# Doppler Radar Data Assimilation with WRF-Var

Juanzhen Sun and Mei Xu, NCAR/MMM/RAL

Email: sunj@ucar.edu

# Outline:

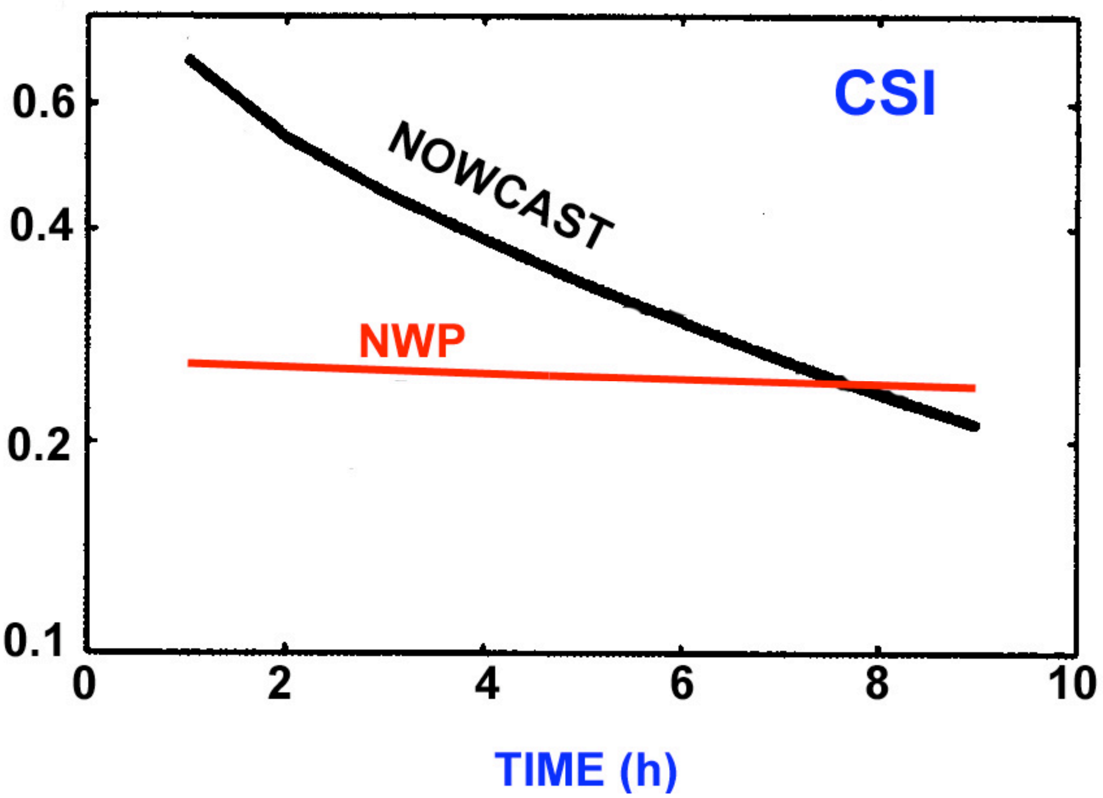
- Introduction
  - Background and motivation
- Radar observations
  - Data
  - Quality issues
- Methodology
  - Observation operator
  - Added increment variables
- Code setup for radar DA
- Ongoing and future development

# 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)

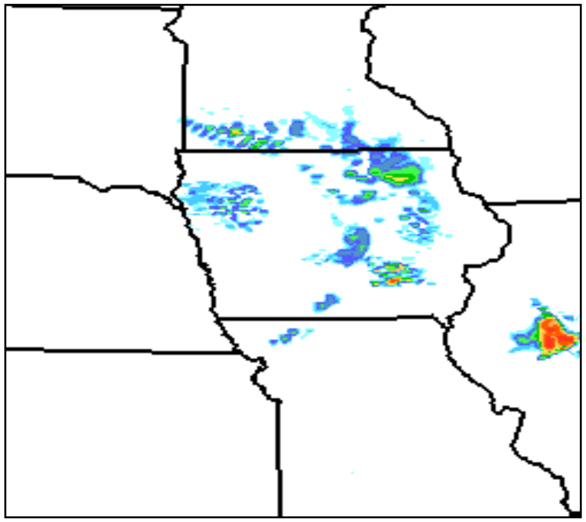
# Example of model spin-up from BAMEX

Without high-resolution initialization:

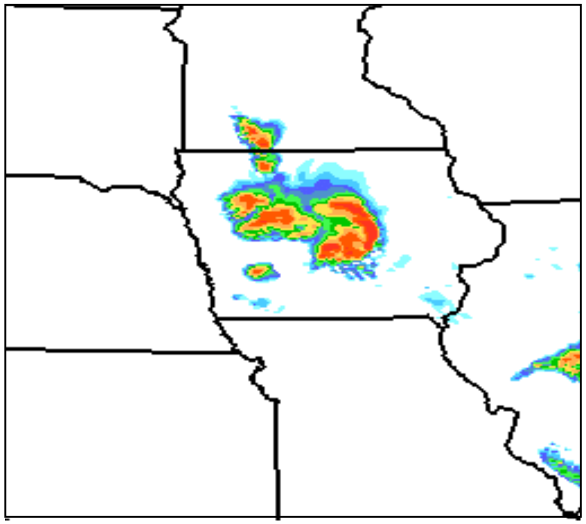
- A model can takes a number of hours to spin up.
- Convections with weak synoptic-scale forcing can be missed.

