WRF Four-dimensional variational data assimilation system Tutorial for V3.6

Xin Zhang, Xiang-Yu Huang, and Michael Kavulich, Jr.

NCAR Earth System Laboratory

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Prerequisites to run WRF 4D-Var

- Knowledge and experience to run the WRF model
- Knowledge and experience to run WRFDA (3D-Var)

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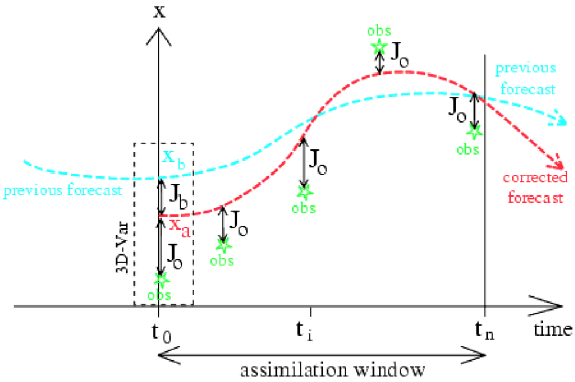

Image courtesy of ECMWF training course

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EXTRA SLIDE: Incremental 4D-Var formulation

As with 3DVAR, the 4DVAR method ultimately boils down to minimizing a cost function.

$$J_j(\delta x_j) = \frac{1}{2}(\delta x_j - \delta x_j^b)^T \mathbf{B}^{-1}(\delta x_j - \delta x_j^b) + \frac{1}{2}\sum_{k=1}^{K}(\mathbf{H}_{j,k}\mathbf{M}_{j,k}\delta x_j - \mathbf{d}_{j,k})^T \mathbf{R}^{-1}(\mathbf{H}_{j,k}\mathbf{M}_{j,k}\delta x_j - \mathbf{d}_{j,k})$$

Where

$$\mathbf{d}_{j,k} \equiv \mathbf{y}_k - \mathbf{H}_k\mathbf{M}_k\mathbf{x}^b \ , \ \delta x_j^b \equiv \mathbf{x}^b - \mathbf{x}_{j-1}$$

EXTRA SLIDE 2: Incremental 4D-Var formulation

Through some ~~magic~~ math, we can re-arrange this to find the gradient of the cost function, which we minimize.

$$\nabla J_b(\delta x_j) = \mathbf{B}^{-1}\delta x_j$$

$$\nabla J_o(\delta x_j) = \sum_{k=1}^{K}(\underbrace{\mathbf{M}_{j,k}^T}_{\text{AD}}\mathbf{H}_{j,k}^T\mathbf{R}^{-1}(\mathbf{d}_{j,k} - \mathbf{H}_{j,k}\underbrace{\mathbf{M}_{j,k}}_{\text{TL}}\delta\mathbf{x}_{j-1} - H_{j,k}\underbrace{M_{j,k}}_{\text{NL}}\mathbf{x}^b))$$

M_k : Model integration from step 0 to step k.
$\mathbf{M}_k$: Linearized version of the model ("tangent linear model").
$\mathbf{M}_k^T$: Adjoint model

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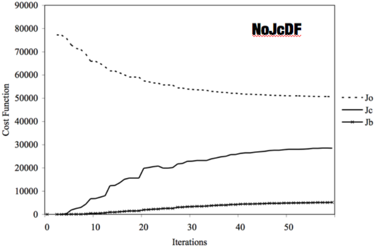
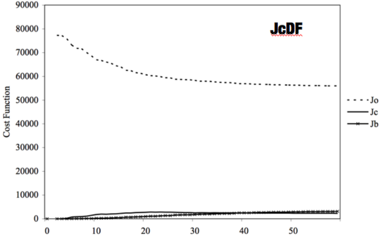
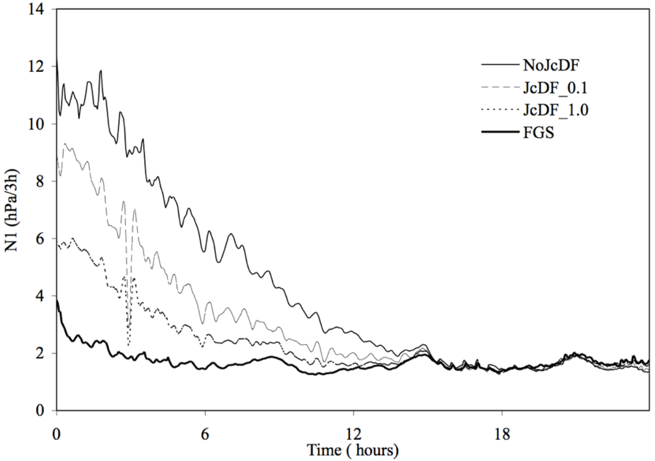
Weak constraint with digital filter

