Testing and Evaluation of the Hybrid 4D EnVar GSI for 3-km High Resolution Regional Applications

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Developmental Testbed Center

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Hybrid 4D Ensemble-Variational (EnVar) Data Assimilation

Cost function of Hybrid 3D EnVar

$$J(x') = \beta_1 \frac{1}{2}(x')^T B^{-1}(x') + \beta_2 \frac{1}{2}\alpha^T A^{-1}\alpha + \frac{1}{2}(Hx' - y')^T (R)^{-1}(Hx' - y')$$

Cost function of Hybrid 4D EnVar

$$J(x') = \beta_1 \frac{1}{2}(x')^T B^{-1}(x') + \beta_2 \frac{1}{2}\sum_{n=1}^{N}(\alpha^n)^T A^{-1}(\alpha^n) + \frac{1}{2}\sum_{k=1}^{K}(H_k x'_k - y'_k)^T (R_k)^{-1}(H_k x'_k - y'_k)$$

Background term:
- Climatology Part
- Ensemble Part

Observation Term

Static background error covariance

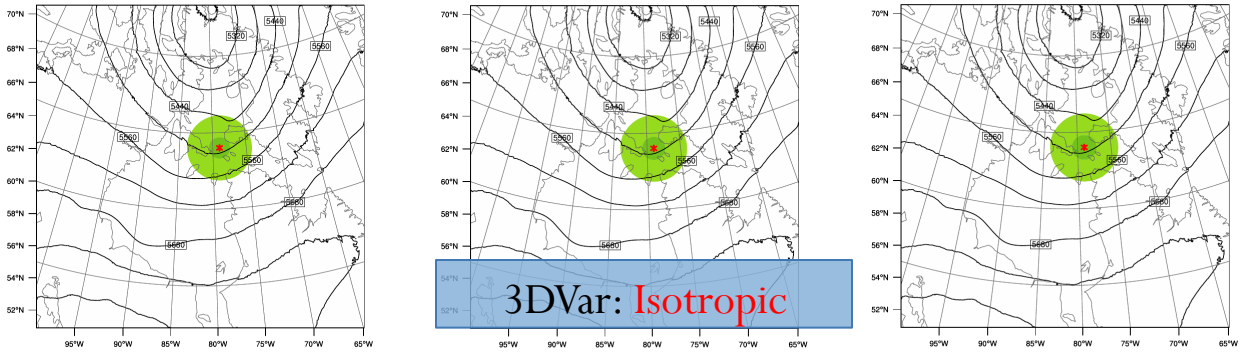
Incorporating ensemble background-error information through extended control variable

x': analysis increment vector
β : weighting function of static and ensemble BE
n: n-th ensemble member
k: k-th time bins
B: Static background error covariance
α: extended control variable
A: correlation matrix
H: foreword operator
y: observation vector
R: observation error covariance

