Radar Data Assimilation with WRFDA

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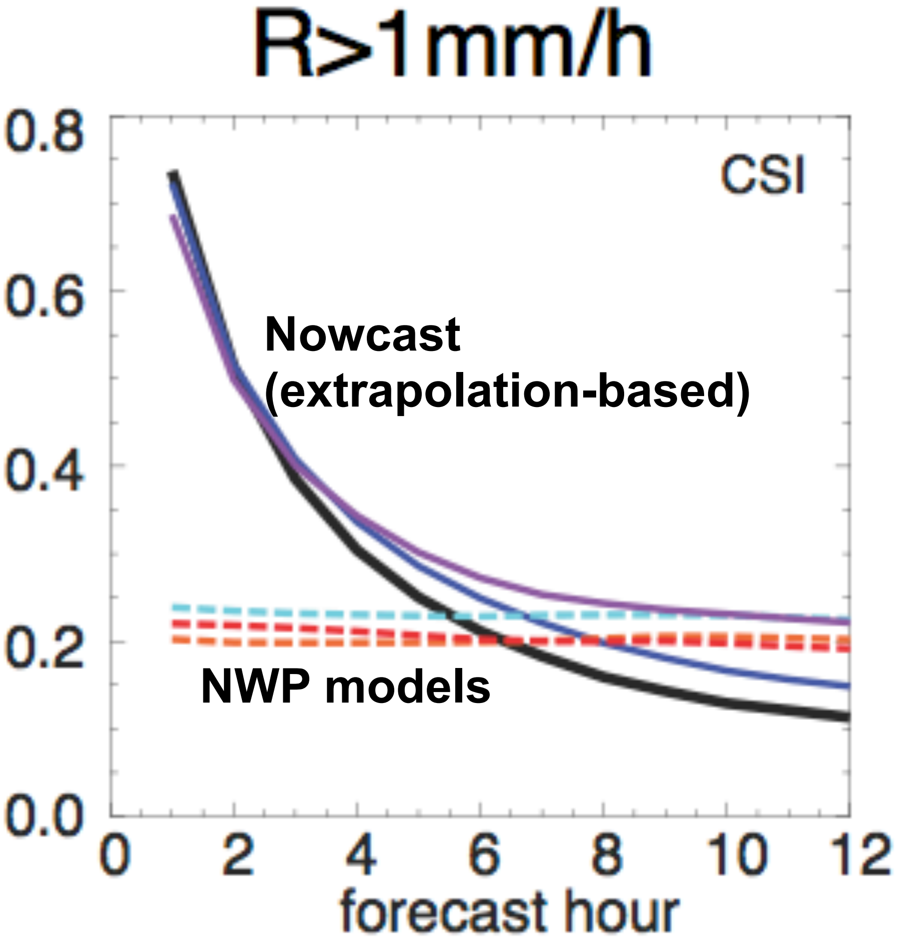
OUTLINE

- **Introduction: motivation, milestones, and current capabilities**
- **WRFDA-radar procedure and methods**
- **Configure and run WRFDA-radar**
- **Applications and ongoing research**

Why radar data assimilation



Courtesy of Isztar Zawadzki (2012)

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

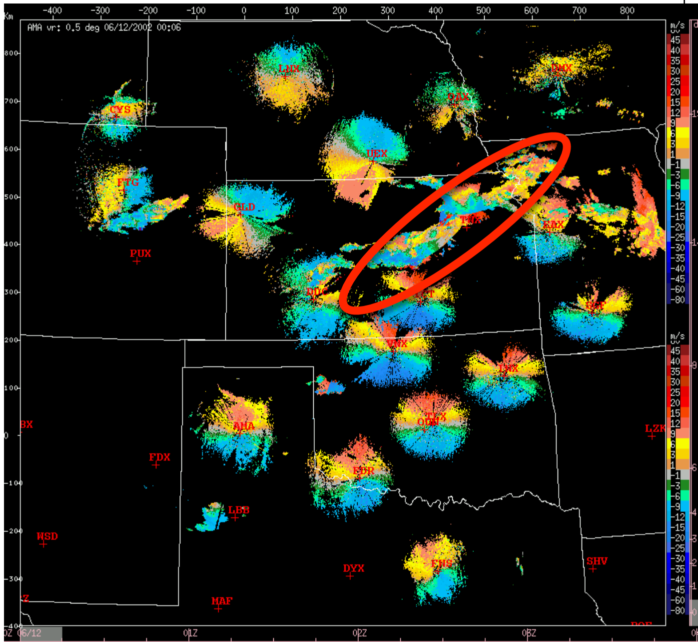
Good

- 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

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

Radial velocities from 20 WSR-88D radars



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. 2015)

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
- Operational capability since 2012
- Hourly cycle tested recently in a real time demonstration in CO

