Doppler Radar Data Assimilation with WRF-Var

Qingnong Xiao, NCAR/MMM

Email: hsiao@ucar.edu

Outline:

- Introduction
  - Background and motivation
  - WRF-Var
- Methodology
  - Radial velocity
  - Reflectivity
- Procedure
  - Data preprocessing
  - Setup of namelist and scripts
- Summary

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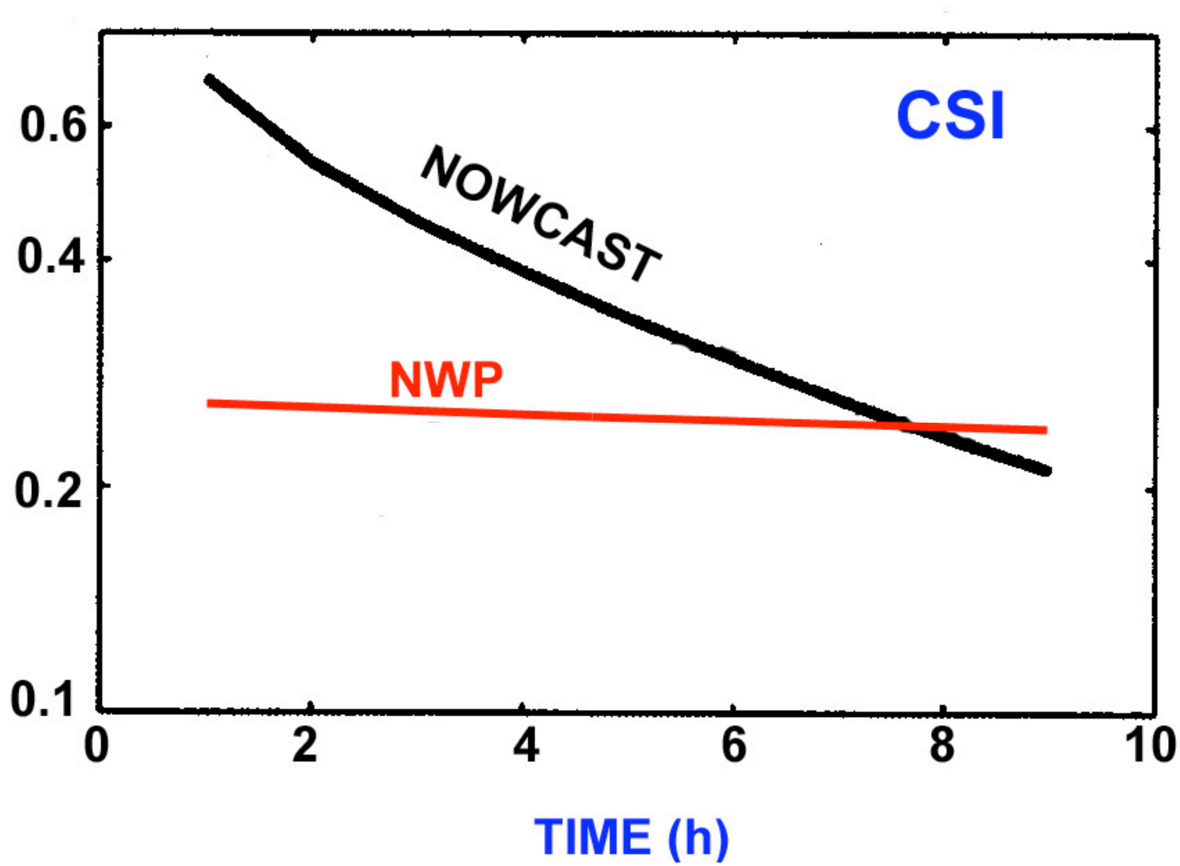
Operational NWP: poor short-term QPF skill

- Current operational NWP can not beat extrapolation-based radar nowcast technique for the first few forecast hours.

- One of the main reasons is that NWP is not initialized by high-resolution observations, such as radar.

0.1 mm hourly precipitation skill scores for Nowcast and NWP averaged over a 21 day period



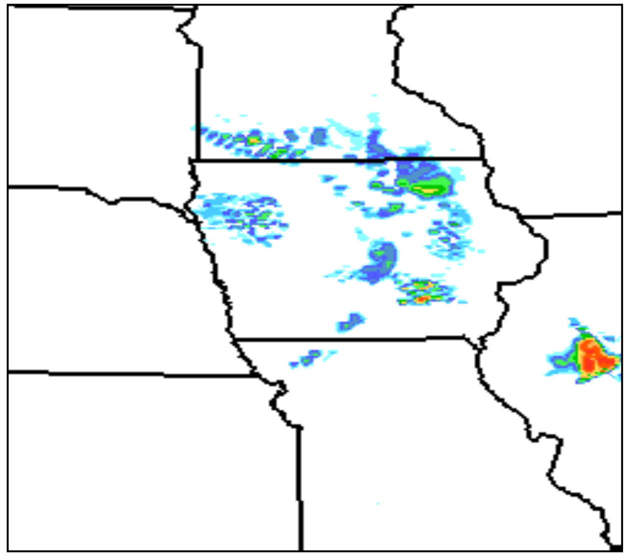
From Lin et al. (2005)

Example of model spin-up from BAMEX

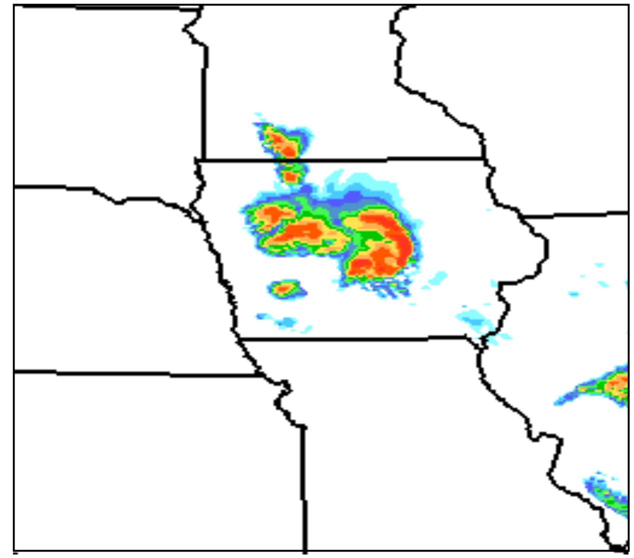
Without high-resolution initialization:

- A model can takes a number of hours to spin up.
- Convections with weak synoptic-scale forcing can be missed.

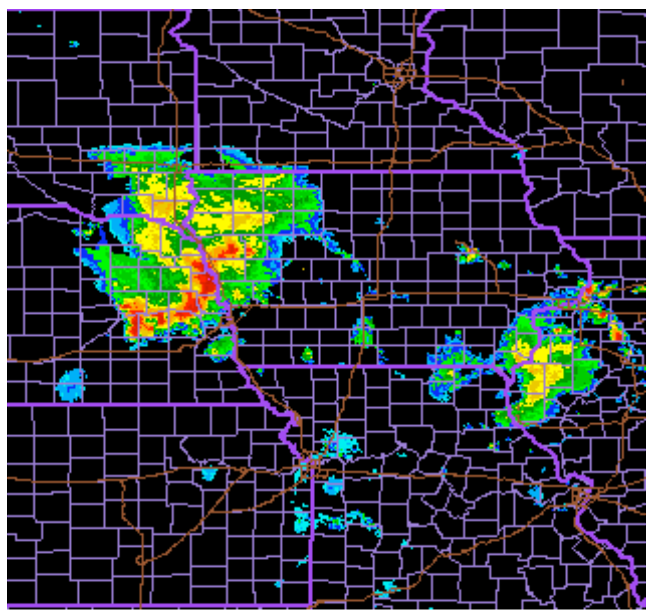
6h forecast (July 6 2003)



