Recent development of WRF 4D-Var and GSI-based WRF 4D-Var

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June 15, 2011

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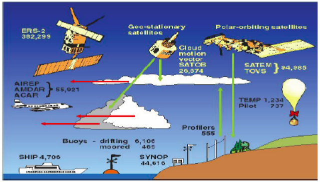
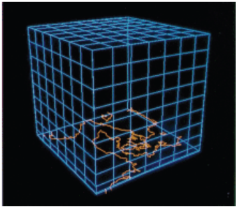
NCAR is sponsored by the National Science Foundation

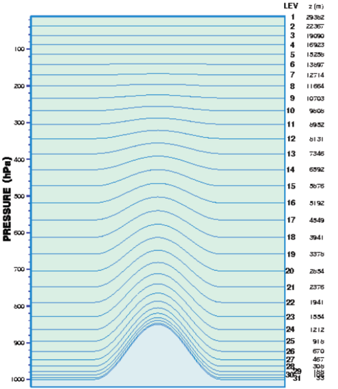
Observation System



Observations
y^o, ~10^5-10^6

Model state
x, ~10^7





Vertical resolution of the DMI-HIRLAM system

Why data assimilation?

- Initial conditions

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- Observing system design, monitoring and assessment

Forecast sensitivity to Observation

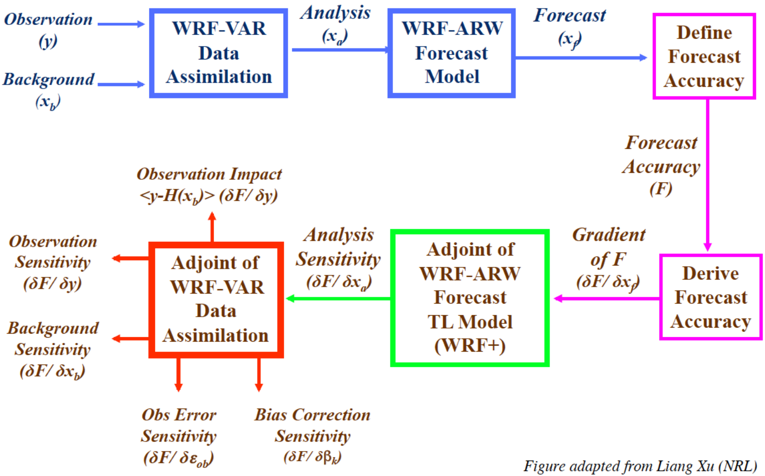

Figure adapted from Liang Xu (NRL)

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- Observing system design, monitoring and assessment
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- Calibration and validation

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  - Successive Correction Method (SCM)
  - Nudging
  - Physical Initialization (PI), Latent Heating Nudging (LHN)

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- 4D-Var combines observations at different times during the 4D-Var window in a way that reduces analysis error
- 4D-Var propagates information horizontally and vertically in a meteorologically more consistent way

Part I

Progress and status of WRF 4D-Var V3.3

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- Hard to do a complete adjoint check due to initial design of framework.

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- WRFPLUS V3.3 can be used as a standalone tool or as a component in 4D-Var system.
- Only serial run is support for V3.3 WRF 4D-Var.

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 subroutines 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

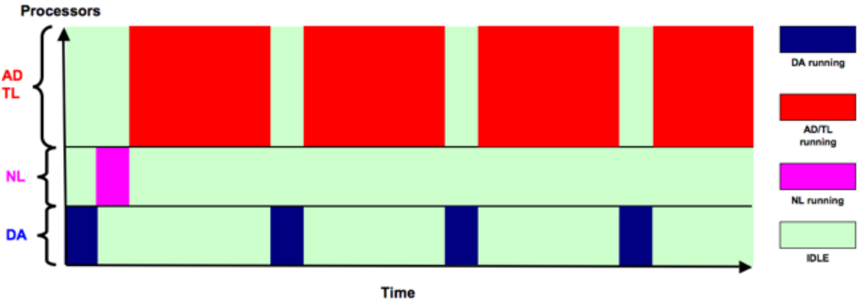
```
old          call da_system ("da_run_wrfplus_tl.ksh")
new          call da_tl_model
```

