Radar Data Assimilation with WRFDA

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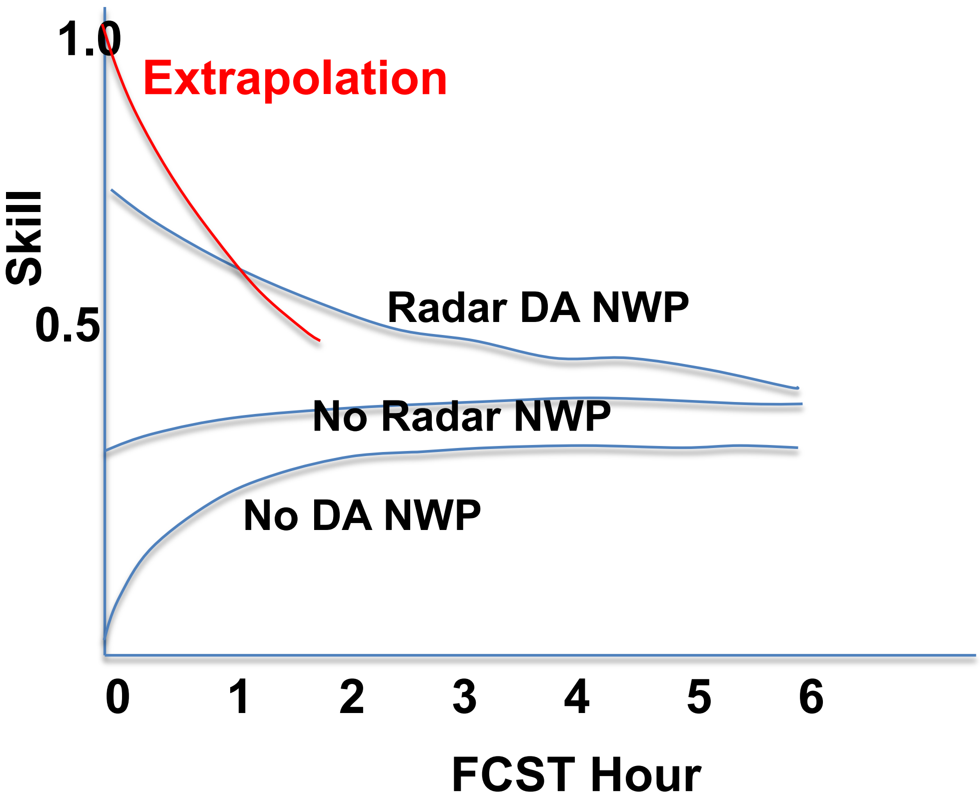
OUTLINE

- **Motivation, milestones, and current capabilities**
- **Radar DA method in WRFDA**
- **Configure and run WRFDA-radar**
- **Combined assimilation of radar and rainfall**
- **Ongoing research**

Why radar data assimilation



Objectives of radar data assimilation

- Improve short-term prediction of high impact weather
  - *for the very short-term range, an ambitious goal is to forecast the timing and location of storms at county/city scale*
- Improved understanding of mesoscale processes contributing to the formation of convective weather

Radar data: the good and the bad

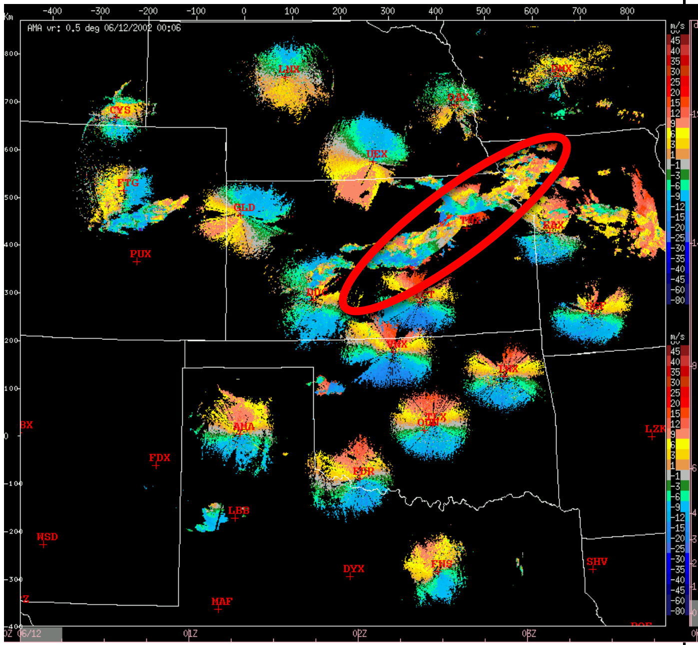
Good

- High spatial and temporal resolutions at convective-scale
- Observes wind (radial velocity) as well as microphysics (reflectivity)
- Accurate observations
- Observations are mostly in the lower atmosphere

Not so good

- Indirect observations – need observation operators
- Incomplete coverage – limited range and limited detection ability in clear air
- Only radial velocity and reflectivity
- Nontrivial for QC – users responsibility
- Locally available

Radial velocities from 20 WSR-88D radars



Scientific issues for radar DA

- Impact of radar data assimilation on convective forecasting
  (Xiao et al. 2005, 2007)
- Validity of the linearization of the observation operator for reflectivity
  (Wang et al. 2013)
- Validity of the tangent linear model approximation in 4DVar for highly convective weather
  (Wang et al. 2014)
- How well does 4DVar perform in comparison with 3DVar
  (Sun and Wang 2014)
- Impact of the choice of momentum control variables
  (Sun et al 2016)
- Controlling noise in high-resolution analysis with multi-scale balance
  (Vendrasco et al. 2016, Tong et al. 2017)

WRFDA-radar development milestones

2005: radial velocity data assimilation with WRFDA 3DVar (Xiao et al. 2005)

2007: reflectivity data assimilation using a partition scheme to obtain microphysics (Xiao et al. 2007)

2013: indirect assimilation of reflectivity using q_r and q_c as control variables (Wang et al. 2013)

2014: adjoint of Kessler scheme for 4DVar radar data assimilation (Wang et al. 2014)

2015: new momentum control variables (u/v) for radar data assimilation (Sun et al. 2016)

2015: a large-scale analysis constraint to maintain large-scale balance (Vendrasco et al. 2016)

2017: a strategy for hourly update cycles (Tong et al. 2017)

2017: a scheme for assimilating “no rain” reflectivity data (Gao et al. 2018)

2018-: Developments of cloud BE, dynamic blending scheme, and MRI

Current capabilities

3DVar

- Assimilate both radial velocity and reflectivity
- Direct and Indirect assimilation of reflectivity
- "Warm start" by assimilating estimated humidity within cloud
- Options for choice of momentum control variables
- Constraint terms (Jc) for controlling analysis noise – LSAC and DIVC
- Assimilate low reflectivity echoes (or "no-rain" data)
- Operational 3h/1h cycles since 2014

4DVar

- Use WRF tangent linear model as constraint with multiple outer loops
- Adjoint of physics schemes: modified Kessler microphysics, large-scale condensation, a simple cumulus scheme, and diffusion scheme
- Assimilate both radar and rainfall data
- 4DVar framework is fully consistent with 3DVar
- Multi-resolution incremental scheme applicable to radar DA