$$J = J_b + J_o + J_c$$





Weak constraint with digital filter (domain averaged surface pressure variation)



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

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

Download code and test data for this tutorial

- download the WRFDA source code from :

  `http://www.mmm.ucar.edu/wrf/users/wrfda/download/get_source.html`

- download the WRFPLUSV3 source code from :

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  - `./compile em_real`
  - `wrf.exe` should be generated under the `WRFPLUSV3/main` directory.
- for csh, tcsh : `setenv WRFPLUS_DIR path_of_wrfplusv3`
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Test for tangent linear model and adjoint model

- After WRFPLUS compilation, it is a good practice to run the tangent linear model test and adjoint model test with your own case's initial and boundary conditions.
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Test for tangent linear model

Taylor formula:

$$\lim_{\alpha \to 0} \frac{\|M(\mathbf{x}+\alpha\delta\mathbf{x}) - M(\mathbf{x})\|}{\|\mathbf{M}(\alpha\delta\mathbf{x})\|} = 1$$

check results

```
 =============== Tangent Linear check ===================
 check==== U === V === W == PH === T == MU == MOIST =====
 check     T     T     T     T     T     T     T
alpha_m=.1000E+00  coef=   0.98250076417818E+00  val_n= 0.3628649E+11  val_l= 0.3693279E+11
alpha_m=.1000E-01  coef=   0.99781045126907E+00  val_n= 0.3685192E+09  val_l= 0.3693279E+09
alpha_m=.1000E-02  coef=   0.99949153238165E+00  val_n= 0.3691401E+07  val_l= 0.3693279E+07
alpha_m=.1000E-03  coef=   0.10002560538015E+01  val_n= 0.3694225E+05  val_l= 0.3693279E+05
alpha_m=.1000E-04  coef=   0.99981685944643E+00  val_n= 0.3692603E+03  val_l= 0.3693279E+03
alpha_m=.1000E-05  coef=   0.10000972073298E+01  val_n= 0.3693638E+01  val_l= 0.3693279E+01
alpha_m=.1000E-06  coef=   0.99996624597337E+00  val_n= 0.3693154E-01  val_l= 0.3693279E-01
alpha_m=.1000E-07  coef=   0.99999992233716E+00  val_n= 0.3693279E-03  val_l= 0.3693279E-03
alpha_m=.1000E-08  coef=   0.10000017668820E+01  val_n= 0.3693285E-05  val_l= 0.3693279E-05
alpha_m=.1000E-09  coef=   0.10000050602279E+01  val_n= 0.3693298E-07  val_l= 0.3693279E-07
alpha_m=.1000E-10  coef=   0.10000451984913E+01  val_n= 0.3693446E-09  val_l= 0.3693279E-09
```

Test for adjoint model

adjoint identity:

$$\forall \mathbf{x}, \forall \mathbf{y} : \langle \mathbf{M} \cdot \mathbf{x}, \mathbf{y} \rangle = \langle \mathbf{x}, \mathbf{M}^{*} \cdot \mathbf{y} \rangle$$

check results

```
ad_check: VAL_TL:    0.41466174569087E+11
ad_check: VAL_AD:    0.41466174569088E+11
```

- Although the tangent linear model might be imperfect.
- The adjoint test must be perfect. otherwise, there are bugs in the adjoint model.

