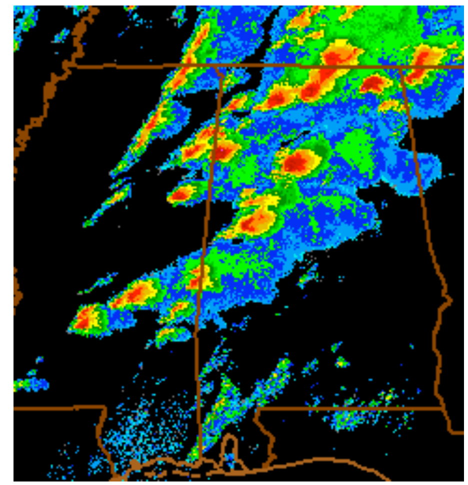
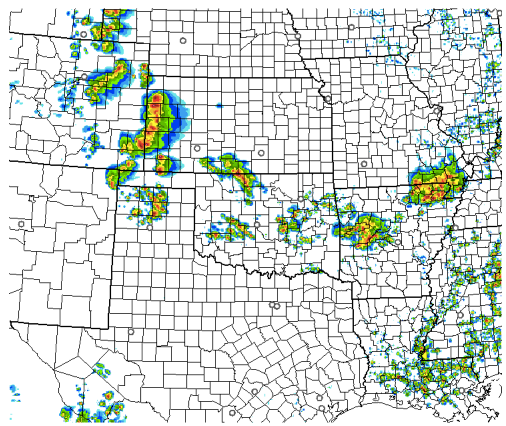
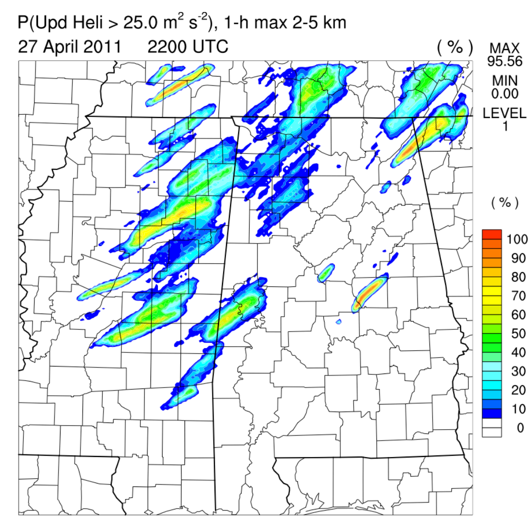
Radar Data Assimilation

David Dowell
Assimilation and Modeling Branch
NOAA/ESRL/GSD, Boulder, CO



Acknowledgment:
Warn-on-Forecast project





Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

Radar Data Assimilation
(for analysis and prediction of convective storms)

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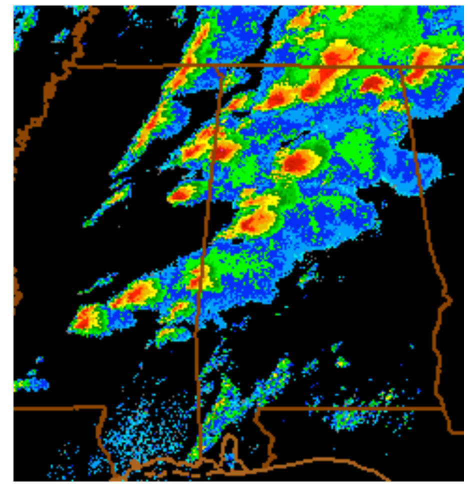

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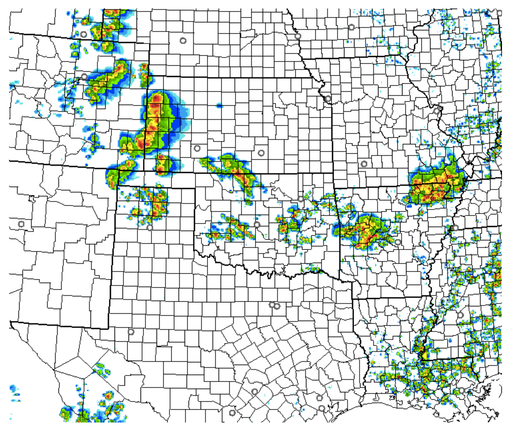

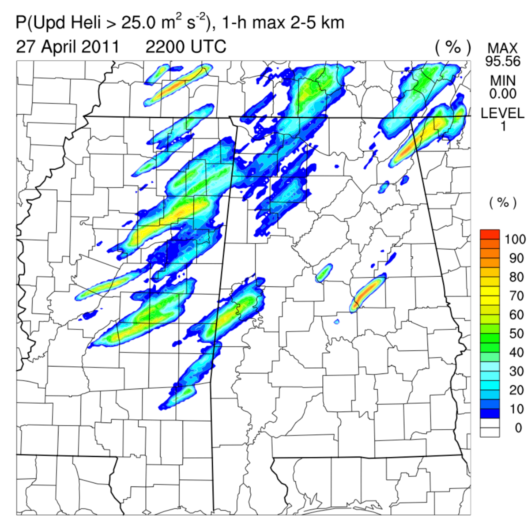

Earth System Research Laboratory
SCIENCE, SERVICE & STEWARDSHIP

Atmospheric Data Assimilation

Definition: using all available information – *observations* and physical laws (*numerical models*) – to estimate as accurately as possible the state of the atmosphere (Talagrand 1997)

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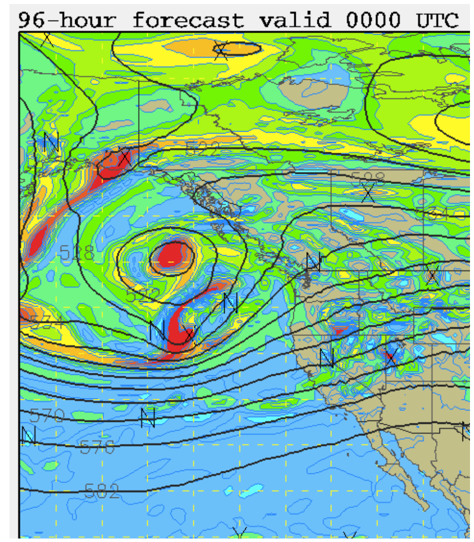
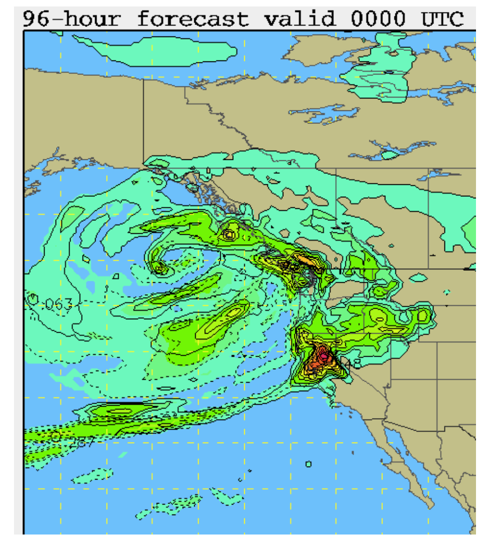
Applications:

1. **Initializing NWP models**





NOAA NCEP, NCAR RAL

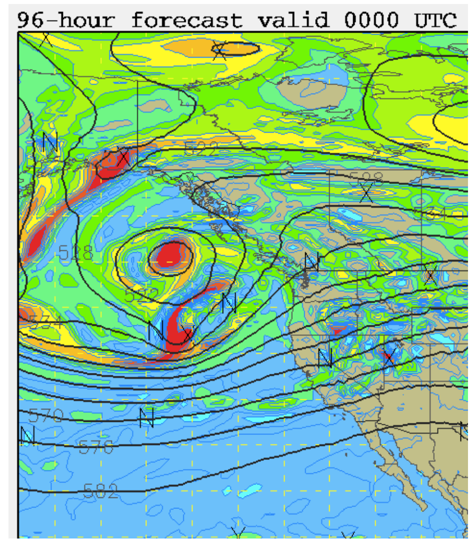
Atmospheric Data Assimilation

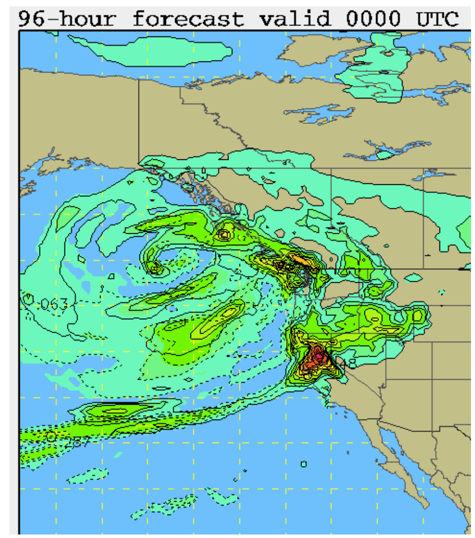
Definition: using all available information – *observations* and physical laws (*numerical models*) – to estimate as accurately as possible the state of the atmosphere (Talagrand 1997)

Applications:

1. **Initializing NWP models**

2. **Diagnosing atmospheric processes (analysis)**





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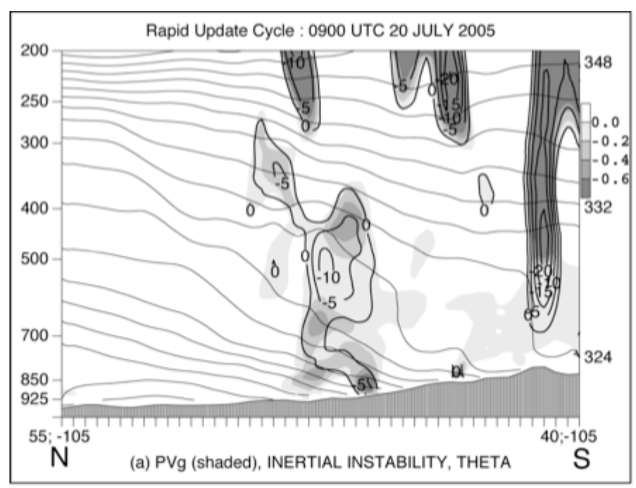
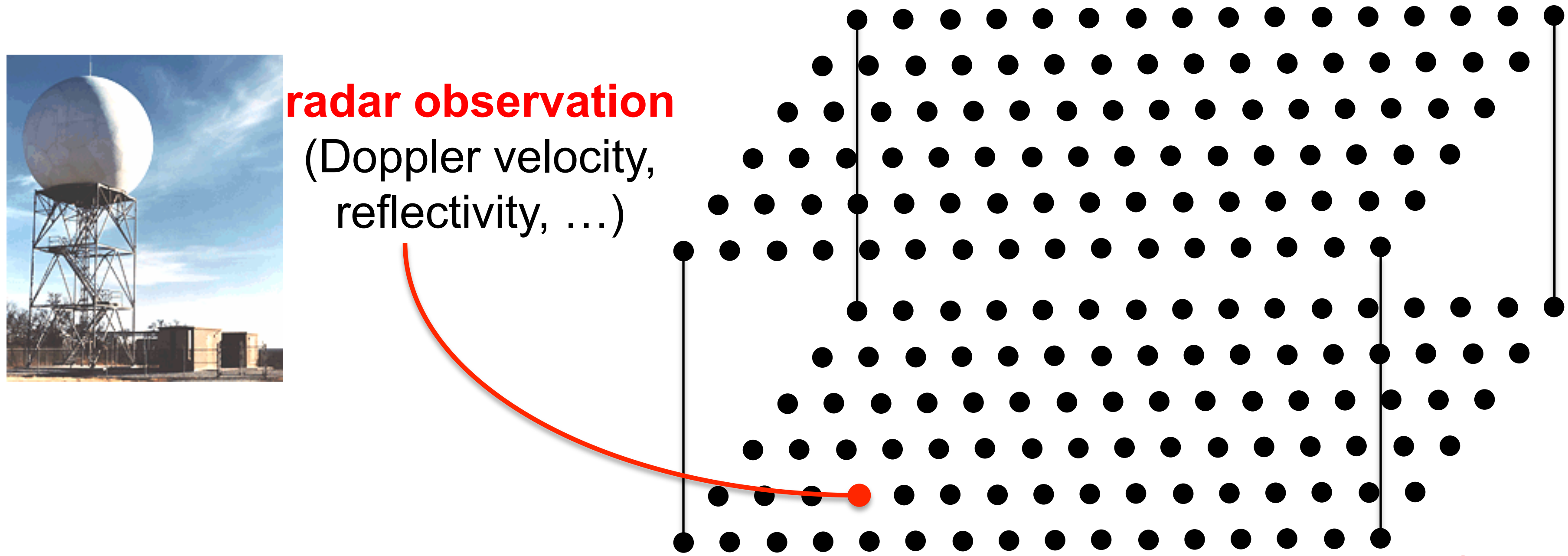


Schultz and Knox 2009

Assimilating a Radar Observation

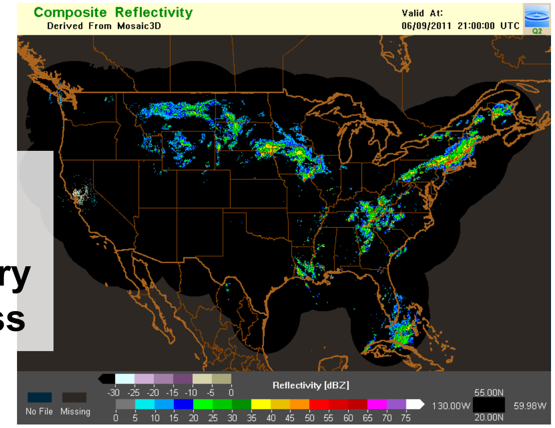


What field(s) should the radar ob. should affect?
By how much? And how far from the ob.?
➔ determined by background error covariances (b.e.c.)

