EnKF Assimilation of high-resolution mobile radar observations into an idealized model of a supercell thunderstorm

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Photo by Sean Waugh
Goals of EnKF analysis

- Increase availability of 3-D kinematic and thermodynamic data (dual-Doppler and in situ obs are spatially/temporally limited).
Goals of ENKF Data Assimilation

• We want a set of smoothly evolving analyses (i.e., We are not using DA to initialize a forecast).

• Analyze roles that mesocyclone-scale processes play in tornadogenesis, maintenance, and decay:
  - trajectory analysis,
  - vorticity, momentum budgets,
  - mid-upper level features,
Model Specifics

- **WRF-ARW 3.2.1:**
  - $\Delta x, y = 500$ m, $80m < \Delta z < 2$km, $[120 \times 80 \times 20]$ km$^3$
  - LFO microphysics,
  - open lateral BCs,
  - no surface fluxes, no radiation, flat terrain.

Homogeneous environment:
DA Specifics

- **DART** *(Anderson et al. 2009)*:
  
  - Ensemble adjustment filter,
  
  - 50 members,
  
  - Localization:
    - Gaspari-Cohn (1999), \( W = 0 @ r = 6 \text{ km} \)
  
  - Ensemble initiation:
    - 10 randomly placed warm bubbles at model \( t_0 \) for each member
  
  - Ensemble spread maintained with:
    - Additive noise to \( T, T_d, U, V \) every 5 min where radar reflectivity is > 25 dBZ, *(Dowell and Wicker 2009)*
    - Perturbation magnitudes \(|0.5| \text{ m/s}, |0.5| \text{ K}\) smoothed to horizontal scales of 4 km & vert scales of 2 km
Radar velocities assimilated every 2 minutes

\[ \sigma_{\text{obs}}^2 = (2 \text{ m/s})^2 \]

OBAN: Cressman weighting

500 m horizontal grid spacing

data along conical slices
Schematic low-level structure of a supercell

Adapted from Lemon & Doswel (1979)
Dual-Doppler – EnKF (ensemble mean) kinematics comparison

$Z = 400 \text{ m AGL}$
Storm structure with/without radar assimilation:

**Top row:** Series of EnKF (Ens. Mean) analyses.

**Bottom row:** Single member forecasted forward from 2157 (no DA).

Model errors/idealized conditions require DA for a good storm.
Unassimilated surface obs overlayed on ensemble mean analyses for comparison.

Surface gust Front(s)
Unassimilated surface obs overlayed on ensemble mean analyses for comparison.
Unassimilated surface obs overlayed on ensemble mean analyses for comparison

Surface gust Front(s)
These two experiments are exactly the same; they were generated from the same restart file using the same radar obs. The only difference is the realizations of additive noise.

Thermodynamic analyses are fairly sensitive to additive noise.
$\theta_v (K)$

More Ensemble Spread in $T$, $T_d$

$T_d = 0.5$ [first try]

$T_d = 0.2$ [second try]

Less Ensemble Spread in $T$, $T_d$

$T_d = 0.2$ [first try]

$T_d = 0.5$ [second try]

$z = 1.5 km$
Trajectories (storm-rel.) calculated from ens. mean analyses

Ring (radius = 1 km) of 20 parcels centered on peak $\zeta$ at $z = 200$ m; integrated \textbf{backward} in time from 4 initial times.

- 2155 UTC - tornadogenesis
- 2205 UTC - intensification
- 2215 UTC - maturity
- 2225 UTC - weakening

$\theta'_{\rho}$ (K)
\[ \begin{align*}
\frac{d\xi}{dt} &= \eta \frac{\partial u}{\partial y} + \zeta \frac{\partial u}{\partial z} + \xi \frac{\partial u}{\partial x} + \frac{\partial B}{\partial y} \\
\frac{d\eta}{dt} &= \xi \frac{\partial v}{\partial x} + \zeta \frac{\partial v}{\partial z} + \eta \frac{\partial v}{\partial y} - \frac{\partial B}{\partial x} \\
\frac{d\zeta}{dt} &= \xi \frac{\partial w}{\partial x} + \eta \frac{\partial w}{\partial y} + \zeta \frac{\partial w}{\partial z}
\end{align*} \]

Ultimately important for generation of low-level mesocyclone

\[ \vec{\omega} = \langle \xi, \eta, \zeta \rangle \]

\[ B = g \frac{\theta - \theta_{env}}{\theta_{env}} \]
Consistency check: Does ens mean vorticity along parcel trajectories match predicted trend?

