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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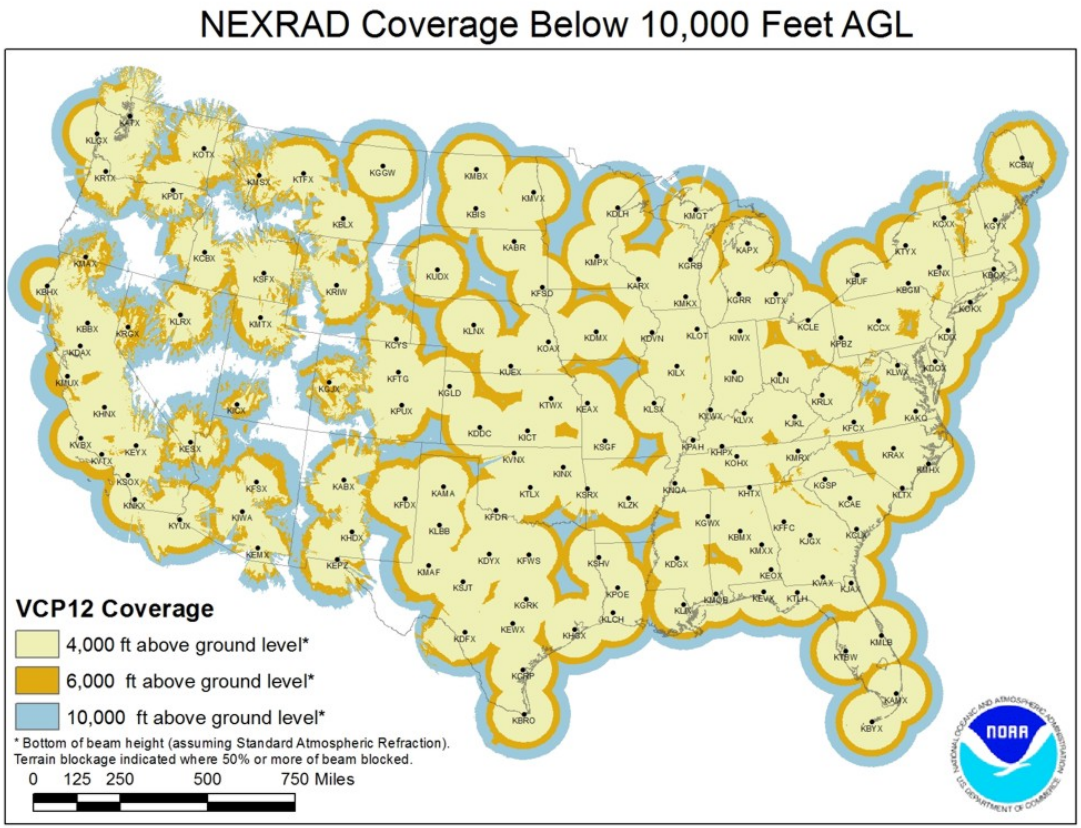
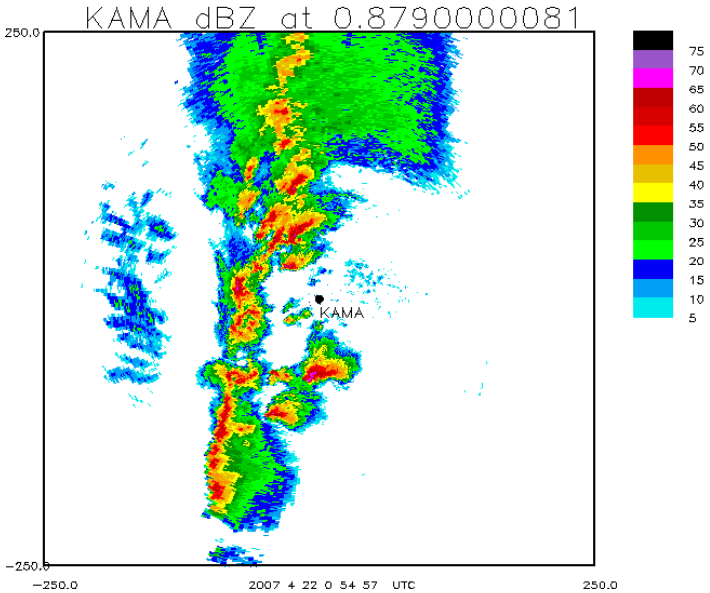
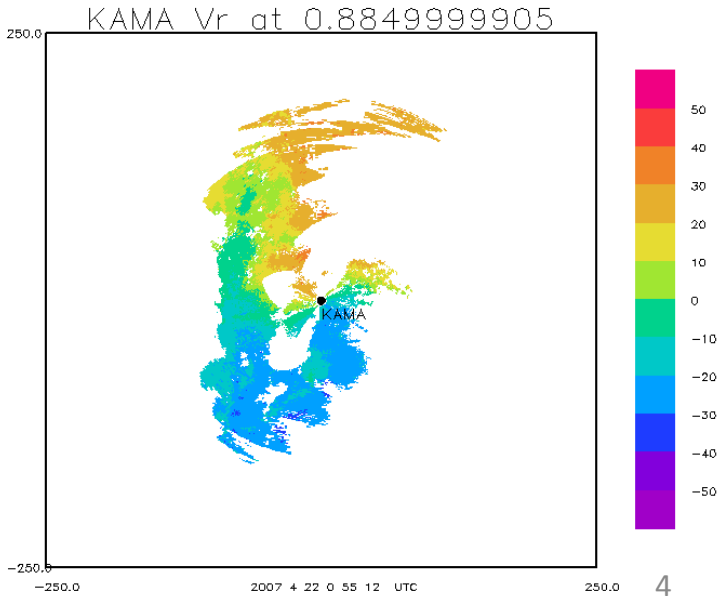
Why Radar Observations?



http://www.roc.noaa.gov/WSR88D/Maps.aspx





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

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)

$$2J(\mathbf{x}_1, \mathbf{a}) = \boxed{\beta_1 \mathbf{x}_1^{\mathrm{T}} \mathbf{B}^{-1} \mathbf{x}_1 + \beta_2 \mathbf{a}^{\mathrm{T}} \mathbf{A}^{-1} \mathbf{a}} + (\mathbf{H}\mathbf{x} - \mathbf{y})^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{H}\mathbf{x} - \mathbf{y})$$

Static + ensemble contribution

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

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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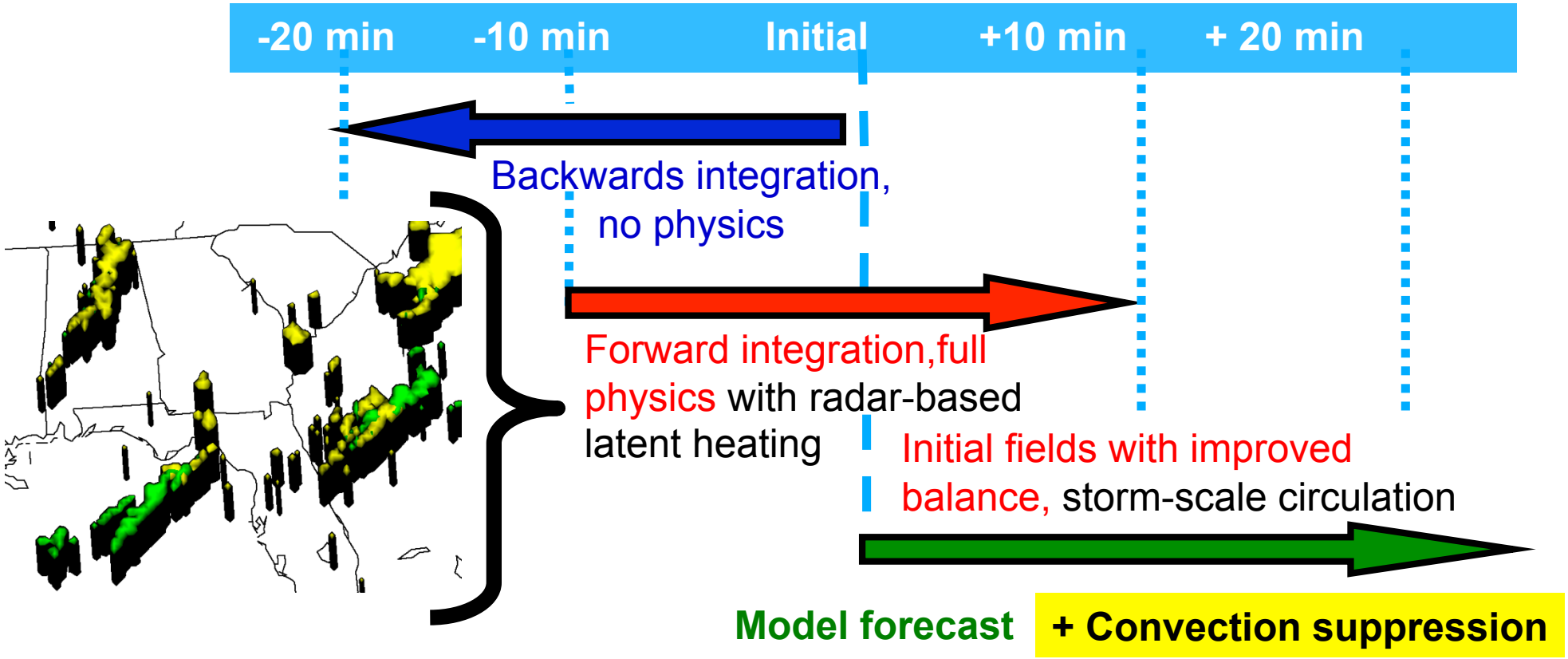
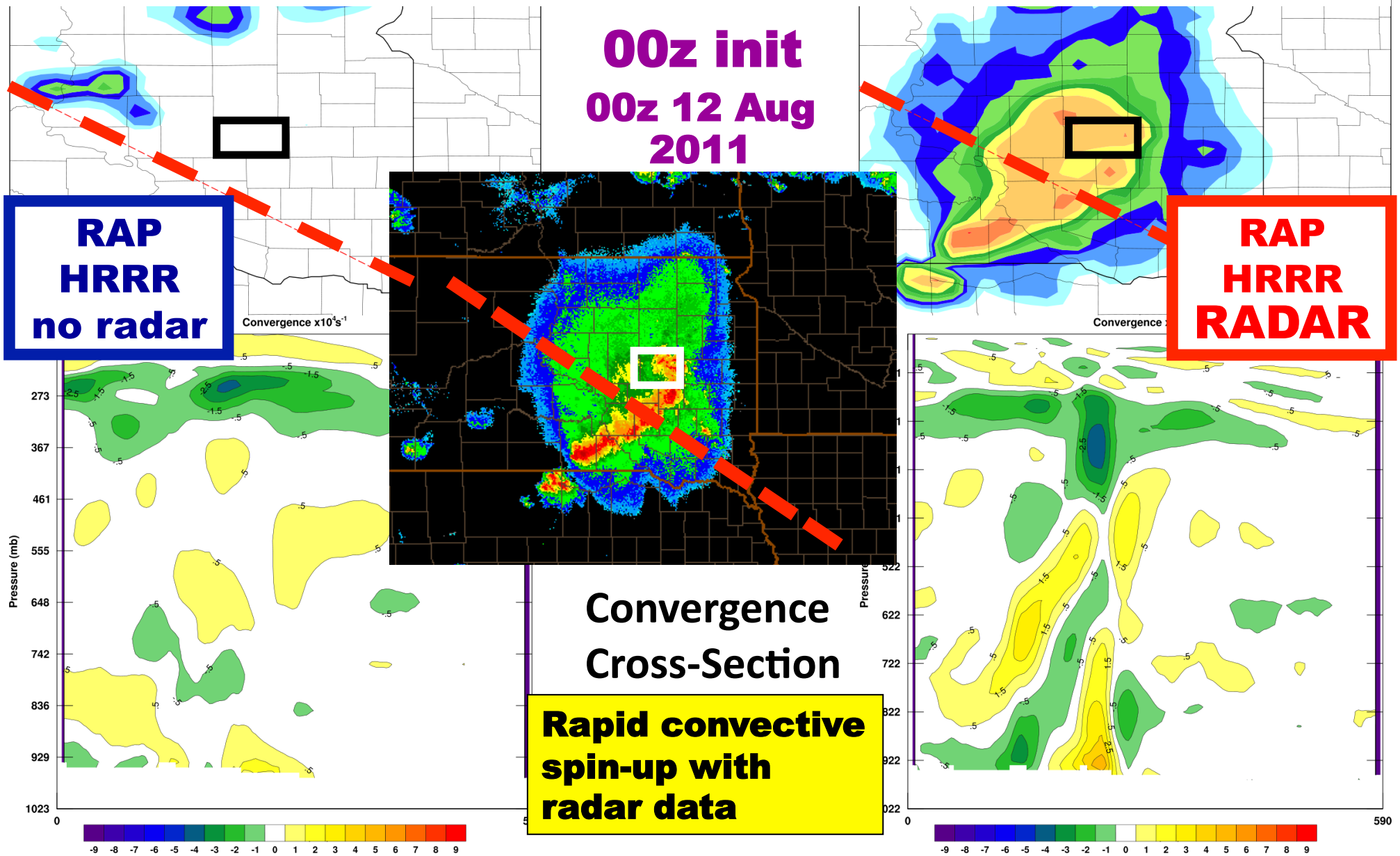
GSD's Digital Filter-Based Reflectivity Assimilation with GSI

- 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



Thanks to Ming Hu for kindly providing this slide.