Various methods have been developed for estimating and using b.e.c.:
3DVar, 4DVar, EnKF, hybrid, …

Most model fields are unobserved on small (e.g., convective) scales.

Challenges of Storm-Scale Radar DA and NWP



190 radars

volumes every
10 min or less

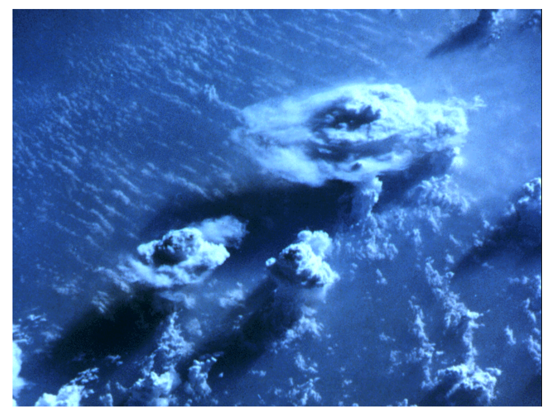
Large radar datasets in need of quality control

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)
prediction of larger-scale processes



Flow-dependent background-error covariances

no quasi-geostrophic balance on small scales

Verifying forecasts (to improve future ones)

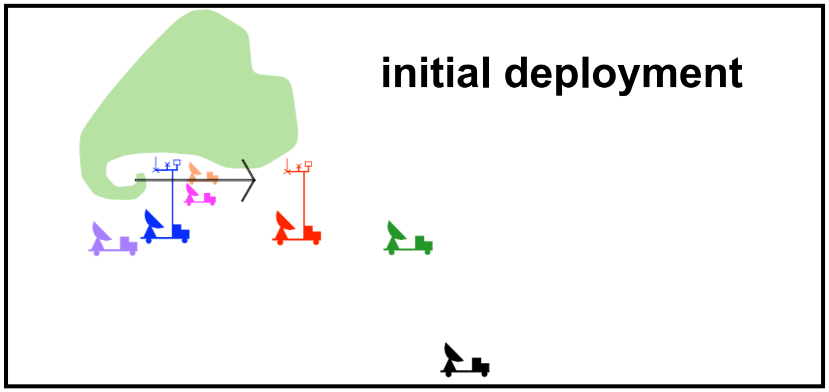
unobserved fields, isolated phenomena

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

within minutes for warning guidance ("Warn on Forecast")

Motivation: Radar DA for Storm-Scale Analysis

The temporal and spatial coverage of mobile radar observations obtained in the field (e.g., VORTEX2) are highly variable. Therefore, traditional multiple-Doppler wind synthesis often isn't feasible.



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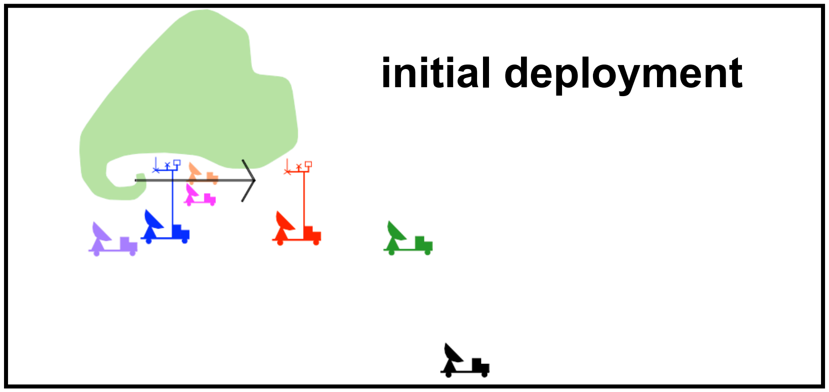

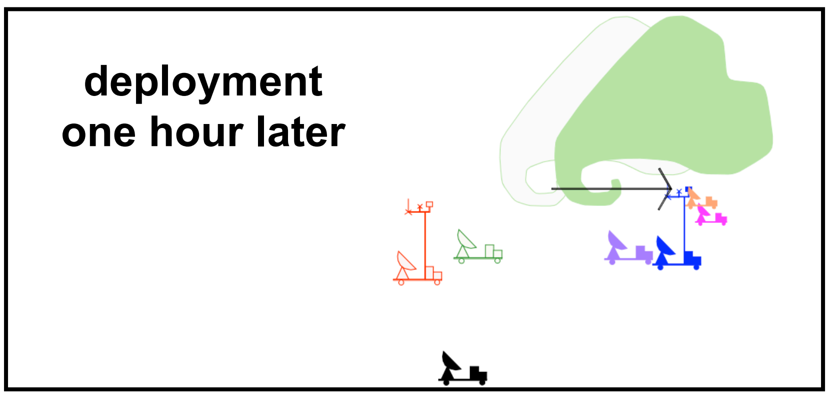

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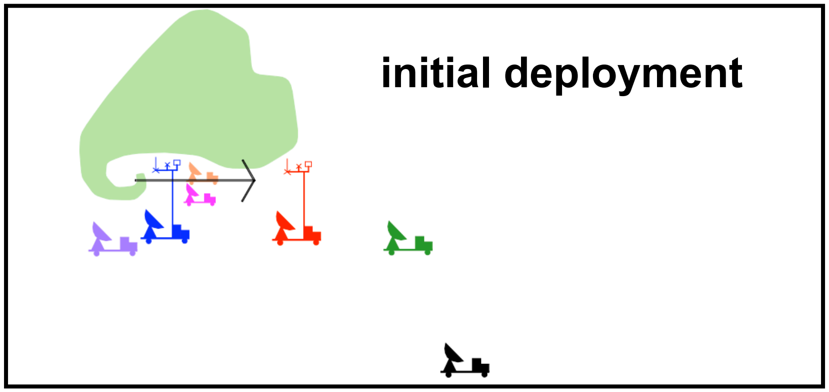
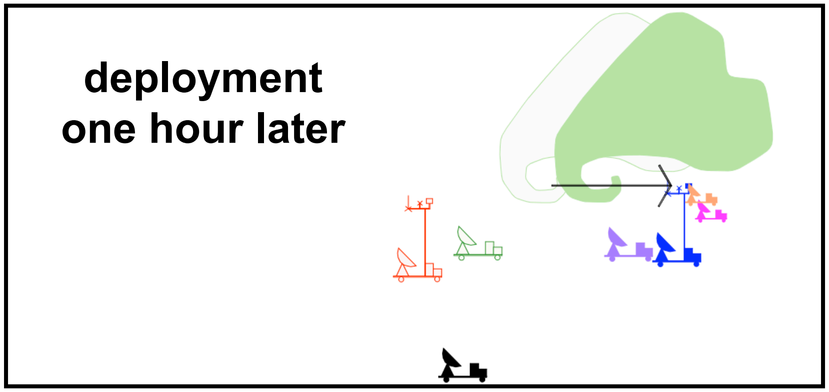




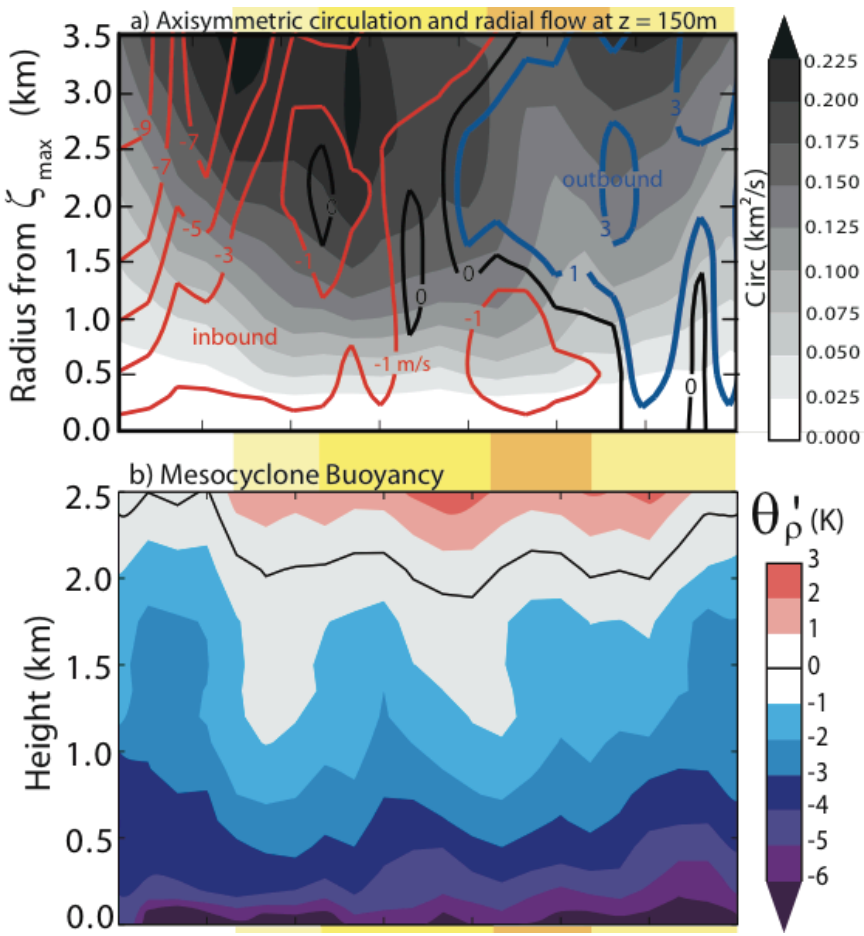
We would also like to include other observation types in the analyses.