Adjoint call

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

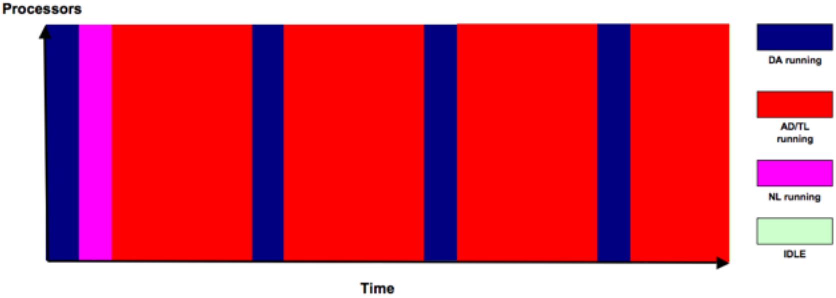
Parallel run mechanism of V3.2

4D-Var is a sequential algorithm. However, the parallel WRF 4D-Var V3.2 was constructed on the Multiple Program Multiple Data mode, which has to split the total processors into 3 subsets for DA, NL and AD/TL. Lots of CPU time are wasted



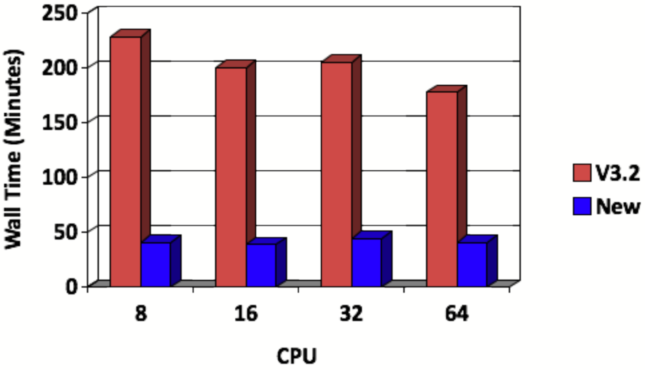
Parallel run using all processors with V3.3

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)



Weak constraint with digital filter (enhanced)

$$J = J_b + J_o + J_c$$

$$J_b(\mathbf{x}_0) = \frac{1}{2}\left[(\mathbf{x}_0 - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x}_0 - \mathbf{x}_b)\right]$$

$$J_o(\mathbf{x}_0) = \frac{1}{2}\sum_{k=1}^{K}\left[(\mathbf{H}_k\mathbf{x}_k - \mathbf{y}_k)^T \mathbf{R}^{-1} (\mathbf{H}_k\mathbf{x}_k - \mathbf{y}_k)\right]$$

$$\begin{aligned} J_c(\mathbf{x}_0) &= \frac{\gamma_{df}}{2}\left[\left(\delta\mathbf{x}_{N/2} - \delta\mathbf{x}^{df}_{N/2}\right)^T \mathbf{C}^{-1} \left(\delta\mathbf{x}_{N/2} - \delta\mathbf{x}^{df}_{N/2}\right)\right] \\ &= \frac{\gamma_{df}}{2}\left[\left(\delta\mathbf{x}_{N/2} - \sum_{i=0}^{N} f_i\delta\mathbf{x}_i\right)^T \mathbf{C}^{-1} \left(\delta\mathbf{x}_{N/2} - \sum_{i=0}^{N} f_i\delta\mathbf{x}_i\right)\right] \\ &= \frac{\gamma_{df}}{2}\left[\left(\sum_{i=0}^{N} h_i\delta\mathbf{x}_i\right)^T \mathbf{C}^{-1} \left(\sum_{i=0}^{N} h_i\delta\mathbf{x}_i\right)\right] \end{aligned}$$

where:

$$h_i = \begin{cases} -f_i, & \text{if } i \neq N/2 \\ 1 - f_i, & \text{if } i = N/2 \end{cases}$$