Digital Filter-Based Reflectivity Assimilation with GSI



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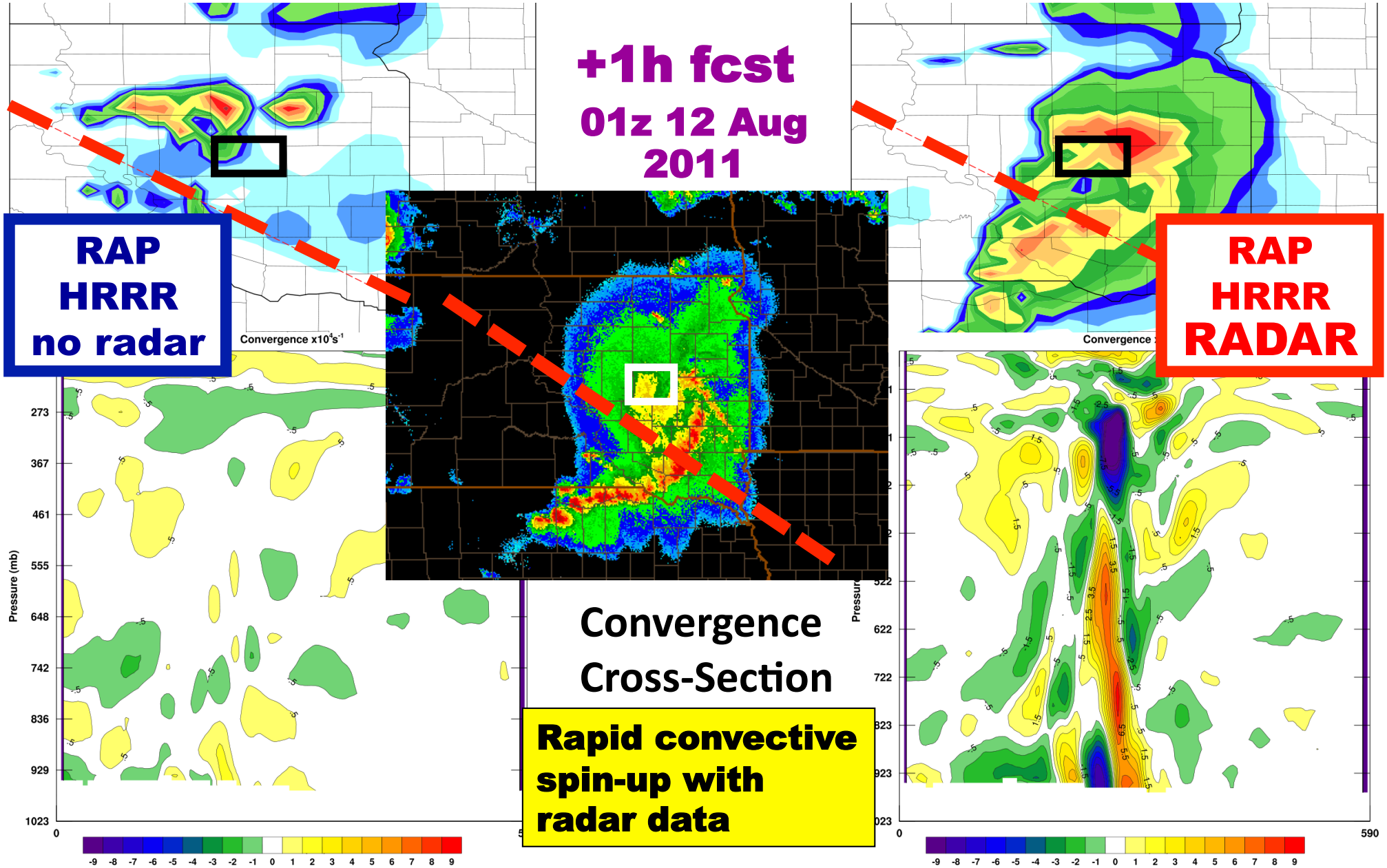

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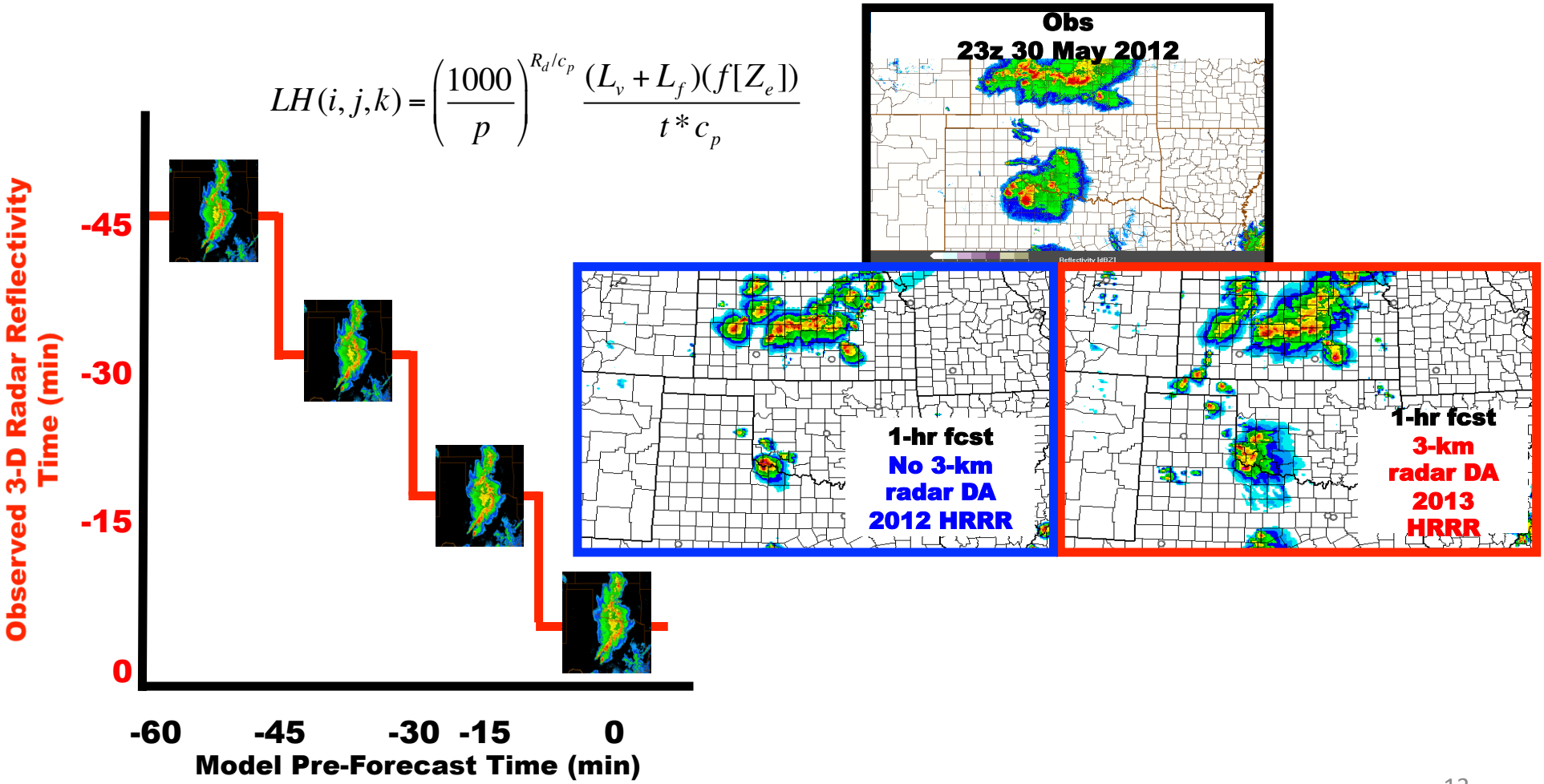
HRRR Pre-Forecast Hour

- 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 ≥ 35 dBZ over depth ≥ 200 mb (avoids bright banding)
  - Zero heating rate where obs reflectivity ≤ 0 dBZ
  - Model microphysics heating rate preserved elsewhere

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



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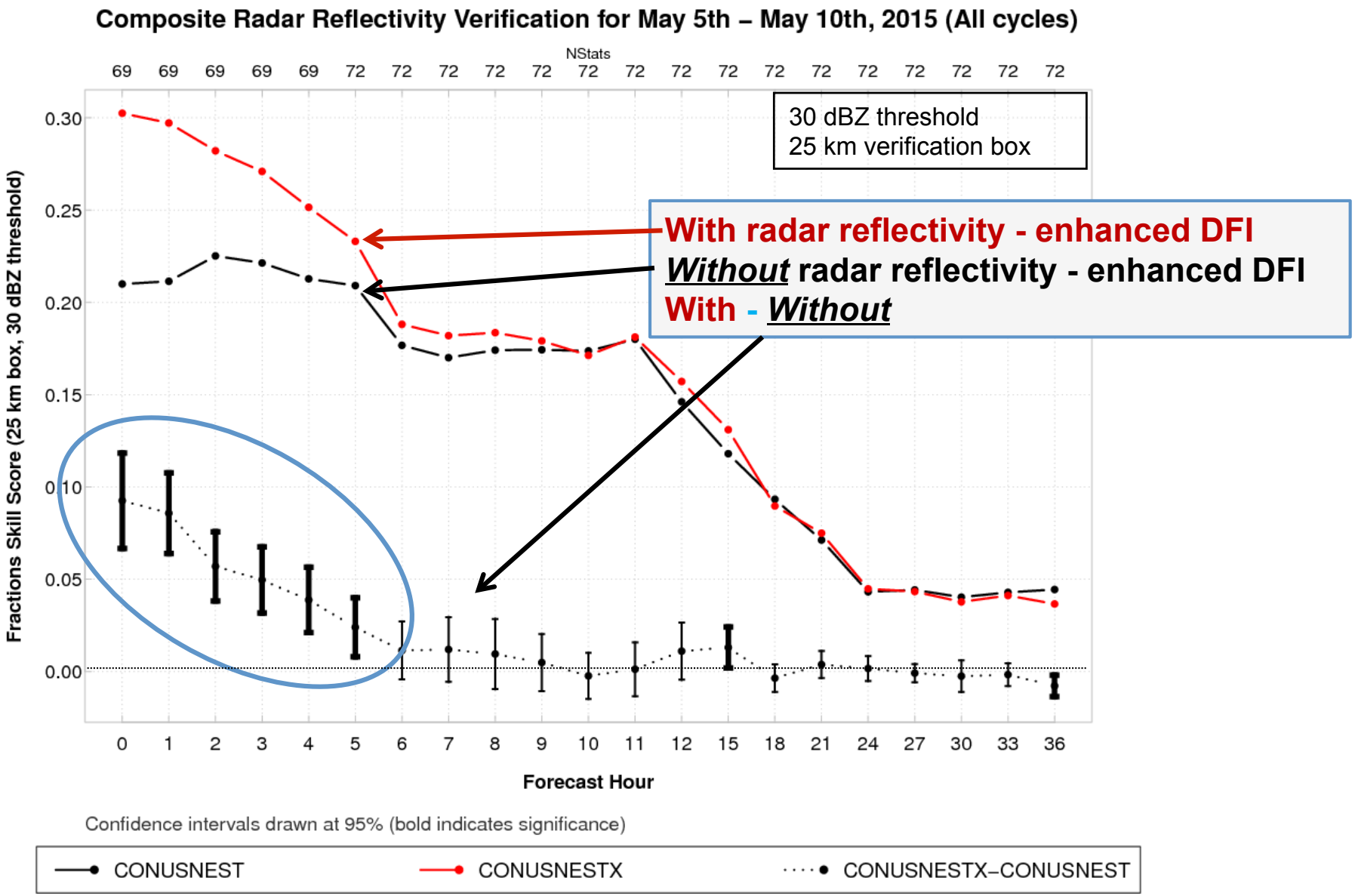
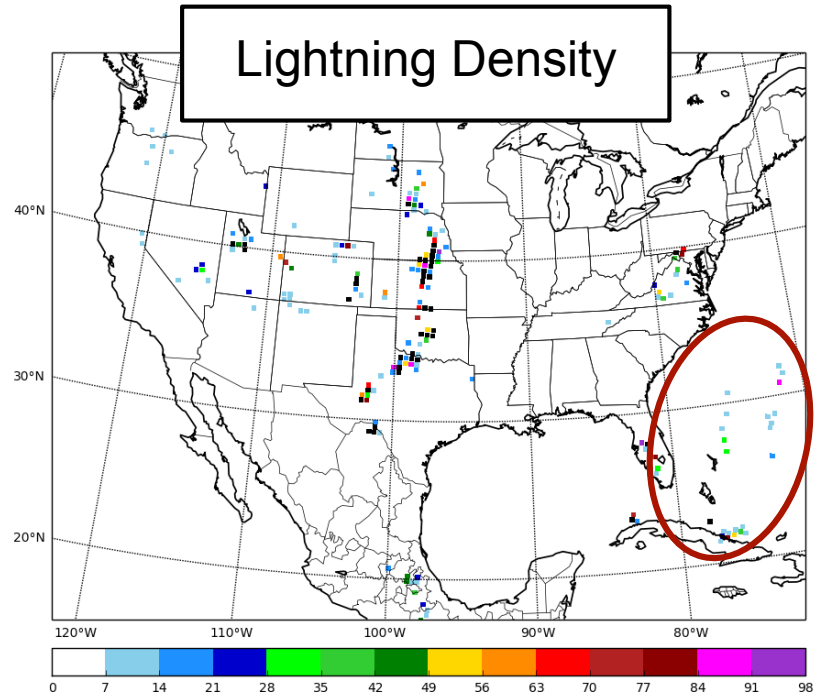
DFI Reflectivity Assimilation in 3 km NAM CONUS Nest