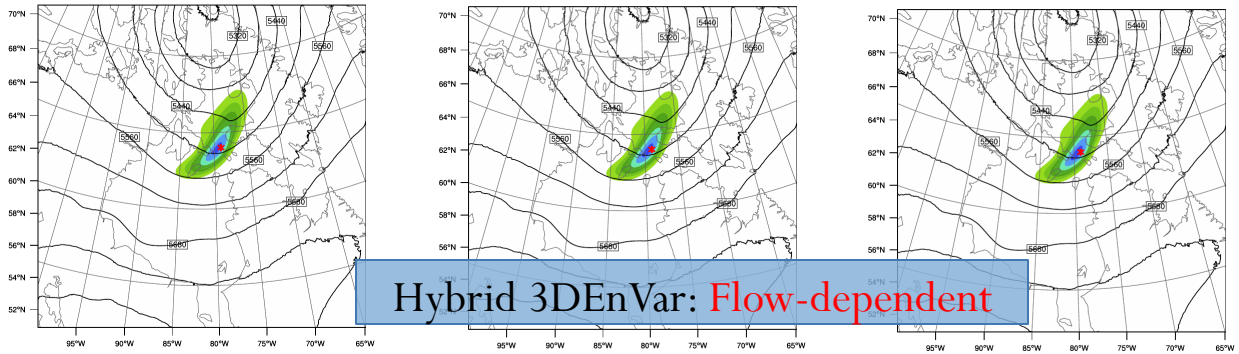
Observation @t-3h

Observation @t+0h

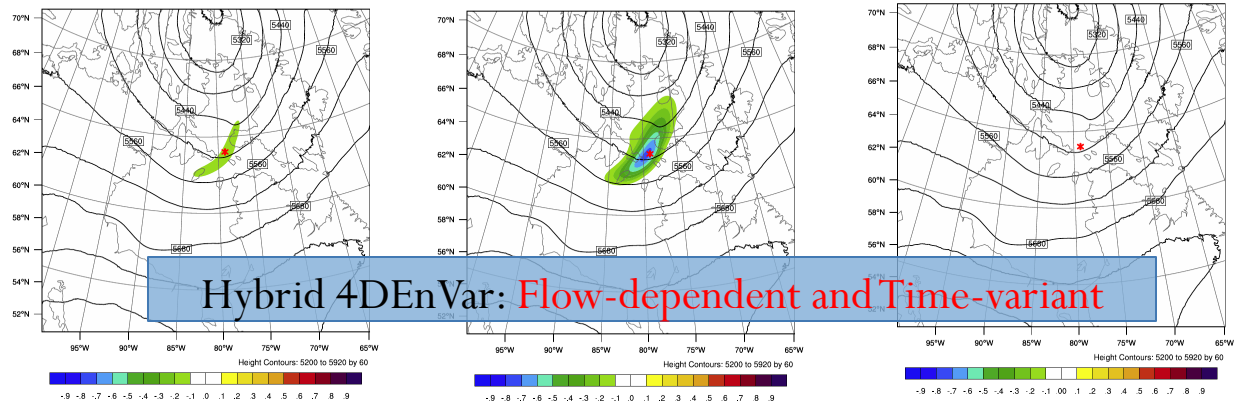
Observation @t+3h



3DVar: Isotropic



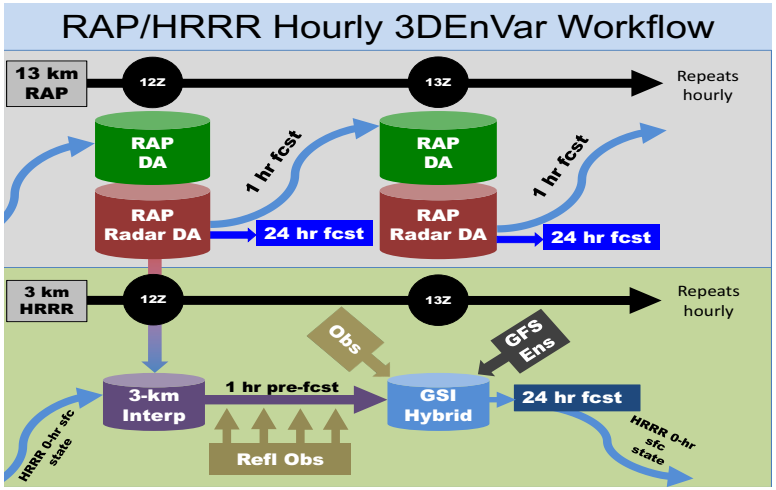
Hybrid 3DEnVar: Flow-dependent



Hybrid 4DEnVar: Flow-dependent and Time-variant

Experimental Design

- HRRR: NOAA real-time 3-km resolution, hourly updated, cloud-resolving, convection-allowing atmospheric modeling system
  - Advanced Research WRF (ARW)
  - GSI 3D hybrid
- Hourly data assimilation analysis from the 13km Rapid Refresh (RAP) provides ICs and boundaries



Experiments:

- Testing period: 3-9 September 2016
- Testing domain: Reduced HRRR domain in central US (computational constraint)
- Hourly 3D (operational) and 4D hybrid EnVar runs
  - Using archived real-time observation feed
  - Removed radar data assimilation ("nudging") during the 1-hour pre-forecast period

3D (CTL): 3D hybrid using GFS ensemble (operational configuration)

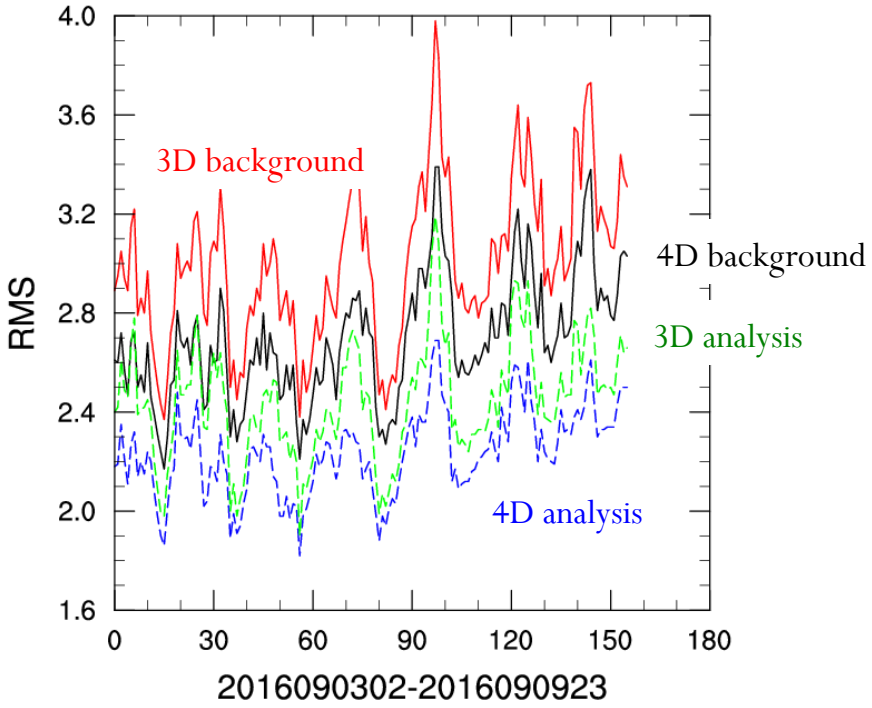
4D: 4D hybrid using GFS ensemble, 3 time bins for each analysis time window

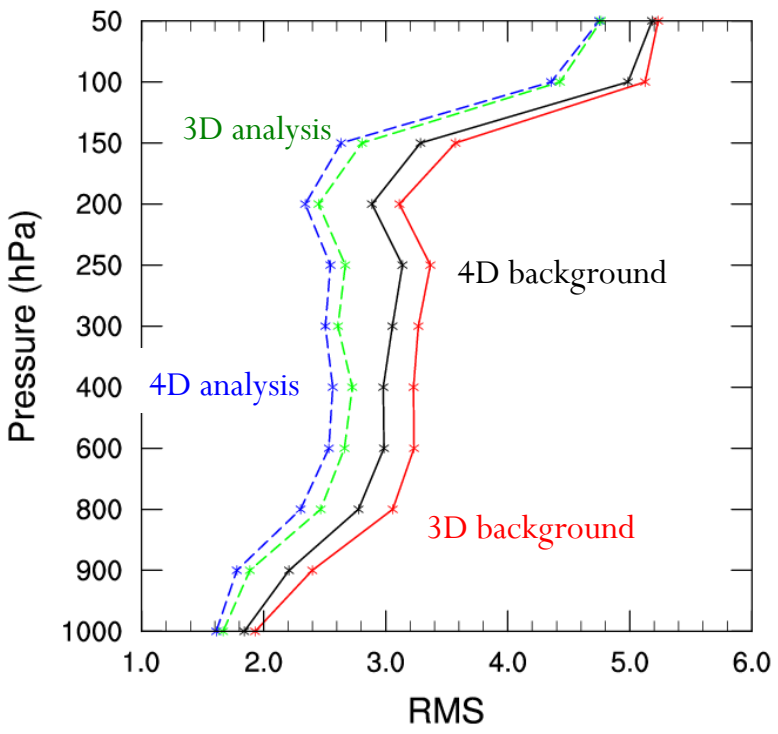
3D_reg: Same as 3D, except for using ARW ensemble (case study)

3D_cycling, 4D_cycling: Hourly cycling 3D and 4D hybrid EnVar (case study)

Domain-averaged Errors

Wind RMSE (m/s)



