Direct Assimilation of Radar Reflectivity without Tangent Linear and Adjoint of the Nonlinear Observation Operator in the GSI-based EnVar System for Convection Allowing Regional Prediction Systems

Xuguang Wang, Yongming Wang, Jeff Duda
Multiscale data Assimilation and Predictability (MAP) Lab
School of Meteorology
University of Oklahoma, Norman, OK

Acknowledgement:
Jacob Carley (NOAA/NCEP/EMC)

David Dowell (NOAA/ESRL/GSD)

Lou Wicker (NOAA/NSSL)

7th WMO Data Assimilation Symposium, Sep. 11-15, 2017, Florianopolis, Brazil
Outline

- Why additional development of GSI EnVar is needed for convective scales? Summary of development made so far.

- Issues of direct radar reflectivity assimilation in EnVar associated with the nonlinear operator and direct assimilation of radar reflectivity without tangent linear and adjoint of the nonlinear observation operator in GSI-based EnVar system (Wang and Wang 2017, MWR)

- Extension of dual resolution GSI based EnVar for sub-kilometer (<1km) analysis and prediction

- Implementation and testing in US HRRR and NAM CONUS operational convection allowing regional prediction systems

- Ongoing and future work
Why further development of GSI EnVar is needed for convective scales?

- Convective scale analysis and forecasting is a multi-scale problem, requiring an accurate estimate of both the synoptic/mesoscale environment and the convective scale details.

- Convective scale observations (i.e., radar, cloudy radiances) require unique observation operators that are often complex and nonlinear.

- Inclusion and proper update of additional state variables (e.g., W, hydrometeors) are required.

- Accurate cross-variable covariance is especially important.

- Comparison study among Var, EnKF, 3DEnVar, 4DEnVar and Hybrid 4DVar for convective scales is still limited.
Development of GSI EnVar so far for convective scales

- GSI-based Var, EnKF, 3DEnVar, 4DEnVar are extended to work with convection-resolving models including WRF ARW (Johnson et al. 2015, MWR; Wang and Wang 2017, MWR) and NMMB (Wang Y. et al. 2017 in preparation).

- Vertical velocity and hydrometeor state variables are added.

- Radar radial velocity and reflectivity observation operators are implemented/extended.

- Capability to use storm scale perturbations to treat model errors is added.

- For direct assimilation of reflectivity observations in GSI based EnVar, a method without tangent linear (TL) and adjoint of the nonlinear operator is proposed and implemented (Wang and Wang 2017, MWR).

- GSI-based dual resolution EnVar is further extended where analysis is produced at high resolution (e.g., 500m) while ensembles ingested are at lower resolution (e.g. at 2km).

- Observation dependent localization are developed for GSI-based EnKF.
Issue with TL of nonlinear reflectivity operator in EnVar

Wang and Wang 2017a, MWR, 145, 1447-1471

- GSI-based EnVar cost function (Wang 2010, MWR)

\[
J(a) = 0.5(a)^T A^{-1}(a) + 0.5(y^{o'} - Hx')^T R^{-1}(y^{o'} - Hx')
\]

\[
\Delta_a J_o = D^T H^T R^{-1} (Hx' - y^{o'})
\]

\[
x' = \sum_{k=1}^{K} (a_k \circ x_k^e)
\]

- Nonlinear radar reflectivity operator

\[
H(q_r, q_s, q_g) = Z_{dB} = 10\log Z_e
\]

\[
Z_e = Z_r + Z_s + Z_g
\]

\[
Z_g = 4.33 \times 10^{10} (\rho q_g)^{1.75}
\]
• Use hydrometeor mixing ratio as state variable

\[ H(q_s, q_r, q_g) \]

Large values of TL of the nonlinear reflectivity associated with the small hydrometeor mixing ratios lead to large differences of cost function gradients, which prevents efficient convergence and therefore under-estimates the hydrometeor increments.
Wang and Wang 2017a, MWR

- Use hydrometeor mixing ratio as state variable $H(q_s, q_r, q_g)$

\[
\frac{\Delta y}{\Delta x} = H(x+\Delta x) - H(x) = HDx
\]

➢ The TL of the reflectivity operators itself further contributes to spuriously small hydrometeor increments
Issue with TL of nonlinear reflectivity operator in EnVar

Wang and Wang 2017a, MWR

- Using logarithm of hydrometeor mixing ratio as state variable $H(\log(q_s), \log(q_r), \log(q_g))$

- Fixes the cost function gradient issue
Issue with TL of nonlinear reflectivity operator in EnVar

Wang and Wang 2017a, MWR

- Use logarithm of hydrometeor mixing ratio as state variable $H(\log(q_i), \log(q_j), \log(q_k))$

However, it produces anomalously large hydrometeor increment partly due to the transform to and from the logarithmic space and partly due to the TL assumption
However, it produces anomalously large hydrometeor increment partly due to the transform to and from the logarithmic space and partly due to the TL assumption.
GSI-based EnVar without tangent linear (TL) and adjoint of the nonlinear reflectivity operator

Wang and Wang 2017a, MWR

- A new method extending state variables by directly including reflectivity as state variable is proposed: $H(ZdB)$

- No reflectivity operator appears in cost function or $H_{ZdB} = I$

- Gradient issues fixed
A new method including reflectivity as state variable is proposed

\[ H(ZdB) \quad H_{ZdB} = I \]

In this method, no TL of the reflectivity operator exists. Hydrometeor is related to reflectivity following the nonlinear relationship.
• An isolated supercell case that produced F-4 intensity tornadoes in Moore and Oklahoma City (OKC) during about 2210—2240 UTC.