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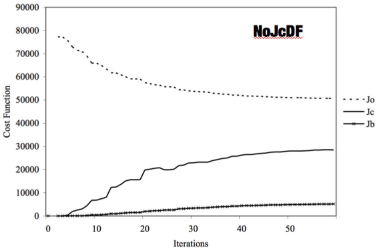
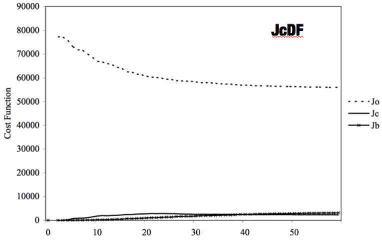
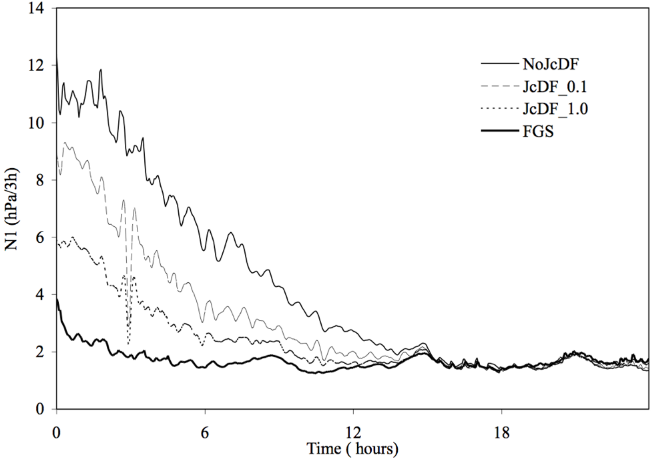




Weak constraint with digital filter

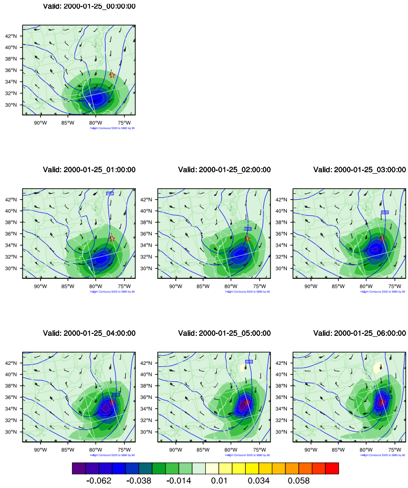
(domain averaged surface pressure variation)



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.

Single observation experiments, LBC control is on



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

Consider Lateral boundary condition as control variable

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

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

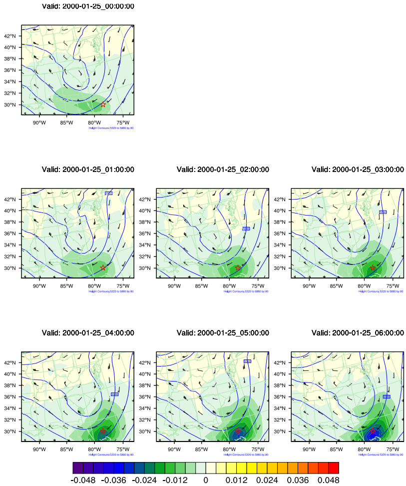
J_{lbc} is the J_b at the end of the assimilation window
lateral boundary control is obtained through

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

Single observation 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.

Single observation experiments, LBC control is on

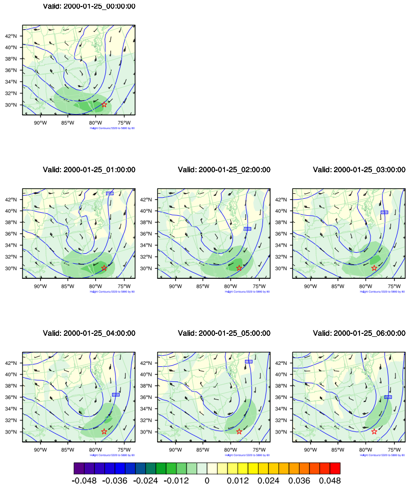


Remarks

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

- ⋆ is the location of obs. at the ending time (6h).
- LBC control is turned on
- Major initial perturbation is in LBC other than inIC (south boundary, invisible here)

Single observation experiments, LBC control is off



Remarks

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- ⋆ is the location of obs. at the ending time (6h).
- LBC control is turned off
- Without perturbation in LBC, it is hard to fit the obs. at 6h

An OSSE radar data assimilation with WRF 4D-Var (Yongrun Guo and Jenny Sun)

- TRUTH —— Initial condition from TRUTH (13-h forecast initialized at 2002061212Z from AWIPS 3-h analysis) run cutted by ndown, boundary condition from NCEP GFS data.