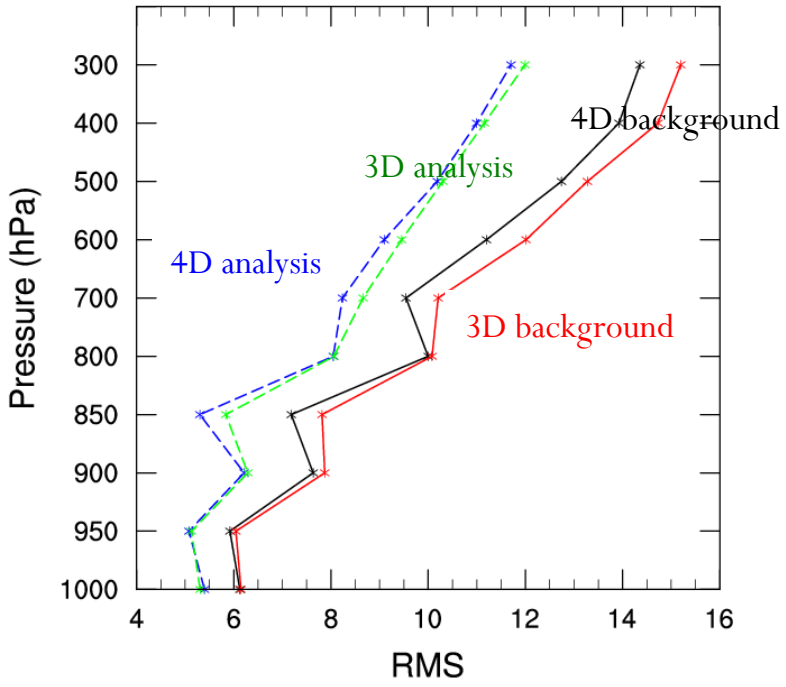


Positive impacts for wind background & analysis fit to observations

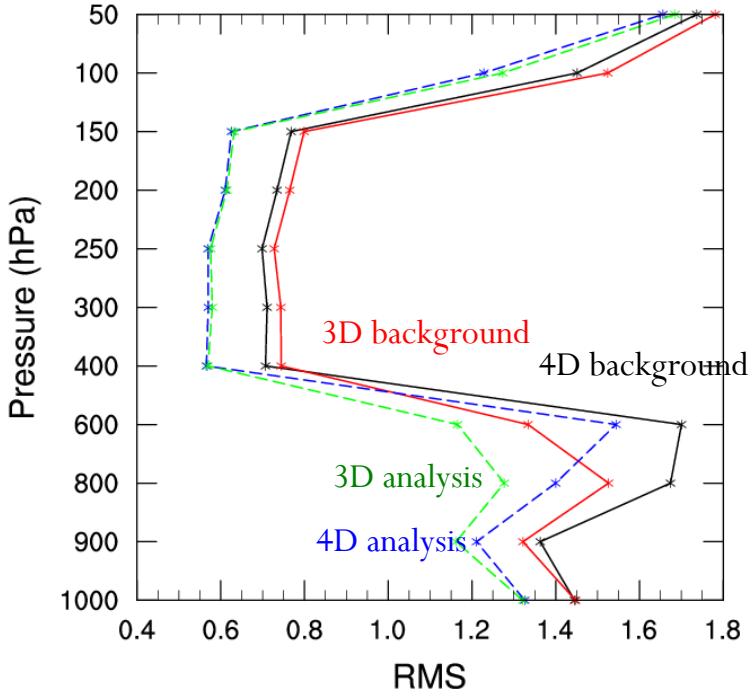
* 156 runs for verification

Domain-averaged Errors (cont)

Mixing ratio RMSE (g/g)



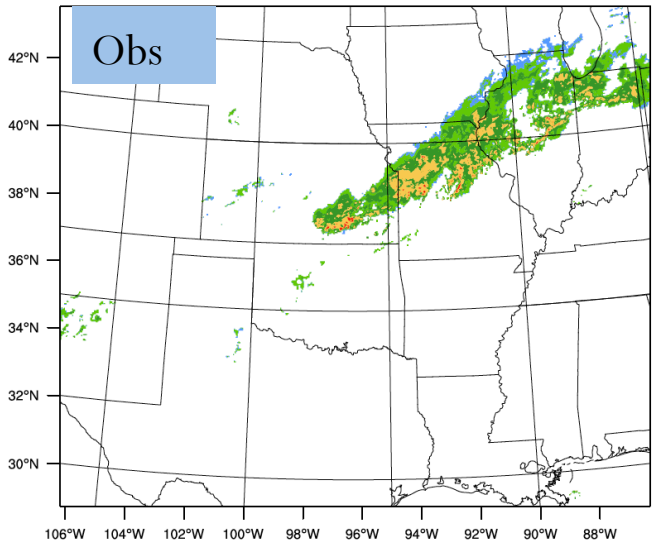
Temperature RMSE (K)



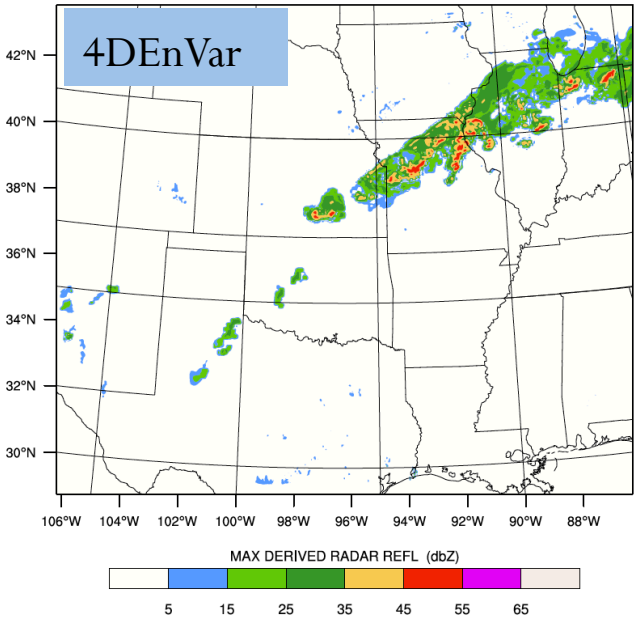
- Positive impacts for humidity but negative impacts for temperature below 400 hPa