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

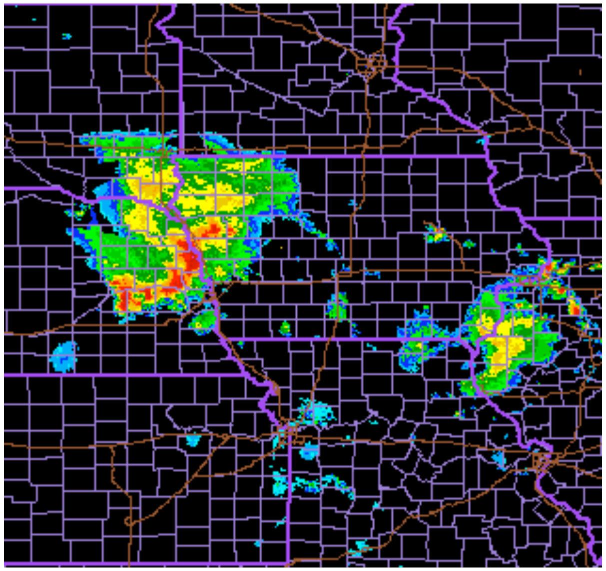
6h forecast (July 6 2003)



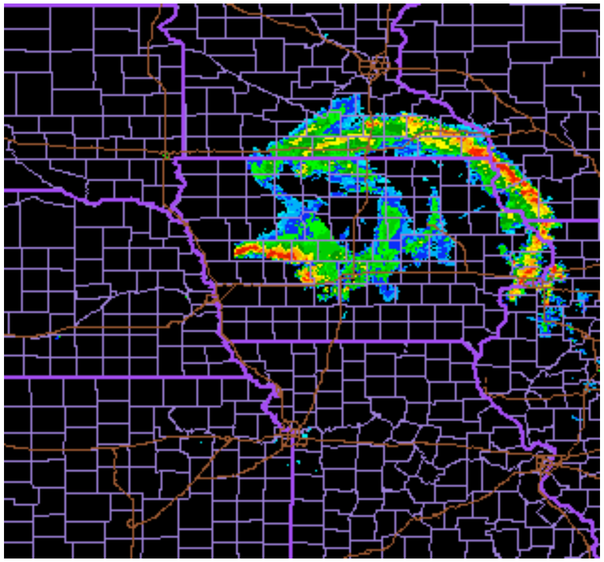
12h forecast



Radar observation at 0600 UTC

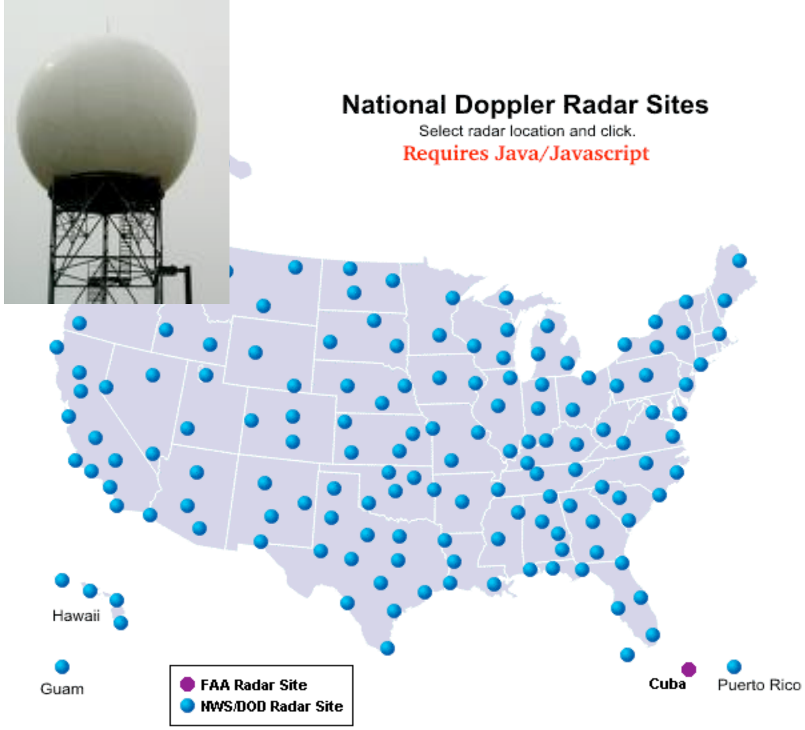


at 1200 UTC



# 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.

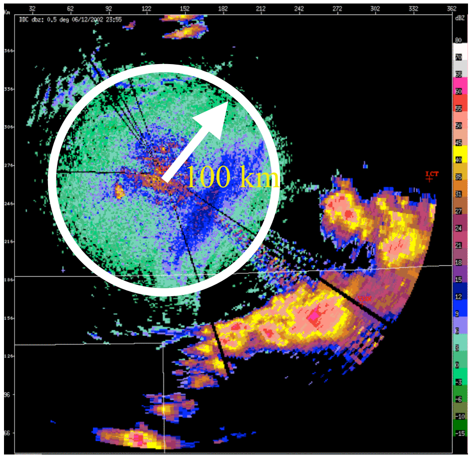
# Doppler radar observations

- The NEXRAD level II data are volumetric radial velocity and reflectivity data with some basic quality control
- High spatial (250m-1km) and temporal resolution (5-10 min), but coverage is limited to regions with reflectors

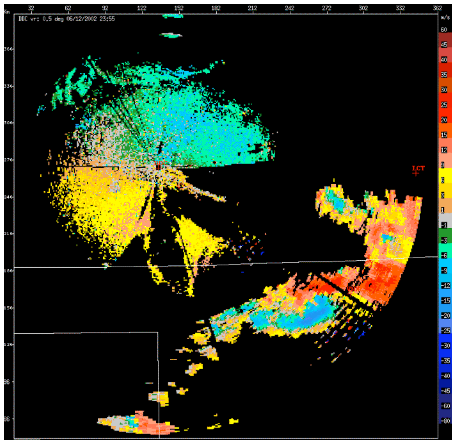
  - Clear-air echo from insects in boundary layer with a typical range of 60-100km

  - Storm echo from hydrometeors in precipitation region
- Huge amount of data (in a storm mode, the estimate number of data is ~3 million/ 5minute from one radar