Radar DA Application: Diagnosis of Tornadogenesis

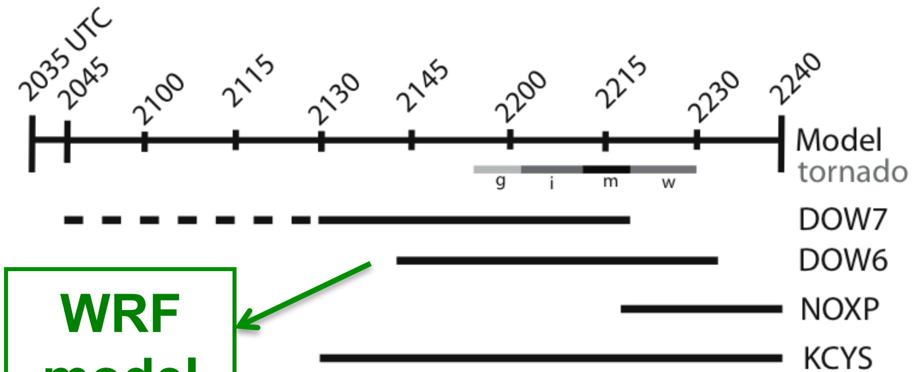
Marquis et al. 2012

AMS Severe Local Storms Conference

Circulation, Radial Flow, and Buoyancy in Mesocyclone



time →

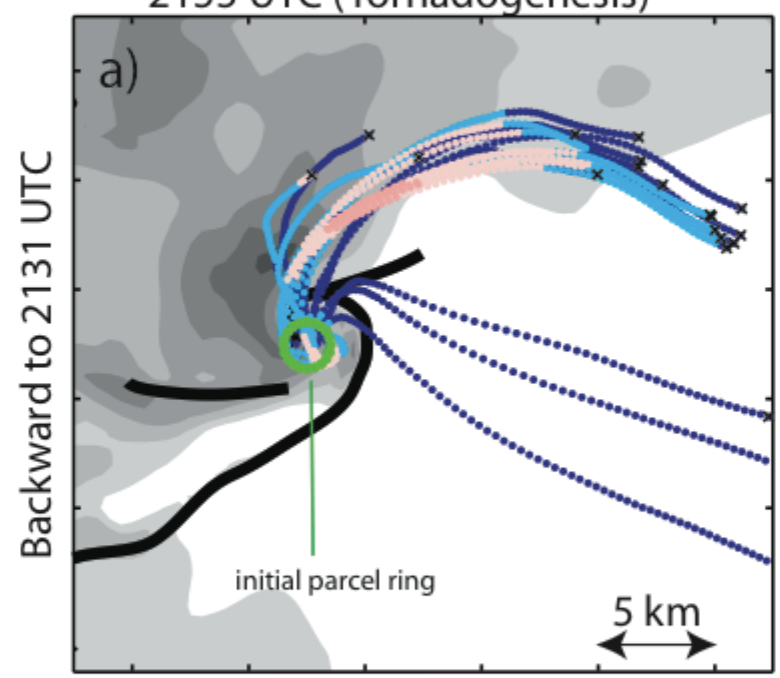


WRF model

5 June 2009 Goshen County, WY case during VORTEX2

Backward Trajectories

2155 UTC (Tornadogenesis)



Some Ongoing Storm-Scale NWP Projects

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

springtime CONUS 4-km ensemble forecasts
NWP research and development

Short-Term Explicit Prediction (STEP) – NCAR

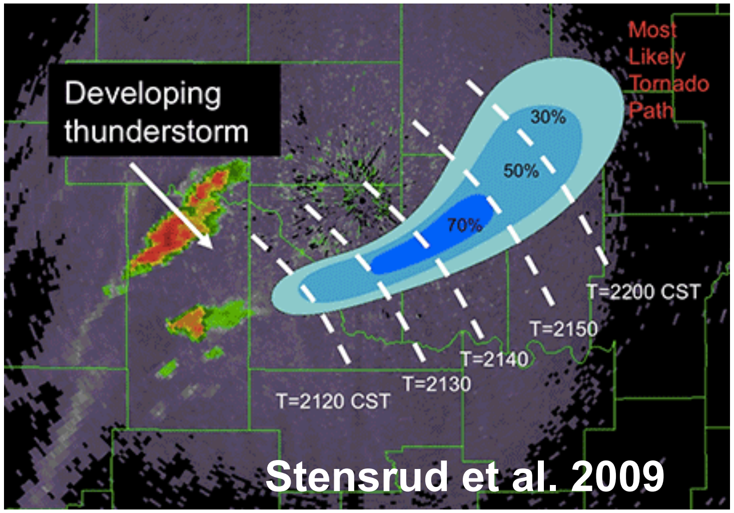
research to improve 0-12 hour forecasting of high-impact weather
recent emphasis on data assimilation, diagnostic tools, orographic convection, and transitions between surface-based and elevated convection

High-Resolution Rapid Refresh (HRRR) – NOAA

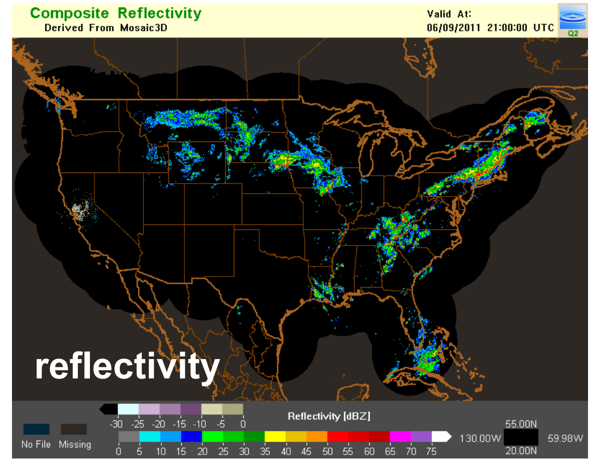
horizontal grid spacing 3 km ➔ convection allowing
near real time, 15-hour forecast every hour
aviation guidance, severe weather forecasting, etc.

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



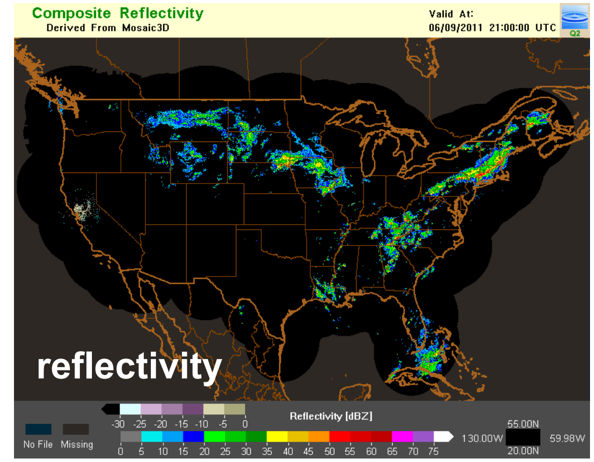
Reflectivity and Doppler Velocity



Reflectivity

- primary information: presence or absence of hydrometeors
- difficulties in direct assimilation (Dowell et al. 2011, Wang et al. 2012)
  - model parameterizations, nonlinear observation operator, radar calibration
- nevertheless, improved forecasts through reflectivity DA
- CONUS qc'd dataset available in near real time (NMQ)

Reflectivity and Doppler Velocity



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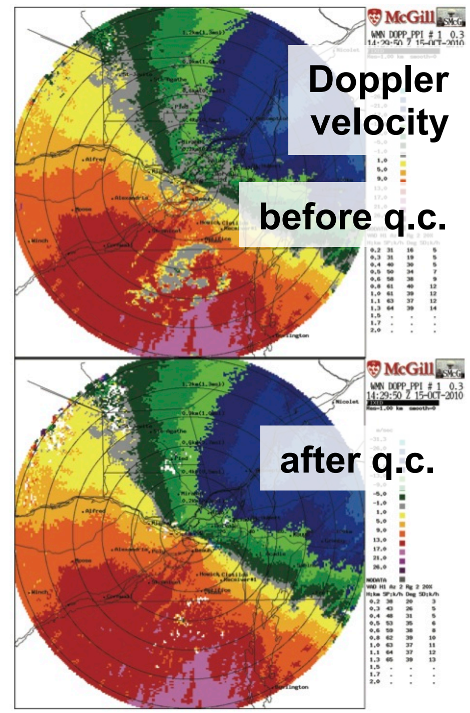


Fabry and Kilambi 2011

Doppler velocity

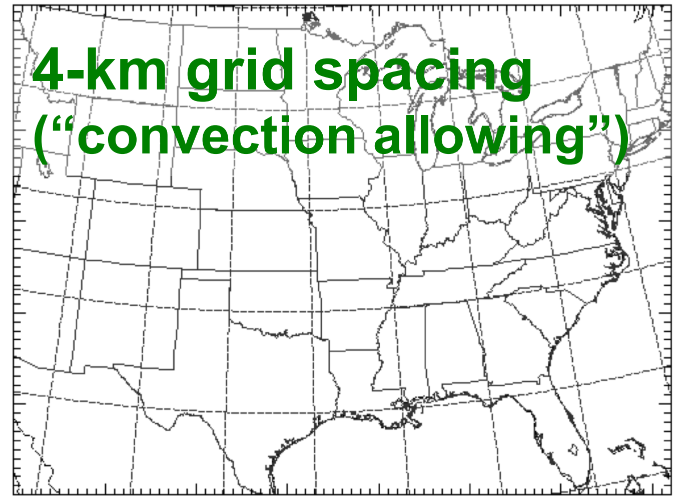
- useful ob. type according to all storm-scale DA studies
- straightforward relationship with (mostly) prognostic model fields, if radar sampling is properly simulated
- quality-controlled (bias-free) CONUS dataset not yet available in real time

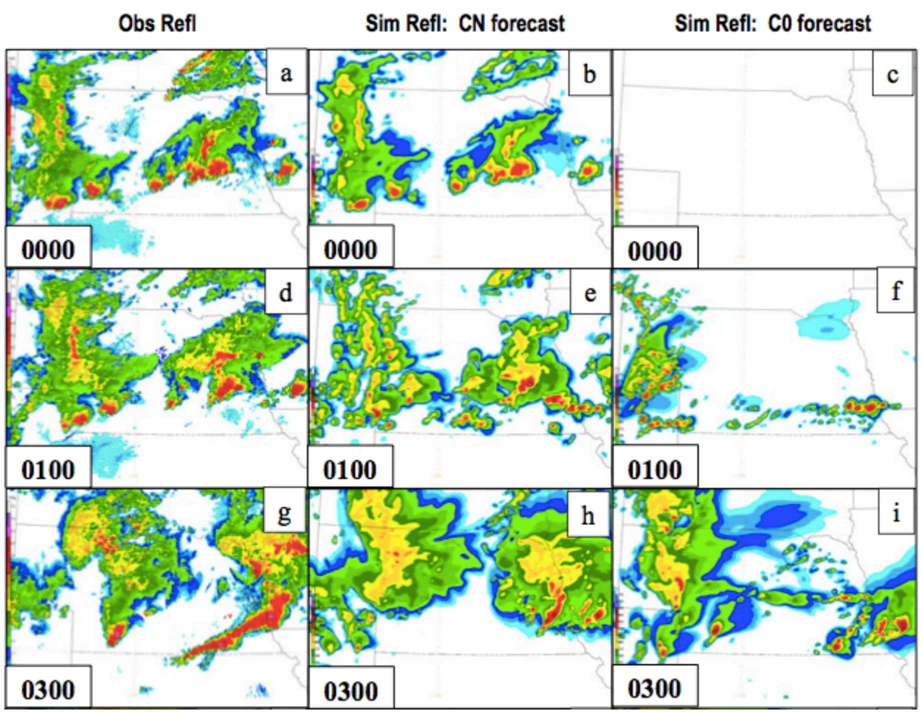
Radar Data Assimilation in CAPS Ensemble

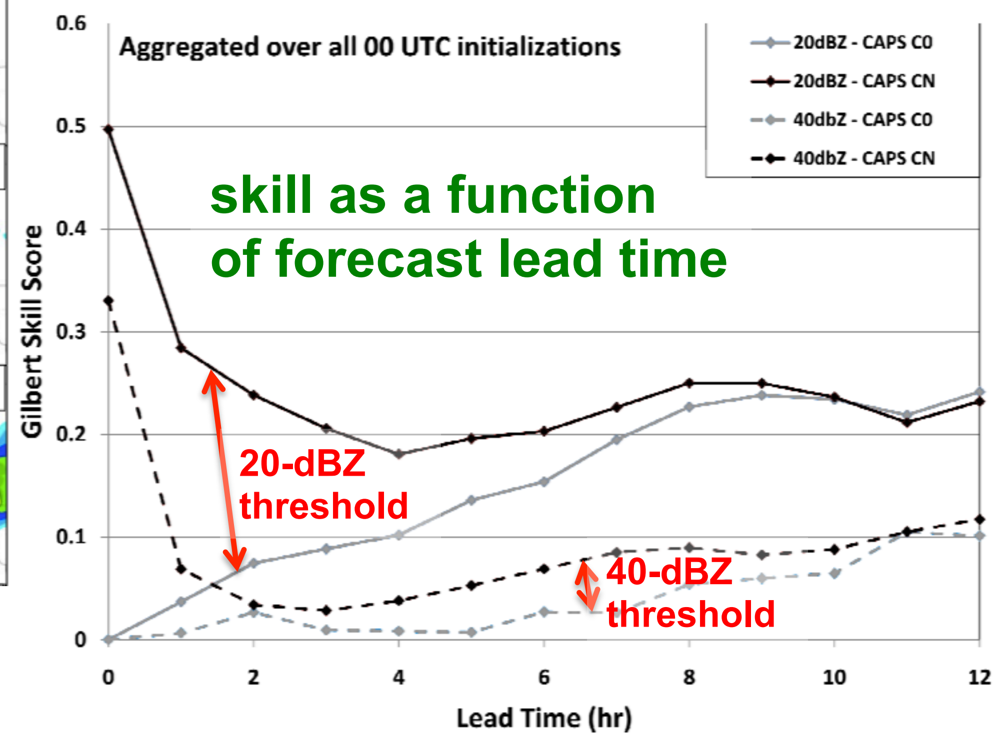
Kain et al. 2010
Weather and Forecasting

