Doppler Radar Data Assimilation with WRFDA

Juanzhen Sun, NCAR

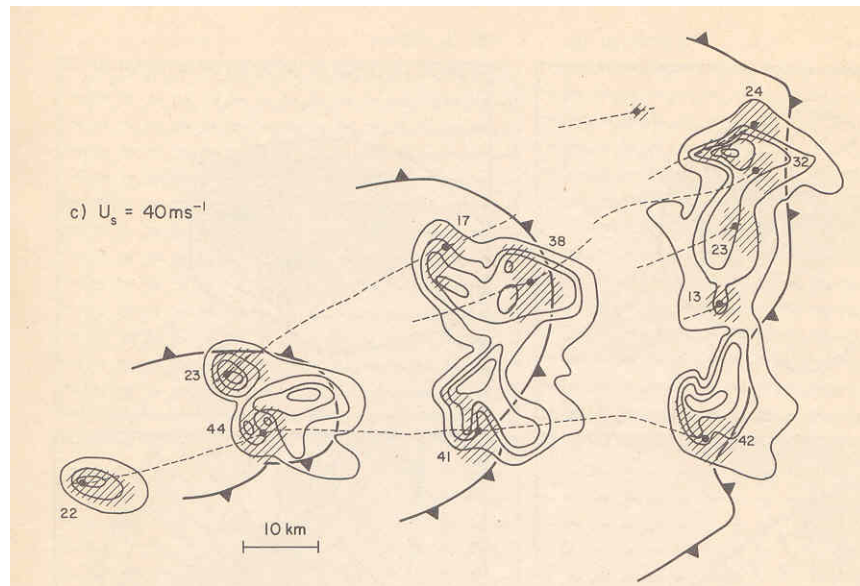
Email: sunj@ucar.edu

Outline

- **Introduction**
  - Review of radar DA
  - Examples of 3DVar radar DA
- **Radar observations and quality issues**
- **Methodology**
  - Observation operator
  - Control variables and increments
- **Procedure**
  - BES generation
  - Input format and configuration
  - Parameter tuning
- **Issues and ongoing development**

Cloud-scale modeling since 1960's

- Used as a research tool to study dynamics of moist convection
- Initialized by artificial thermal bubbles superimposed on a single sounding
- Rarely compared with observations

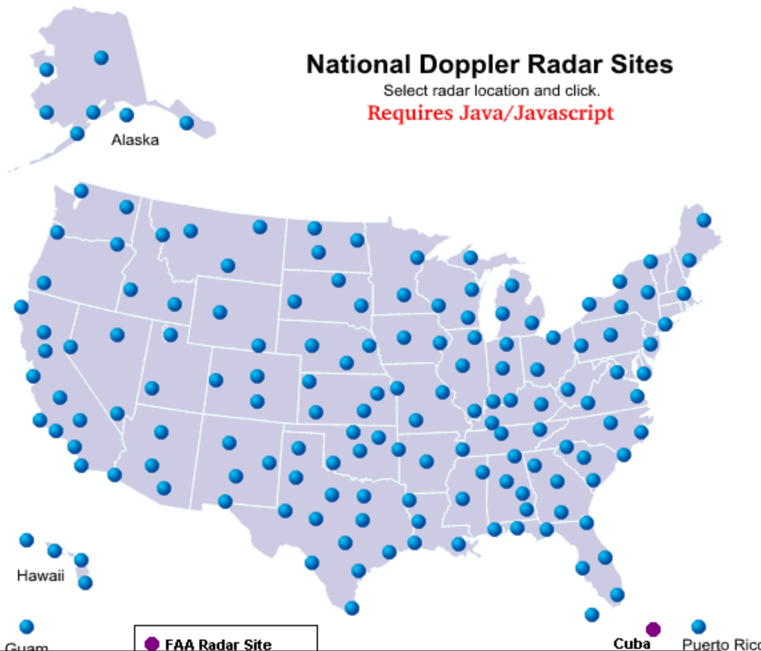


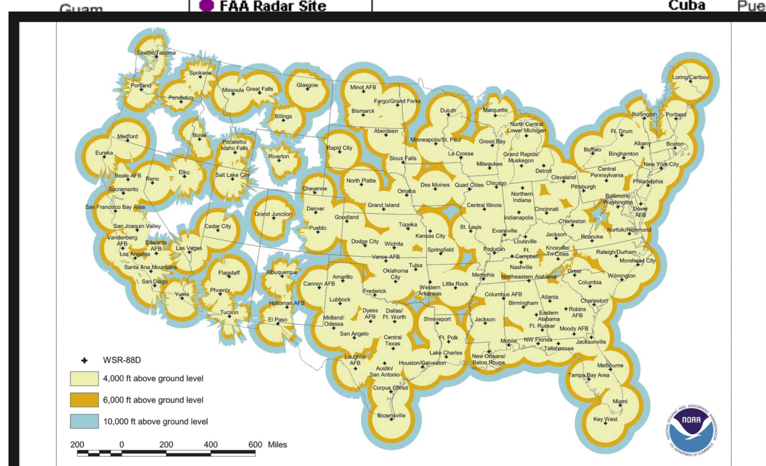
From Weisman and Klemp (1984)

NWP of thunderstorms - has its time come?

Lilly's motivating publication (1990)

- NEXRAD network
- Increasing computer power
- Advanced DA techniques
- Experience in cloud-scale modeling
- Increasing need for accurate forecast of precipitation timing & location
- The key is to initialize models with high-resolution radar data





Doppler weather radar coverage of CONUS at 4,000, 6,000, and 10,000 feet above radar ground elevation from the nationwide network of WSR-88Ds (Next Generation Weather Radars). (Courtesy of SRI International)

From 1990 to now

- Single Doppler retrieval (e.g., Sun et al. 1990)

- Assimilation into NWP models

  - Successive correction (LAPS, Albers 1995)
  - Newtonian nudging (Xu et al. 2004)
  - 3DVar (Xiao et al., 2005)
  - 4DVar (Sun and Crook, 1997)
  - EnKF (Snyder and Zhang, 2004)

- Impact studies on precipitation forecast

  - NCAR WRF (Xiao and Sun 2007)
  - CAPS ARPS (Hu et al., 2006)
  - JMA NHM (Kawabata et al. 2007)
  - UK Met Office Unified Model

Applications of radar data assimilation

- Improvement of cloud-permitting simulation and forecast
- Analysis and study of high impact weather
- Nowcasting
- Wind energy prediction
- Prediction of chemical dispersion

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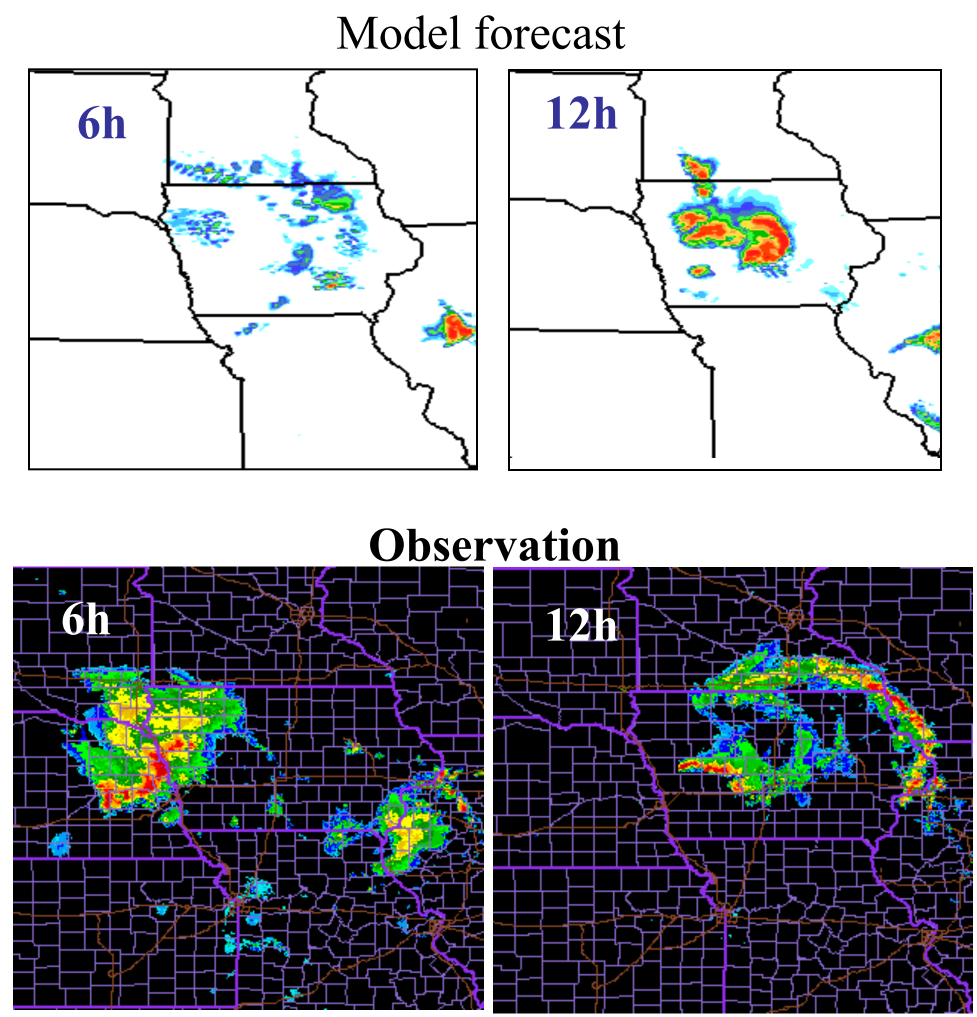
An example of model spin-up