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- Application examples and ongoing research

Two methods for reflectivity DA

1. *Direct assimilation of reflectivity (Xiao et al. 2007)*
   - An empirical reflectivity observation operator to link reflectivity with rain water
   - Total liquid water is used as microphysics control variable
   - A warm rain partition scheme used to partition the total water
   - Vertical velocity is diagnosed using the Richardson equation
   - A new and improved direct method considering ice is being developed (Wang et al. 2019)

2. *Indirect assimilation of reflectivity (Wang et al. 2013, most used)*
   - Diagnose microphysics (q_r, q_s, q_g) and humidity from reflectivity (Gao and Stensrud 2012)
   - Assimilate the diagnosed quantities
   - Cloud control variables and vertical velocity control variable
   - Assimilate low reflectivity echoes

Cost Function

Indirect method with cloud control variables

$$J = J_b + J_o + \underbrace{J_{v_r} + J_{q_r} + J_{q_v}}_{\text{For radar DA}}$$

- **Control variables :**

u/v (or ψ/χ_{u}), T (or T_u), Ps (or Ps_u), RHs, q_c, q_r, and w

- **3DVar critically depends on a cloud analysis scheme that assimilates estimated in-cloud humidity**

- **A modified Kessler scheme along with its adjoint produces analyses of microphysics in 4DVar**

Radial velocity observation operators

$$J_{vr} = \frac{1}{2}\sum (V_r - V_r^{ob})^2 / \sigma_{vr}$$

V_r **Radial velocity from the model**

V_r^{ob} **Radial velocity observations**

σ_{vr} **Observation error variance**

v_r - (u, v, w, q_r) Relation:

$$v_r = \frac{x - x_r}{r} u + \frac{y - y_r}{r} v + \frac{z - z_r}{r} (w - V_T(q_r))$$

Reflectivity observation operator

$$J_{qr} = \frac{1}{2}\sum (q_r - q_r^{ob})^2 / \sigma_{qr}$$

q_r **Model rainwater mixing ratio**

q_r^{ob} **Estimated rainwater mixing ratio from reflectivity**

σ_{qr} **Observation error variance**

Z-q_r Relation (assume Marshal-Palmer DSD)

$$Z = 43.1 + 17.5 \log_{10}(\rho q_r)$$ **Sun and Crook (1997)**

Z-q_s and Z-q_h follow Gao and Stensrud (2012)

Pseudo humidity assimilation

$$J_{qv} = \frac{1}{2}\sum (q_v - q_v^{ob})^2 / \sigma_{qv}$$

q_v **Model water vapor mixing ratio**

q_v^{ob} **Estimated water vapor mixing ratio by assuming near saturation above LCL within cloud**

σ_{qv} **Observation error variance**

Namelist options:

cloudbase_calc_opt

Option for calculating cloud-base height: below this height retrieved humidity will not be assimilated for the use_radar_rqv option

0: fixed value of 1500 meters

1 (default): KNU scheme

2: NCAR scheme

radar_saturated_rf

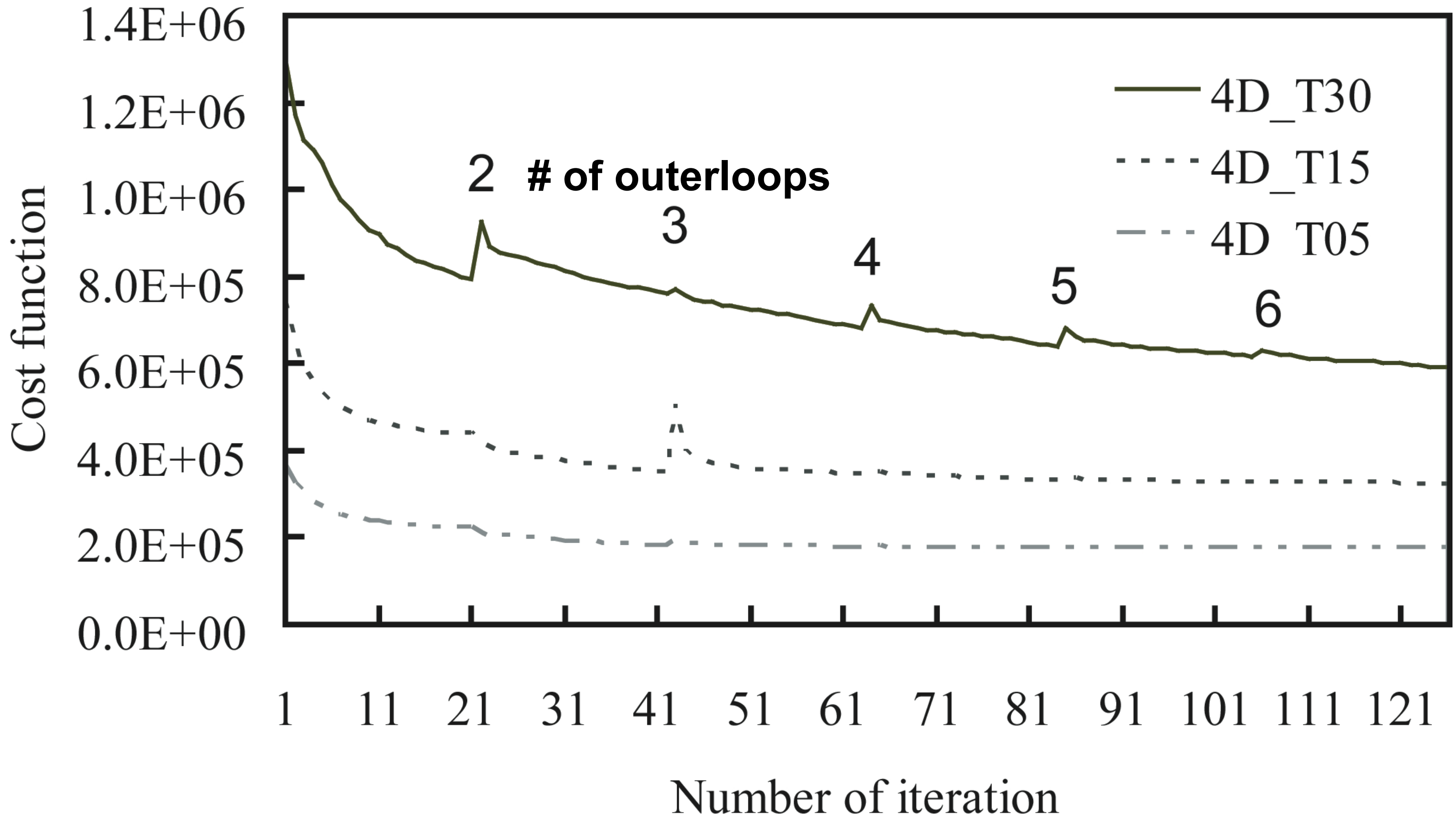
rf value (dBz) used to indicate precipitation for rqv (default 25.0)

Multi-incremental 4DVar

WRFDA uses a multi-incremental formulation, meaning

- The forward prediction model within the 4DVar window is an approximation of the nonlinear model
- The control variables are increments from the forward model trajectory
- The formulation requires the update of analysis increment in an inner loop but also the update of the nonlinear model in an outer loop
- It makes the cost function better conditioned and allows different spatial resolutions for the inner and outer loops – multi-incremental, but does it work for severe convection?