\[ \bar{\xi}_{\text{parcel}} = \bar{\xi}_{t_0} + \int \left( \eta \frac{\partial u}{\partial y} + \zeta \frac{\partial u}{\partial z} + \xi \frac{\partial u}{\partial x} + \frac{\partial B}{\partial y} \right) dt \]

\[ \eta_{\text{parcel}} = \eta_{t_0} + \int \left( \xi \frac{\partial v}{\partial x} + \zeta \frac{\partial v}{\partial z} + \eta \frac{\partial v}{\partial y} - \frac{\partial B}{\partial x} \right) dt \]

\[ \zeta_{\text{parcel}} = \zeta_{t_0} + \int \left( \xi \frac{\partial w}{\partial x} + \eta \frac{\partial w}{\partial y} + \zeta \frac{\partial w}{\partial z} \right) dt \]
Vertical vorticity history along parcel trajectories

Tornadogenesis

Intensification

Maturity

Weakening

\[ \Theta'_p (K) \]

\[ Z (\text{km}) \]

\[ -7 \quad -5 \quad -3 \quad -1 \]

\[ 0.0 \quad 0.1 \quad 0.2 \quad 0.5 \]

\[ 0 \quad 0.01 \quad 0.02 \quad 0.03 \quad 0.04 \quad 0.05 \quad 0.06 \quad 0.07 \]

Ensemble mean \( \zeta \) along trajectory

\[ \zeta_{parcet} = \zeta_{t_0} + \int (\text{tilting} + \text{stretching})dt \]
Horizontal vorticity history along parcel trajectories

\[ \xi_{\text{parcel}} = \xi_{t_0} + \int (\text{tilting} + \text{stretching} + \text{baroclinic}) \, dt \]

Ensemble mean \( \xi \) along trajectory

\[ \eta_{\text{parcel}} = \eta_{t_0} + \int (\text{tilting} + \text{stretching} + \text{baroclinic}) \, dt \]

Ensemble mean \( \eta \) along trajectory
Summary

• **EnKF Kinematic Analyses:**
  - Compare well with dual-Doppler fields of similar scale.
  - Most trajectories seem believable, though horizontal vorticity budgets have some inconsistencies.

• **EnKF Thermo Analyses:**
  - Mixed success with comparisons to MM in situ obs (where available).
  - Careful consideration of ensemble spread necessary; and/or more ensemble members?
Extras
Future work

1) How do EnKF horizontal vorticity analyses compare to dual-Doppler wind syntheses?

2) Continue analysis of storm:
   - Diagnosis of rear-flank downdraft source regions.
   - Causes for changes in low-level convergence near tornado.
Acknowledgements

• The EnKF experiments were performed using NCAR CISL supercomputing facilities with the Data Assimilation Research Testbed (DART) and WRF-ARW software.

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Vertical vorticity history along parcel trajectories

2155 UTC (T-genesis)

2215 UTC (Maturity)

2225 UTC (Weakening)

Stretching (1/s²)
Tilting (1/s²)

sfc gust front

Trajectory projected onto sfc plane
Spatial relationship b/w mid-level updraft and low-level rotation

Schematic representation of Dowell and Bluestein (2002)

$t_0$ balanced outflow and inflow $t_1$ imbalanced outflow and inflow

5 June 2009

2151 UTC

mid-level updraft

Near-sfc mesocyclone

2213 UTC

Near-sfc Gust front

2225 UTC

2233 UTC

Pre-tornadic/T-genesis

maturity

weakening

dissipated
Spatial relationship b/w mid-level updraft and low-level rotation

Schematic representation of current storm

$t_0$ balanced outflow and inflow  \hspace{1cm} t_1$ imbalanced outflow and inflow

- main updraft
- mature tornado
- weakening tornado

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5 June 2009

![Image of storm development over time]

- 2151 UTC
  - mid-level updraft
  - Near-sfc mesocyclone
- 2213 UTC
  - Near-sfc Gust front
- 2225 UTC
- 2233 UTC
Storm structure with/without radar assimilation:

**Top row:** Series of EnKF (Ens. Mean) analyses.

**Bottom row:** Single member forecasted forward from 2157 (no DA).

Model errors/idealized conditions require DA for a good storm.
Mesocyclone buoyancy (function of height & time)

Positively buoyant
Negatively buoyant

Circulation and radial motion (function of radius & time)

Inbound
0 m/s
Outbound

Time (UTC)