Comparing radar DA with conventional DA

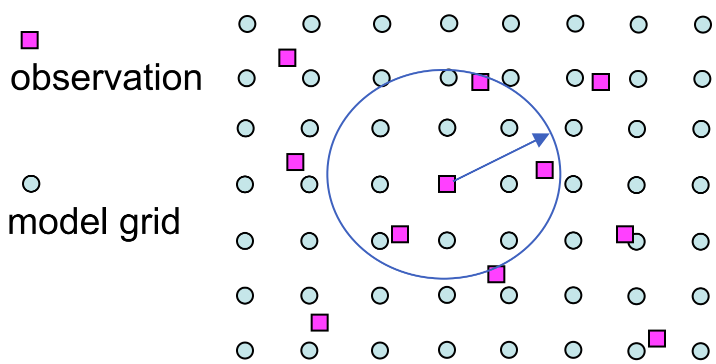
Conventional DA

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

Every variable (except for w) is observed

Optimal Interpolation

Balance relations



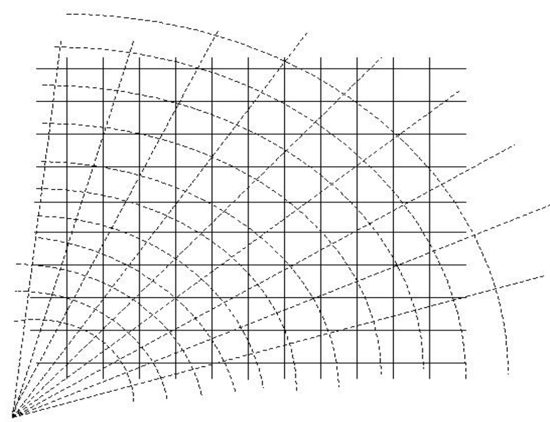
Radar DA

Obs. resolution ~ a few km -- equivalent to model resolutions

Only radial velocity and reflectivity are observed

Retrieval of the unobserved fields

Temporal terms essential



History of WRF-Var radar DA

- 2002-2005 Development of WRFDA 3DVar radial velocity data assimilation (Xiao et al. 2005)
- 2004-2007 Development of WRFDA 3DVar reflectivity data assimilation (Xiao et al. 2007)
- 2008 Operational testing and implementation at KMA (Xiao et al. 2008)
- 2005-now Impact studies with ground-based and airborne radars (Xiao and Sun 2006, Li et al., 2009)
- 2008-now Development and testing of WRFDA 4DVar radar data assimilation

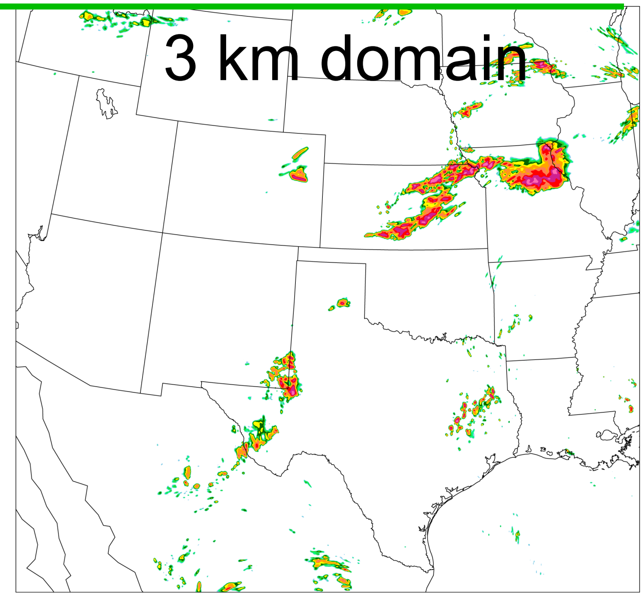
Impact of 3DVar radar DA with IHOP one week data

CTRL Baseline run initialized by ETA analysis MYJ PBL, Thompson microphysics

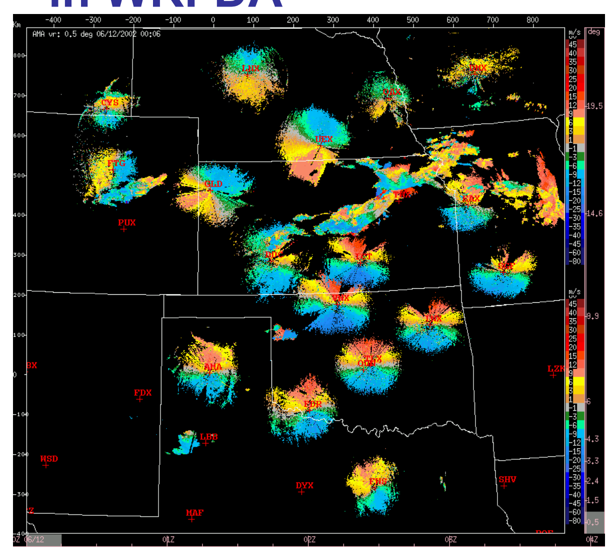
GFS Same as CTRL but initialized by GFS global analysis