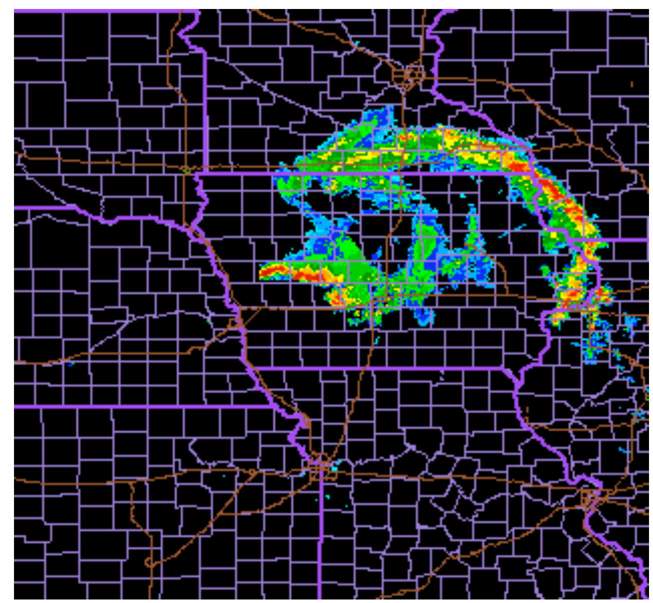
12h forecast



Radar observation at 0600 UTC



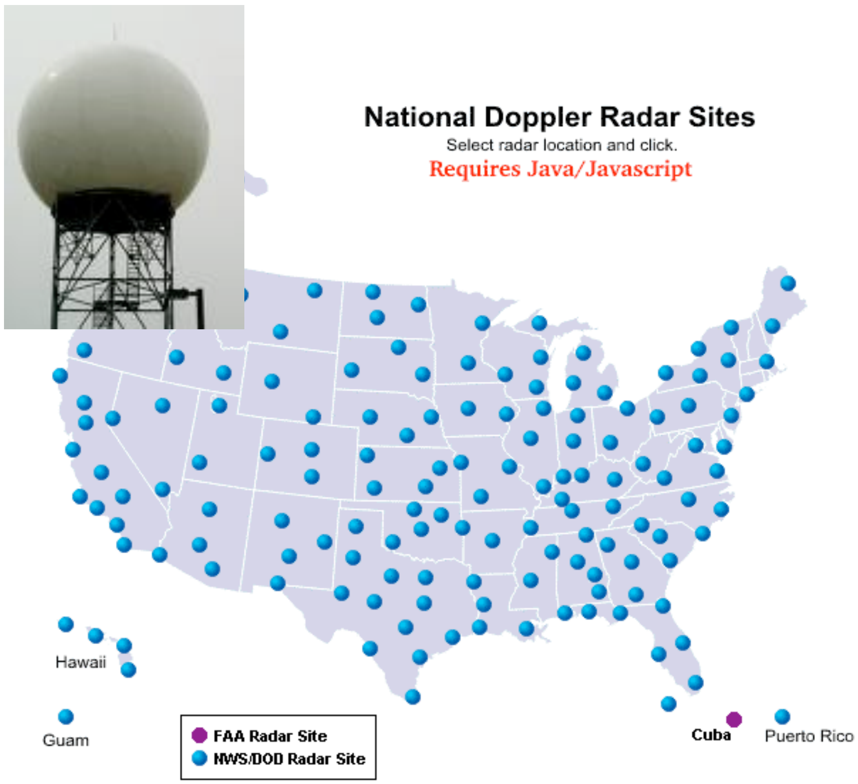
at 1200 UTC



Graphic source: http://www.joss.ucar.edu

Opportunities

- There are wealth of Doppler radar observations from ground-based, airborne, and DOW radars.



- Assimilation of Doppler radar data should improve the small-scale structures in the initial conditions, reduce the model spin-up time, and enhance the short-time NWP skills.

Doppler radar observations

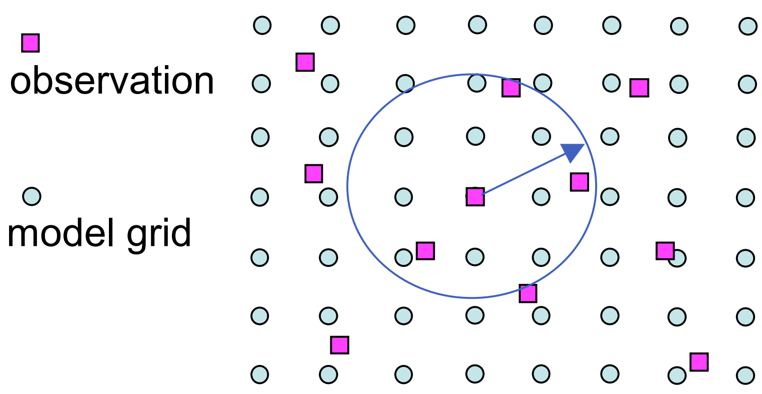
- The level II data are radial velocity and reflectivity
- High spatial (~1 km) and temporal (5-10 minutes) resolution, but coverage is limited to regions with hydrometeors
- Huge amount of data (in a storm mode, the estimate number of data is ~3 million/ 5minute from one radar

Doppler radar observations

Conventional Observation:

Resolution ~ a few 100 km -- much poorer than model resolutions.

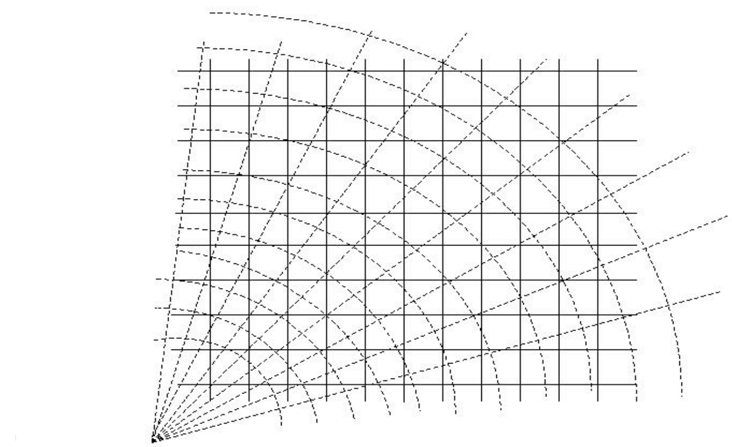
The observed is usually model variables.



Radar observation:

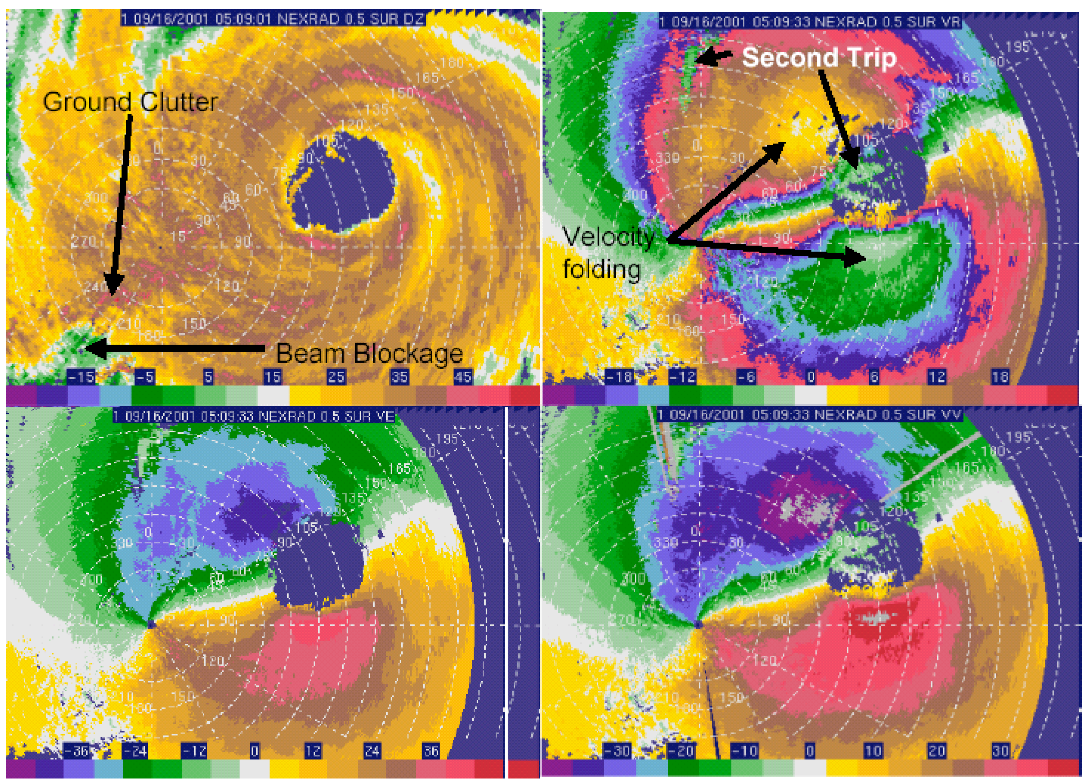
Resolution ~ a few km -- equivalent to model resolutions.

Radial velocity and reflectivity data are not model variables.