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
- 4DVar framework is fully consistent with 3DVar

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 methods (options)

- **Radial velocity or reflectivity or both**

  use_radarobs=true,

  use_radar_rv=true,
- **3DVar (default) or 4DVar**

  var4d=true
- **Two methods for reflectivity DA**

  use_radar_rf = true

  use_radar_rhv = true
- **Microphysics control variables**

  cloud_cv_options = 3   BE of regular variables are from gen_be; cloud variables hard coded
- **Cloud analysis scheme (assimilate estimated water vapor)**

  use_radar_rqv=true
- **u/v momentum control variables**

  cv_options = 5   5: standard psi/chi CV   7: new u/v CV
- **Choice of data: radar only, GTS+radar, or GTS then radar**

Observation operators

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

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

Z-q_r Relation (assume Marshal-Palmer DSD)

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

Can also use empirical relations obtained by fitting with disdrometer data

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

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)**
   - **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 $\psi/\chi_{u)}$, 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**

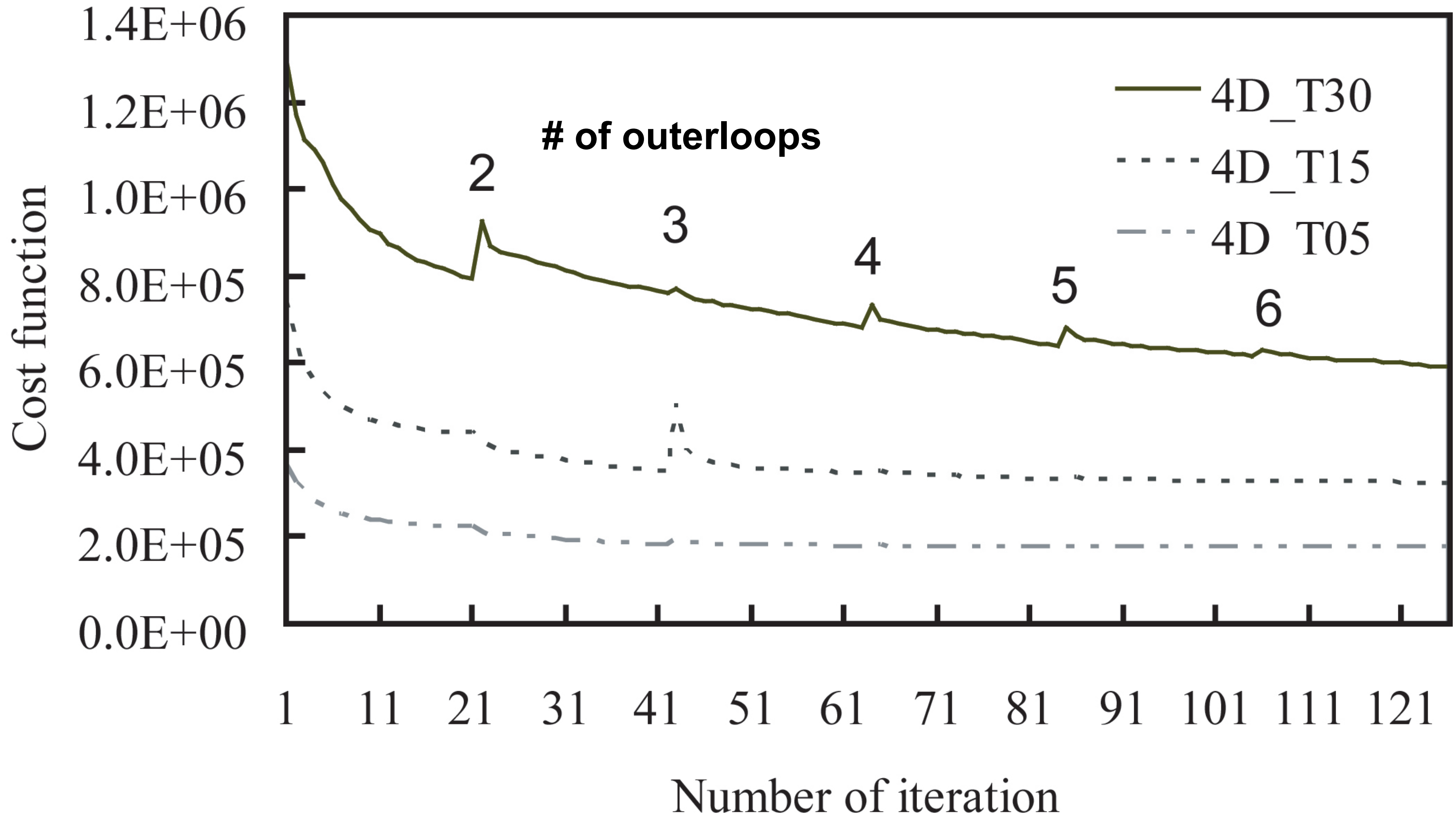
Multi-incremental 4DVar

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 different lengths of windows