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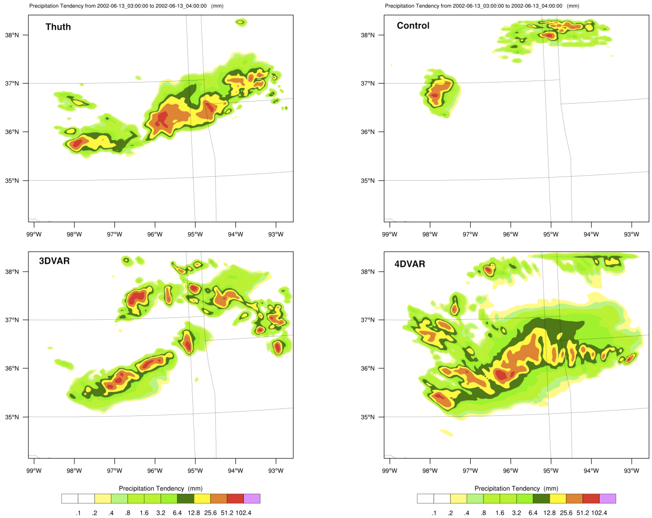
- 4DVAR —— 4DVAR analysis at 2002061301Z used as initial condition, and boundary condition from NCEP GFS. The radar radial velocity at 4 times: 200206130100, 05, 10, and 15, are assimilated (total data points = 384,304), 3 outer loops.

OSSE 3rd hour precipitation simulation



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Quick Start

Install WRFPLUS and WRFDA for WRF 4D-Var

- WRFPLUS : WRF adjoint and tangent linear codes

```
> configure [-d] wrfplus
> compile em_real
```

- Set the the $WRFPLUS\_DIR$ environmental variable, it will be used in WRFDA compilation

```
> setenv WRFPLUS_DIR full_path_of_wrfplus
```

- WRFDA

```
> configure [-d] 4dvar
> compile all_wrfvar
```

Part II

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

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- The Major development in GSI had finished, GSI codes had been coupled with the WRFPLUS V3.3

Current Status of GSI-based WRF 4D-Var

- The development of GSI-based WRF 4DVAR is based on GSI Boulder's version as of February 2011
- The Major development in GSI had finished, GSI codes had been coupled with the WRFPLUS V3.3
- Because the parallelization of the latest WRFPLUS is still on going, only serial run is doable at this moment

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- 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.

The New Module wrf_pertmod

The coupler and utilities used to couple GSI and WRFPLUS.

```
module wrf_pertmod
    subroutine model_nl_wrf            ! Subroutine to call WRF nonlinear model
    ...
    end subroutine model_nl_wrf
    subroutine model_tl_wrf            ! Subroutine to call WRF tangent linear model
    ...
    end subroutine model_tl_wrf
    subroutine model_ad_wrf            ! Subroutine to call WRF adjoint model
    ...
    end subroutine model_ad_wrf
    subroutine gsi2wrf_tl              ! Transfer GSI perturbation to WRF perturbation
    ...
    end subroutine gsi2wrf_tl
    subroutine gsi2wrf_ad              !  Adjoint of gsi2wrf_tl
    ...
    end subroutine gsi2wrf_ad
    subroutine wrf2gsi_tl              ! Transfer WRF perturbation to GSI perturbation
    ...
    end subroutine wrf2gsi_tl
    subroutine wrf2gsi_ad              ! Adjoint of wrf2gsi_tl
    ...
    end subroutine wrf2gsi_ad
end module wrf_pertmod
```

Quick Start

Install WRFPLUS and GSI

- WRFPLUS : WRF adjoint and tangent linear codes

```
> configure [-d] wrfplus
> compile em_real
```

- Set the the WRF_DIR environmental variable

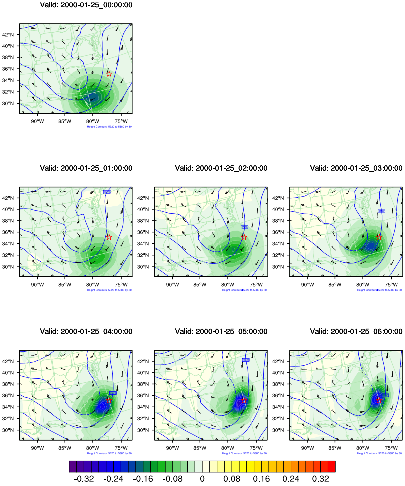
```
> setenv WRF_DIR full_path_of_wrfplus
```

- GSI

```
> configure
> compile
```

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.