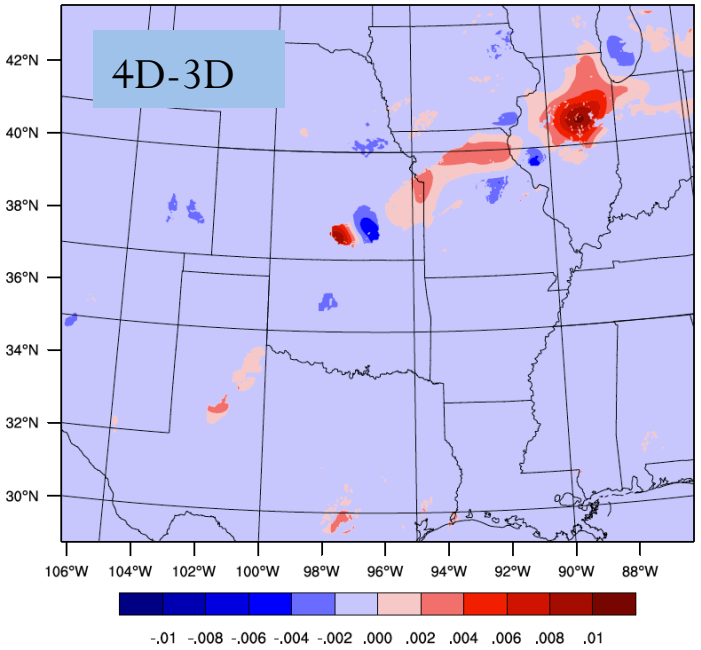
* 156 runs for verification

Reflectivity @2016090812

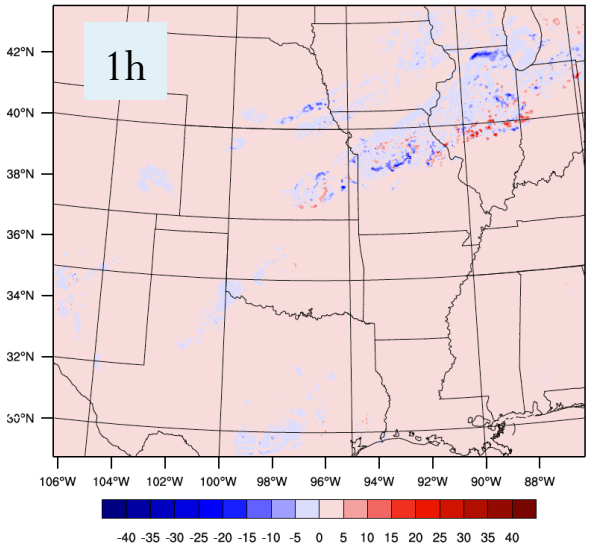


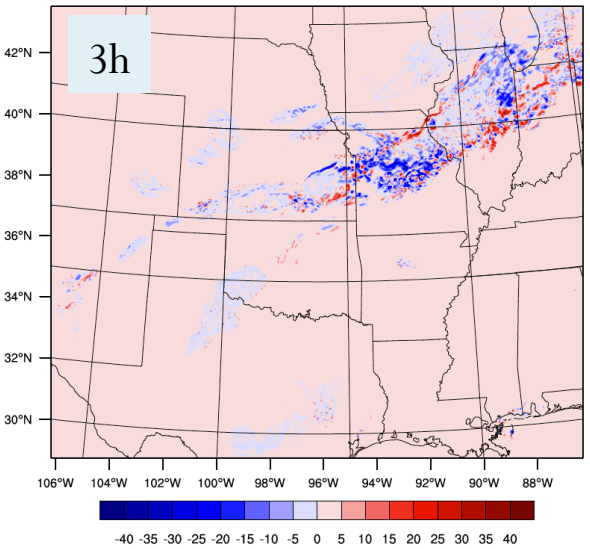
- Both 4DEnVar and 3DEnVar capture the observed convection well at analysis time
- The difference between 4DEnVar and 3DEnVar is negligible



