Radar data assimilation at sub-kilometer scales: A case study of Phased-Array Weather Radar Assimilation

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Motivation

- The resolution of radar observation data can be usually higher than the model resolution; in particular, Phased-Array Weather Radar (PAWR).

- We explore radar data assimilation at 1-km – 100-m model resolution with a 30-s rapid-update cycle using the K computer!
Phased Array Weather Radar (PAWR)

10x more data in a 1/10 period

3-dim measurement using a parabolic antenna (150 m, 15 EL angles in 5 min)

100x more data!

3-dim measurement using a phased array antenna (100 m, 100 EL angles in 30 sec)
SCALE-LETKF  (Lien et al. 2016)

- Model:
  - Regional model
  - Scalable Computing for Advanced Library and Environment (Nishizawa et al. 2015; Sato et al. 2015)
  - An open-source basic library for weather and climate model.
  - Developed also at RIKEN AICS.

- Data assimilation:
  - Local Ensemble Transform Kalman Filter (LETKF; Hunt et al. 2007)
**Experimental settings**

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Size</th>
<th>Observation</th>
<th>Cycle length</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>15 km</td>
<td>5760 x 4320 km</td>
<td>PREPBUFR</td>
</tr>
<tr>
<td>D2</td>
<td>5 km</td>
<td>1280 x 1280 km</td>
<td>PREPBUFR</td>
</tr>
<tr>
<td>D3</td>
<td>1 km</td>
<td>180 x 180 km</td>
<td>PAWR</td>
</tr>
<tr>
<td>D4</td>
<td>1 km, 500 m, 250 m, 100 m</td>
<td>120 x 120 km</td>
<td>PAWR</td>
</tr>
</tbody>
</table>

Ensemble size: 100
State variables: U, V, W, P, T, Q, Qc, Qr, Qs, Qi, Qg

00:00Z July 1 ...
00:00Z July 12

02:00Z July 13
06:00Z July 13 (15:00L)

30-min forecasts every 10 min
Experimental settings

After a very long process of tuning..............

- Assimilate both reflectivity (Ref) and radial velocity (Vr) data.
- Radar data QC (Ruiz et al. 2015): remove ground clutter and attenuated data.
- Superob to model resolution (use only the data below 11 km).
- Define Ref_rain: raw Ref >= 10 dBZ
  Ref_clear: raw Ref < 10 dBZ
- Set all Ref_clear (both observation and background) to 5 dBZ. (Similar to Aksoy et al. 2009 but leave a 5-dBZ gap between minimum Ref_rain and Ref_clear)
- Observation errors: Ref: 5 dBZ
  Vr: 3 m/s
- Reject data when [y – H(x)] > 10 x obs error
- Reject data when there are too few “raining” (Ref_rain) background members: (similar to Lien et al. 2013, 2016 for precipitation assimilation)
  Ref_rain obs: require >= 1 (out of 100) background members having Ref_rain
  Ref_clear obs: require >= 20 (out of 100) background members having Ref_rain
- Limit number of observations used per grid (Hamrud et al. 2015): Max = 100
- Relaxation to prior spread (Whitaker and Hamill 2012): α = 0.95
- Covariance localization:
  Horizontal (Ref_rain and Vr): 4 km
  Horizontal (Ref_clear): 2 km
  Vertical (all): 2 km
10-min analyses and 30-min forecasts

15:00L – 15:10L: Analysis
15:10L – 15:40L: Forecast
3-km height

OBS After QC (Ruiz et al. 2015)

Obs superobed to the model resolution

250 M (D4)
30-min forecasts at 250-m model resolution

**Initial time: 15:10L**

**15:20L**

**15:30L**

**15:40L**

**15:50L**

**16:00L**

Observation:  
- 10 dBZ
- 40 dBZ
## Resolution dependence

- Compare the 30-min forecast skills at different resolutions:

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Model resolution</th>
<th>Observation resolution</th>
<th>Cycle length</th>
<th># forecast cases (every 10 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3_1 KM</td>
<td>1 km</td>
<td>1 km</td>
<td>5 min</td>
<td>6</td>
</tr>
<tr>
<td>1 KM (D4)</td>
<td>1 km</td>
<td>1 km</td>
<td>30 sec</td>
<td>6</td>
</tr>
<tr>
<td>500 M (D4)</td>
<td>500 m</td>
<td>500 m</td>
<td>30 sec</td>
<td>6</td>
</tr>
<tr>
<td>250 M (D4)</td>
<td>250 m</td>
<td>250 m</td>
<td>30 sec</td>
<td>6</td>
</tr>
<tr>
<td>100 M (D4)</td>
<td>100 m</td>
<td>100 m</td>
<td>30 sec</td>
<td>1</td>
</tr>
</tbody>
</table>
10-min analyses and 30-min forecasts at different model resolutions

1 KM (D3; 5-min cycle)

Radar reflectivity [Z = 2995m] [06:00 UTC]

250 M (D4)

Radar reflectivity [Z = 3068m] [06:00 UTC]

500 M (D4)

Radar reflectivity [Z = 3068m] [06:00 UTC]

OBS

Obs superobed to the model resolution

100 M (D4)

Radar reflectivity [Z = 3068m] [06:00 UTC]

531 node-hours / cycle

22 node-hours / cycle

79 node-hours / cycle

4444 node-hours / cycle
Threat scores compared to the PAWR reflectivity observation and calculated in 3 dimensions (entire domain, 2.5–4 km height) at 1-km grids (0610Z; 1 forecast).