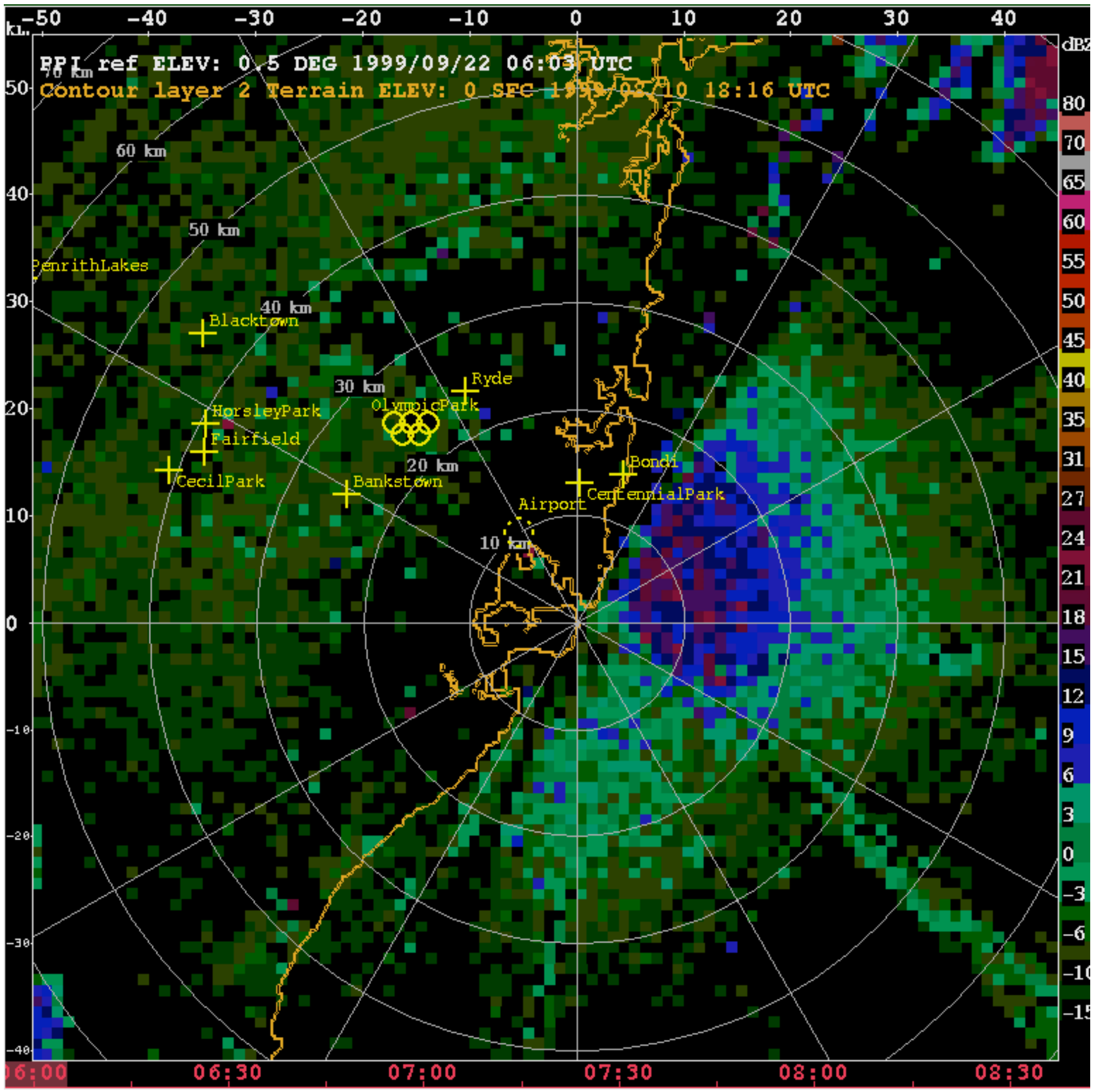


Doppler radar observations

- Data quality control is a major issue for radar data assimilation
  - Dealiasing
  - Removal of clutters, second-trip echo and other noises

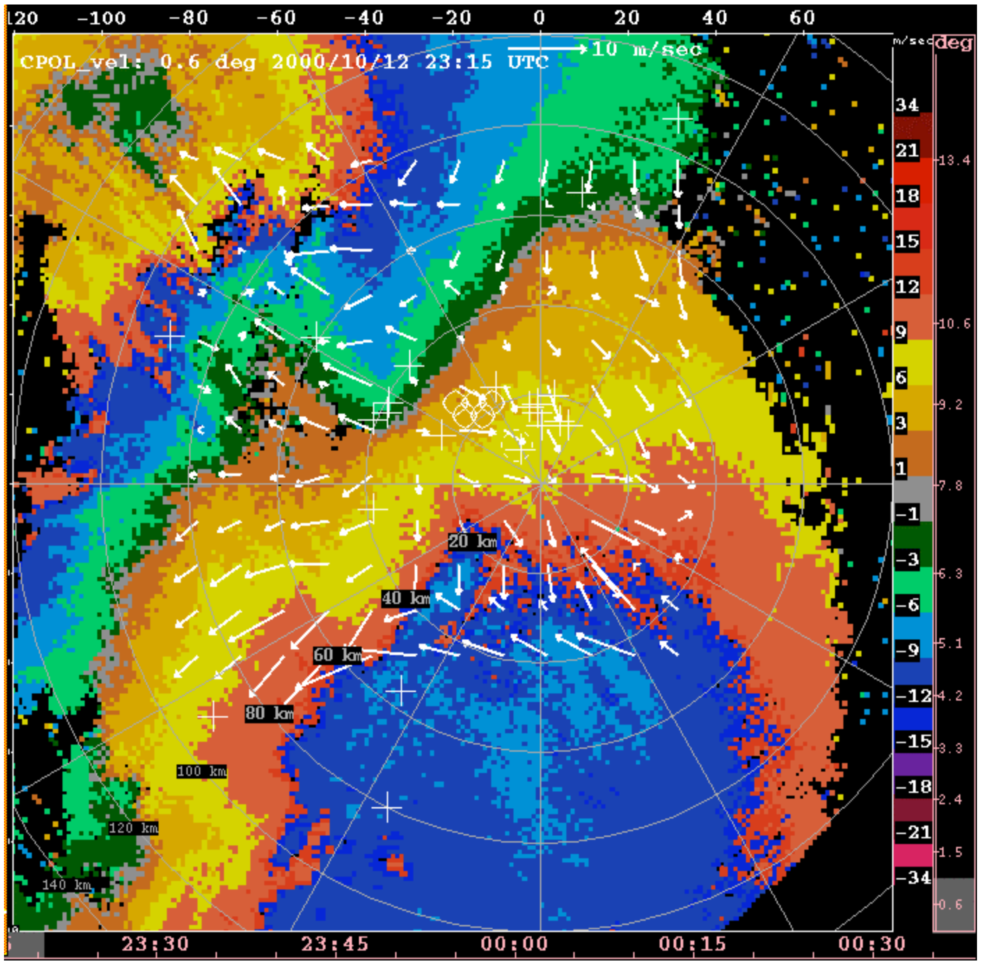


Doppler radar observations

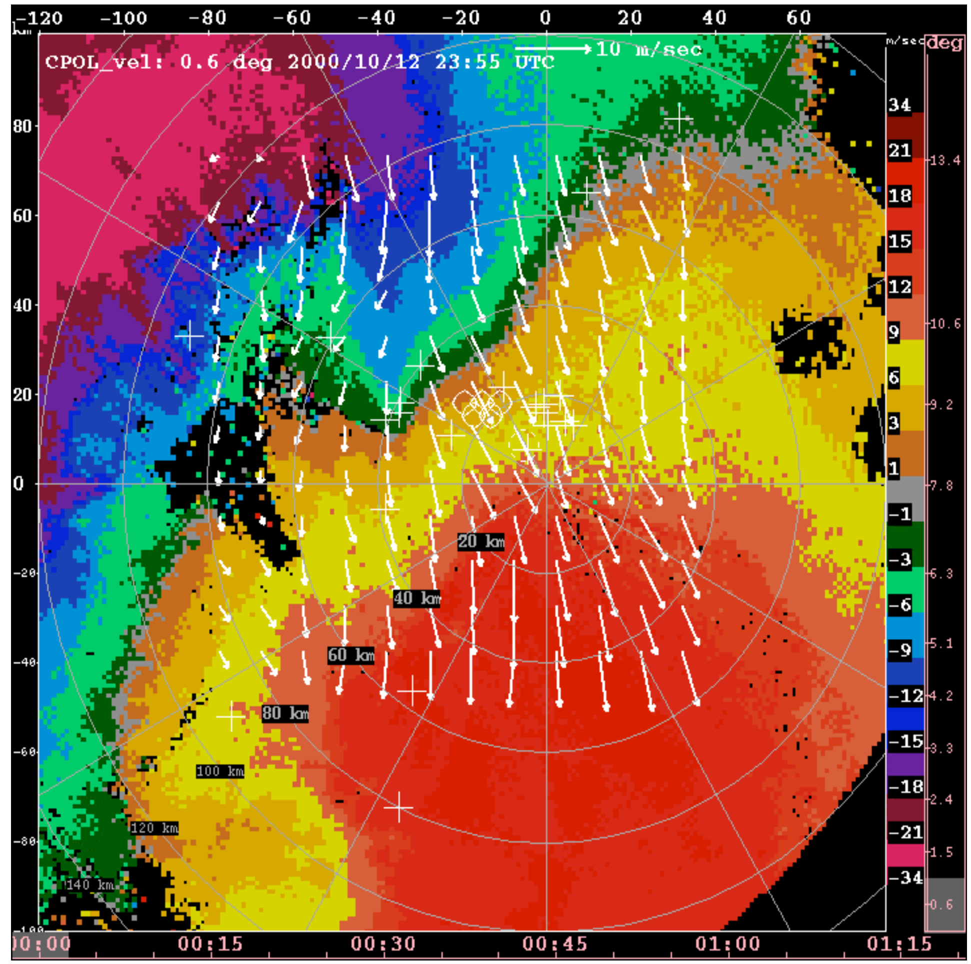


Sea clutter: Radar echo has vertical gradient near the surface.

