Recently upgrades and improvements of WRF 4D-Var system

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

NCAR Earth System Laboratory

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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

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- Add capability to do tangent linear and adjoint test over any length of time window.
- Add option to control if all inputs and outputs were happen in disk or memory, so WRFPLUS can be used as a standalone tool or as a component in 4DVAR system.

Sample Tangent Linear and Adjoint Check

Tangent linear check

```
...
tl_check: alpha=.1000E-04  coef=0.10000447262220E+01
tl_check: alpha=.1000E-05  coef=0.99999981575068E+00
tl_check: alpha=.1000E-06  coef=0.99999998152933E+00
tl_check: alpha=.1000E-07  coef=0.99999990980017E+00
tl_check: alpha=.1000E-08  coef=0.99999956711797E+00
...
```

Adjoint check

```
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, other than being called via shell scripts.

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 list.

Read basic states

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

Save TL perturbation

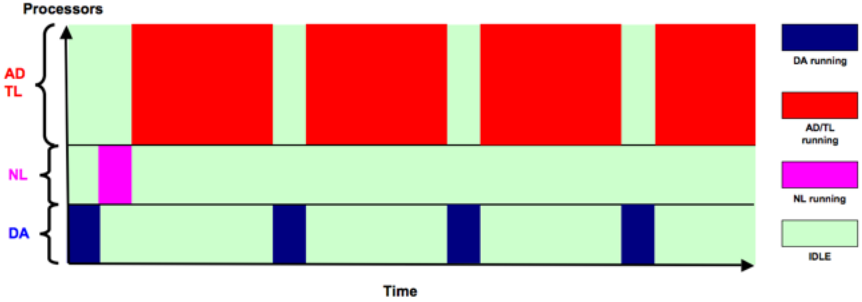
```
call push_tl_pert (timestr)
```

Save AD forcing