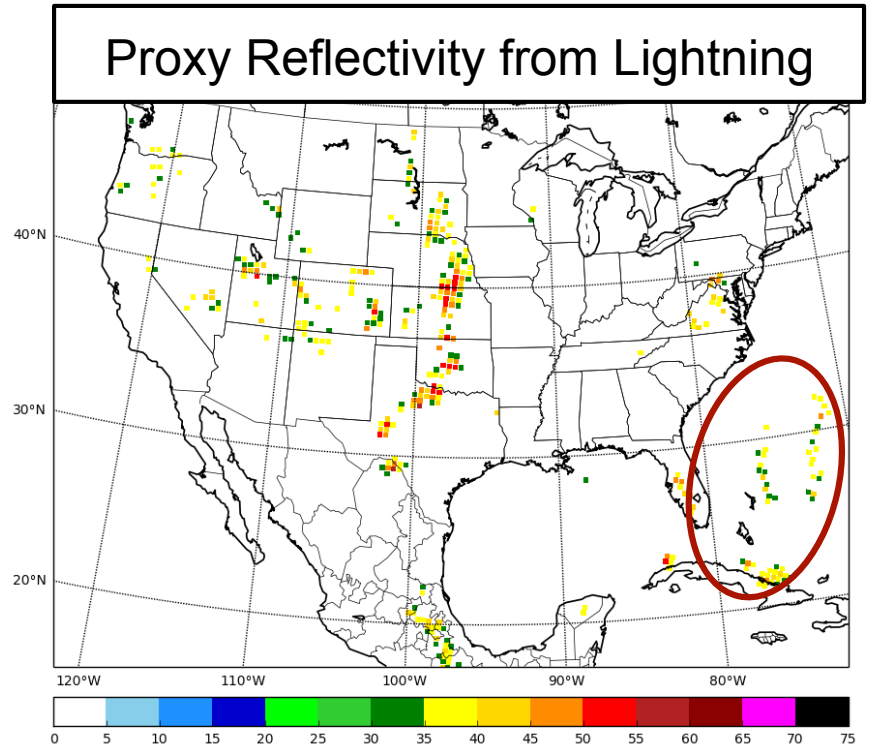


- Statistically significant improvement in FSS in first 5 forecast hours
- Very typical result with radar DA, improvement is often in the short term

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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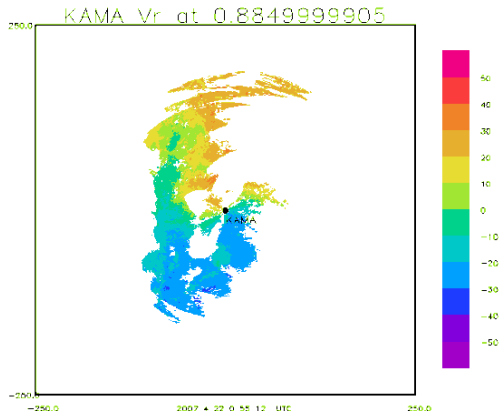
GSI: Radial Velocity Obs. Operator

Elevation angle

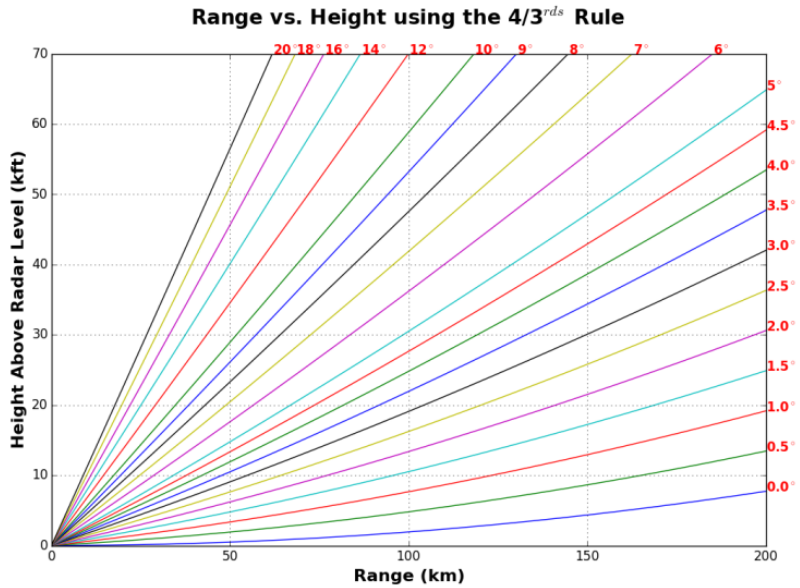
90°- azimuth angle

$$V_r(\theta, \alpha) = u \cos\alpha \cos\theta + v \cos\alpha \sin\theta$$

Model-predicted horizontal wind components



- *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!



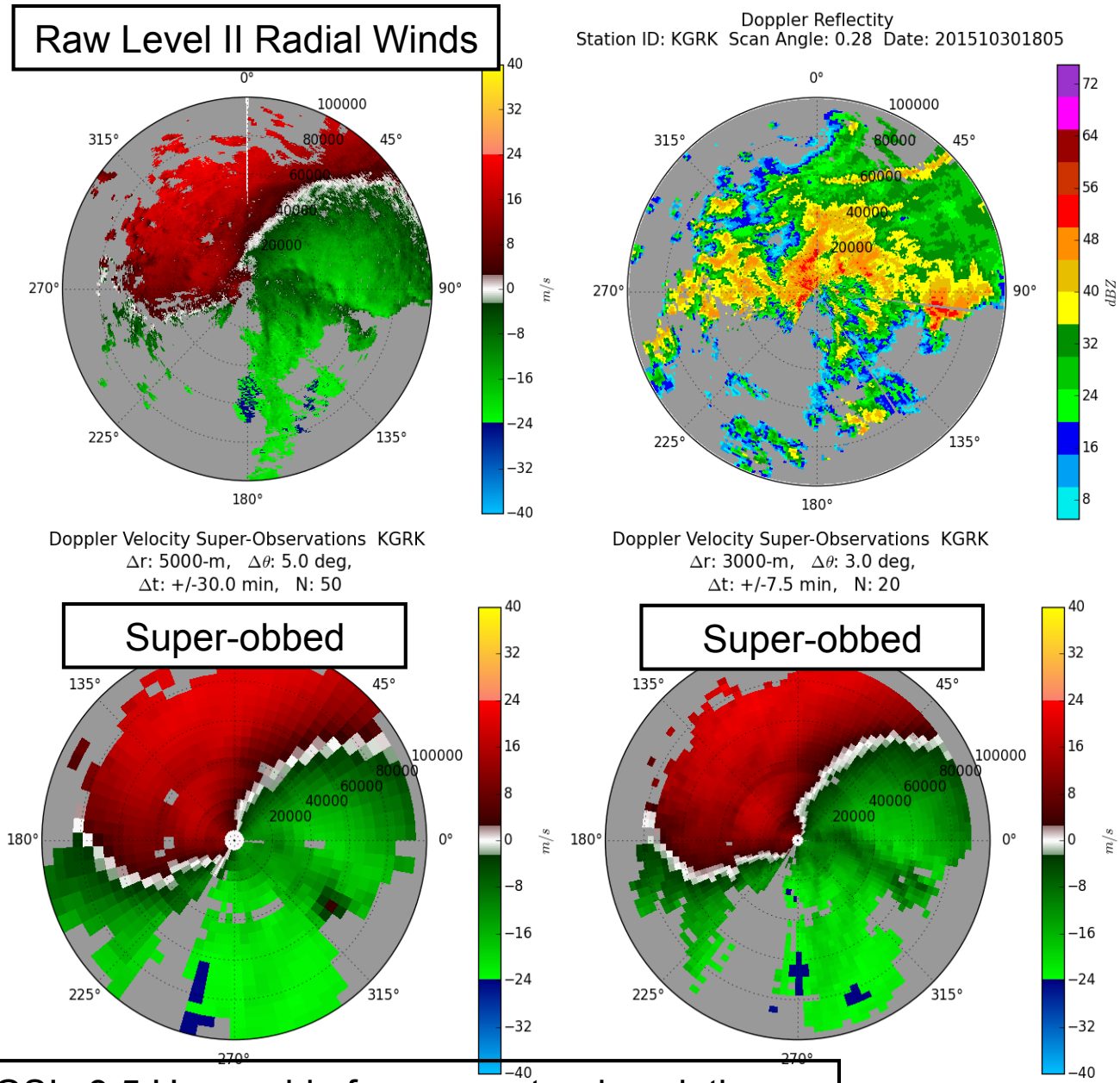
GSI: Radial Velocity Obs. Operator

- Relevant GSI codes:
  - read_l2bufr_mod.f90 (read 'l2rwbufr' 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 'l2rwbufr' 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

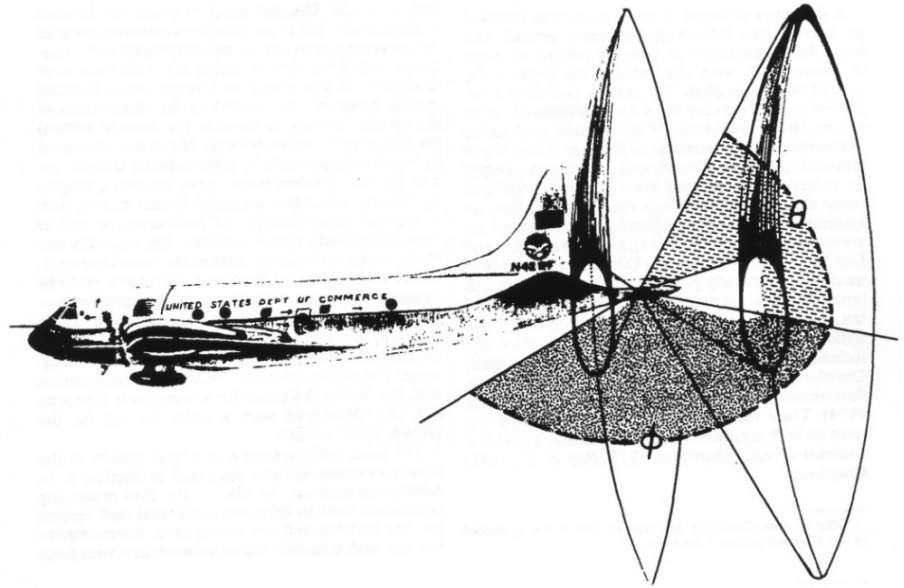


FIG. 1. Schematic diagram of the WP-3D tail radar scanning plane. The elevation angle (θ) is varied with azimuth (ϕ) to maintain an antenna pointing angle that is normal to the aircraft's ground track.