NAM background

3DVar assimilation of Doppler velocity and reflectivity at a single time





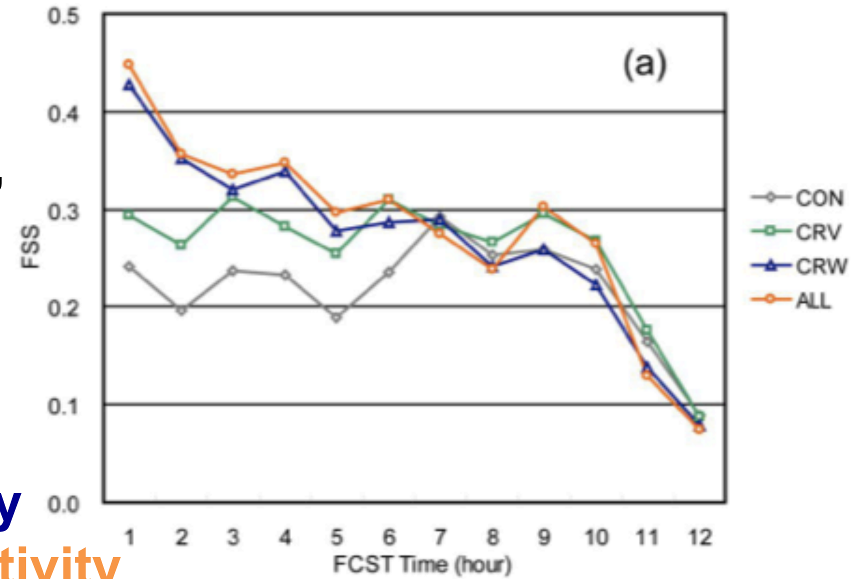


Assimilation of Doppler Velocity and Reflectivity

Wang, Sun, Fan, and Huang 2012
J. Appl. Meteor. Climatology

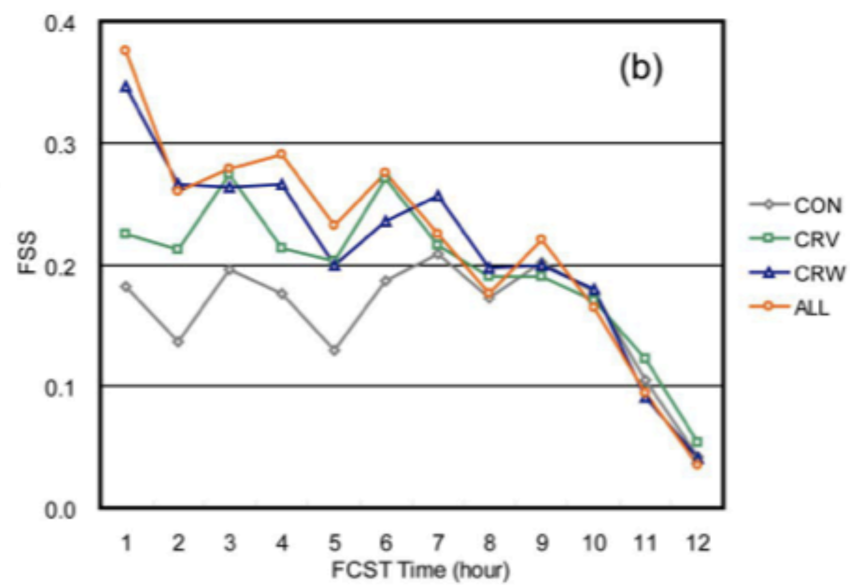
3DVar Assimilation into WRF Model
(4 summertime convective cases in China)

fractional skill score, 5 mm h^{-1} threshold



velocity only
reflectivity only
velocity and reflectivity

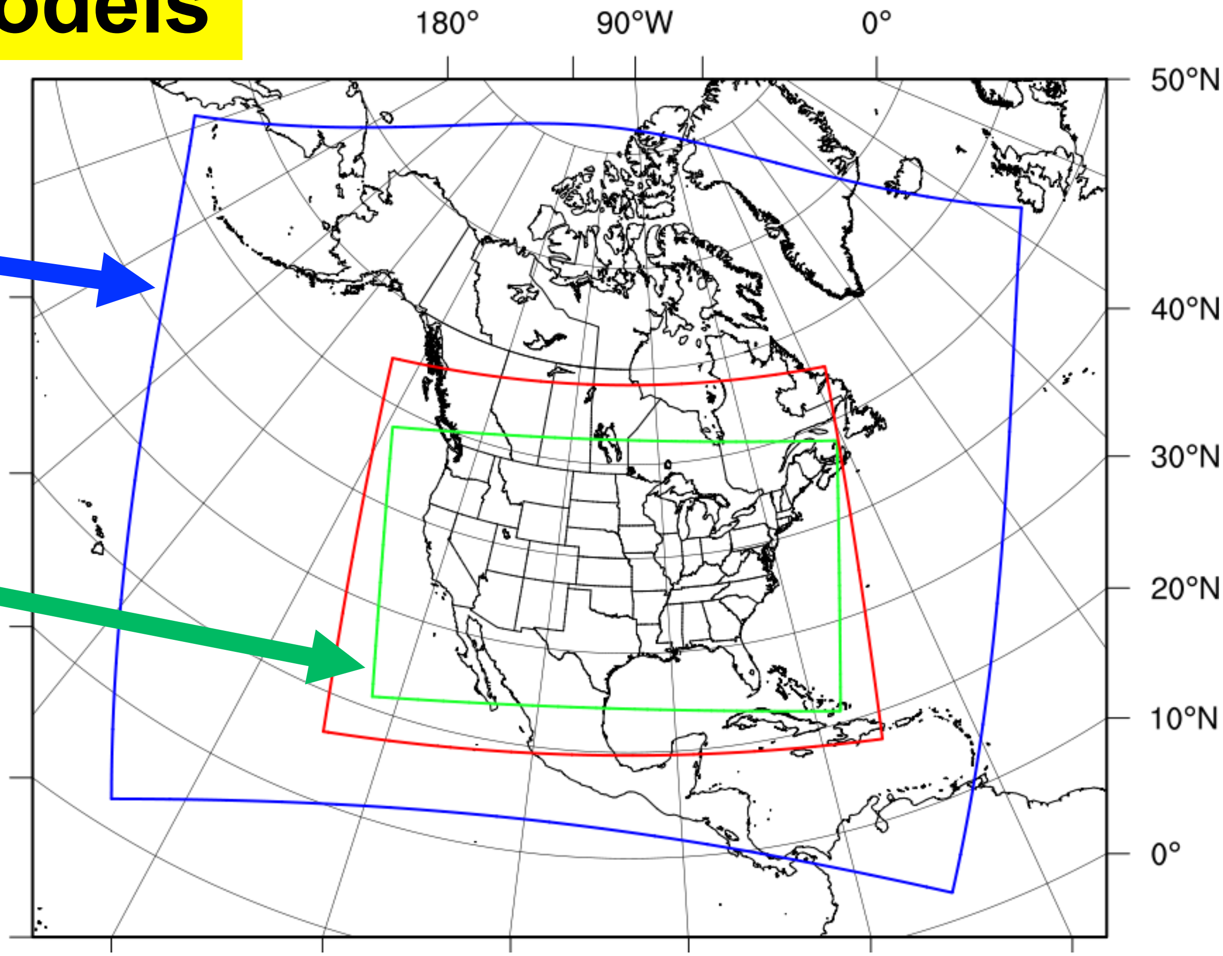
fractional skill score, 10 mm h^{-1} threshold



Hourly Updated NOAA NWP Models

13km Rapid Refresh

3km HRRR



Rapid Refresh (RAP):

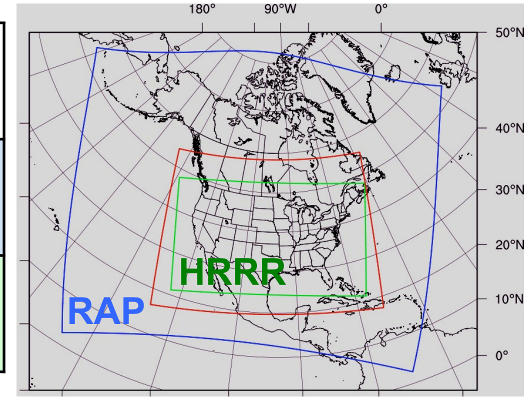
WRF-ARW; GSI + RUC-based enhancements; new 18-h fcst every hour run operationally at NCEP and experimentally (version 2) at ESRL

High-Resolution Rapid Refresh (HRRR):

WRF-ARW; experimental 3-km nest inside RAP; new 15-h fcst every hour

2012 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)



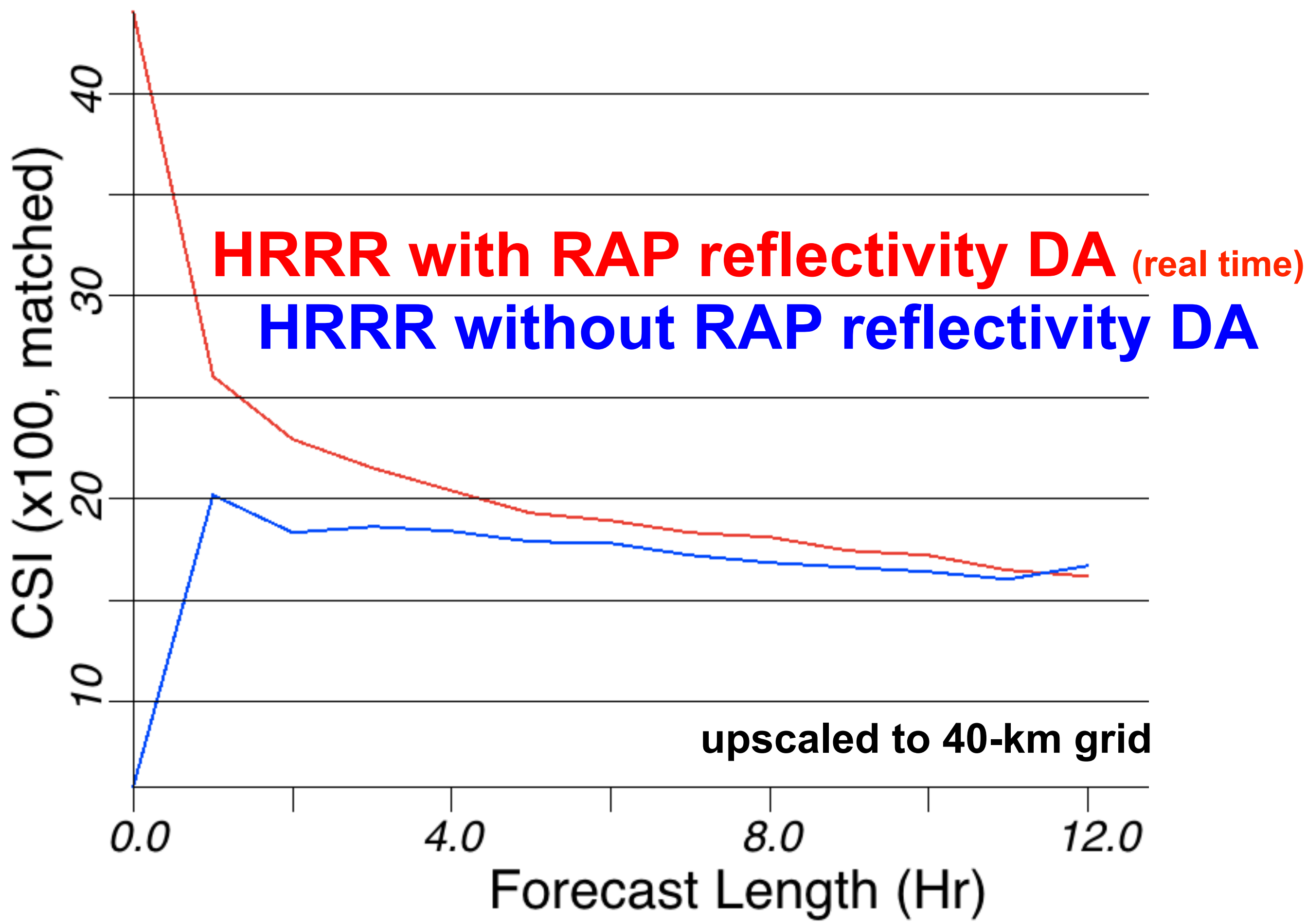
Model	Version	Assimilation	Radar DFI	Radiation	Microphysics	Cum Param	PBL	LSM
RAP-ESRL	WRF-ARW v3.3.1+	GSI-3DVar	Yes	RRTM/ Goddard	Thompson v3.3.1	G3 + Shallow	MYJ	RUC v3.3.1
HRRR	WRF-ARW v3.3.1+	None: RAP I.C.	No	RRTM/ Goddard	Thompson v3.3.1	None	MYJ	RUC v3.3.1

