Radar Data Assimilation with WRFDA

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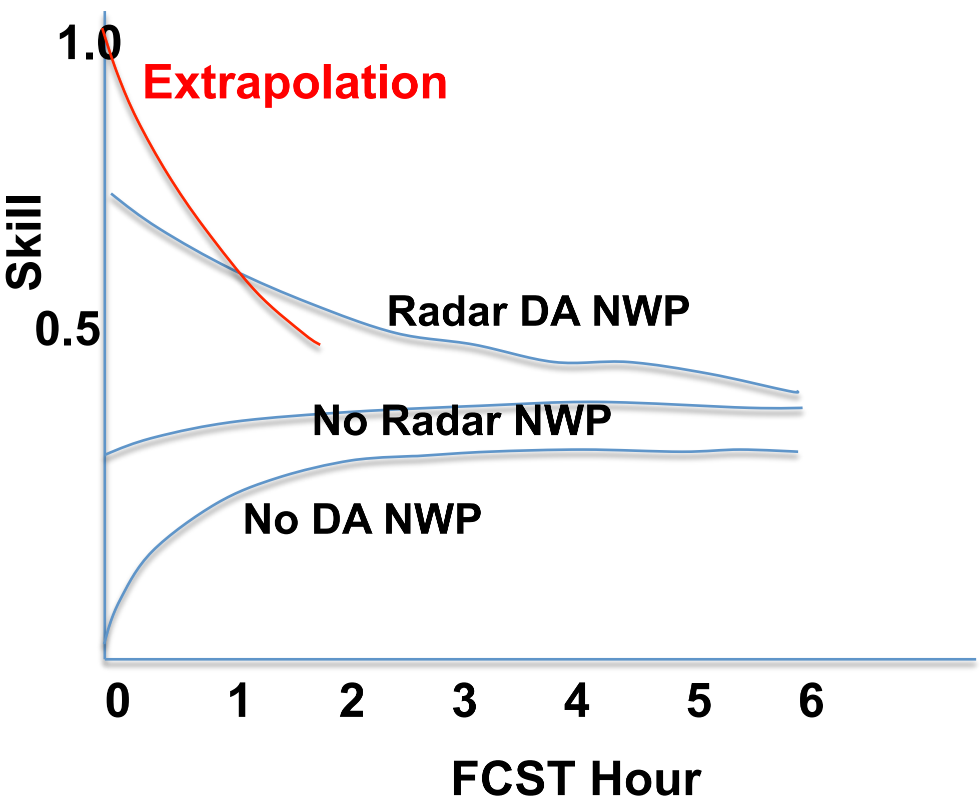
OUTLINE

- **Motivation, milestones, and current capabilities**
- **Radar DA method in WRFDA**
- **Configure and run WRFDA-radar**
- **Applications and ongoing research**

Why radar data assimilation



Objectives of radar data assimilation

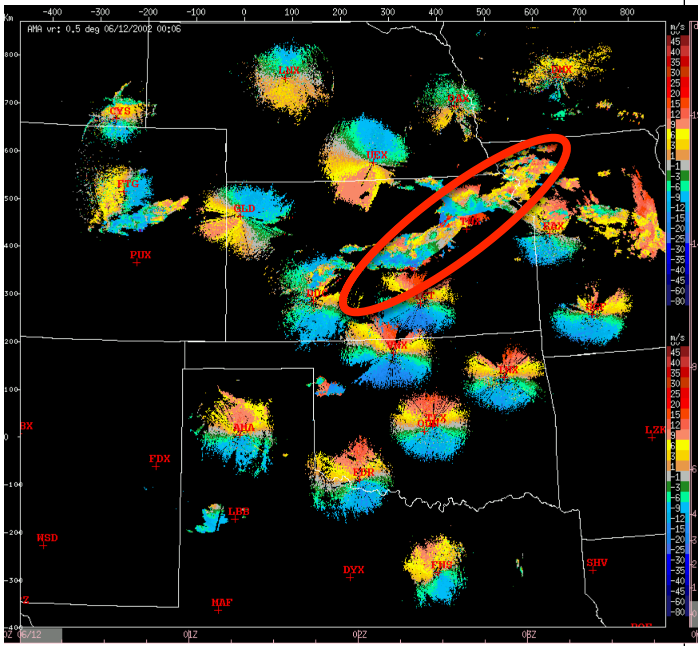
- Improve short-term prediction of high impact weather
- For the very short-term range, an ambitious goal is to forecast the timing and location of storms at county/city scale
- Improved understanding of mesoscale processes contributing to the formation of convective weather (may require advanced DA techniques)

Radar data: the good and the bad

Good

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

Radial velocities from 20 WSR-88D radars



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
- Locally available

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 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., submitted)

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
- Operational 3h/1h cycles since 2014

4DVar

- Use WRF tangent linear model as constraint with multiple outer loops
- Can be run with multi-incremental option
- 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

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Two methods for reflectivity DA

1. ***Direct assimilation of reflectivity (Xiao et al. 2007)***
   - Requires an observation operator to link the reflectivity with microphysics
   - No cloud control variables
   - Vertical velocity is diagnosed using the Richardson equation
   - Microphysics are diagnosed using a warm rain partition scheme
2. ***Indirect assimilation of reflectivity (Wang et al. 2013, preferred)***
   - Diagnose microphysics (q_r, q_s, q_g) and humidity from reflectivity
   - Assimilate the diagnosed quantities
   - Cloud control variables and vertical velocity control variable