WRFDA WRF 3DVAR with 3-hourly update cycle radial velocity data assimilation

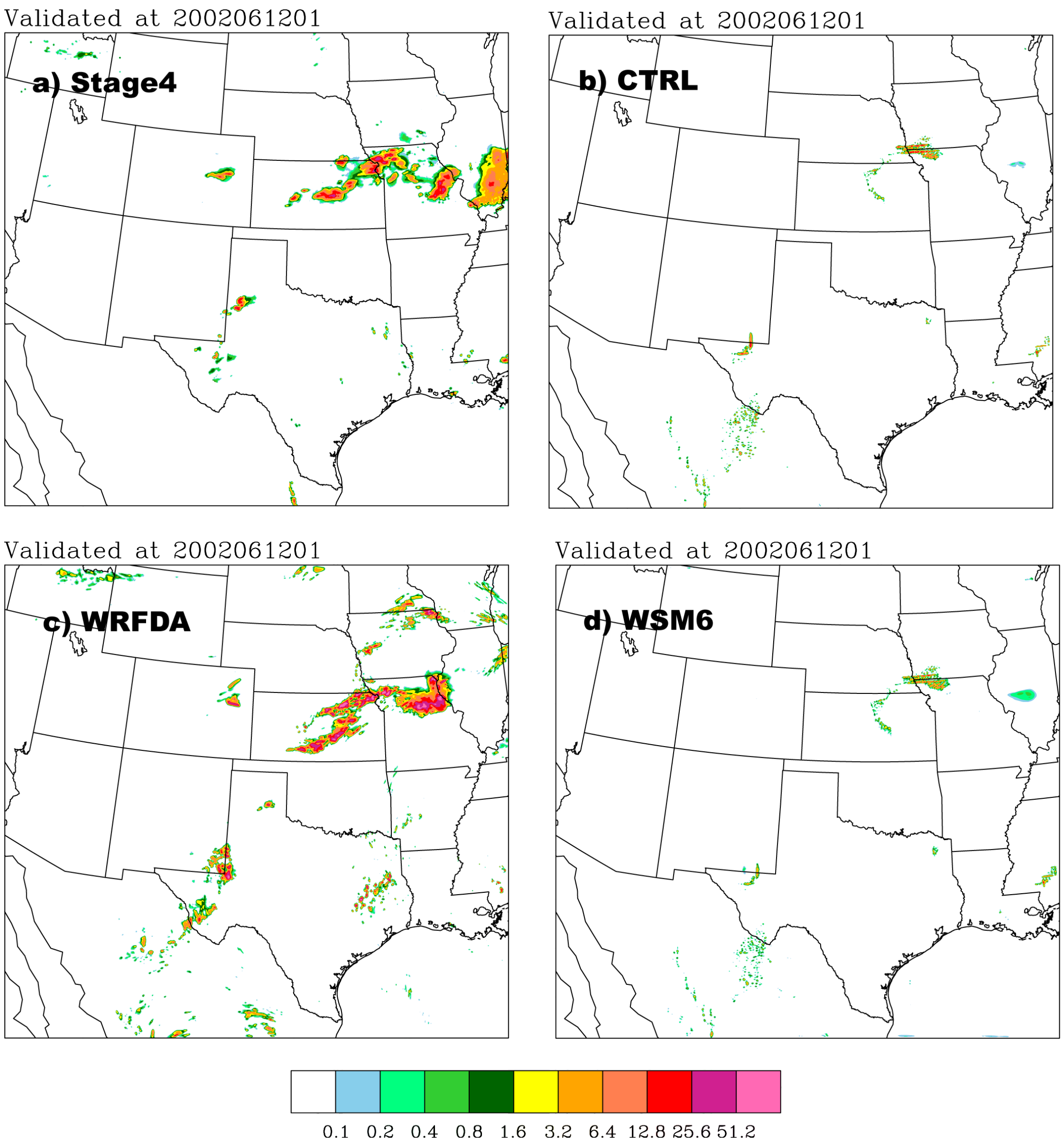
WSM6 Same as CTRL but with WSM6 microphysics



25 NEXRADs assimilated in WRFDA



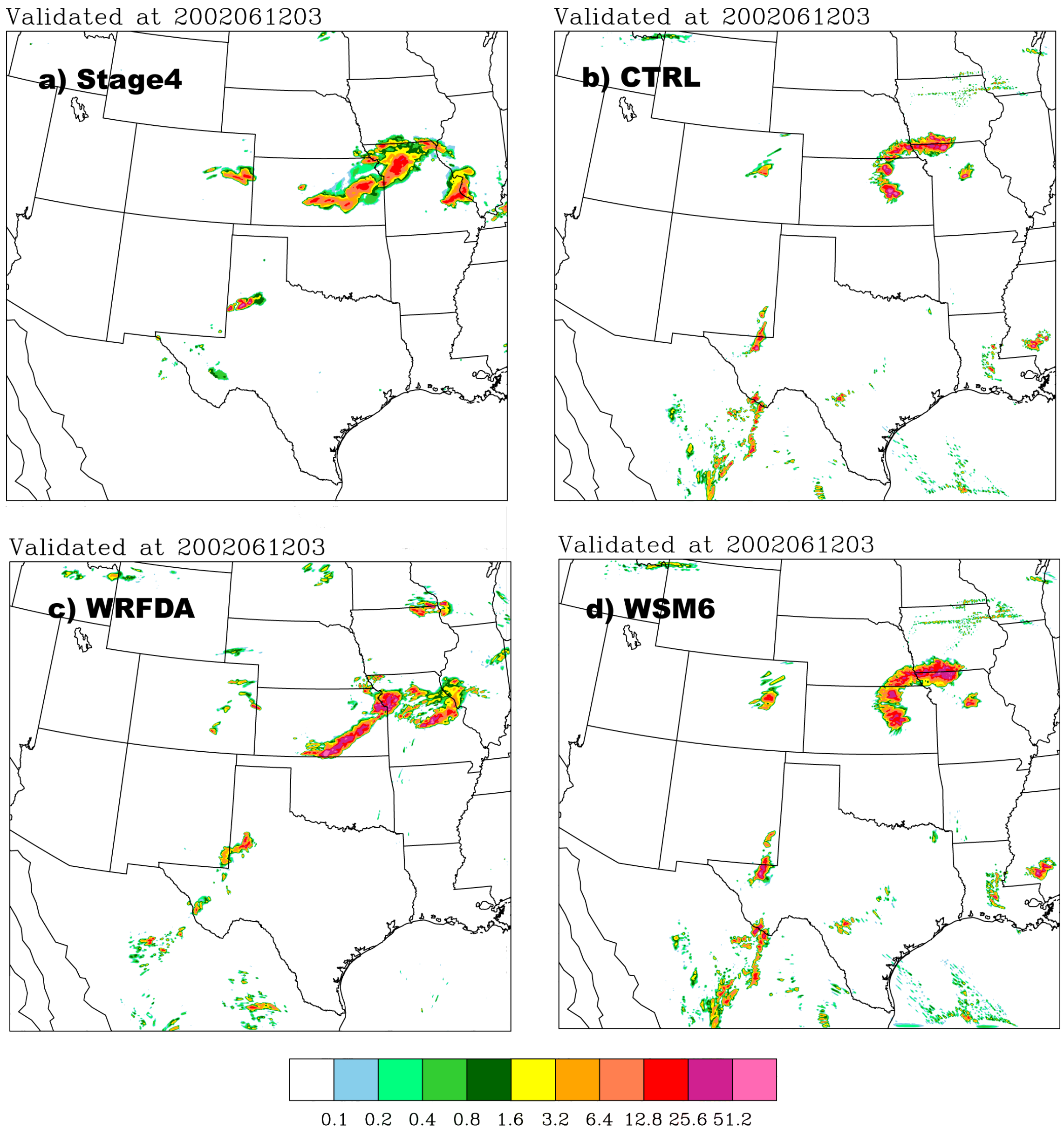
1-hour forecast of hourly precipitation valid at 01 UTC on June 12, 2002.