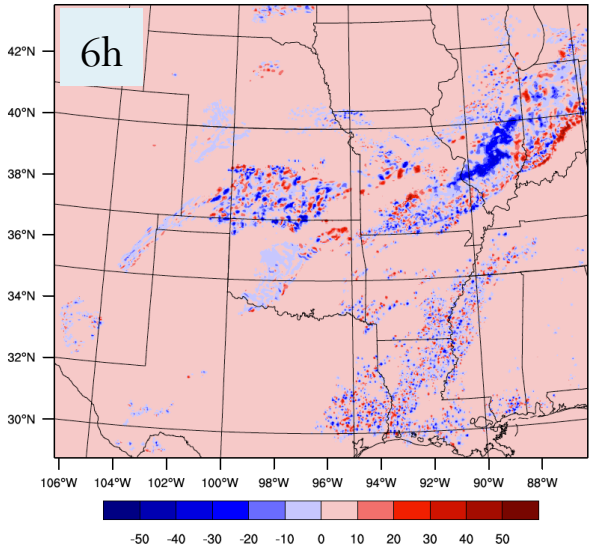


Reflectivity: 4D-3D

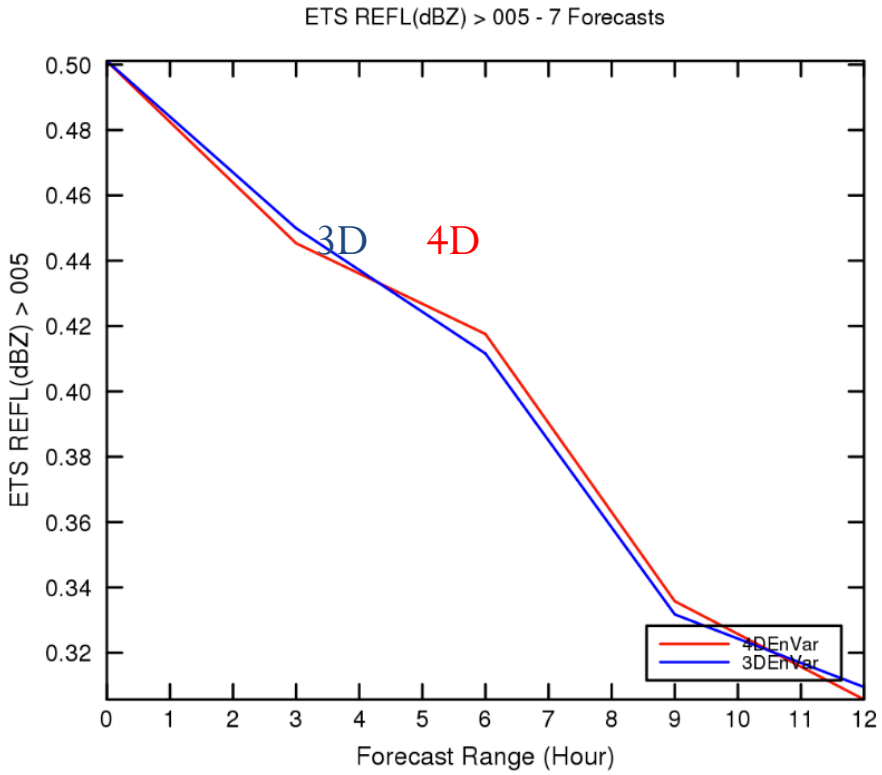


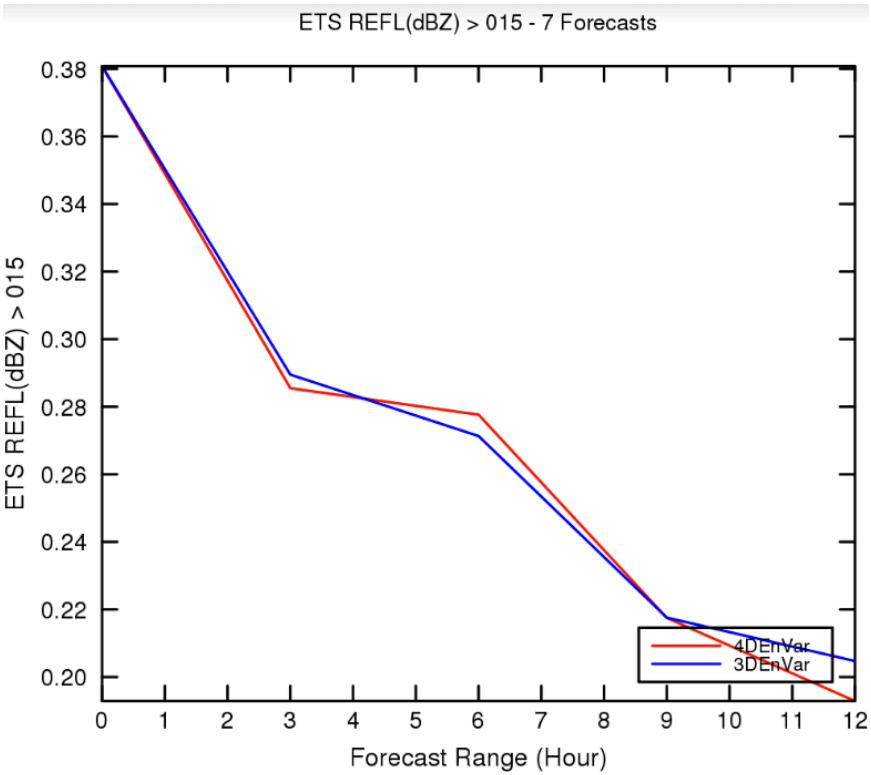


- Forecast differences become bigger with longer forecast ranges
  - Convective features



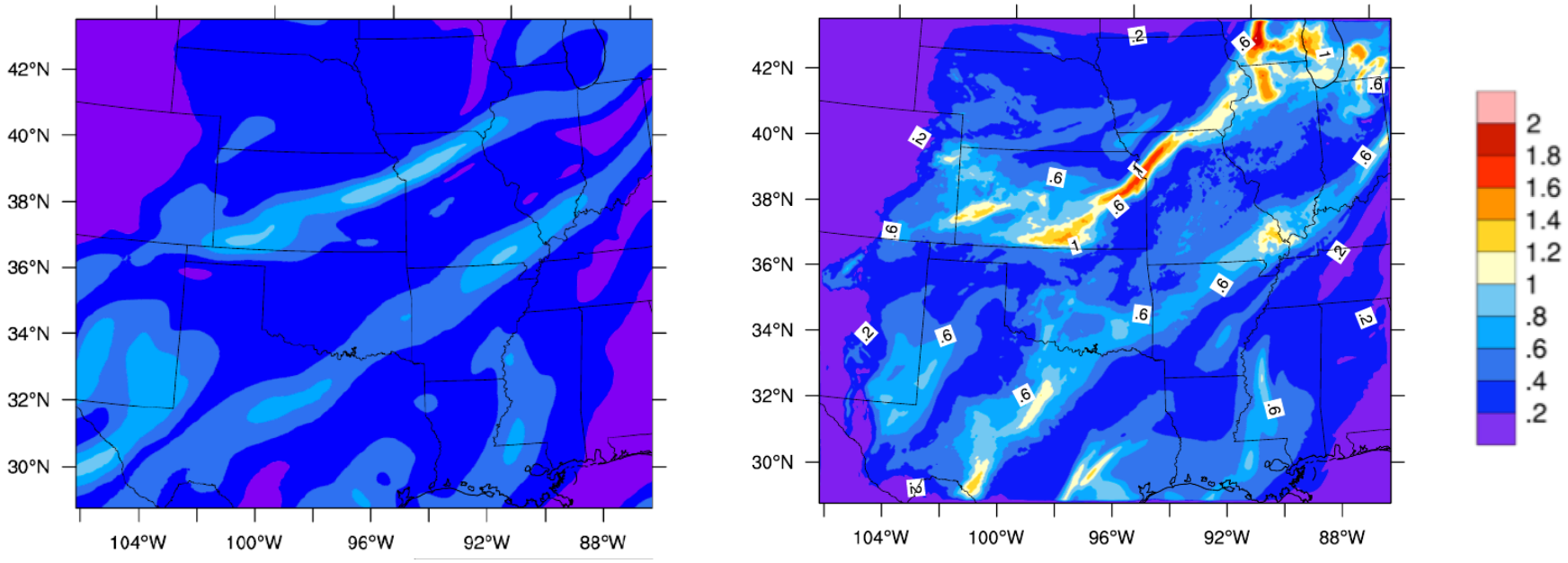
Composite reflectivity verification: ETS





Ensemble Representation for Background Errors

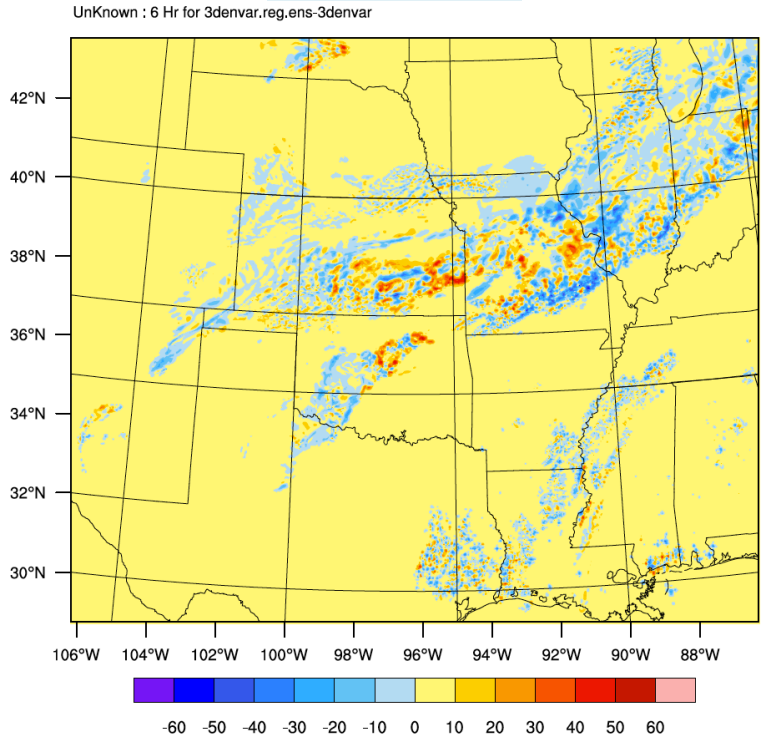
- GFS ensemble (~30km)
  - Heavily under-dispersive – lack of representation of BEs
- ARW ensemble (3km) - dynamic downscaling from GFS ensemble
  - Improved magnitude and convective scale structure
  - Not yet enough for solving the under-dispersive issues (figure not shown)