Cost function reduction with 6 outer loops and 3 different lengths of windows



The longer window length (30 min) shows stronger rebounds at outer loop updates, but the cost function is steadily reduced, indicating the tangent linear forward operator is a good approximation of the nonlinear model

4DVar physics options

	WRFTL & AD	WRFNL
mp_physics	mp_physics_ad=98 Large scale condensation Mp_physics_ad=99 Modified Kessler scheme	mp_physics can be set to any options for WRF It can also be set to 98 or 99, same as WRFTL & AD
cu_physics	cu_physics = 0: no cumulus scheme cu_physics=98: Simplified CU scheme Any other numbers will be Defauted to 98	Same as the left column

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Radar DA options in Namelist

- Read radar data
  use_radarobs = true,
- Assimilate radial velocity
  use_radar_rv=true,
- Two methods for reflectivity assimilation
  use_radar_rf =true; (direct method; Xiao et al. 2007)
  use_radar_rhv=true; (indirect method; Wang et al. 2013)
- Assimilate pseudo humidity
  use_radar_rqv=true,
- 3DVar (default) or 4DVar
  var4d=true
- Microphysics control variables
  cloud_cv_options = 3   BE of regular variables are from gen_be; cloud variables hard coded
- u/v momentum control variables
  cv_options = 7   5: psi/chi CV   7: u/v CV (7 is recommended for radar)
- Several options for assimilating weak radar echoes – "no rain" data
  See the user guide
- Options for LSAC DIVC constraints
  See the user guide

Basic steps for radar DA

Step 1: prepare radar data in the correct format and write the data into ob.radar (ob01.radar, ob01.radar, … for 4DVar)

- Use your own QC software
- (φ,r,θ) => (x,y,θ) => Lat/lon profiles => merge the radars into one file

Step 2: produce 1-3 month WRF forecasts (12h & 24h) over the study domain, and then compute BE using the WRFDA utility gen_be

Step 3: modify the namelist.input to make radar DA choices

Step 4: conduct single observation tests to tune the length scale and variance for your specific domain

- 100-200km for GTS data and 30km for radar data are commonly used (Tong et al. 2016, two-step procedure)

Step 5: configure WRFDA: to invoke the "CLOUD_CV" option, do the following in the configure script

setenv CLOUD_CV 1 - for csh

Export CLOUD_CV = 1 - for both ksh and bash

STEP 6: link ob.radar and other other observation files and first guess

Tuning BES parameters

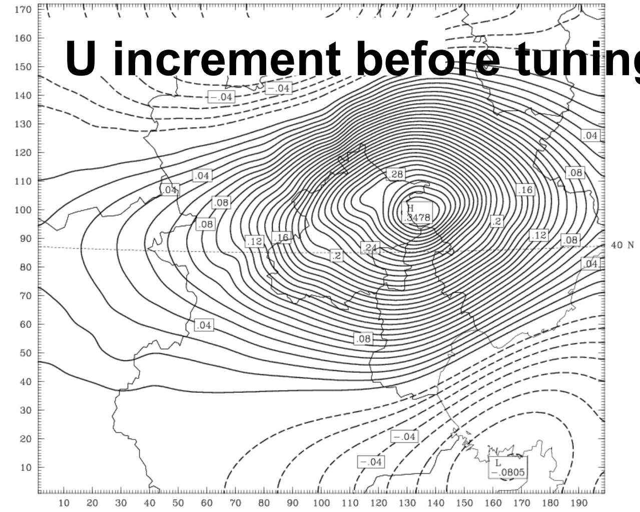
To change BES variance and length scale, do the following in your namelist.input:

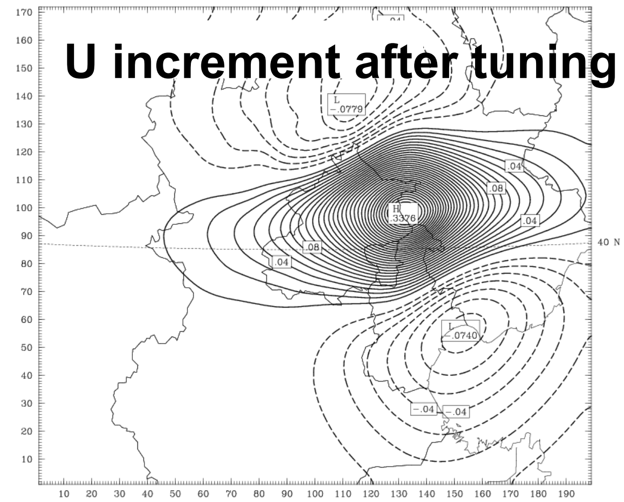
To decrease the weight of the background

VAR_SCALING1=2.0
VAR_SCALING2=2.0
VAR_SCALING3=2.0
VAR_SCALING4=2.0
VAR_SCALING5=2.0

To decrease the length scale

LEN_SCALING1=0.5
LEN_SCALING2=0.5
LEN_SCALING3=0.5
LEN_SCALING4=0.5
LEN_SCALING5=0.5





Data format

```
write(301,'(a14,i3)') 'Total number =', nrad
 write(301,'(a)')
 '#----------------------------#'
write(301,'(a)') '                              '
do irad = 1, nrad   ! nrad: total # of radar
 !---Write header
write(301,'(a5,2x,a12,2(f8.3,2x),f8.1,2x,a19,2i6)') 'RADAR',  &
 radar_name, rlonr(irad), rlatr(irad), raltr(irad)*1000.,       &
 trim(radar_date), np, imdv_nz(irad)      write(301,'(a)')     &       '#-----------------------------------
-------------------#'
 write(301,*)
!----Write data
 do i = 1,np    ! np: # of total horizontal data points
write(301,'(a12,3x,a19,2x,2(f12.3,2x),f8.1,2x,i6)')  'FM-128 RADAR',    &
 trim(radar_date), plat(i), plon(i), raltr(irad)*1000, count_nz(i)
  do m = 1,count_nz(i)    ! count_nz(i): # of vertical elevitions for each radar
write(301,'(3x,f12.1,2(f12.3,i4,f12.3,2x))')  hgt(i,m), &
 rv_data(i,m), rv_qc(i,m), rv_err(i,m),        &
 rf_data(i,m), rf_qc(i,m), rf_err(i,m)
enddo
enddo
enddo
```

