Assimilation of Radar Observations with the GSI

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2017 GSI Summer Tutorial

Huge thanks to the following individuals who kindly provided material for this talk:
Ming Hu (GSD), Ting Lei (IMSG/EMC), Donnie Lippi (UMD/IMSG/EMC), Shun Liu (IMSG/EMC), Mingjing Tong (IMSG/EMC), Xuguang Wang (Univ. of Oklahoma)
Outline

• Radar data assimilation background

• GSI and radar data assimilation
  – Radar reflectivity and lightning
    • Cloud analysis/DFI
  – Radial velocity
    • Airborne radars (TDRs)
    • Ground based radars (88Ds)
  – Convection allowing DA experiments
    • Featuring direct assimilation of reflectivity (e.g. no nudging of heating tendencies) and assimilation of radial velocity

• Challenges
  – QC, background errors, choice of control variable, etc.

• Closing
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Why Radar Observations?

One of the only networks of fairly comprehensive, storm-scale data

http://www.roc.noaa.gov/WSR88D/Maps.aspx
Radar Data Assimilation Methods

• Many approaches, what may be the most suitable? Depends on the Situation?
  – Retrieval (e.g.; Gal-Chen, 1978; Lin et al., 1993)
    • Temperature and pressure perturbations from 3D wind field
  – Empirical/Nudging/DFI
    • Latent heat based temperature adjustment for areas of observed radar reflectivity factor*
      – Nudging (e.g. Jones and Macpherson, 1997; Rossa and Leuenberger, 2008)
      – Cloud analysis (e.g. Albers et al., 1996; Hu et al., 2006)

*"Reflectivity is used throughout the remainder of this talk for brevity."
Radar Data Assimilation Methods

– Variational (GSI)
  • Globally adjust model solution to all observations
  • Direct use of observations
  • 3DVar (e.g. Gao et al., 2004; Xiao et al., 2007)
    – Static background error (i.e. no flow dependence)
    – Applied at a single time, but pretty fast
  • 4DVar (e.g. Sun et al., 1991; 1997; 2001)
    – Minimization between model forecast and time distributed observations
    – Implicit flow dependence (e.g. Daley, 1991)
    – Many forward/backward iterations with adjoint model needed
Radar Data Assimilation Methods

- Ensemble Kalman filter (EnKF; e.g. Snyder and Zhang, 2003)
  - Ensemble of forecasts to estimate and evolve forecast error covariance
  - Demonstrated encouraging results (e.g. Dawson et al., 2012)
  - Received much attention in the Warn on Forecast effort (Stensrud et al. 2009)

- Hybrid ensemble-3(4)DVar?
  - Ensemble forecast error covariance combined with 3DVar background error covariance
    - Benefits of Var DA + flow dependence from ensemble
  - e.g., Gao et al. (2010), Li et al. (2012), and Carley (2012)

\[
2J (x_1, a) = \beta_1 x_1^\top B^{-1} x_1 + \beta_2 a^\top A^{-1} a + (Hx - y)^\top R^{-1} (Hx - y)
\]

If $\beta_2^{-1} = 0$
then we have 3DVar

Static + ensemble contribution
Radar Data Assimilation in the GSI

- VAD winds (not focusing on this in this talk)
- Radar reflectivity via GSD’s complex cloud analysis and heating tendency (non-variational)
  - Works for both WRF-ARW and NEMS-NMMB
  - Used in RAP, HRRR, NAM, and NAM CONUS nest
- Radial velocity
  - Ground based radars (convinfo file data type = 999)
    - Used in NAM and NAM CONUS nest
  - Tail Doppler Radars (convinfo file data types = 990 to 993)
  - *Current* Forward operator only considers u+v (no w or hydrometeor sedimentation considered)
    - Will change soon – examples to follow
- Reflectivity (variational + hybrid methods)
  - Capability will be in trunk GSI ~ 6 months
  - Been tested in both NMMB and WRF-ARW
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• Closing
GSD’s Digital Filter-Based Reflectivity Assimilation with GSI