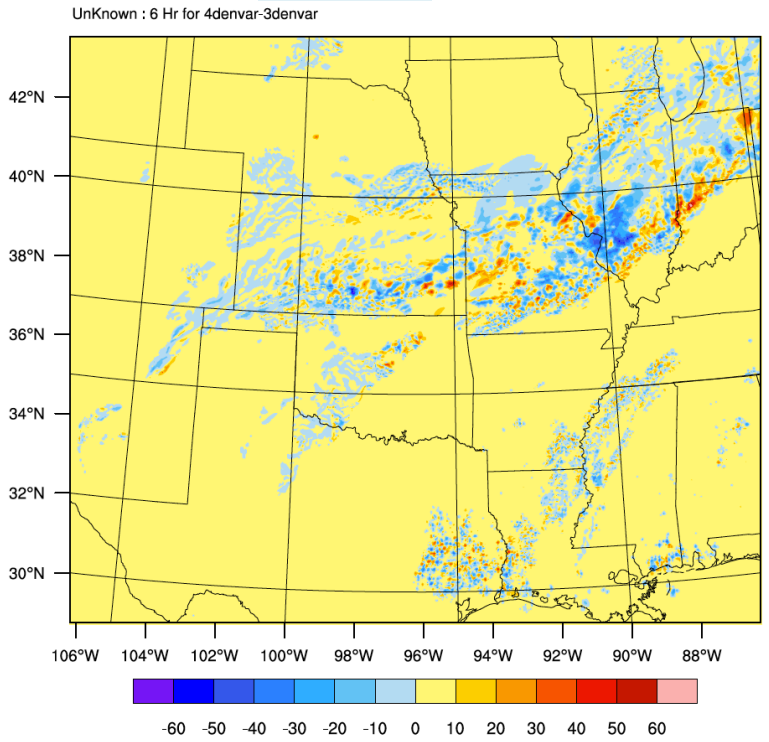
Ensemble spread for mixing ratio (g/g)

Composite Reflectivity 6h Forecast Differences

3D_reg -3D



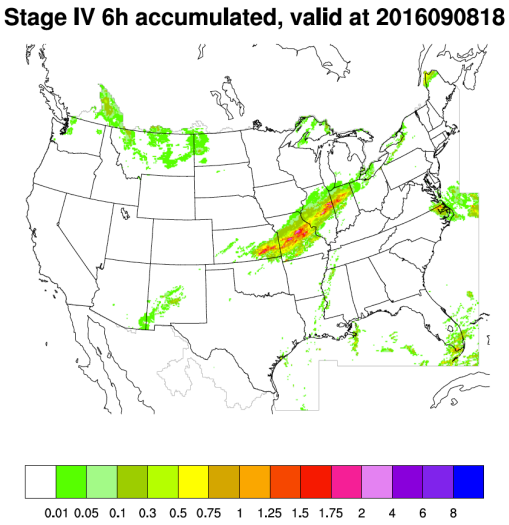
4D -3D

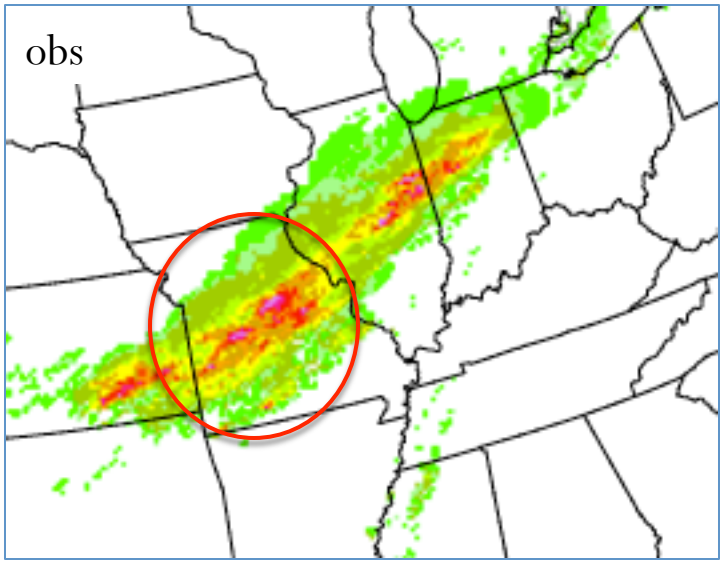


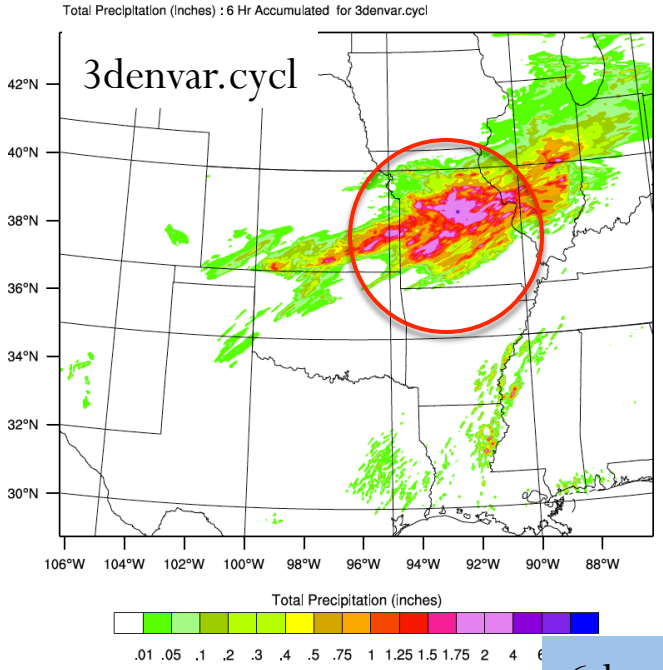
Though still under-dispersive, high-resolution ARW ensemble leads to significant differences in 3D hybrid runs, with comparable magnitudes to those between 4D and 3D runs