Data format

Header

nrad: total number of radars

radar_name: name of the ith radar (irad)

rlonr, rlatr, raltr: longitude, latitude, and altitude of irad

radar_date: date of irad observation

np: number of total data points for irad

imdv_nz: number of total elevation angles of irad

Data

plat, plon, raltr: longitude, latitude, and altitude of the ith data point

count_nz: number of data levels at the ith data point

hgt(i,m): height of ith data point at m level

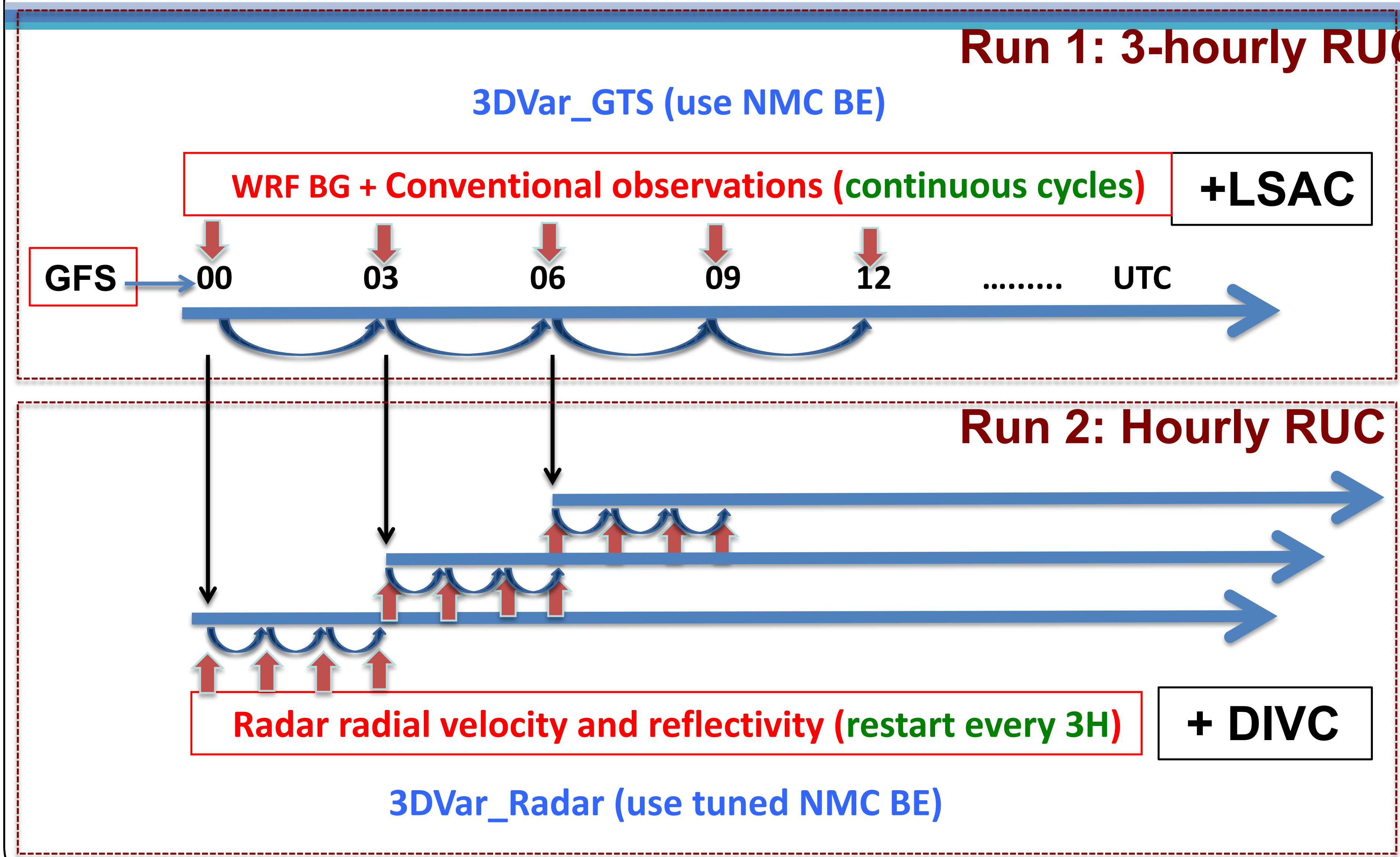
rv_data(i,m), rv_qc(i,m), rv_err(i,m): radial velocity value, qc index, and obs error. The qc index >= 0 means good data; otherwise bad data.

rf_data(i,m), rf_qc(i,m), rf_err(i,m): reflectivity value, qc index, and obs error

Example of radar input data

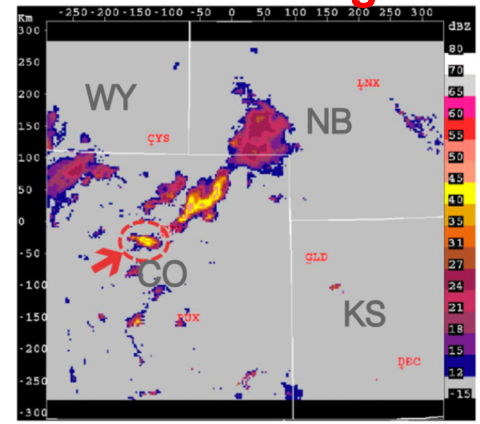
```
TOTAL NUMBER = 16
#-----------------#

RADAR      KCYS    -104.806    41.152    1887.0  2015-07-07_21:00:00  5497    11
#-----------------------------------------------------------#

FM-128 RADAR   2015-07-07_21:00:00         41.165      -107.189    1887.0       3
         3735.9 -888888.000 -88 -888888.000       10.288    0       0.576
         5128.9 -888888.000 -88 -888888.000       13.029    0       0.944
         6870.5 -888888.000 -88 -888888.000        8.192    0       1.229
FM-128 RADAR   2015-07-07_21:00:00         41.192      -107.189    1887.0       3
         3737.3 -888888.000 -88 -888888.000       10.262    0       0.746
         5130.6      -7.381   0       1.692       13.338    0       0.473
         6872.5 -888888.000 -88 -888888.000        8.373    0       0.626
FM-128 RADAR   2015-07-07_21:00:00         41.219      -107.189    1887.0       3
         3740.0 -888888.000 -88 -888888.000        9.447    0       1.072
         5133.9      -8.476   0       1.632       12.828    0       0.833
         6876.7 -888888.000 -88 -888888.000        8.969    0       0.991
FM-128 RADAR   2015-07-07_21:00:00         41.246      -107.189    1887.0       3
         3744.2 -888888.000 -88 -888888.000       12.750    0       1.918
         5139.0 -888888.000 -88 -888888.000       15.127    0       0.948
         6883.0 -888888.000 -88 -888888.000       11.409    0       0.932
FM-128 RADAR   2015-07-07_21:00:00         41.138      -107.153    1887.0       3
         3645.0 -888888.000 -88 -888888.000       11.011    0       0.882
         5017.0 -888888.000 -88 -888888.000       12.650    0       0.879
         6732.4 -888888.000 -88 -888888.000        6.896    0       1.287
FM-128 RADAR   2015-07-07_21:00:00         41.165      -107.153    1887.0       3
         3645.0 -888888.000 -88 -888888.000       11.477    0       0.804
         5017.0      -5.278   0       1.641       13.550    0       0.990
         6732.4 -888888.000 -88 -888888.000        9.280    0       2.035
FM-128 RADAR   2015-07-07_21:00:00         41.192      -107.153    1887.0       3
         3646.4      -0.267   0       4.448       11.606    0       1.225
         5018.7      -5.217   0       1.843       14.294    0       0.731
         6734.5 -888888.000 -88 -888888.000       10.094    0       2.072
```