Threat scores [10 dBZ] [30 dBZ]

Resolution dependence (obs limit = 100)

D3_1 KM (5-min update cycle)

Experiments are performed with the same localization settings while also using the same observation number limit

1 KM
500 M
250 M
100 M
Resolution dependence
(\text{obs limit} = 100)

**Threat scores**

(0610Z - 0700Z; 6 forecasts)

- [10 dBZ]
- [30 dBZ]

- 1 KM
- 500 M
- 250 M

D3_1 KM (5-min update cycle)
Observation number limit  (Hamrud et al. 2015)

- Limit the **number of observations assimilated per grid point** for each combination of different report types (e.g., radiosonde) and variables (e.g., U-wind).
  - Observations **spatially closest to the analyzed grid point** are selected.
- In their system (i.e., ECMWF global model):
  - **Maximum observation number per grid (NOBS) = 30**
  - **Advantages:**
    - Save the computational time.
    - **Significantly increase the forecast scores** in the Northern Hemisphere (3-5% anomaly correlation metric).
- **Modifications in our study:**
  - Observations with **smallest “localization-modified observation errors”** are selected.
  - Optimal **NOBS = 100** by sensitivity experiments at 250-m resolution.
Impact of obs number limit (250 m)

Threat scores
(0610Z - 0620Z; 2 forecasts)

NOBS = 30 : Second best results
NOBS = 100 : Best results
NOBS = 500
NOBS = ∞
Impact of obs number limit - \#OBS (250 m; 1st cycle)

\[
\text{NOBS} = 30 \quad \text{NOBS} = 100 \quad \text{NOBS} = 500
\]

\[
\begin{align*}
\text{Computational time:} & \quad T = 276 \text{ s} \\
\text{NOBS} = \infty & \quad \text{More than 100,000 observations!}
\end{align*}
\]

\[
\begin{align*}
\text{Localization cut-off area for Ref\_rain and Vr} & \\
\text{Covariance localization:} & \\
\text{Horizontal (Ref\_rain and Vr):} & \quad 4 \text{ km (cut-off radius 14.6 km)} \\
\text{Horizontal (Ref\_clear):} & \quad 2 \text{ km (cut-off radius 7.3 km)} \\
\text{Vertical (all):} & \quad 2 \text{ km (cut-off radius 7.3 km)}
\end{align*}
\]
Impact of obs number limit - Increment Ref (dBZ) (250 m; 1st cycle)

<table>
<thead>
<tr>
<th>NOBS</th>
<th>Map</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td><img src="image" alt="Map" /></td>
</tr>
<tr>
<td>100</td>
<td><img src="image" alt="Map" /></td>
</tr>
<tr>
<td>500</td>
<td><img src="image" alt="Map" /></td>
</tr>
<tr>
<td>∞</td>
<td><img src="image" alt="Map" /></td>
</tr>
</tbody>
</table>

Very similar!
Impact of obs number limit - \#OBS (250 m; 1st cycle)

- **NOBS = 30**
- **NOBS = 100**
- **NOBS = 500**
- **NOBS = \(\infty\)**
- **1 km thinning**
- **4 km thinning**
Impact of obs number limit - Increment Ref (dBZ) (250 m; 1st cycle)

NOBS = 30

NOBS = 100

NOBS = 500

NOBS = ∞

1 km thinning

4 km thinning

Smaller increment
Impact of obs number limit (250 m)

Threat scores

(0610Z - 0620Z; 2 forecasts)

[10 dBZ]

[30 dBZ]

NOBS = 30
NOBS = 100
NOBS = 500
NOBS = ∞

1 km thinning (NOBS = ∞)
4 km thinning (NOBS = ∞)
Impact of covariance inflation methods

- Relaxation to prior perturbation (RTPP; Zhang et al. 2004) vs. Relaxation to prior spread (RTPS; Whitaker and Hamill 2012)

- In the LETKF:
  
  **RTPP:** \( \mathbf{W} \leftarrow (1 - \alpha)\mathbf{W} + \alpha\mathbf{I} \)

  **RTPS:** \( \mathbf{W} \leftarrow \left(\alpha \frac{\sigma^b - \sigma^a}{\sigma^a} + 1\right)\mathbf{W} = \left(\alpha \sqrt{\frac{\mathbf{X}^b \mathbf{X}^{bT}}{(k - 1)\mathbf{X}^b \tilde{\mathbf{P}}^a \mathbf{X}^{bT} - \alpha + 1}}\right)\mathbf{W} \)

  \( \alpha = 0.95 \)
Impact of relaxation method
(1 km; obs limit = 100; alpha = 0.95)

Threat scores
(0610Z - 0700Z; 6 forecasts)

Relaxation to prior spread (RTPS)
Relaxation to prior perturbation (RTPP)
Impact of relaxation method
(1 km; obs limit = 100; alpha = 0.95)

3-km height relative humidity:
Analysis at 15:40L

**RTPS**

**RTPP**
Too noisy and too dry

Radar reflectivity [Z = 3068m] [06:40:00 UTC]
Impact of relaxation method
(1 km; obs limit = 100; alpha = 0.95)

Imbalance measured by domain-averaged $|dP/s/dt|$
30-min forecast started from 15:40L
Summary

● The sub-kilometer radar data assimilation using the LETKF can work!
  ● Higher resolution assimilation up to 100 m leads to a better fit to observation, *although the benefit does not last beyond 10 minutes in our current experiments.*
  ● The 30-second update cycle is advantageous over the 5-minutes update cycle.

● Optimal settings are suggested:
  ● Observation number limit (*Hamrud et al.* 2015)
  ● Relaxation to prior spread (RTPS) (*Whitaker and Hamill* 2012)

● Potential drawbacks:
  ● The model may not be well tuned in the sub-kilometer resolution.
  ● No consideration of model errors:
    ● e.g., “Additive noise” method (*Dowell and Wicker* 2009)