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:

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

Radial velocity 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)

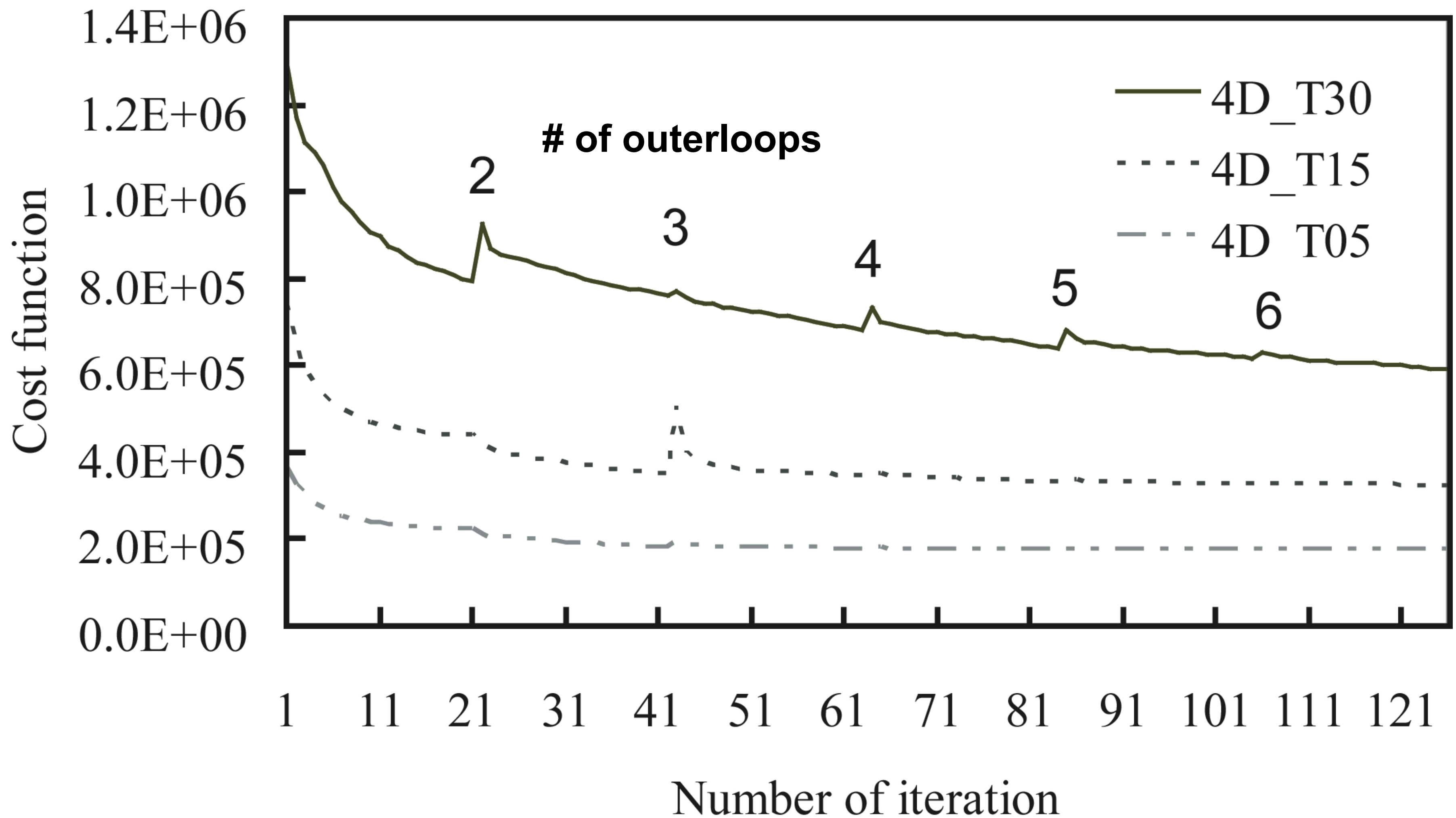
Multi-incremental 4DVar

Following Courtier et al. 1994, WRFDA uses a multi-incremental formulation, which means

- **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**

Details in Huang et al. (2010) and Wang et al (2013)

