Progress and preliminary evaluation of upgraded WRF 4D-Var and GSI-based WRF 4D-Var

Xin Zhang Xiang-Yu Huang
Ning Pan Qiang Cheng Junmei Ban

NCAR Earth System Laboratory

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Status of WRF 4D-Var V3.2

- WRF 4D-Var was firstly released in April, 2009 with V3.1.
- WRF adjoint and tangent linear codes (WRFPLUS) were developed based on WRF V2.0.2 around 2005.
- Multiple Program Multiple Data (MPMD) framework, needs 3 executables: WRFDA, WRFNL and WRFPLUS.
- Simplified physical packages: surface drag, large scale condensation and a cumulus parameterization schemes.
- Weak constraint with digital filter.

Know issues of WRF 4D-Var V3.2

- Numerous bug fixes, upgrades and improvements in WRF model since 2005. V3.3 is released.
- Particularly, WRF infrastructure changes invalid some interfaces in WRFPLUS, such as the boundary variables can not be read in anymore.
- MPMD WRF 4D-Var is too complicate, most of the community users could not get it run without help.
- Very high disk IO overhead associated with the number of processors.
- Only runs good on IBM machines; unstable on other platforms and compilers.
- 4D-Var support for Prepbufr and radiance bufr data is not clear.
- Hard to do a complete adjoint check due to initial design of framework.

WRFPLUS V3.3 Upgrades

- WRF adjoint and tangent linear codes V3.3 based on the latest WRF V3.3.
- Constructed interfaces through which other applications can call WRF adjoint and tangent linear model directly.
- Testing the code on various platforms and compilers (IBM, Linux, Mac : xlf, g95, pgi, intel, gfortran).
- Capability to do tangent linear and adjoint test over any length of time window.
- WRFPLUS V3.3 can be used as a standalone tool or as a component in 4D-Var system.

Sample Tangent Linear and Adjoint Check of WRFPLUS V3.3

Tangent linear check:6 hours

```
alpha_m=.1000E+00  coef=   0.98186174930325E+00  val_n= 0.3725210E+11  val_l= 0.3794027E+11
alpha_m=.1000E-01  coef=   0.99807498026522E+00  val_n= 0.3786723E+09  val_l= 0.3794027E+09
alpha_m=.1000E-02  coef=   0.99970559707666E+00  val_n= 0.3792910E+07  val_l= 0.3794027E+07
alpha_m=.1000E-03  coef=   0.99992019503144E+00  val_n= 0.3793724E+05  val_l= 0.3794027E+05
alpha_m=.1000E-04  coef=   0.10000447262220E+01  val_n= 0.3794196E+03  val_l= 0.3794027E+03
alpha_m=.1000E-05  coef=   0.99999981575068E+00  val_n= 0.3794026E+01  val_l= 0.3794027E+01
alpha_m=.1000E-06  coef=   0.99999998152933E+00  val_n= 0.3794027E-01  val_l= 0.3794027E-01
alpha_m=.1000E-07  coef=   0.99999990980017E+00  val_n= 0.3794026E-03  val_l= 0.3794027E-03
alpha_m=.1000E-08  coef=   0.99999956711797E+00  val_n= 0.3794025E-05  val_l= 0.3794027E-05
alpha_m=.1000E-09  coef=   0.10000030220656E+01  val_n= 0.3794038E-07  val_l= 0.3794027E-07
alpha_m=.1000E-10  coef=   0.99996176999678E+00  val_n= 0.3793882E-09  val_l= 0.3794027E-09
```

Adjoint check: 6 hours

```
ad_check: VAL_TL:    0.42476489986911E+11
ad_check: VAL_AD:    0.42476489986912E+11
```

Single executable 4D-Var

WRFPLUS includes WRF NL, AD and TL model and they are used as a subroutine in WRF 4D-Var V3.3, other than being called via shell scripts in V3.2.

Nonlinear call

old	`call da_system ("da_run_wrf_nl.ksh")`
new	`call da_nl_model`

Tangent linear call

old	`call da_system ("da_run_wrfplus_tl.ksh")`
new	`call da_tl_model`

Adjoint call

old	`call da_system ("da_run_wrfplus_ad.ksh")`
new	`call da_ad_model`

Memory exchange

The information (TL perturbation, adjoint forcing, basic states and gradient) is exchanged via linked lists.