- Following full GSI analysis - a non-variational cloud analysis can be run which specifies heating tendencies as a function of observed radar reflectivity
- Digital filter-based reflectivity assimilation initializes ongoing precipitation regions
  - During forward part of DFI – replace heating from microphysics scheme with heating from radar-based heating tendencies

<table>
<thead>
<tr>
<th>-20 min</th>
<th>-10 min</th>
<th>Initial</th>
<th>+10 min</th>
<th>+ 20 min</th>
</tr>
</thead>
</table>

- Backwards integration, no physics
- Forward integration, full physics with radar-based latent heating
- Initial fields with improved balance, storm-scale circulation
- Model forecast + Convection suppression

Thanks to Ming Hu for kindly providing this slide.
Digital Filter-Based Reflectivity Assimilation with GSI

RAP HRRR no radar

RAP HRRR RADAR

00z init
00z 12 Aug 2011

Convergence Cross-Section

Rapid convective spin-up with radar data

Thanks to Ming Hu for kindly providing this slide.
Digital Filter-Based Reflectivity Assimilation with GSI

+1h fcst
01z 12 Aug 2011

RAP HRRR no radar

RAP HRRR RADAR

Convergence Cross-Section
Rapid convective spin-up with radar data

Thanks to Ming Hu for kindly providing this slide.
HRRR Pre-Forecast Hour

- Temperature Tendency (i.e. Latent Heating) = f(Observed Reflectivity)
- LH specified from reflectivity observations applied in four 15-min periods
- NO digital filtering at 3-km
- Reflectivity observations used to specify latent heating in previous 15-min period as follows:
  - Positive heating rate where obs reflectivity $\geq 35$ dBZ over depth $\geq 200$ mb (avoids bright banding)
  - Zero heating rate where obs reflectivity $\leq 0$ dBZ
  - Model microphysics heating rate preserved elsewhere

$$LH(i,j,k) = \left(\frac{1000}{p}\right)^{R_e/c_p} \frac{(L_v + L_f)(f[Z_e])}{t^* c_p}$$

Thanks to Ming Hu for kindly providing this slide.
DFI Reflectivity Assimilation in 3 km NAM CONUS Nest

Composite Radar Reflectivity Verification for May 5th – May 10th, 2015 (All cycles)

- With radar reflectivity - enhanced DFI
- Without radar reflectivity - enhanced DFI
- With - Without

30 dBZ threshold
25 km verification box

- Statistically significant improvement in FSS in first 5 forecast hours
- Very typical result with radar DA, improvement is often in the short term
Assimilation of Lightning Observations

- Clear indication of convective storm(s)
  - Can provide data where radar coverage is poor or non-existent
  - Current obs from NLDN and ENI networks
- Current approach: Convert lightning observations to reflectivity
  - Use reflectivity in cloud analysis
  - Discussion ongoing with colleagues for other methods
- Future: GOES-R GLM
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• Closing
GSI: Radial Velocity Obs. Operator

*Note* - No term for the vertical velocity (w)
  - Similar to operator implemented in Montmerle and Faccani (2009)

Suggest only radial velocity observations from lower elevations should be considered
  - Avoid contamination of the horizontal wind field, especially due to hydrometeor sedimentation
  - Controlled via the &SUPEROB_RADAR namelist

Vertical velocity will be in the GSI in a few months!
**GSI: Radial Velocity Obs. Operator**

- Relevant GSI codes:
  - `read_l2bufr_mod.f90` (read ‘l2rwbfr’ if present, process level II winds into superobs and write to ‘radar_supobs_from_level2’)
  - `read_radar.f90` (read radial wind observations – ‘radar_supobs_from_level2’, ‘radarbufr’, ‘tldplrbufr’, or ‘tldplrso’)
    - Velocities from ground based radars (88Ds) use data type = 999 in the convinfo file
    - Velocities from TDRs use data types = 990 to 993 in the convinfo file
  - `setuprw.f90` (forward operator)
  - `intrw.f90, stprw.f90` (inner loop routines for minimization)