A two-step cycling strategy for radar DA



2-STEP vs. 1-STEP (Tong et al. 2017)

Denver flood on Aug 9 2008



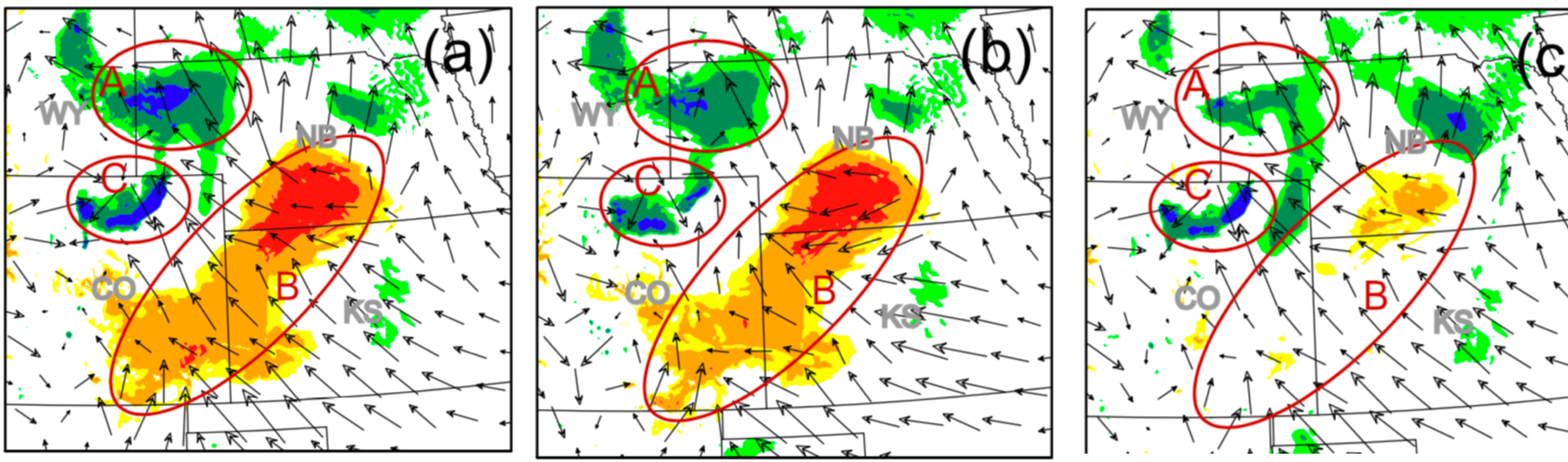
2STEP: 30km length scale for the 2st step radar DA and **200km** length scale for the 1st step assimilation of all other observations

1STEP200: 200km length scale for all observations

1STEP30: 30km length scale for all observations

Temperature increment after DA

2STEP | **1STEP200** | **1STEP30**



Captured both in-storm cooling and pre-storm warming

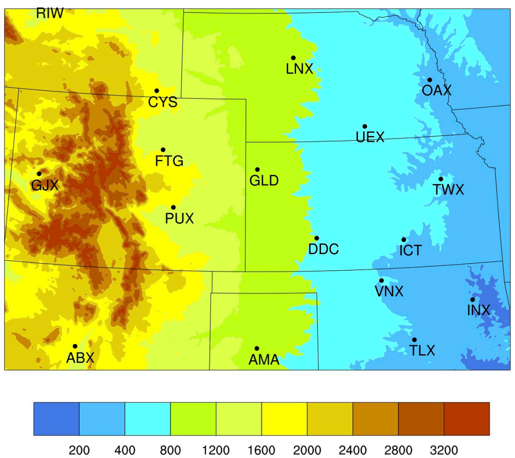
Captured pre-storm warming but weaker cold pools

Captured cold pools well but weak pre-storm warming

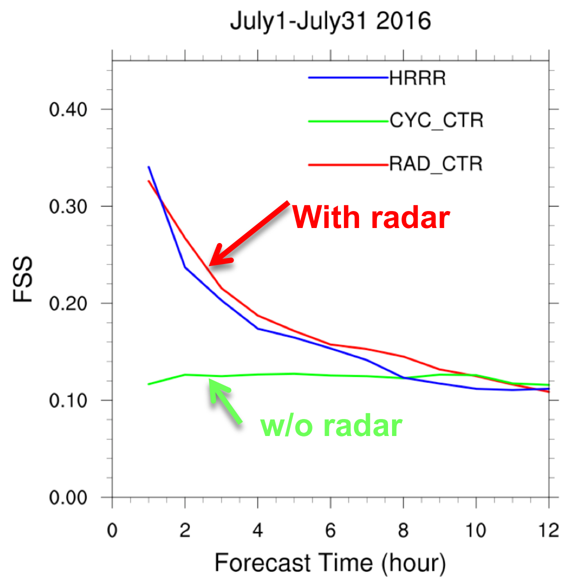
Impact of radar data assimilation

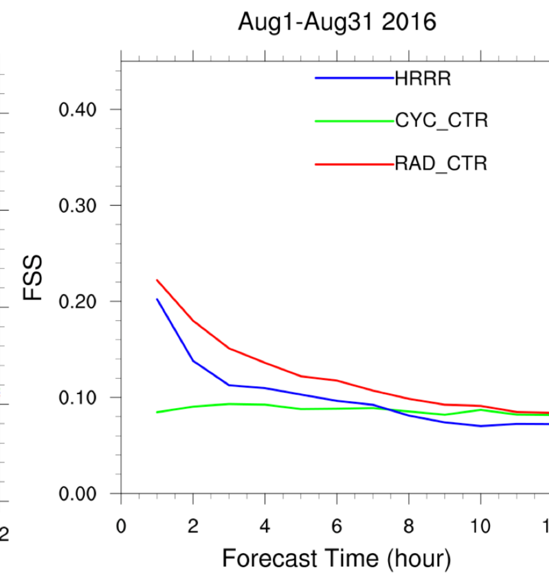
Verified against QPE (MRMS) during July and Aug 2016