Jorgensen D. P, P. H. Hildebrand, and C. L. Frush, 1983, *J. Climate Appl. Meteor,* 22, 744-757

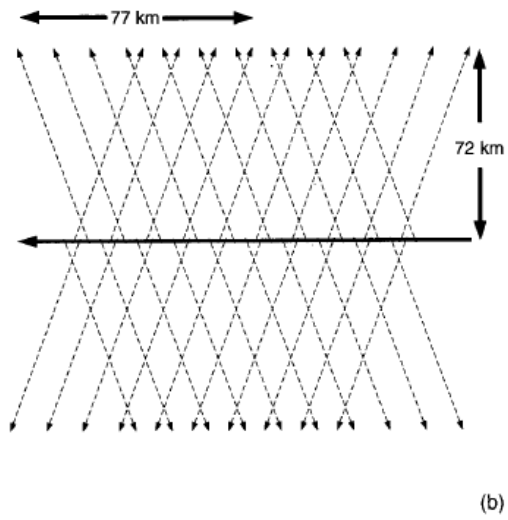
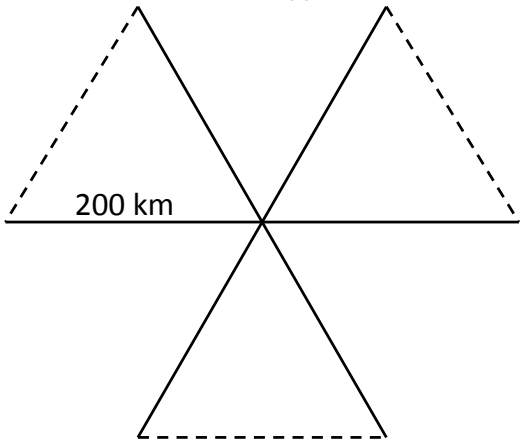


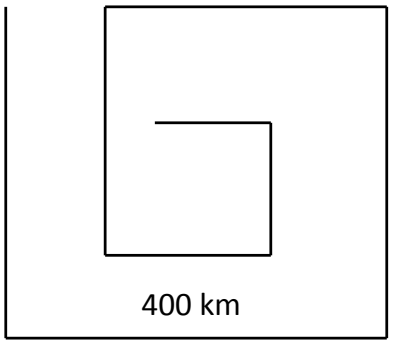
FIG. 3. Schematic showing the horizontal projections of Doppler radials as they would appear at flight level when operating in (a) normal-plane scanning mode or (b) FAST mode. Normal-plane mode shown in (a) is for two aircraft flying orthogonal tracks. Bold arrows show flight tracks; dashed arrows show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

Gamache. J, F. D. Marks Jr., and F. Roux, 1995, J. Atmos. Oceanic Technol., 12, 171–181



P-3 regular

P-3 weak storm



P-3 weak storm

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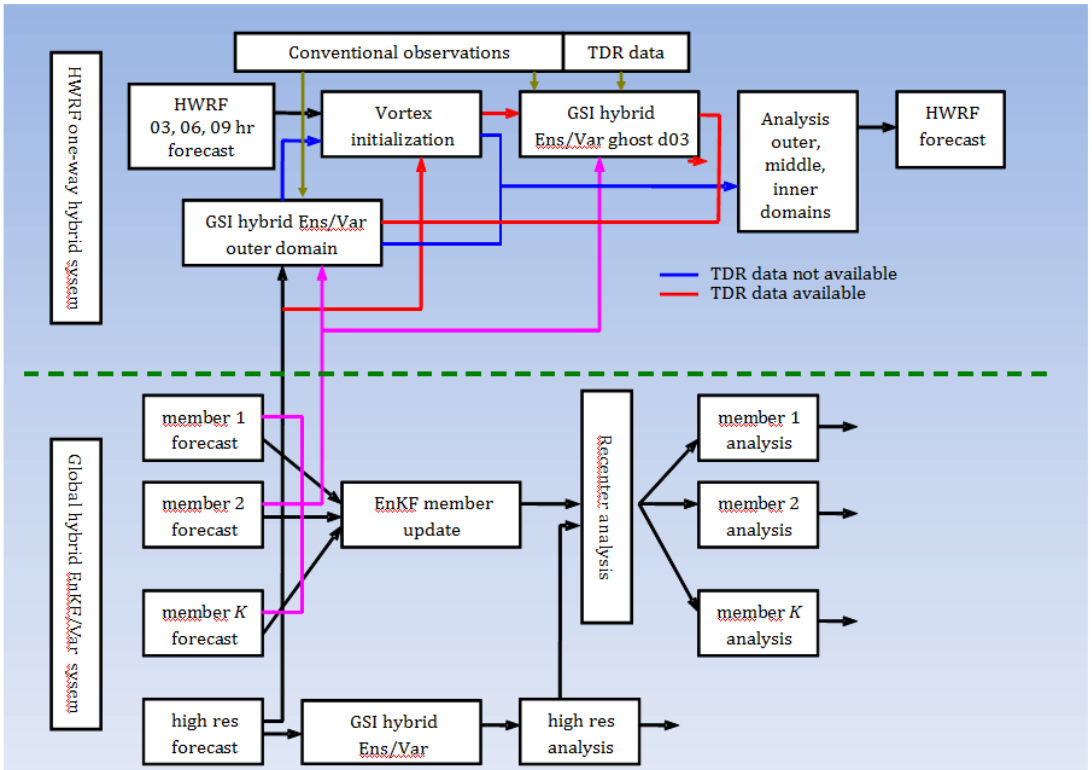
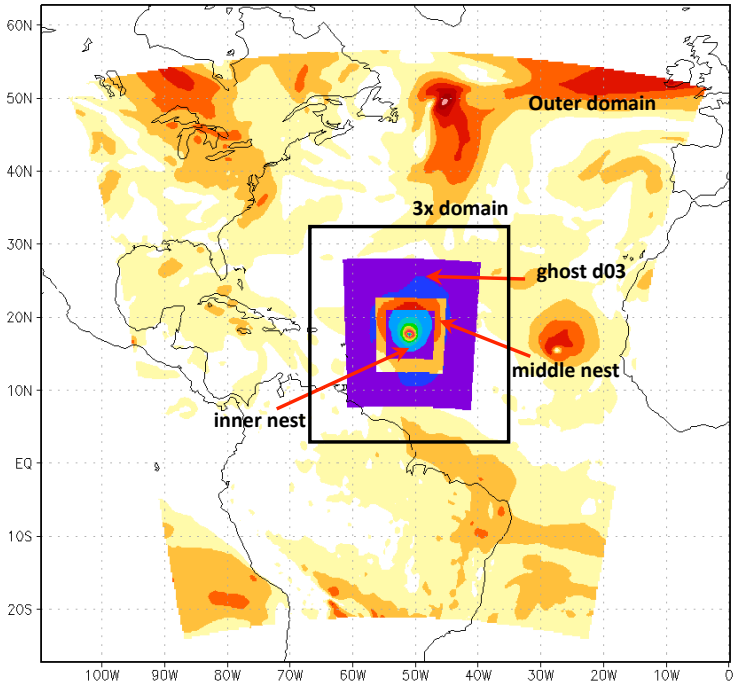
2013 Operational HWRF Data Assimilation System (HDAS)





- 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.

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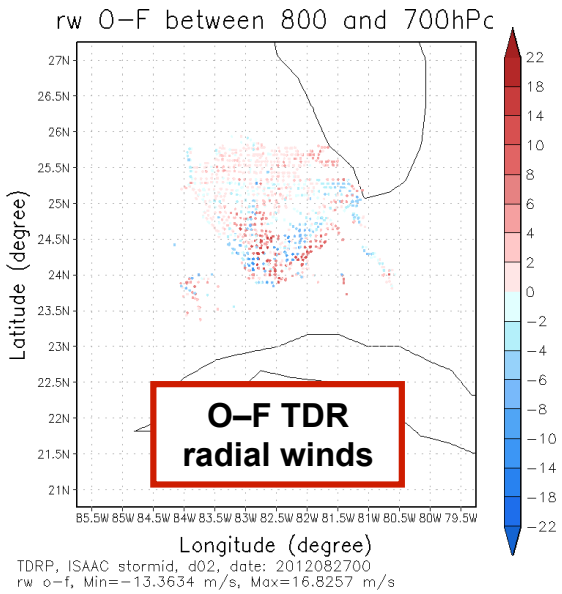
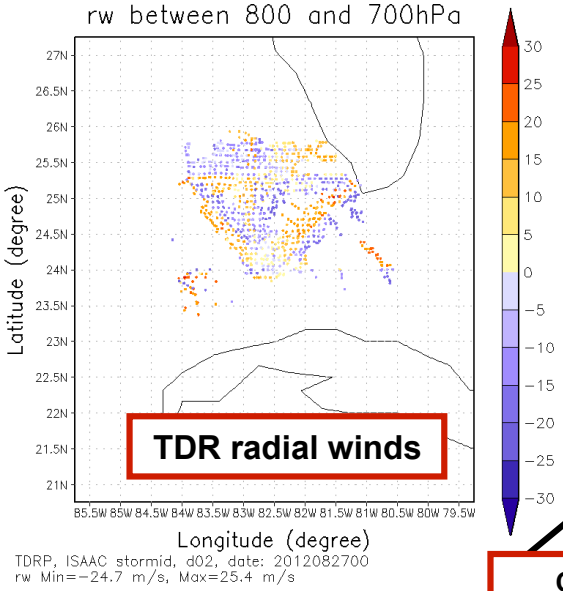
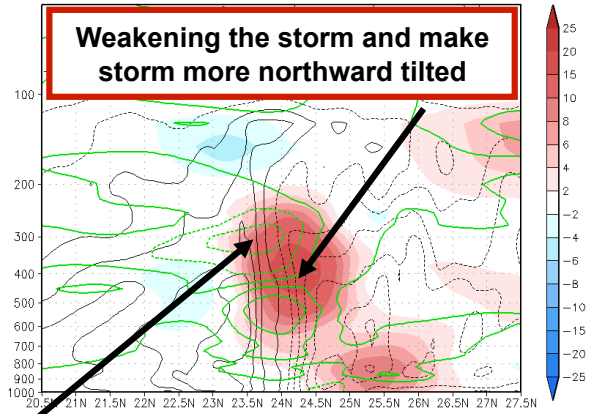
Impact of TDR data assimilation

Tropical storm Isaac 09l 2012



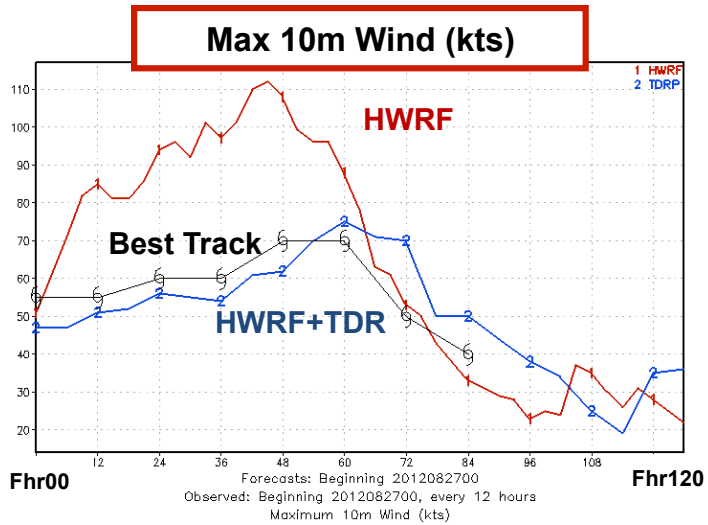


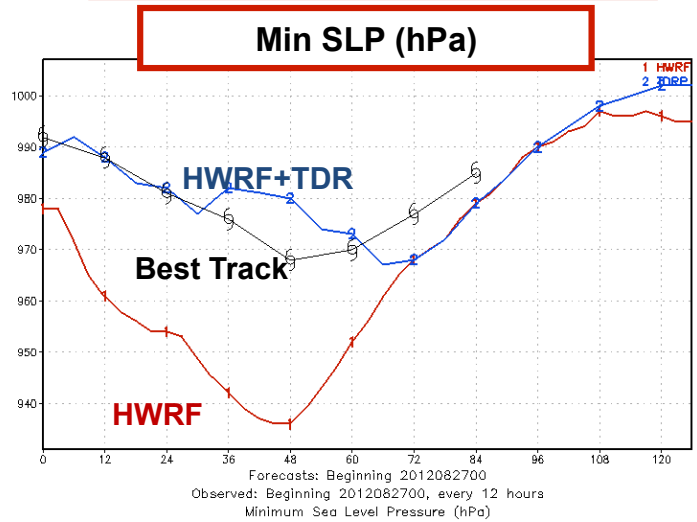
analysis increment



Black contour – first guess u
Color shade – u increment
Green contour – T increment

Cooling upper level and warming middle level TC center





Assimilation of TDR data prevents the storm from over intensification

Thanks to Mingjing Tong for kindly providing this slide.