Read basic states

```
call domain_clock_get( grid, current_timestr=timestr )
call da_read_basicstates ( xbx, grid, ... )
```

Save TL perturbation

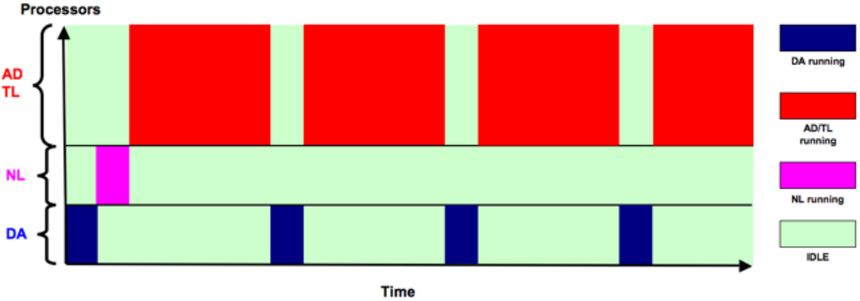
```
call push_tl_pert (timestr)
```

Save AD forcing

```
call push_ad_forcing (timestr)
```

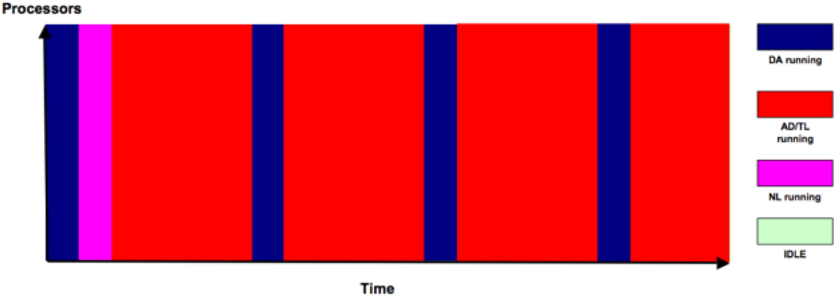
Parallel run using all processors

4D-Var is a sequential algorithm. However, the current parallel WRF 4D-Var constructed on the Multiple Program Multiple Data mode, which have to split the total processors into 3 subsets for DA, NL and AD/TL. Lots of CPU time are wasted



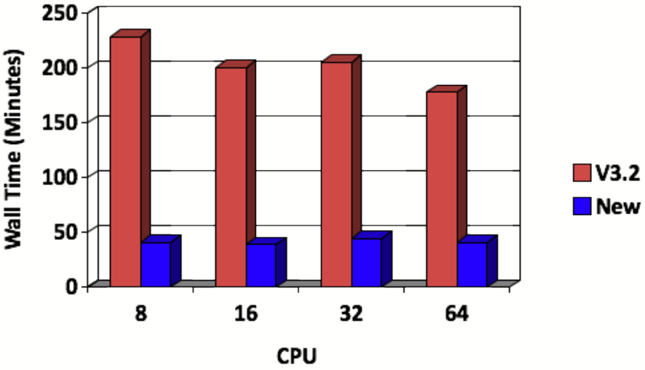
Parallel run using all processors

Benefit from the single executable framework, every CPU is working at any time. No IDLE any more.



Performance improvement WRF 4DVar framework only

- $270x180x41@20km$,6h window, 1h obs_bin, 10 iterations
- 10 iterations FGAT, NCAR bluefire (IBM P6)



Consider Lateral boundary condition as control variable

$$J = J_b + J_o + J_c + J_{lbc}$$

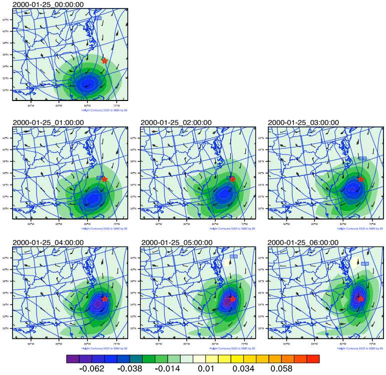
$$\begin{aligned} J_{lbc} &= \frac{1}{2}(\mathbf{x}(t_k) - \mathbf{x}_b(t_k))^T \mathbf{B}^{-1} (\mathbf{x}(t_k) - \mathbf{x}_b(t_k)) \\ &= \frac{1}{2}\delta\mathbf{x}(t_k)^T \mathbf{B}^{-1} \delta\mathbf{x}(t_k) \end{aligned}$$