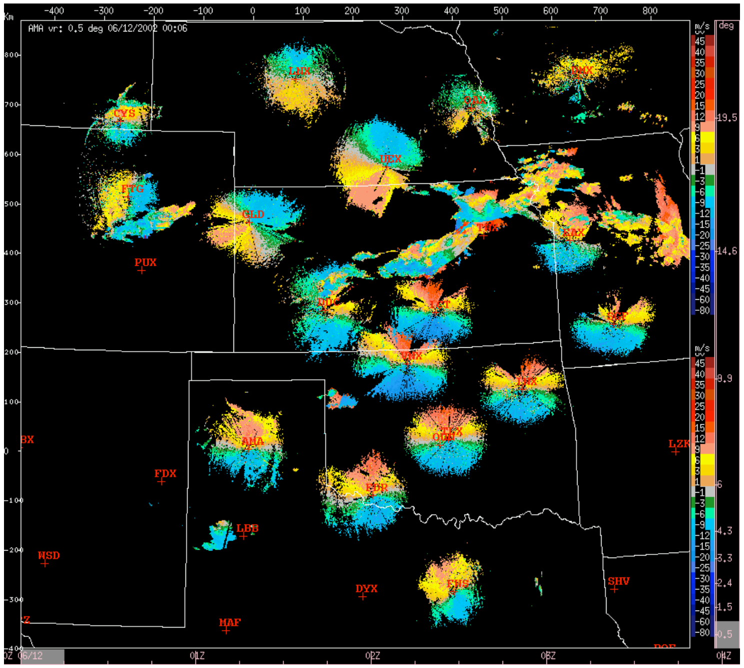
KDDC Reflectivity



KDDC radial velocity

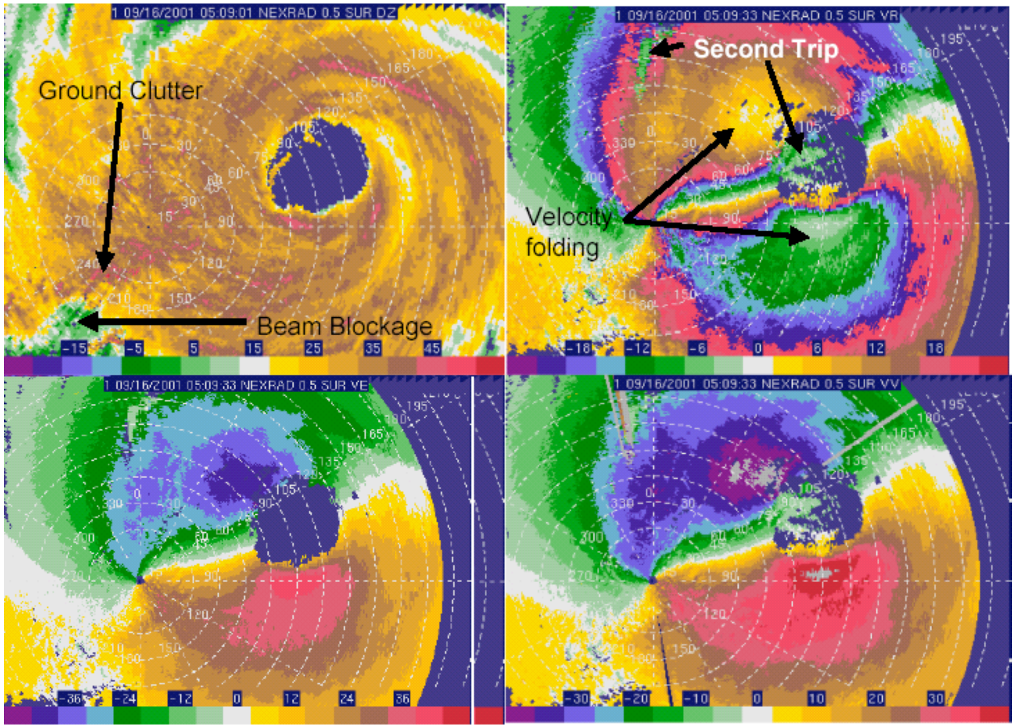


Radial velocity from multiple radars

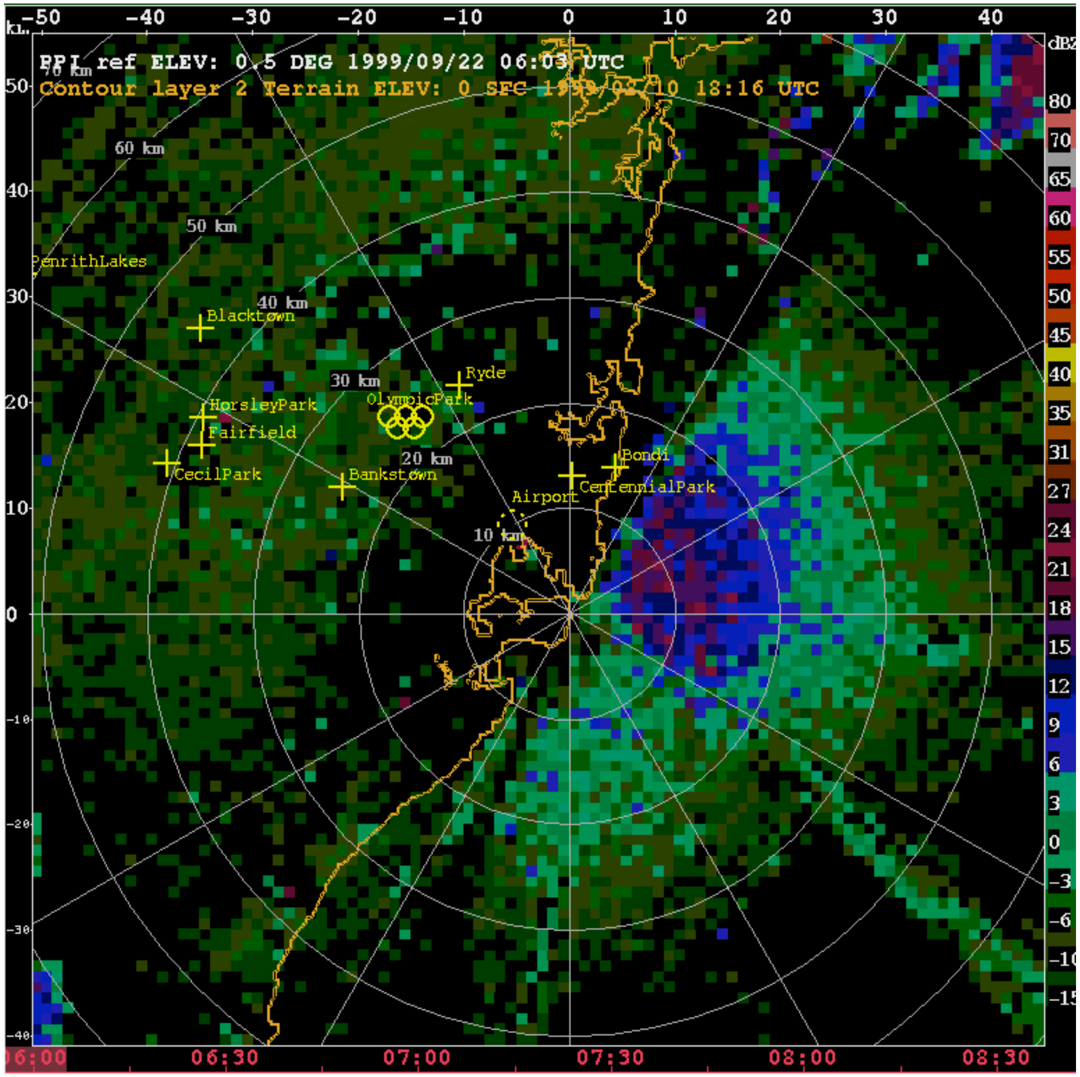


