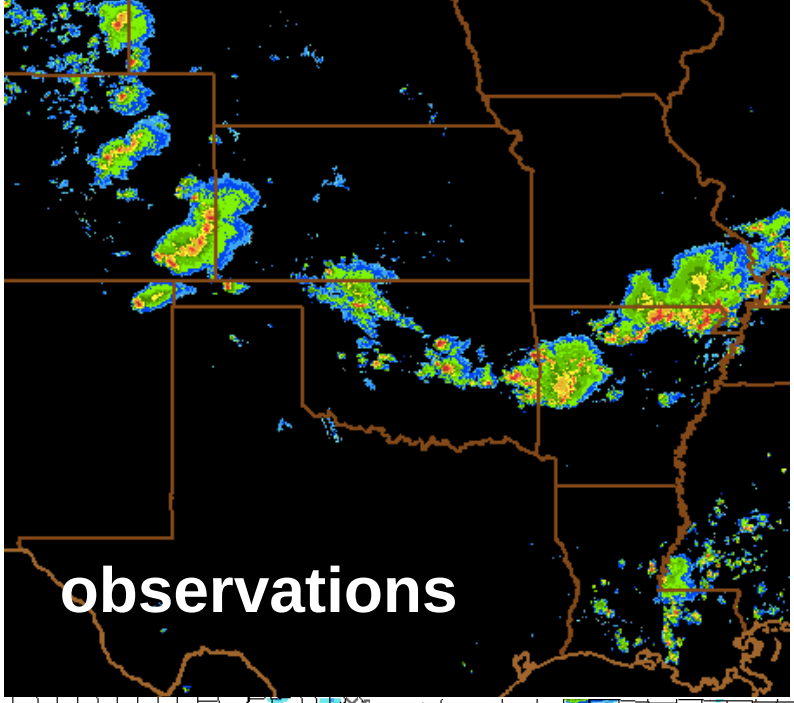
NSSL Mosaic3D

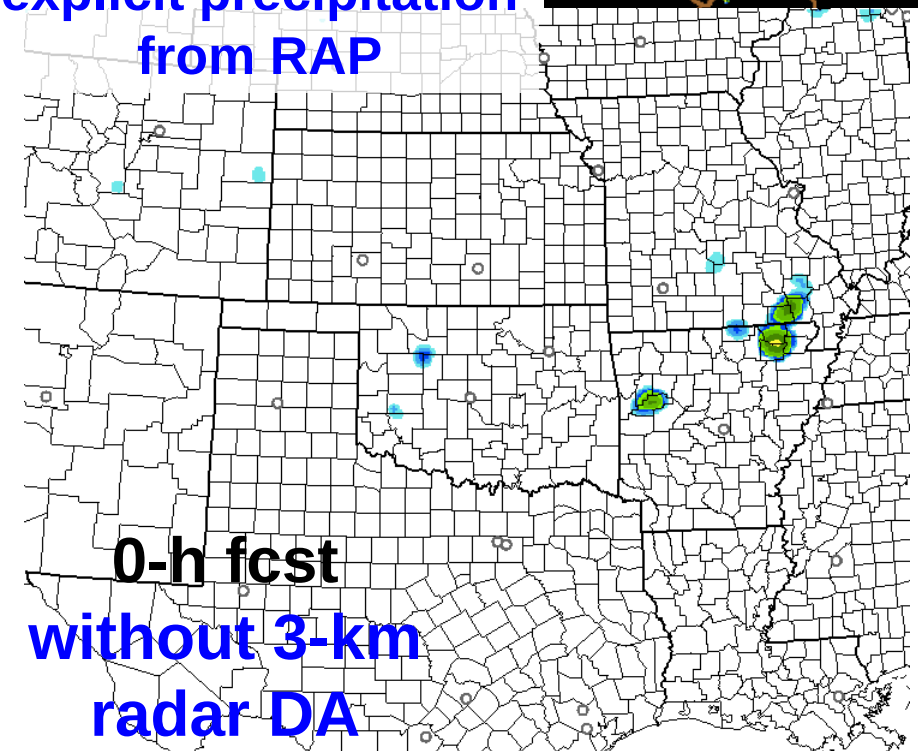
Composite Reflectivity 2200 UTC 11 June 2011

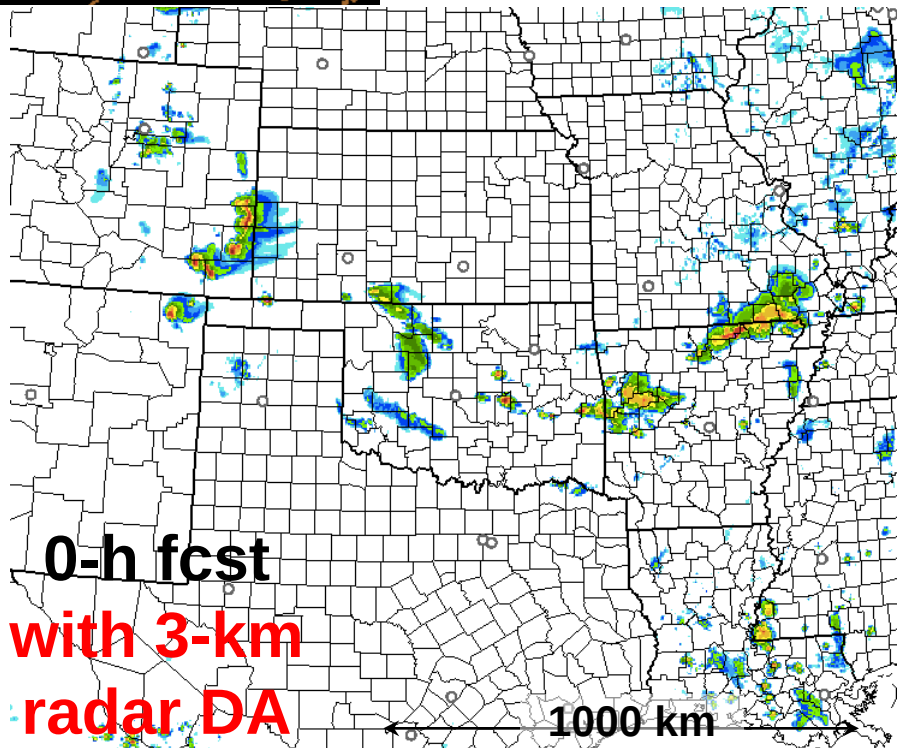


NSSL Mosaic3D

Composite Reflectivity 2200 UTC 11 June 2011







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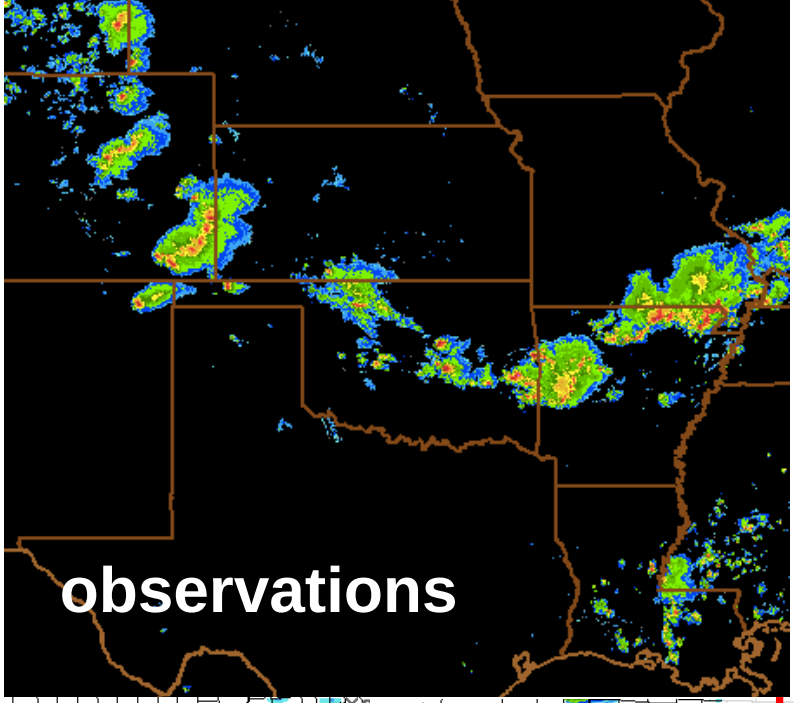
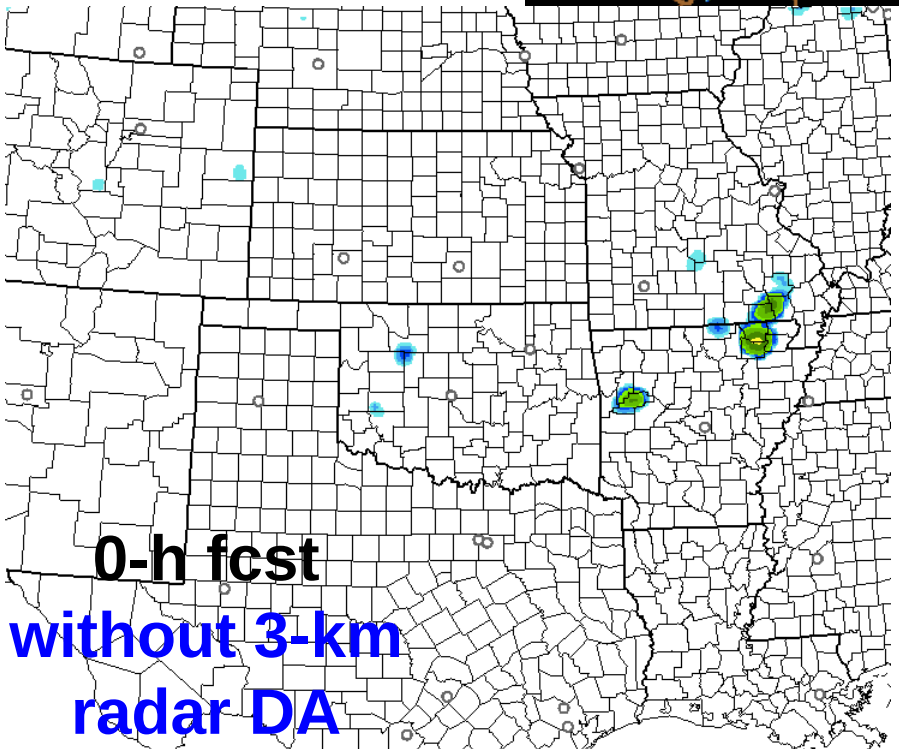
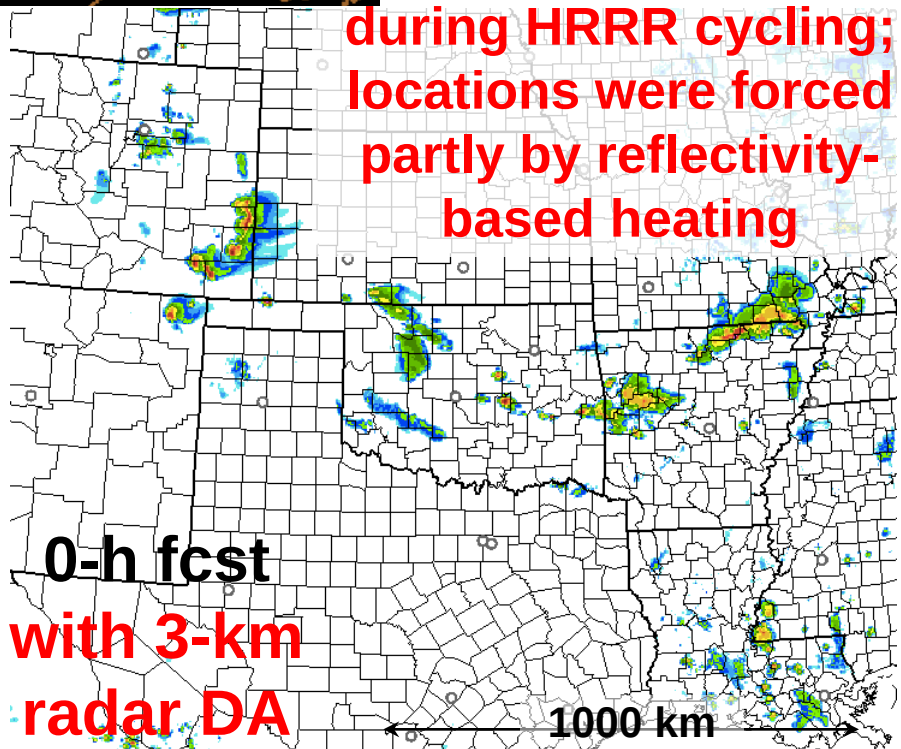
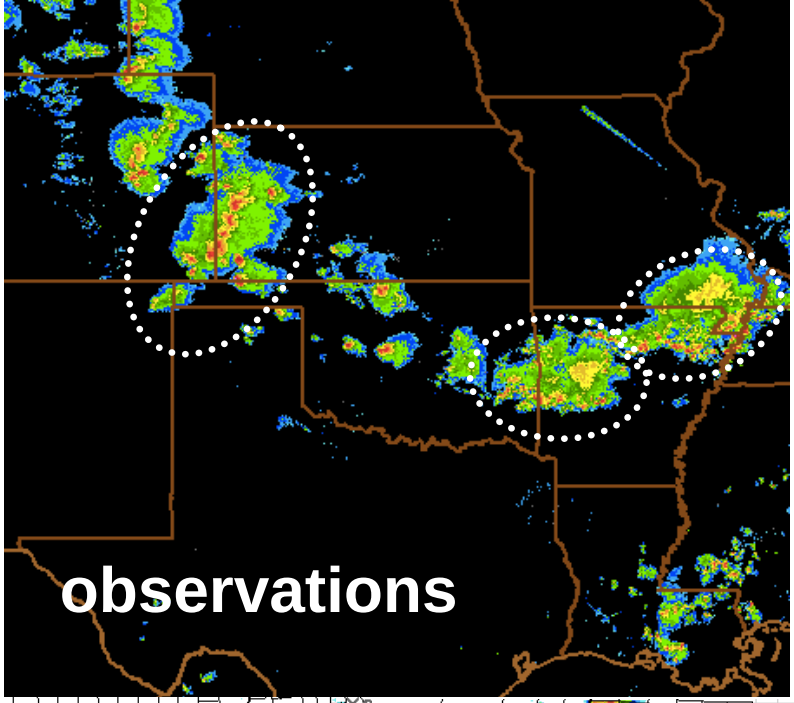