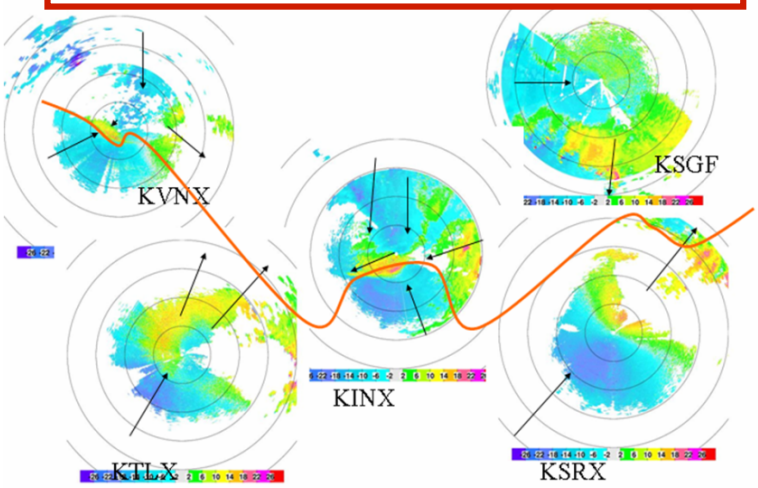
Some Examples of Radial Wind Assimilation with the GSI

Tests with 3DVar

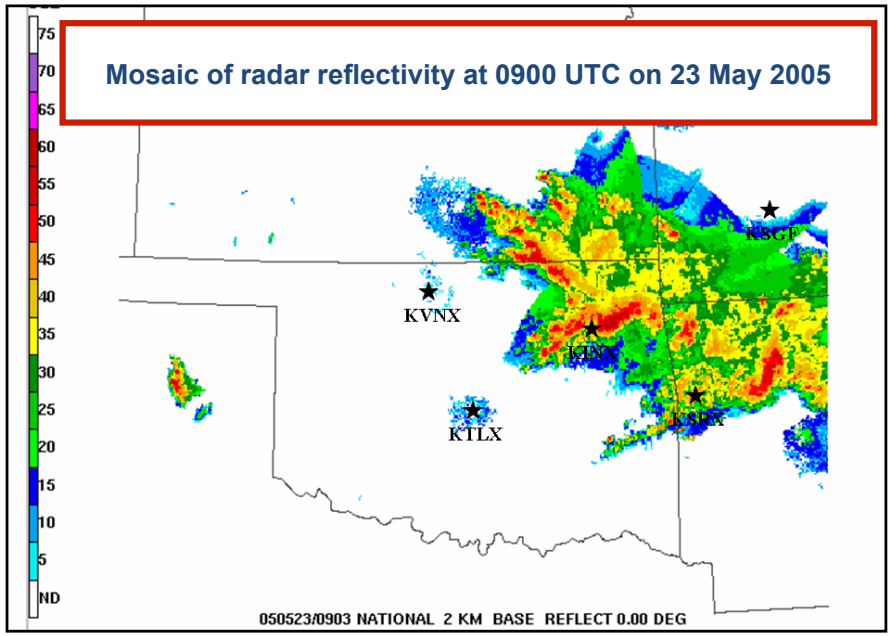
Impact of Background Error Decorrelation Length
3DVar GSI Analysis Tests

- **B** is modeled using a recursive filter (Purser et al. 2003a; 2003b).
- The <u>default decorrelation length</u> 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 <u>0.25</u>, 0.5 and 2 times the <u>default value</u> are performed.
- Only assimilate radial winds using 8 km WRF-NMM
- Case: May 23rd, 2005 - severe storms form along/near the Kansas-Oklahoma boundary, along a frontal zone

Mosaic of radial velocity at 0900 UTC on 23 May 2005 from five radars



Mosaic of radar reflectivity at 0900 UTC on 23 May 2005



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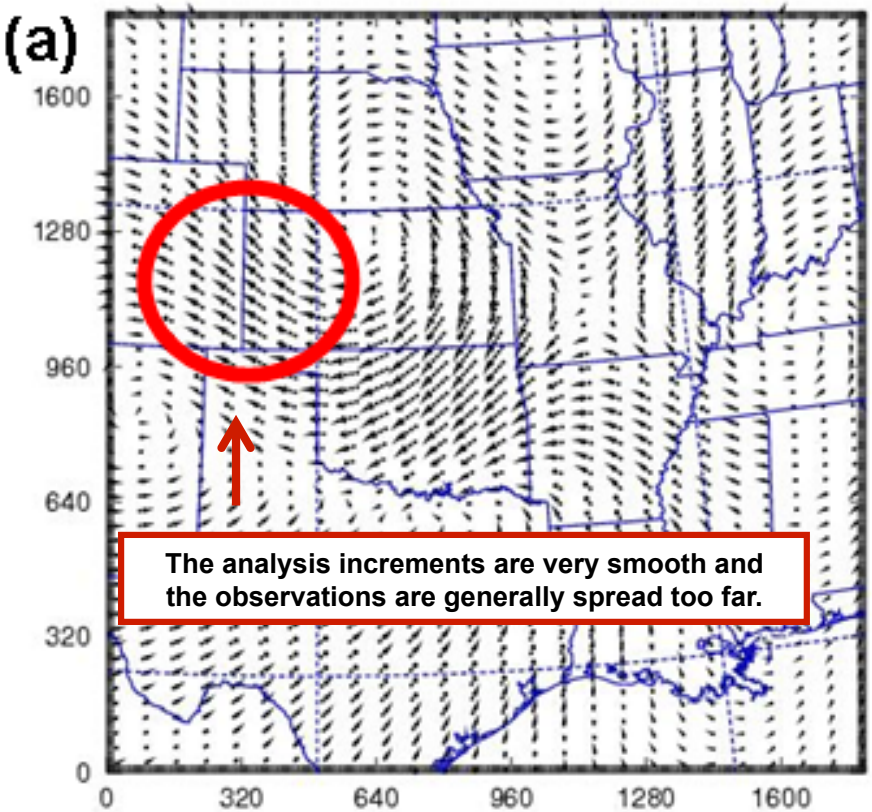
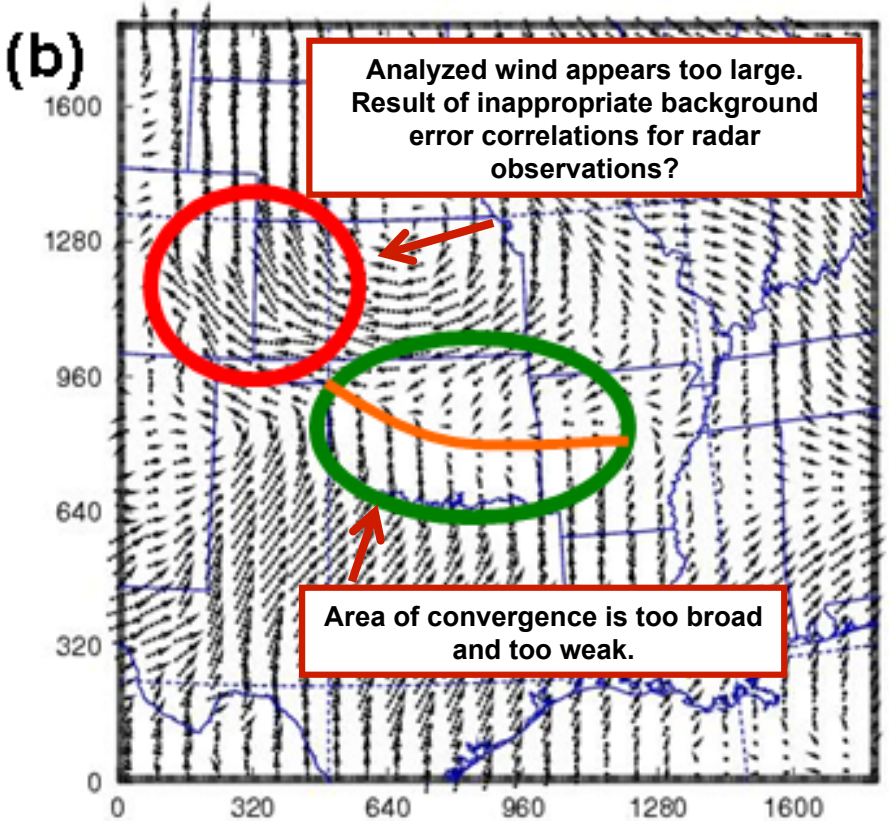
Analysis using default decorrelation length

Increment of the analyzed winds



Full wind vectors



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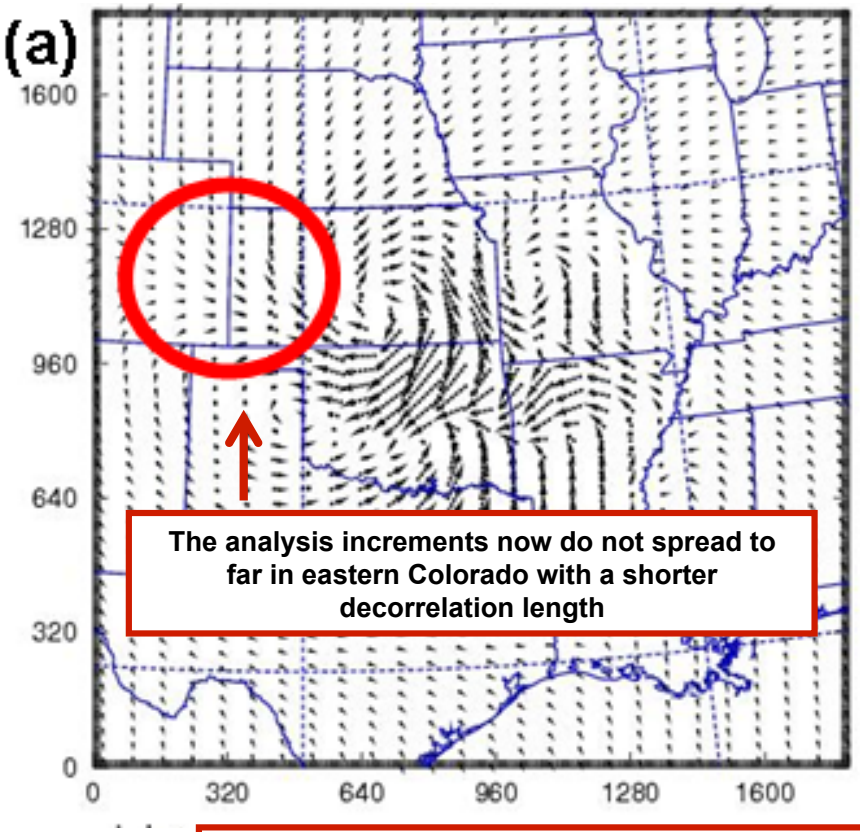
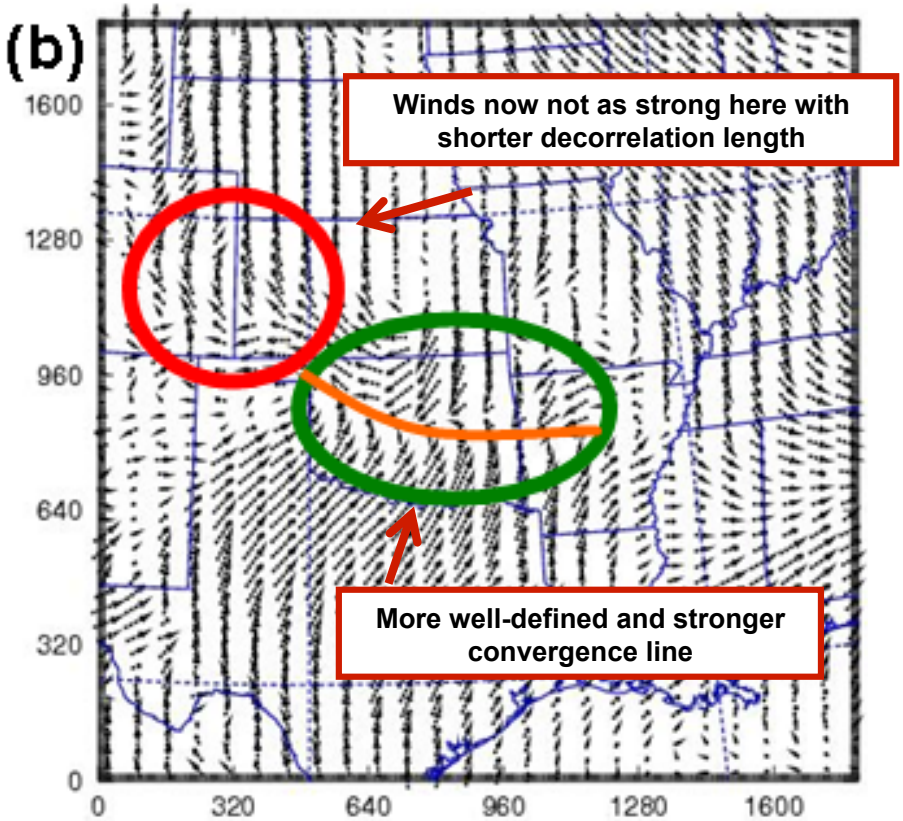
Analysis using 0.25 times the default decorrelation length