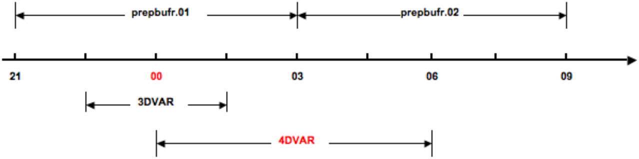


Remarks

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

Tutorial case – Observation Usage



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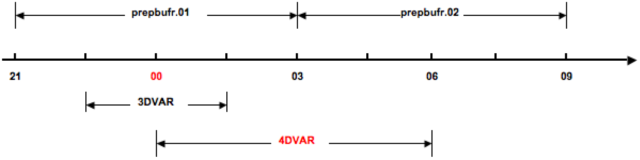


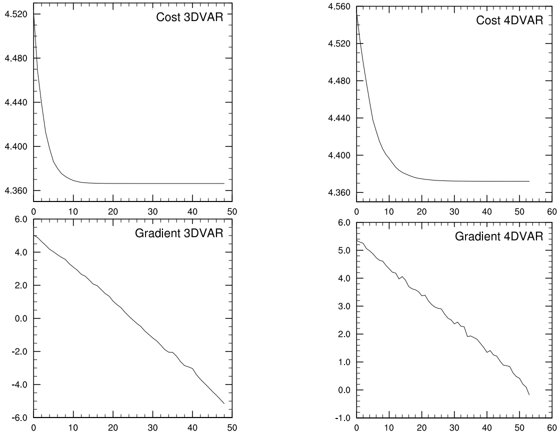
3DVAR

```
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
```

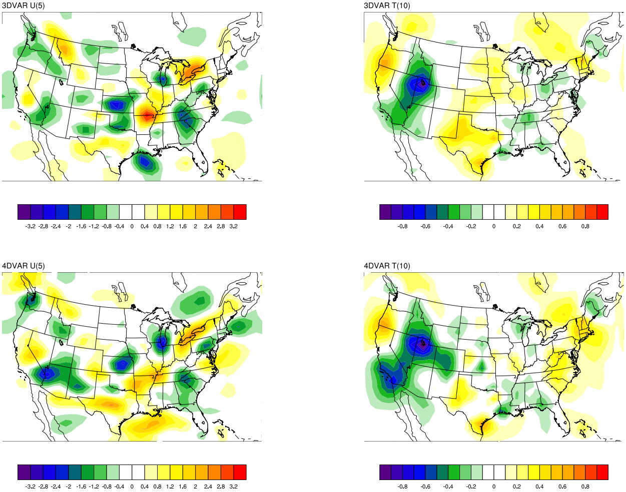
4DVAR

```
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
```

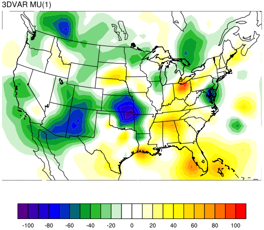
Cost functions and gradients –scaled by ALOG10