- **GSI Namelist Settings/Tuning**
  - `&SUPEROB_RADAR`
    - Applies *only* when ‘l2rwbfr’ files are present in the GSI run directory
    - Controls how winds are superobbed
  - `&OBSQC`
    - `ERRADAR_INFLATE` → multiplicative inflation (or deflation) for all oberrors with velocities from ground-based radars
    - `TDRERR_INFLATE` → Logical for Tail Doppler radial wind ob error inflation

*GSI Advanced User Guide has excellent details*
Super-obbing

• Radar data is very dense compared to most model grids
  • Representativeness
  • 250m gates and 1deg beamwidth for 88D
• Much of the data may be redundant
• Super-obbing
  • Reduces the data volume
  • Reduces representativeness issues
  • Effectively averaging obs in radar coordinates and time

• See page 135 of the GSI v3.5 User guide for parameter descriptions
• Many details in the Advanced GSI User Guide (v3.5)

Thanks to Donnie Lippi for kindly providing this slide.
Some Examples of Radial Wind Assimilation with the GSI

HWRF
Assimilation of NOAA-P3 Tail Doppler Radar Data

Fig. 1. Schematic diagram of the WP-3D tail radar scanning plane. The elevation angle (θ) is varied with azimuth (φ) to maintain an antenna pointing angle that is normal to the aircraft’s ground track.


Thanks to Mingjing Tong for kindly providing this slide.

Fig. 3. Schematic showing the horizontal projections of Doppler radials as they would appear at flight level when operating in (a) normal-plane scanning mode or (b) FAST mode. Normal-plane mode shown in (a) is for two aircraft flying orthogonal tracks. Bold arrows show flight tracks; dashed arrows show projections of Doppler radials.

• Data assimilation performed on outer domain. When TDR data are available, data assimilation also performed on ghost d03 after vortex initialization. Vortex initialization performed on 3x domain prior to the DA.
• GSI hybrid analysis using global 80 EnKF ensemble member at T254L64.
• First guess
  - TC environment cold start from GDAS forecast
  - TC vortex cycled from HWRF forecast
  - First Guess at Appropriate Time (FGAT)
• Observational data
  - outer domain: conventional data (radiosondes, dropsondes, aircraft reports, surface ship and buoy observations, surface observations over land, pibal winds, wind profilers, VAD wind, scatterometer winds, GPS-derived integrated precipitable water)
  - ghost d03: conventional data and TDR data
  - satellite radiance, satellite derived wind and GPS RO data are not assimilated in the 2013 operational HWRF.

Thanks to Mingjing Tong for kindly providing this slide.
Impact of TDR data assimilation

Tropical storm Isaac 09L 2012

Assimilation of TDR data prevents the storm from over intensification

Thanks to Mingjing Tong for kindly providing this slide.
Some Examples of Radial Wind Assimilation with the GSI

Tests with 3DVar
Impact of Background Error Decorrelation Length
3DVar GSI Analysis Tests

- **B** is modeled using a recursive filter (Purser et al. 2003a; 2003b).
- The default decorrelation length of the background errors used in GSI is estimated using the NMC method. It may not be suitable for analyzing radar data representing convective scales.
  - Can be tuned by adjusting the recursive filter scales
- Experiments with decorrelation lengths that are 0.25, 0.5 and 2 times the default value are performed.
- Only assimilate radial winds using 8 km WRF-NMM
- Case: May 23\textsuperscript{rd}, 2005 - severe storms form along/near the Kansas-Oklahoma boundary, along a frontal zone

Thanks to Shun Liu for kindly providing this slide.
Analysis using default decorrelation length

Increment of the analyzed winds

The analysis increments are very smooth and the observations are generally spread too far.

Full wind vectors

Area of convergence is too broad and too weak.

Analyzed wind appears too large. Result of inappropriate background error correlations for radar observations?

Thanks to Shun Liu for kindly providing this slide.
Analysis using 0.25 times the default decorrelation length

Increment of the analyzed winds

Full wind vectors

The analysis increments now do not spread to far in eastern Colorado with a shorter decorrelation length.

Winds now not as strong here with shorter decorrelation length.

More well-defined and stronger convergence line.

The decorrelation length can have a substantial influence on the analysis, especially with radial wind observations. One must be cautious of representativeness issues.