J_{lbc} is the J_b at the end of the assimilation window
lateral boundary control is obtained through

$$\frac{\partial \delta \mathbf{x}_{lbc}}{\partial t} = \frac{\delta\mathbf{x}(t_k) - \delta\mathbf{x}(t_0)}{t_k - t_0}$$

Single observation experiments

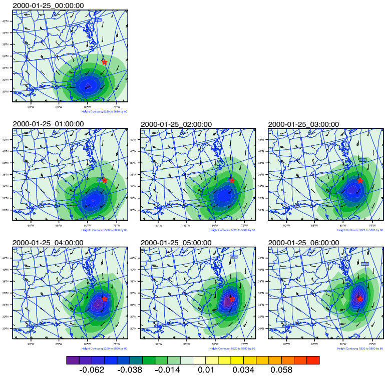
- Initial time: 2000_01_25_00 : 00 : 00
- Ending time: 2000_01_25_06 : 00 : 00
- Observation: 500 mb Temperature at ending time
  $O - B = -1.168K$
- To investigate the difference at ending time between the forecast from analysis and from background.



Remarks

Forecasted 500mb T difference (DA forecast - reference forecast)

- ⋆ is the location of obs. at the ending time (6h).
- JcDF is turned on
- LBC control is turned on
- Initial perturbation is on the upstream of the obs.
- Evolved perturbation at 6h hit the obs. location



Remarks

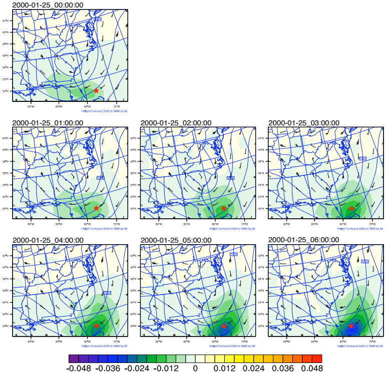
Forecasted 500mb T difference (DA forecast - reference forecast)

- ⋆ is the location of obs. at the ending time (6h).
- JcDF is turned on
- LBC control is turned off

Additional experiments design

Observation close to boundary

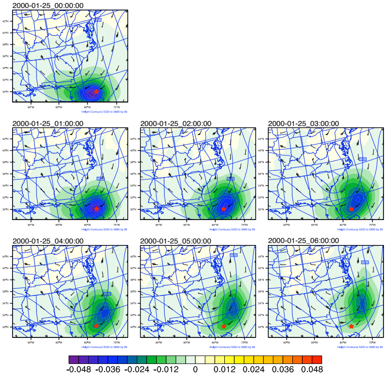
To investigate the impact of including boundary condition in data assimilation, the 6h observation is close to boundary and downstream of the boundary, we expect that the analysis response at 0h should be in boundary condition other than initial condition.



Remarks

Forecasted 500mb T difference (DA forecast - reference forecast)

- ⋆ is the location of obs. at the ending time (6h).
- JcDF is turned on
- $O - B = -0.95K$
- LBC control is turned on
- Main initial perturbation is in the boundary condition other than in the initial condition (south boundary, invisible here)
- Evolved perturbation is coming from boundary, pay attention to some positive increments along south boundary



Remarks

Forecasted 500mb T difference (DA forecast - reference forecast)

- ⋆ is the location of obs. at the ending time (6h).
- JcDF is turned on
- LBC control is turned off
- Main Initial perturbation is in the location of the obs., it is fake
- Evolved perturbation at 6h is moving out from the obs. location

Summary

- The single executable WRF 4DVar system was developed and has showed promising performance.
- The new WRF 4DVar system has the capability to assimilate conventional observational data (little_r or prepbufr format),radiance in bufr format and radar data.
- The new WRF 4DVar system is able to consider lateral boundary condition as control variable and digital filter can be used as a weak constraint to suppress the high frequency noise.

Under development

- Enhance WRFPLUS V3.3 with simplified physics packages: surface drag(done), large scale condensation, a simplified moist cumulus scheme, as well as a radiation scheme.
- Parallelization of WRF tangent linear code has been done. We are working on the parallelization of WRF adjoint codes.