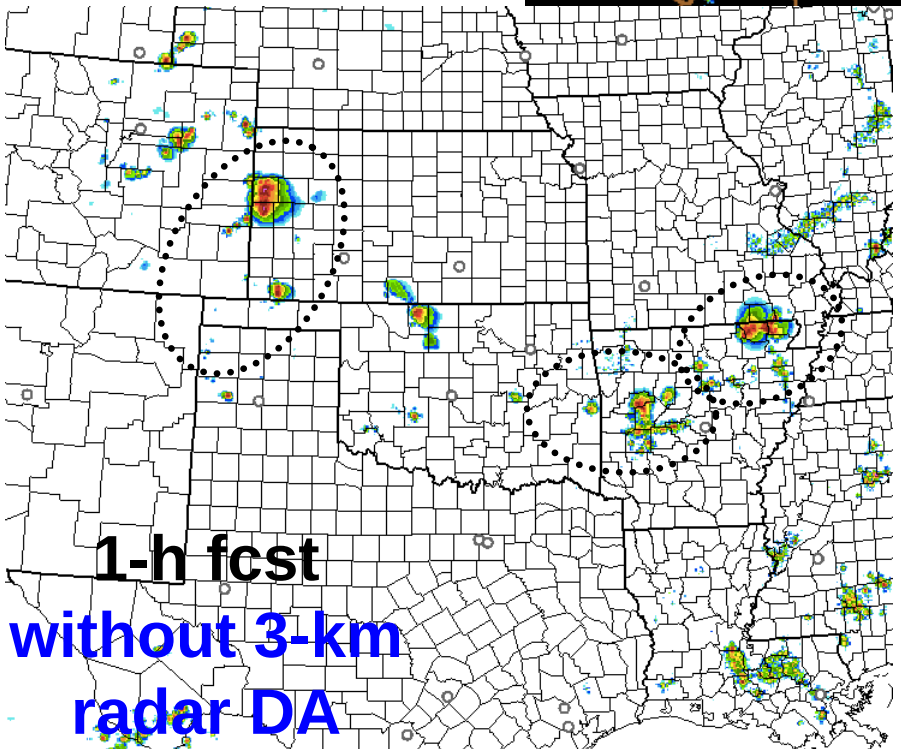


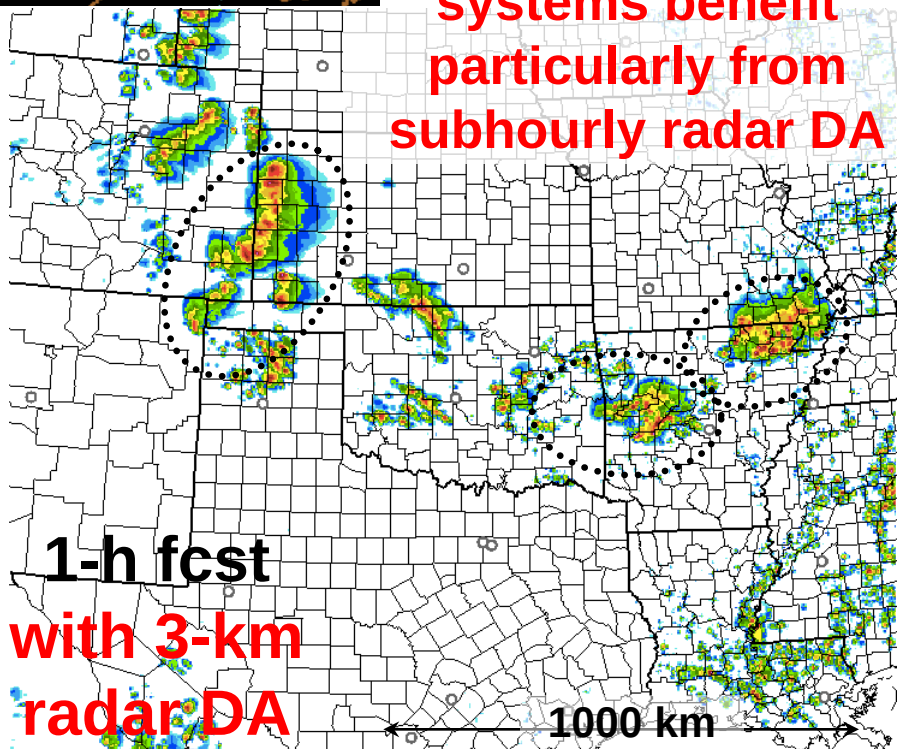
storms developed during HRRR cycling; locations were forced partly by reflectivity-based heating

Composite Reflectivity 2300 UTC 11 June 2011

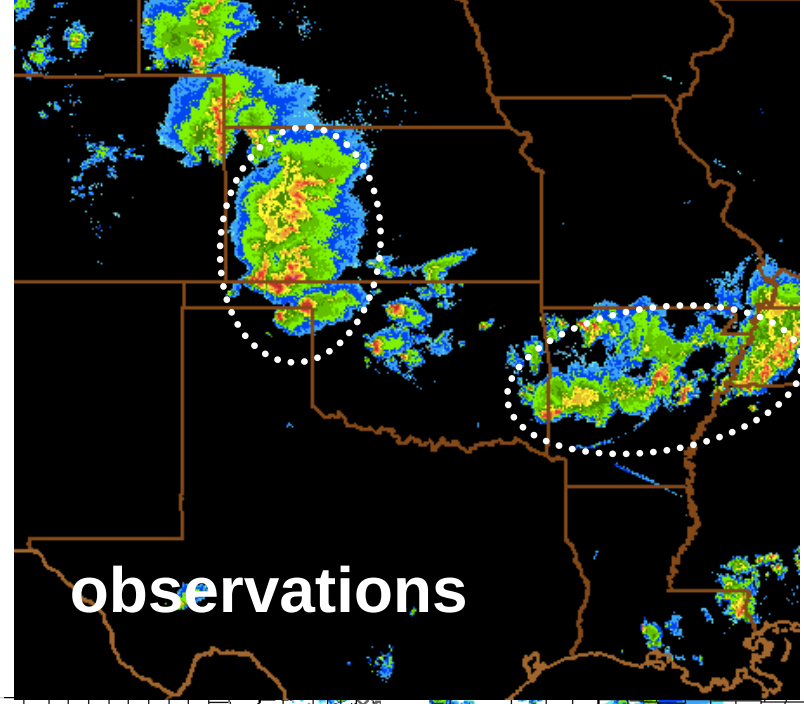


mature convective systems benefit particularly from subhourly radar DA

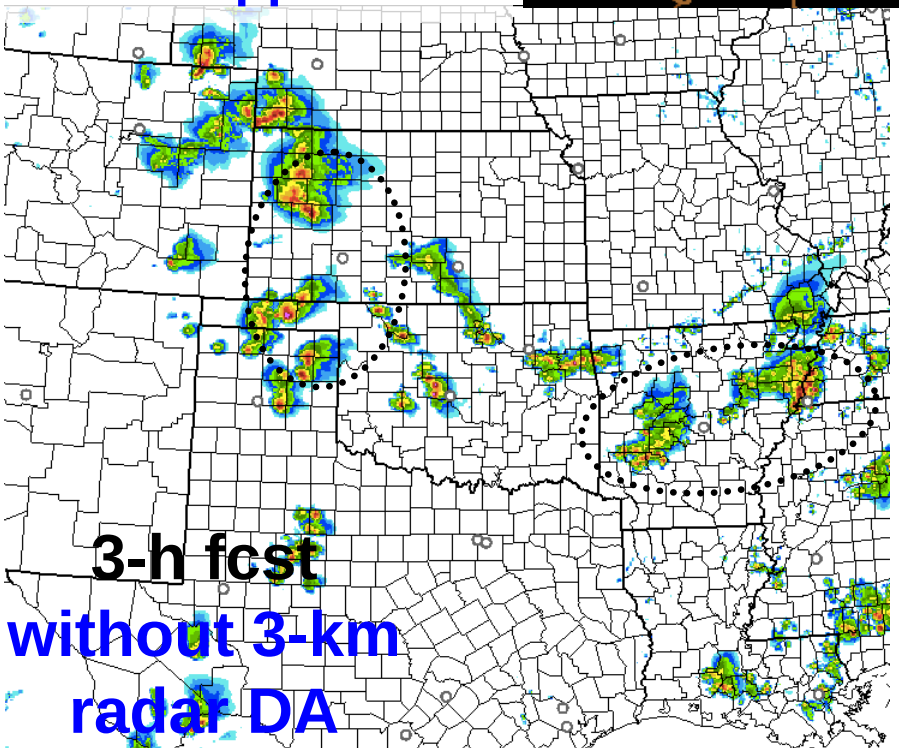


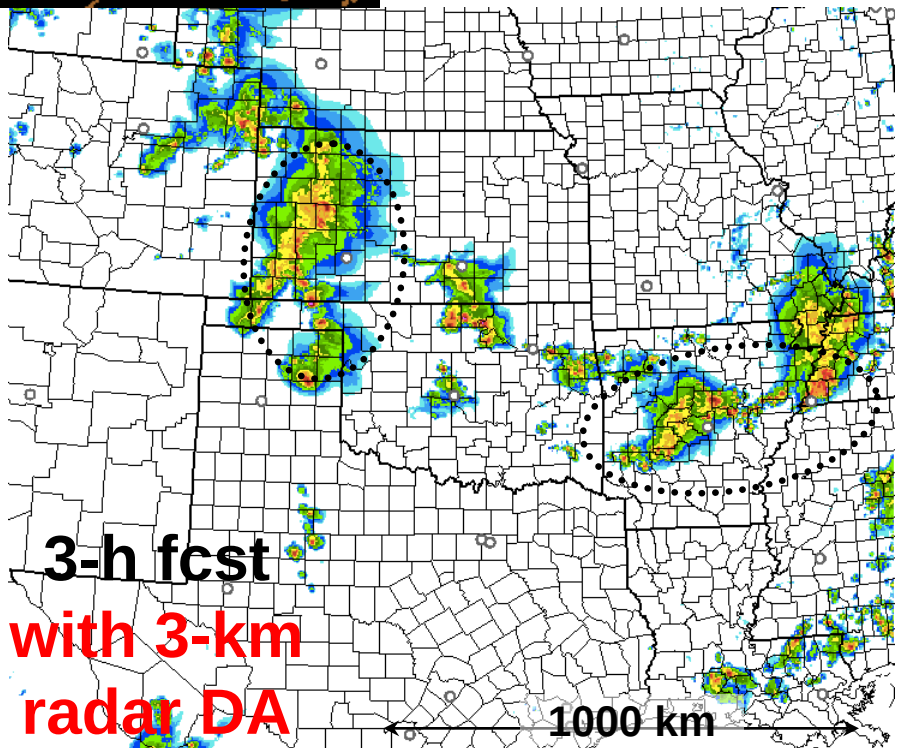


Composite Reflectivity 0100 UTC 12 June 2011



convective systems maturing; errors apparent





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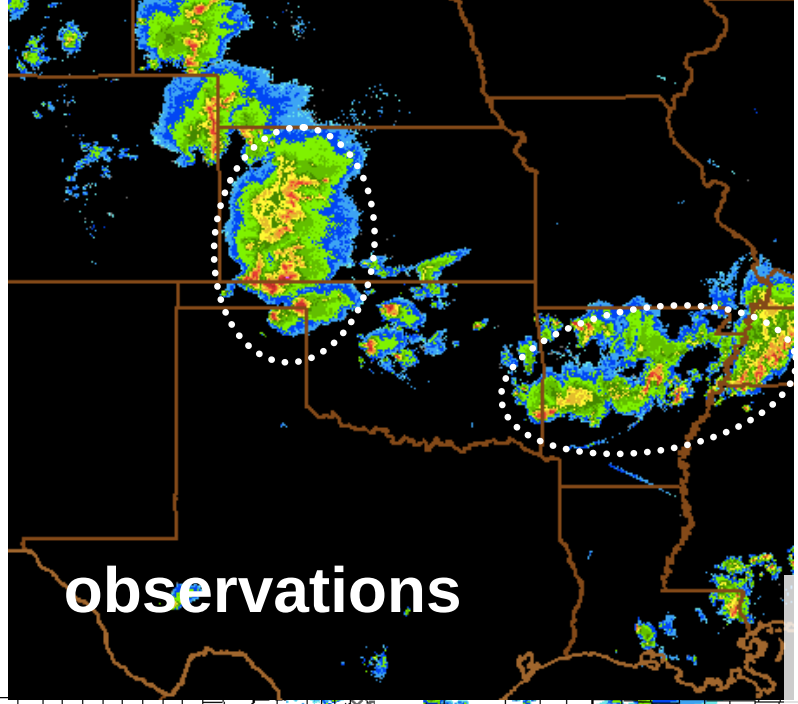
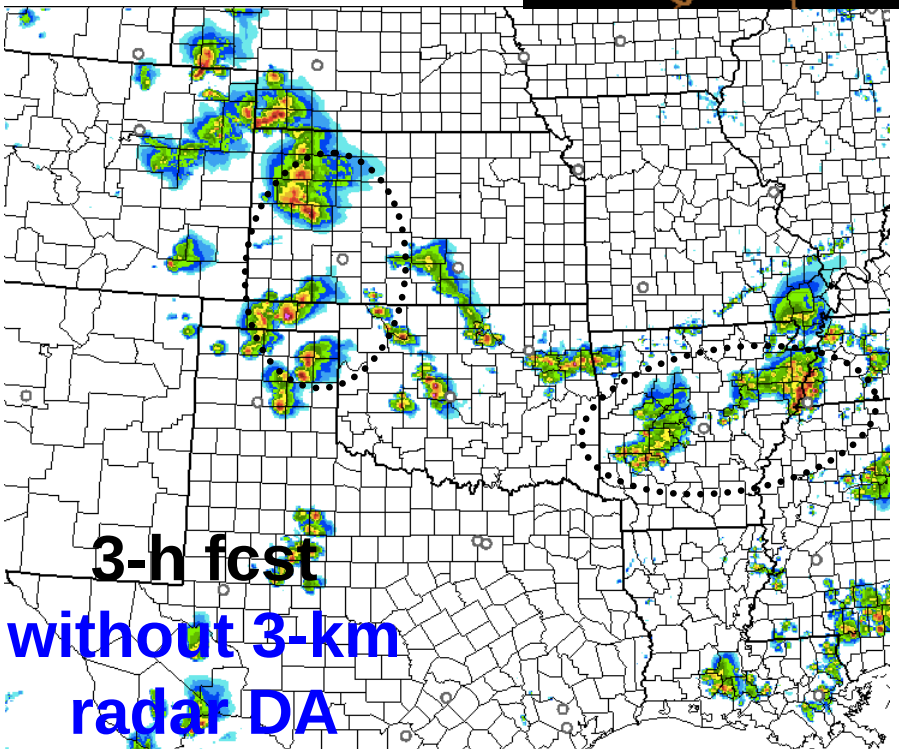
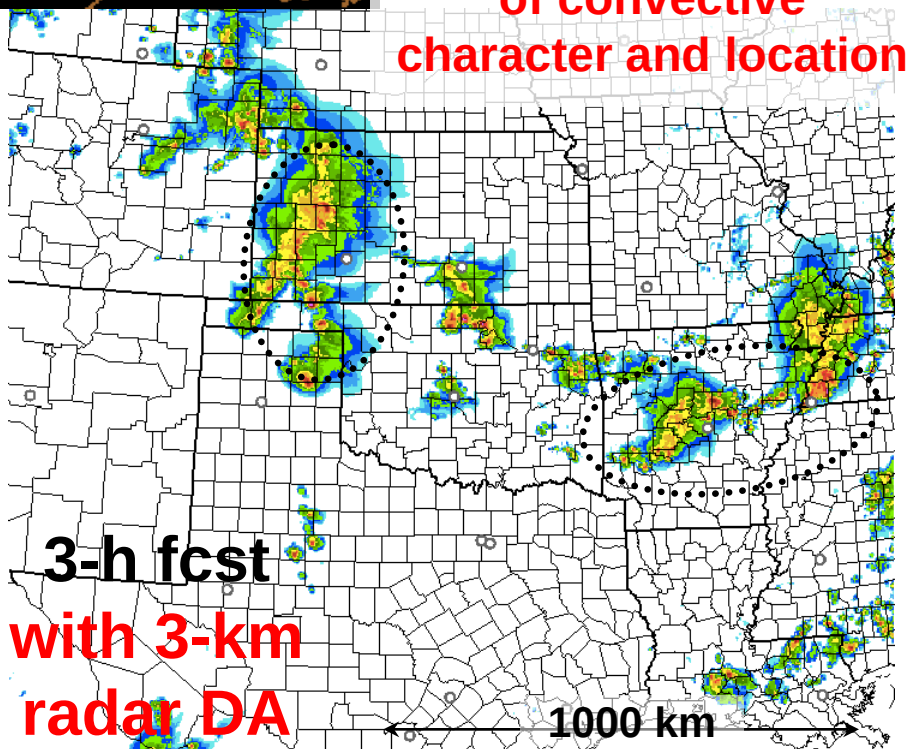
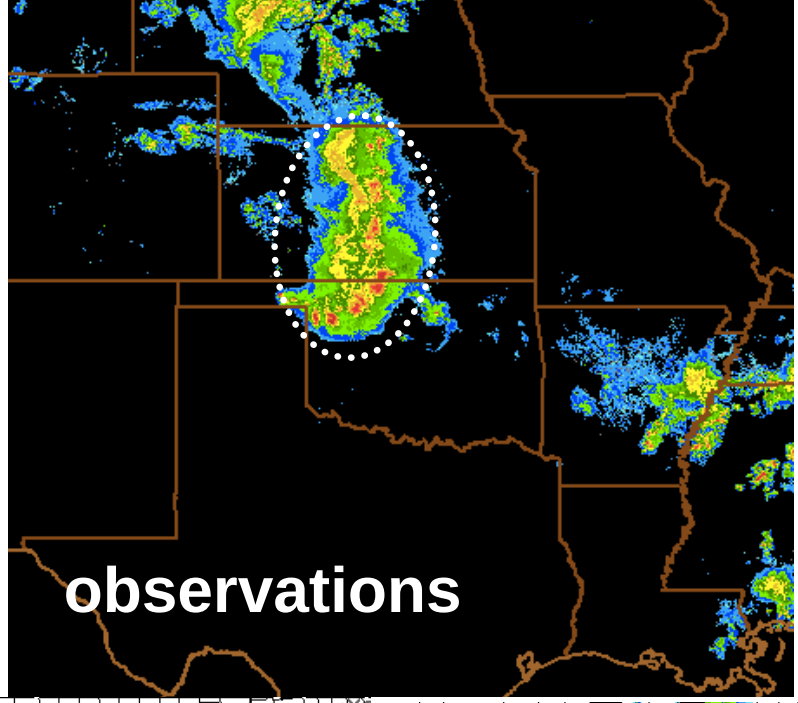