Verification domain & topography

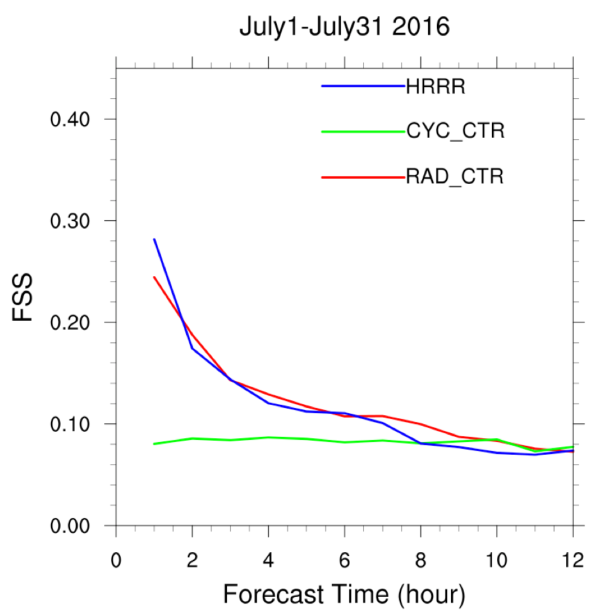


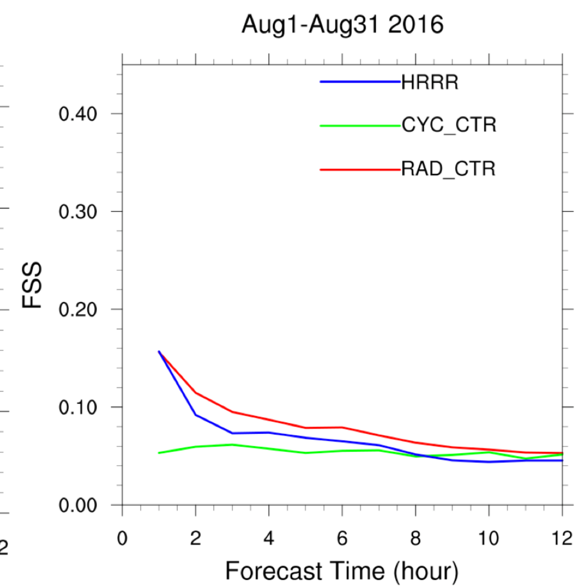
17 radars were assimilated with WRFDA 3DVar





1mm





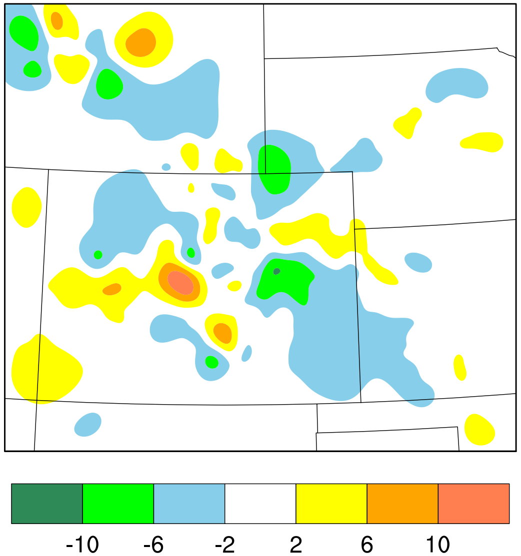
2.5 mm

Momentum control variables

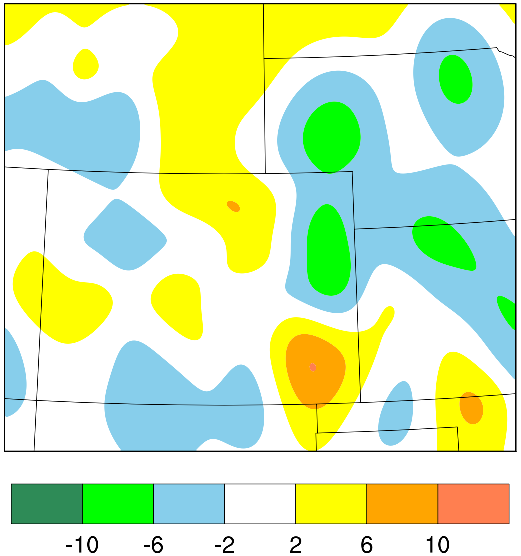
- The new control variable (CV) option **CV7** which uses **u/v** instead of psi/chi as momentum control variables has been added since WRFDA3.7
- CV7 requires the computation of BES of u and v
- In the current version, correlation between variables is not considered
- But a divergence constraint (DIVC) is included in the cost function to force some correlation between u and v
- See Sun et al. (2016) and Tong et al. (2017)

Comparison of CV7 with CV5

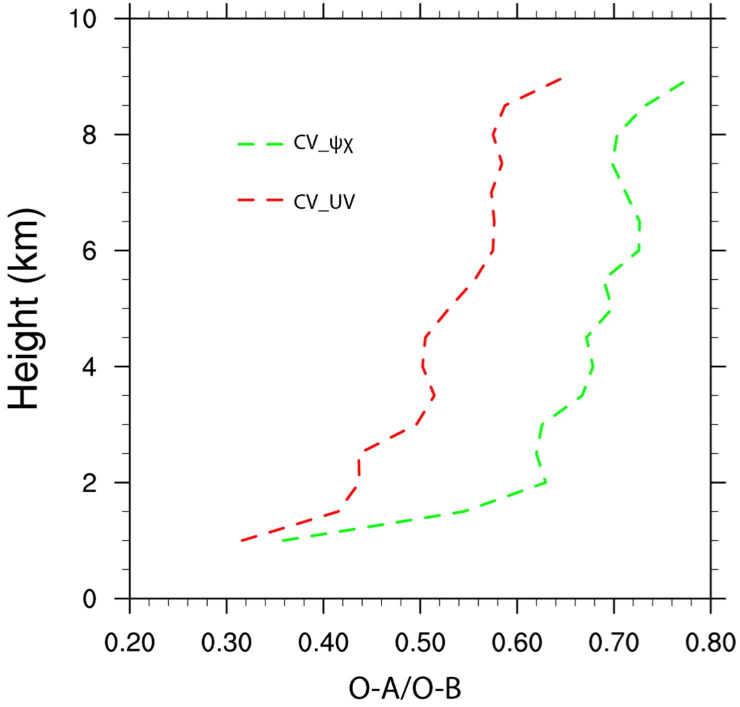
U' from CV7 (UV)



U' from CV5 (χψ)



O-A/O-B for radial velocity



- **CV7 produces increments with small-scale details and it allows a closer fit to radar observations**

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Cost function with radar and rainfall DA

$$J = J_b + J_o + J_{v_r} + J_{q_r} + J_{q_v} + J_{rn}$$

Other obs (↑ J_o) — For radar DA ($J_{v_r} + J_{q_r} + J_{q_v}$) — Rainfall DA (↑ J_{rn})

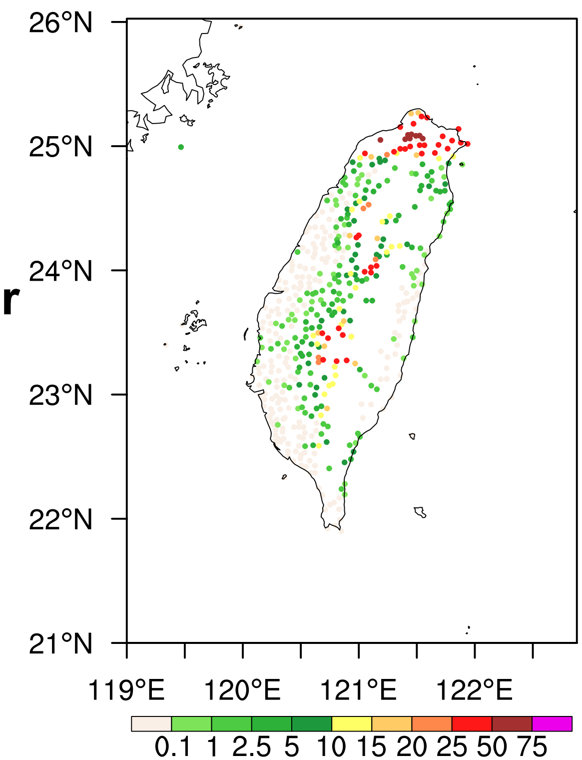
$$J_{rn} = \sum_{t=0}^{t=N} (RN) - RN^{ob}$$