Current Status of GSI-based WRF 4D-Var

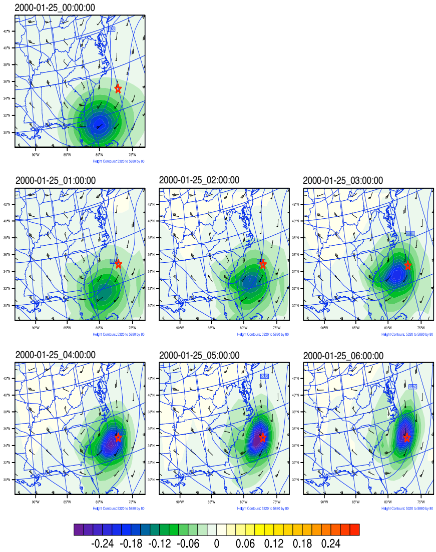
- The development of GSI-based WRF 4DVAR is based on Boulder's version as of February 2011
- The Major development in GSI had finished, GSI codes had been coupled with the WRF tangent linear and adjoint model
- The WRF tangent linear and adjoint codes (hereafter, WRFPLUS) have been updated to be consistent with the latest WRF repository codes
- Because the parallelization of the latest WRFPLUS is still on going, only 1 processor parallel run is doable at this moment

Modification in GSI

- Modified the capabilities to read and process multiple first guess and process obs. data for multiple time slots (?)
- Added a new module which serves the hub between GSI and WRFPLUS
- Added WRF TL/AD subroutines calling interface in model_tl and model_ad
- Added capability to do adjoint test with WRF AD/TL.

Single observation exp.

- Initial time: $2000\_01\_25\_00:00:00$
- Ending time: $2000\_01\_25\_06:00:00$
- Observation: 500 mb Temperature at ending time
  $O - B = -1.17K$
- To investigate the difference at ending time between the forecast from analysis and from background.

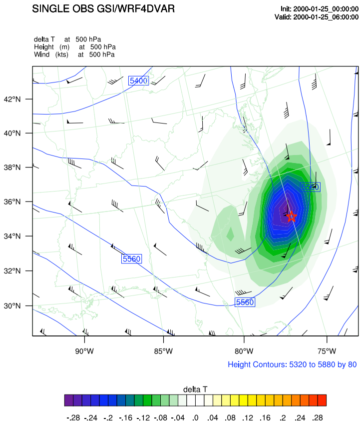


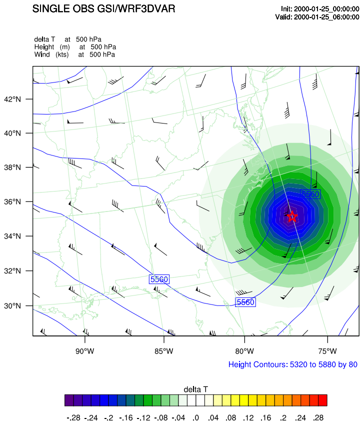
Remarks

Forecasted 500mb T difference (DA forecast - reference forecast)

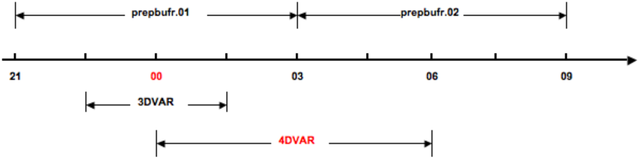
- ⋆ is the location of obs. at the ending time (6h).
- Initial perturbation is on the upstream of the obs.
- Evolved perturbation at 6h hit the obs. location
- Very obvious flow dependent characteristics

Analysis increment comparison valid@6h—4DVAR and 3DVAR





Tutorial case – Observation Usage



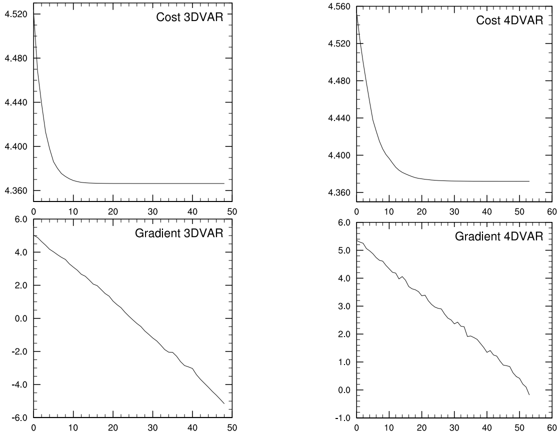
3DVAR

```
0:OBS_PARA: ps            13842
0:OBS_PARA: t             20114
0:OBS_PARA: q             18743
0:OBS_PARA: uv            30894
0:OBS_PARA: spd              48
0:OBS_PARA: sst             503
0:OBS_PARA: pw              880
----------------Total--------------------
47675
```