better representation of convective character and location

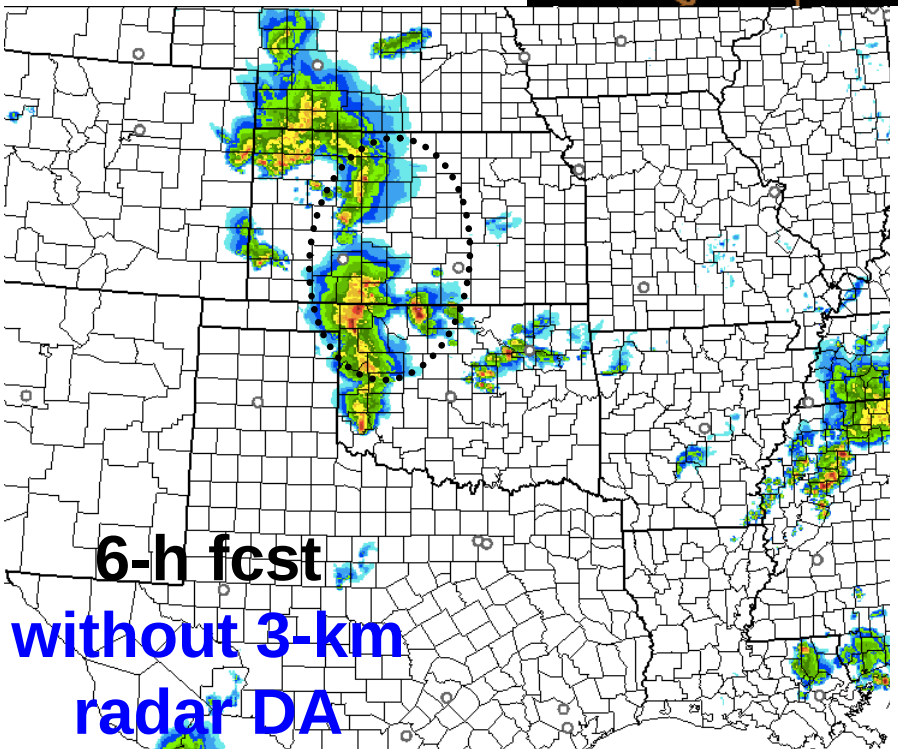


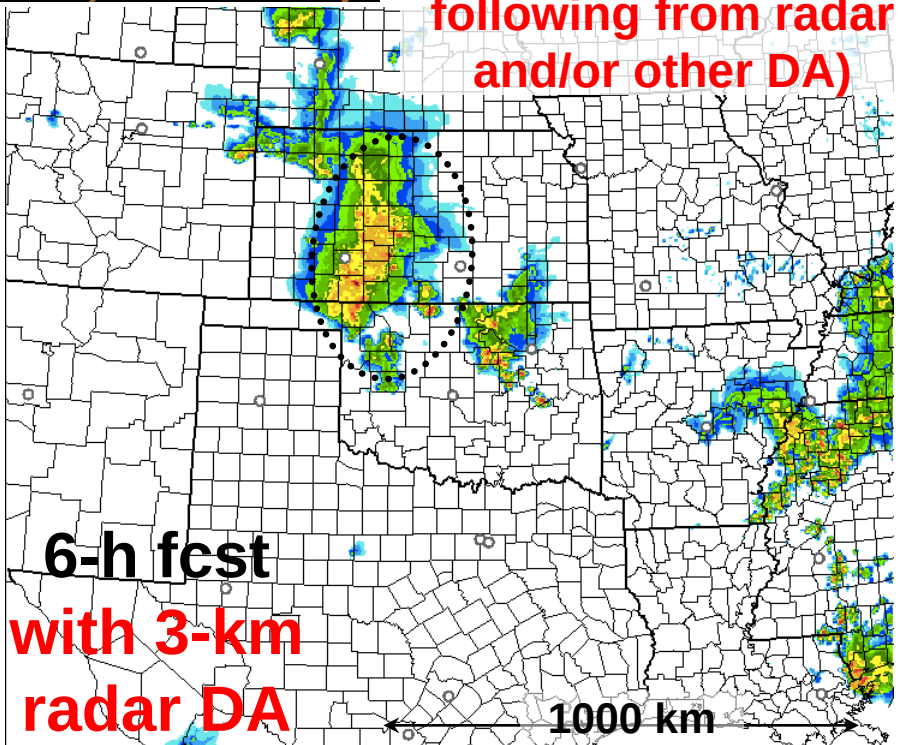


Composite Reflectivity 0400 UTC 12 June 2011



differences persist (cumulative effects following from radar and/or other DA)



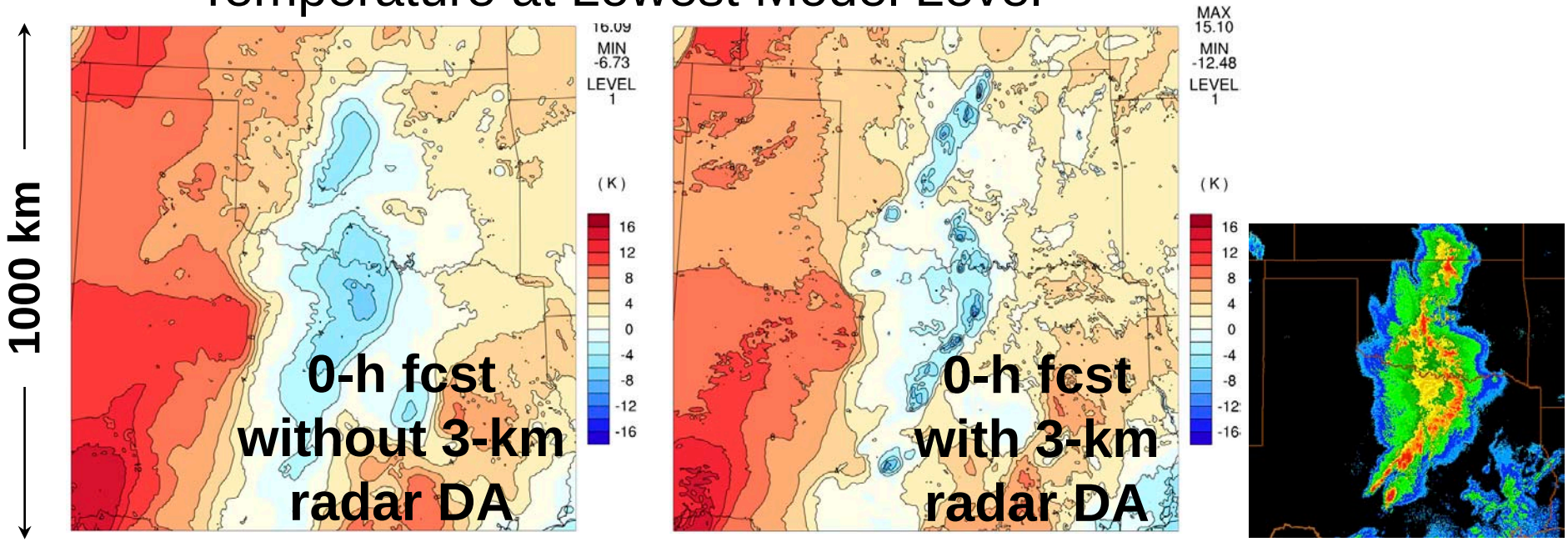


Impressions of 1 Hour of Reflectivity DA in HRRR

Reflectivity DA in HRRR (through temperature forcing) changes convective forecasts on storm scale but not larger scales.

- **increased CSI in first 3 to 5 hours**
- **organization of cold pools during subhourly radar DA**

Temperature at Lowest Model Level



The cost of this method is low: one hour of model integration before the 15-hour forecast. But more costly approaches (Doppler velocity DA and continuous cycling on 3-km grid) will be needed to achieve full potential of HRRR storm-scale forecasts.

Some Ongoing Storm-Scale NWP Projects

High-Resolution Rapid Refresh (HRRR) – NOAA

Short-Term Explicit Prediction (STEP) – NCAR

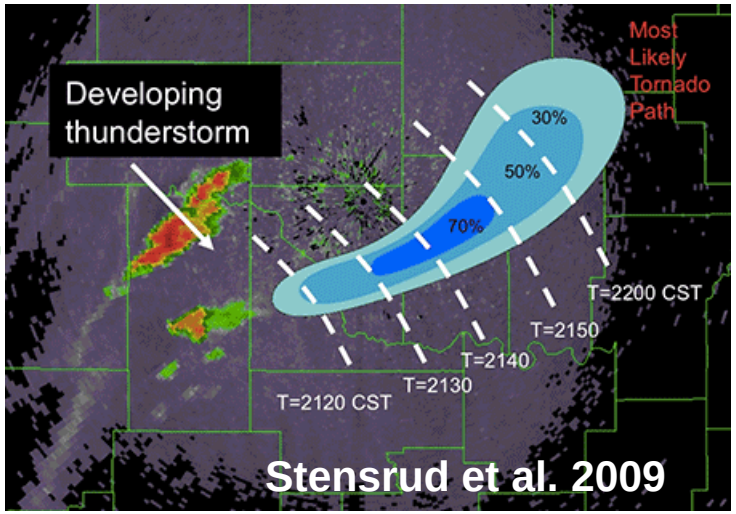
- research to improve 0-12 hour forecasting of high-impact weather
- recent emphasis on data assimilation, diagnostic tools, orographic convection, and transitions between surface-based and elevated convection

Center for Analysis and Prediction of Storms (CAPS) – Univ. of Oklahoma

- springtime CONUS 4-km ensemble forecasts
- NWP research and development

Warn on Forecast – NOAA

- development of probabilistic numerical forecasting systems for guidance in warnings of tornadoes, severe thunderstorms, and flash floods
- NOAA collaboration with Center for Analysis and Prediction of Storms, Social Science Woven into Meteorology, and other partners



Stensrud et al. 2009

Multi-Scale Ensemble DA and Forecasting

collaborators: Glen Romine and Chris Snyder at NCAR

WRF model and Data Assimilation Research Testbed (DART) system

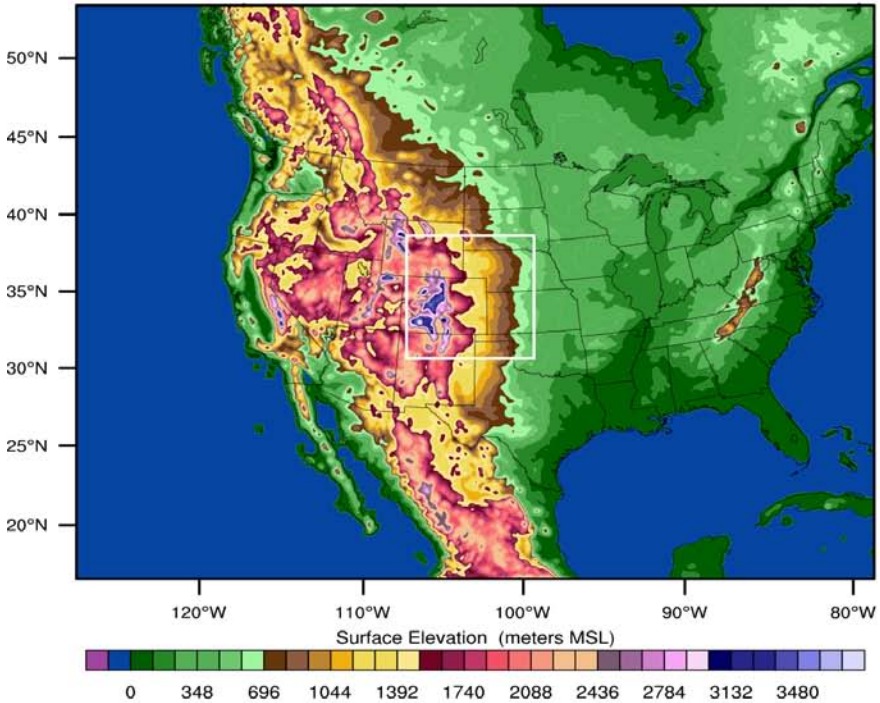
Mesoscale DA on CONUS domain

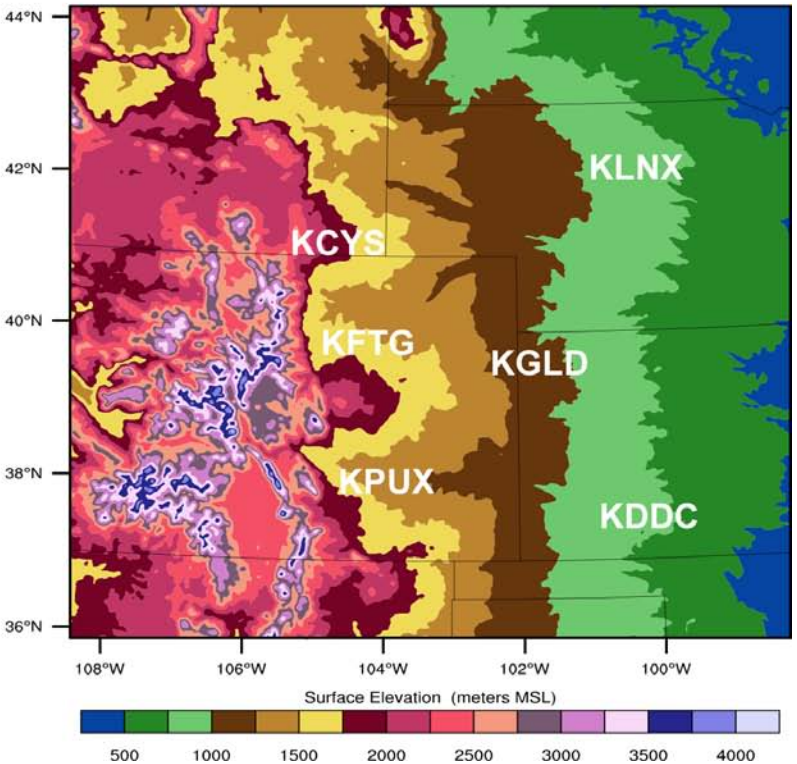
Radar DA on nested storm-scale domain (complex terrain)