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

<u>observations assimilated with GSI (3DVar) into experimental RAP at ESRL</u>
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

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

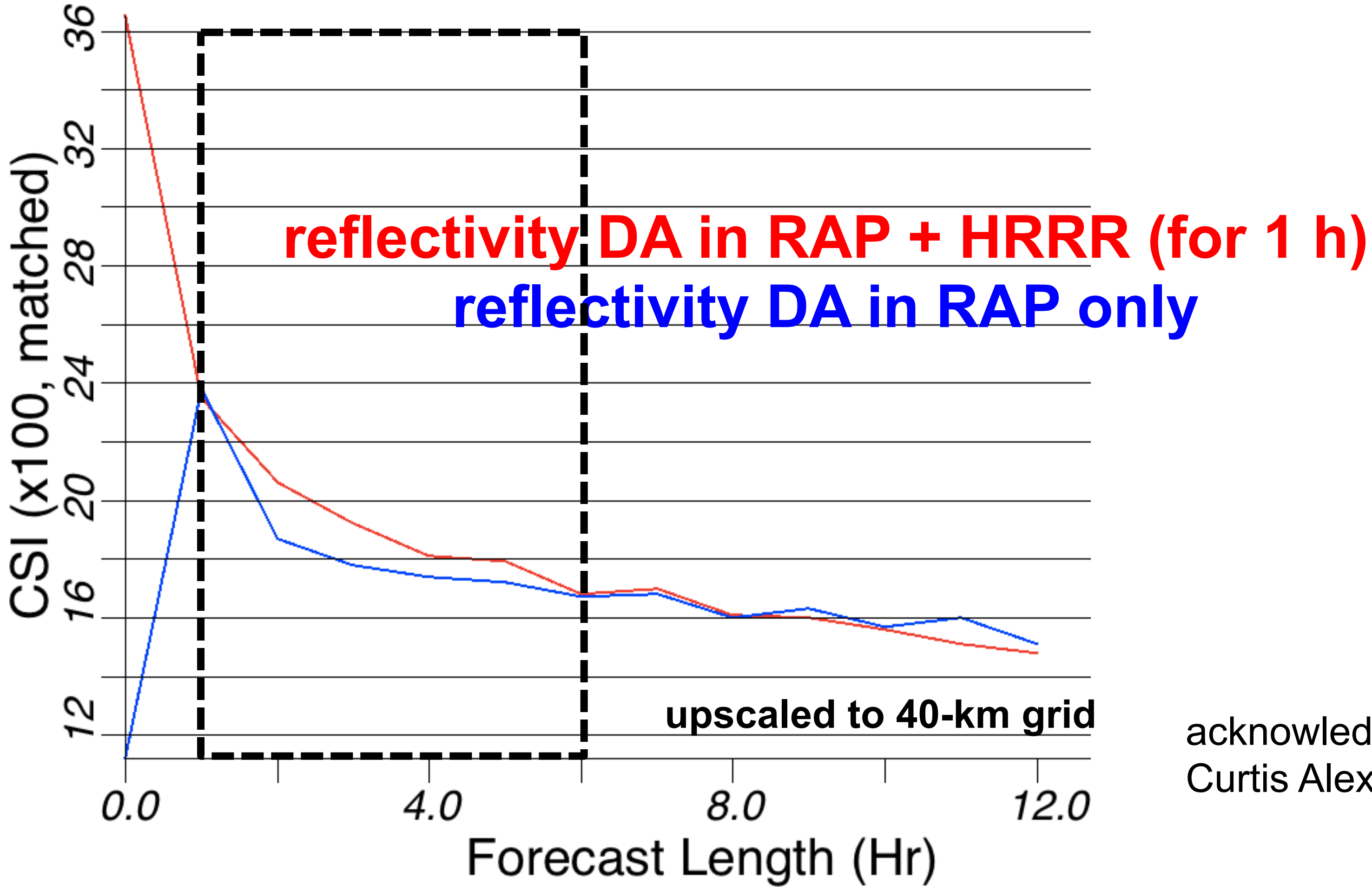
Critical Success Index (CSI) for 25-dBZ Composite Reflectivity



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

Additional Positive Contribution to HRRR (3-km) Forecasts from Reflectivity DA in HRRR

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



acknowledgment:
Curtis Alexander

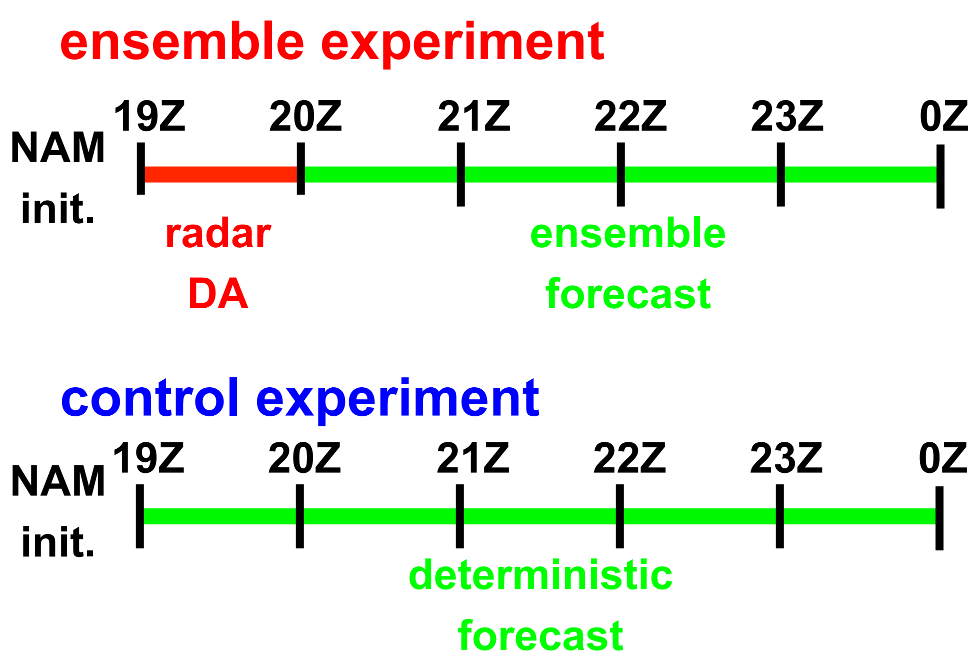
14-day June 2011 retrospective period
verification over eastern half of US (widespread convective storms)

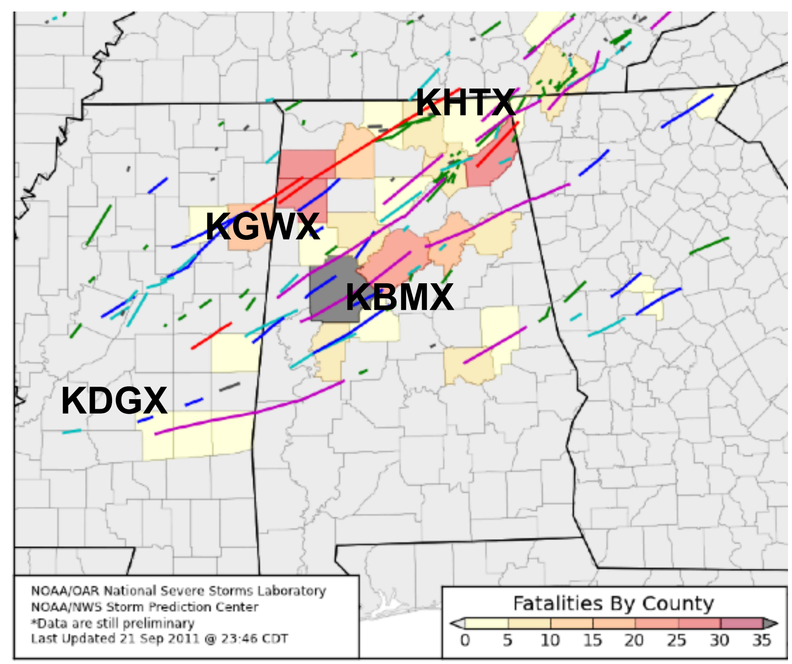
Warn-on-Forecast Research: 4/27/2011 Tornado Outbreak

45-member WRF ensemble (Δx=3 km) initialized from NAM (Δx=12 km)
600-km domain for these preliminary experiments

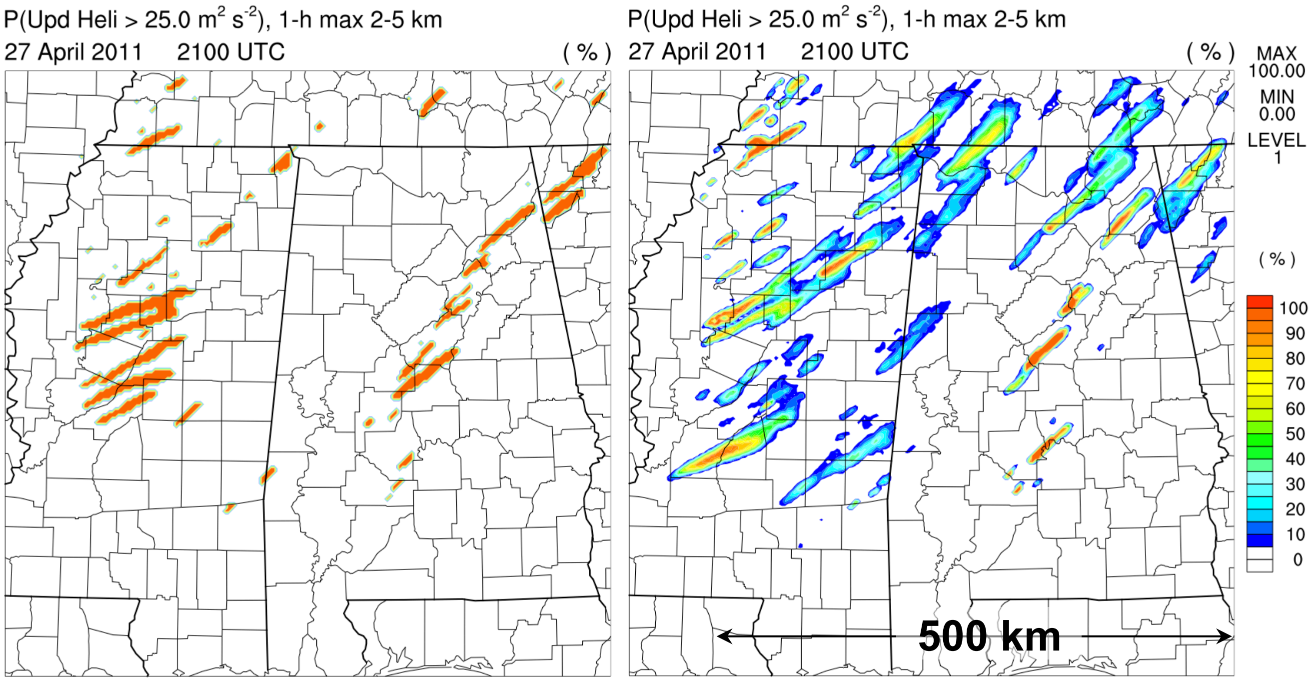
Velocity and reflectivity data assimilated every 3 min for 1 h
KBMX, KDGX, KGWX, KHTX ; simple, automated quality control
additive noise during cycled radar DA -- *only source of ensemble spread*
WRF-DART ensemble adjustment Kalman filter (Anderson et al. 2009, *BAMS*)