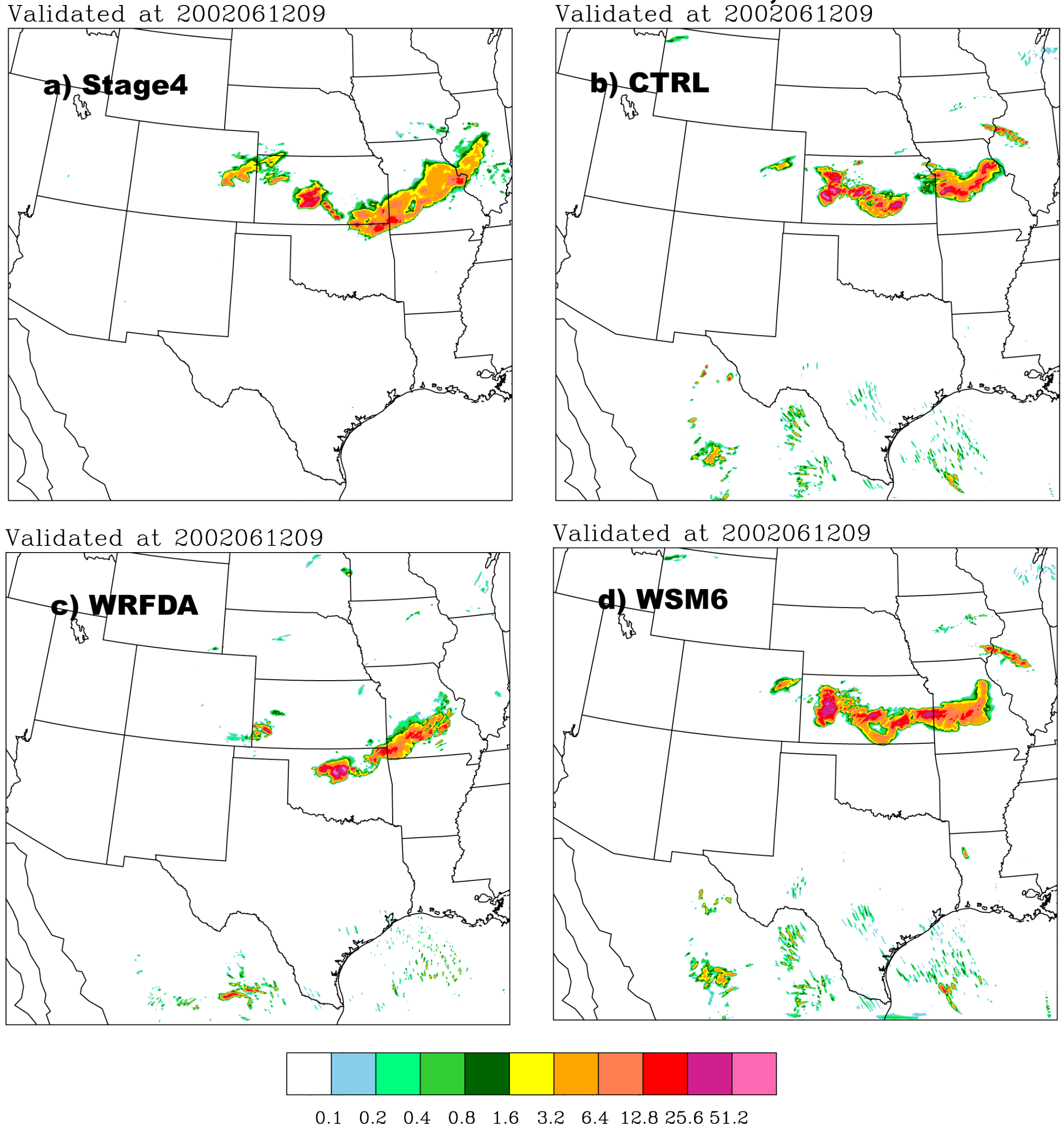
Success Case

Surface based convection

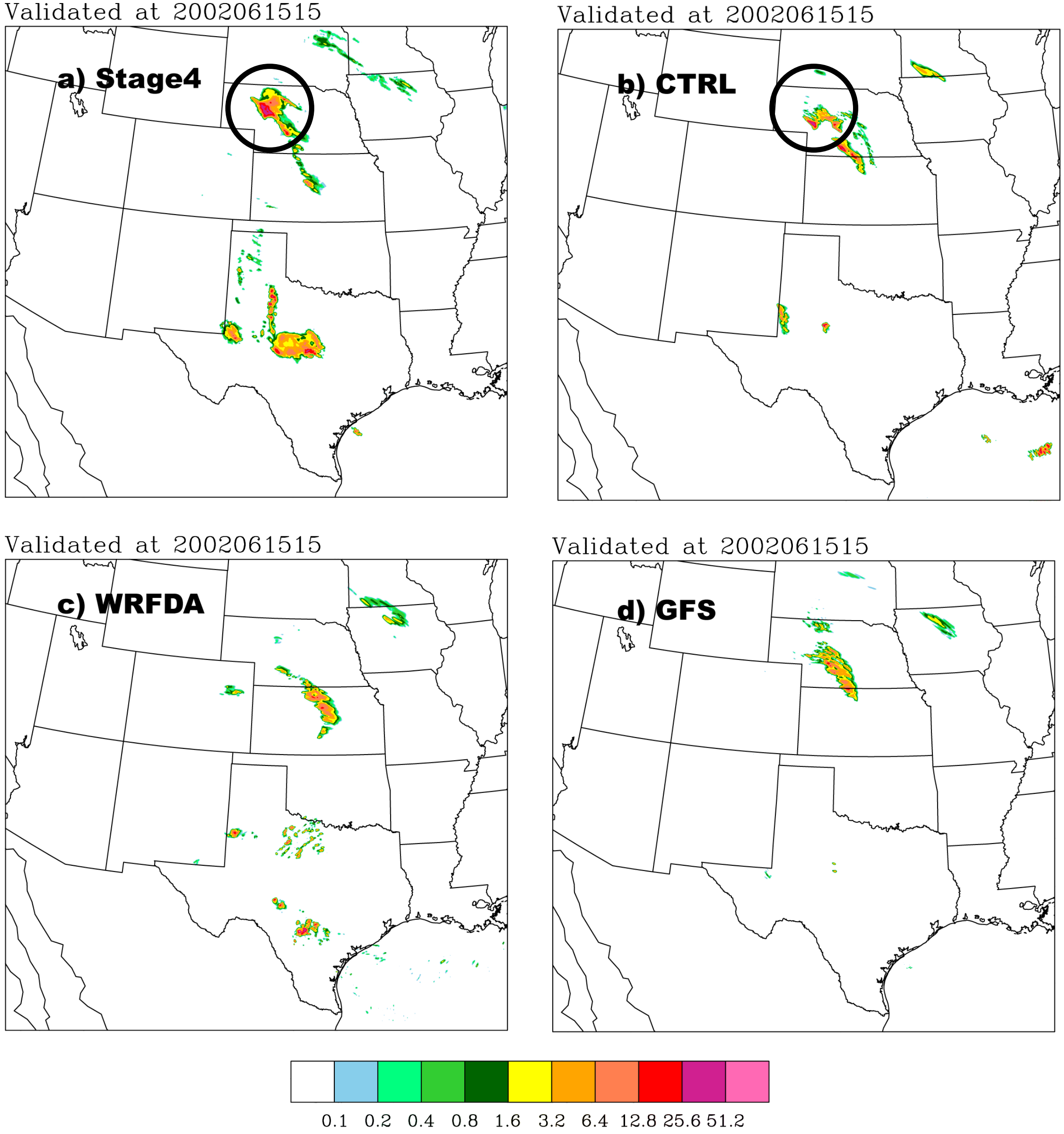
3-hour forecast of hourly precipitation valid at 03 UTC on June 12, 2002.



9-hour forecast of hourly precipitation valid at 09 UTC on **June 12**, 2002.