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



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

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

- 200km for GTS data and 30km for radar data are commonly used

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

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
```

Tuning BES parameters

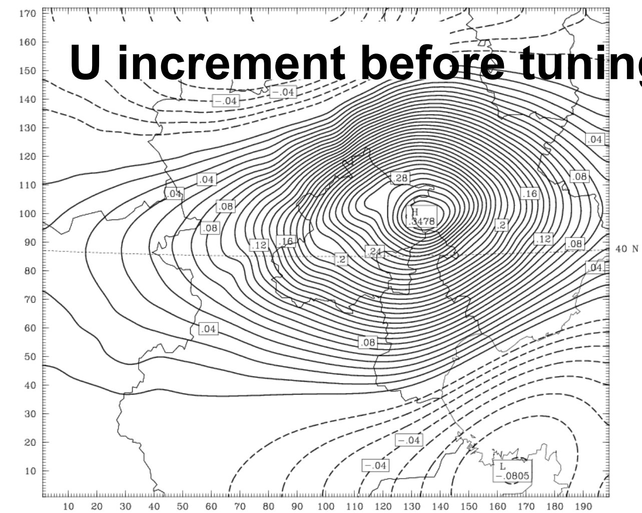
To change BES variance and length scale, do the following in your namelist.input:

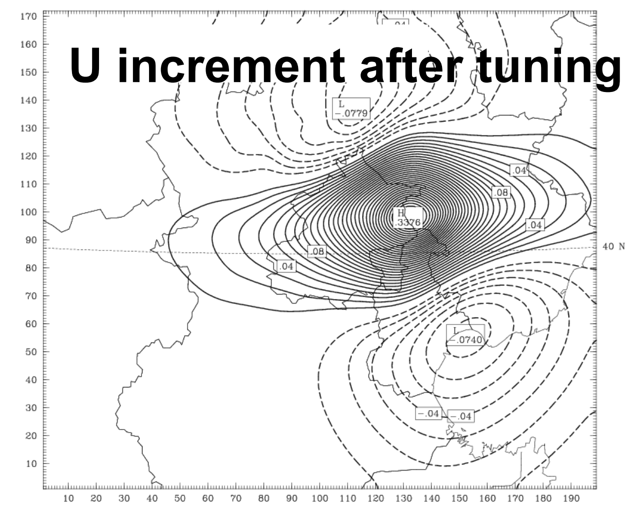
To decrease the weight of the background

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