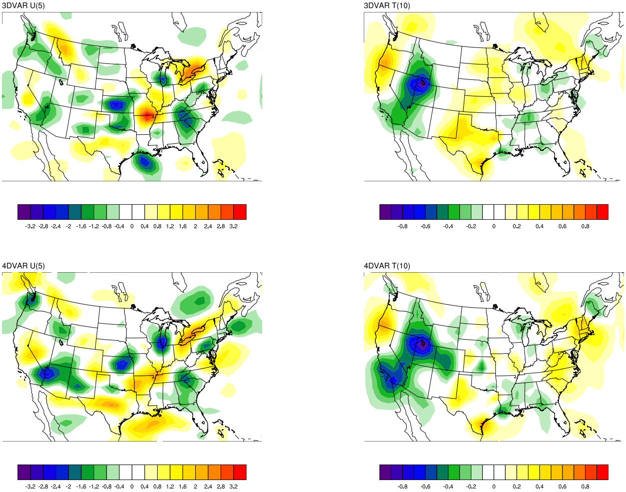
4DVAR

```
0:OBS_PARA: ps            13585
0:OBS_PARA: t             20639
0:OBS_PARA: q             19180
0:OBS_PARA: uv            28802
0:OBS_PARA: spd              80
0:OBS_PARA: sst             494
0:OBS_PARA: pw              766
------------------------------
0:OBS_PARA: ps               10
0:OBS_PARA: t               552
0:OBS_PARA: q               490
0:OBS_PARA: uv              568
----------------Total-------------------
45040 ???
```

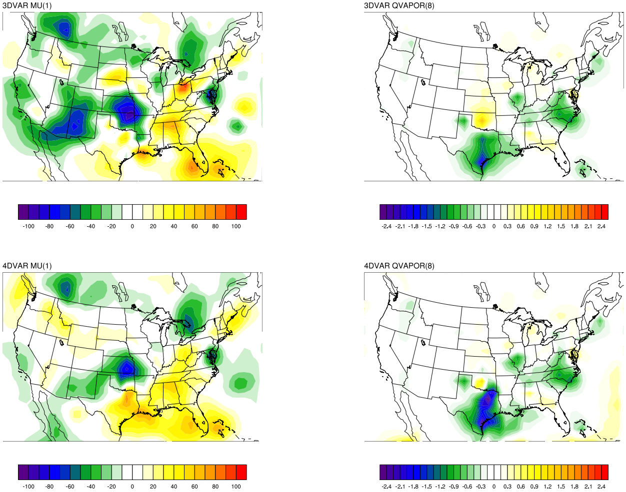
Cost functions and gradients –scaled by ALOG10