# Doppler radar observations

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

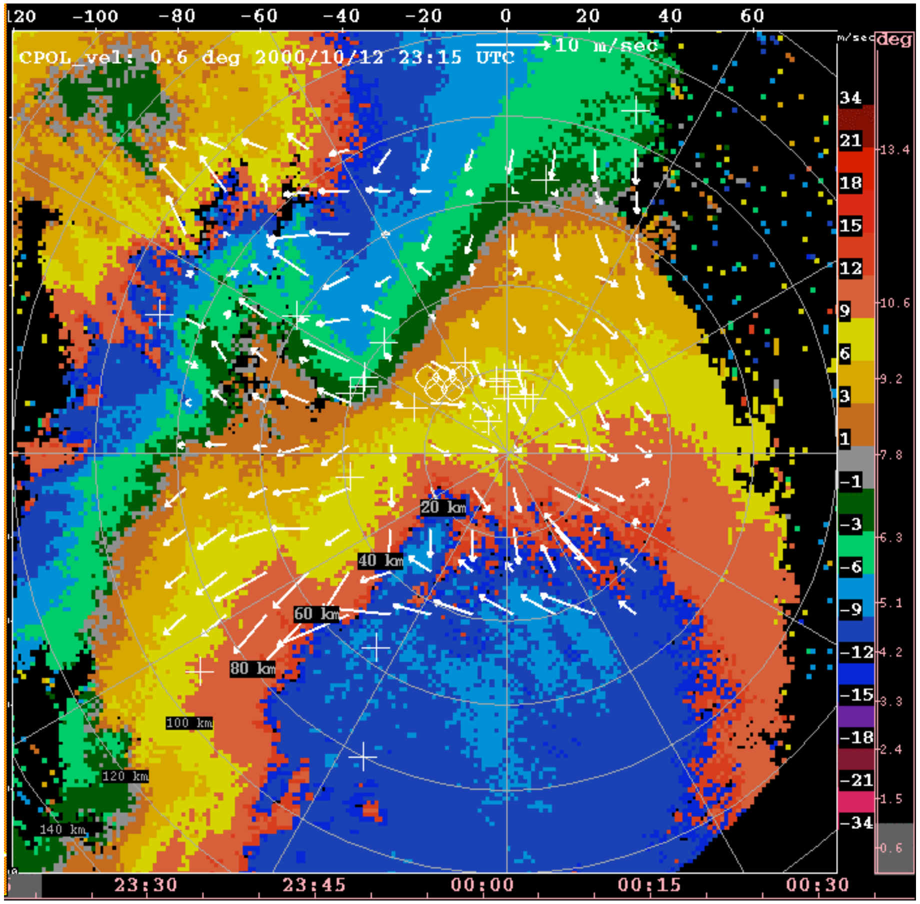


# Doppler radar observations

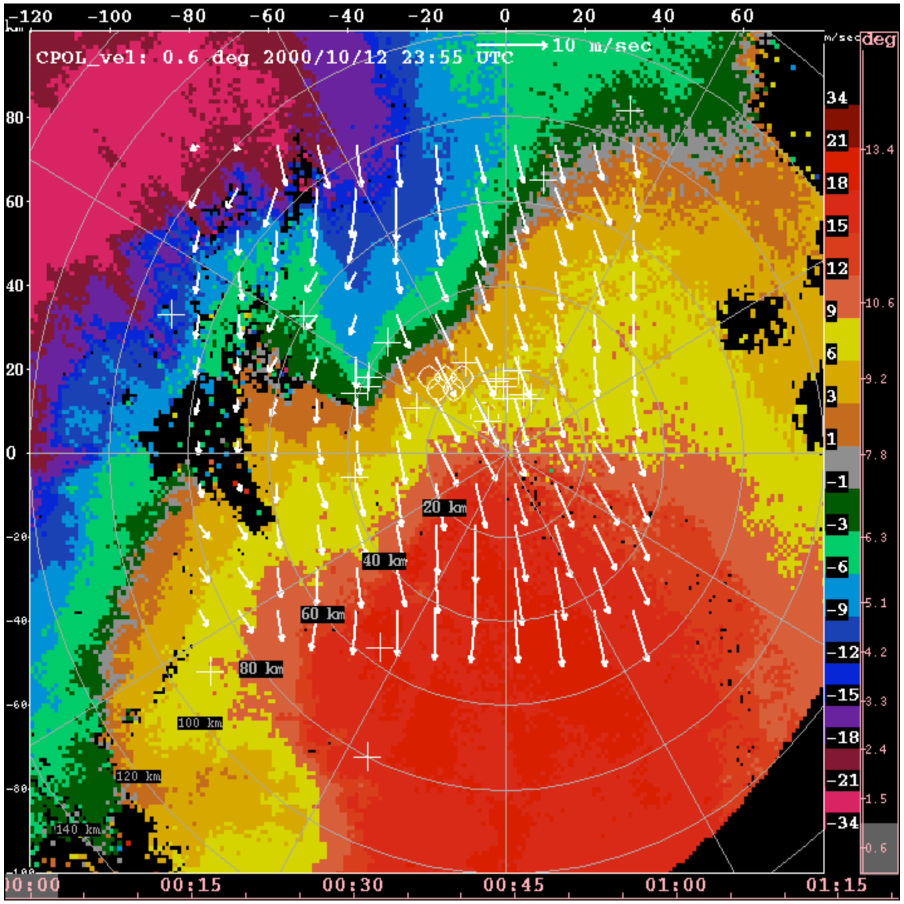


Sea clutter: Radar echo has vertical gradient near the surface.