Pre-tornadic
T-genesis
Intensification
Maturity
Weakening

Periods of tornado lifecycle
Trajectories (storm-rel.) calculated from ens. mean analyses

Ring (radius = 1 km) of 20 parcels centered on peak $\zeta$ at $z = 200$ m; integrated forward in time from 4 times

Most parcels rising into updraft

Some parcels rising into updraft

Few/no parcels rising into updraft

No parcels rising into updraft
Mesocyclone buoyancy (function of height & time)

Positively buoyant
Negatively buoyant

Circulation and radial motion (function of radius & time)

Pre-tornadic
T-genesis
Intensification
Maturity
Weakening

Periods of tornado lifecycle
Ensemble mean analyses – temperature fields

(Note: these experiments conducted with 1-km model grid)
2217 UTC

M-Y (2-mom ice)

LFO (single-mom ice)

$\theta'_{(K)}$

$Z = 50 \text{ m}$

Mob. Mesonets
Mob. Mesonets
DA Specifics

• **DART:**
  
  – Ensemble adjustment filter,
  
  – 50 members,
  
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  – **Ensemble initiation:**
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  – **Ensemble spread maintained with:**
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    • Perturbations smoothed to 4 km (horiz), 2 km (vert) scales
Thinning the amount of observations assimilated:

<table>
<thead>
<tr>
<th>Unthinned</th>
<th>50% assim’ed</th>
<th>25% assim’ed</th>
</tr>
</thead>
</table>

No thinning done in vertical direction shown today; though, experiments show poor storm structure when low-level elevation angles are neglected.
(Note: these experiments conducted with 2-km model grid)
Future Work

• **Storm-scale/mesocyclone-scale analysis:**
  
  - Trajectory calculations,
  
  - Circulation budgets,
  
  - CAPE, CIN, LFC, etc. of outflow parcels
  
  - Structure/formation of downdraft surges.
Computational Cost:
On NCAR-Bluefire; async = 2 (parallel filter, serial filter), 64 processors:

• **1-km model grid, Unthinned obs:**
  - 

• **1-km model grid, 50% obs assim’ed:**
  - 5.5 wallclock hours, 500 gaus, 4.2 GB analyses

• **0.5-km model grid, 50% obs assim’ed:**
  - 40 wallclock hours, 3500 gaus, 17 GB analyses
Circulation (shaded) and radial winds (outward, inward, zero; 1 m/s increment) calculated or averaged in rings of expanding radius (r = 0 to 5 km; vertical axis) from the EnKF vortmax as a function of time (horizontal axis) and height (z = 100, 200, 300 m; each in their own panel).
EnKF Thermodynamic Verification

Mob. Mesonets (single-moment) (dual-moment)

Radar only

Radar and Mob Mesonets

\[ \zeta \]

\[ Z = 50 \, \text{m} \]
Ensemble mean analyses – temperature fields

M-Y (2-mom ice)  LFO (single-mom ice)

(Note: these experiments conducted with 1-km model grid)
$\zeta$

$Z = 50 \text{ m}$

Mob. Mesonets

2217 UTC

M-Y (2-mom ice)

LFO (single-mom ice)

$\theta' (\text{K})$

$Z = 50 \text{ m}$
MM obs – EnKF outflow comparison

- Sequence of EnKF analyses of theta’ and MM obs (valid +/- 1 min from EnKF analysis) overlayed:

  - MM’s only just getting into storm, but so far - not good
  - Not great, particularly in far left FF
  - Better overall, but still disagreement in FF
  - Decent, but still disagreement in FF

My < 1 sentence impression of the agreement of MM obs and each EnKF analysis

- Low-level $w_{max}$ trace:
MM obs – EnKF outflow comparison

- Sequence of EnKF analyses of theta’ and MM obs (valid +/- 1 min from EnKF analysis) overlayed:

  MM’s only just getting into storm, but so far - not good
  2147 UTC

  Not great, particularly in far left FF
  2151 UTC

  Better overall, but still disagreement in FF
  2155 UTC

  Decent, but still disagreement in FF
  2159 UTC

  Warmth (lasts 2-3 analysis times) - Seems to disagree With few available MM obs
  2203 UTC

  Pretty good
  2207 UTC

  decent
  2211 UTC

  decent
  2215 UTC

My < 1 sentence impression of the agreement of MM obs and each EnKF analysis

Low-level $w_{\text{max}}$ trace:

MM obs:
MM obs – EnKF outflow comparison... continued

Disagreement everywhere

2219 UTC

Disagreement everywhere

2223 UTC

decent

2227 UTC

2231 UTC

Fair

2235 UTC

Pretty good

Low-level $w_{\text{max}}$ trace:

dBZ

MM obs:
Trajectories (storm-rel.) calculated from ens. mean analyses

Ring (radius = 1 km) of 20 parcels centered on peak $\zeta$ at $z = 200$ m; integrated forward from 4 times

(tornadogenesis) 2155 UTC (intensification) 2205 UTC (maturity) 2215 UTC (weakening) 2225 UTC

$\theta'$

Parcels with net ascent by 2237 UTC
Parcels with net descent by 2237 UTC

$W (z = 200\text{m})$
Surface & mid-upper-level features

5 June 2009

2151 UTC (pre-tornado/tornadogenesis)

2213 UTC (tornado mature)

2225 UTC (tornado weakening)

2233 UTC (tornado dissipated)

W > 5 m/s (z = 5km)

Surface gust front (z = 300m)

Low-level meso cyclone/tornado stays beneath mid-level updraft
Surface & mid-upper-level features

5 June 2009

2151 UTC
(pre-tornadic)

2213 UTC
(tornado mature)

2225 UTC
(tornado weakening)

2233 UTC
(dissipated)

3 June 1999

0036 UTC

0040 UTC

0044 UTC

0048 UTC
Obs-space diagnostics for thinning experiments:

*Volume-mean of total prior ensemble spread (Stand. Dev.) as a function of time.*

Thinning increases ensemble spread (at least marginally).

(Note: these experiments conducted with 2-km model grid)
Theta Ens. Spread averaged at all grid points with model-computed dBZ > 25 at various heights

Unthinned, 50% assimilated, 25% assimilated.

Horiz thinning
Largest effects appear to be in the EnKF-retrieved temperature fields, mostly on the far left-through-rear flanks of the storm.

There are seemingly few differences in the kinematic /reflectivity fields at all three times between the ‘unthinned’ and ‘50% assimilated’ experiments. There is some degradation of the vorticity field in the ‘25% assimilated’ experiment, particularly at 2205 and 2219 UTC; presumably unrealistic because this is near peak tornado time.

**Conclusions:** If we were to thin the assimilated radar obs, we still seem to be getting decent-looking analyses (with 50% thinning), and we are saving resources

resource cost: unthinned – 365 gaus, 4.1 hrs wallclock time
50% assim – 265 gaus, 3.0 hrs
25% assim – 230 gaus, 2.6 hrs

So, with this in mind, does thinning beneficially affect the amount/evolution of spread?
Ensemble spread (Stand. Dev.) of potential temp. averaged at all grid points with model-computed dBZ > 25 at z = 250 m AGL:

Drop-off when all radars are assimilated, no matter the amount of thinning.

Thinning increases ensemble spread (marginally).

(Note: these experiments conducted with 2-km model grid)
• Again, thinning obs maintains some spread, but not much more than when obs are unthinned. But at least ensemble spread is, on average, a bit larger in the |1.0| K, m/s run.

• Previous result were from experiments with thinning only in the X & Y directions, but no thinning in the Z direction (Radar velocities have been OBANed to a regular horizontal grid, but are analyzed at their observed vertical locations along the radar beam). What if we thin in the vertical too, particularly near the ground?

[NEXT 2 SLIDES]: Compare ensemble mean storm structures and spread evolution from two experiments: 1) full elevation angle list and 50% of horizontal grid assimilated (blue + pink dots). 2) 1.0, 3.0, 5.0 degree sweeps removed from analysis and 50% of horizontal grid assimilated (blue dots).
There is more spread when vertical thinning the runs that only assimilate 25% of the data (in horizontal grid). [right panels – spread of theta from 2 runs: 25% of the horizontal grid with full elev angle list assimilated (black), and 25% of the horizontal grid with 1,3,5 degree sweeps removed (blue)].

But vertically thinning the 25% runs makes them even yuckier.

No Elev. Angle thinning  Yes Elev. Angle thinning

50% radar assimilated

25% radar assimilated

the dBZ

zeta

W > 0

Yuck!
Dual-Doppler – EnKF (ensemble mean) kinematics comparison (DOW6 & NOXP)

\[ \eta = 400 \text{ m AGL} \]
Low-level \( w_{\text{max}} \) trace:

MM obs:
Left: instantaneous terms; red-str, green-tilt, blue-B, white-zeta(ens mean).

Right: integrated terms; white-zeta(ens mean), yellow – B only, red – B + str + tilt, black – str + tilt.