Increment of the analyzed winds



Full wind vectors



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

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Observation Operator and Choice of Analysis Variable for Reflectivity

$$2J(\mathbf{x}_1, \mathbf{a}) = \beta_1 \mathbf{x}_1^{\mathrm{T}} \mathbf{B}^{-1} \mathbf{x}_1 + \beta_2 \mathbf{a}^{\mathrm{T}} \mathbf{A}^{-1} \mathbf{a} + (\mathbf{Hx} - \mathbf{y})^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{Hx} - \mathbf{y})$$

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

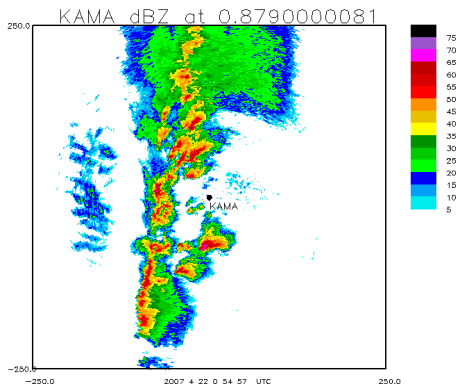
$$Z_{dB} = 10 \log_{10} \left[\mathrm{C_r} \left(\rho \exp \left[\hat{q}_r \right] \right)^{1.75} + \mathrm{C_{li}} \left(\rho \exp \left[\hat{q}_{li} \right] \right)^2 \right]$$

Carley (2012)

Rain

Precipitation ice

- 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 <u>diagnostic</u> 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

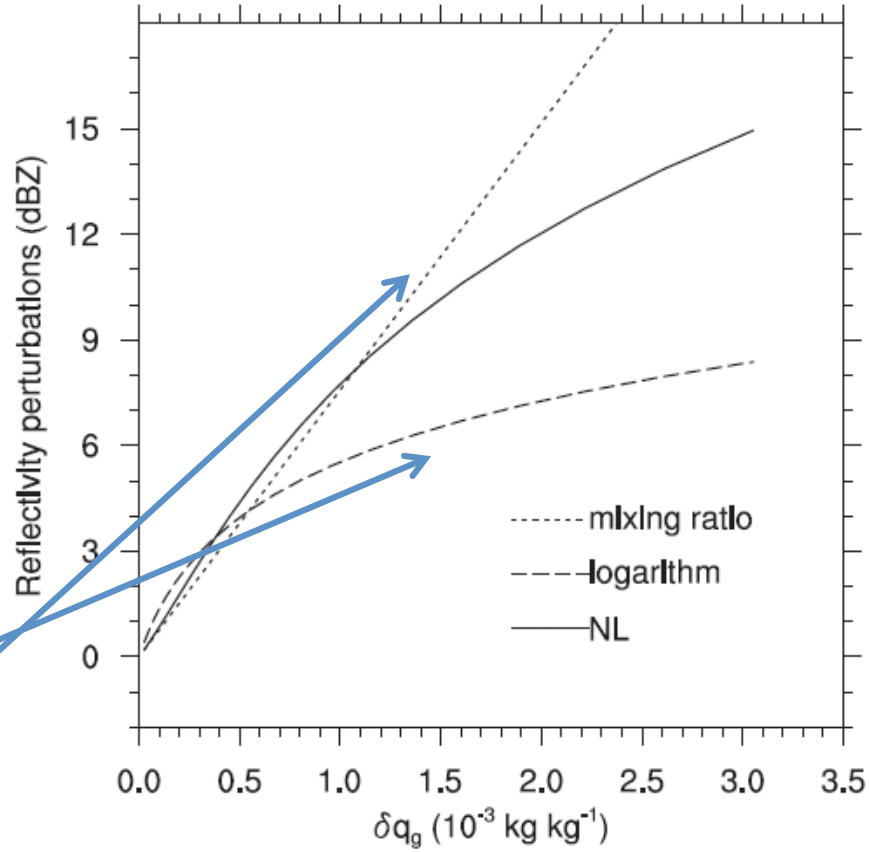
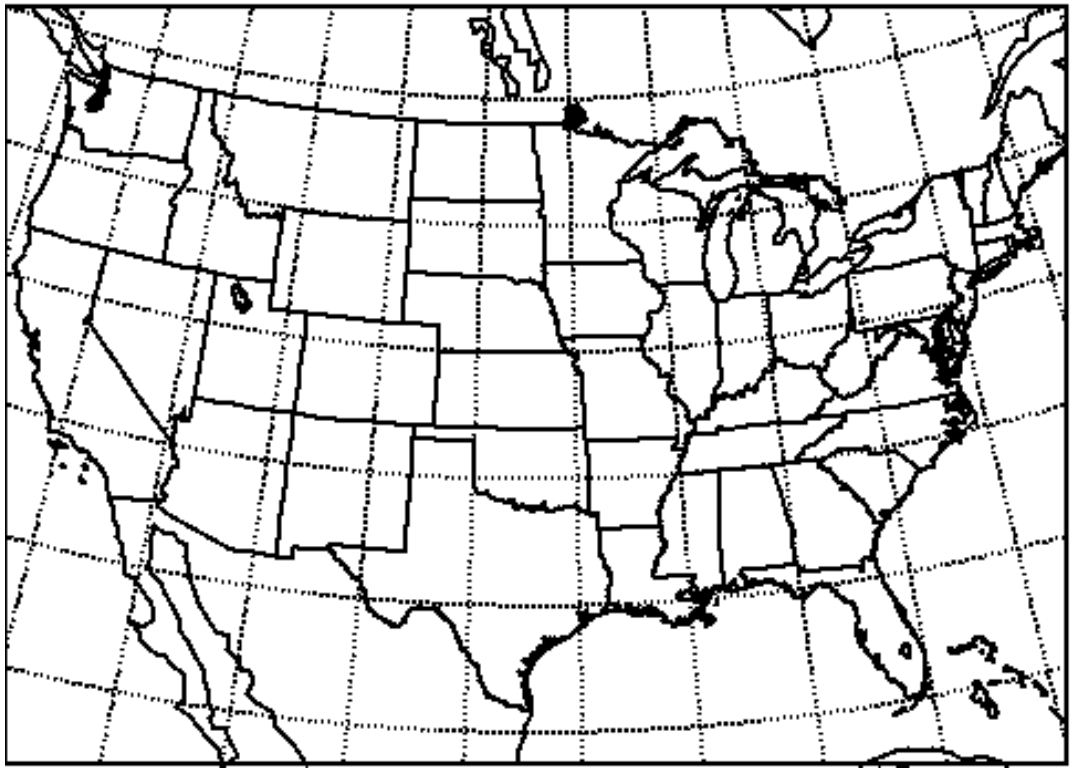


FIG. 5. Relationship between radar reflectivity perturbations and graupel mixing ratio increments for the tangent linear reflectivity operator w.r.t hydrometeor mixing ratios (dotted line) and logarithm of hydrometeor mixing ratio (dashed line). The nonlinear (NL) reflectivity perturbation (solid line) used in method dBZ is shown as a reference.

Wang and Wang (2017; *MWR*)

Direct assimilation of radar observations using GSI based EnKF-Var hybrid (EnVar)

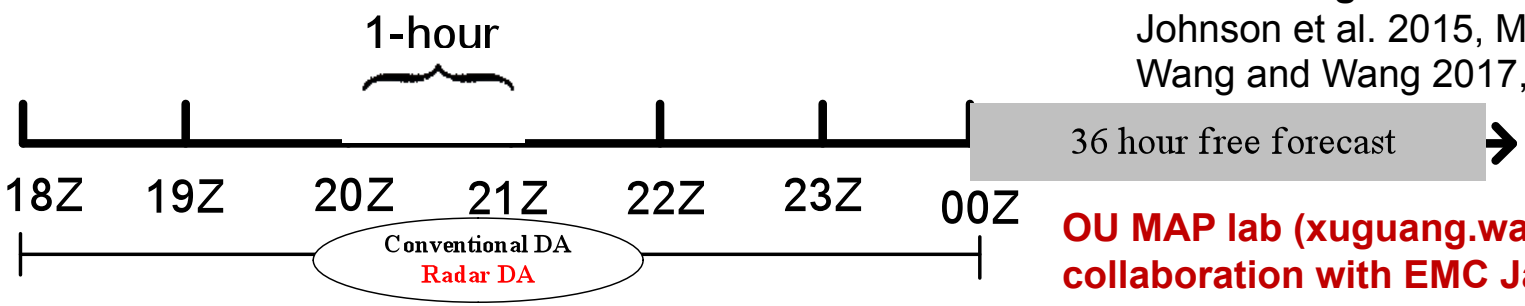


Model/Domain:
- NMMB
- Resolution: 3 km
- Grid: 1568 X 1120 X 50
- Same as HWT CLUE

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

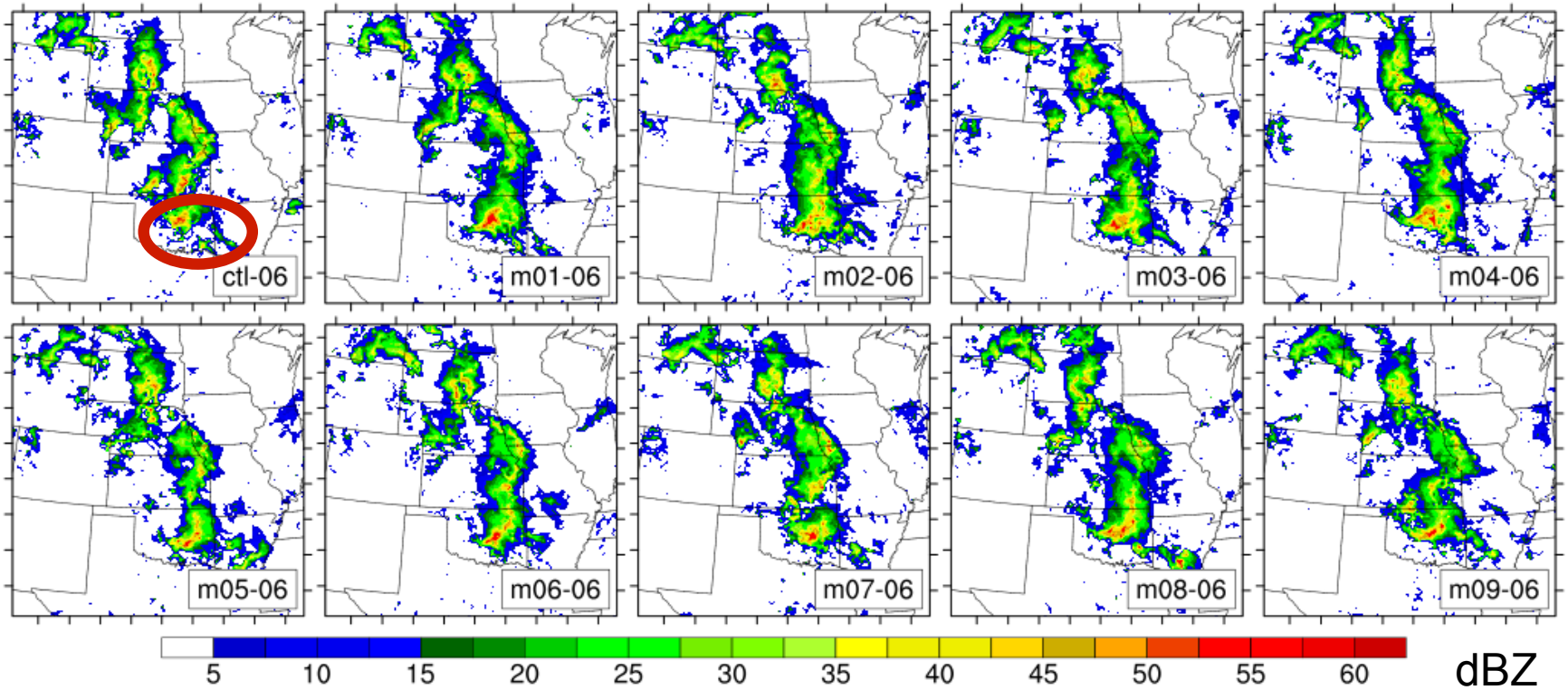
GSI EnKF/EnVar radar DA methodologies:
Johnson et al. 2015, MWR
Wang and Wang 2017, MWR

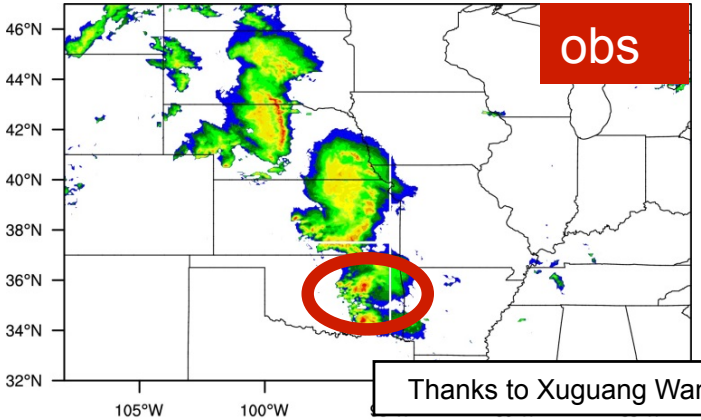


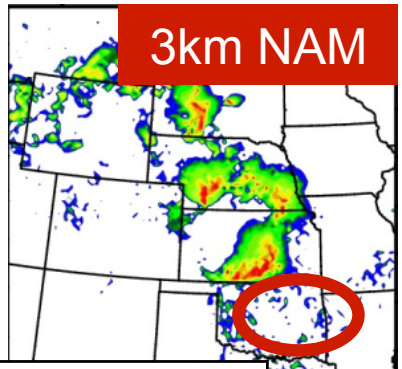
OU MAP lab (xuguang.wang@ou.edu) in collaboration with EMC Jacob Carley

Thanks to Xuguang Wang for kindly providing this slide.