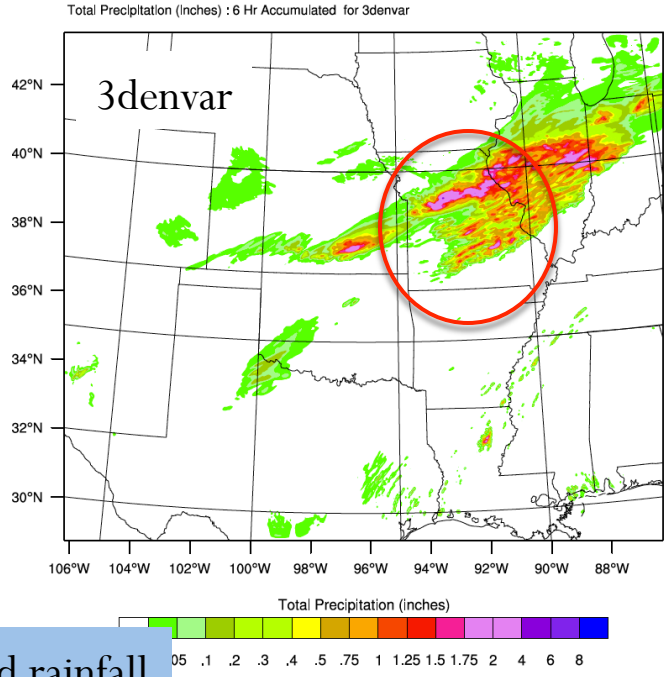
(dBZ, level 9)