A note on u/v momentum CV

- The new control variable (CV) option CV7 which uses u/v instead of psi/chi as momentum control variables is added in WRFDA3.7
- CV7 requires the computation of BES of u and v
- In the current version, correlation between variables is not considered
- But will be studied and included in a future release
- Sun et al. (2016, MWR)

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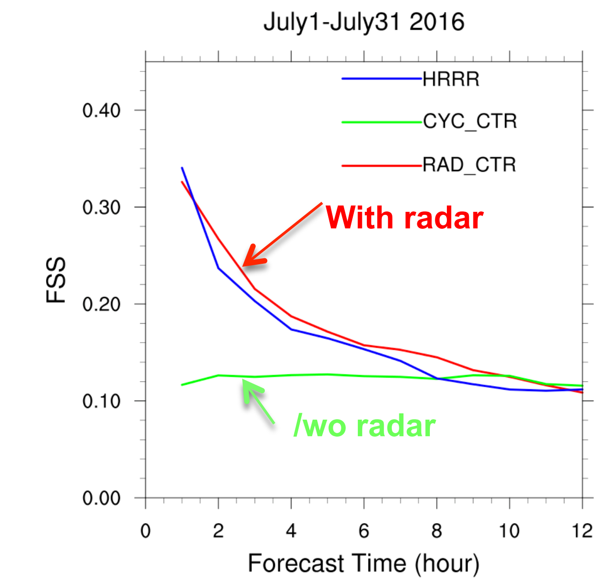
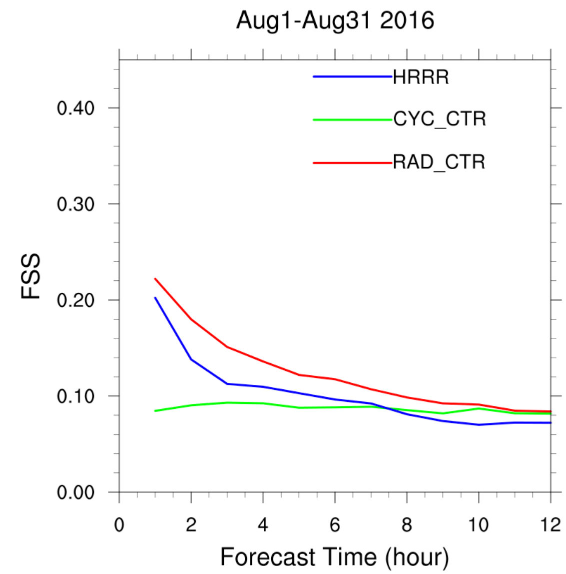
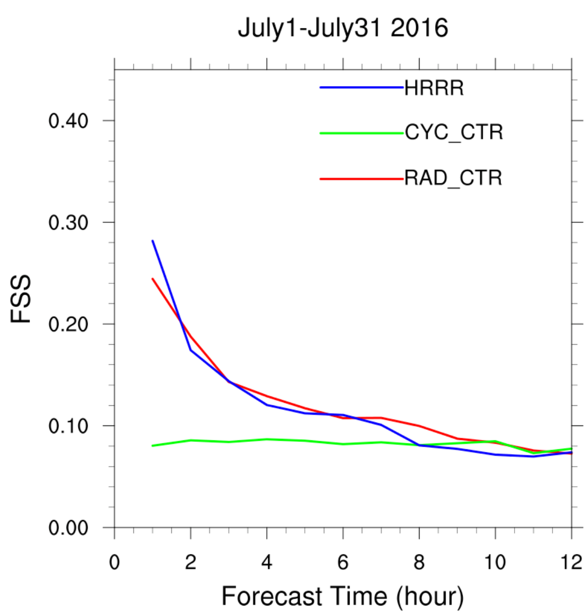
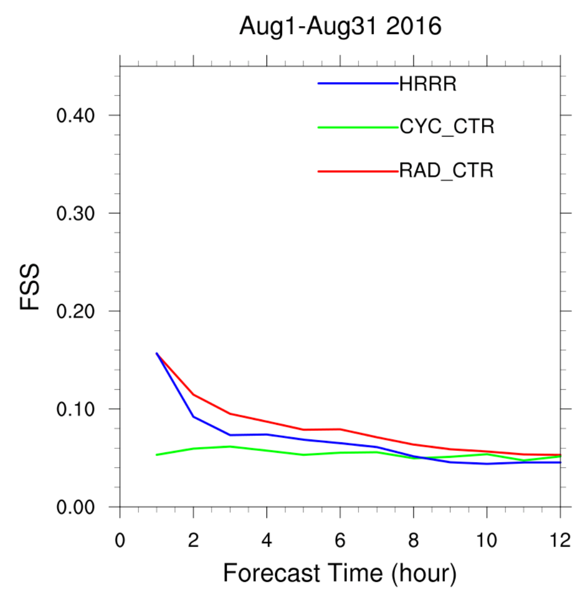
Impact of radar data assimilation (FSS)





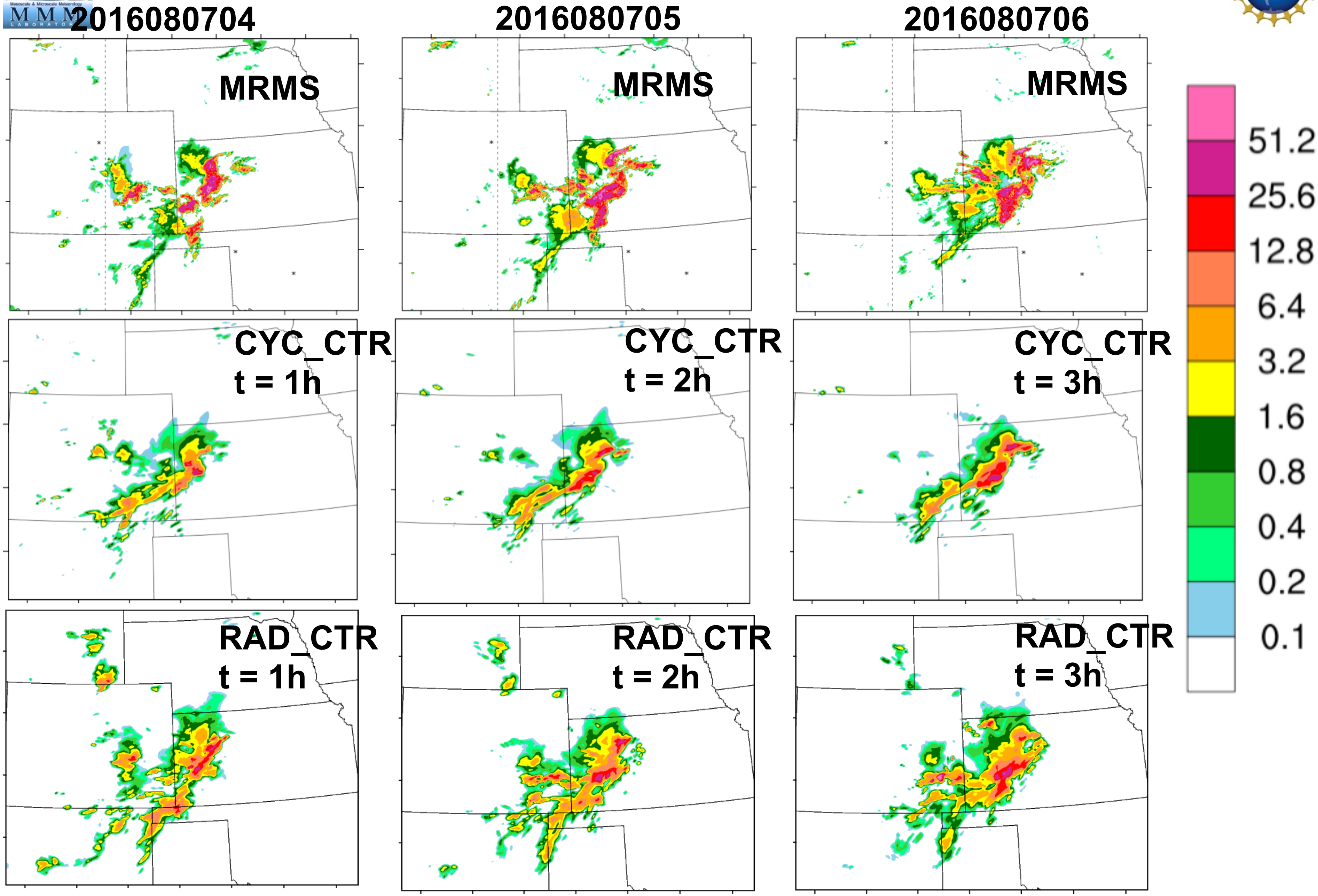