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Basic steps for radar DA

Step 1: prepare radar data in the correct format and write the data into ob.radar (ob01.radar, ob02.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 prior to compiling

setenv CLOUD_CV 1 - for csh

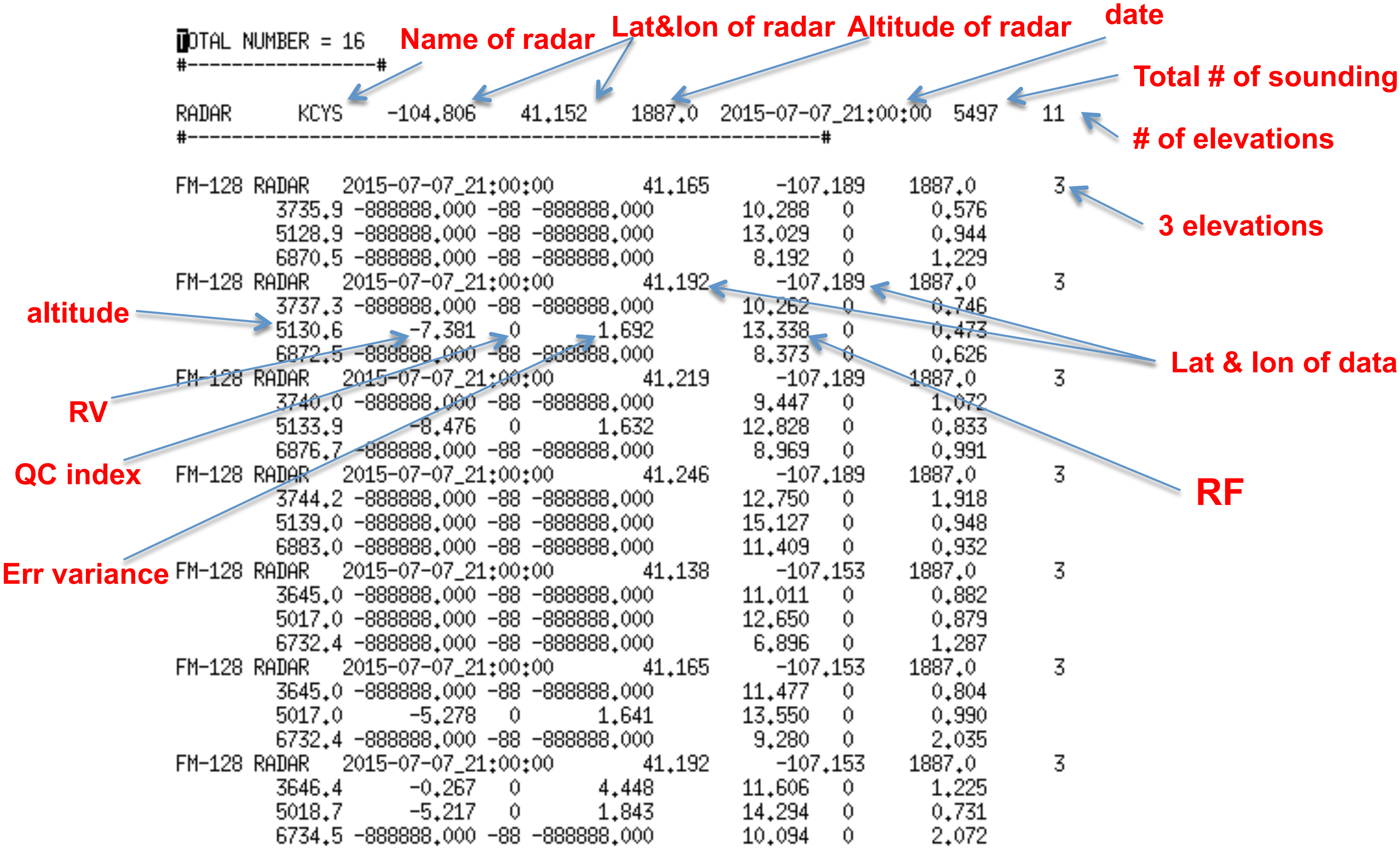
export CLOUD_CV = 1 - for both ksh and bash

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
```

Example of data format



