Radar Data Assimilation

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Acknowledgment:
Warn-on-Forecast project
Radar Data Assimilation
(for analysis and prediction of convective storms)

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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)

(NOAA NCEP, NCAR RAL)

(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

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”)

190 radars

volumes every 10 min or less
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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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.

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

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

Stensrud et al. 2009
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
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• 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
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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

Fabry and Kilambi 2011
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

4-km grid spacing ("convection allowing")

Skill as a function of forecast lead time

Aggregated over all 00 UTC initializations

20-dBZ threshold

40-dBZ threshold
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
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

<table>
<thead>
<tr>
<th>Model</th>
<th>Domain</th>
<th>Grid Points</th>
<th>Grid Spacing</th>
<th>Vertical Levels</th>
<th>Boundary Conditions</th>
<th>Initialized</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP-ESRL</td>
<td>North America</td>
<td>758 x 567</td>
<td>13 km</td>
<td>50</td>
<td>GFS</td>
<td>Hourly (cycled)</td>
</tr>
<tr>
<td>HRRR</td>
<td>CONUS</td>
<td>1799 x 1059</td>
<td>3 km</td>
<td>50</td>
<td>RAP-ESRL</td>
<td>Hourly (no-cycle)</td>
</tr>
</tbody>
</table>

#### Model Details

- **RAP-ESRL**
  - **Domain**: North America
  - **Grid Points**: 758 x 567
  - **Grid Spacing**: 13 km
  - **Vertical Levels**: 50
  - **Boundary Conditions**: GFS
  - **Initialized**: Hourly (cycled)

- **HRRR**
  - **Domain**: CONUS
  - **Grid Points**: 1799 x 1059
  - **Grid Spacing**: 3 km
  - **Vertical Levels**: 50
  - **Boundary Conditions**: RAP-ESRL
  - **Initialized**: Hourly (no-cycle)

### Assimilation and Radiation Details

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

**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 with radar-reflectivity and lightning (proxy refl.) data**
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

- reflectivity DA in RAP + HRRR (for 1 h)
- reflectivity DA in RAP only

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 ($\Delta x=3$ km) initialized from NAM ($\Delta x=12$ 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

ensemble experiment

<table>
<thead>
<tr>
<th>Time</th>
<th>Radar DA</th>
<th>Ensemble Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>19Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20Z</td>
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<tr>
<td>21Z</td>
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<tr>
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<td></td>
<td></td>
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<tr>
<td>0Z</td>
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</table>

control experiment

<table>
<thead>
<tr>
<th>Time</th>
<th>Deterministic Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>19Z</td>
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<tr>
<td>20Z</td>
<td></td>
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<td>21Z</td>
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<td>22Z</td>
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<tr>
<td>23Z</td>
<td></td>
</tr>
<tr>
<td>0Z</td>
<td></td>
</tr>
</tbody>
</table>
Probability of Rotating Updrafts
(2-5 km updraft helicity > 25 m² s⁻²)
2000-2100 UTC

P(Upd Heli > 25.0 m² s⁻²), 1-h max 2-5 km
27 April 2011  2100 UTC

control experiment
(no radar DA, deterministic forecast)

P(Upd Heli > 25.0 m² s⁻²), 1-h max 2-5 km
27 April 2011  2100 UTC

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

radar DA has not eliminated spurious storms from forecast
Probability of Rotating Updrafts
(2-5 km updraft helicity > 25 m² s⁻²)
2000-2100 UTC

P(Upd Heli > 25.0 m² s⁻²), 1-h max 2-5 km
27 April 2011 2100 UTC

P(Upd Heli > 25.0 m² s⁻²), 1-h max 2-5 km
27 April 2011 2100 UTC

control experiment
(no radar DA, deterministic forecast)

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 m² s⁻²)
2000-2100 UTC

P(Upd Heli > 25.0 m² s⁻²), 1-h max 2-5 km
27 April 2011  2100 UTC

control experiment
(no radar DA, deterministic forecast)

radar DA, 0-1 h ensemble forecast

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 m² s⁻²)
2000-2100 UTC

control experiment
(no radar DA, deterministic forecast)
radar DA, 1-2 h ensemble forecast

some storms introduced by radar DA persist; probabilities vary among storms
Probability of Rotating Updrafts
(2-5 km updraft helicity > 25 m² s⁻²)
2000-2100 UTC

control experiment
(no radar DA, deterministic forecast)

radar DA, 2-3 h ensemble forecast

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

NSSL Composite Reflectivity

2200 UTC

2300 UTC
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

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!