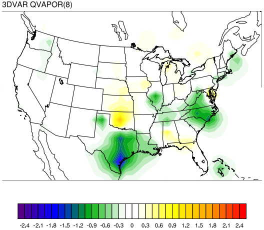


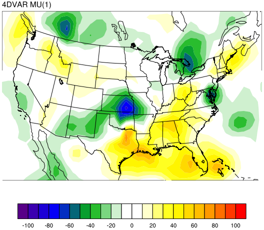
Sample increments comparison – U, T

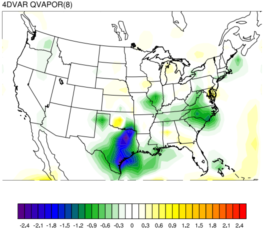


Sample increments comparison – MU, QVAPOR



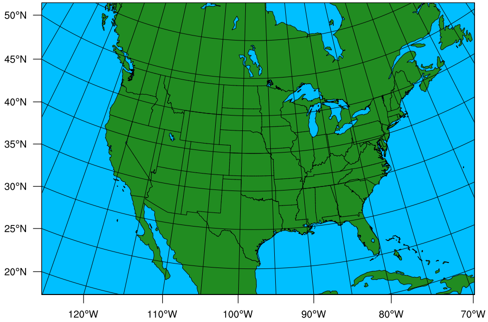




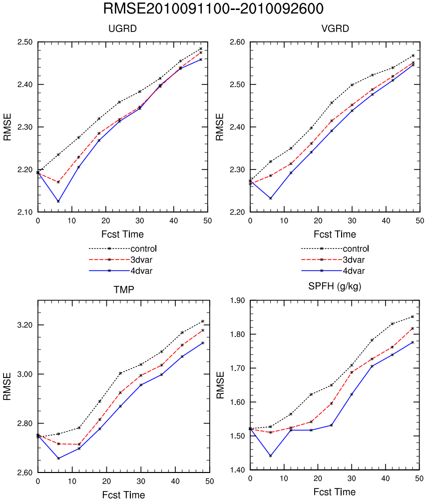


Domain

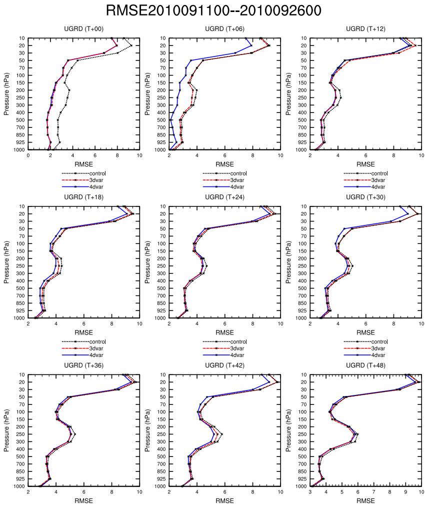
- Grids: 105x72x28L
- Resolution: 60km
- Period: 2010091100-2010092600 @0Z,6Z,12Z,18Z
- First guess is the 12h forecast from NCEP FNL
- 48h forecasts from FG, 3DVAR and 4DVAR
- Verified against NCEP GDAS prepbufr data, done by NCAR MET



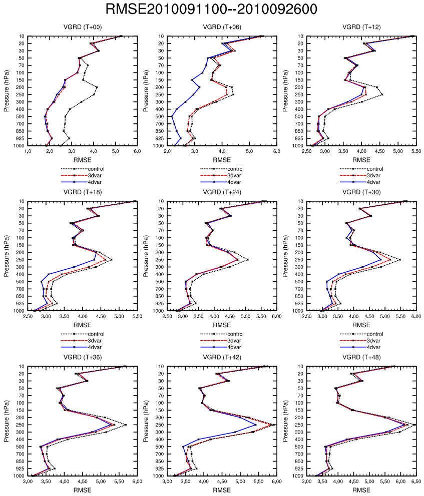
Averaged RMSE of surface forecasts



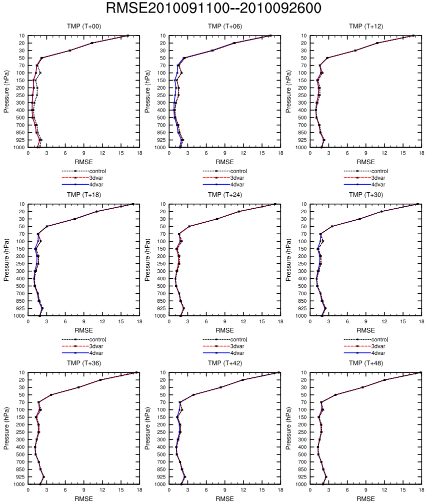
Averaged RMSE of upper level U component



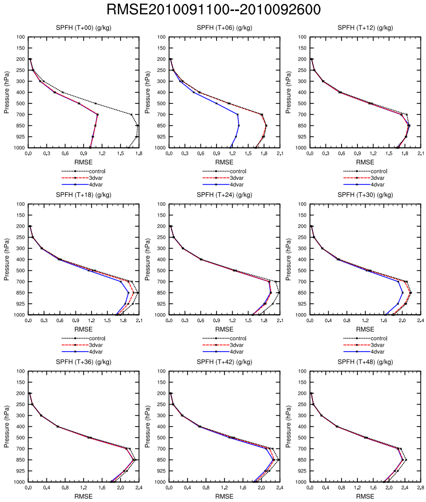
Averaged RMSE of upper level V component



Averaged RMSE of upper level Temperature



Averaged RMSE of upper level Moisture



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- The single observation exp. preliminarily confirm that the system is valid and is able to produce flow dependent increments.
- The real case shows the desirable performance of 4DVAR.

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- Adapt gradient check for GSI-based WRF 4DVAR.
- Adapt digital filter as a weak constrain for GSI-based WRF 4DVAR.

Thank You

The NESL Mission is:
To advance understanding of weather, climate, atmospheric composition and processes;
To provide facility support to the wider community; and,
To apply the results to benefit society.

NCAR is sponsored by the National Science Foundation