```
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

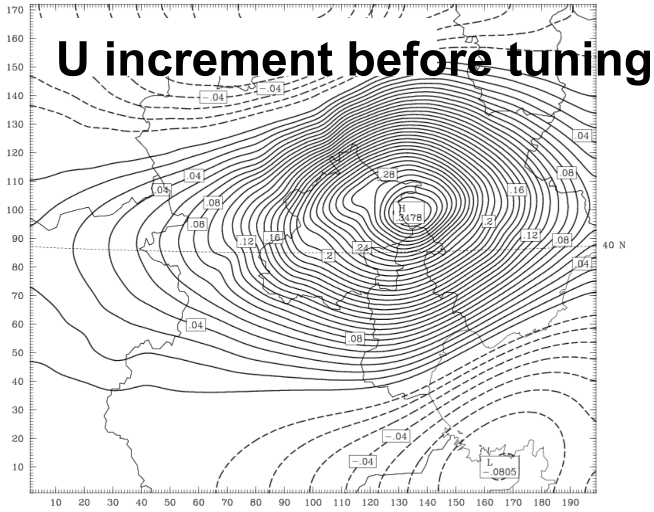
To change BES variance and length scale, do the following in your namelist.input:

To decrease the weight of the background

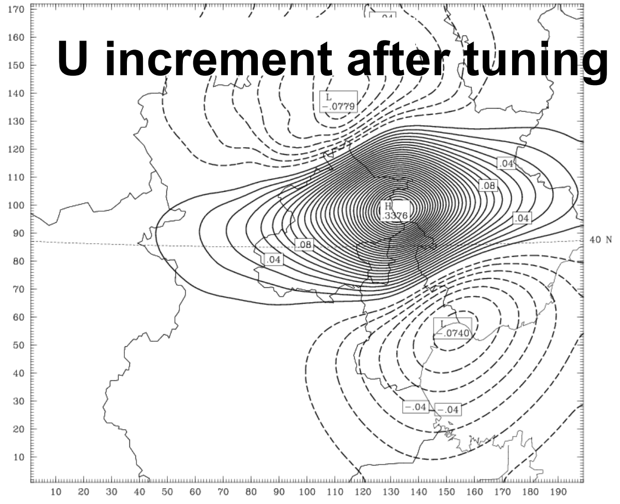
```
VAR_SCALING1=2.0
VAR_SCALING2=2.0
VAR_SCALING3=2.0
VAR_SCALING4=2.0
VAR_SCALING5=2.0
```