Composite reflectivity @ 06Z May 24 2016







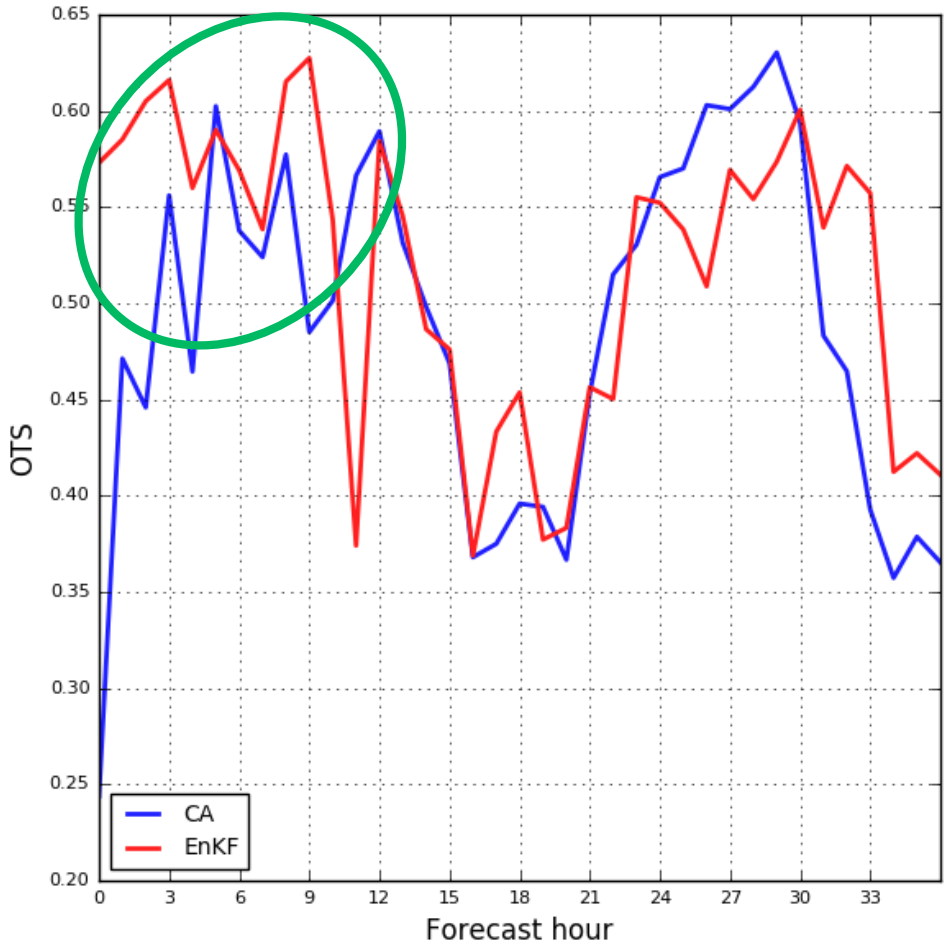
Forecast hour 6

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)

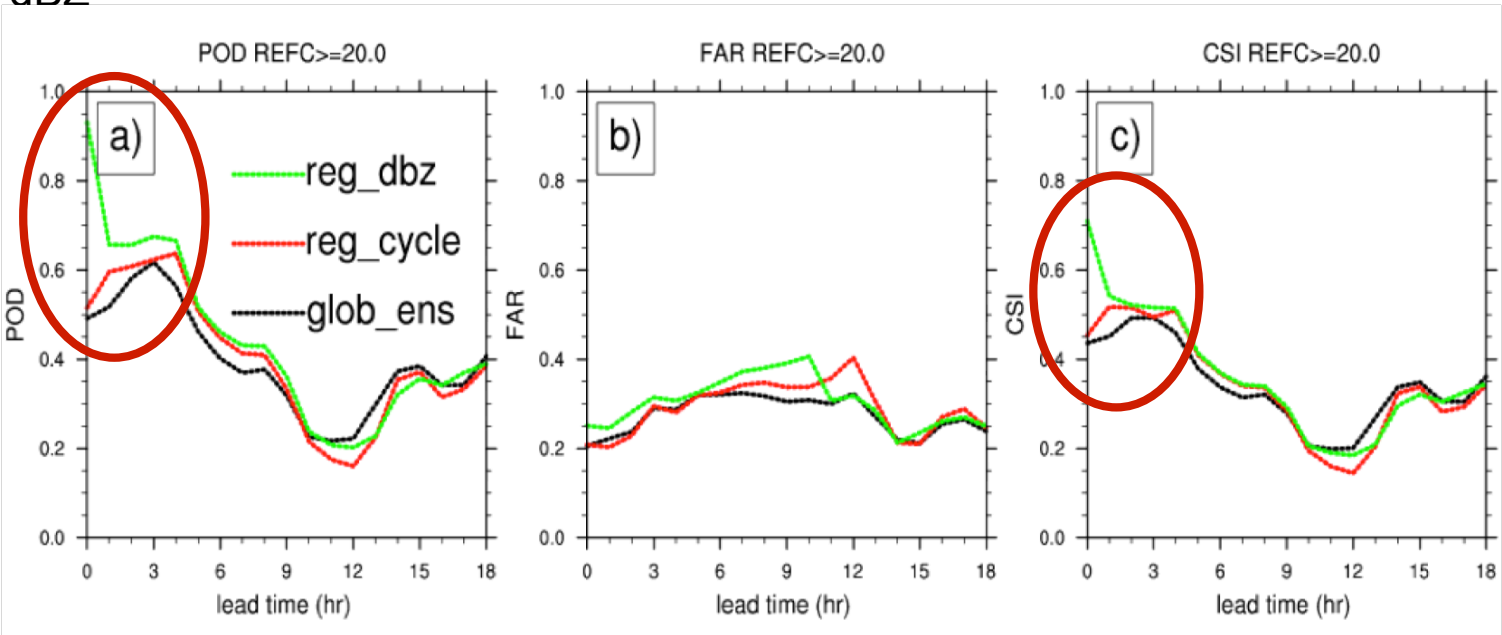
$$OTS = \sum_{obj_pair} INTEREST_{f,o} \frac{INTERSECTION_AREA_{f,o}}{AREA_f + AREA_o}$$

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 <u>direct assimilation of</u> dBZ

Ens3DVa	Ensemble (regional ensembles are hourly cycled)	Cloud analysis	Direct DA of dBZ
Glob_ens	80 global members	Yes	No
Reg_cycle	40 regional members	Yes	No
Reg_dbz	40 regional members	No	Yes



Thanks to Ting Lei for kindly providing this slide.

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

Radar DA Challenges + the GSI

B for hydrometeors

Hybrid ensemble-3D Var cost function

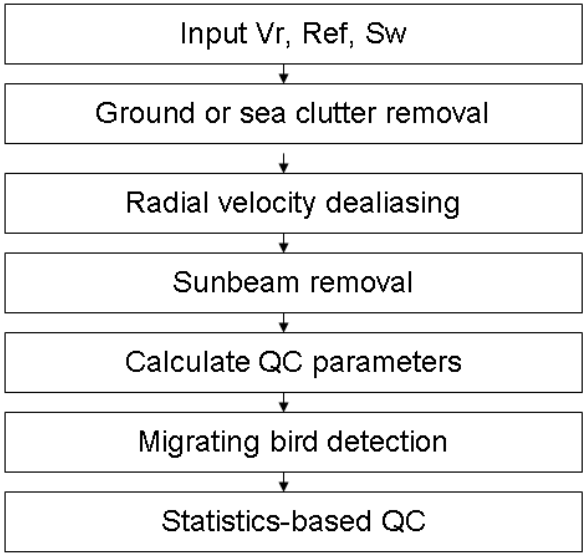
$$2J\left(\mathbf{x}_1, \mathbf{a}\right) = \beta_1 \mathbf{x}_1^{\mathrm{T}} \boxed{\mathbf{B}^{-1}} \mathbf{x}_1 + \beta_2 \mathbf{a}^{\mathrm{T}} \mathbf{A}^{-1} \mathbf{a} + \left(\mathbf{H}\mathbf{x} - \mathbf{y}\right)^{\mathrm{T}} \mathbf{R}^{-1} \left(\mathbf{H}\mathbf{x} - \mathbf{y}\right)$$

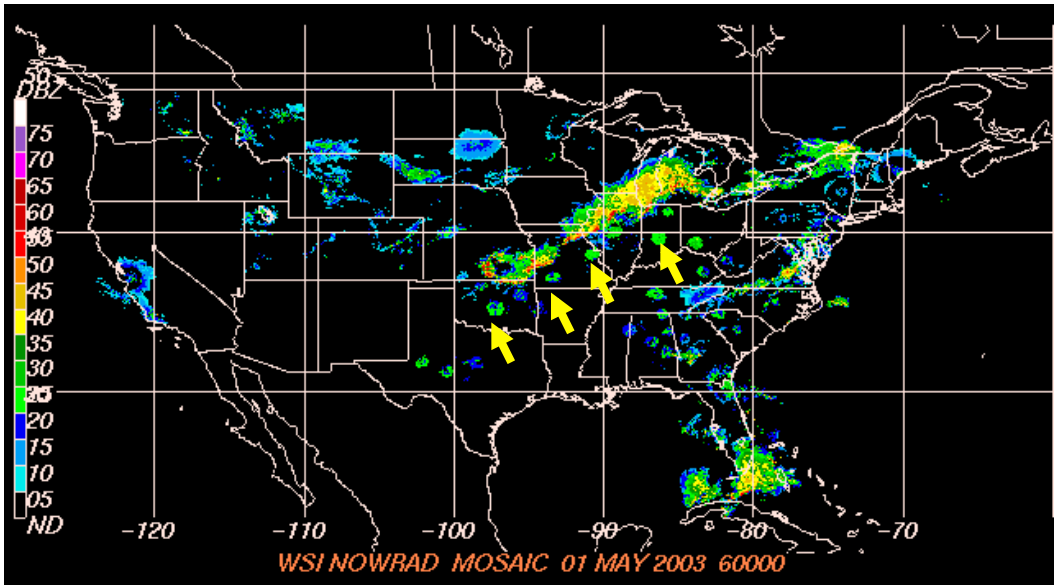
- Difficult for fields that are not continuous (i.e. rain mixing ratio)
  - NMC method (Parrish and Derber, 1992) will not work (e.g. Xiao et al., 2007)
- Past approach to *estimate* magnitudes of hydrometeor variances in GSI
  - Horizontal averages over several cases to produce mean vertical profiles
  - 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 DA Challenges + the GSI

Radar Data Quality Control (Operational Perspective)

- 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.





Migrating Bird Contamination in Reflectivity Mosaic

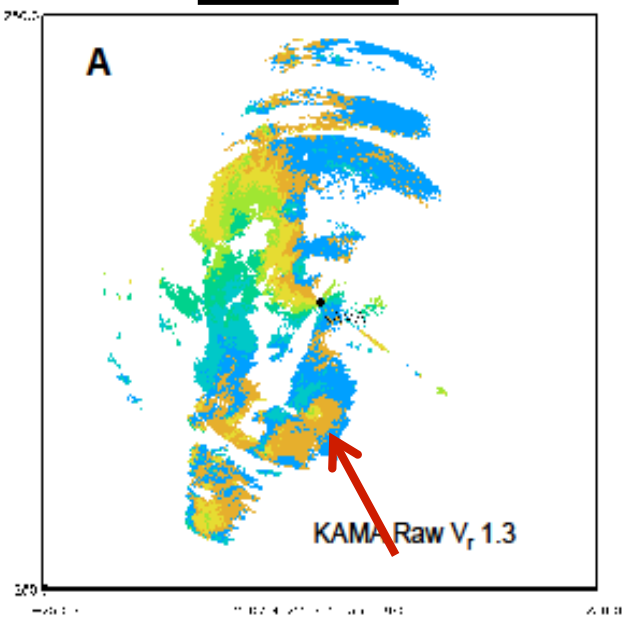
Thanks to Shun Liu for kindly providing this slide.