- **The temporal window in 4DVAR makes it feasible for assimilating temporally accumulated quantity such as rainfall**
- **It does not require ad-hoc adjustment of moisture or latent heat because of the adjoint of model microphysics**
- **Both radar and rainfall should use a short 4DVAr window (<30 min) in order to resolve severe convection**

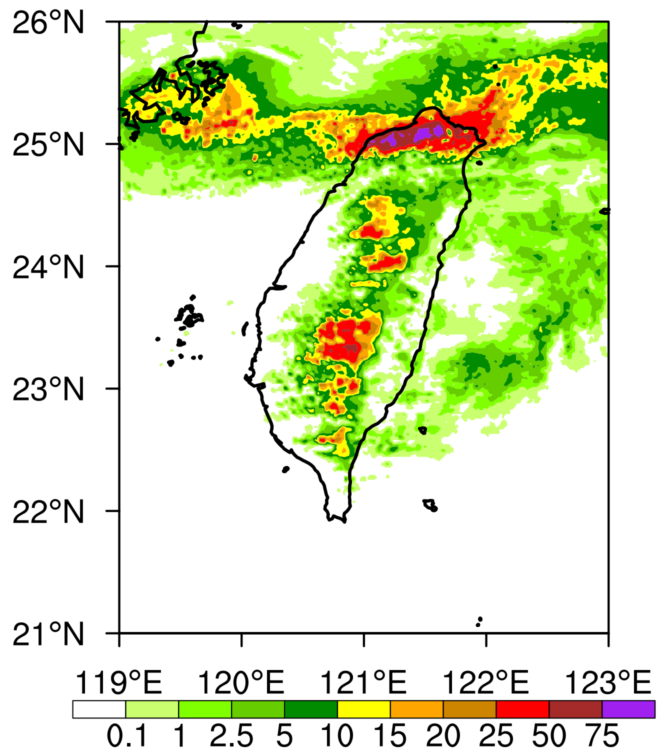
Rain gauge or radar QPE?

- Rain gauge obs is considered more accurate, but
- its spatial coverage is much poorer than radar data, so it can be outweighed by radar in the cost function minimization
- The gridded QPE product has the same order of data amount as radar data; so a better choice in this regard

Rain gauge obs

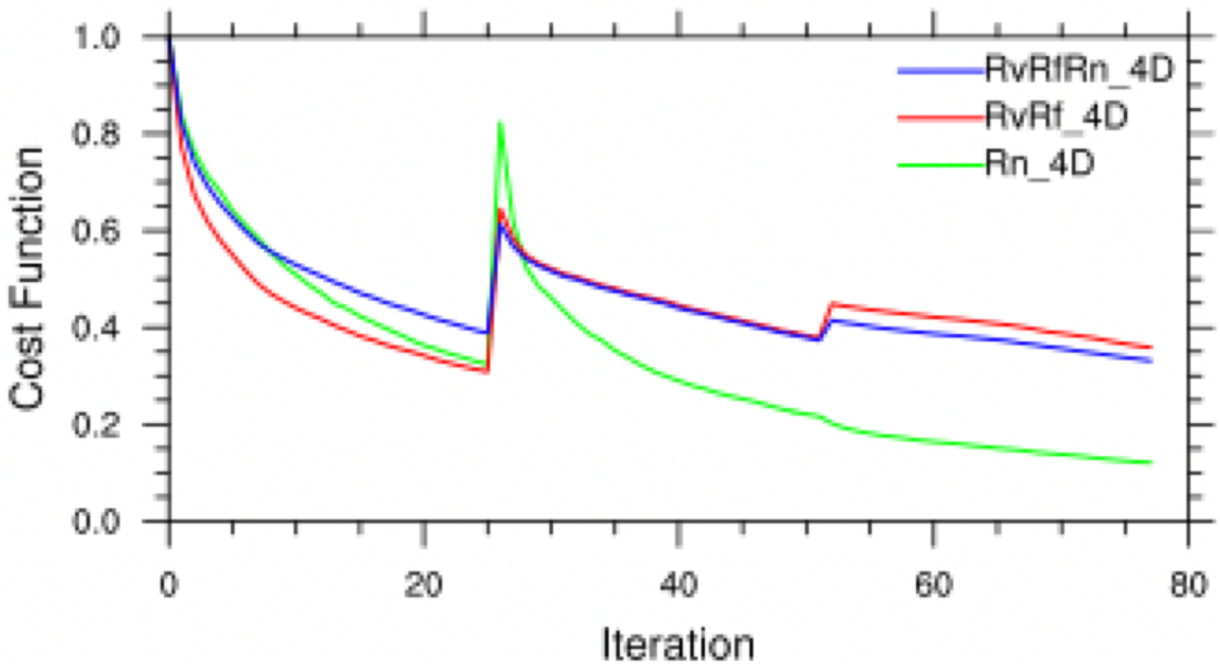


QPE with gauge adjustment



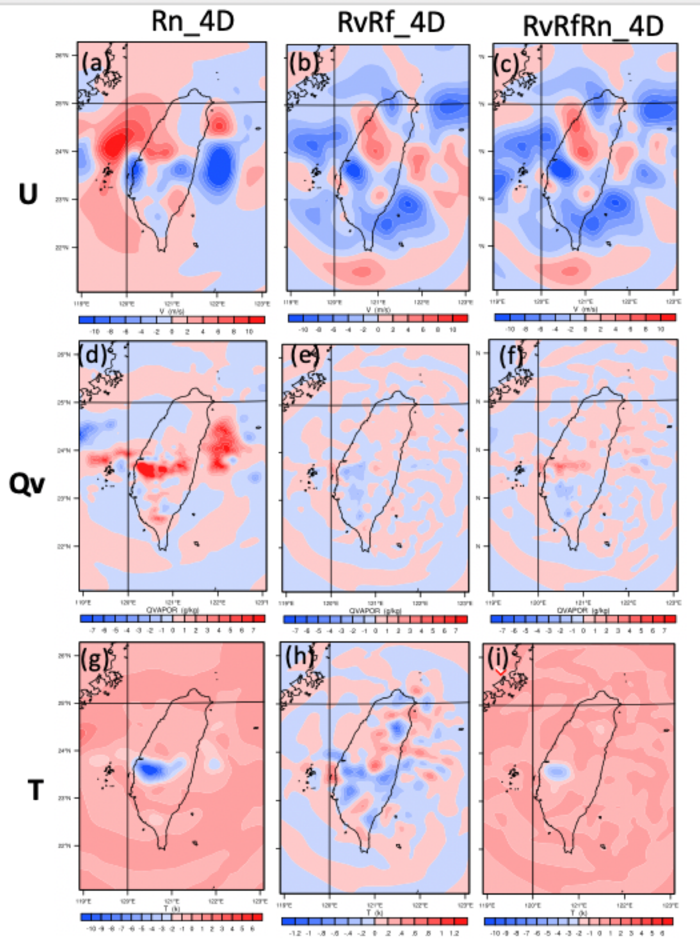
Cost function reduction

Rn_4D: rainfall DA with 4DVar
RvRf_4D: radar DA with 4DVar
RvRfRn_4D: combined DA with 4DVar
CTRL_3D: Background for the above experiments