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
```



U increment before tuning



U increment after tuning

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. (2015, MWR under review)**

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Scientific issues of radar DA

- **Impact of radar data assimilation on convective forecasting**

- **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)

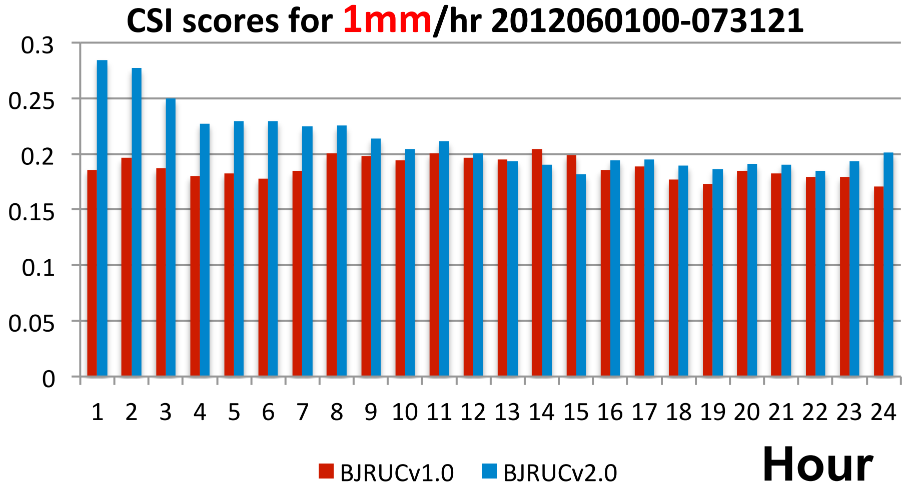
- **Comparison of 4DVar and 3DVar**
  (Sun and Wang 2014)

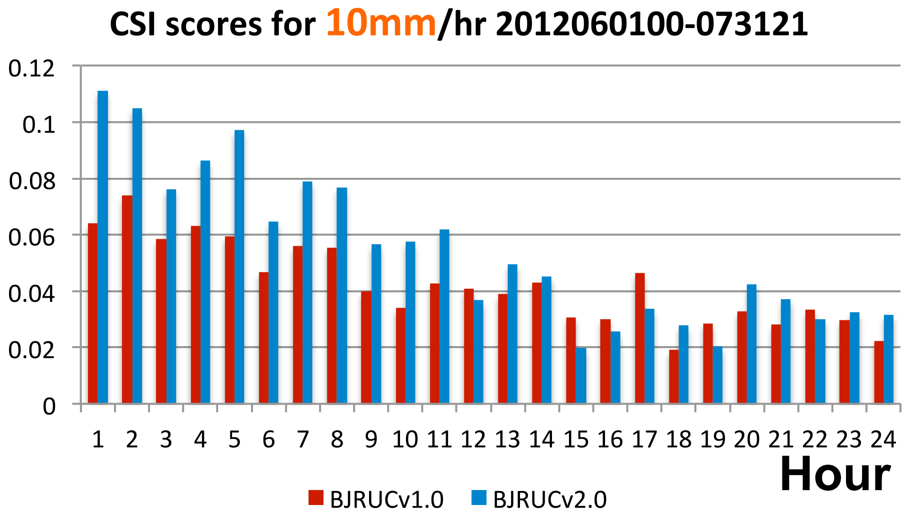
- **Impact of the choice of momentum control variables**
  (Sun et al 2015, under review)

- **Controlling noise in high-resolution analysis with multi-scale balance**
  (Vendrasco et al. 2015, under review)

Operational performance of WRFDA-radar at BMB

Precipitation verification for June & July 2012