1mm





2.5 mm

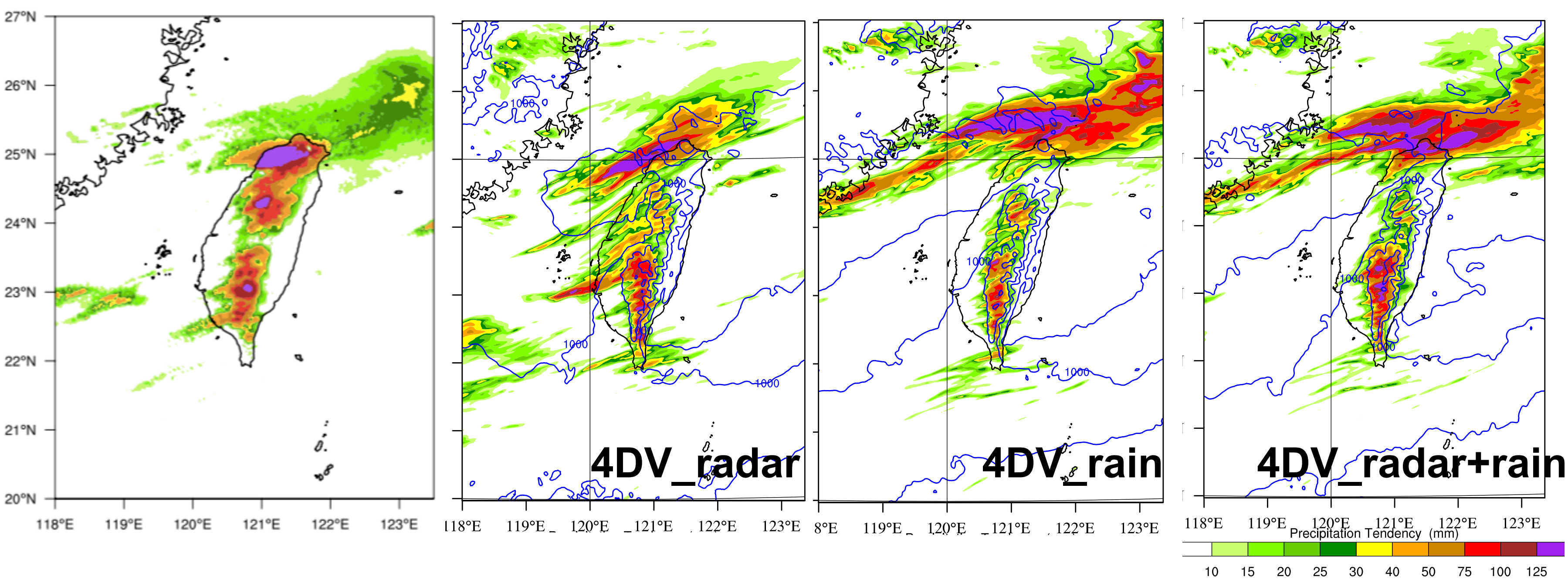
Comparing forecasts with/wo radar



Impact of assimilating both radar and rainfall

6hour Precip(QPE): 2012061121

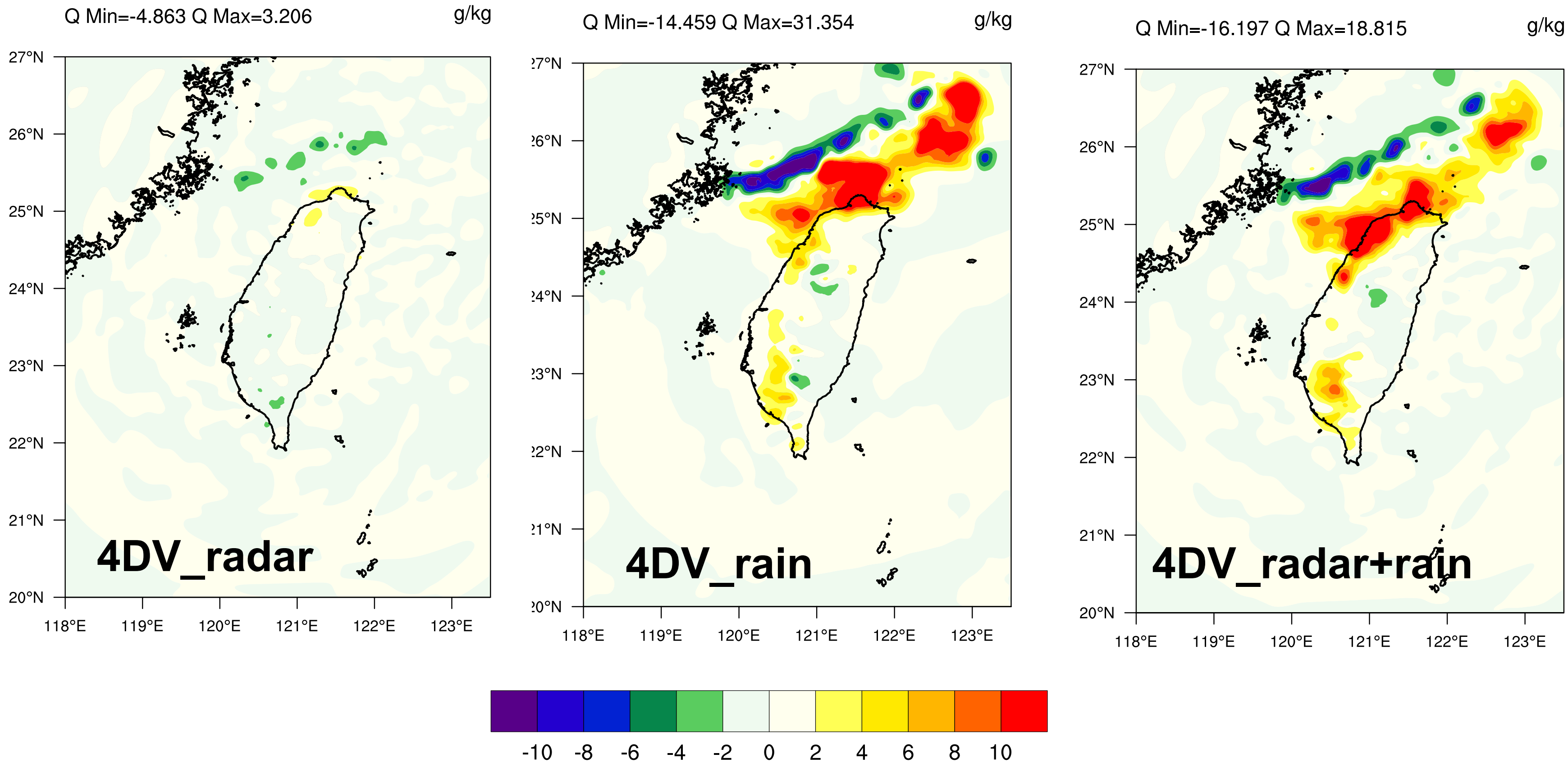
6h accumulated rainfall forecasts



- Radar+rain shifted the northern rain band to the land, agreeing better with QPE
- Radar+rain also improved the intensity of the precipitation on the mountains in southern Taiwan
- Combined assimilation of radar and 10min rainfall data with a 20min 4DVAR window is an innovative study; the result is promising

Comparison of humidity increments

850hpa

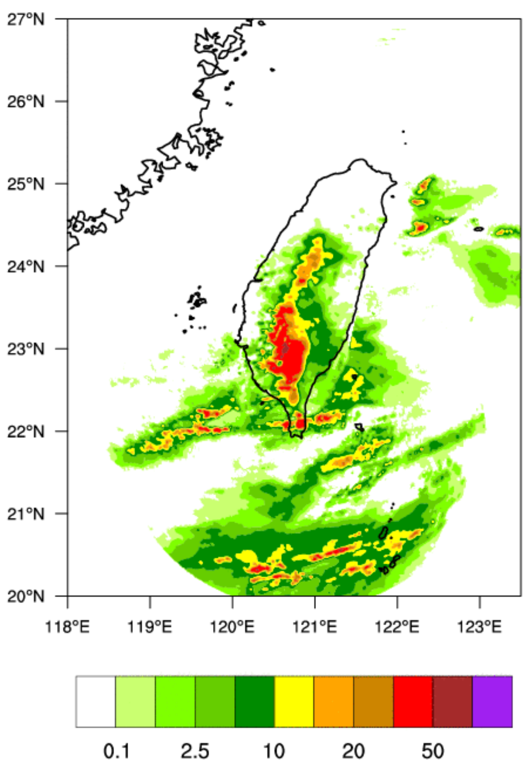