Ensemble forecast produced after radar DA





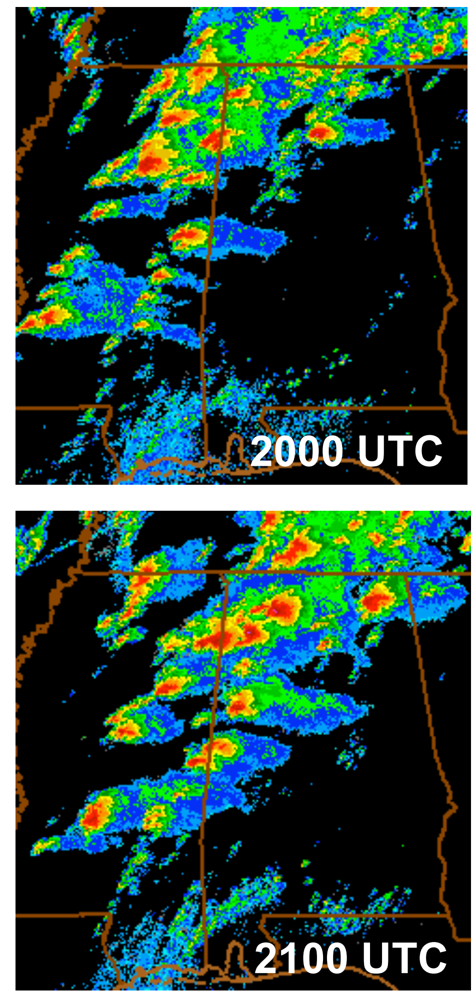
Probability of Rotating Updrafts (2-5 km updraft helicity > 25 $m^2 s^{-2}$) 2000-2100 UTC



control experiment
(no radar DA, deterministic forecast)

radar DA, 0-1 h ensemble forecast

NSSL Composite Reflectivity



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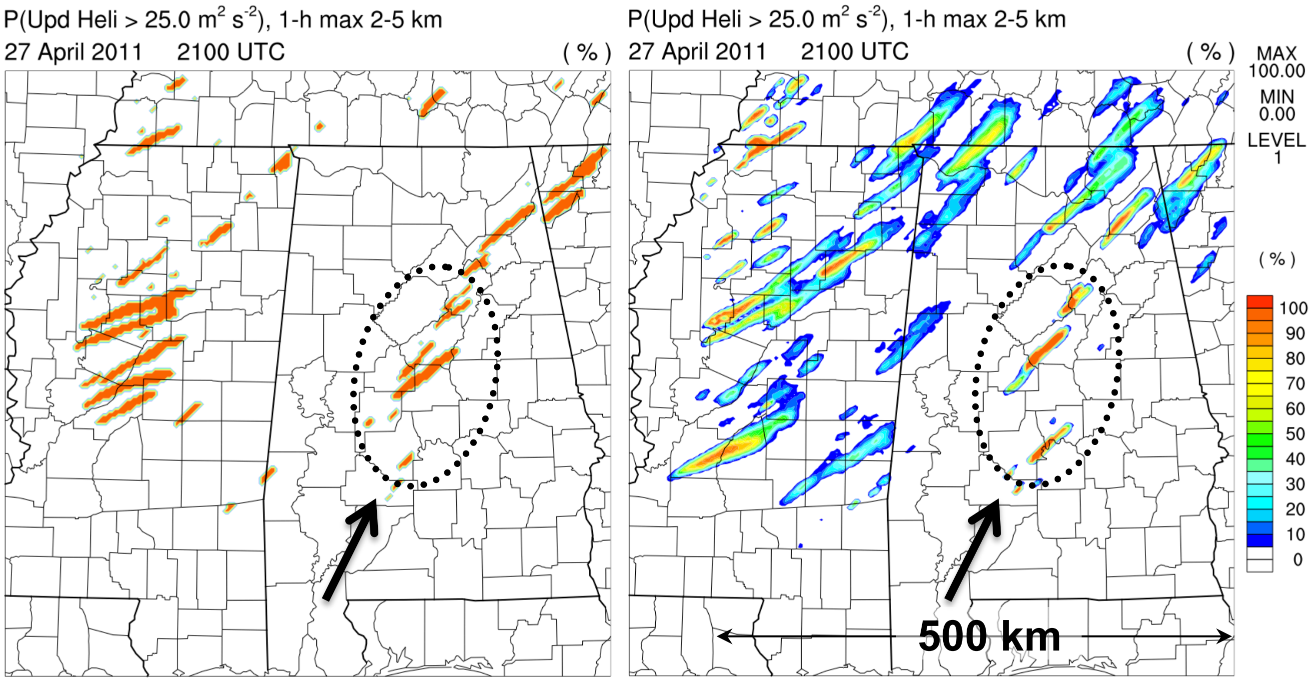

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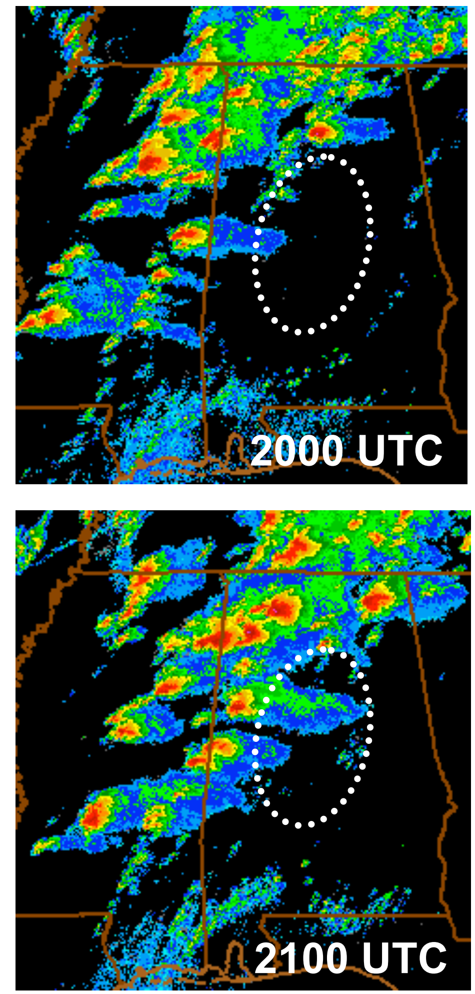
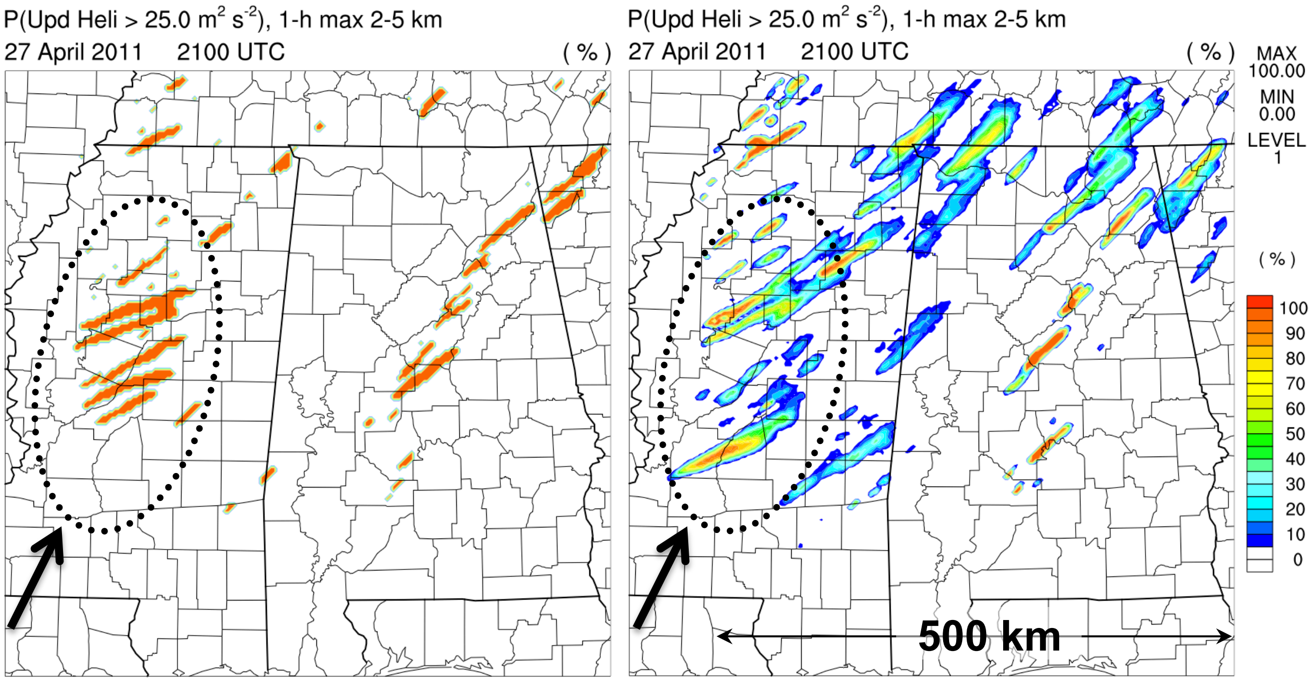


radar DA has not eliminated spurious storms from forecast

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

NSSL Composite Reflectivity



control experiment
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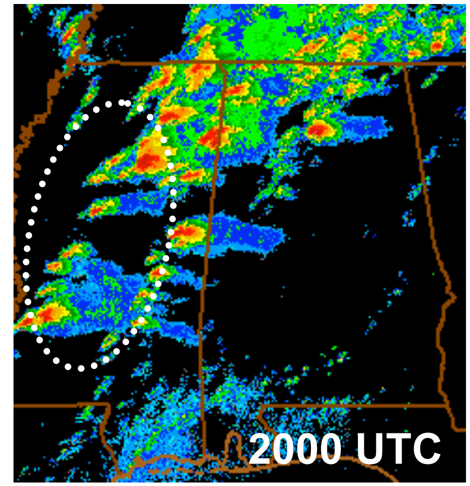
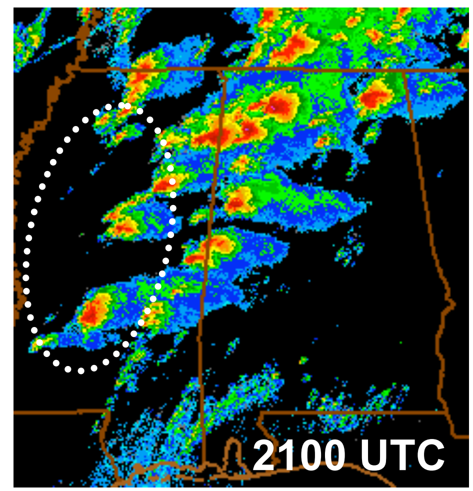
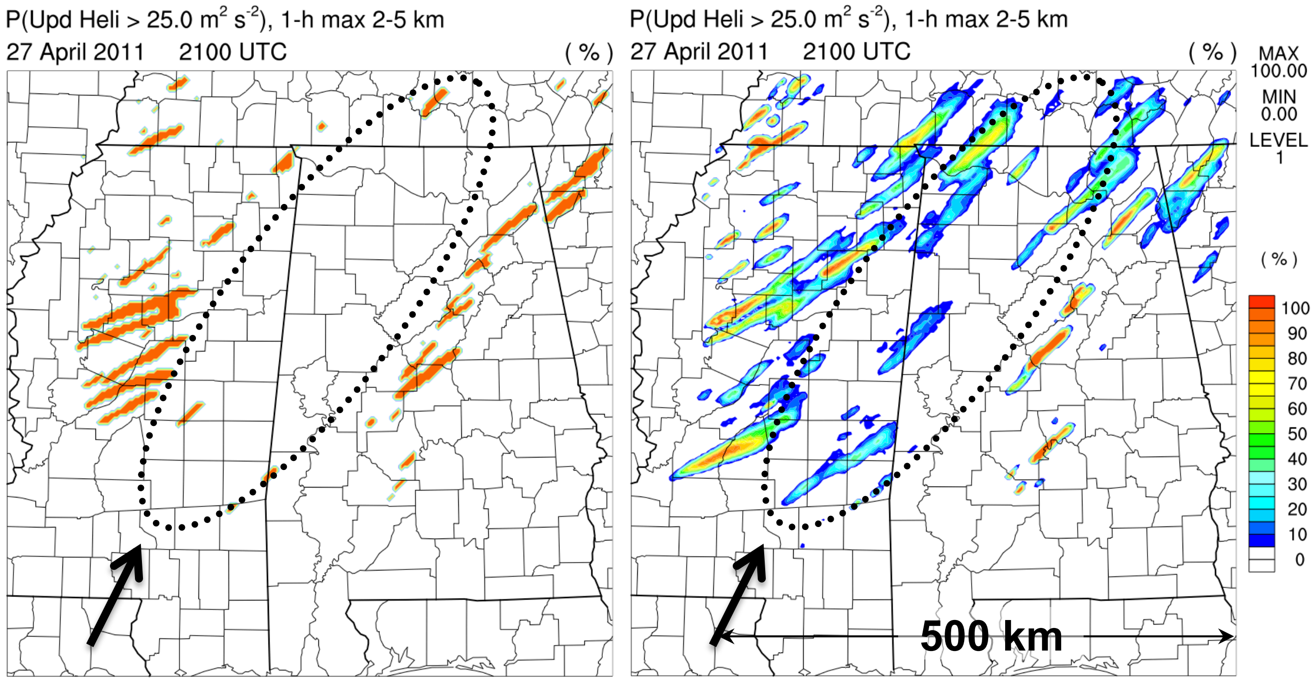
radar DA, 0-1 h ensemble forecast