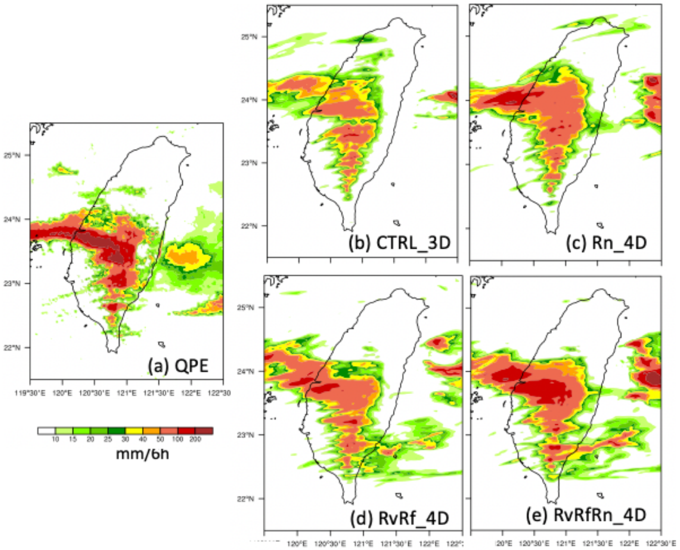


Comparing increments and 6h rainfall forecasts

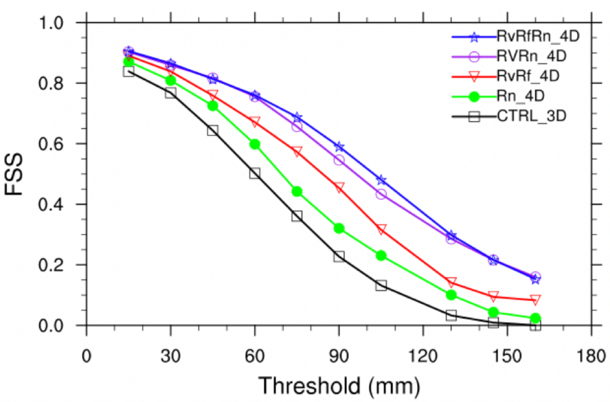
Analysis increments



Forecasts of 6h accumulated rainfall



Rainfall fcst verification



Ongoing research

- **Improve flow-dependent BE using the ensemble method**

  - Application of WRFDA hybrid-3DVar to radar data assimilation

  - Benefit of using EnKF to update perturbation (En3DVar vs. 3DEnVar)

- **Multi-timescale 4DVar**

  - A shorter 4DVar window for reflectivity and longer window for radial velocity because nonlinear errors of microphysics grow much faster

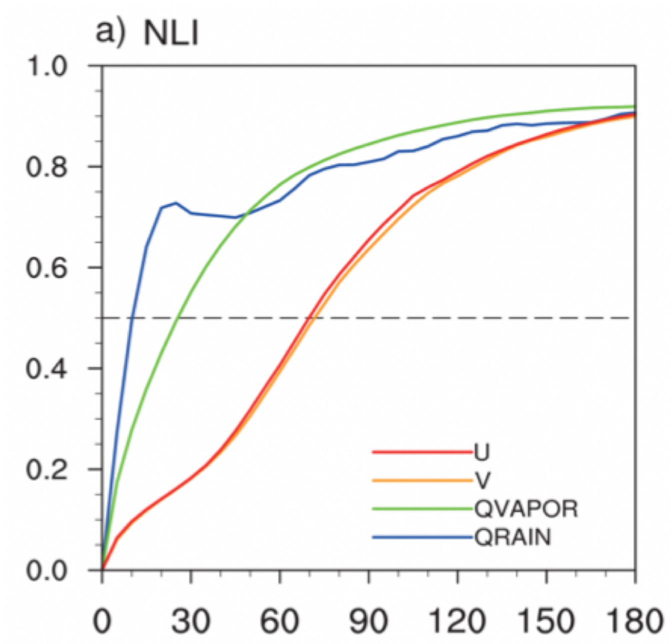
- **Dual-pol radar data assimilation**

  - Developing schemes for both direct and indirect methods

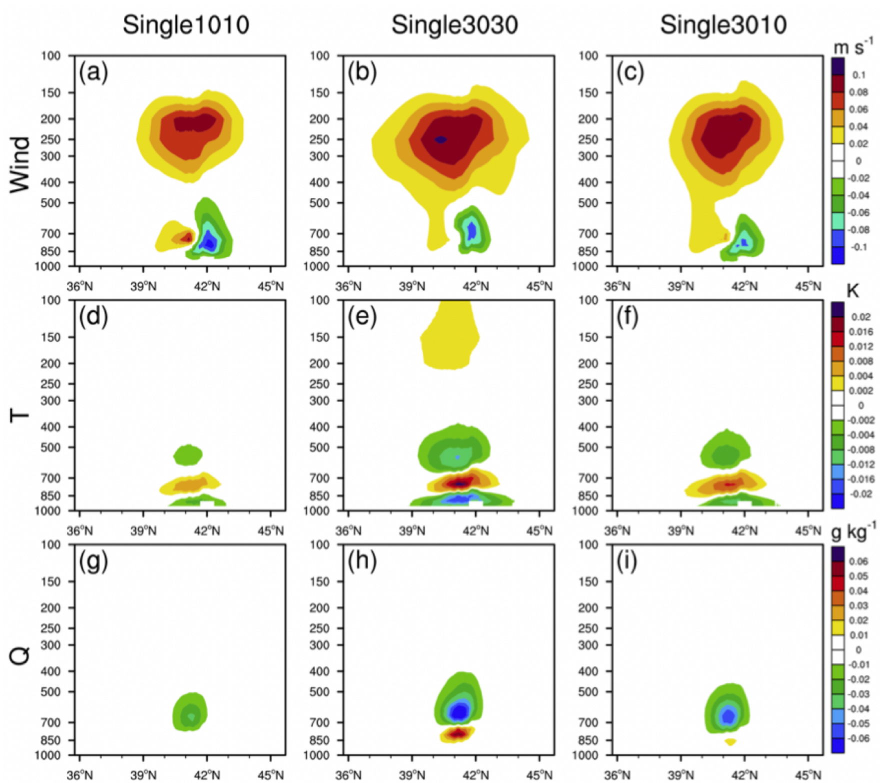
Multi-timescale 4DVar (Sun et al. 2019)

Single1010: use 10min window for both radial wind and reflectivity
Single3030: use 30min window for both
Single3010: use 30min for wind and 10min window for reflectivity

Nonlinea Error Growth



Single obs tests



Dual-pol data assimilation

Improved rainfall estimate with dual-pol observation can potentially Improve convective-scale initial analysis