Doppler radar observations

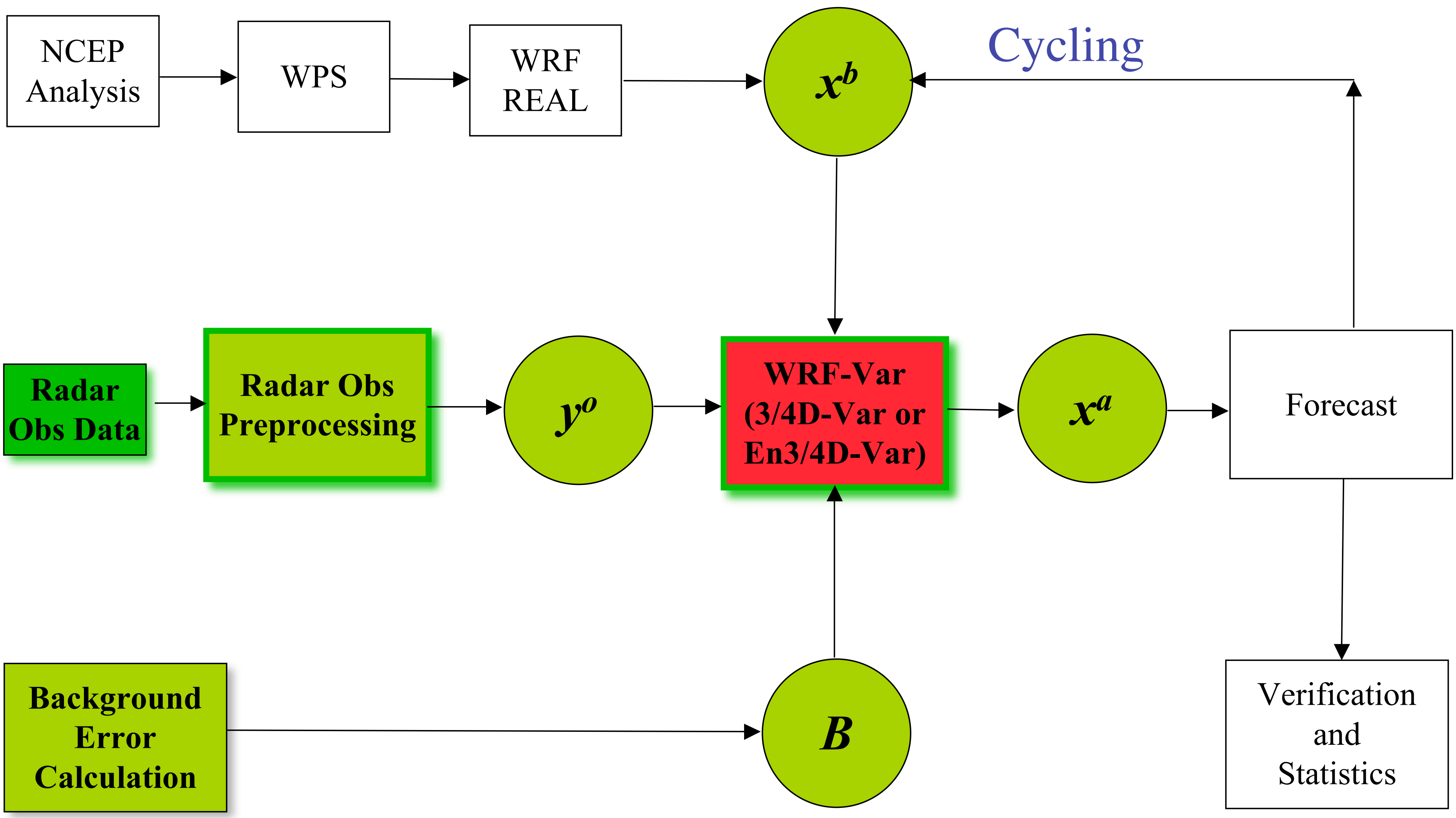


Aliased velocities



De-aliased velocities

WRF-Var Flow Chart



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Challenges for radar DA with 3D-Var

- Cost function

$$J(\mathbf{x}) = \frac{1}{2}\left(\mathbf{x} - \mathbf{x}^b\right)^T \mathbf{B}^{-1}\left(\mathbf{x} - \mathbf{x}^b\right) + \frac{1}{2}\left[H(\mathbf{x}) - \mathbf{y}^o\right]^T O^{-1}\left[H(\mathbf{x}) - \mathbf{y}^o\right]$$

- To assimilate data, we need to construct observation operators.
- The possibly simplest operators for radial velocity and reflectivity:
  - Radial velocity:

$$v_r = u\frac{x - x_i}{r_i} + v\frac{y - y_i}{r_i} + (w - v_T)\frac{z - z_i}{r_i}$$

$$v_T = 5.40a \cdot q_r^{0.125}, \qquad a = (p_0 / \overline{p})^{0.4}$$

  - Reflectivity:

$$dbZ = 43.1 + 17.5\log(\rho q_r)$$

Challenges for radar DA with 3D-Var

- The WRF 3D-Var cost function minimization is performed in the control variable space via preconditioning.

$$J(\mathbf{v}) = \frac{1}{2}\mathbf{v}^T\mathbf{v} + \frac{1}{2}(\mathbf{H}(\mathbf{Uv}) - \mathbf{d})^T \mathbf{O}^{-1}(\mathbf{H}(\mathbf{Uv}) - \mathbf{d})$$

- The preconditioning control variables are **v** : (ψ', χ_u', T'_u, p'_{su}, and r'_s).
- The analysis increments **x**' are obtained through a series of transform: $\mathbf{x}' = \boldsymbol{U}\mathbf{v} = \boldsymbol{U}_p \boldsymbol{U}_v \boldsymbol{U}_h \mathbf{v}$.

Challenges for radar DA with 3D-Var

- The relation between control variable space and model space is through "physical transform in WRF 3D-Var system, $\boldsymbol{U}_p$, and its adjoint $\boldsymbol{U}_p^T$.
  - $\boldsymbol{U}_p$: Convert control variables (ψ', χ_u', T'_u , p'_{su}, and r'_s) to model variables (u', v', T', p', q')

WRF 3D-Var

- Control variables (ψ', χ_u', T'_u, p'_{su}, r'_s) <=> model variables (u', v', T', p', q')

Doppler radar data assimilation

Radial velocity data

3D-Var needs vertical velocity increments (w')

to have a full assimilation of radial velocity data.

Reflectivity data

3D-Var needs at least rainwater increments (q_r').

It is better to have increments of all other

hydrometeor variables as well in 3D-Var analysis.

Challenges for radar DA with 3D-Var

- There is an inconsistency between what the WRF 3D-Var increments have and what the Radar data assimilation needs.
- To overcome the problem, we need either to introduce new control variables (e.g. w', q_r', etc.), or to construct new "physical transforms $\boldsymbol{U}_p$ and its adjoint $\boldsymbol{U}_p^T$" in WRF 3D-Var system".

Challenges for radar DA with 3D-Var

- If new control variables are introduced, then it is required to modify the whole system. In addition, the background error statistics for the new control variables (e.g. w' and q_r') are very difficult.
- We selected to construct new "physical transform" to enable WRF 3D-Var assimilate Doppler radar data.

W Increments in WRF 3D-Var

- Richardson's Equation ($\psi', \chi_u', T'_u, p'_{su} \rightarrow u', v', T', p' \rightarrow w'$)

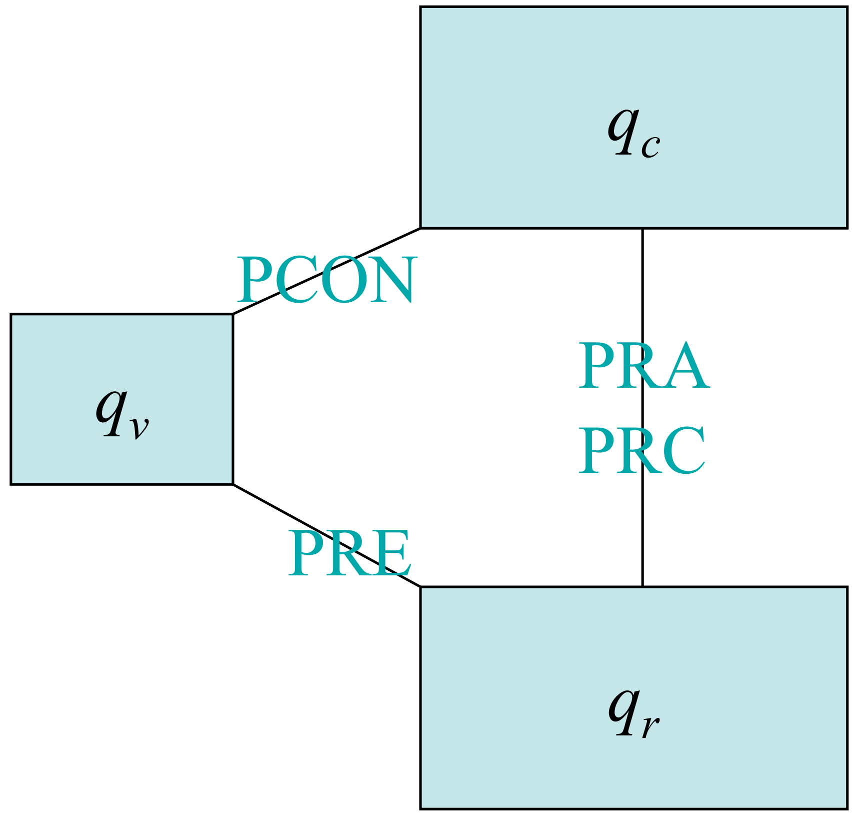
$$\gamma \bar{p} \frac{\partial w'}{\partial z} = -\gamma p' \frac{\partial \bar{w}}{\partial z} - \gamma \bar{p} \nabla \cdot \vec{v}'_h - \gamma p' \nabla \cdot \vec{\bar{v}}_h - \vec{\bar{v}}_h \nabla p'$$

$$-\vec{v}' \nabla \bar{p} + g \int_z^\infty \nabla \cdot (\rho \vec{v}'_h) dz + g \int_z^\infty \nabla \cdot (\rho' \vec{\bar{v}}_h) dz$$