4-17 June 2009 retrospective (overlaps VORTEX2 field program)

Probabilistic analyses and 6-h forecasts from 50 ensemble members

surface elevation (m MSL)





15 km mesoscale, 3 km storm-scale

Multi-Scale Ensemble DA and Forecasting

collaborators: Glen Romine and Chris Snyder at NCAR

<u>Mesoscale (15-km) 50-member WRF ensemble</u>

Standard "mesoscale" observations every 3 hours: radiosonde, surface, buoy, aircraft, satellite cloud-track winds

DART ensemble adjustment Kalman filter (EAKF), adaptive prior inflation, 320 km (350 mb) horiz. (vert.) localization half width

<u>Storm-scale (3-km) 50-member WRF ensemble</u>

One-way nest within mesoscale ensemble

Doppler velocity and "no precipitation" reflectivity* every 3 min from 6 radars (WSR-88D)

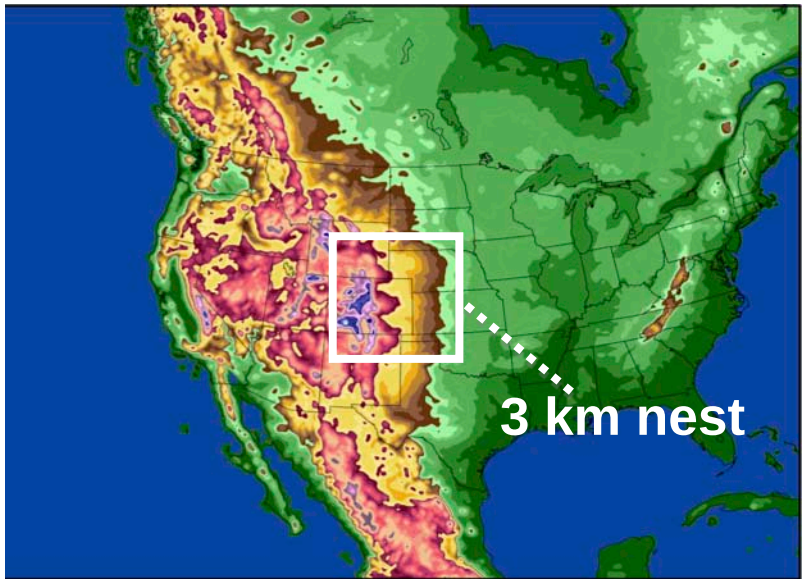
Simple quality control and superobbing

(Overly) simple observation operators and observation errors

Additive noise + adaptive inflation

12 km (6 km) localization half width in horizontal (vertical)

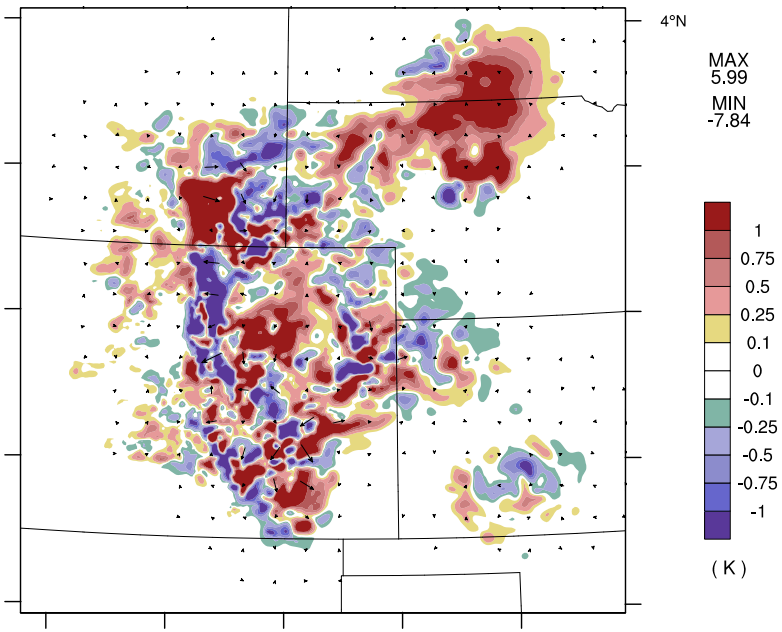
Velocity unfolding during cycled radar DA



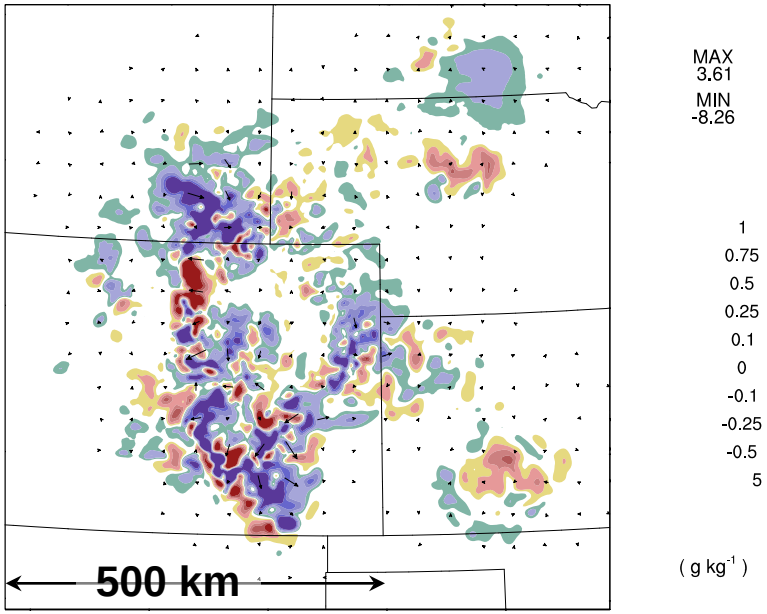
* low values of reflectivity, indicating no precipitation (multiple issues worthy of discussion here)

Cumulative Effects of 1 Hour of Radar DA

total temperature increment
lowest model level

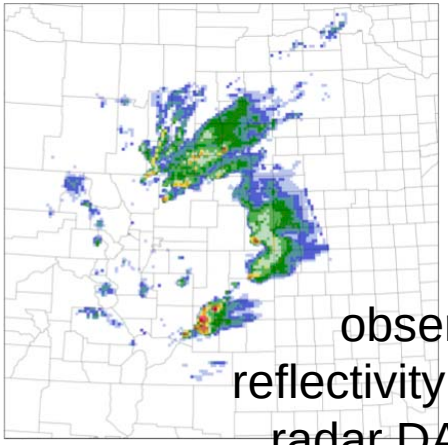


total water-vapor increment
lowest model level



warming and moistening typical near convection

large increments outside precipitation regions, too



observed reflectivity at end of radar DA period

Ensemble-Based Probabilistic Storm-Scale Forecasts

Probability of updraft helicity* > 75 $m^2 s^{-2}$ during 6-hour forecast

* vertical velocity and rotation about vertical axis, vertically integrated

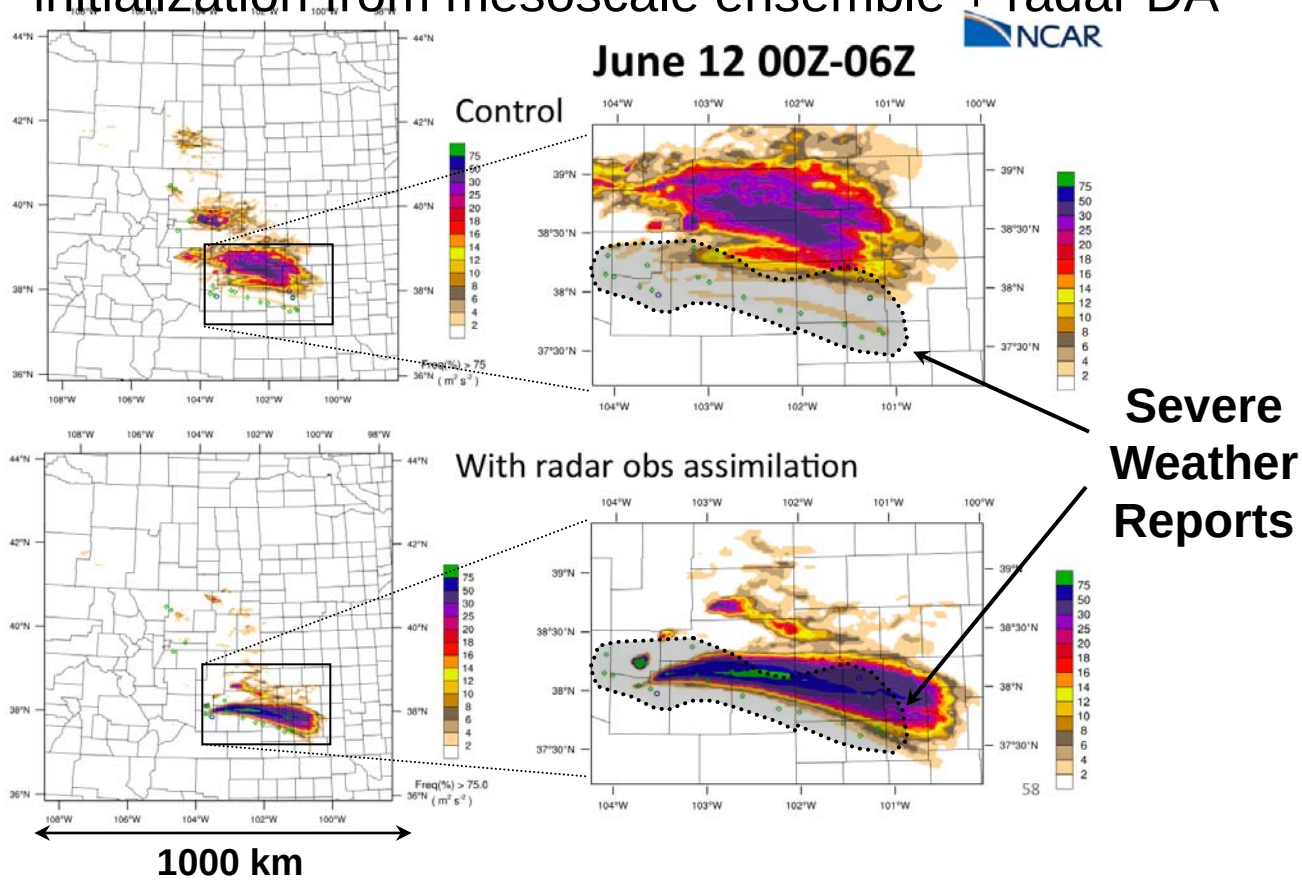
Two 50-member ensemble forecasts

"control": members initialized from mesoscale ensemble without radar DA

"with radar DA": initialization from mesoscale ensemble + radar DA

Control (no radar DA)

With radar DA

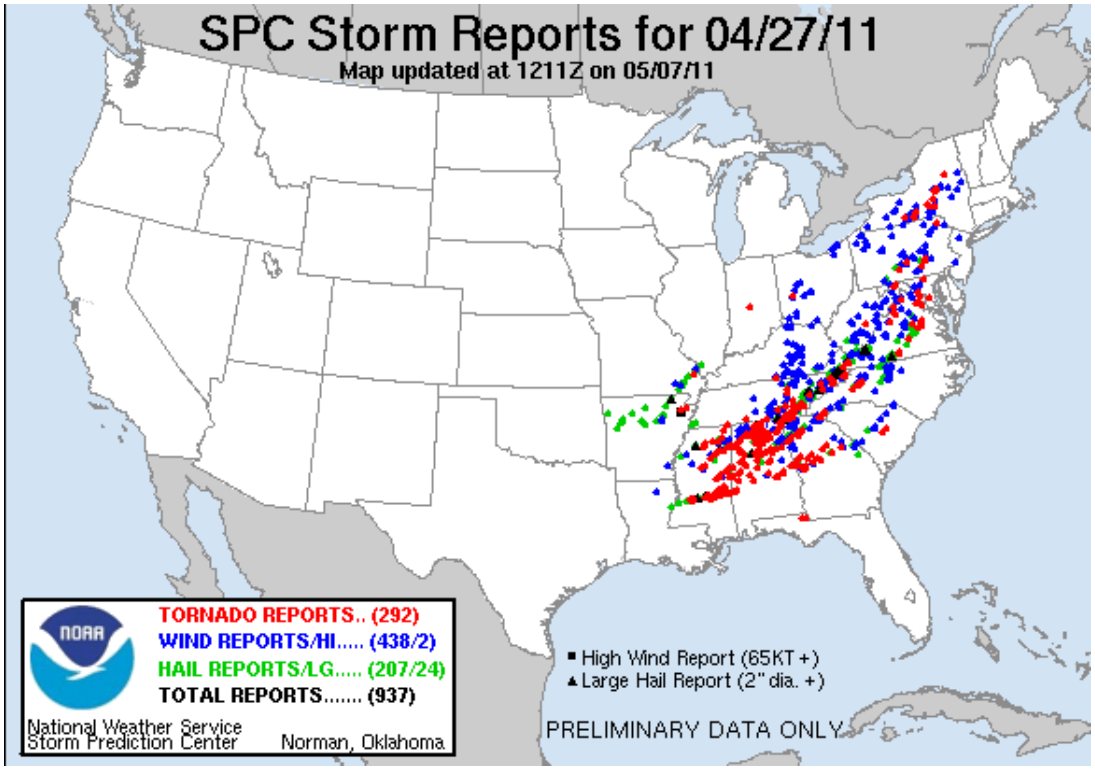


Severe Weather Reports

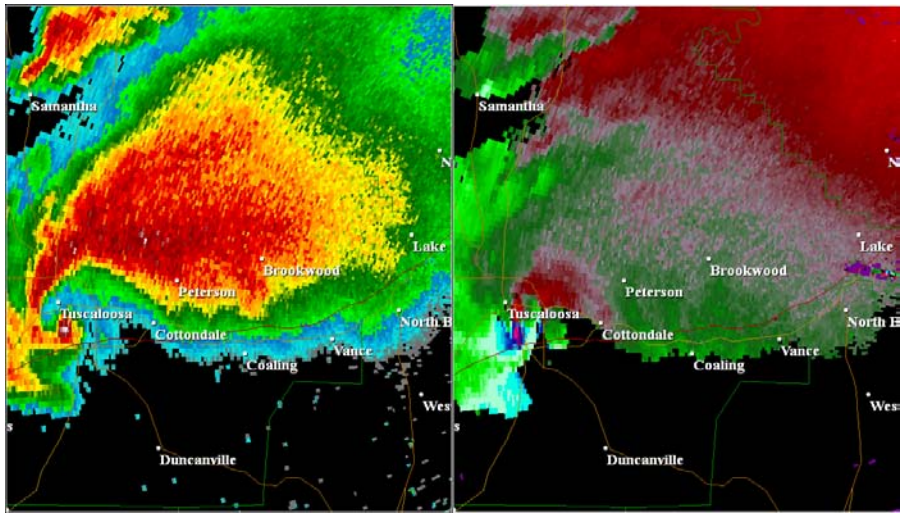
27 April 2011 Supercell Tornado Outbreak