# Doppler radar observations



Aliased velocities



De-aliased velocities

# 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, and other noises
  - 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:
  - VDRAS: Variational Doppler Radar Analysis System
  - VDRAS is not released to the public
- There is no standard software included in WRF-VAR

# Cost Function

- Cost function

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

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

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

- The preconditioning control variables are **v** : ($\psi'$, $\chi_u'$, $T'_u$, $p'_{su}$, and $r'_s$).
- The analysis increments **X**' are obtained through a series of transform: **X**'=***U*v**=$\boldsymbol{U}_p\boldsymbol{U}_v\boldsymbol{U}_h$**v**.
- 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 ($\psi'$, $\chi_u'$, $T'_u$ , $p'_{su}$, and $r'_s$) to model variables ($u'$, $v'$, $T'$, $p'$, $q'$)

# 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

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

# Increment variables w’ and $q_r$’

- **WRF 3D-Var**
  - Control variables ($\psi'$, $\chi_u'$, $T'_u$, $p'_{su}$, $r'_s$) <=> 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.
- **w’ and $q_r$’ are obtained through diagnostic relations**

# W Increments in WRF 3D-Var

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

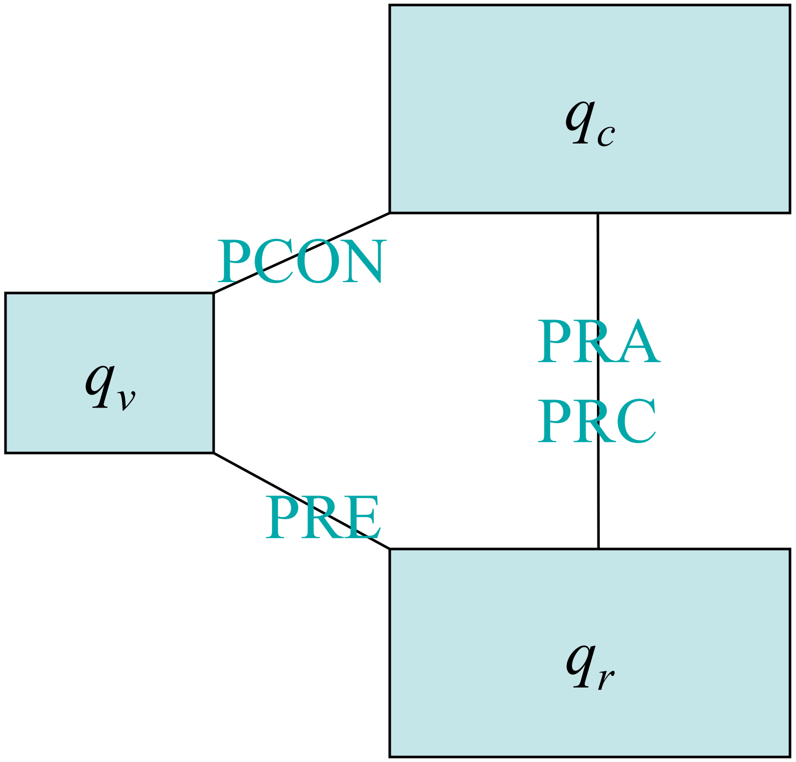
$$\gamma \bar{p} \frac{\partial w'}{\partial z} = -\gamma p' \frac{\partial \bar{w}}{\partial z} - \gamma \bar{p} \nabla \cdot \vec{v}'_h - \gamma p' \nabla \cdot \vec{\bar{v}}_h - \vec{\bar{v}}_h \nabla p'$$

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

  - ➢ 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.