  - ➢ Richardson's equation is a higher-order approximation of the continuity equation than the incompressible continuity equation or anelastic continuity equation.
  - ➢ It can build an efficient linkage between dynamic and thermodynamic fields because the thermodynamic equation is directly involved.
  - ➢ Its computation is affordable, just a little more than the anelastic continuity equation.

Hydrometeor increments in WRF 3D-Var

A warm rain process is currently built in WRF 3D-Var to bridge water hydrometeors and other variables.



PCON: condensation/evaporation;
PRA: accretion; PRC: conversion;
PRE: evaporation/deposition

Observation operators

- Radial velocity

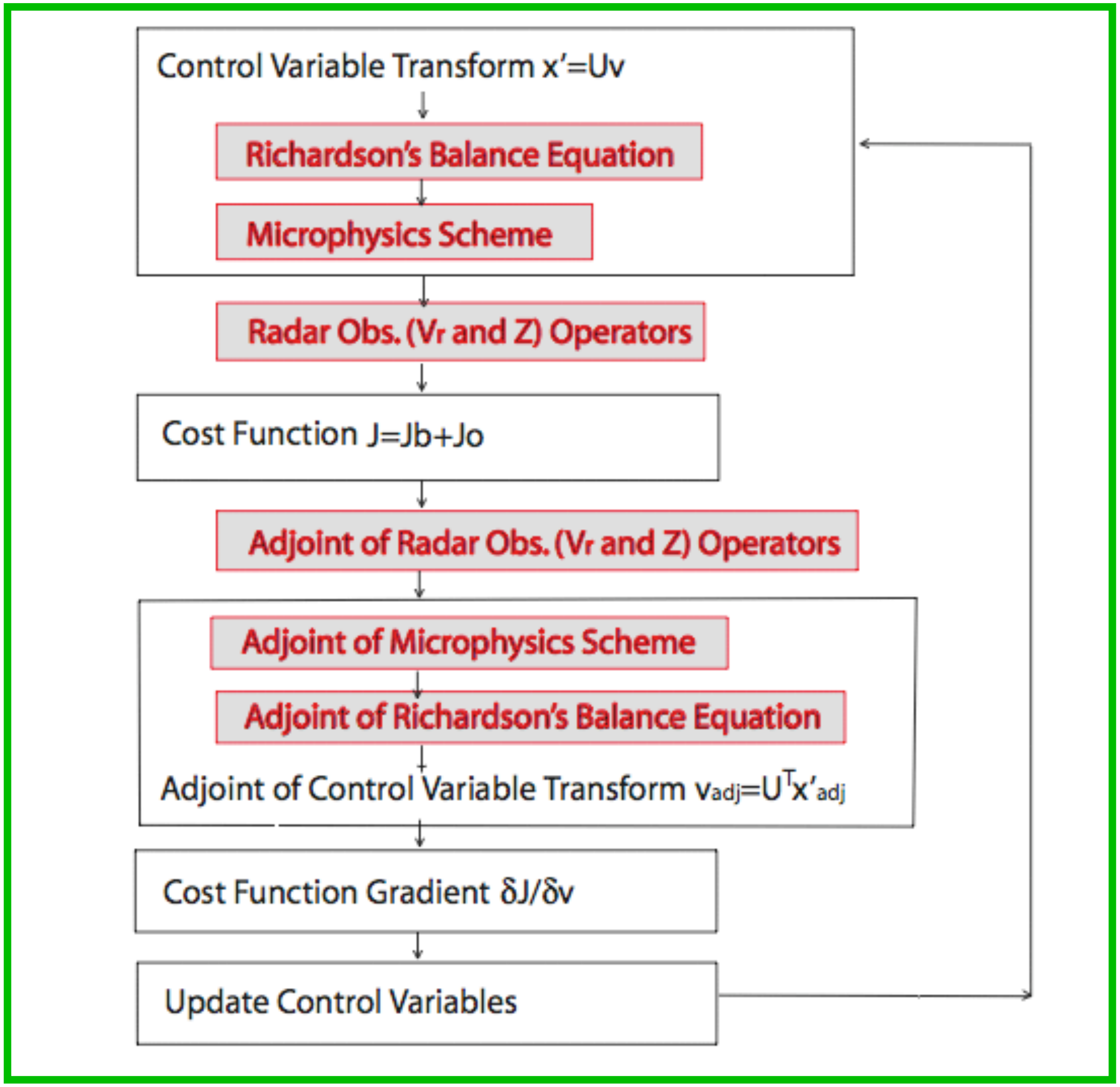
$$v_r = u\frac{x - x_i}{r_i} + v\frac{y - y_i}{r_i} + (w - v_T)\frac{z - z_i}{r_i}$$

$$v_T = 5.40a \cdot q_r^{0.125}, \qquad a = (p_0 / \overline{p})^{0.4}$$

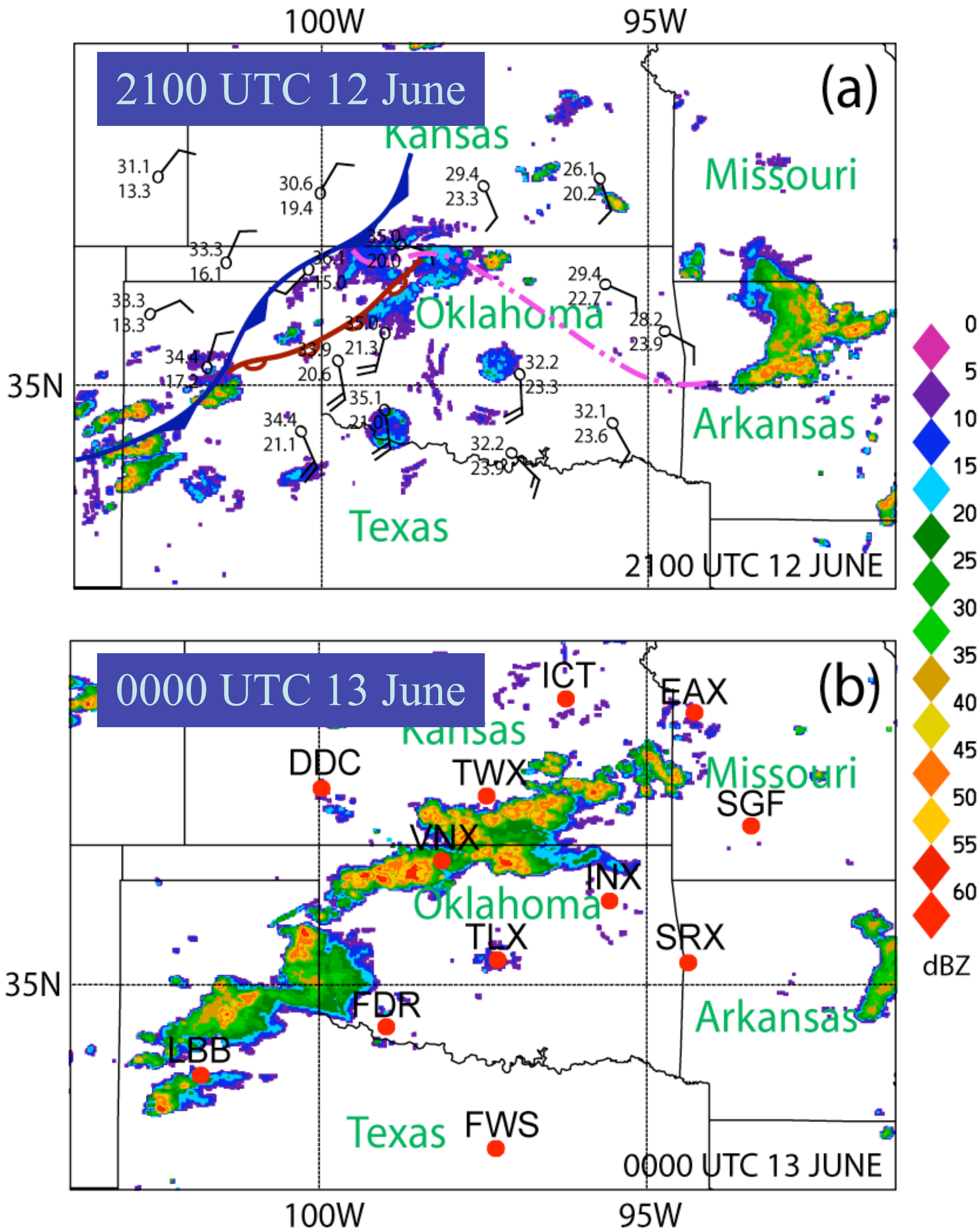
- Reflectivity

$$dbZ = 43.1 + 17.5\log(\rho q_r)$$

Flow Chart of Radar Data Assimilation in WRF 3D-Var



QPF of an IHOP_2002 Squall Line Case



Xiao and Sun (2007), *Mon. Wea. Rev.*, **135**, 3381-3404.