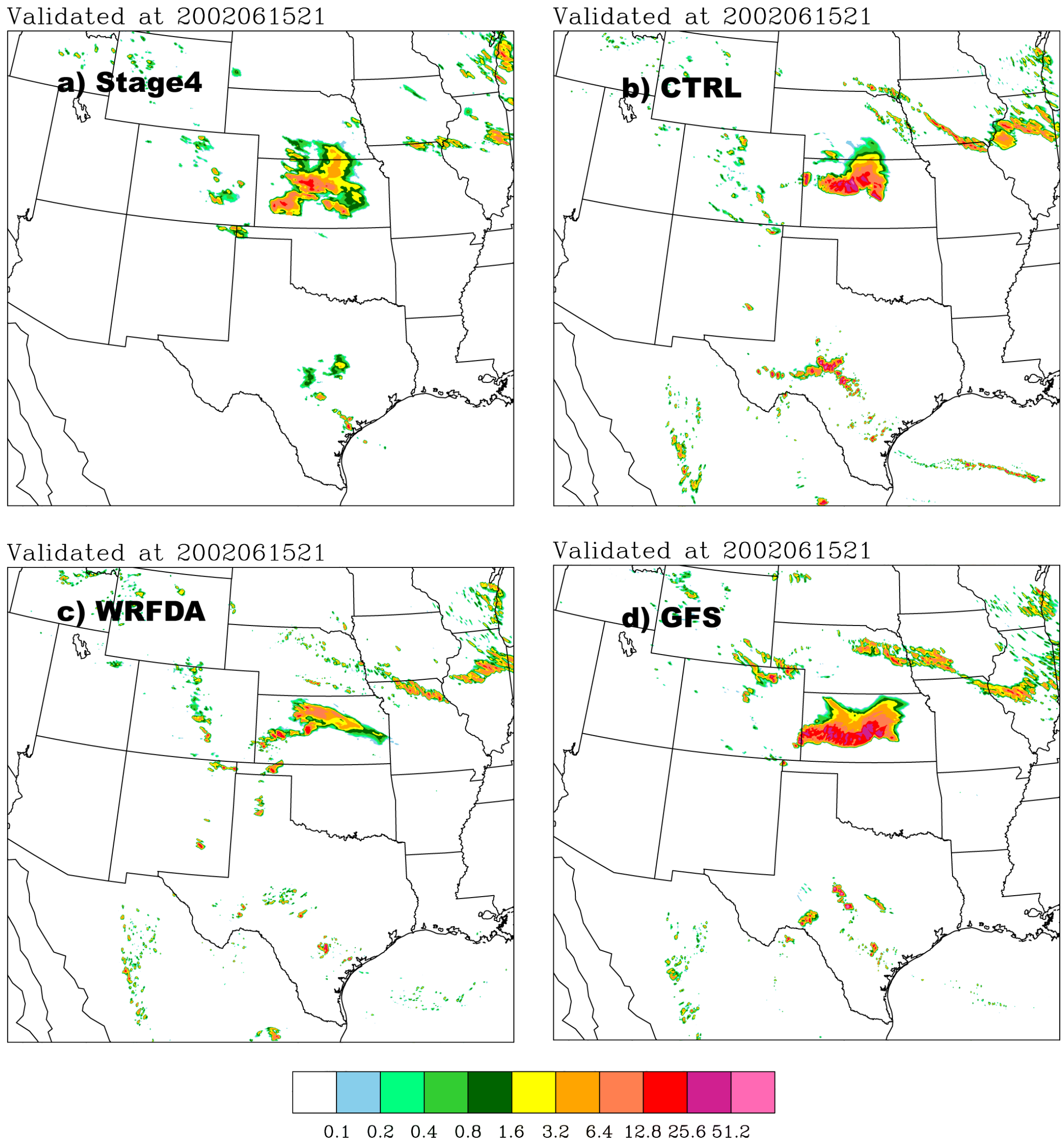
1-hour forecast of hourly precipitation valid at 13 UTC on June 15, 2002.



Failure case

Elevated convection

9-hour forecast of hourly precipitation valid at 21 UTC on **June 15**, 2002.

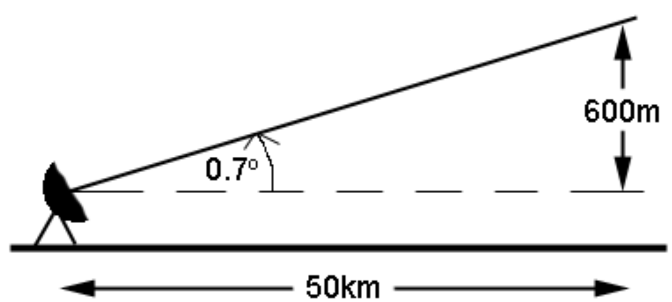


Doppler radar observations

- 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

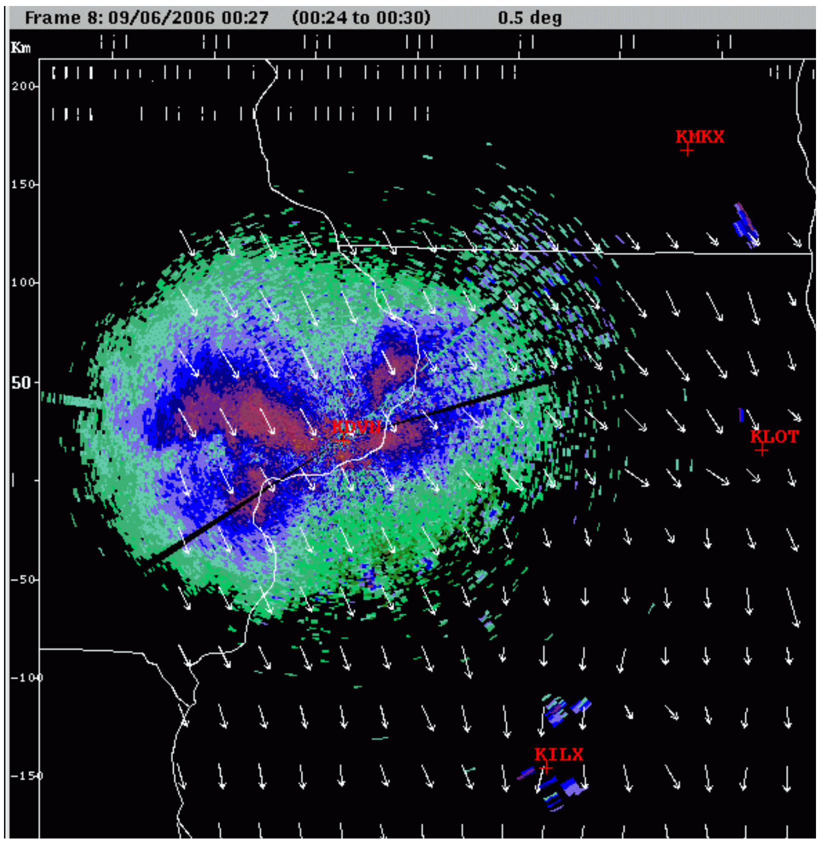
  - Clear-air echo from insects in boundary layer with a typical range of 60-100km
  - Storm echo from hydrometeors in precipitation region with a range of 230 km

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

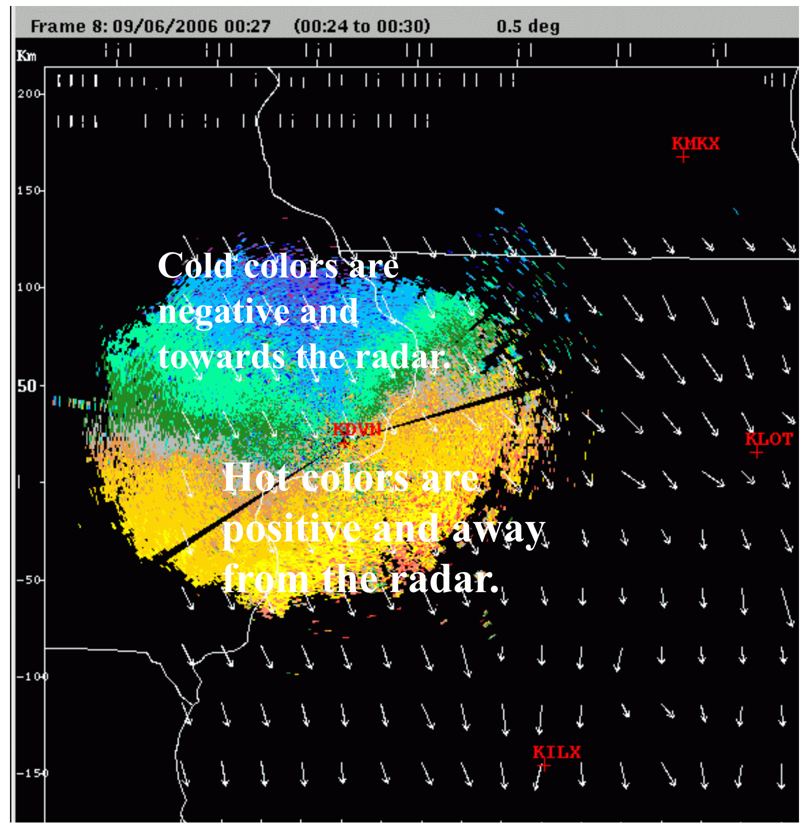


Examples of radar observations
1. No rain (clear air)