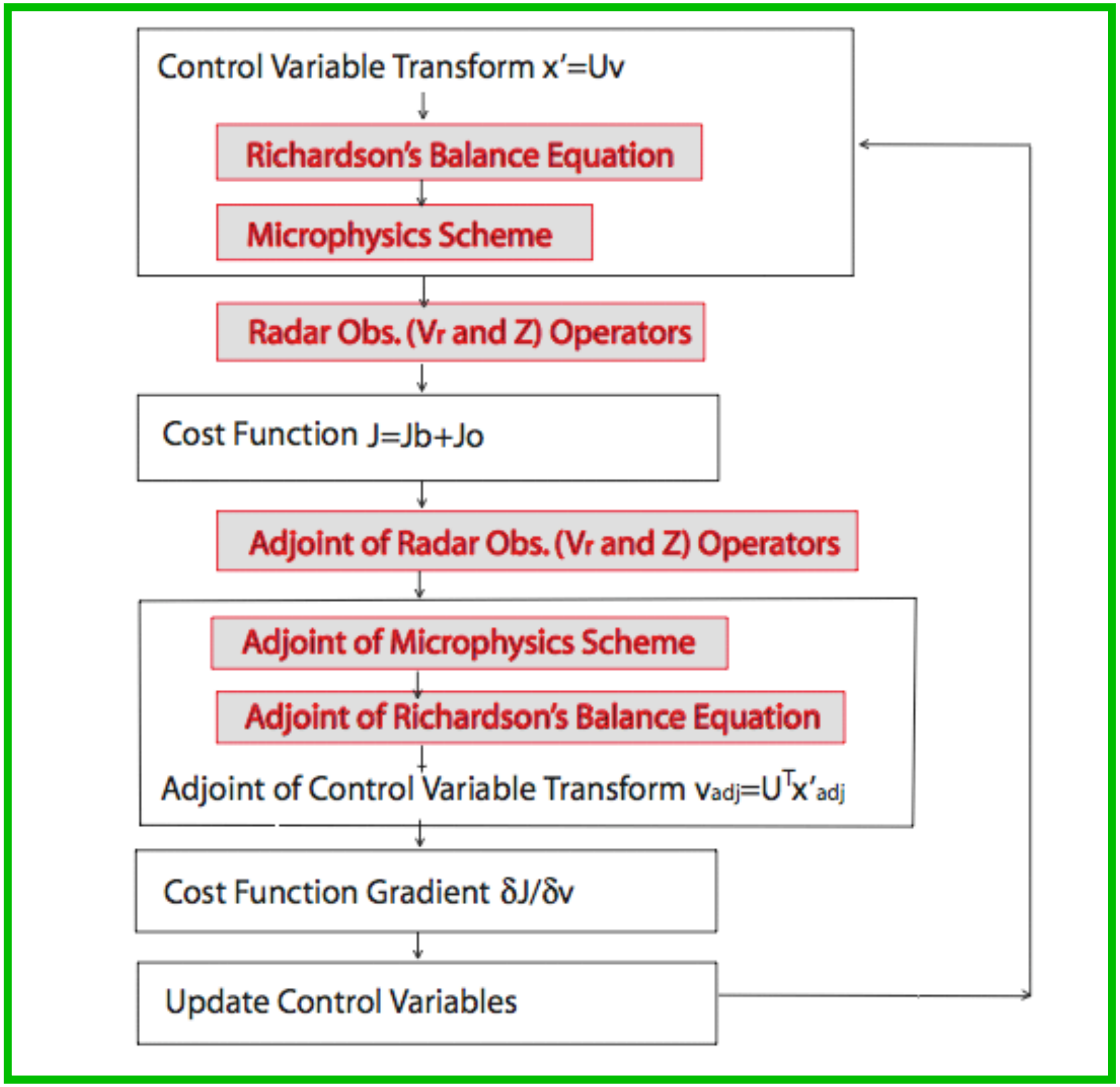
# Hydrometeor increments in WRF 3D-Var

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

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



Control Variable Transform $x'=Uv$

Richardson's Balance Equation

Microphysics Scheme

Radar Obs. ($V_r$ and Z) Operators

Cost Function $J=Jb+Jo$

Adjoint of Radar Obs. ($V_r$ and Z) Operators

Adjoint of Microphysics Scheme

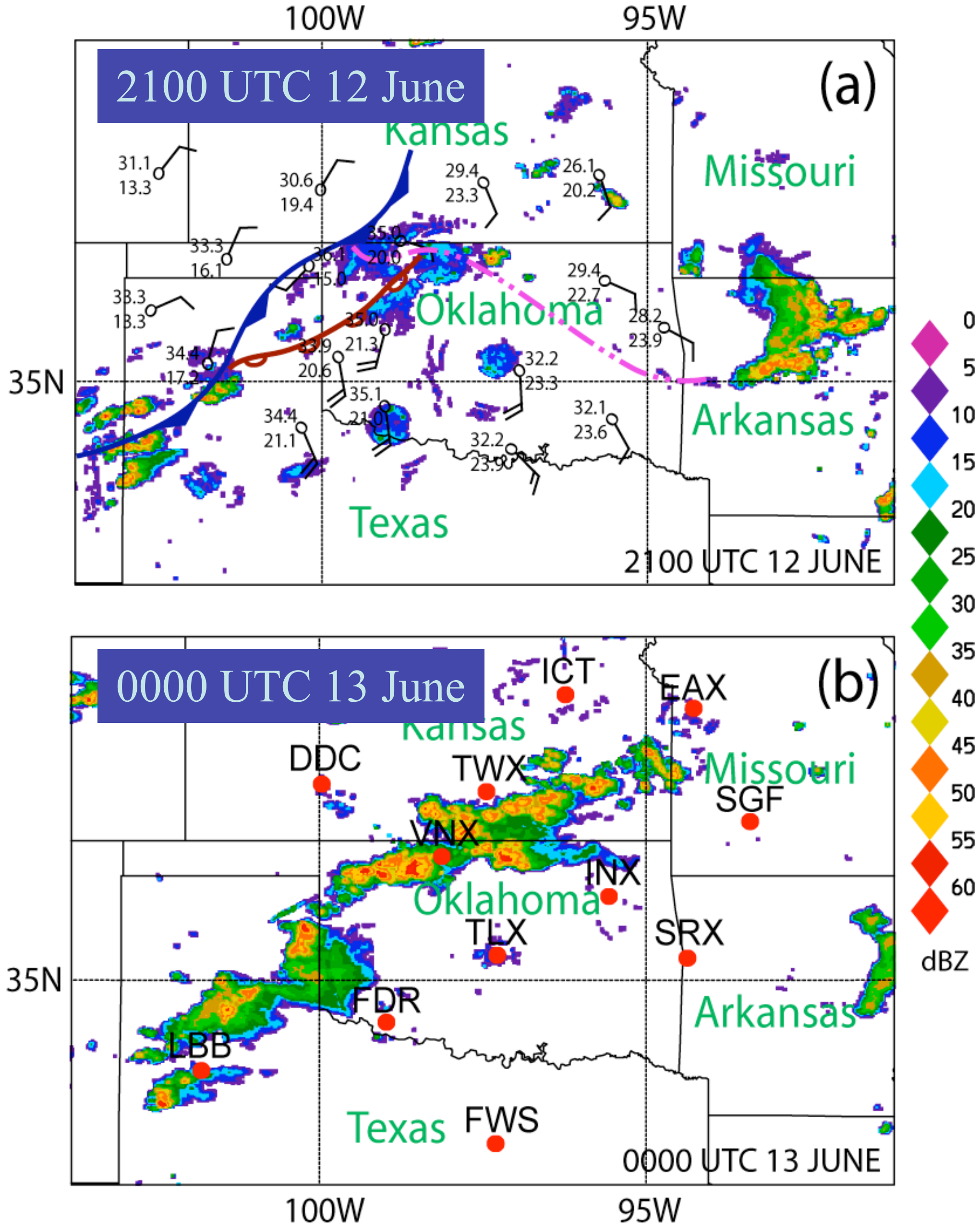
Adjoint of Richardson's Balance Equation