Cycling vs “Warm” Start: 3D



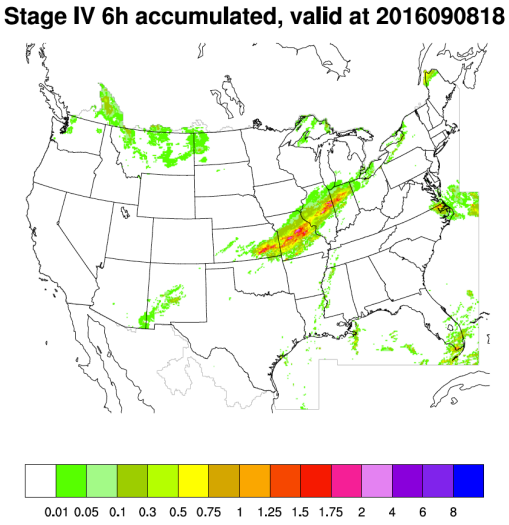


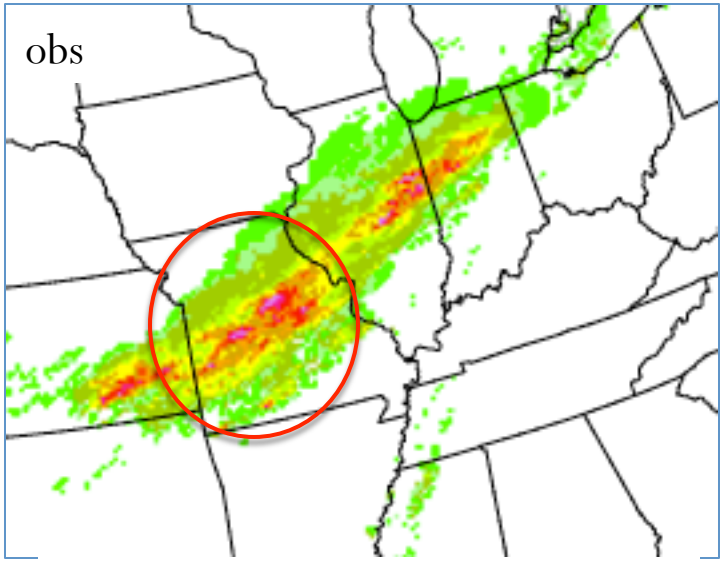


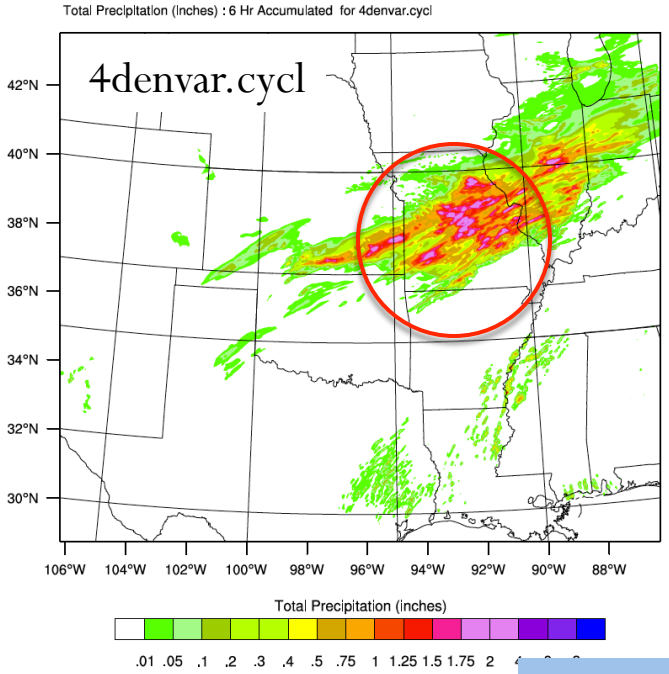


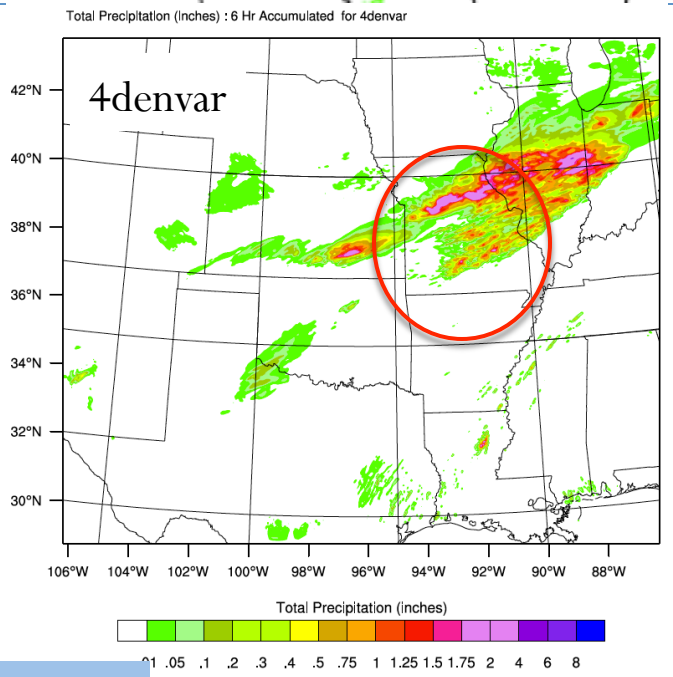
6-hr accumulated rainfall

Cycling vs “Warm” Start: 4D





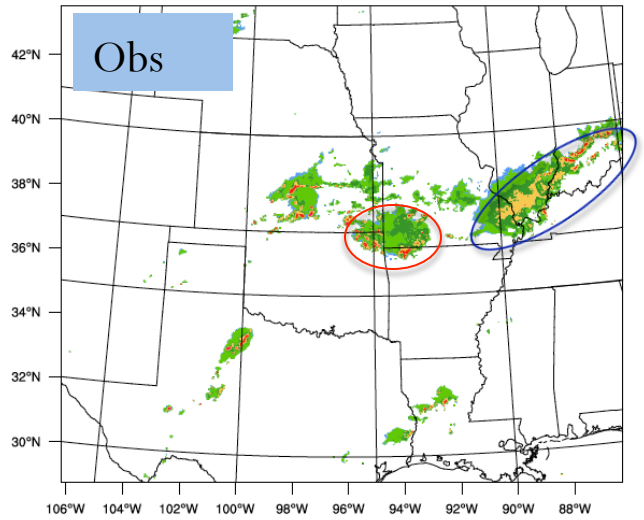


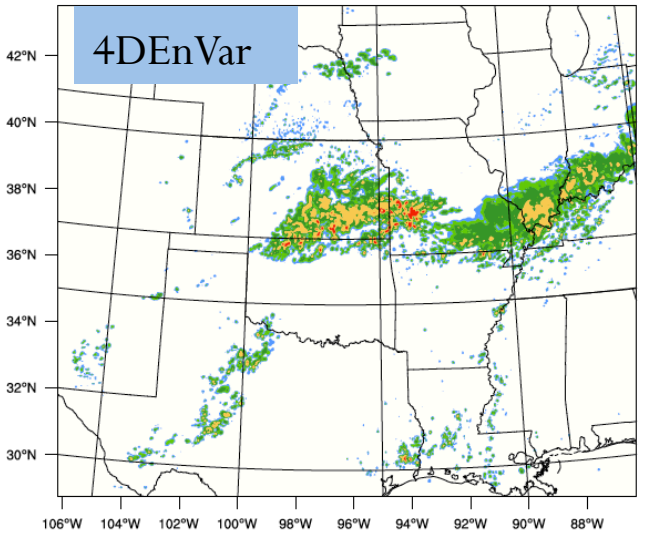


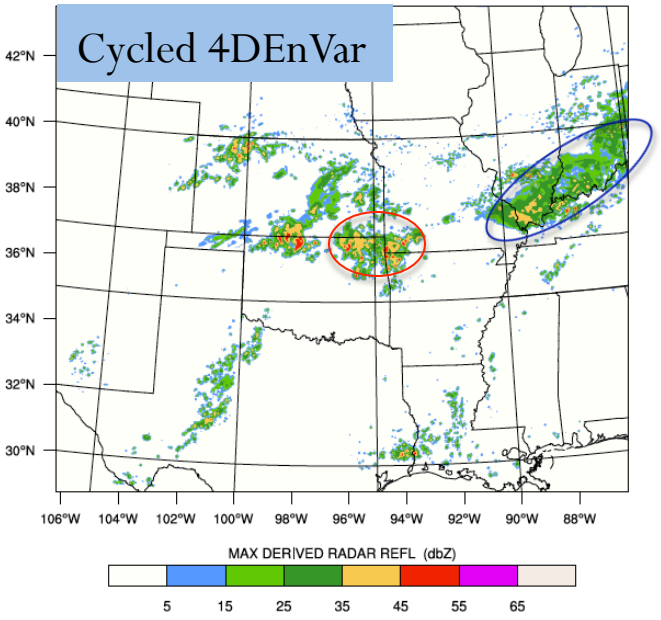
6-hr accumulated rainfall

Cycling vs "Warm" Start

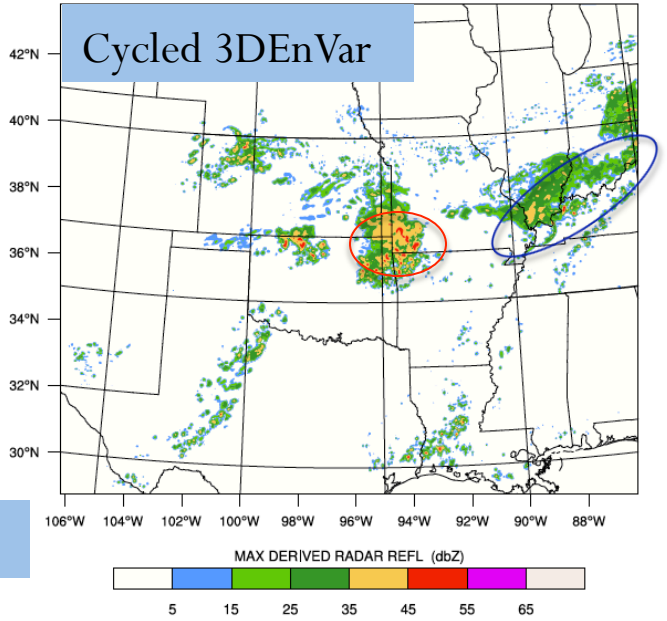
Reflectivity @2016090900







12hr fcst



Summary

- Hybrid 4DEnVar runs indicate positive impacts on HRRR backgrounds and analyses for wind and humidity (better fit to observations) but negative impacts on temperature below 400 hPa
- Cycling 4DEnVar and 3DEnVar provides better forecast of the convective system than the "warm" start 4DEnVar and 3DEnVar
- Cycling 4DEnVar improves the forecast upon cycling 3DEnVar
- Ongoing work:
  - Ensemble background error representation:
    - Further studies on high-resolution ensemble and forecast impacts
    - Temporal representation is critical for 4D as well

DTC Visitor Program

Proposals to work directly with the DTC-supported Gridpoint Statistical Interpolation (GSI) and/or the NOAA Ensemble Kalman Filter (EnKF) DA systems are strongly encouraged.
http://www.dtcenter.org/visitors/opportunity/