Thanks to Shun Liu for kindly providing this slide.
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• Closing
Observation Operator and Choice of Analysis Variable for Reflectivity

\[ 2J(x_1, a) = \beta_1 x_1^T B^{-1} x_1 + \beta_2 a^T A^{-1} a + (Hx - y)^T R^{-1} (Hx - y) \]

• What should we use for the analysis variable(s)?
• The operator *could* be pretty nonlinear, which isn’t desirable

\[ Z_{dB} = 10 \log_{10} \left[ C_r (\rho \exp[\hat{q}_r])^{1.75} + C_{li} (\rho \exp[\hat{q}_{li}])^2 \right] \]

Carley (2012)

• Vulnerable to errors associated with linearization
  – Linearization necessary for inner-loop routines
    • int*f90 and stp*f90
  – Error is larger for larger O-Fs
    • Can lead to spurious increments!
  – Convergence problems
Observation Operator and Choice of Analysis Variable for Reflectivity

• One solution: make dBZ the analysis variable
  – Wang and Wang (2017; MWR)

• No nonlinear forward operator
  – Simply using the diagnostic dBZ output from the model

• Issue: dBZ is not a model prognostic variable
  – Relies on the background error cross-covariances to update prognostic terms, including hydrometeors
    • Naturally applicable to ensemble approaches (e.g. EnVar)
    • More difficult for 3DVar – correlations would need to be built into the static B. (more later)
Observation Operator and Choice of Analysis Variable for Reflectivity

• Example
  – As increments in graupel increase so do the errors in the linearized obs operator
    • Log-control variable
      – Under estimates dBZ
      – Over estimates q
    • Mixing ratio control variable
      – Over estimates dBZ
      – Under estimates q

Wang and Wang (2017; MWR)
Direct assimilation of radar observations using GSI based EnKF-Var hybrid (EnVar)

Model/Domain:
- NMMB
- Resolution: 3 km
- Grid: 1568 X 1120 X 50
- Same as HWT CLUE

Observations:
- Both radar and conventional obs. (RAP-prepbufr) are assimilated hourly from 18z to 00z;

IC and LBC ensemble are provided by GEFS (20) and SREF (20)
Control member is from GFS control

GSI EnKF/EnVar radar DA methodologies:
Johnson et al. 2015, MWR
Wang and Wang 2017, MWR

OU MAP lab (xuguang.wang@ou.edu) in collaboration with EMC Jacob Carley

Thanks to Xuguang Wang for kindly providing this slide.
Composite reflectivity @ 06Z May 24 2016

Thanks to Xuguang Wang for kindly providing this slide.
Objective verification-OTS

CA – GSI cloud analysis

EnKF – EnVar control member

OTS: Object based Threat Score (Eq. 3 of Johnson et al. 2011)

$$OTS = \sum_{obj\_pair} \frac{INTEREST_{f,o} \cdot \text{INTERSECTION\_AREA}_{f,o}}{\text{AREA}_f + \text{AREA}_o}$$

Thanks to Xuguang Wang for kindly providing this slide.
Impact of Direct Assimilation of dBZ

- Hybrid Ensemble 3Dvar Experiments
  - Regional DA using a global ensemble and cloud analysis (similar to operational NAMv4 3km CONUS nest)
  - Regional DA with its own regional ensemble and cloud analysis
  - Regional DA with its own regional ensemble and direct assimilation of dBZ

<table>
<thead>
<tr>
<th>Ens3DVA</th>
<th>Ensemble (regional ensembles are hourly cycled)</th>
<th>Cloud analysis</th>
<th>Direct DA of dBZ</th>
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<tr>
<td>Glob_ens</td>
<td>80 global members</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Reg_cycle</td>
<td>40 regional members</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Reg_dbz</td>
<td>40 regional members</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
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Thanks to Ting Lei for kindly providing this slide.
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Radar DA Challenges + the GSI

B for hydrometeors

\[
2J(x_1, a) = \beta_1 x_1^T B^{-1} x_1 + \beta_2 a^T A^{-1} a + (Hx - y)^T R^{-1} (Hx - y)
\]