Adjoint of Control Variable Transform $v_{adj}=U^T x'_{adj}$

Cost Function Gradient $\delta J/\delta v$

Update Control Variables

# 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.

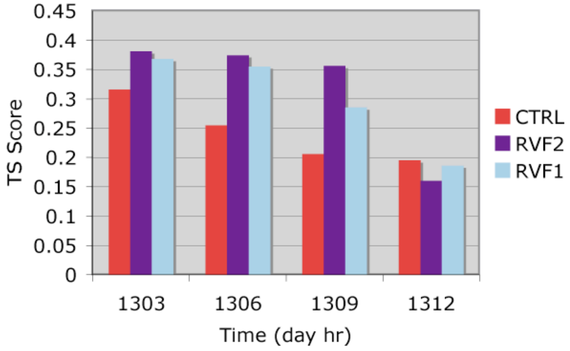
# QPF of an IHOP_2002 Squall Line Case

Red:
CTRL

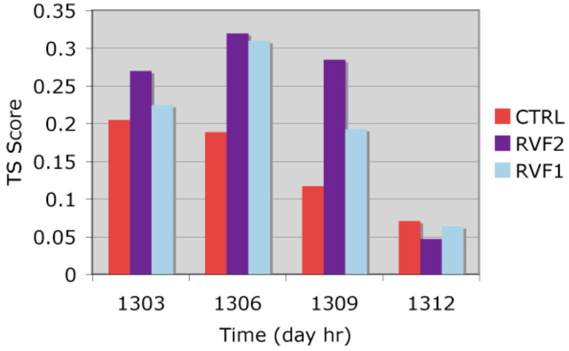
Purple:
Cycling

Light blue:
No cycling

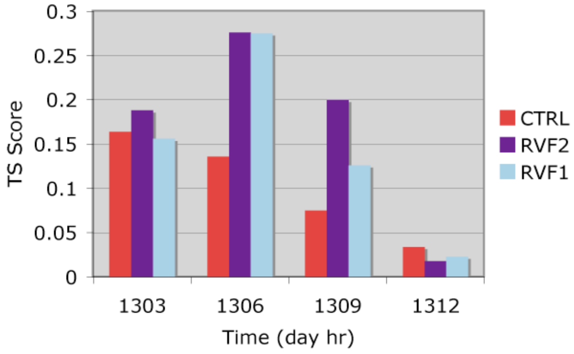
(a) Threshold = 1 mm



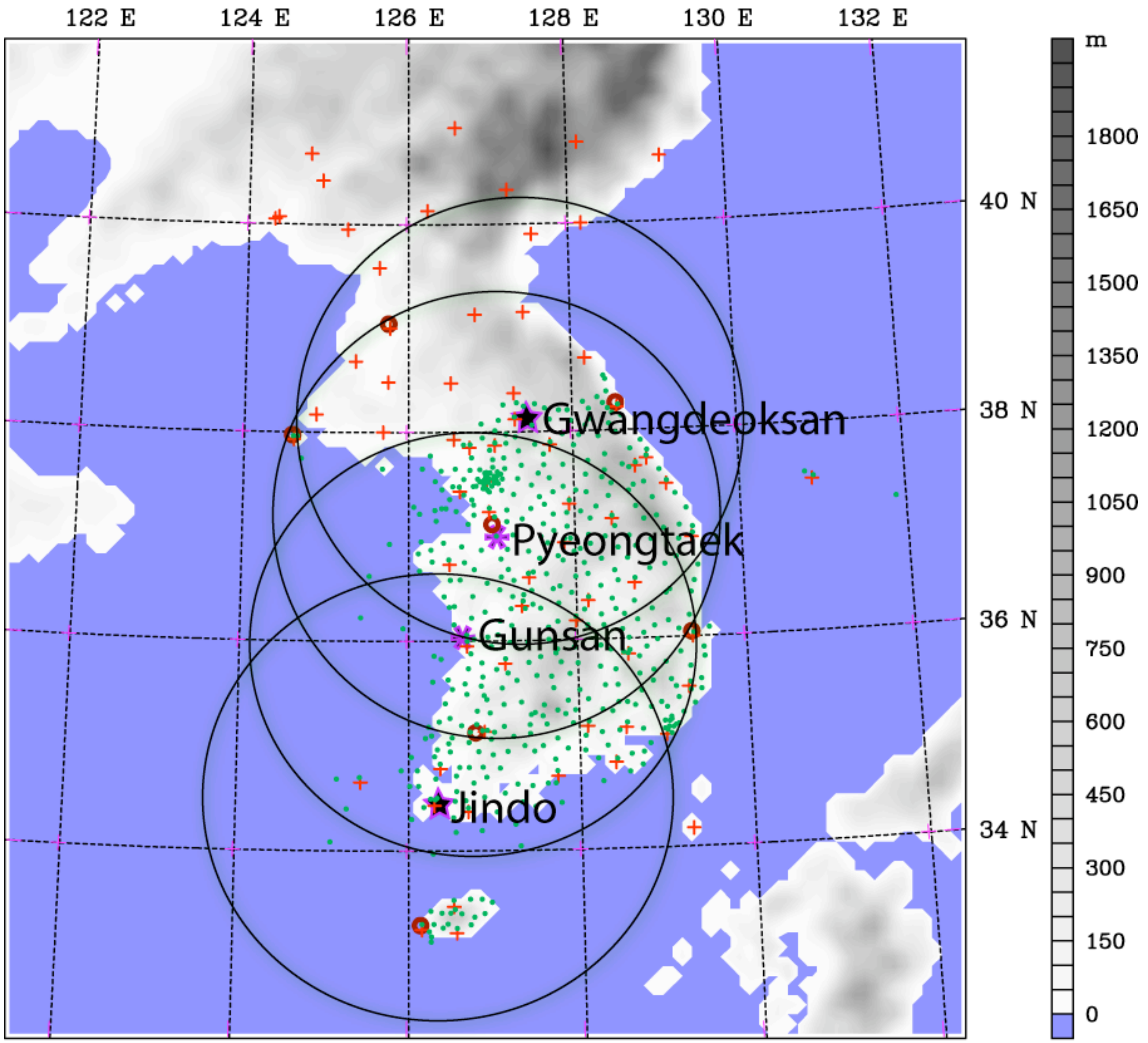
(b) Threshold = 5 mm



(c) Threshold = 10 mm



# KMA radars used in 3D-Var analysis

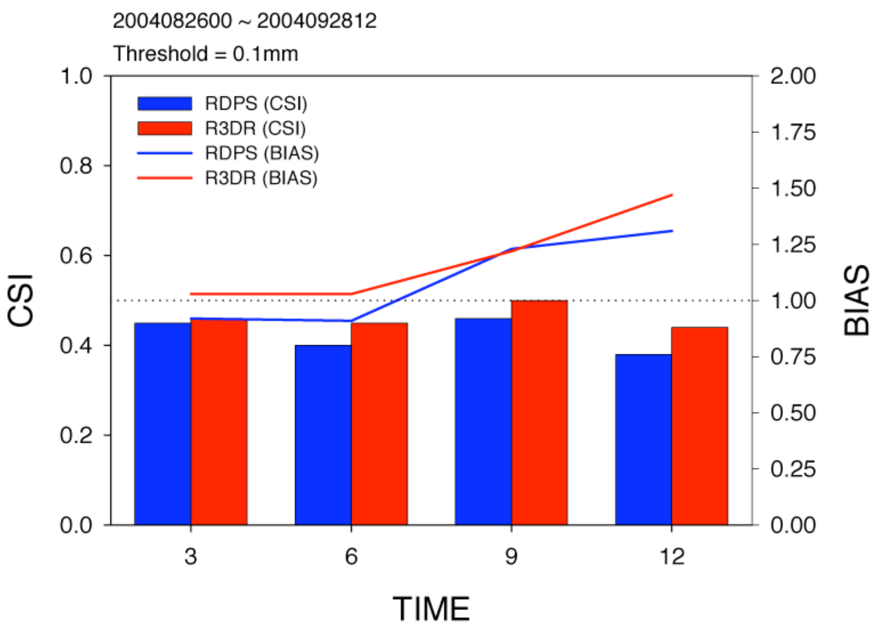


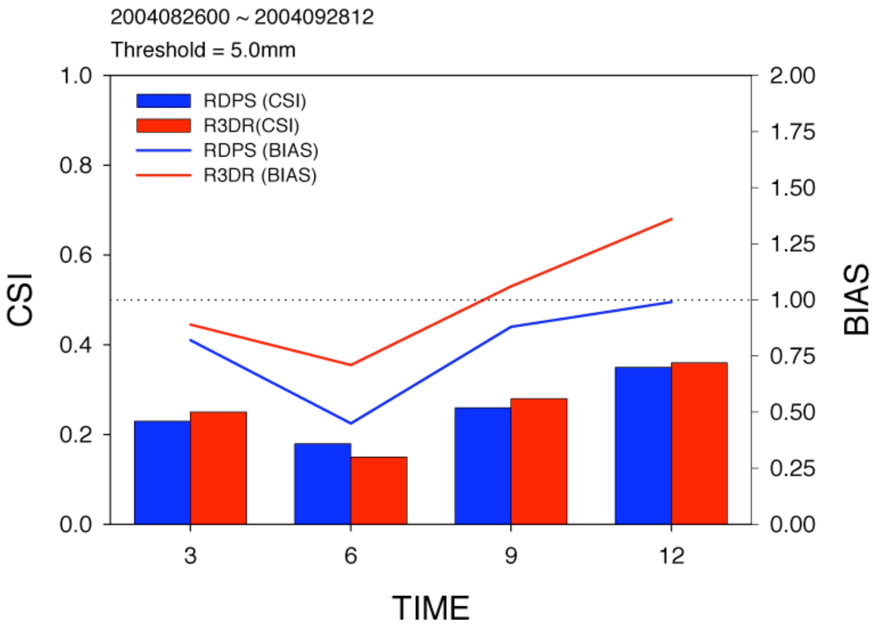
Doppler radar data from 4 radar sites were included in assimilation In 2006

# 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.





# Sample data

```
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

.........................................................................................................................................

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
.........................................................................................................................................
```

total number of radars

number of profiles for the radar

head record for radar 1

header for profile 1

data at a specific level

number of levels in the profile

bad data flag

head record for radar 2

# 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 in run directory

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

```
ln  -sf  /ptmp/tutorial2010/ob.radar  ob.radar
```

1. This is the only additional dataset that is required for radar data assimilation.  Other input files to WRF-Var for radar data assimilation are the same as for conventional data.

2. The file name “ob.radar” is defined in da_setup_structures/da_setup_obs_structures_ascii.inc

# Namelists

- In the namelist.input file, set the following for radar data assimilation.

&wrfvar2
calc_w_increment=T, (to include w increments)

&wrfvar4
use_radarobs=T, (to assimilate radar data)
use_radar_rv=T, (to assimilate radial velocity)
use_radar_rf=T, (to assimilation radar reflectivity)

# Namelists

- The O-B correlation lengths for radar data are typically smaller than the scale lengths derived via the “NMC-method. The use of shorter scale lengths are recommended. For example,

```
&wrfvar7
len_scaling1 = 0.1, # reduce psi length scale to 10%