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
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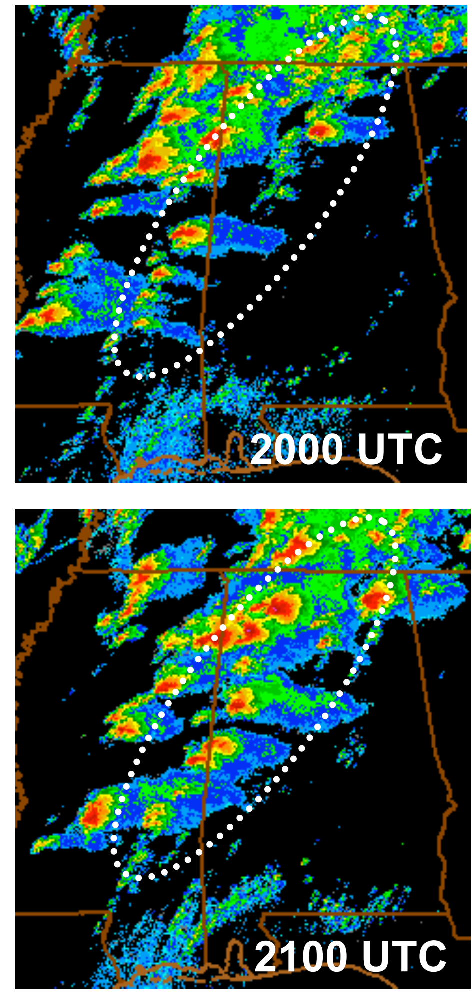
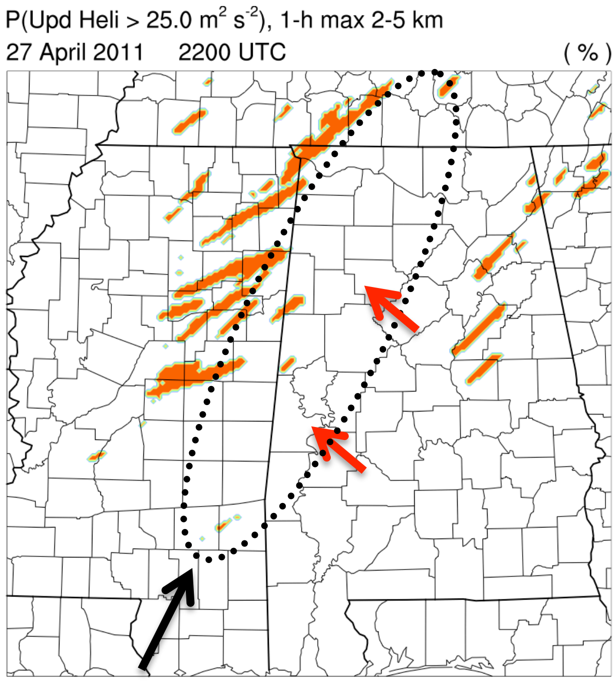
radar DA, 0-1 h ensemble forecast

NSSL Composite Reflectivity



radar DA introduces viable storms where they were needed
(CI enhanced through radar DA, maintenance supported by mesoscale environment in model)

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



control experiment
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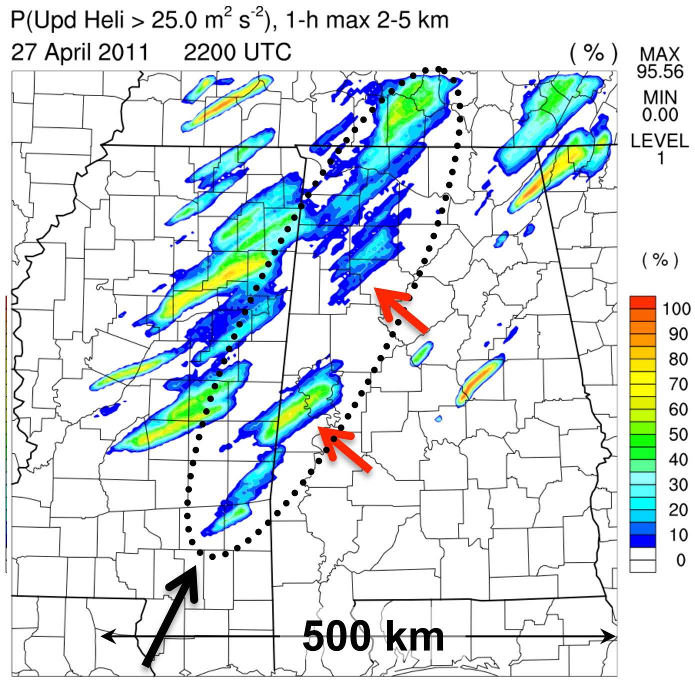
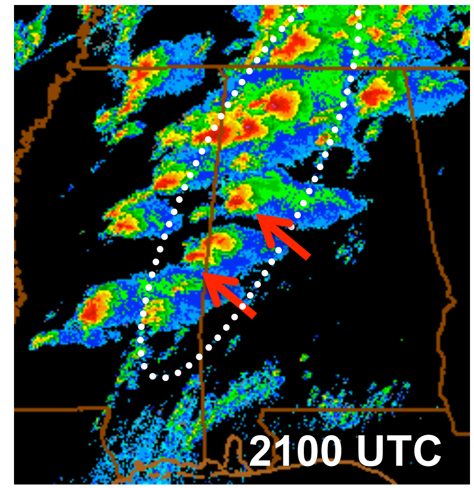
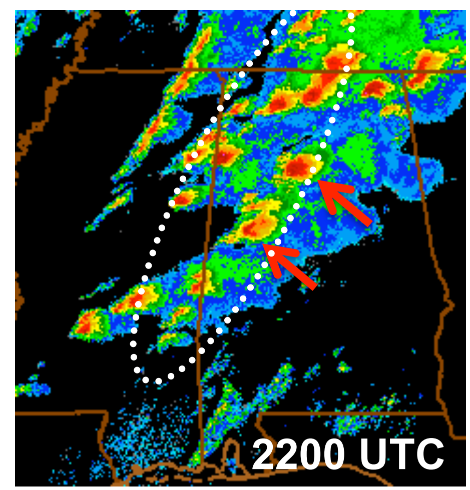


radar DA, 1-2 h ensemble forecast

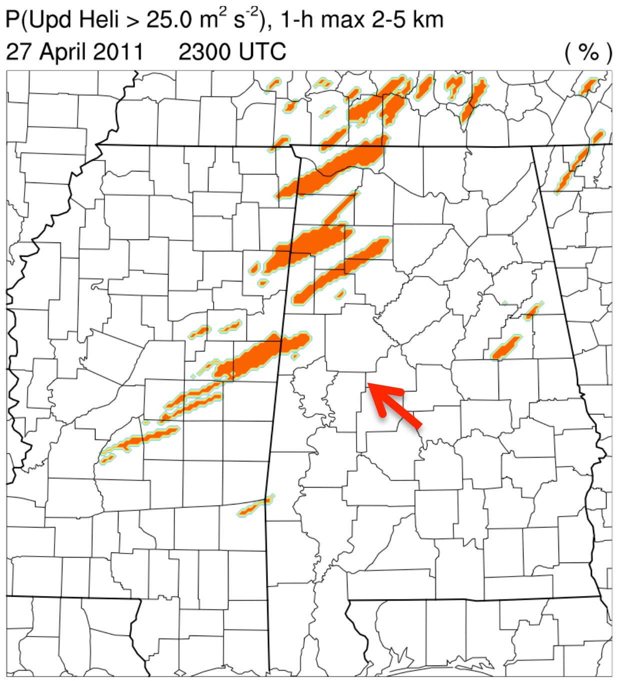
NSSL Composite Reflectivity





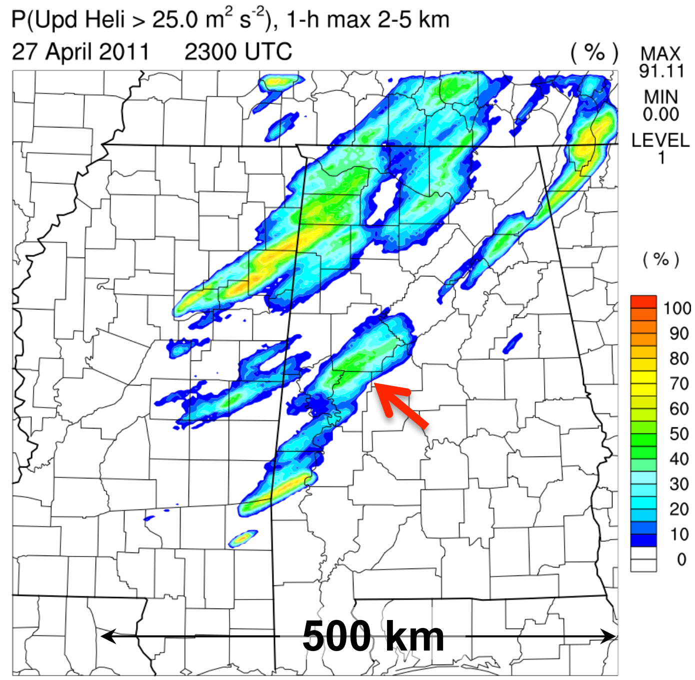
some storms introduced by radar DA persist; probabilities vary among storms

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



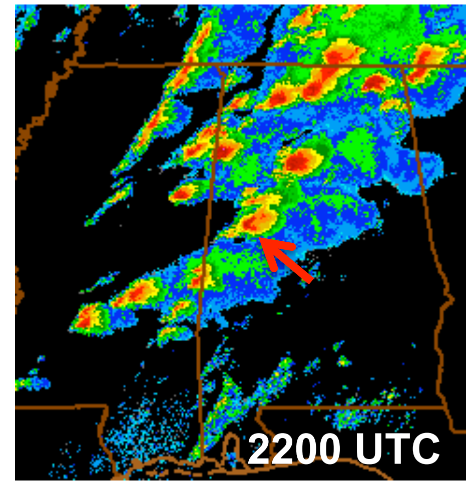
control experiment

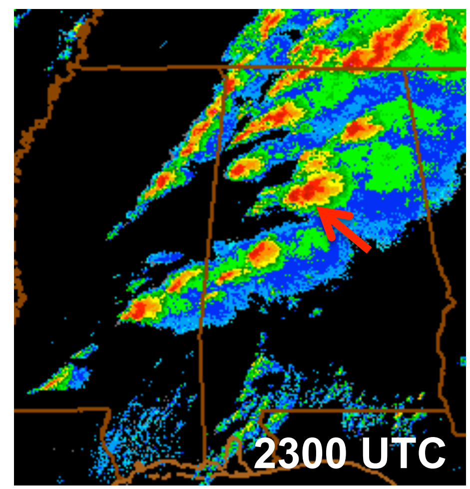
(no radar DA, deterministic forecast)



radar DA, 2-3 h ensemble forecast

NSSL Composite Reflectivity





ensemble shows a strong signal for Tuscaloosa storm, but has become underdispersive overall