CSI scores for 1mm/hr 2012060100-073121


CSI scores for 10mm/hr 2012060100-073121

🟦 **With radar**

🟥 **Without radar**

- **WRFDA-radar has been operational at Beijing Meteorological Bureau since 2012**
- **The local forecasters has become dependent on the system to forecast localized convective weather**

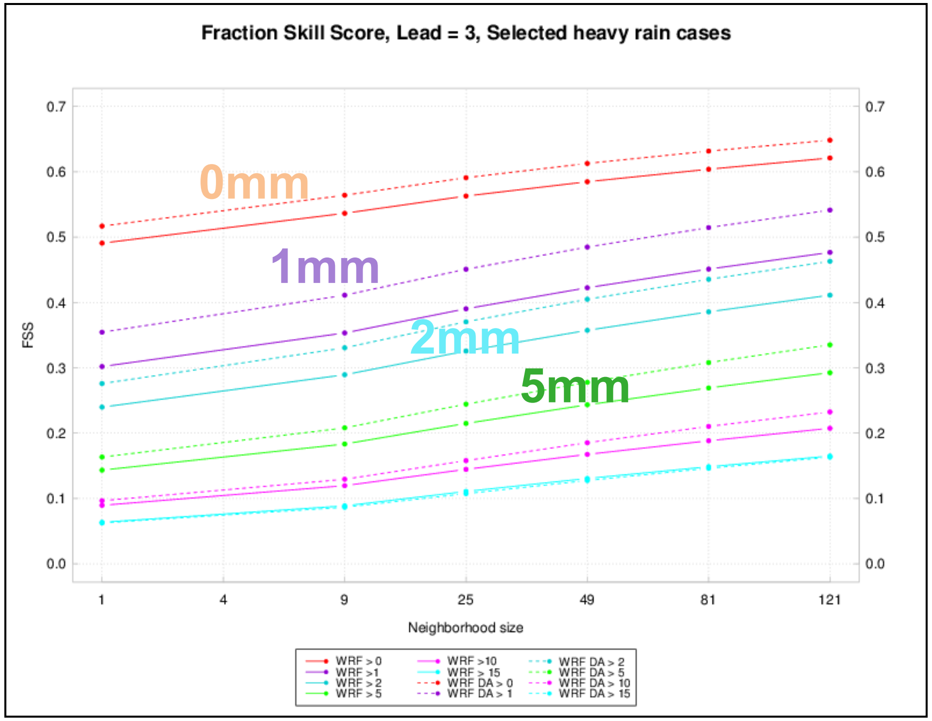
Courtesy of S. Fan

WRFDA realtime demonstration in CO Front Range with hourly update cycles

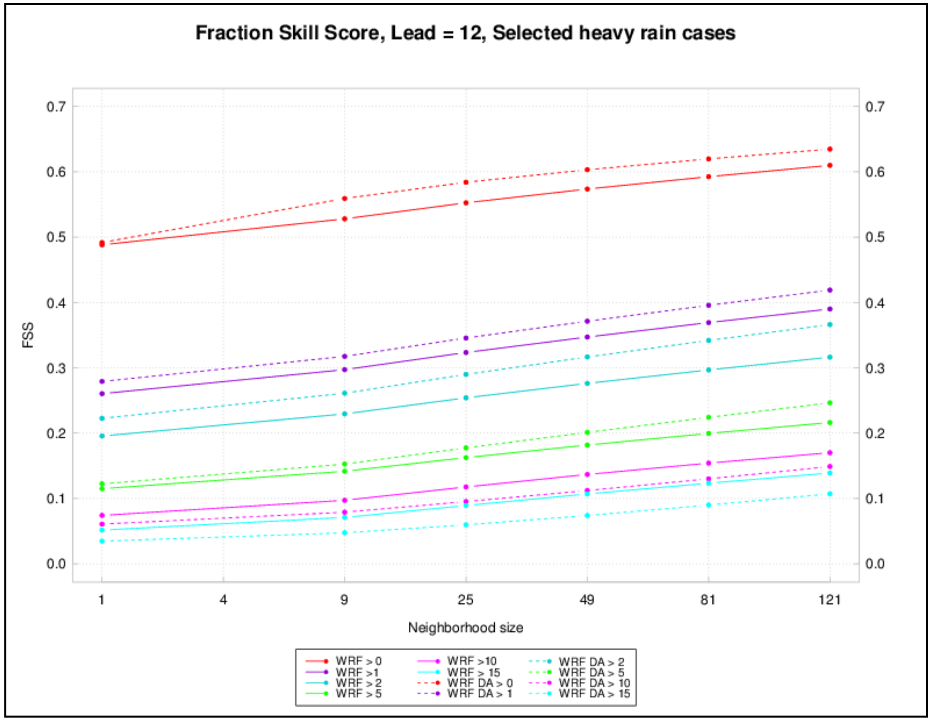
Precipitation verification for 7 July – 15 August

Solid lines: no radar **Dashed lines: with radar**

t = 3h



t = 12h

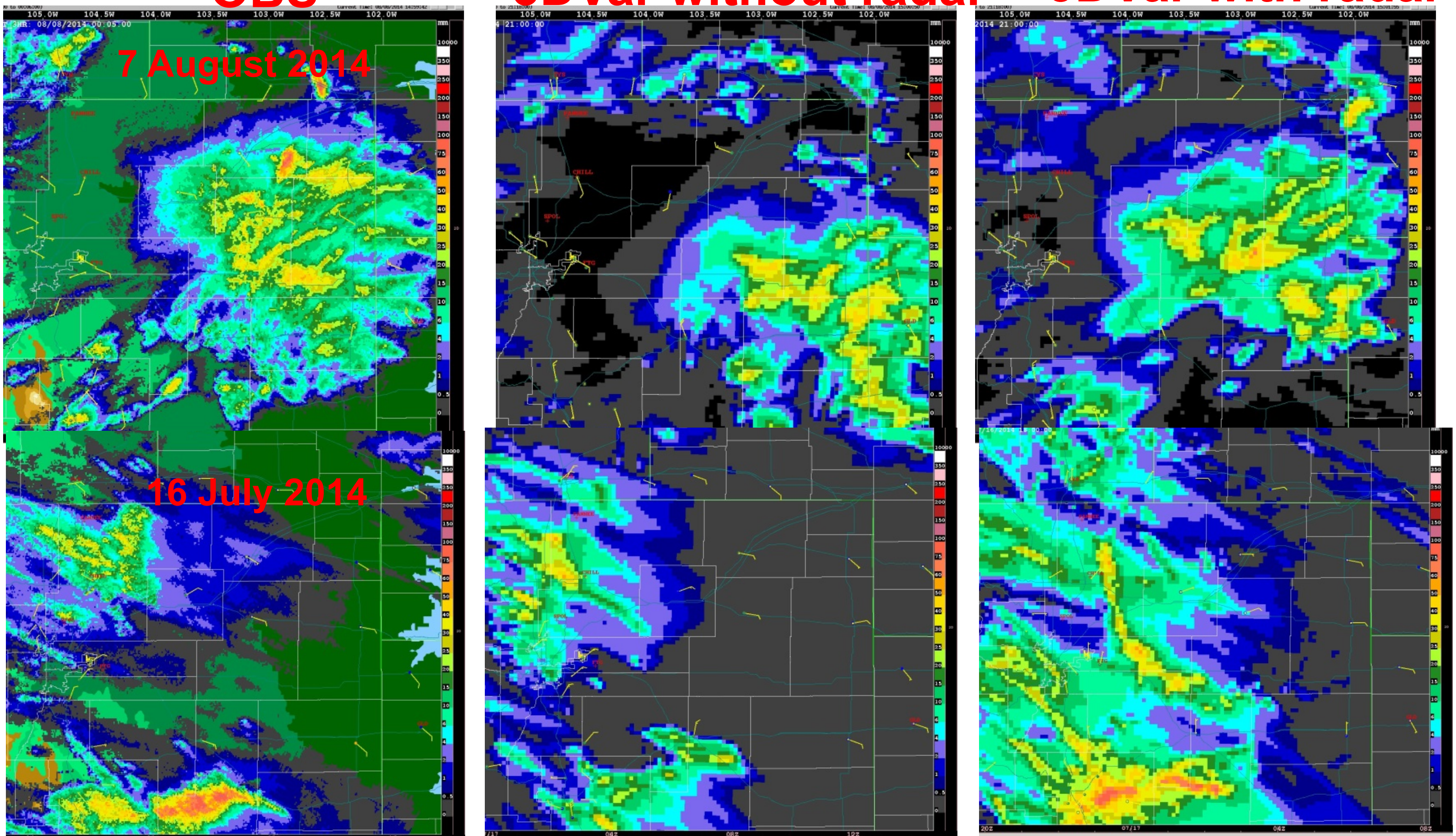


Courtesy of Barb Brown

WRFDA realtime demonstration in CO Front Range with hourly update cycles

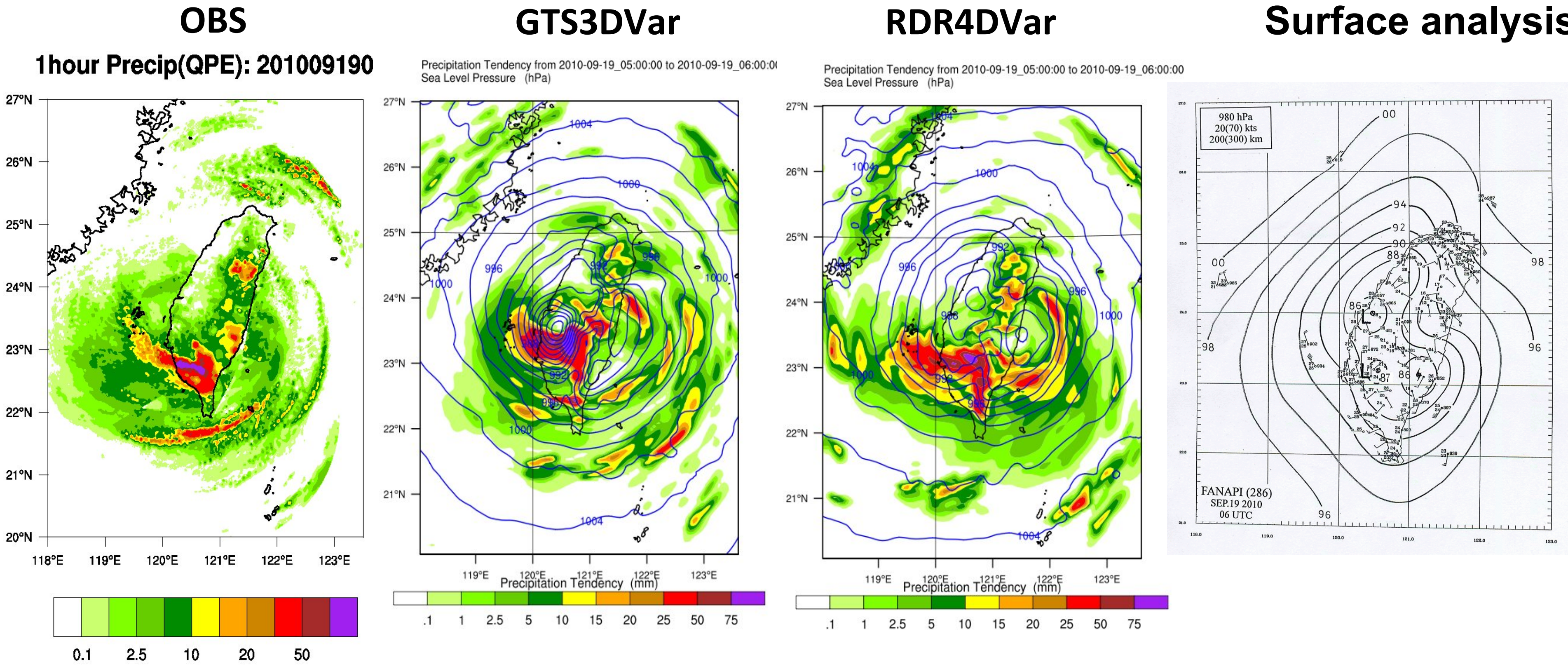