- **Combined assimilation of radar and rainfall tuned down the overly large humidity increment from that of the rainfall only experiment**
- **Combined assimilation also moved the humidity increment to the land**

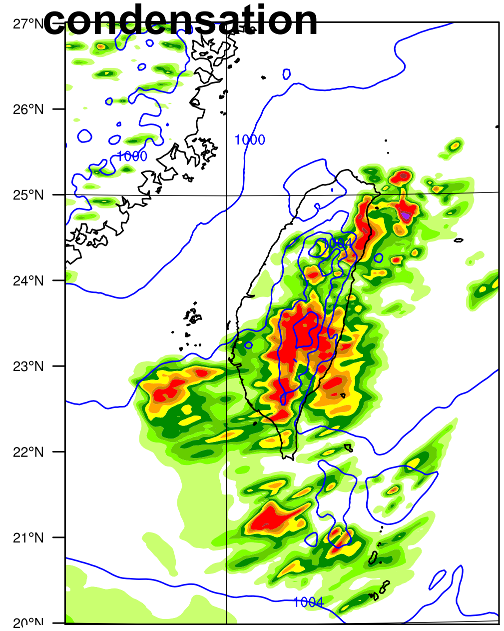
Sensitivity of physics in the TL and AD models

Precipitation forecasts at t = 2h for a Meiyu case occurred in Taiwan

1hour Precip(QPE): 2012061002

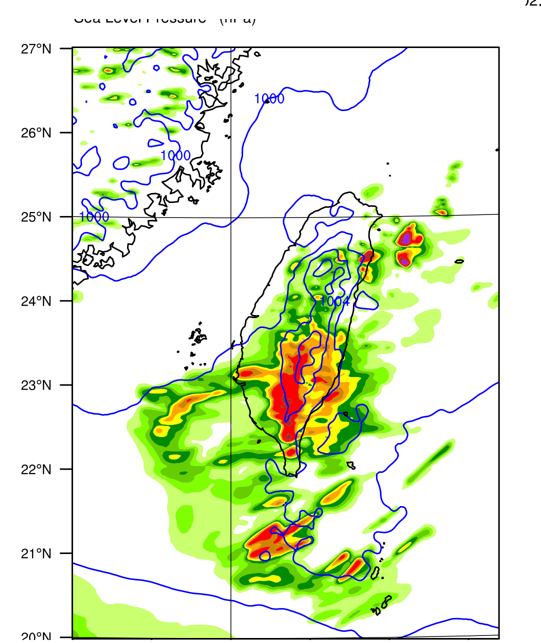


Large-scale condensation



118^{o}E 120^{o}E 122^{o}E

Kessler scheme



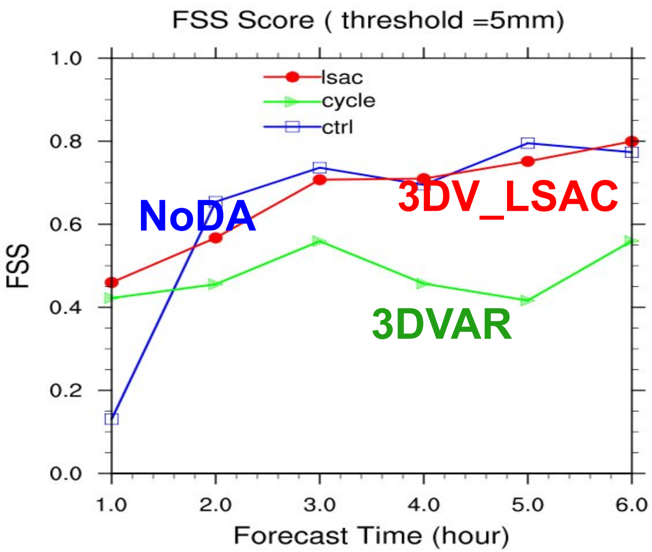
118^{o}E 120^{o}E 122^{o}E

Impact of LSAC on 3DVAR DA (future release)