Radar DA Challenges + the GSI

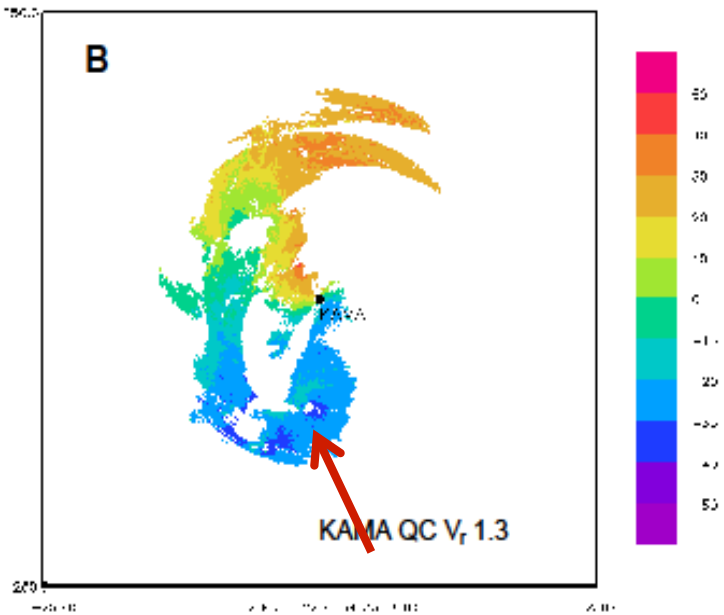
Radar Data Quality Control (Operational Perspective)

- 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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GSI Radar DA Documentation

- The GSI Advanced User's Guide includes *excellent* details on radar data assimilation

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Thanks to Ming Hu for kindly providing information on this slide.

Closing

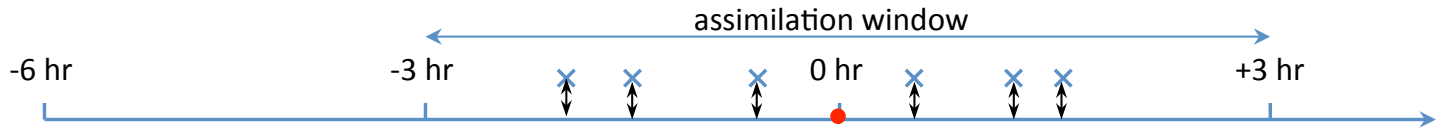
- Need continued community involvement in GSI, especially for DA at convection-allowing scales (and multiscale)

Thank You!
Contact: jacob.carley@noaa.gov

Supplemental Slides

Assimilation of NOAA-P3 Tail Doppler Radar (TDR) Radial Velocity Data in HWRF

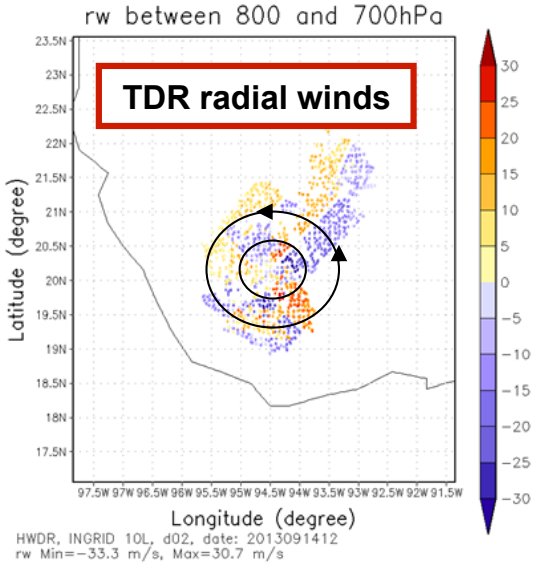
- Automatic quality control of TDR radial velocities, including dealiasing, erroneous data removal and navigation correction, is done on aircraft before data are transferred to the ground
- TDR data are assimilate in ghost domain after vortex initialization
- Data with innovation (o-f) greater than 20 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

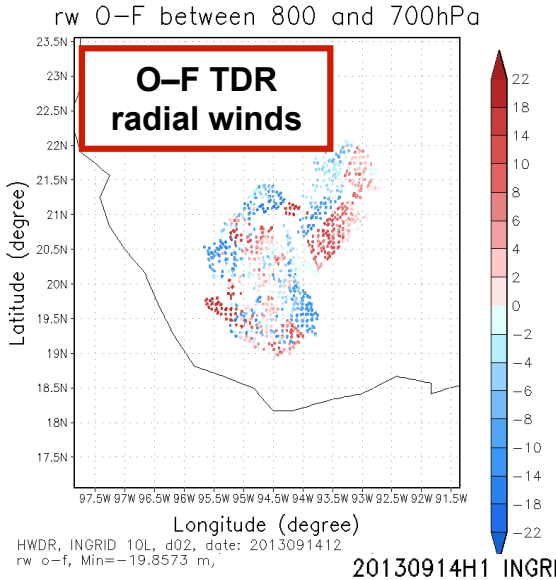


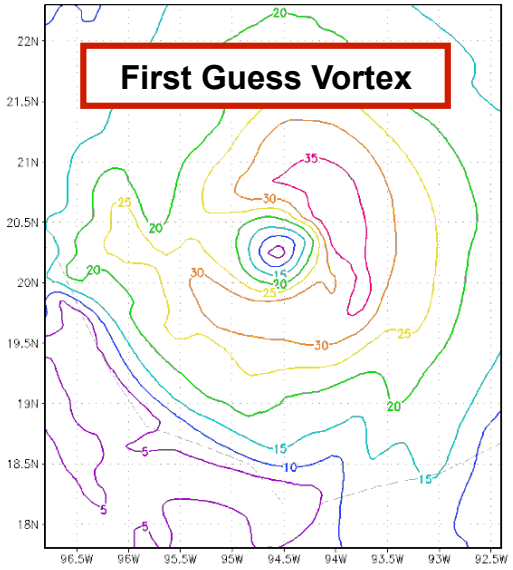
Thanks to Mingjing Tong for kindly providing this slide.

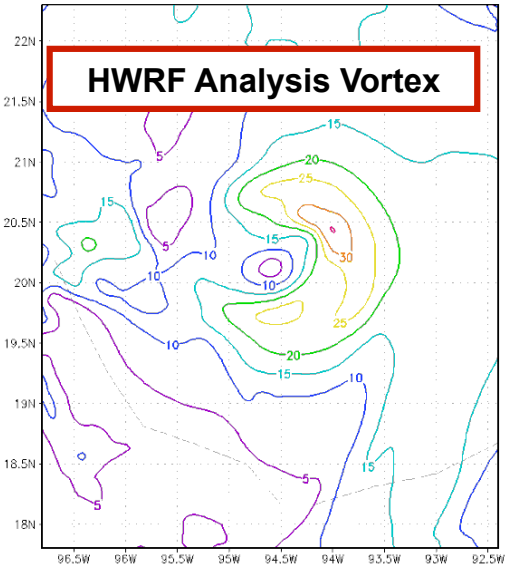
Impact of TDR data assimilation

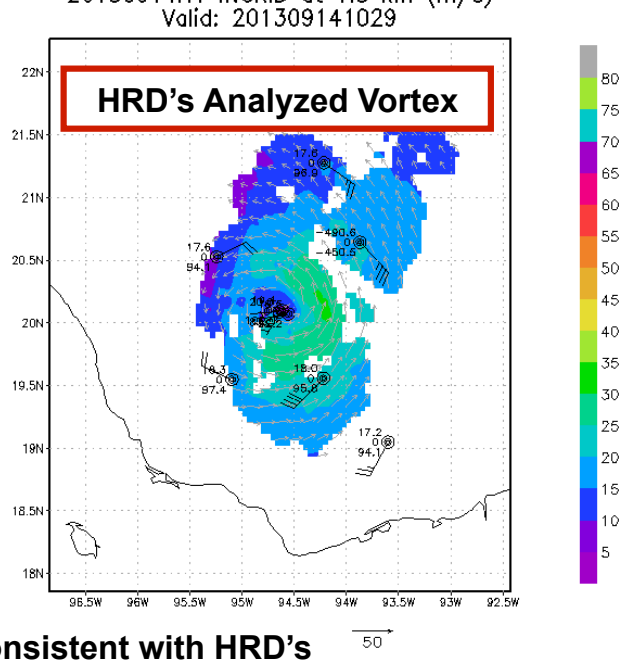
Hurricane Ingrid 10l 2013









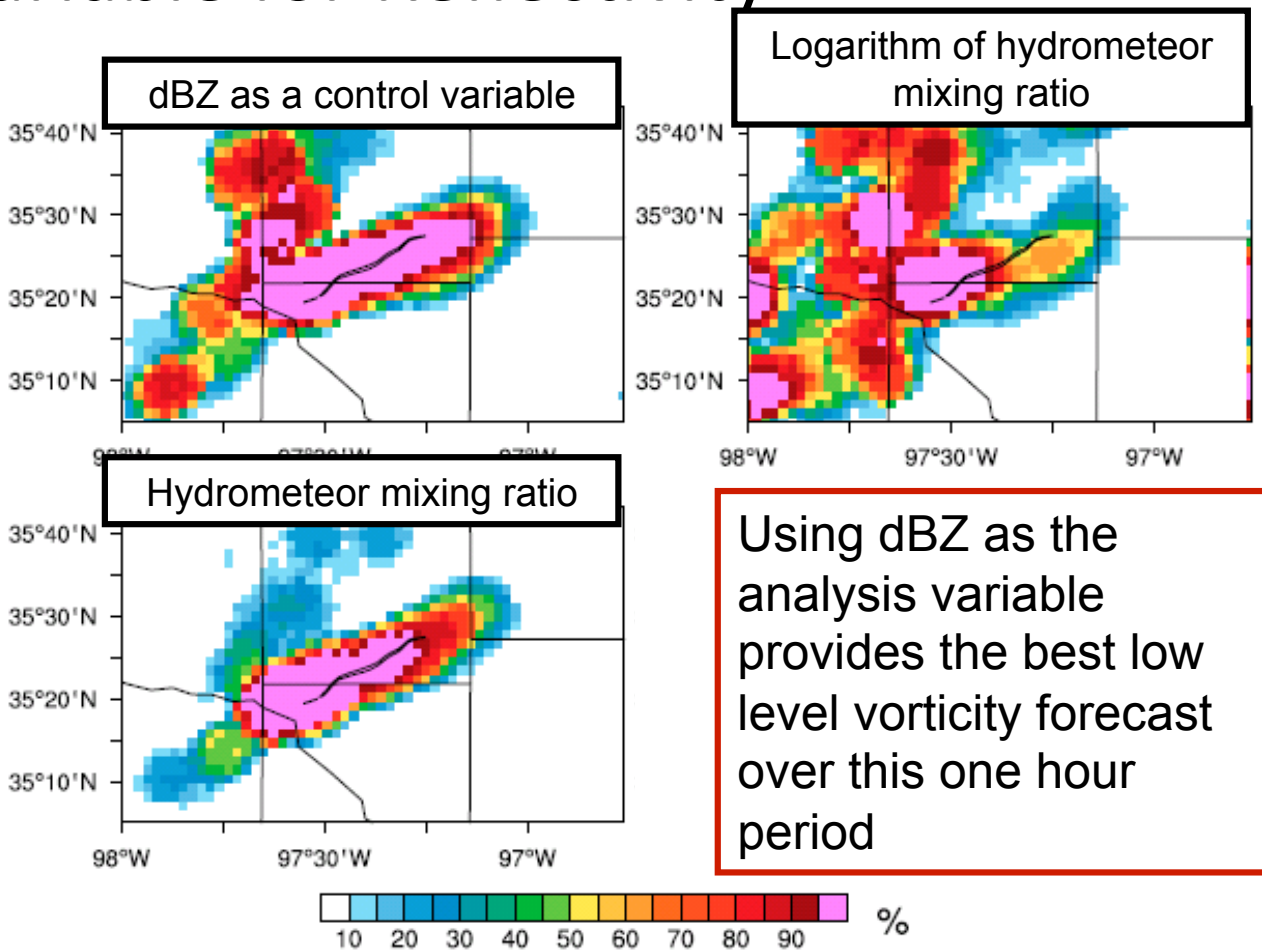


First guess vortex is much bigger than observed vortex. HWRF analysis is consistent with HRD's radar wind analysis

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

FIG. 10. Neighborhood ensemble probability (%) of vorticity exceeding thresholds of 0.003 s^{-1} at 150 m AGL during 1-h forecast period initialized from the analyses at 2200 UTC and ending at 2300 UTC for the (a) method dBZ, (b) method logarithm, (c) method mixing ratio, and (d) method dBZ thom. The overlaid squiggly line in each panel is the NWS-observed tornado damage track during 2210–2238 UTC.

Wang and Wang (2017; *MWR*)