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WRF 4D-Var observation preparation

- Conventional observation — LITTLE_R format

  `http://www.mmm.ucar.edu/wrf/users/wrfda/Tutorials/2014_July/docs/WRFDA_obsproc.pdf`

- OR Conventional observation — PREPBUFR format
  - near real-time data : `ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod`
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  Precipitation

Important namelist variables for 4D-Var run

- &wrfvar1
  - var4d: logical, set to .true. to use 4D-Var
  - var4d_lbc : logical, set to .true. to include lateral boundary condition control in 4D-Var
  - var4d_bin: integer, seconds, length of sub-window to group observations in 4D-Var
- &perturbation
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Important namelist variables for 4D-Var run, cont'd

- `&physics`
  - all physics options must be consistent with which used in wrfinput or fg
- `&wrfvar18,21,22`
  - `analysis_date` is the start time of the assimilation window
  - `time_window_min` is the start time of the assimilation window
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You can see a list of all available options in `WRFPLUSV3/Registry/registry.wrfplus`. Be warned: some options may not work!

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Adjoint check before 4D-Var run

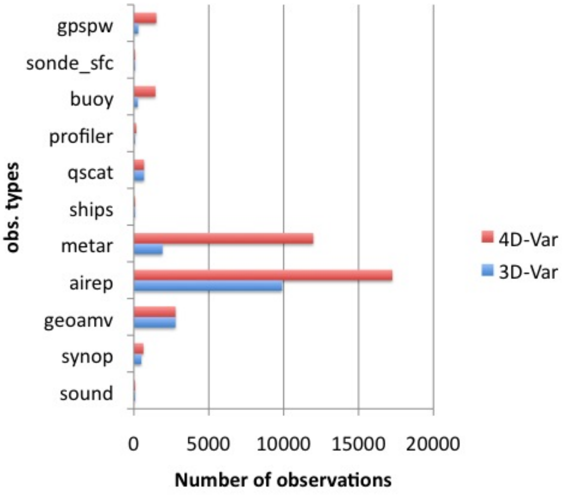
It is a good practice to run adjoint check before a 4d-Var run.
How:

- `&wrfvar10`
  `test_transforms=true,`
- run `da_wrfvar.exe`

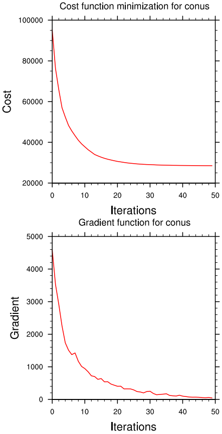
Check results

```
...
 wrf: back from adjoint integrate
 d01 2008-02-05_21:00:00 read nonlinear xtraj time stamp:2008-02-05_21:00:00
 Single Domain < y, y     > =   2.15435506772433E+06
 Single Domain < x, x_adj > =   2.15435506772431E+06

 Whole Domain < y, y     > =   2.15435506772433E+06
 Whole Domain < x, x_adj > =   2.15435506772431E+06

da_check_xtoy_adjoint: Test Finished:

 *** WRF-Var check completed successfully ***
```