Sample increments comparison – U, T

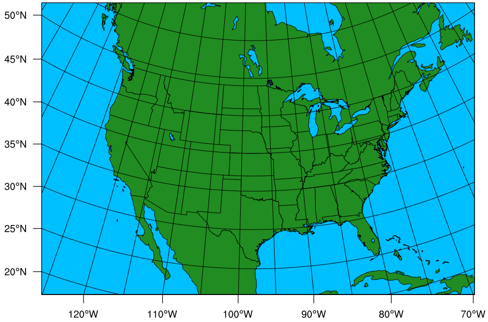


Sample increments comparison – MU, QVAPOR

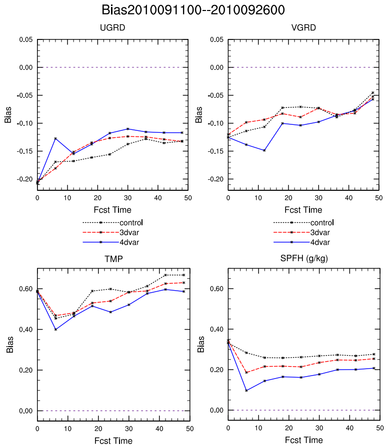


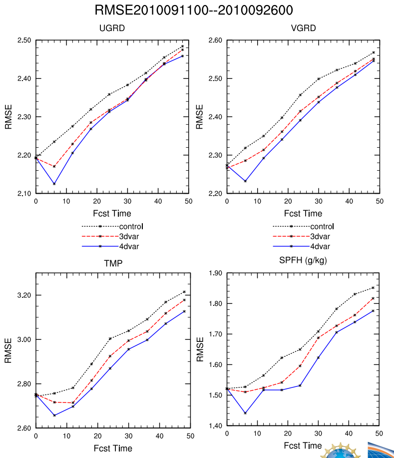
Domain

- Grids: 105x72x28L
- Resolution: 60km
- Period: 2010091100-2010092600 @0Z,6Z,12Z,18Z
- First guess is the 12h forecast from NCEP FNL
- 48h forecasts from FG, 3DVAR and 4DVAR
- Verified against NCEP GDAS prepbufr data, done by NCAR MET

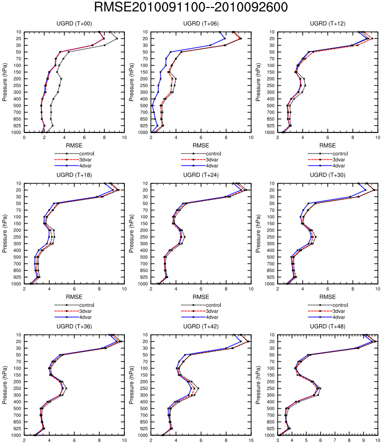


Averaged Bias and RMSE of surface forecasts

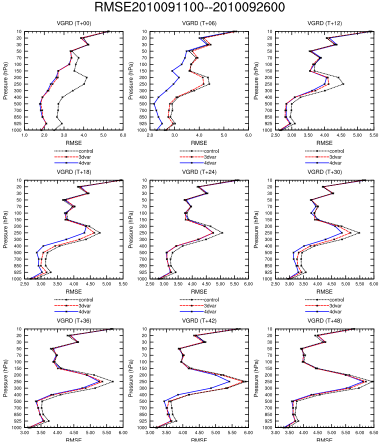




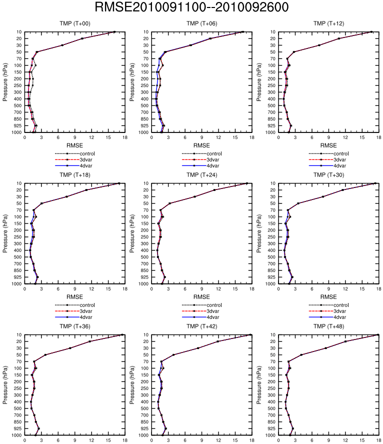
Averaged Bias and RMSE of upper level U component



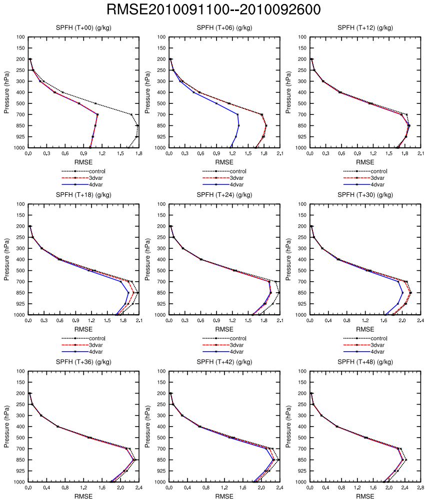
Averaged Bias and RMSE of upper level V component



Averaged Bias and RMSE of upper level Temperature



Averaged Bias and RMSE of upper level Moisture



Summary

- The basic GSI/WRF 4DVAR system was developed with minimum codes modification.
- The single observation exp. preliminarily confirm that the system is valid and is able to produce flow dependent increments.
- The increments produced by 4DVAR run with tutorial case are comparable with the 3DVAR run.
- The real case shows the desirable performance of 4DVAR.

Under development

- Add simplified physics packages into WRFPLUS: surface drag(done), large scale condensation, a simplified cumulus scheme, as well as a radiation scheme.
- Parallelization of WRF adjoint codes.
- The observation processing for 4DVAR mode is still a black box for us, need to be investigated.
- Adjoint check achieved 5-digital identical, need to debug the code to find the bugs.
- Multiple outer loops for 4DVAR.
- Assimilation of radiance data.
- Adapt gradient check for GSI-based WRF 4DVAR.
- Adapt digital filter as a weak constrain for GSI-based WRF 4DVAR.

Thank You

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