roughly 300 tornadoes

348 fatalities from tornadoes and other thunderstorm hazards



Tuscaloosa, AL tornado
source: CBS 42 Birmingham, AL



Experiment Summary: Supercell Tornado Outbreak

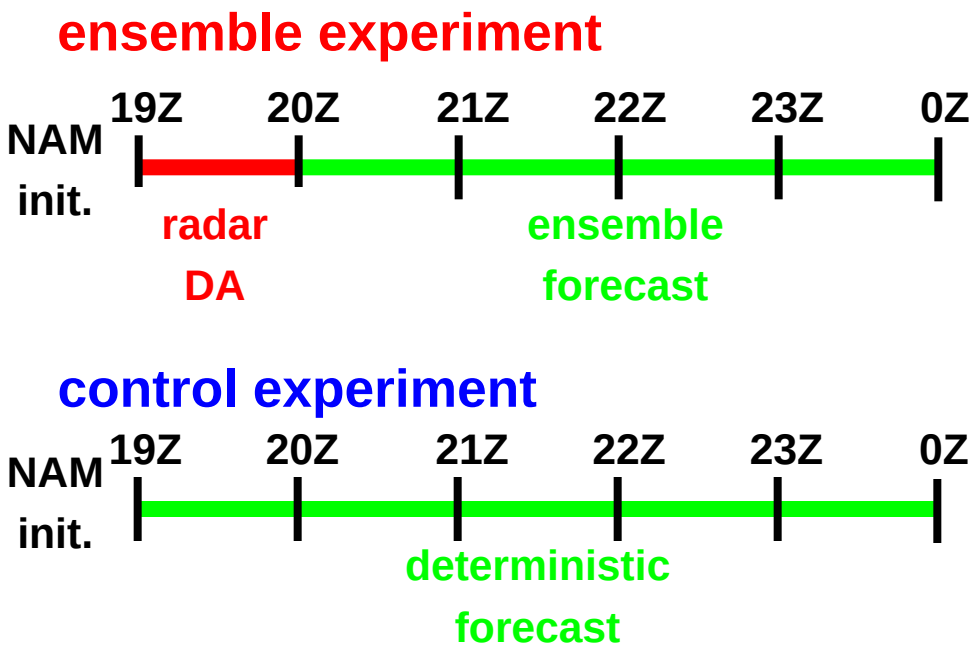
45-member WRF ensemble (Δx=3 km) initialized from NAM (Δx=12 km)

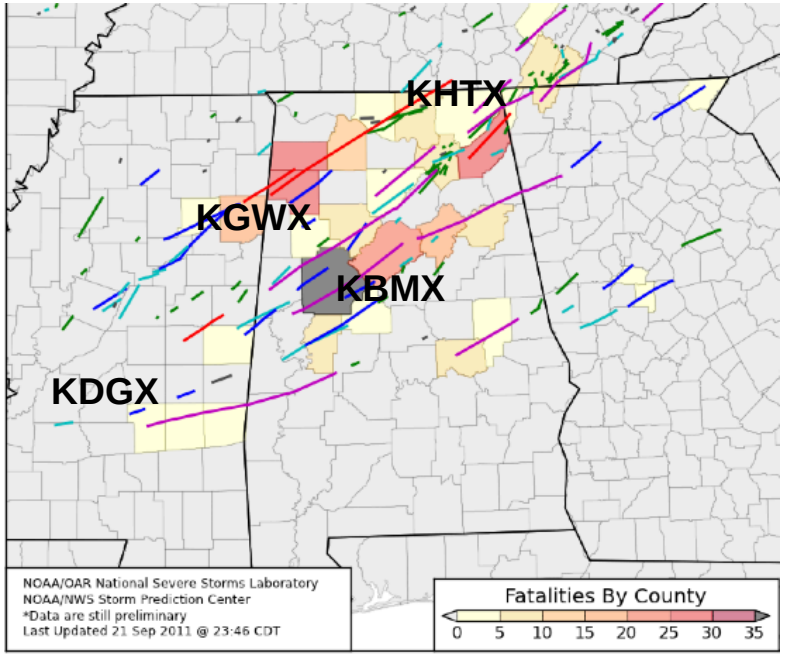
- 600-km domain for these preliminary experiments; 1200-km domain planned

Velocity and reflectivity data assimilated every 3 min for 1 h

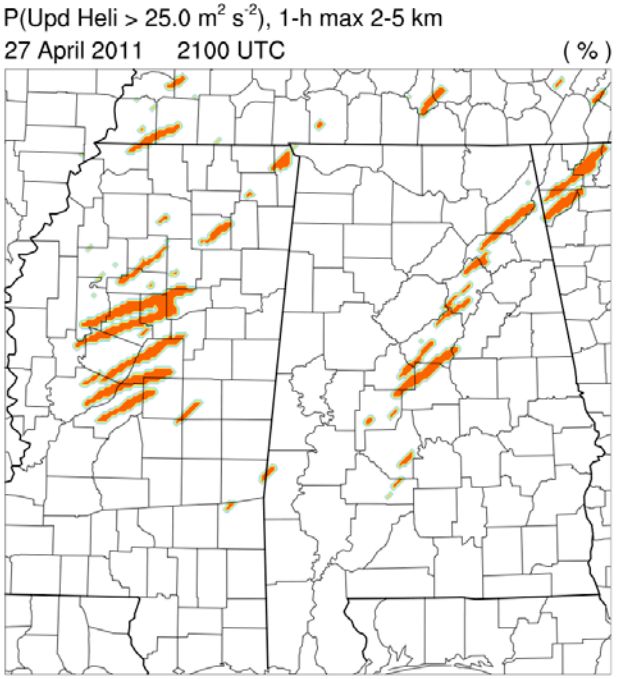
- KBMX, KDGX, KGWX, KHTX ; simple, automated quality control
- additive noise during cycled radar DA -- *only source of ensemble spread*
- WRF-DART ensemble adjustment Kalman filter

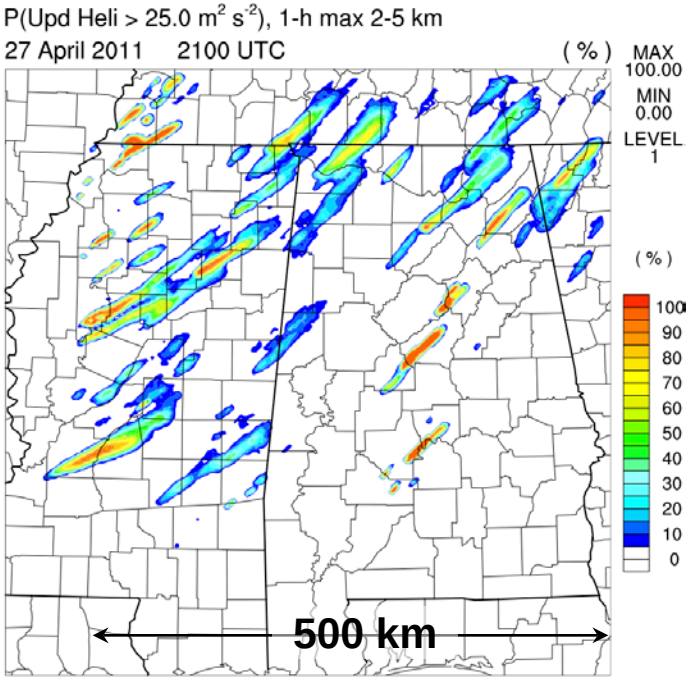
Ensemble forecast produced after radar DA





Probability of Rotating Updrafts (2-5 km updraft helicity > 25 $m^2 s^{-2}$) 2000-2100 UTC

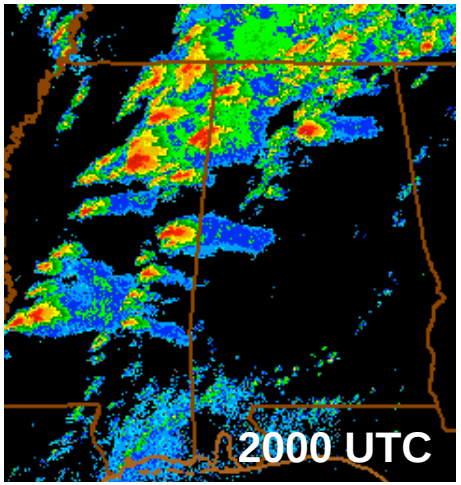


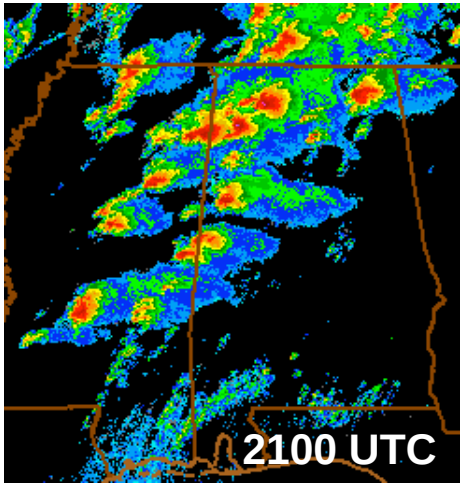


control experiment
(no radar DA, deterministic forecast)

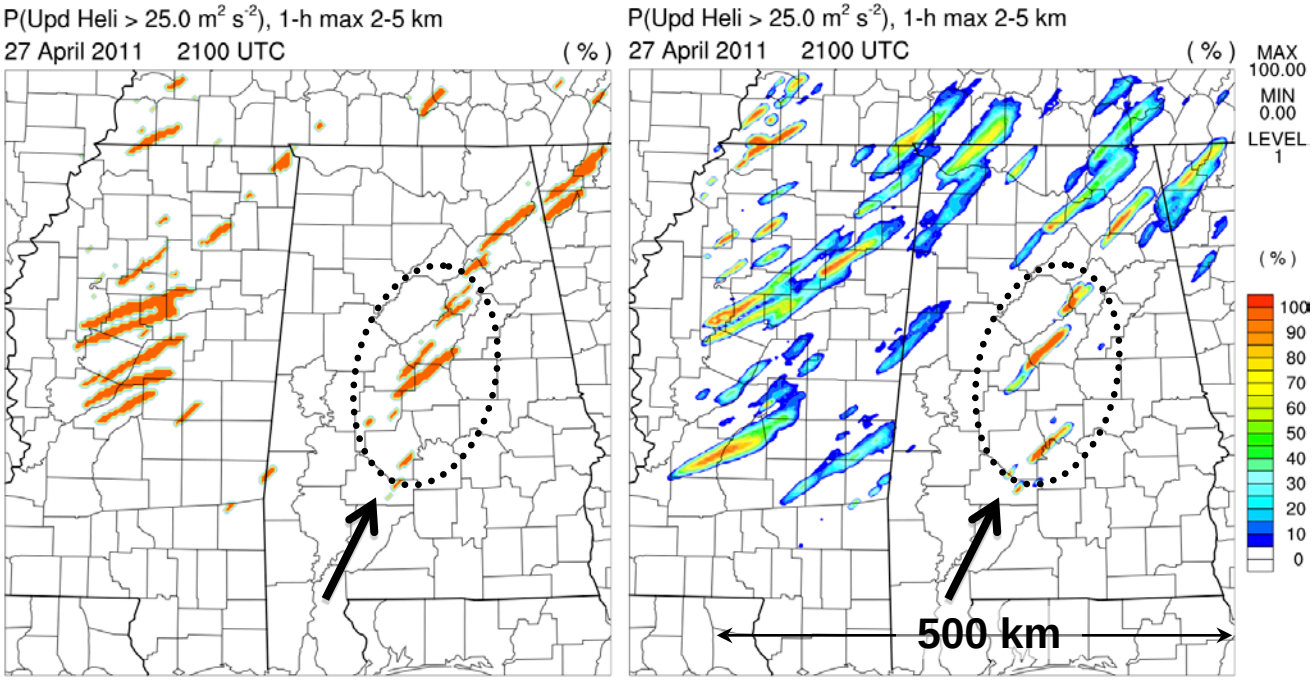
radar DA, 0-1 h ensemble forecast

NSSL Composite Reflectivity





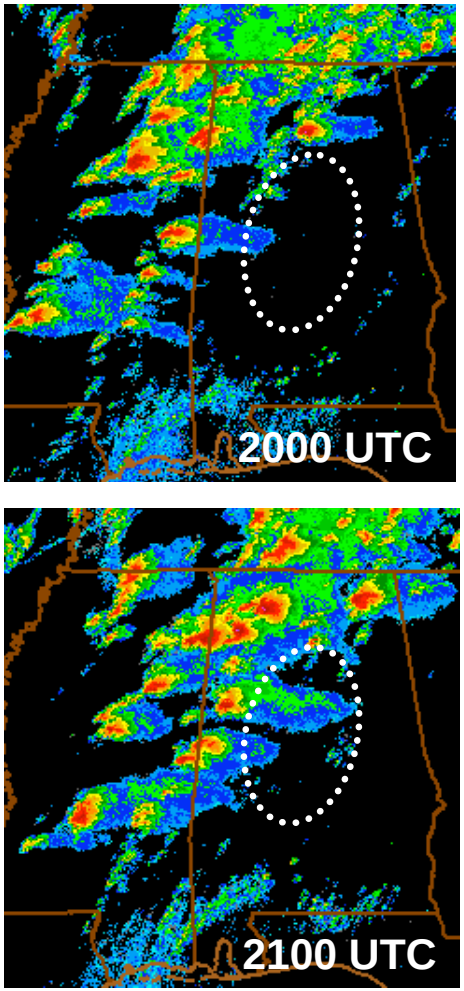
Probability of Rotating Updrafts (2-5 km updraft helicity > 25 $m^2 s^{-2}$) 2000-2100 UTC



control experiment
(no radar DA, deterministic forecast)