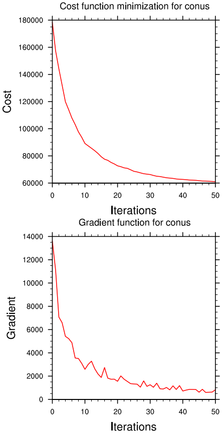
Comparison of obs. usage on 2008020600



Minimization comparison

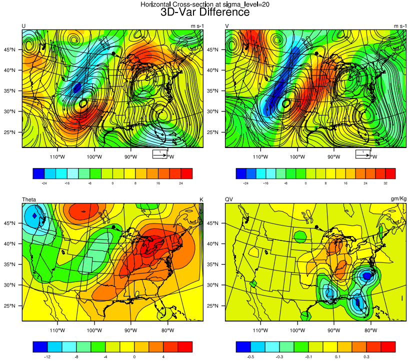


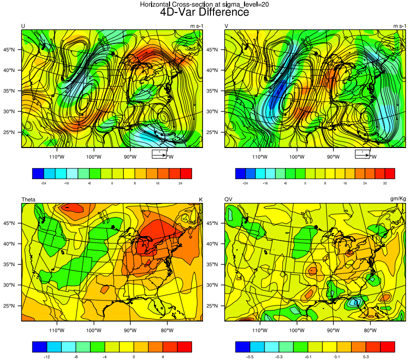
3D-Var



4D-Var

Sample analysis increments valid on 2008020600





Assimilate satellite radiance data

Here is an example of common namelist settings for radiance data assimilation:

```
&wrfvar4
use_amsuaobs=true,
use_amsubobs=true,
&wrfvar14
rtminit_nsensor=6,
rtminit_platform=1,1,1,1,1,1,
rtminit_satid=15,16,18,15,16,17,
rtminit_sensor=3,3,3,4,4,4,
thinning_mesh=120.0,120.0,120.0,120.0,120.0,120.0,
thinning=true,
qc_rad=true,
rtm_option=2,
use_varbc=true,
use_crtm_kmatrix=true,
```

Full instructions for setting up radiance assimilation can be found in the WRFDA User's Guide

(http://www.mmm.ucar.edu/wrf/users/wrfda/Docs/user_guide_V3.6/users_guide_chap6.htm#_Radiance_

Data_Assimilations) or the presentation on Radiance Assimilation

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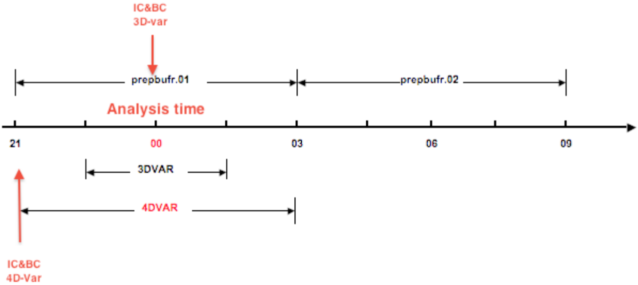
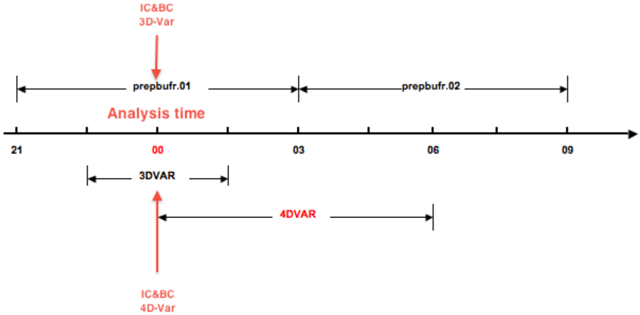
4D-Var assimilation window



- IC & BC for 3D-Var is valid for 00Z
- IC & BC for 4D-Var is valid for 21Z

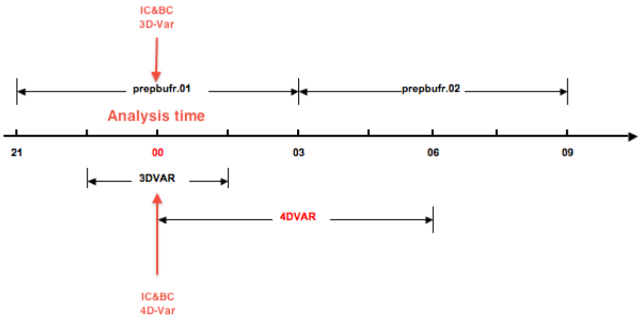
Using multiple .bufr files



BUFR and PREPBUFR files typically contain 6 hours of data. Since assimilation windows will often span more than one 6-hour period, it will often be necessary to use two different files for each data type. You should link them as follows:

- link/copy prepbufr data at 00Z as `ob01.bufr`
- link/copy prepbufr data at 06Z as `ob02.bufr`

Using multiple .bufr files



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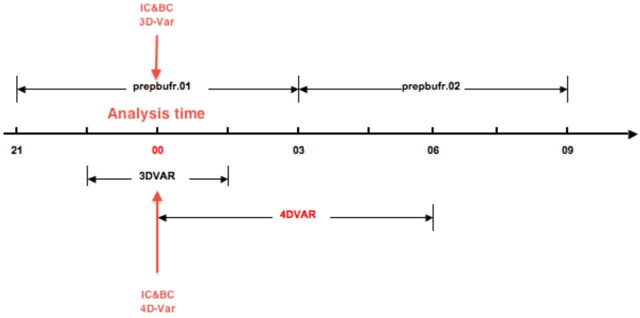
- link/copy prepbufr data at 00Z as `ob01.bufr`
- link/copy prepbufr data at 06Z as `ob02.bufr`
- link/copy amsua data at 00Z as `amsua01.bufr`
- link/copy amsua data at 06Z as `amsua02.bufr`
- ...

Using multiple .bufr files



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- link/copy prepbufr data at 00Z as `ob01.bufr`
- link/copy prepbufr data at 06Z as `ob02.bufr`
- link/copy amsua data at 00Z as `amsua01.bufr`
- link/copy amsua data at 06Z as `amsua02.bufr`
- ...

An OSSE radar data assimilation with WRF 4D-Var

- TRUTH —– Initial condition from TRUTH (13-h forecast initialized at 2002061212Z from AWIPS 3-h analysis) run cut by ndown, boundary condition from NCEP GFS data.
- CONTROL —– Both initial condition and boundary condition from NCEP GFS data.

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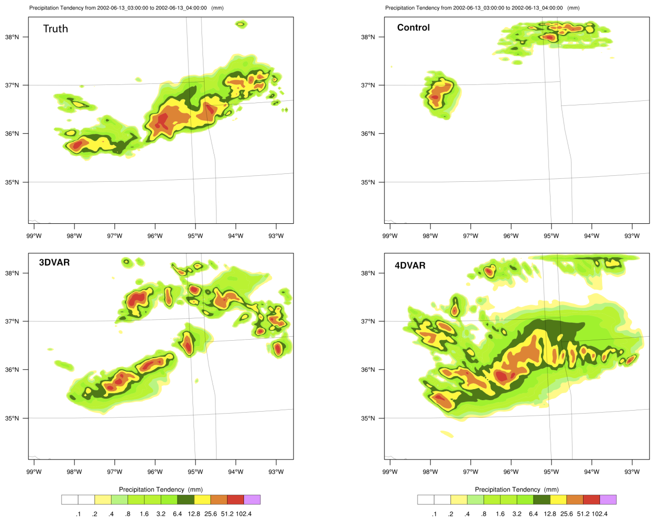
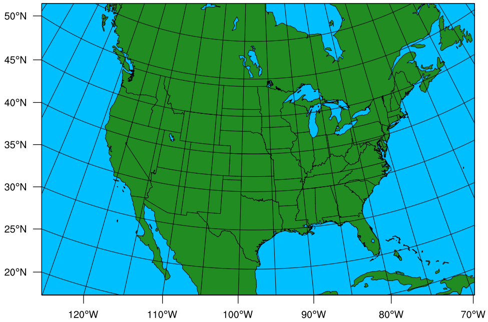
OSSE 3rd hour precipitation simulation



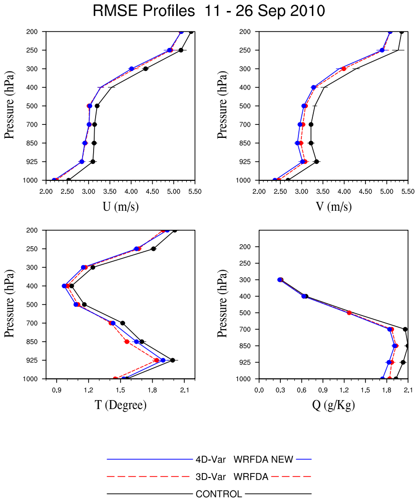
Real data case

Experiment configuration:

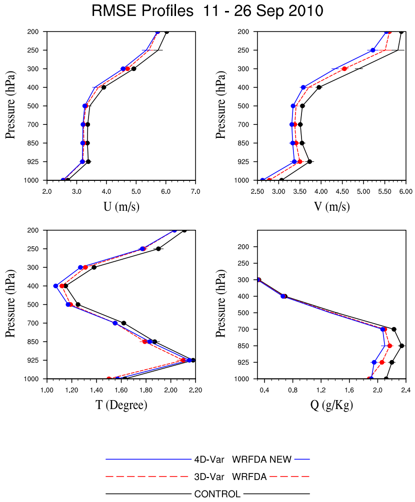
- Grids: 105x72x28L
- Resolution: 60km
- Period: 2010091100-2010092600 @0Z,6Z,12Z,18Z
- First guess is the 12h forecast from NCEP FNL
- 48h forecasts from FG, 3DVAR and 4DVAR
- Verified against NCEP GDAS prepbufr data



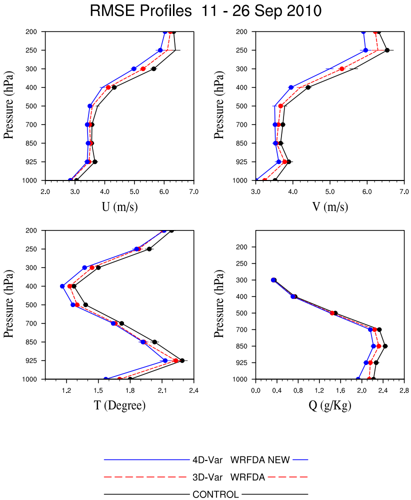
Averaged RMSE of 24H forecast verification



Averaged RMSE of 36H forecast verification

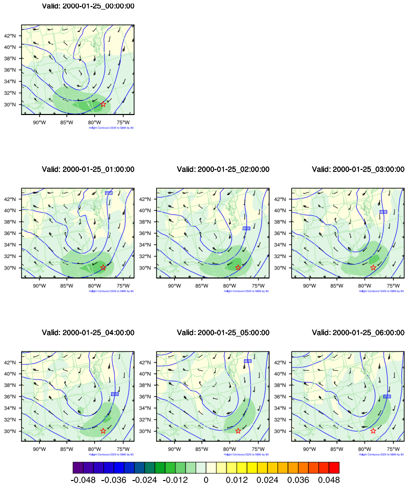


Averaged RMSE of 48H forecast verification



Lateral boundary condition as control variable

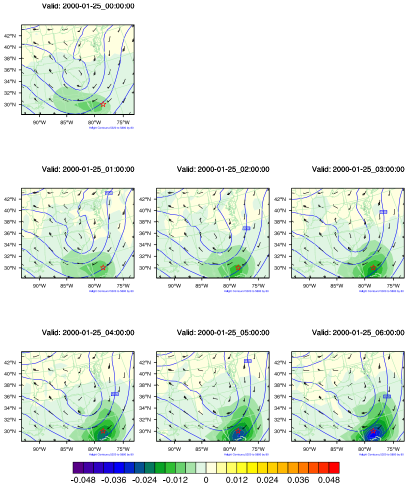
To investigate the impact of including boundary condition control in data assimilation, a 6h observation close to boundary is put at the downstream of the boundary inflow, we expect that the major analysis increments response at 0h should be in boundary condition and outside of domain.



Remarks

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

- ⋆ is the location of obs. at the ending time (6h).
- $O - B = -0.95K$
- LBC control is turned off



Remarks

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

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

Thank You

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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.

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