3h accumulated rainfall in northeastern Colorado during STEP Hydromet realtime experiment at t = 3h

OBS — 3DVar without radar — 3DVar with radar



4DVar radar DA for Typhoon Fanapi

Hourly precipitation at t = 6h



OBS

GTS3DVar

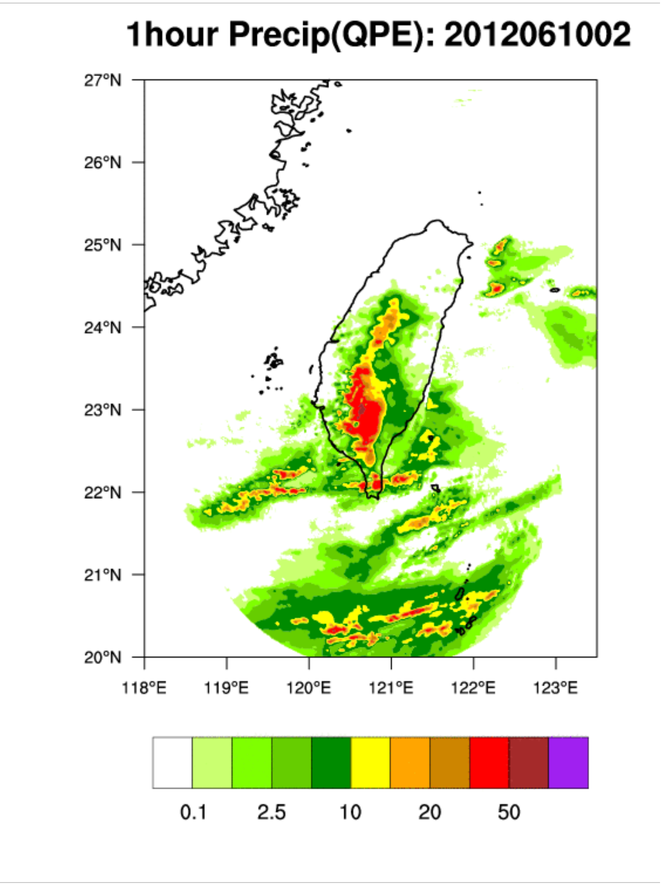
RDR4DVar

Surface analysis

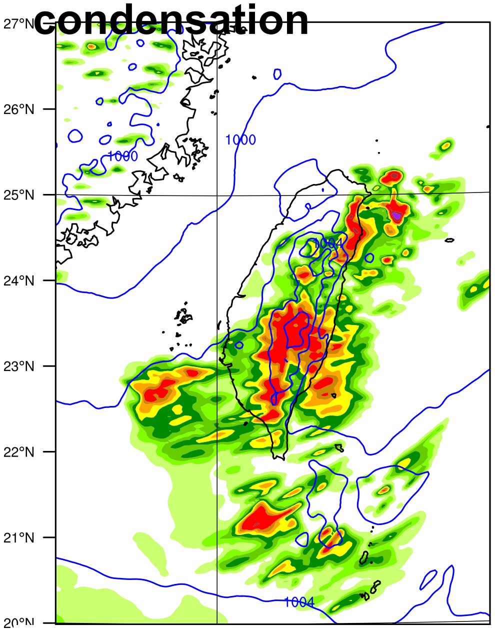
- **4DVar successfully predicts the two low pressure centers with similar magnitudes as in the surface analysis**

Sensitivity of physics in the TL and AD models

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

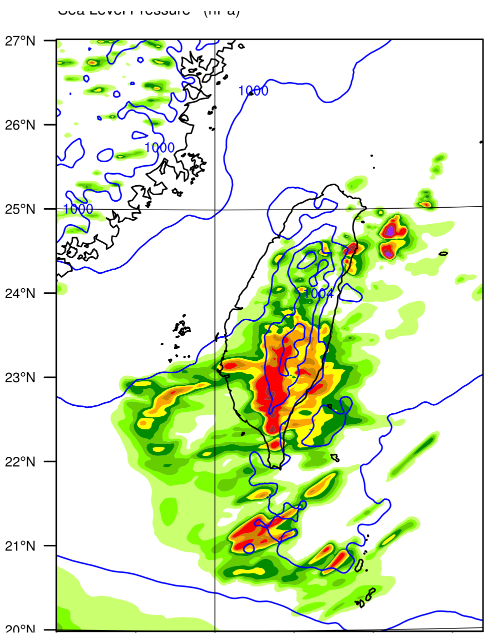


Large-scale condensation



118°E 120°E 122°E

Kessler scheme



118°E 120°E 122°E

Ongoing research

- **Improve 3DVar hourly cycle, especially the issue of overprediction in the first few hours**
  - ***Improve the cloud analysis scheme using PW from GPS network***
  - ***Develop a scheme that maintains total water conservation***

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

- **Reduce noise in the analysis using constraints in the cost function**
  - ***Bias in the background; the imbalance issue in the analysis***

Future research

- **Improve flow-dependent BE (error of the day) using the ensemble method**

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

- **Improve climatology BE**

  - The effect of geographic inhomogeneity (Wang et al. 2015)

  - The effect of diurnal cycle

- **Improve 4DVar for convective-scale DA**

  - How to do multi-incremental DA for the convective-scale?

  - The short window vs. long window dilemma

  > multi-step approach?

  > 3DVar/4DVar hybrid?

  - En-4DVar

  - Consider uncertainties in physics

- ***Polarimetric radar data assimilation***