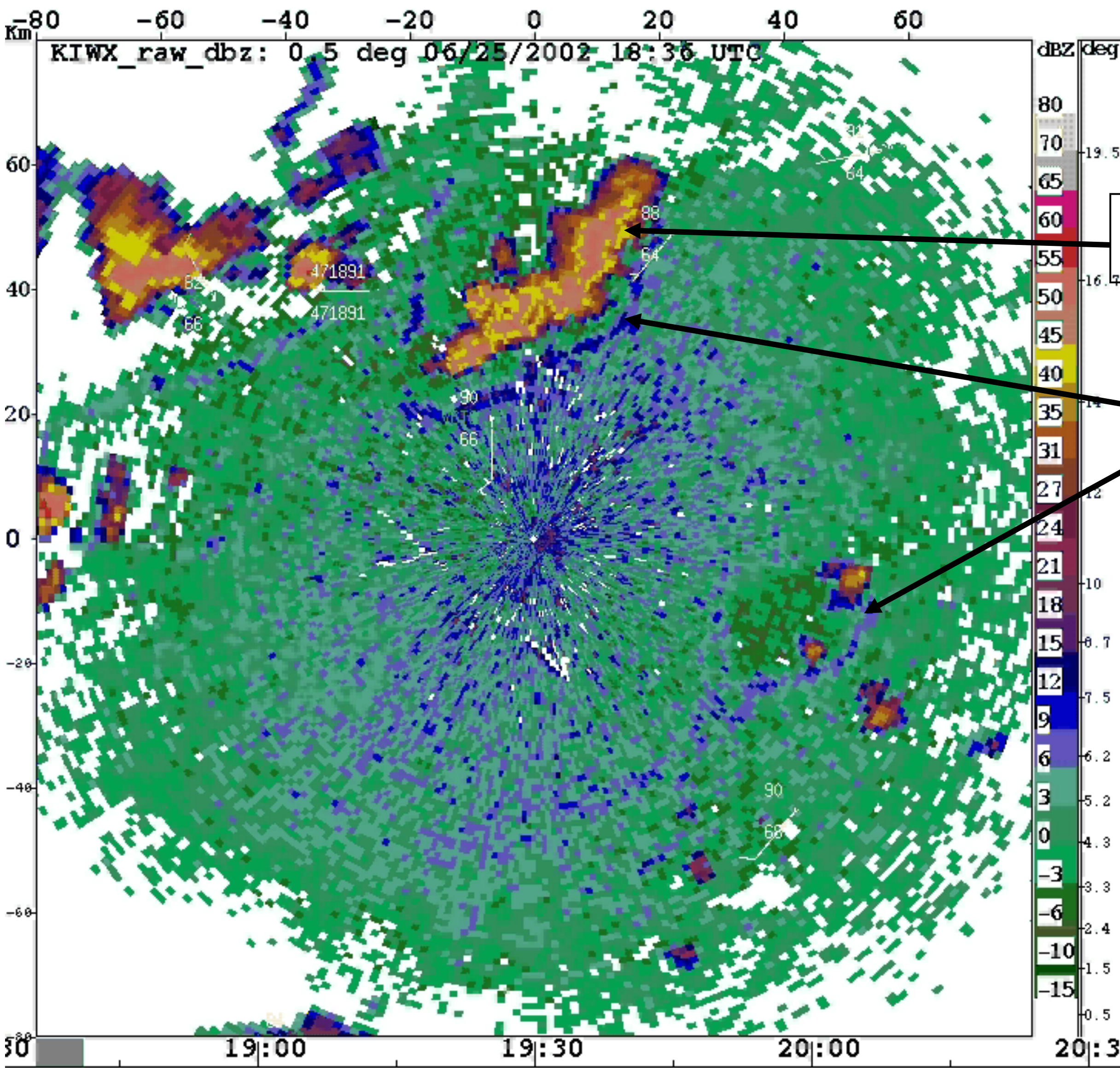
Reflectivity



Radial velocity



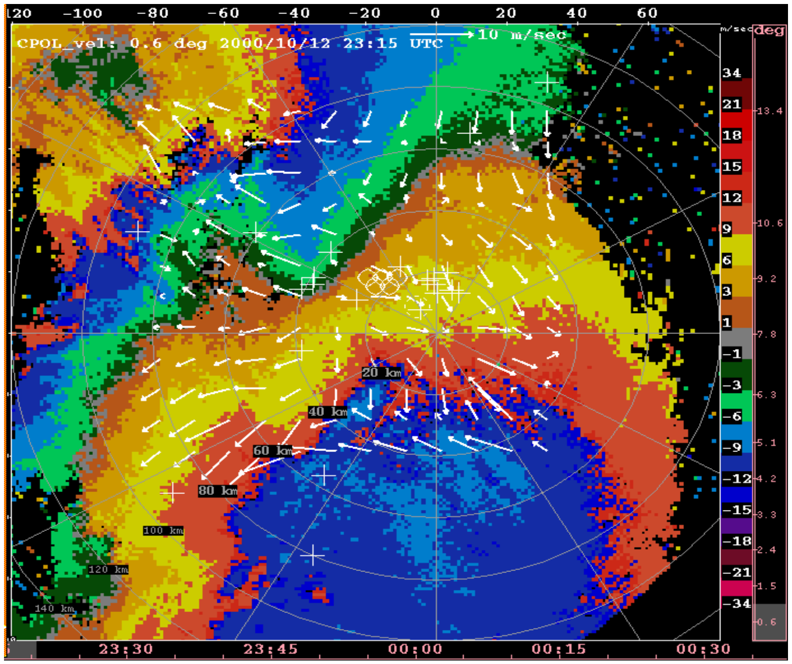
Examples of radar observations
2. Convective storm



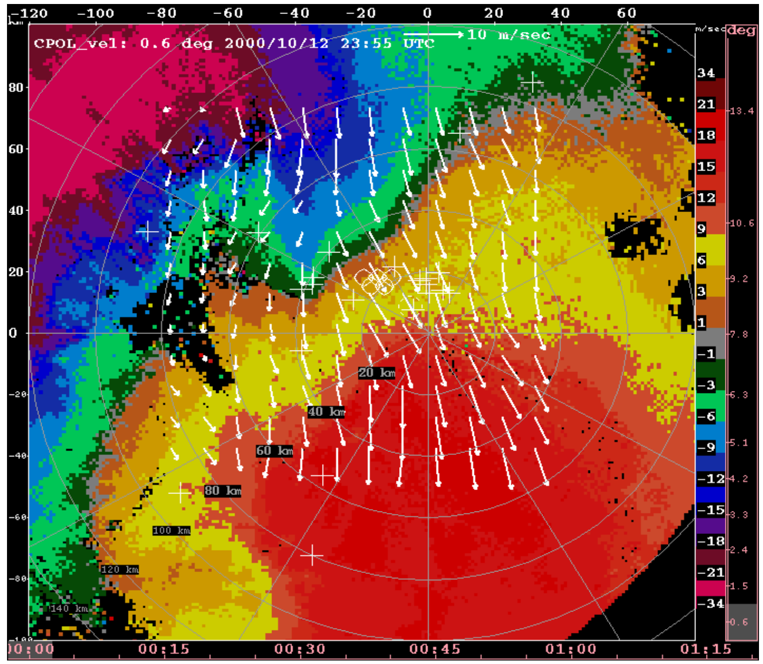
Doppler radar quality control

- Data quality control is a major issue for radar data assimilation
  - Dealiasing

    - radial velocity greater than Nyquest velocity is aliased
  - Removal of clutters, second-trip echo and other noises