• Supercell maintained well beyond 2300 until about 0000 UTC.
Experiment design
Wang and Wang, 2017a, MWR

- **Model**: WRF-ARW 2km
- **Observation**: radar radial wind and reflectivity from KTLX
- **IC and LBC ensemble**: A 45-member ensemble downscaled from a mesoscale ensemble at 2100 UTC.
GSI based 3DVar: analysis and 1h forecast from 2200UTC

Ref and vorticity at 1 km

W at 4 km
GSI based EnVar: analysis and 1h forecast from 2200UTC

Ref and vorticity at 1 km

W at 4 km
1 hour forecast: $w$ and vorticity at 4km

New: extend state variable with reflectivity

Use log transform ($q_{\text{hydrometeor}}$) as state variable

Use $q_{\text{hydrometeor}}$ as state variable

New: $ZdB$
Graupel ($q_g$) analysis

New: $ZdB$

$log(q_g)$

$q_g$ (g/kg)

Reference Vector

Height (km)

°C

-10 -9 -8 -7 -6
Early study has demonstrated the need for ~100m possibly ~10’s m grid spacing to fully resolve convective motions (Bryan et al. 2003). Studies on the impact of analysis resolution during DA on tornado prediction are limited.

Given the large expense of running all ensemble members at sub-kilometers in EnVar or EnKF, the dual resolution EnVar is further extended in GSI where the analysis is produced at sub-kilometer (e.g., 500m) whereas the ingested ensemble is still at lower kilometer resolution (e.g., 2km).
**Experiment design**

- Both SR_2km and DR ingest the ensemble at 2-km resolution during DA

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR_2km</td>
<td>Analysis produced at 2-km resolution ingesting 2-km ensemble. Free forecast at 500 m resolution downscaled from 2-km analysis</td>
</tr>
<tr>
<td>DR</td>
<td>Analysis produced at 500-m ingesting 2-km ensemble through dual resolution capability. Free forecast at 500 m resolution</td>
</tr>
</tbody>
</table>
Composite maximum sfc vorticity and 10-m wind improved by dual resolution EnVar

- The predicted vorticity is enhanced after 20-min forecast in DR. Its vorticity evolution is much more consistent with the reality than SR_2km.
- DR is able to predict tornado strength sfc wind with longer duration and greater intensity (≥ EF1).
- Detailed diagnostics have shown both thermo and dynamical fields were analyzed better with DR that lead to better forecast.

**SR_2km**
- Sfc vorticity
- Vorticity begins to decay at this time

**DR**
- Sfc vorticity
- Vorticity begins to decay at this time

**10-m wind**
- SR_2km
- DR
- \( U_h \) max = 36.6 m/s (EF0)
- \( U_h \) max = 41.4 m/s (EF1)

**EF0 ≥29 m/s**
- EF0 ≥29 m/s

**EF1 ≥38.4 m/s**
- EF1 ≥38.4 m/s
Implementation in operational HRRR & NAM CONUS

Direct assimilation of reflectivity using GSI EnVar/EnKF implemented in HRRR and NAM CONUS replacing “cloud analysis”

Real time test conducted in HWT in 2017 Spring Forecast Experiment

Domain:
- Resolution: 3 km
- Grid: 1568 X 1120 X 50

Observations:
- Conventional obs. are assimilated hourly from 18z to 23z;
- Radar obs. (including Vr and dBZ) are assimilated at every 10/15 min from 23z to 00z.
Composite reflectivity matches observations better in the EnVar analysis compared to the cloud analysis analysis.

Also, spurious convection is better suppressed by the EnVar.
The improved reflectivity analysis also corresponds to a remarkably better forecast using the EnVar compared to the cloud analysis.
Objective verifications: EnVar vs. cloud analysis

The superior analyses produced by the EnVar also result in an improved reflectivity/precipitation forecast for early lead times.
Summary and future work

- For direct reflectivity assimilation in EnVar, a method without tangent linear (TL) and adjoint of the nonlinear operator is developed to solve the issues associated with the TL of the reflectivity operator in EnVar.

- Idea maybe useful for observations with complicated operators where TLA may not be easy to develop or observation operators sharing similar issue as described here (e.g. space radar in EC 4DVar in yesterday's talk).

- With this approach, 4DEnVar is not only TLA free for forecast model, but also TLA free for nonlinear obs. operator.

- Issue is specific for Var, not applied for EnKF.

- Idea of extending state to include observed variables analogous to state augmentation of parallel implementation of serial EnKF but for addressing different issues.

- In collaboration with NOAA colleagues continue R&D for US NWS convective scale ensemble DA and forecasting:
  - Using the new FV3 model.
  - R&D on multi-scale data assimilation.
  - Developing GOES-R cloudy radiance DA capability on top of radar DA.
  - Assimilating new emerging ground based remote sensing observations e.g. AERI, UAV observations, etc.
References