Radar DA and Verification of Polarimetric Signatures

Jung et al. 2012
Monthly Weather Review

ARPS Analysis of 29 May 2004 Geary Supercell
(assimilation of reflectivity and Doppler velocity)

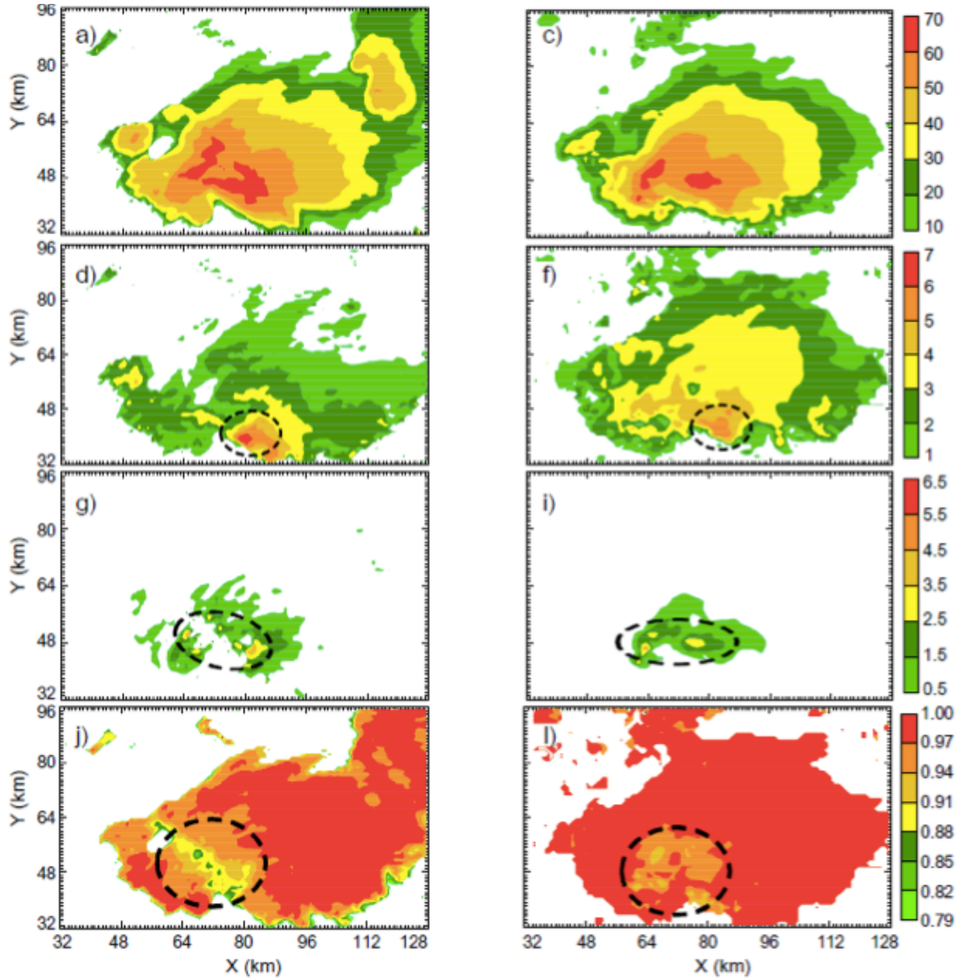
Observations **Model**

Reflectivity (Z_H)

Differential Reflectivity (Z_{DR})

Differential Phase (K_{DP})

Correlation Coefficient (ρ_{HV})



Actually assimilating Z_{DR} data into cloud models has so far produced mixed results (Glen Romine 2006 PhD research; Jung et al. 2012).

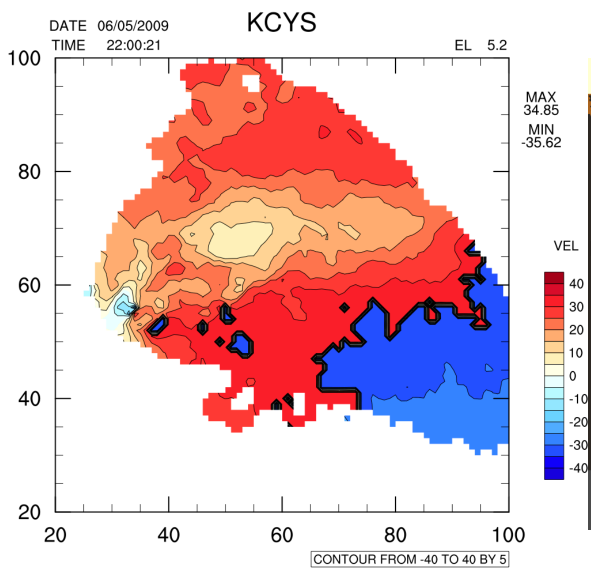
Radar-Data Quality Control

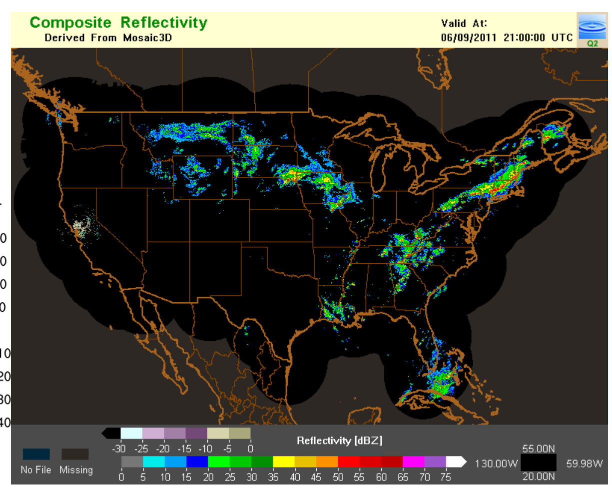
For radar DA, the primary task is to **eliminate all questionable data**.

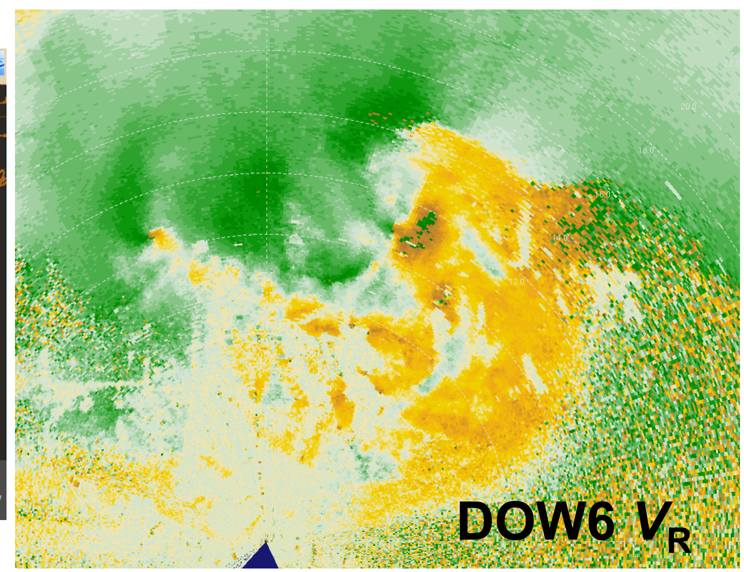
Unfolding aliased velocity data during cycled radar DA is **relatively easy** because a background 3D wind field is available.

Operational q.c. of **WSR-88D data** has been improving, and further improvements are expected through the polarimetric capability.

For radar DA case studies employing **mobile radar data**, quality control (e.g., removing ground clutter) remains a very time-consuming process.





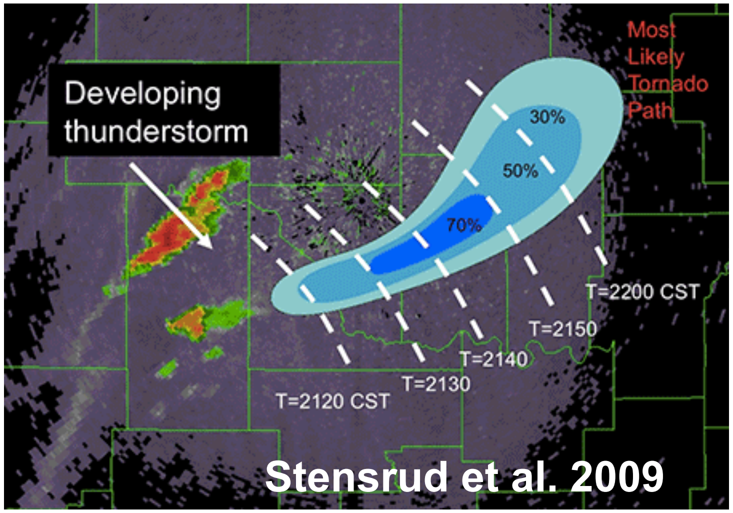


Radar Data Assimilation for Real-Time NWP

The future is now. Reflectivity data, and to some degree Doppler velocity data, are already being assimilated into real-time models.

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.

- **availability within minutes, particularly for "Warn on Forecast" applications**



Research is ongoing to improve how we use radar obs. in NWP.

- **methods (variational / ensemble / hybrid)**
- **observation operators**
- **observation types: "no precipitation" reflectivity, K_{DP}, LWC, …**
- **how many and which observations to assimilate**
- **model improvement (high-res. verification with field-program datasets)**

Warn-on-Forecast Storm-Scale Radar DA Workshops

http://www.nssl.noaa.gov/projects/wof/documents/radarda2011/

first meeting October 2011 in Norman, Oklahoma

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

radar-data quality control

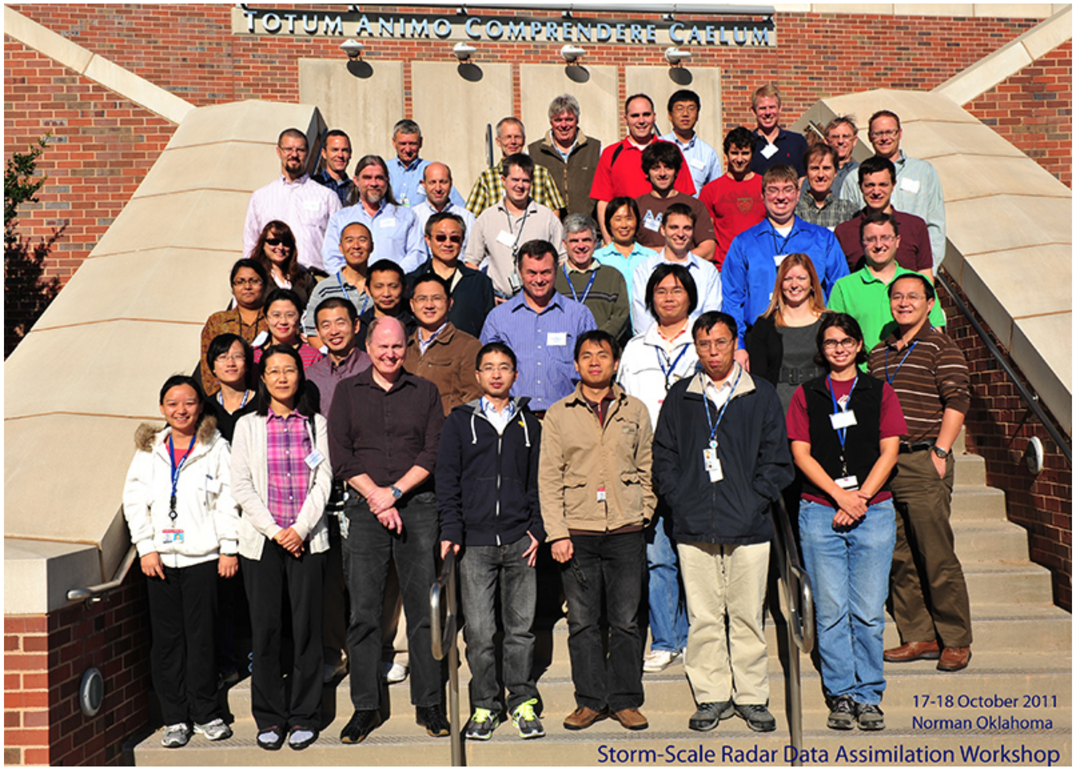
multiple radar-DA methods

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!