Surface analysis and Composite radar reflectivity observations at (a) 2100 UTC 12 and (b) 0000 UTC 13 June 2002.

The cold front (blue line), dry line (brown line), and outflow boundary (pink line) at 2100 UTC 12 June are depicted in (a). The 12 red dots in (b) indicate 12 WSR-88D radar stations with their station name above the red dot. The data from the 12 WSR-88D radars are used for the Doppler radar data assimilation experiments.

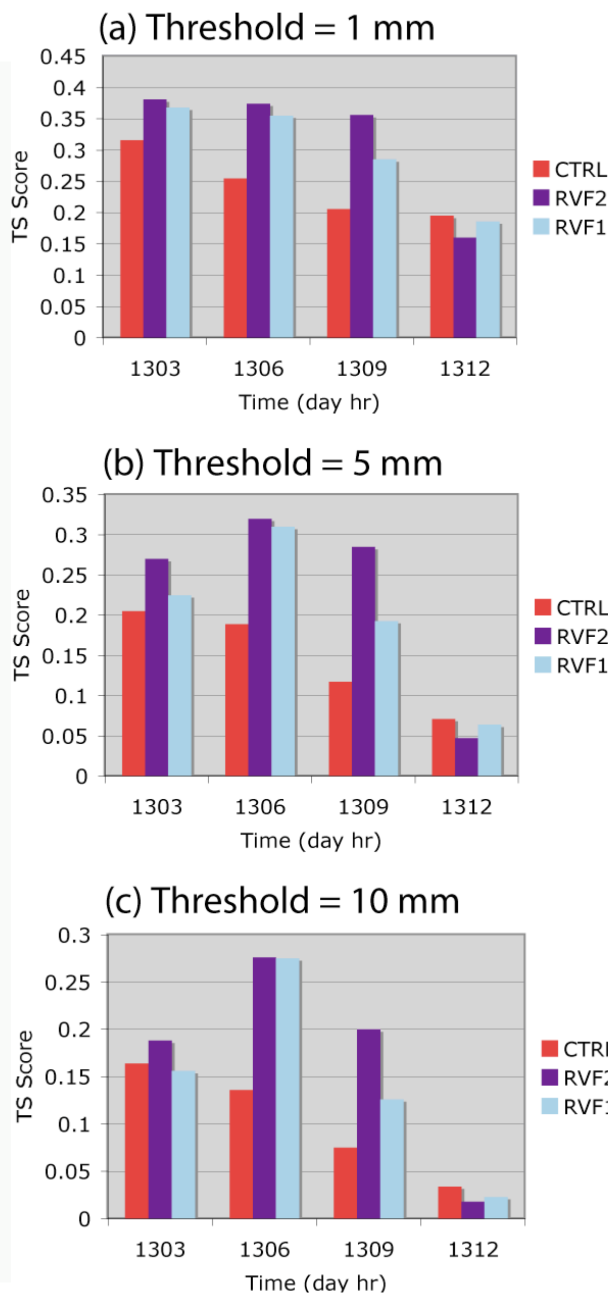
QPF of an IHOP_2002 Squall Line Case

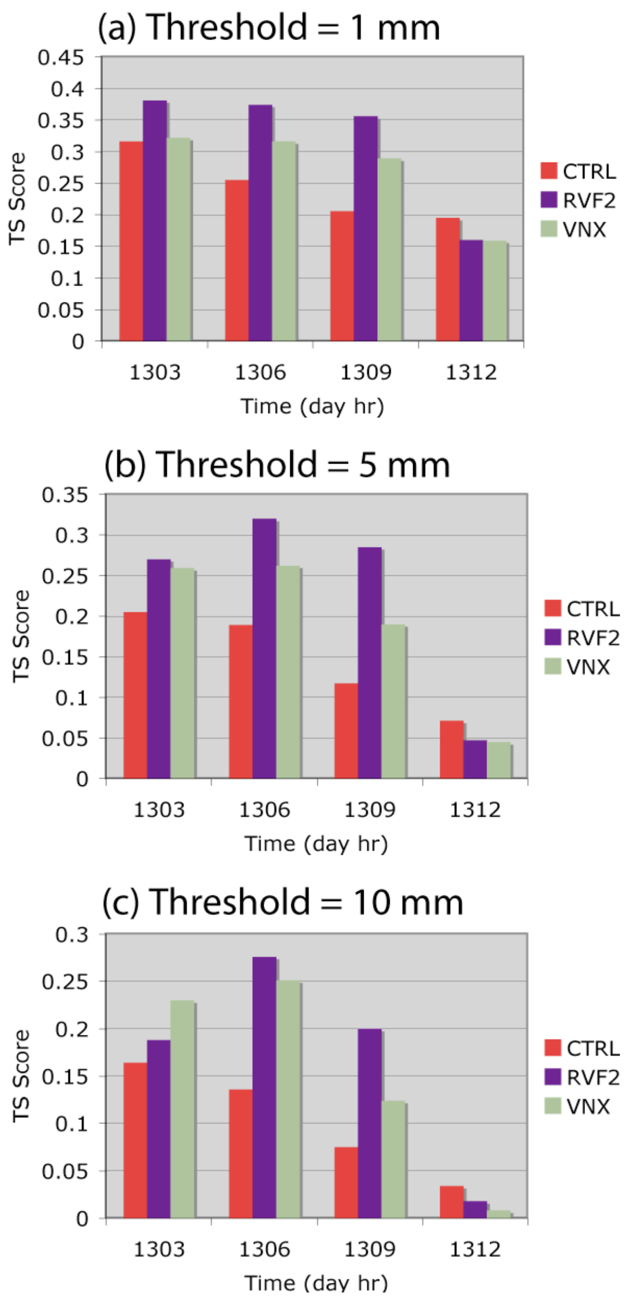
Left panel

Red: CTRL

Blue: Cycling

Cyan: No cycling





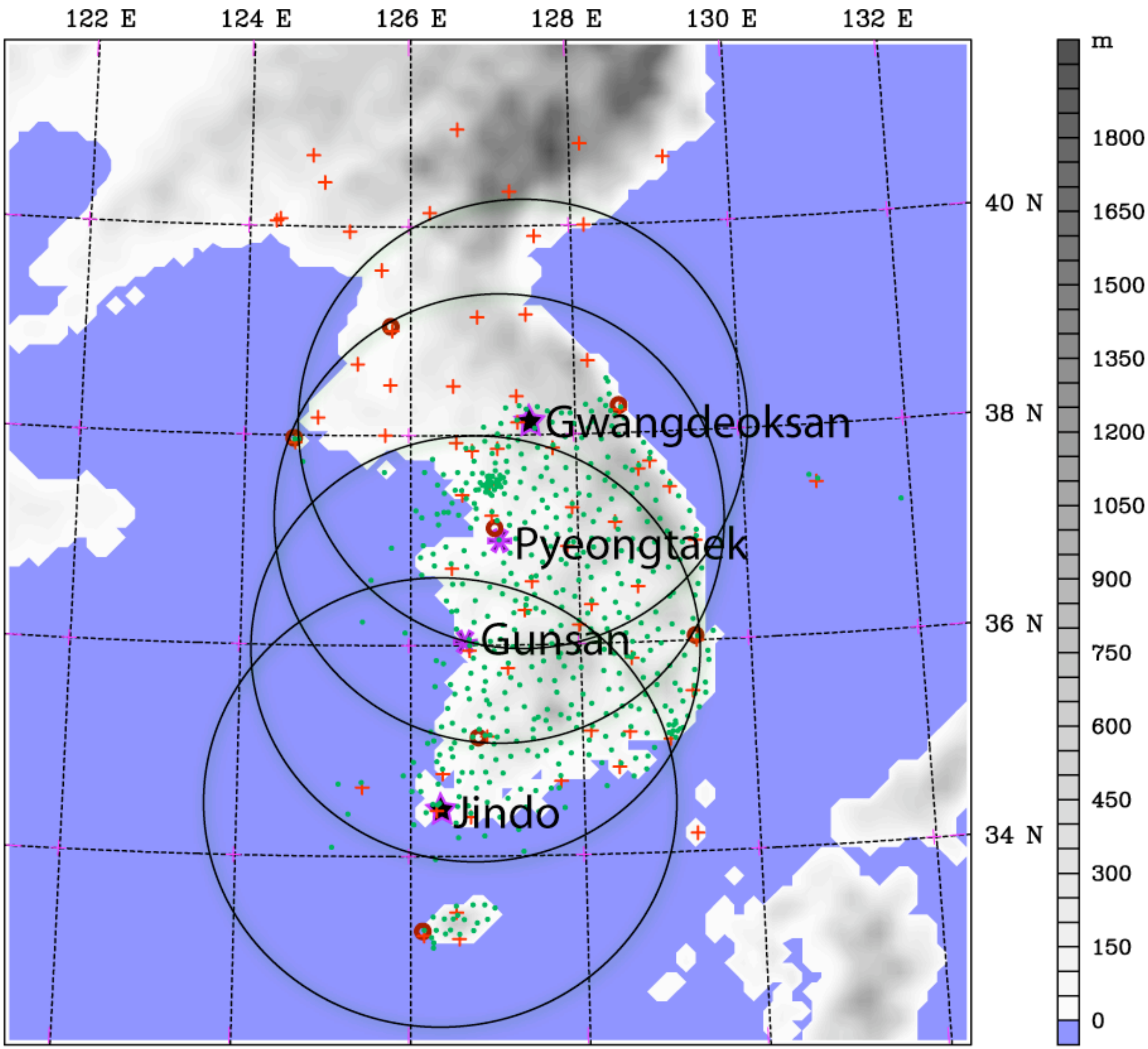
Right panel

Red: CTRL

Blue: 12 radars

Grey: Single radar

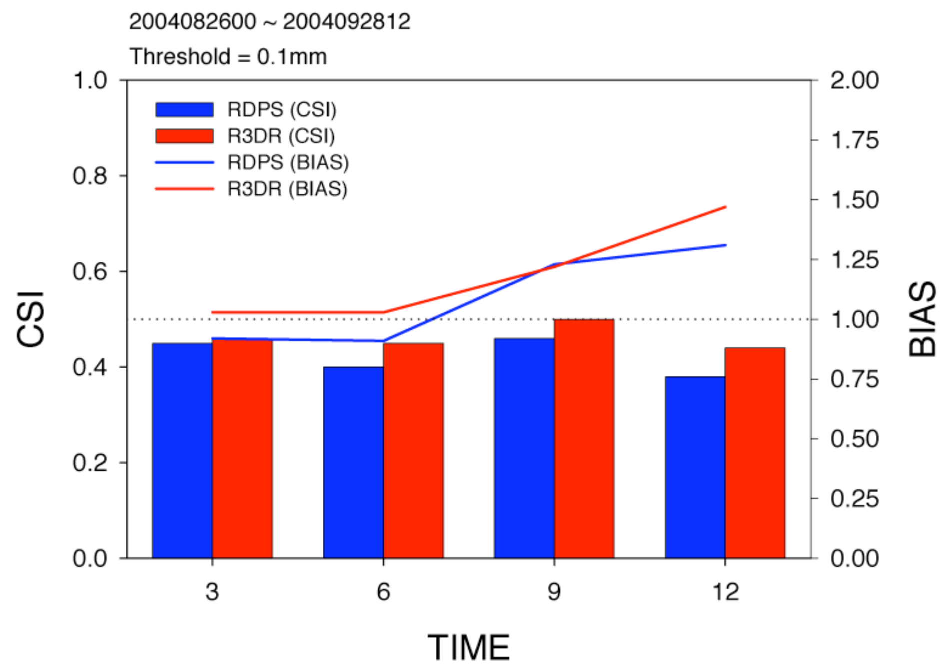
KMA radars used in 3D-Var analysis

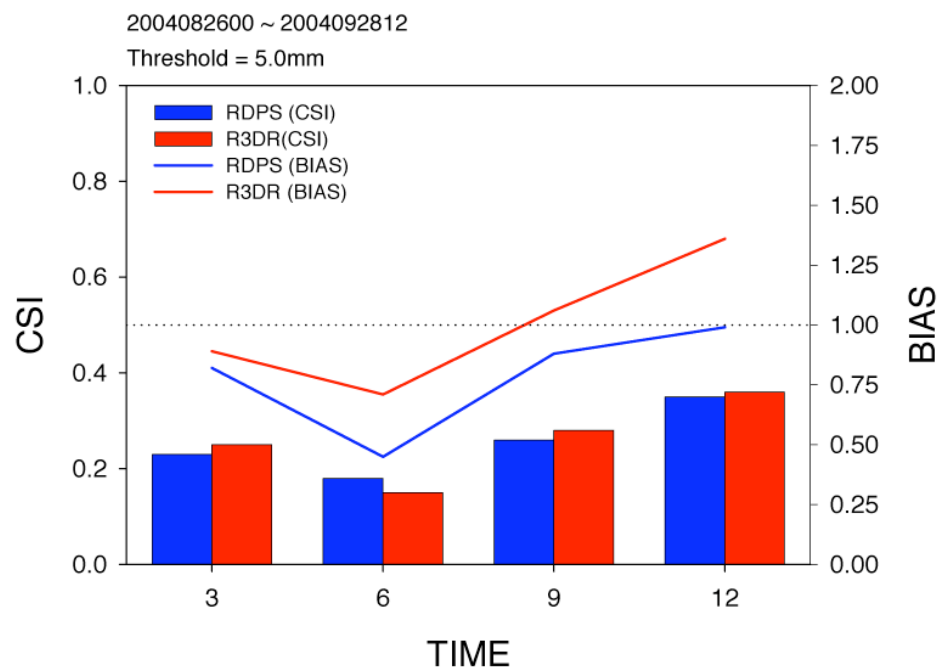


Doppler radar data from 4 radar sites were included in assimilation In 2006

One-month Verification in KMA

- Period: 2004. 8. 26. 00UTC ~ 2004. 9. 28. 12UTC (3hr-accumulated rainfall)
- Operation without radar data/experiment with radar data (blue/red)





- 0.1mm threshold (top) : CSI is increased, but BIAS is also increased at the 12 hour forecasts.
- 5.0 mm threshold (bottom) : CSI is increased except for the 6 hour forecast, BIAS is increased at the 12 hour forecasts.
- Xiao et al. (2008), *Bull. Amer. Met. Soc*. **89**, 39-43.

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Doppler radar data preprocessing

- Preprocessing Doppler radar data is an important procedure before assimilation.
- It usually contains the following:
  - Quality control
    - To deal with clutter, AP, folded velocity, bird contamination, …
  - Mapping
    - Interpolation, smoothing, super-observation, data filling, …
  - Error statistics
    - Variance and covariance

Doppler radar data preprocessing

- NCAR software:
  - SPRINT: Sorted Position Radar INTerpolation
  - CEDRIC: Custom Editing and Display of Reduced Information in Cartesian-space
  - SPRINT and CEDRIC are released in NCAR/MMM website http://www.mmm.ucar.edu/pdas/pdas.html
- NCAR software:
  - ANT: Auto-Nowcasting System
  - VDRAS: Variational Doppler Radar Analysis System
  - ANT and VDRAS are not released to the public
- There is no standard and automatic software to perform radar data preprocessing.