len_scaling2 = 0.1, # reduce chi_u length scale to 10%
len_scaling3 = 0.1, # reduce T length scale to 10%
len_scaling4 = 0.1, # reduce q length scale to 10%
len_scaling5 = 0.1, # reduce Ps length scale to 10%
```

# Code directory

## WRFDA_V3.1.1/var/da/da_radar

- da_ao_stats_radar.inc
- da_calculate_grady_radar.inc
- da_check_max_iv_radar.inc
- da_get_innov_vector_radar.inc
- da_jo_and_grady_radar.inc
- da_max_error_qc_radar.inc
- da_oi_stats_radar.inc
- da_print_stats_radar.inc
- da_radar.f90
- da_radial_velocity_adj.inc
- da_radial_velocity.inc
- da_radial_velocity_lin.inc
- da_residual_radar.inc
- da_transform_xtoy_radar_adj.inc
- da_transform_xtoy_radar.inc

## WRFDA_V3.1.1/var/da/da_obs_io

- da_read_obs_radar.inc
- da_scan_obs_radar.inc

# Summary of Current WRF-VAR radar DA capability

- Assimilation of radial velocity
  - Observation operator
  - w' is obtained through Richardson equation
  - Tested on case studies and near-operational setting

- Assimilation of reflectivity
  - Observation operator
  - $q_r$' is diagnosed through warm rain microphysics
  - Impact is not as much as radial velocity

- Continuous cycling
  - Mostly run with cold start and 3 hourly cycle in the past
  - Needs more testing on more frequent cycling
    - > DFI or grid nudging

- Multiple outer loops
  - Works but may need more testing

# Ongoing and future development

3DVAR:

- Add the effect of diabatic heating
  - Cloud analysis as initial condition; or
  - Add an additional term in the Richardson equation; or
  - Add the diabatic heating in DFI
- $q_r$ as control variable
- Further testing of cycling and multiple outer loop using a consecutive period of data

# Ongoing and future development

4DVAR:

- Reflectivity data assimilation
  - Adjoint of microphysics - start from simple scheme
  - Control variables of microphysics

- Adjoint code optimization

- Multiple outer loop

- Continuous cycling

- Full-nonlinear 4DVAR for cloud scale

- Improvement of surface data assimilation

# Thanks for your attention

## Some references with WRF-VAR 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.
- Sugimoto, S., N. A. Crook, J. Sun, Q. Xiao, and D. Barker, 2008: An examination of WRF 3DVAR radar data assimilation on its capability in retrieving unobserved variables and forecasting precipitation through observing system simulation experiments. *Mon. Wea. Rev.,* 137, 4011-4029.