Aliased velocities

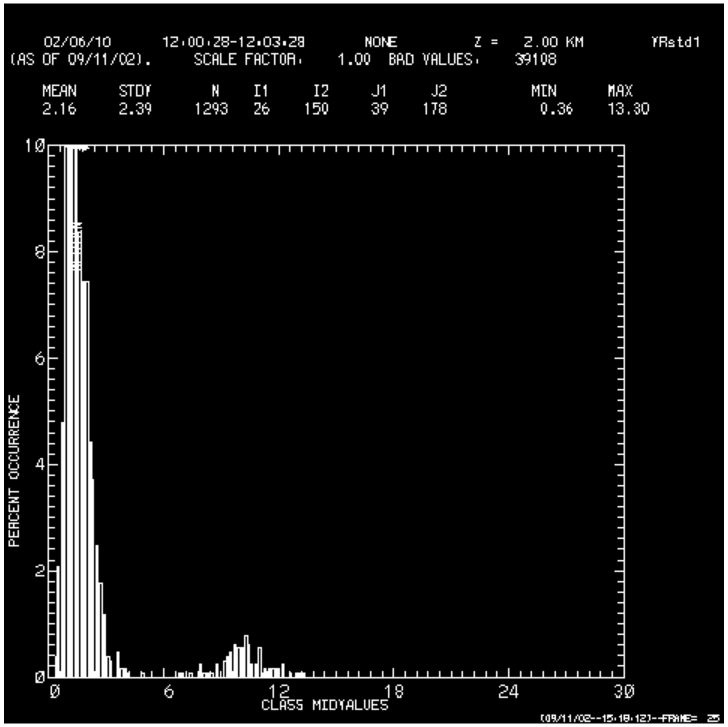


De-aliased velocities

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

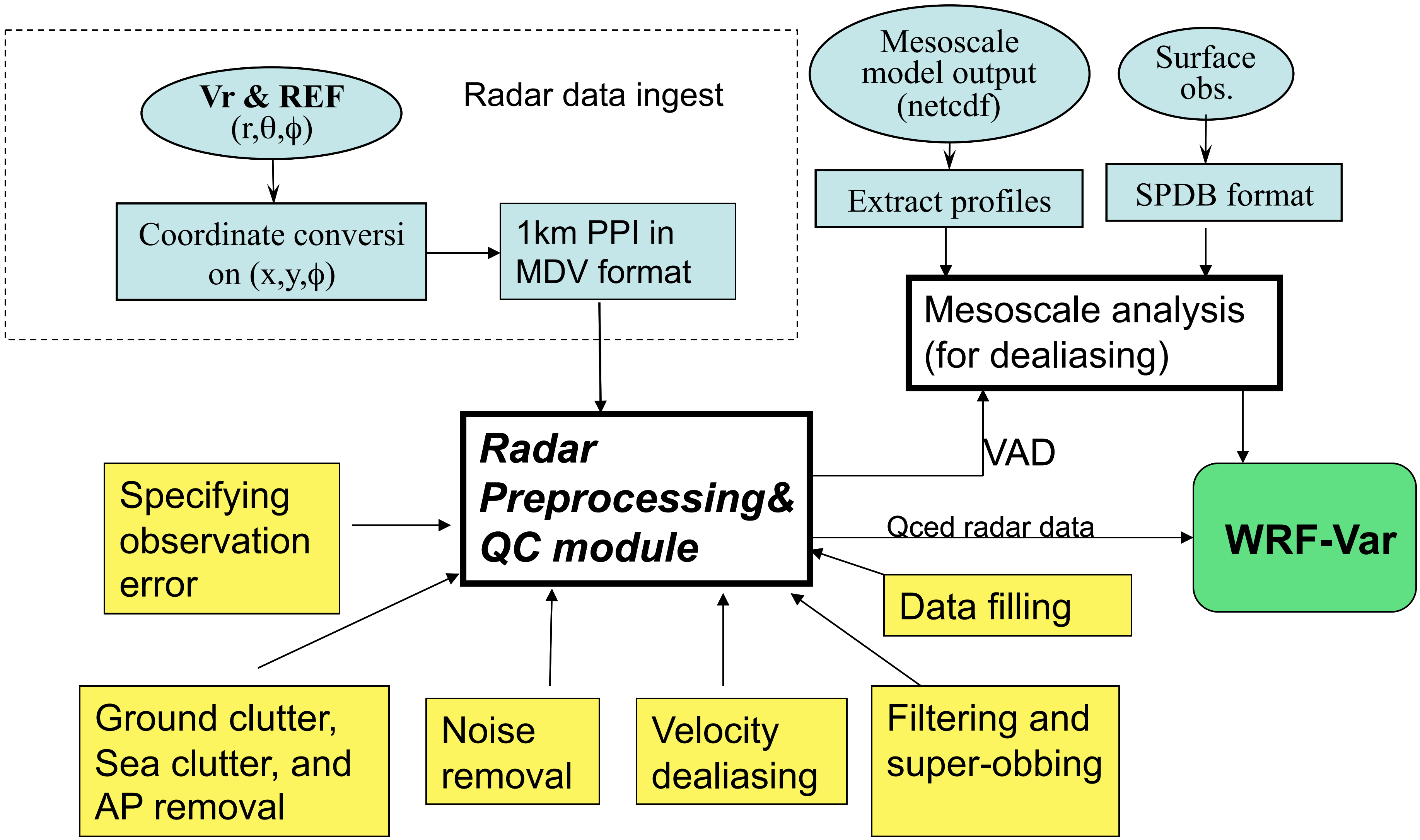
Local Standard Deviation as an error estimator



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

VDRAS data ingest, preprocessing, & QC



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

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

Additional increments w' and qr'

- **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.

- **w' and q_r' are obtained through diagnostic relations**

Diagnose W Increment

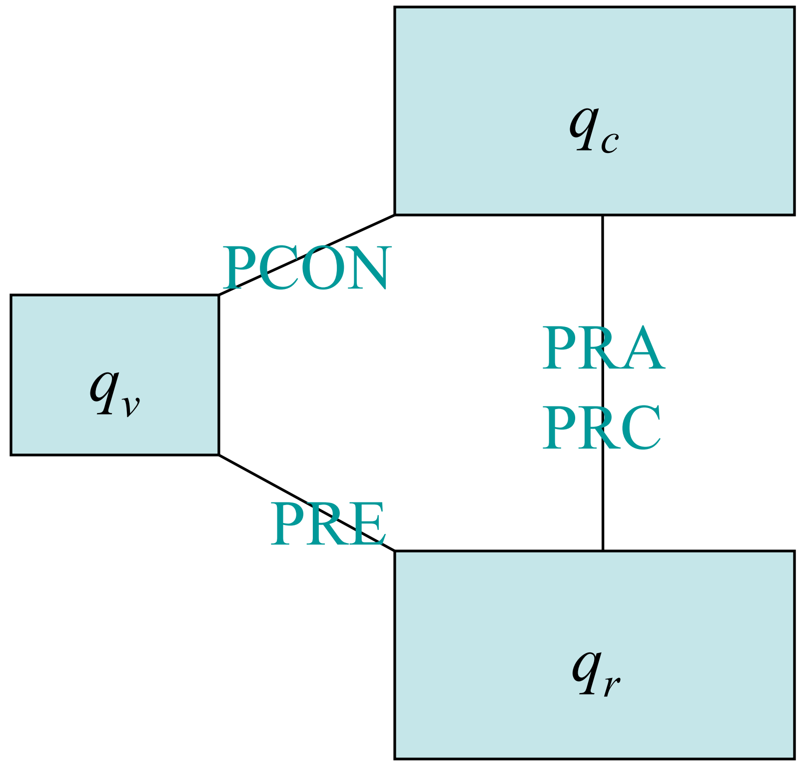
- Richardson's Equation ($\psi', \chi_u', T'_u, p'_{su} \rightarrow u', v', T', p' \rightarrow w'$)

$$\gamma \bar{p} \frac{\partial w'}{\partial z} = -\gamma p' \frac{\partial \bar{w}}{\partial z} - \gamma \bar{p} \nabla \cdot \vec{v}'_h - \gamma p' \nabla \cdot \vec{\bar{v}}_h - \vec{\bar{v}}_h \nabla p'$$
$$- \vec{v}' \nabla \bar{p} + g \int_z^{\infty} \nabla \cdot (\rho \vec{v}'_h) dz + g \int_z^{\infty} \nabla \cdot (\rho' \vec{\bar{v}}_h) dz$$

  - 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.