Radar data preprocessing

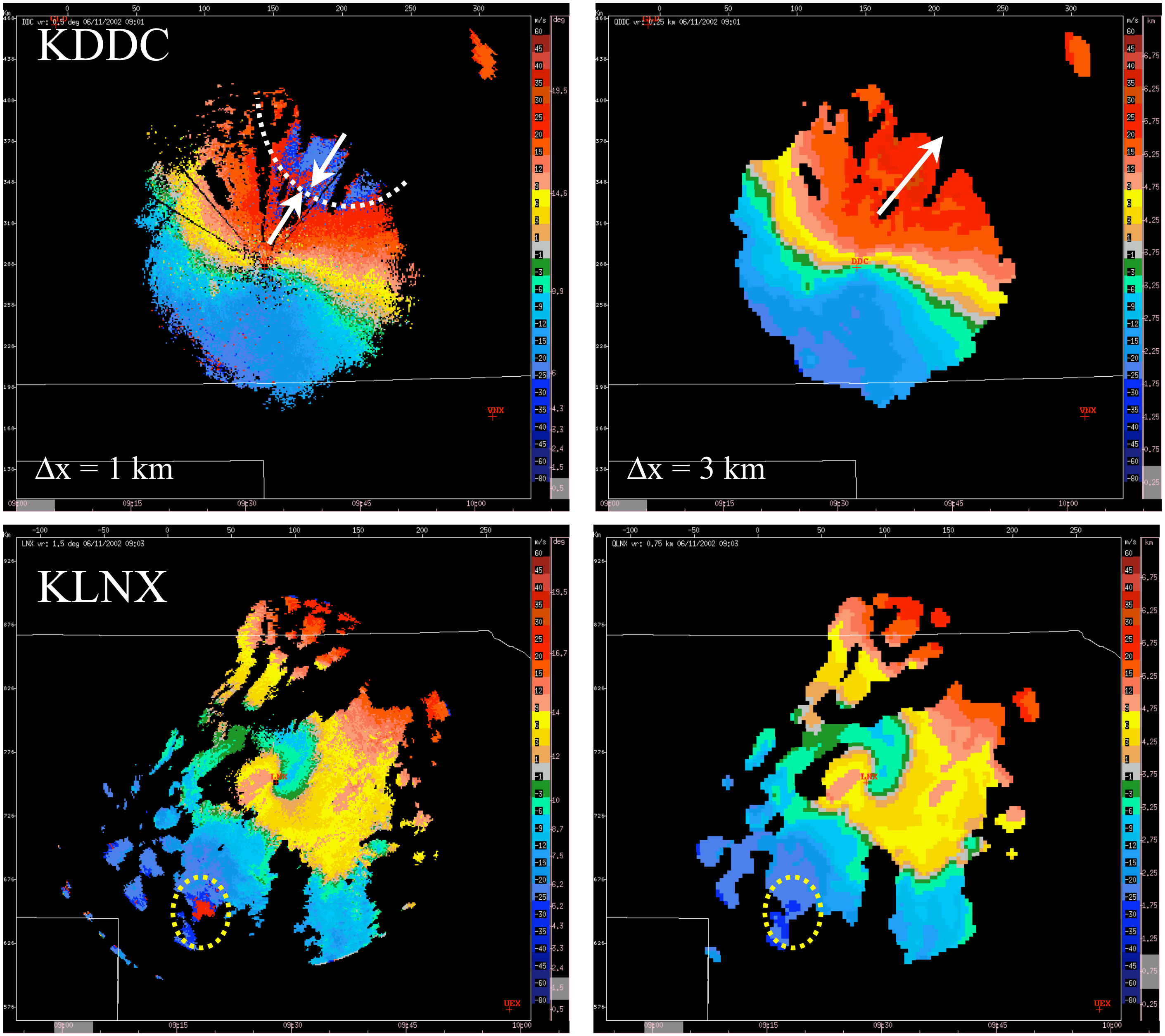
- An example: VDRAS preprocessor
- Input: griddid data at elevation angles
- Eliminate ground-clutter contamination
  - ✓ $v_r < 0.1\ ms^{-1}$
- Remove noises
  - ✓ Remove data with high local variance of v_r and reflectivity
    - $> 60\ m^2s^{-2}$ / $150\ dbZ^2$ (empirical values) in 3×3 grid points
  - ✓ Filter out isolated and questionable velocities
    - 3×3 filter (Bargen and Brown 1980)
      - If more than 3 of its 8 neighboring are missing, it is assigned a missing value

Radar data preprocessing

- Dealias
  - ✓ 1st step: Compare with a reference wind from model run (automatic)
  - ✓ 2nd step: Compare with local average wind (automatic)
  - ✓ 3rd step: Examine velocity at each elevation angle (manual)
- Fill missing data
  - ✓ 9×9 grid points, more than 20 grid points in at least 2 quadrates
- Interpolate data to the same resolution as model runs (3 km)
  - ✓ Bi-linear interpolation to 3×3 km on elevation angles
- Final output
  - ✓ Radial velocity, reflectivity and their errors
    - Error: standard deviation from values at 3×3 grid points
    - Min/Max radial velocity error is 1.0/10.0 ms^{-1}

Radar data preprocessing

20020611 09UTC



Radial velocity de-aliasing

Data format

TOTAL RADAR (14X, I3) – FMT = (A14,I3)

#--

Head record for specific Radar information (site, lat0, lon0, elv, date, # of data locations, max_levs)

– FMT = (A5,2X,A12,2(F8.3,2X),F8.1,2X,A19,2I6)

#--

Head record for the specific location (FM-128 RADAR, date, lat, lon, elv, levs)

-- FMT=(A12,3X,A19,2X,2(F12.3,2X),F8.1,2X,I6)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

……………………………………………………………………………………

– FMT=(3X,F12.1,2(F12.3,I4,F12.3,2X))

Head record for specific Radar information (site, lat0, lon0, elv, date, # of data locations, max_levs)
#--

Head record for the specific location (FM-128 RADAR, date, lat, lon, elv, levs)
Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)
Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)
……………………………………………………………………………………

Data format

```
TOTAL RADAR =   2
#-----------------------------------------------------------------------------#

RADAR        JINDO 126.328    34.471     499.0  2002-08-31_00:00:00  5706     9
#-----------------------------------------------------------------------------#
FM-128 RADAR   2002-08-31_00:00:00       34.314       124.003     499.0       2
        3803.5           7.918    1           0.500          17.704    1           1.125
        7480.6 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
FM-128 RADAR   2002-08-31_00:00:00       34.360       124.002     499.0       2
        3795.2           7.125    1           0.500          18.214    1           1.160
        7467.1 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
FM-128 RADAR   2002-08-31_00:00:00       34.405       124.000     499.0       2
        3790.2           6.714    1           0.598          14.864    0           0.707
        7459.0 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
FM-128 RADAR   2002-08-31_00:00:00       35.275       123.974     499.0       2
        4325.9           4.118    0           0.500          16.650    0           3.959
        8315.9 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
.....................................................................................................................................

RADAR        JINDO 126.328    34.471     499.0  2002-08-31_00:00:00  5706     9
#-----------------------------------------------------------------------------#
FM-128 RADAR   2002-08-31_00:00:00       34.314       124.003     499.0       2
        3803.5           7.918    1           0.500          17.704    1           1.125
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        3795.2           7.125    1           0.500          18.214    1           1.160
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FM-128 RADAR   2002-08-31_00:00:00       35.275       123.974     499.0       2
        4325.9           4.118    0           0.500          16.650    0           3.959
        8315.9 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
.....................................................................................................................................
```

Namelist

- In the namelist.input, the following additions should be made for radar data assimilation:

&wrfvar2
CALC_W_INCREMENT = T (to have w increments)

&wrfvar4
USE_RADAROBS = T (to assimilate radar data)
USE_RADAR_RV = T (to assimilate radial velocity)
USE_RADAR_RF = T (to assimilate reflectivity)

Linking the radar observation file

- In the run working directory, please link the radar observation file.

  ln -sf /ptmp/hsiao/tutorial08/ob.radar ./test/ob.radar

  – This is the only additional dataset you should include for radar data assimilation. Other input files for WRF-Var are the same as conventional data assimilation.

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Summary

- The WRF 3D-Var with Doppler radar data assimilation showed positive impact, and was implemented in KMA operational numerical weather prediction in Korea. However, we found several issues to work on in order to improve the capability of the system:

  - Latent heat release with reflectivity assimilation - Reflectivity assimilation not only changes hydrometeors, but it also has direct impact on vertical velocity and temperature by including latent heat release in 3D-Var constraint.

  - More sophisticated microphysics - The tangent linear and adjoint of WSM6 microphysics are coded. We will implement them in WRF 3D-Var to have analysis of ice-phase hydrometeors with assimilation of reflectivity data. The TGL and ADJ codes will also be used in WRF 4D-Var.

  - Implementation of digital filtering with rapid update cycling of radar data in WRF 3D-Var. WRF 3D-Var analysis can still have spin-up problem. DFI can alleviate the problem.

Summary

- Doppler radar data assimilation using WRF 4D-Var
  - WRF 3D-Var Doppler radar data assimilation shows promises. However, studies using WRF 4D-Var for radar data assimilation should be our major focus in the next several years.
  - There are several scientific studies and technical developments for WRF 4D-Var Doppler radar data assimilation.
    - Incremental or non-incremental approach?
    - Control variables change?
    - Coding the tangent linear and adjoint of sophisticated microphysics schemes and included in WRF 4D-Var.
- Doppler radar data assimilation using WRF En4D-Var
  - It uses flow-dependent background error covariance matrix constructed by ensemble forecasts and performs 4D-Var optimization.
  - It avoids the tangent linear and adjoint so that it can be easily implemented.

Thanks for your attention

Some references with Doppler radar data assimilation:

- Xiao, Q., Eunha Lim, D.-J. Won, J. Sun, W.-C. Lee, M.-S. Lee, W.-J. Lee, J. Cho, Y.-H. Kuo, D. Barker, D.-K. Lee, and H.-S. Lee, 2008: Doppler radar data assimilation in KMA's operational forecasting. *Bull. Amer. Meteor. Soc.*, **89**, 39-43.
- Xiao, Q., and J. Sun, 2007: Multiple radar data assimilation and short-range quantitative precipitation forecasting of a squall line observed during IHOP_2002. *Mon. Wea. Rev.*, **135**, 3381-3404.
- Xiao, Q., Y.-H. Kuo, J. Sun, Wen-Chau Lee, D. M. Barker, and Eunha Lim, 2007: An approach of radar reflectivity data assimilation and its assessment with the inland QPF of Typhoon Rusa (2002) at landfall. *J. Appl. Meteor. Climat.*, **46**, 14-22.
- Xiao, Q., Y.-H. Kuo, J. Sun, Wen-Chau Lee, Eunha Lim,Y.-R. Guo , and D. M. Barker, 2005: Assimilation of Doppler radar observations with a regional 3D-Var system: Impact of Doppler velocities on forecasts of a heavy rainfall case. *J. Appl. Meteor,* **44**, 768-788.