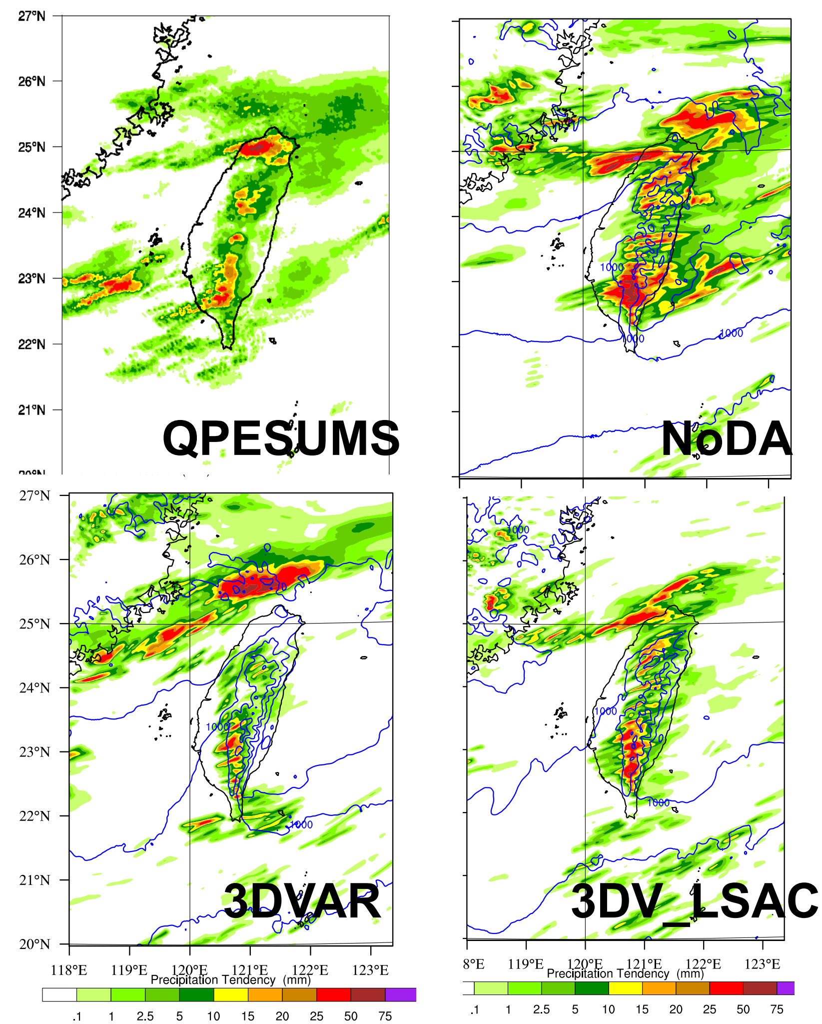
$$J = J_b + J_o + \frac{1}{2}(\mathbf{x}_0 - \mathbf{x}_0^{la})\mathbf{A}^{-1}(\mathbf{x}_0 - \mathbf{x}_0^{la})$$

LSAC: Large Scale Analysis Constraint

$\mathbf{x}_0^{\mathbf{la}}$ **: large-scale analysis (GFS)**



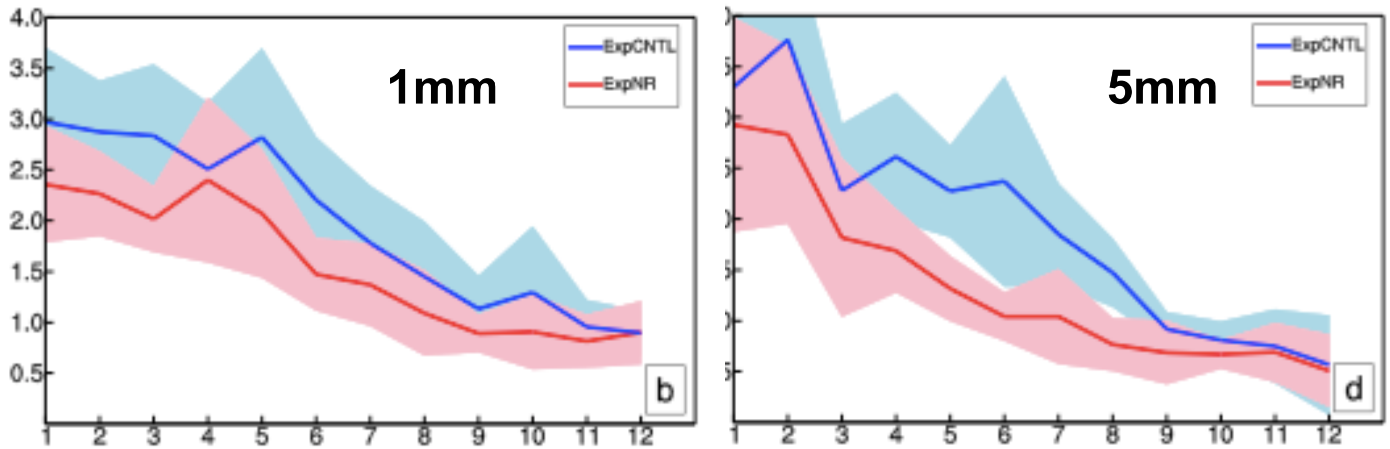
6th hour rainfall forecasts



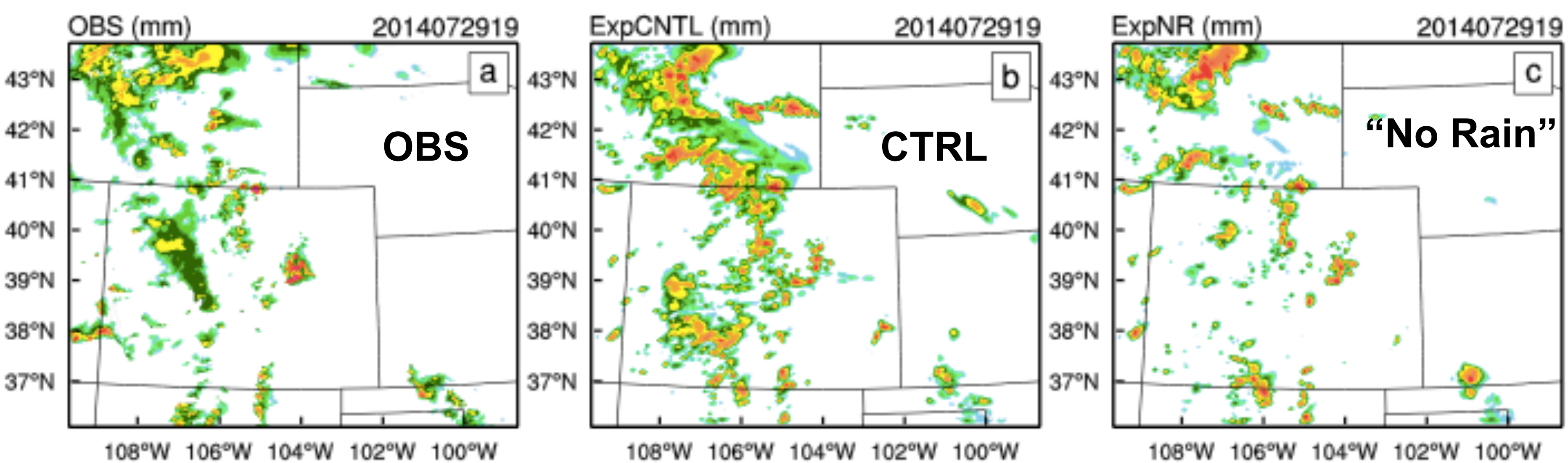
- **3DVAR w/o LSAC eliminates noise in NoDA, but also some signals**
- **3DVAR_LSAC is able to keep the analysis close to high resolution observations while still maintaining large-scale balance, resulting in improved rainfall forecast**

Reducing BIAS by assimilating "no rain" reflectivity data (future release)

BIAS **July 1 – August 31 2016**



Red: "no rain" DA
Blue: Control



Ongoing research

- **How to configure 4DVar for radar data assimilation and short-term convective forecasting?**
  - physics options
  - cycling strategy
  - multi-incremental method

- **Improve flow-dependent BE (error of the day) using the ensemble method**
  - Application of WRFDA hybrid-3DVar to radar data assimilation
  - Benefit of using EnKF to update perturbation (En3DVar vs. 3DEnVar)

- **Combined assimilation of radar and rainfall**
  - How to define rainfall error
  - Assimilate radar QPE and surface rainfall