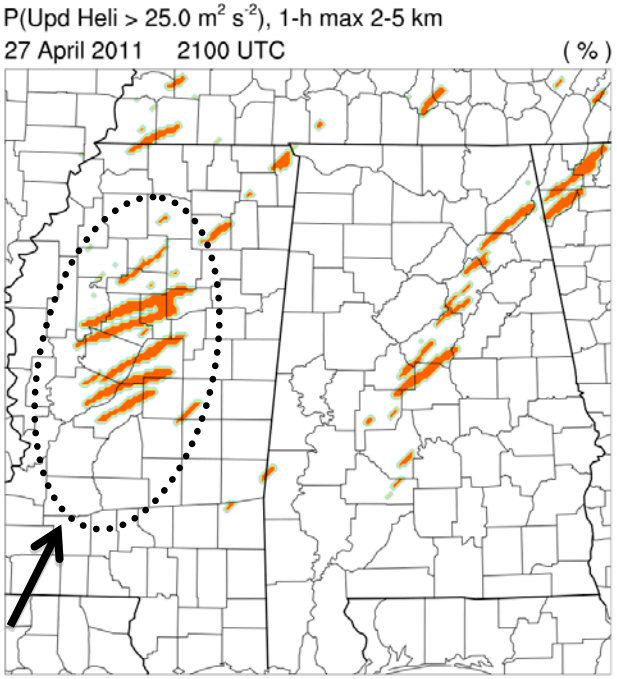
radar DA, 0-1 h ensemble forecast

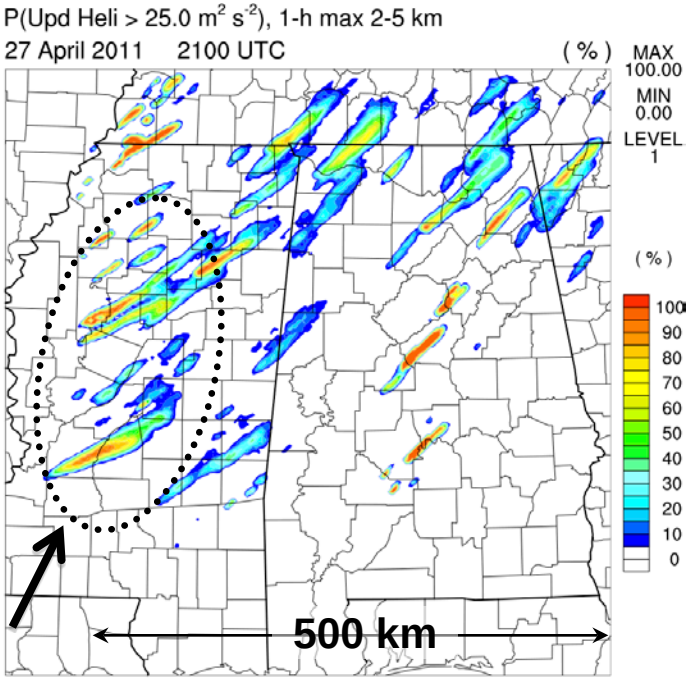
NSSL Composite Reflectivity



radar DA has not eliminated spurious storms from forecast

Probability of Rotating Updrafts (2-5 km updraft helicity > 25 $m^2 s^{-2}$) 2000-2100 UTC

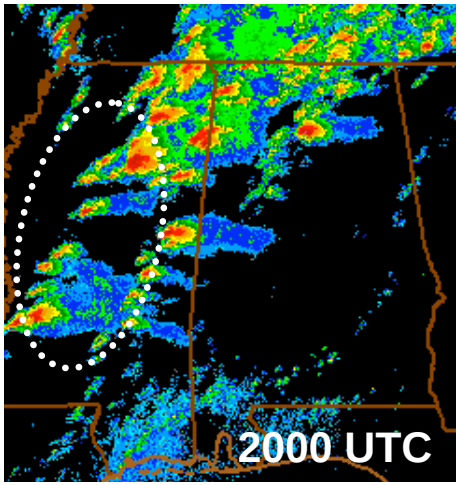


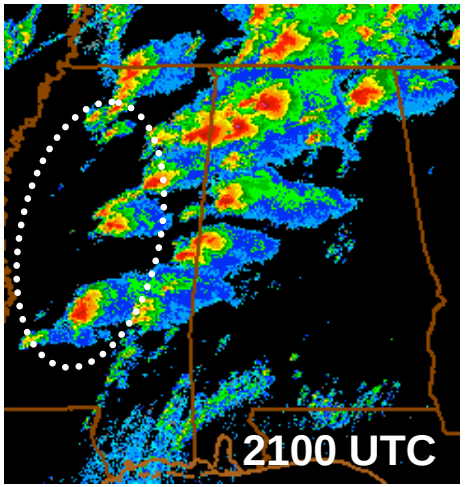


control experiment
(no radar DA, deterministic forecast)

radar DA, 0-1 h ensemble forecast

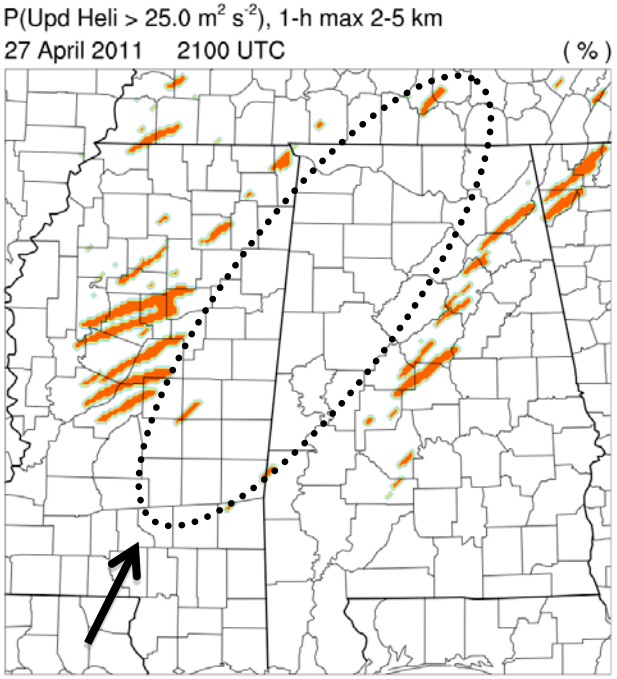
NSSL Composite Reflectivity

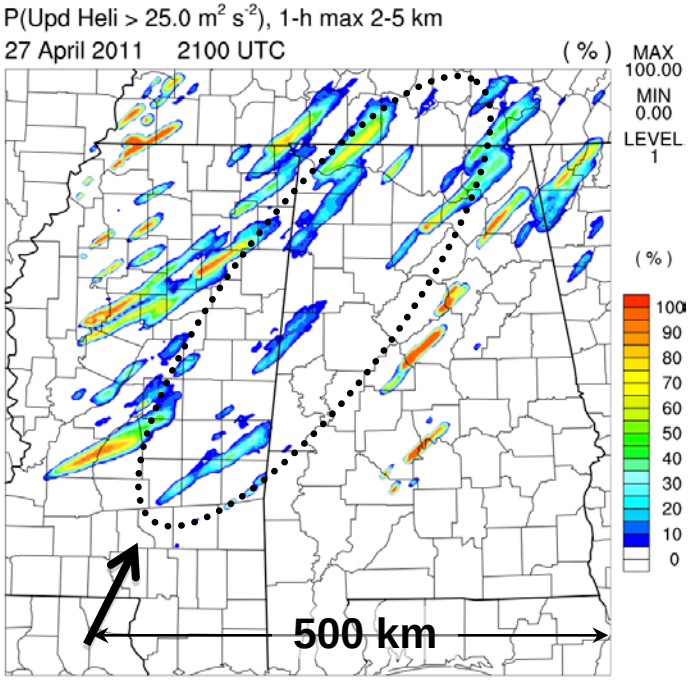




radar DA reorganizes storms in region where mesoscale environment (observed and simulated) was already supportive of convective storms

Probability of Rotating Updrafts (2-5 km updraft helicity > 25 $m^2 s^{-2}$) 2000-2100 UTC

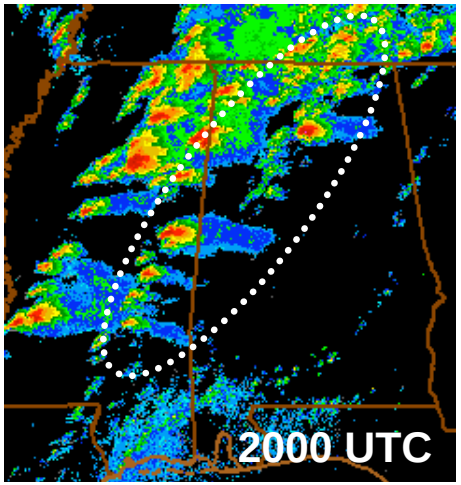


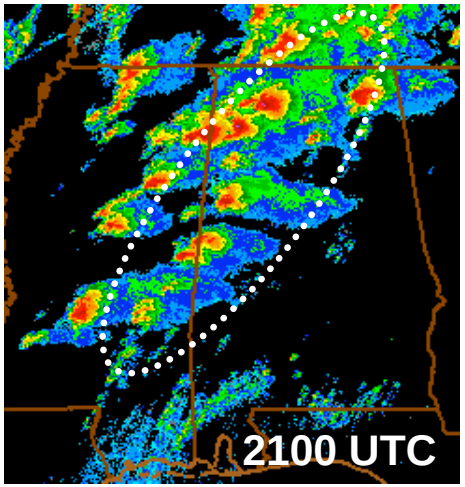


control experiment
(no radar DA, deterministic forecast)

radar DA, 0-1 h ensemble forecast

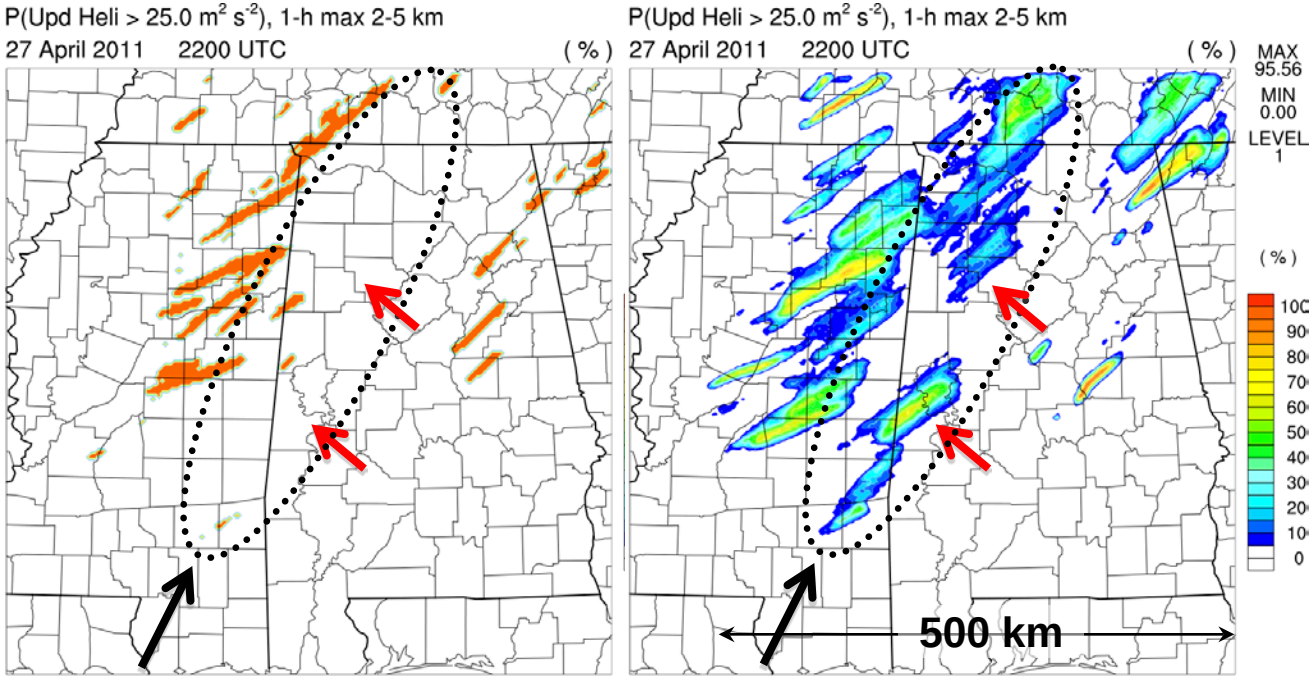
NSSL Composite Reflectivity





radar DA introduces viable storms where they were needed; simulated mesoscale environment must have been nearly supportive of convective storms

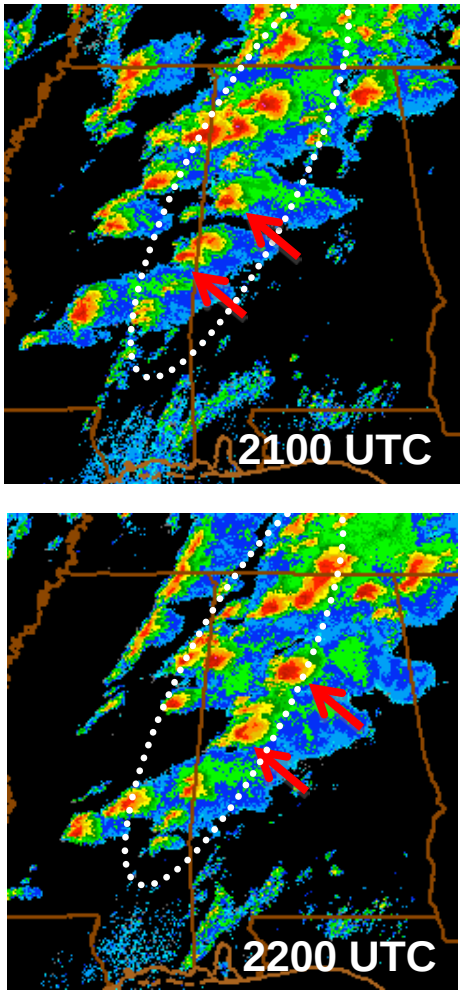
Probability of Rotating Updrafts (2-5 km updraft helicity > 25 $m^2 s^{-2}$) 2000-2100 UTC



control experiment
(no radar DA, deterministic forecast)