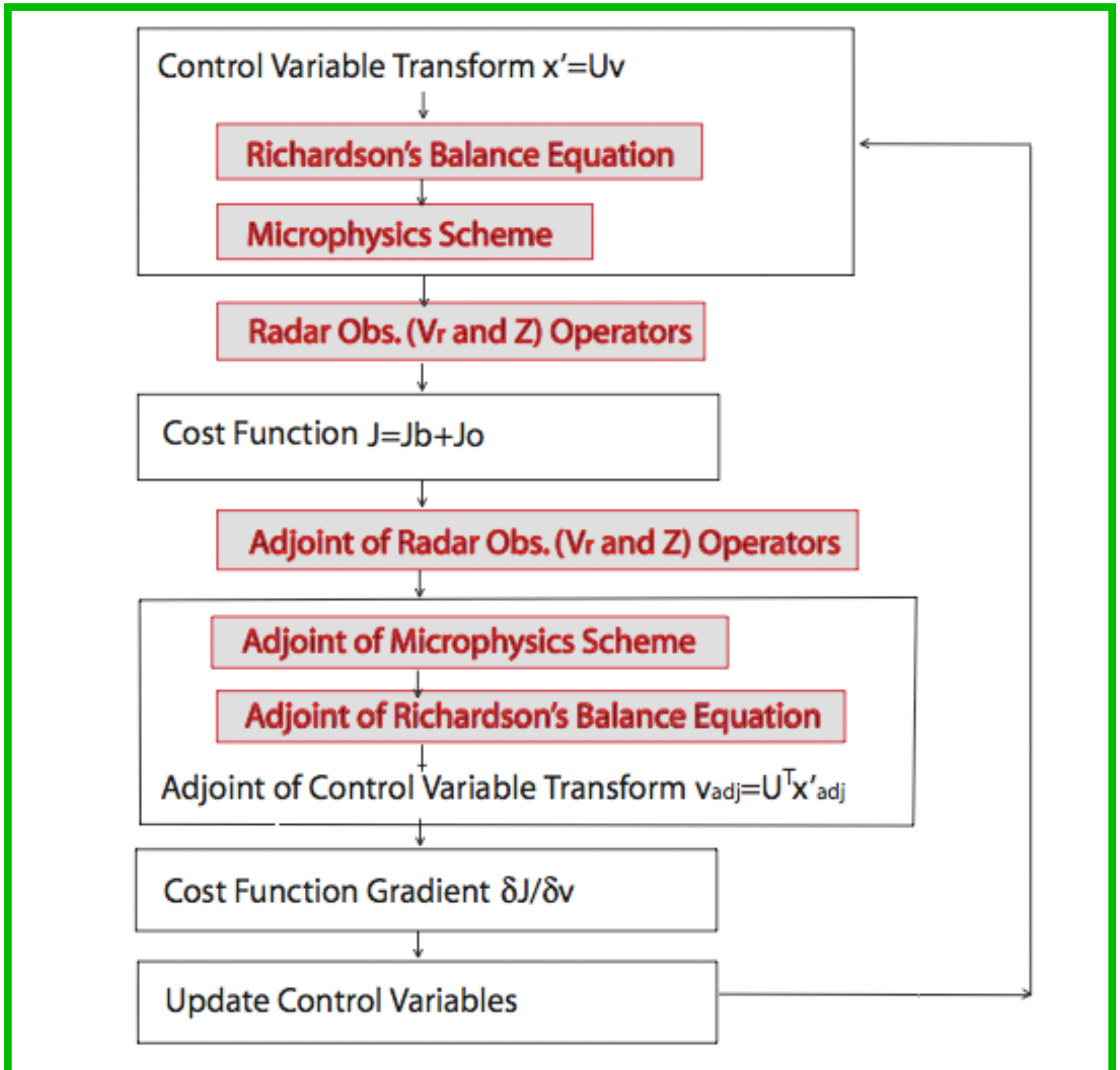
Diagnose hydrometeor increments

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



Steps to run WRFDA 3DVar with radar data

- Prepare the background error statistics (BES) file for your application domain
  - Create the BES from an existed BES file by using the interpolation function in WRFDA, or
  - Run WRF model to get a set of the forecasts initiated from a period of initial times, then create the BES by using the script: *WRFDA/var/scripts/gen_be/gen_be_wrapper.ksh*

- Prepare the first guess: either from WPS+WRF/*real.exe* (cold-start) or from the WRF model historic output file (warm-start)

- Prepare the observation data files including the radar radial velocity and reflectivity data, and/or the conventional observation data

- Edit the *namelist.input* file and Build the executable: *wrfvar.exe*

- Link the input files, wrfvar.exe, and certain ancillary files: *LANDUSE.TBL, gribmap.txt,* etc. in your working directory

- Run *wrfvar.exe,* and check the results

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)

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– 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)

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An example of input 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
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
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FM-128 RADAR   2002-08-31_00:00:00       34.314       124.003      499.0       2
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        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, link the radar observation file.

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

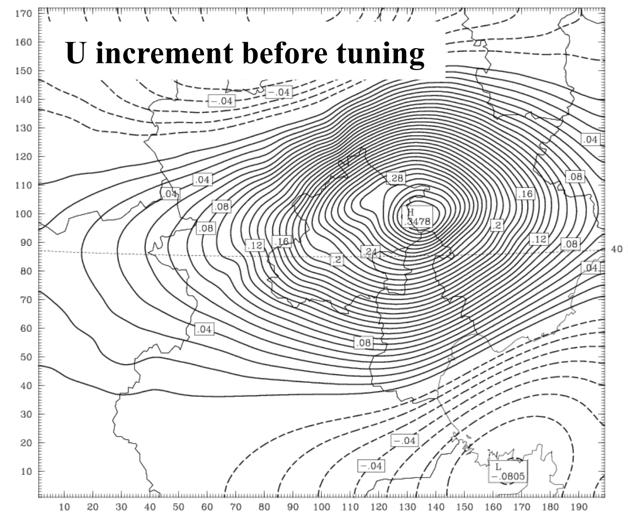
  – This is the only additional dataset you should include for radar data assimilation. Other input files for WRF-Var are the same as conventional data assimilation.

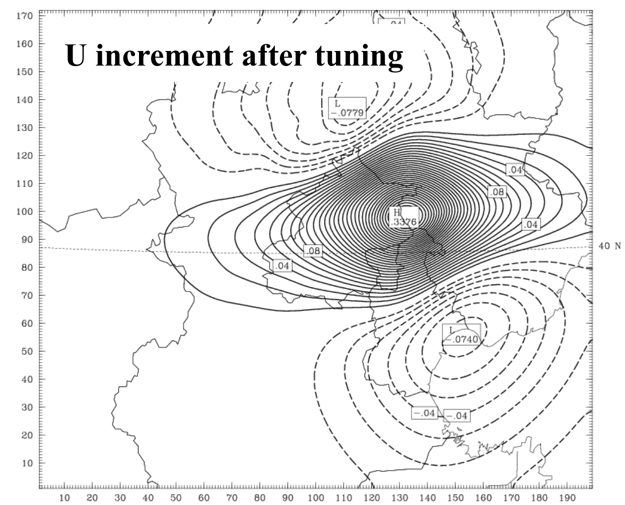
Tuning BES parameters

To change BES variance and length scale, do the following in your execution script:

export NL_VAR_SCALING1=0.5
export NL_VAR_SCALING2=0.5
export NL_VAR_SCALING3=0.5
export NL_VAR_SCALING4=0.5
export NL_VAR_SCALING5=0.5

export NL_LEN_SCALING1=0.5
export NL_LEN_SCALING2=0.5
export NL_LEN_SCALING3=0.5
export NL_LEN_SCALING4=0.5
export NL_LEN_SCALING5=0.5





Tuning O-B error tolerance

The parameter max_error_rv in Registry/Registry.wrfvar has a default value of 5.0.
When o-b is <= max_error_rv*rv_error, the observation will be assimilated in WRFDA.

Change max_error_rv or/and rv_error in Registry/Registry.wrfvar

```
rconfig   real     max_error_rv          namelist,wrfvar5  1   5.0     -
"max_error_rv"          ""  ""
rconfig   real     max_error_rf          namelist,wrfvar5  1   5.0     -
"max_error_rf"          ""  ""
```

Issues and ongoing development

3DVar radar DA

- More evaluation and study are needed
  - Why performance is situation dependent
  - BES tuning
  - Continuous cycle
- Improve the reflectivity data assimilation

4DVar Radar DA

- New control variables (w and microphysics are added)
- Adjoint of dynamical core and warm rain microphysics are developed
- A case study is being conducted