• Difficult for fields that are not continuous (i.e. rain mixing ratio)
  – NMC method (Parrish and Derber, 1992) will not work (e.g. Xiao et al., 2007)

• Past approach to estimate magnitudes of hydrometeor variances in GSI
  – Horizontal averages over several cases to produce mean vertical profiles
  – Tuning via single observation tests

• Geographic binning method?
  – (Michel et al., 2011; Montmerle, 2012)
  – Stratify B into rainy and non-rainy areas

• Worth the effort or should we use the hybrid to set the weight of the static B quite small?
  – Static B can help when the ensemble is completely wrong (e.g. storm forecast where there is no storm)
  – Mitigates influence of erroneous ensemble covariance as storms become established in the model
Radar data QC is a necessary and initial step for operational applications of radar data

- See Liu et al. (2016, WaF) for information on radar processing at NCEP
- Must be efficient and robust
- However radar data QC is also very difficult and presents many challenges (e.g. migrating birds, aliased winds, etc.)

Measured velocities can be very different (≥10 m/s) from the air velocities in the presence of migrating birds.
Radar DA Challenges + the GSI
Radar Data Quality Control (Operational Perspective)

- Quality controlled winds (Liu et al., 2009)
  - Velocities de-aliased using VAD wind (Liu et al., 2009; Xu et al., 2011)
  - Limited in areas of strong shear and rotation
- Operational Vr QC is improving
- Dual-pol data are also used in reflectivity mosaic QC

Pre-QC

Post-QC

Aliased Radial Velocities in broad mesocyclone

Yikes! Where is the other half of the mesocyclone?
Looking Ahead

• Upcoming changes to GSI and EnKF codes:
  – Vertical velocity is being added to the radial wind observation operator
    • In GSI repository in a few months
  – dBZ-based control variable and associated observation operator for Var and EnKF (Wang and Wang 2017, MWR)
    • Courtesy of the Multiscale data Assimilation and Predictability Lab at OU
    • In GSI repository in ~3-6 months

• Future research area? Multiscale data assimilation
  – Simultaneous assimilation of broadly distributed observations alongside comparatively dense observations
    • e.g. rawinsonde data + Doppler radial winds
      – These networks are able to resolve different scales
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The GSI Advanced User’s Guide includes *excellent* details on radar data assimilation.

**Chapter 9 Radar Data Assimilation**

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Closing

• Need continued community involvement in GSI, especially for DA at convection-allowing scales (and multiscale)

Thank You!
Contact: jacob.carley@noaa.gov
Supplemental Slides
Assimilation of NOAA-P3 Tail Doppler Radar (TDR) Radial Velocity Data in HWRF

- Automatic quality control of TDR radial velocities, including dealiasing, erroneous data removal and navigation correction, is done on aircraft before data are transferred to the ground.
- TDR data are assimilated in ghost domain after vortex initialization.
- Data with innovation (o-f) greater than 20 m/s are rejected.
- Observation error is 5 m/s and gradually increases to 10 m/s as o-f is greater than 10 m/s.
- Reject small data dump at the ends of assimilation window.
- Data thinned to 9 km horizontal resolution.
- Assimilation time window – analysis time ±3 hours.
- To deal with the distribution of the inner core observations in hours of time window within 3D data assimilation framework, FGAT (First Guess at Appropriate Time) is used.

Thanks to Mingjing Tong for kindly providing this slide.
Impact of TDR data assimilation
Hurricane Ingrid 10l 2013

First guess vortex is much bigger than observed vortex. HWRF analysis is consistent with HRD’s radar wind analysis.

Thanks to Mingjing Tong for kindly providing this slide.
Observation Operator and Choice of Analysis Variable for Reflectivity

- GSI EnVar DA system
  - 5 min cycling
  - 2 km grid
  - assimilate reflectivity and radial velocity
- Test choice of analysis variable and observation operator
- Forecasts of low level vorticity corresponding to an observed tornado event

Using dBZ as the analysis variable provides the best low level vorticity forecast over this one hour period.

Wang and Wang (2017; MWR)