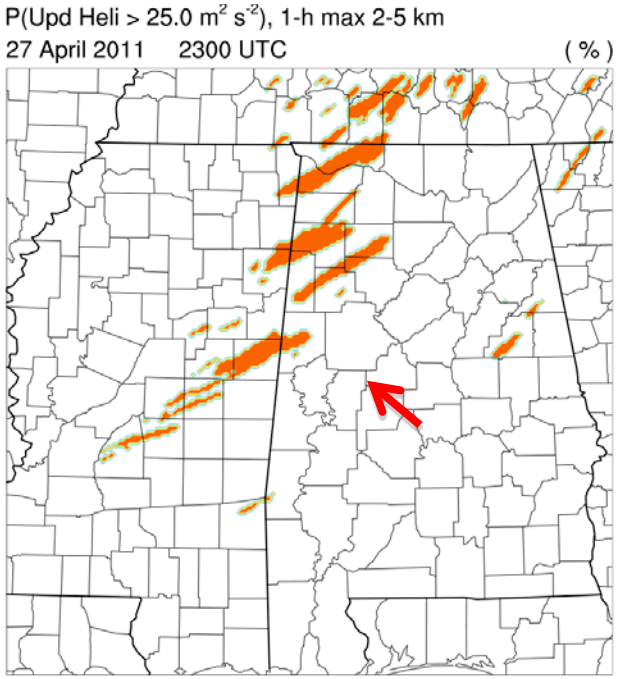
radar DA, 1-2 h ensemble forecast

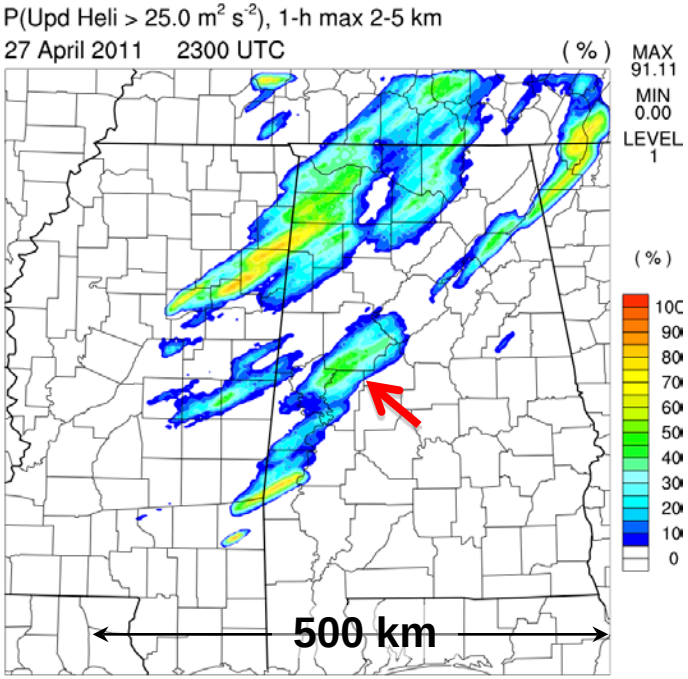
NSSL Composite Reflectivity



some storms introduced by radar DA persist; probabilities vary among storms

Probability of Rotating Updrafts (2-5 km updraft helicity > 25 $m^2 s^{-2}$) 2000-2100 UTC

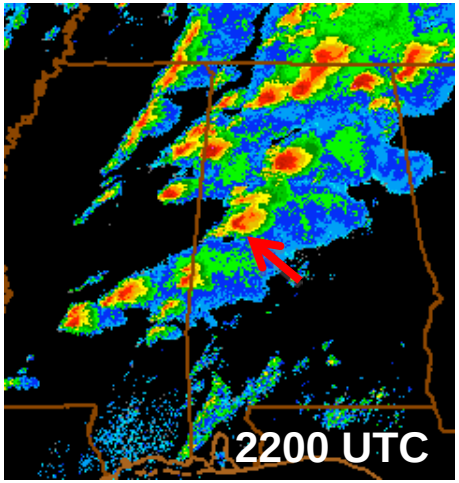


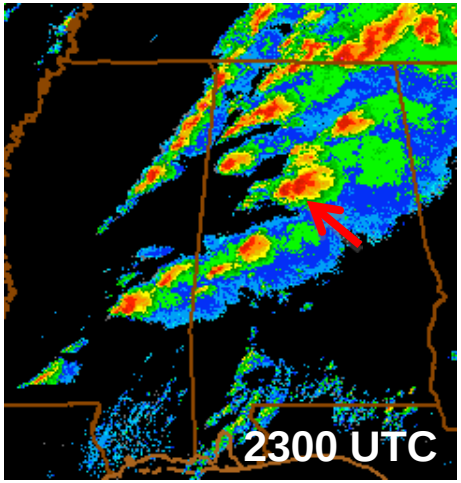


control experiment
(no radar DA, deterministic forecast)

radar DA, 2-3 h ensemble forecast

NSSL Composite Reflectivity



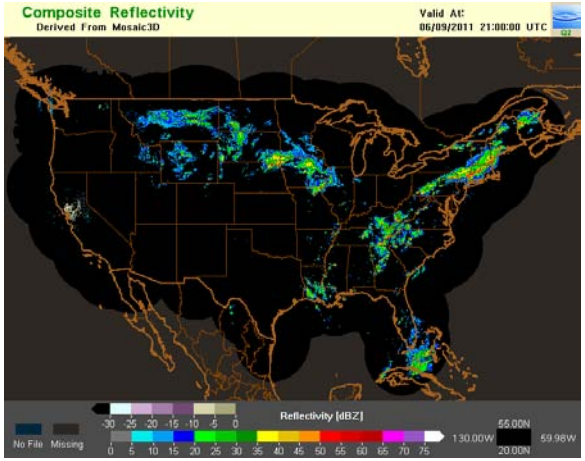


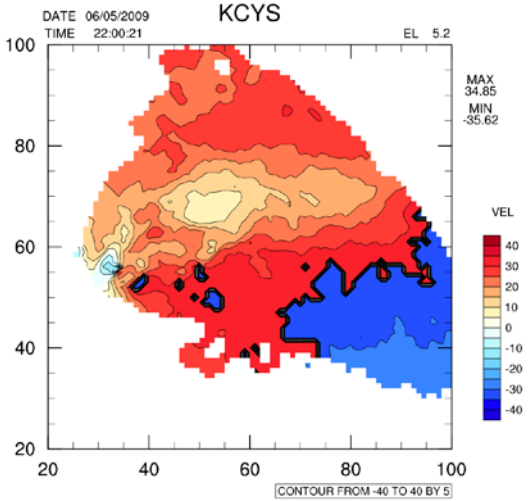
although ensemble continues to show signal for Tuscaloosa storm, ensemble has become underdispersive overall

Storm-Scale Radar DA: Where to Go from Here

To support convective storm NWP, a multi-national real-time radar dataset that includes Doppler velocity is needed ASAP, with quality control geared toward NWP (next presentation).

- homemade tools for q. c. used for case studies just shown
- some q. c. (e.g., velocity unfolding) best handled during cycled radar DA





There is significant room for improvement in how we use conventional radar observations in storm-scale DA.

- "no precipitation" reflectivity observations
- observation operators
- situation-dependent observation selection for DA (reducing the size of the assimilated dataset by orders of magnitude)

Storm-Scale Radar DA: Where to Go from Here

Research experience is needed with continuous cycling of all observations – including radar – in convection-allowing models.

- results shown today and in research literature instead involve cycling in larger-scale model, followed by short period of radar DA in convection-allowing model

The community is moving toward variational-ensemble hybrid methods for mesoscale DA in general. Success with ensemble methods will depend particularly on the quality of the NWP model.

- detection and reduction of model biases (parameterizations particularly important for convective scales)
- ensemble design

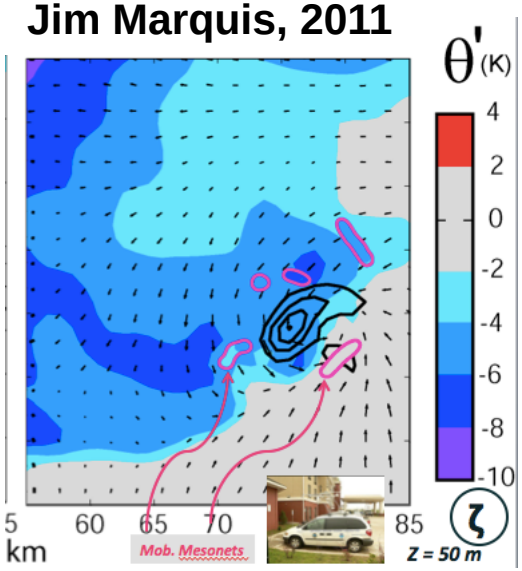
Continue to make NWP a component of convective-storm field programs.

- best opportunity to verify high-resolution forecasts

Have realistic expectations for storm-scale radar DA.

- forecast improvement on small scales, first ~3 hours

Jim Marquis, 2011



Warn-on-Forecast Storm-Scale Radar DA Workshops

first meeting October 2011 in Norman, Oklahoma

organizers: David Stensrud (NOAA), Ming Xue (CAPS), David Dowell (NOAA)

radar-data quality control

multiple radar DA methods

high-resolution storm analysis

NWP successes and failures

model error

polarimetric radar

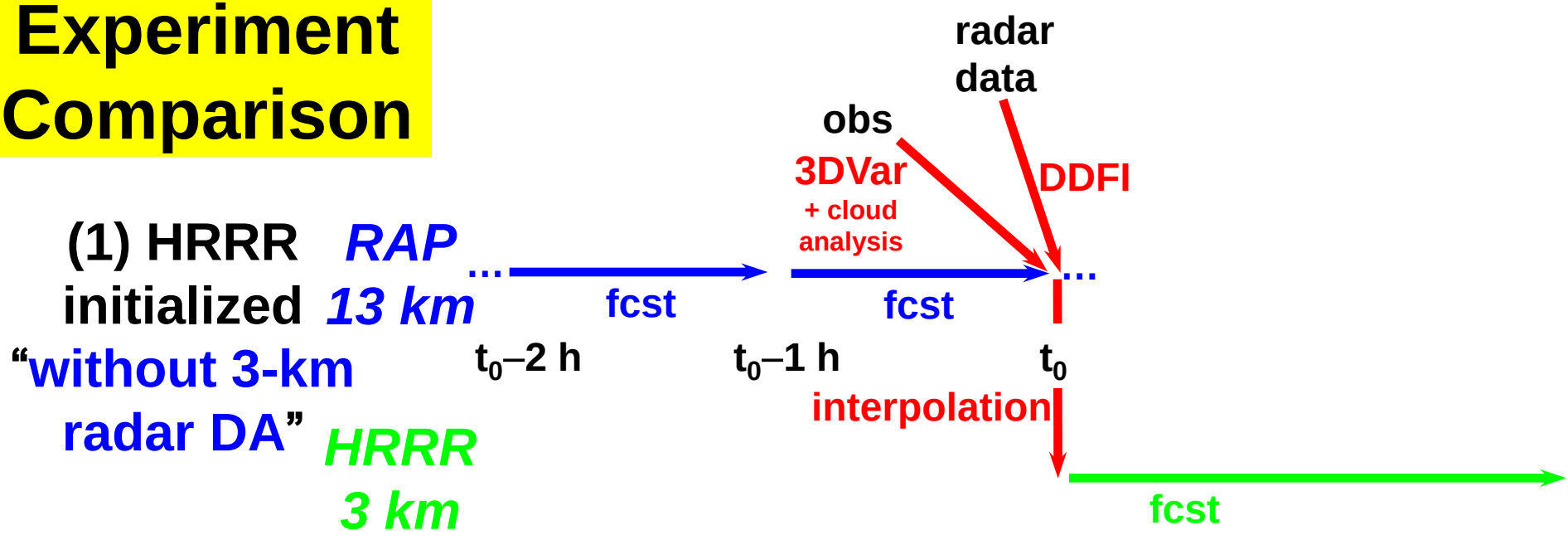
next meeting in 2013 or 2014

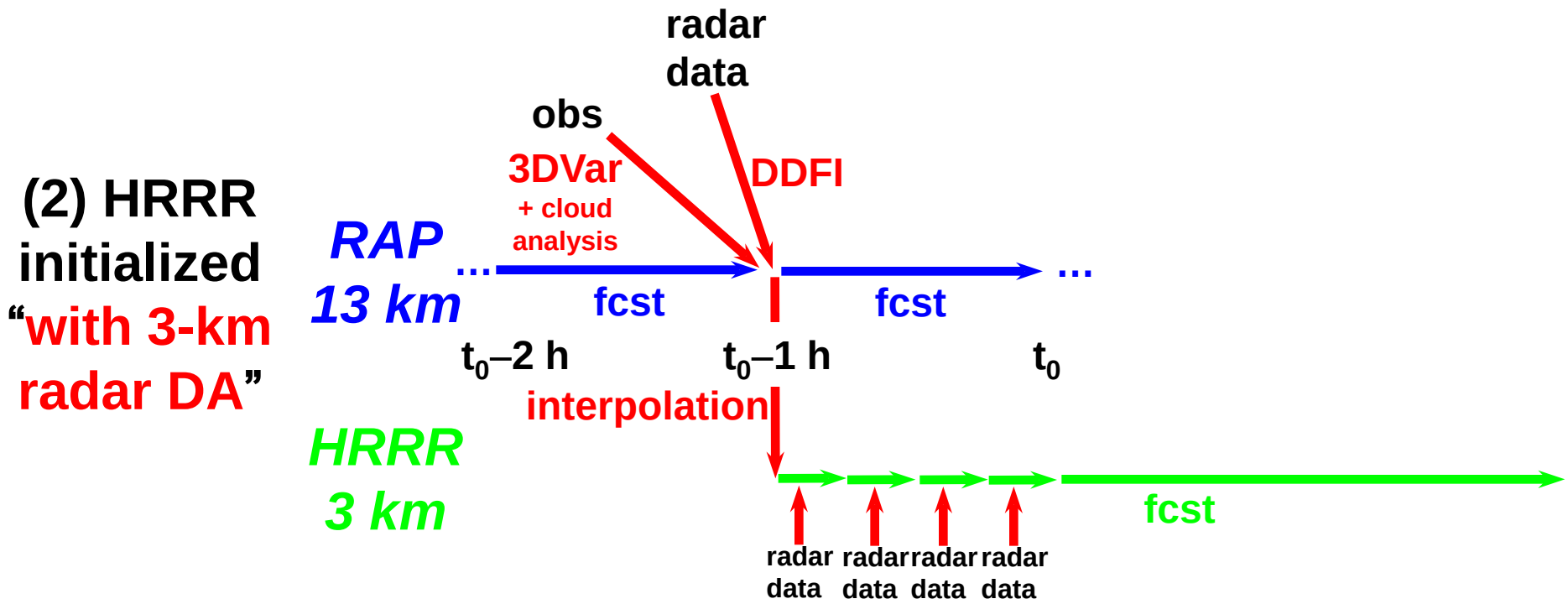
We hope that many of you here will be interested in participating!

NOAA/ESRL/GSD Assimilation and Modeling Branch
presentations on regional and global NWP

Tuesday	**Global model (FIM) development (John Brown)**
Tuesday	**Boundary-layer wind simulation in low-level jets (Joe Olson)**
Tuesday	**Gridpoint Statistical Interpolation for Rapid Refresh (Ming Hu)**
Wednesday	**Storm-scale radar-data assimilation (David Dowell)**
Wednesday	**High-Resolution Rapid Refresh climatology (Eric James)**
Wednesday	**GSI cloud analysis and rawinsonde DA (Patrick Hofmann)**
Thursday	**Rapid Refresh implementation at NCEP (John Brown)**
Thursday	**High-Resolution Rapid Refresh overview (Curtis Alexander)**
Thursday	**NWP guidance for a high-impact snowstorm (Ed Szoke)**
Friday	**Spatial discretization for global models (Shan Sun)**
Friday	**Snow and ice enhancements for RUC LSM (Tanya Smirnova)**

Experiment Comparison

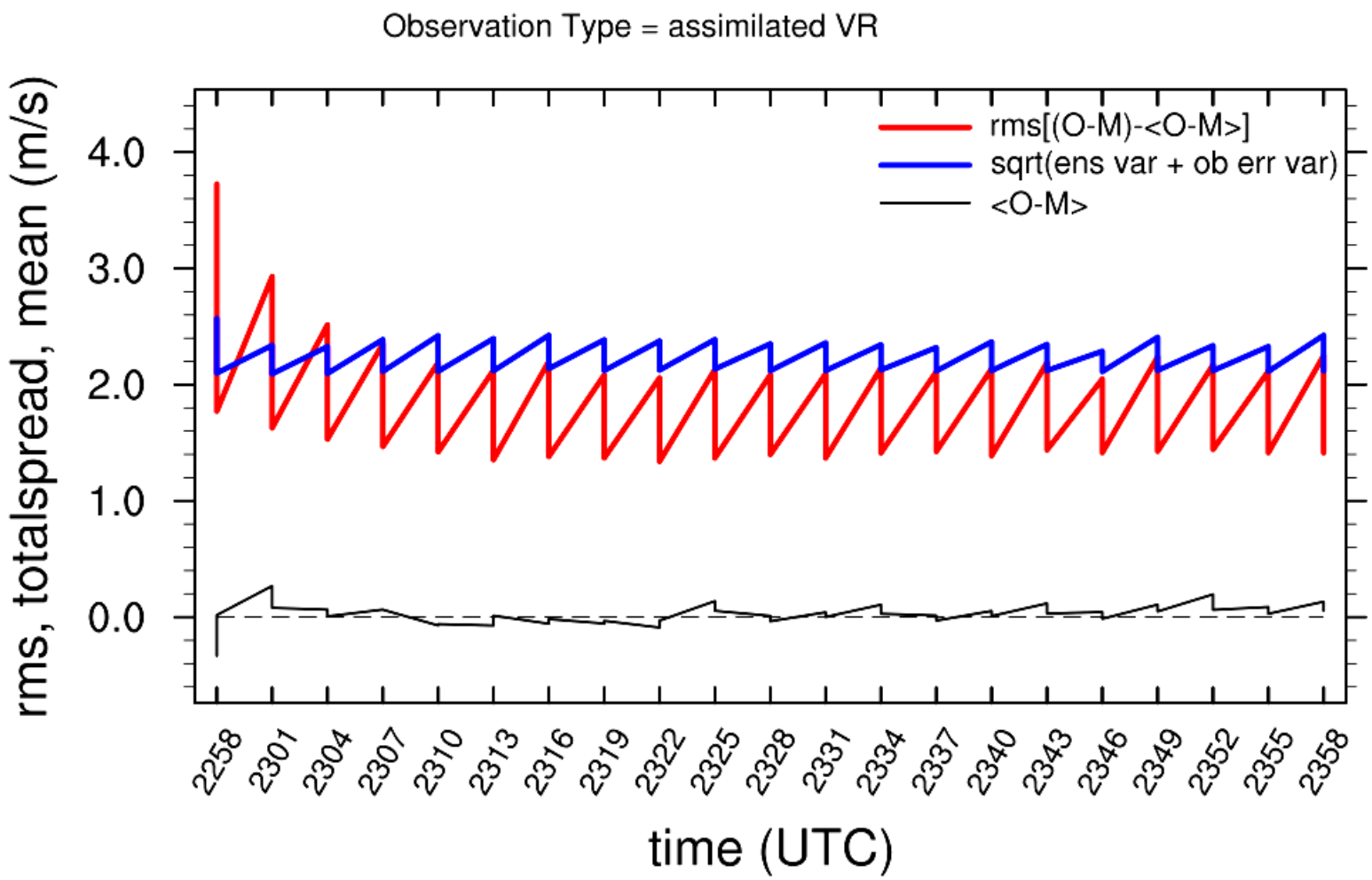




Doppler-velocity diagnostics

one hour beginning 2300 UTC 11 June 2009

RMS of innovations
total spread
bias

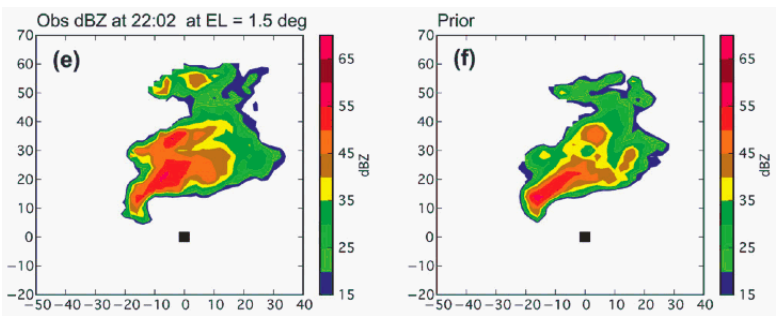


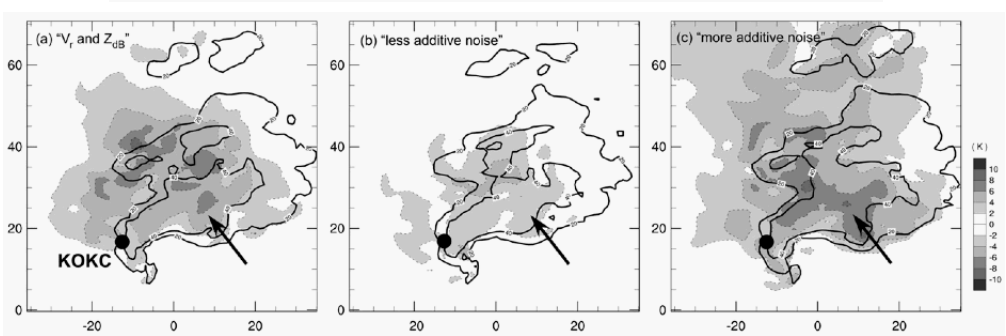
Storm-scale reflectivity data assimilation

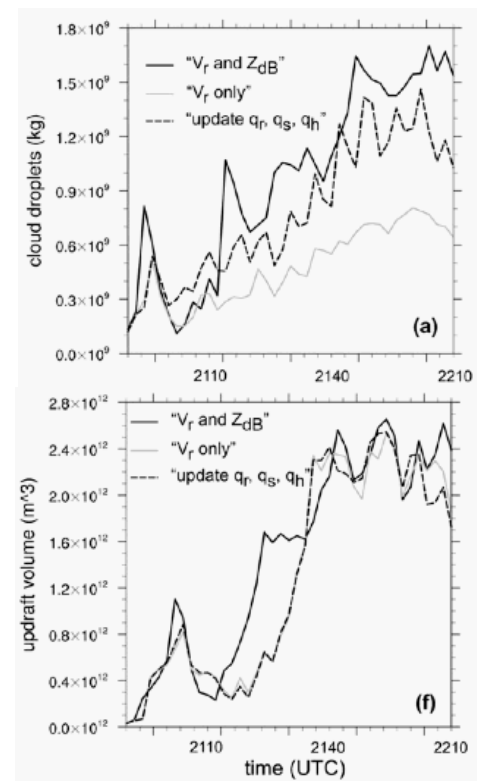
Dowell, D. C., L. J. Wicker, and C. Snyder, 2011: Ensemble Kalman filter assimilation of radar observations of the 8 May 2003 Oklahoma City supercell: Influences of reflectivity observations on storm-scale analyses. *Mon Wea Rev.*, 272-294.

Pros and cons of reflectivity DA:

- more rapid storm development in model (cloud water, vertical velocity) than when only Doppler velocity data are assimilated
- bias errors (model microphysics, observations, observation operators) projected onto all state variables
- cold-pool sensitivity to details of DA, ensemble design





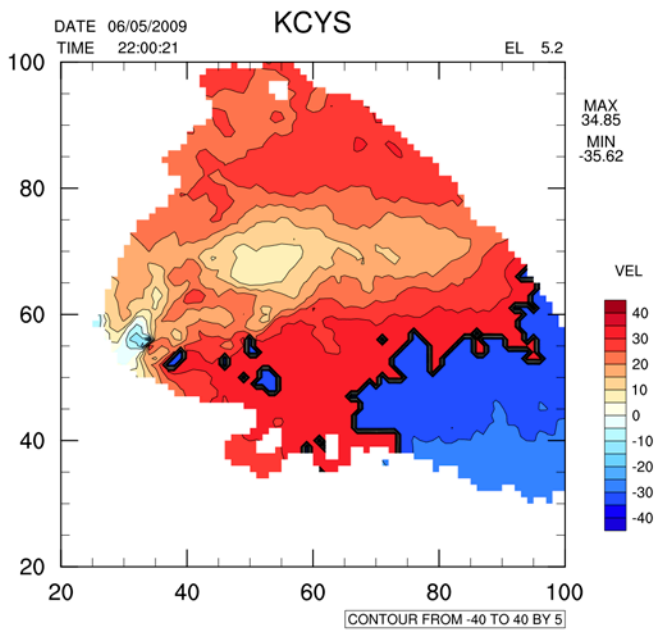


Doppler-Velocity Dealiasing in DART

(Miller et al. 1986; Dowell et al. 2010)

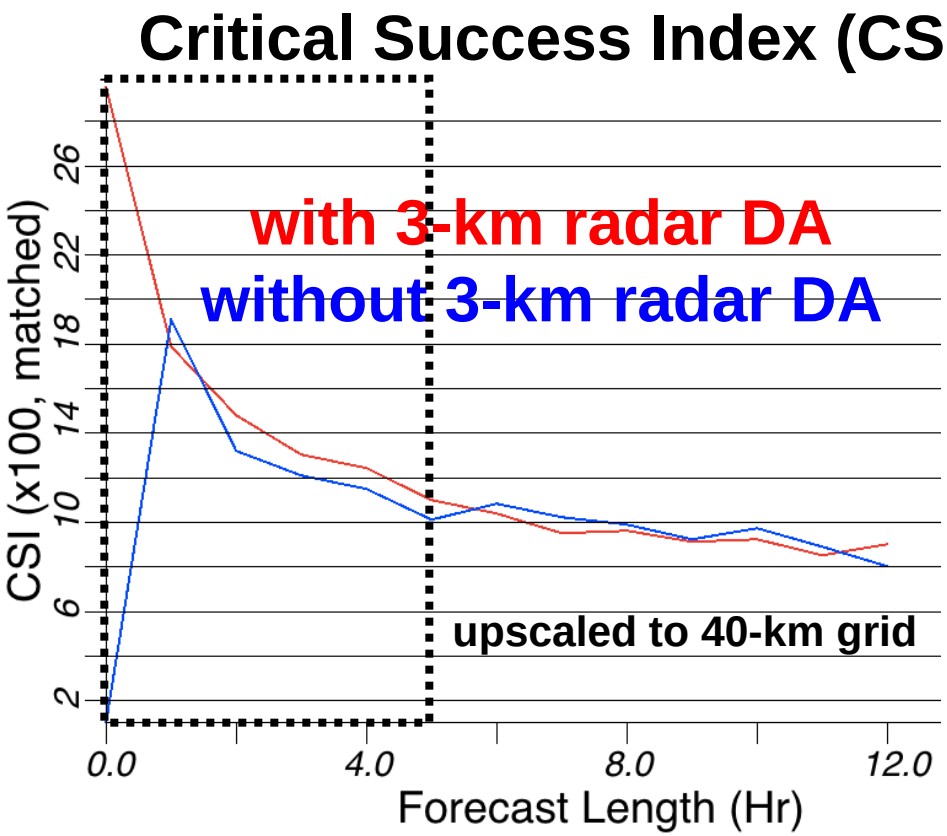
- **Velocities are locally dealiased during preprocessing (objective analysis).**

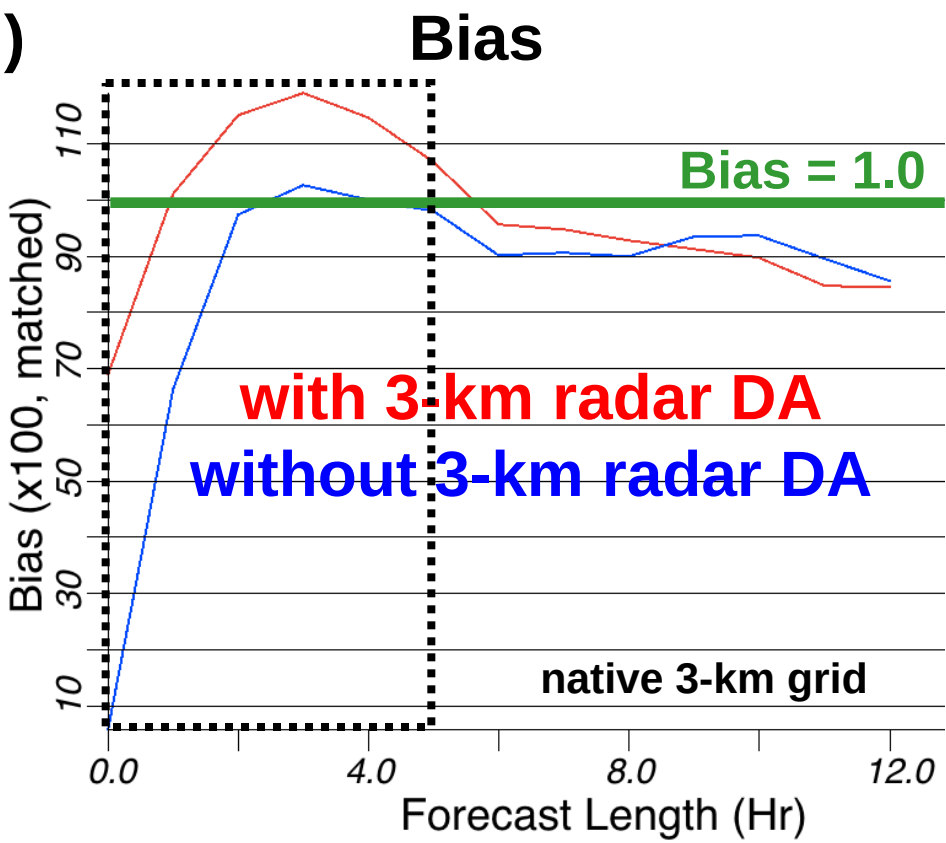
- **Final dealiasing occurs within DART immediately before the observation is assimilated (i.e., the observation is unfolded into the Nyquist-velocity bin closest to the prior ensemble mean).**



locally-unfolded, objectively-analyzed Doppler velocity before final DART dealiasing

HRRR Skill: 35 dBZ threshold (moderate precip.)





3-day retrospective period June 2011, forecasts every 2 hours
composite reflectivity
verification over eastern half of US (widespread convective storms)