```
call push_ad_forcing (timestr)
```

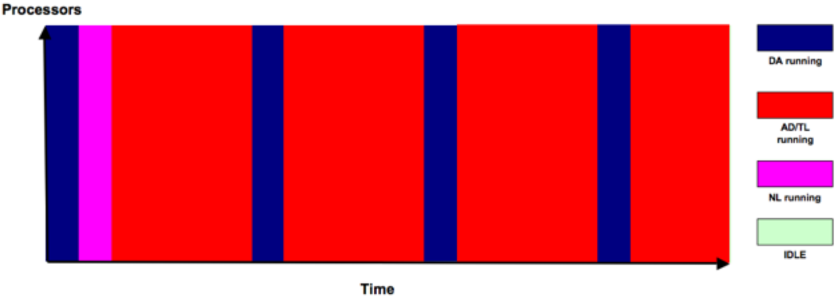
Parallel run using all processors

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



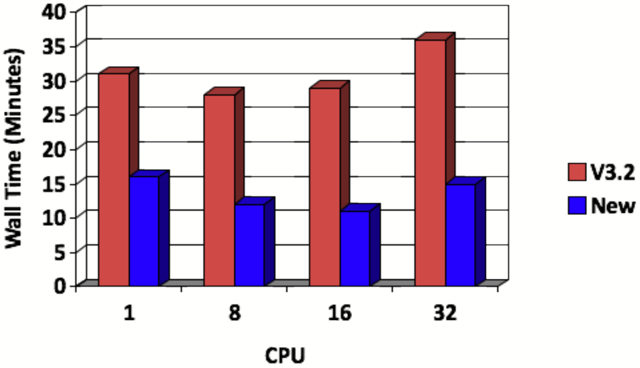
Parallel run using all processors

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



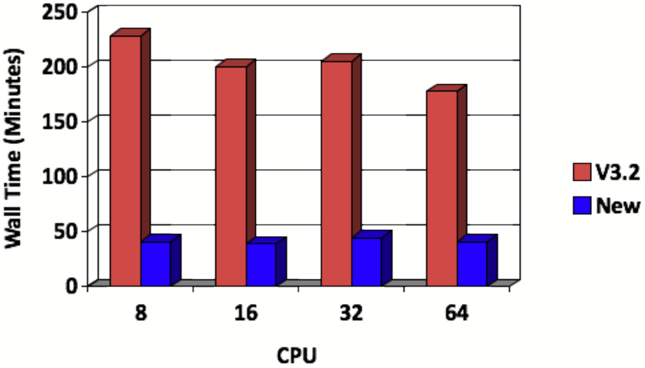
Performance improvement WRF 4DVar framework only

- $90x60x41@60km$, 6h window, 1h obs_bin
- 27 iterations FGAT, NCAR bluefire (IBM P6)



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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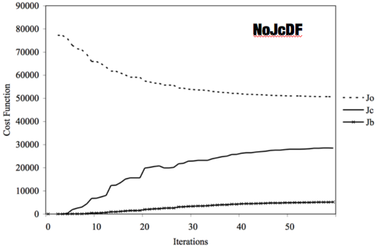
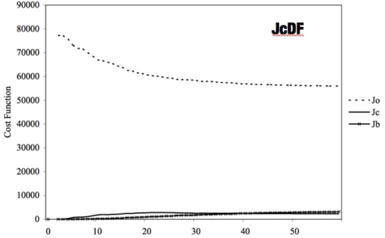
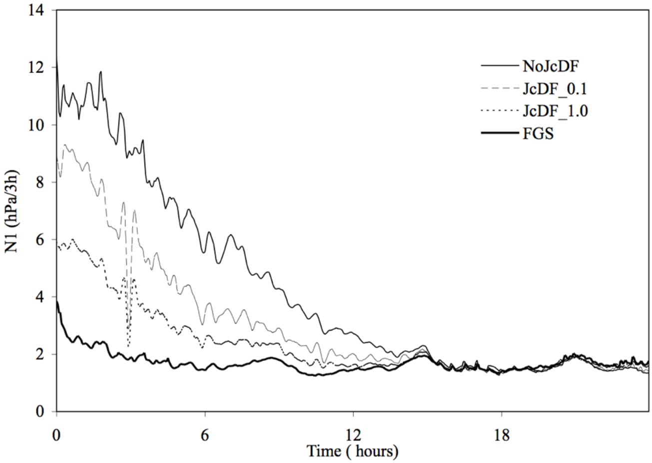




Weak constraint with digital filter (domain averaged surface pressure variation)



Consider Lateral boundary condition as control variable

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

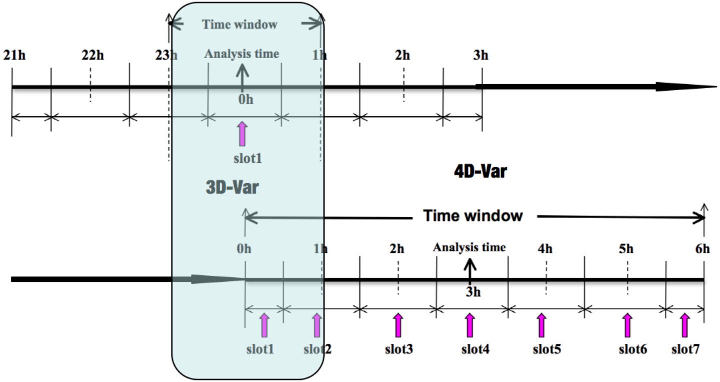
$$\begin{aligned} J_{lbc} &= \frac{1}{2}(\mathbf{x}(t_k) - \mathbf{x}_b(t_k))^T \mathbf{B}^{-1} (\mathbf{x}(t_k) - \mathbf{x}_b(t_k)) \\ &= \frac{1}{2}\delta\mathbf{x}(t_k)^T \mathbf{B}^{-1} \delta\mathbf{x}(t_k) \end{aligned}$$

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

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

Observations used by 4D-Var

- Conventional observational data (little_r, prepbufr)
- Radar radial velocity
- Radiance satellite data



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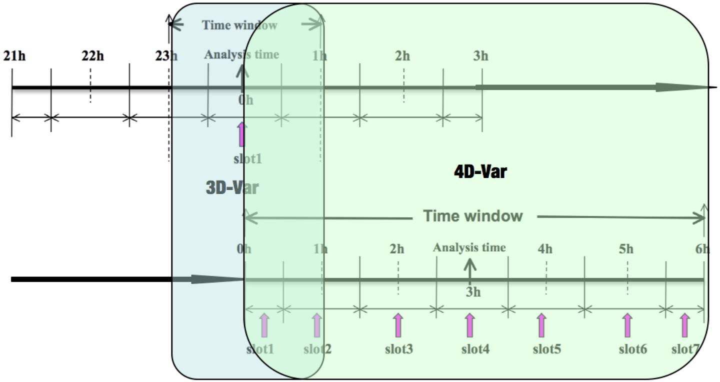

Single observation exp.

- Initial time: 2000_01_25_00 : 00 : 00
- Ending time: 2000_01_25_06 : 00 : 00
- Observation: 500 mb Temperature at ending time
  $O - B = -2.7K$
- To investigate the difference at ending time between the forecast from analysis and from background.

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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

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

- ⋆ is the location of obs. at the ending time (6h).
- JcDF is turned off
- LBC control is turned on
- Lots of noise compared to the exp. w/ JcDF.

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.

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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
- *Jb* : 0.174; *Jo* : 3.166; *Jl* : 0.000
- Main Initial perturbation is in the location of the obs., it is fake
- Evolved perturbation at 6h is moving out from the obs. location

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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
- *Jb* : 0.025; *Jo* : 3.174; *Jl* : 0.224
- w/o LBC control
  Jb : 0.174; *Jo* : 3.166; *Jl* : 0.000
- 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

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

- ⋆ is the location of obs. at the ending time (6h).
- JcDF is turned off
- LBC control is turned on
- Noise development dominant the domain, the perturbation development is totally different, hard to see the impact of boundary.

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 cutted by ndown, boundary condition from NCEP GFS data.

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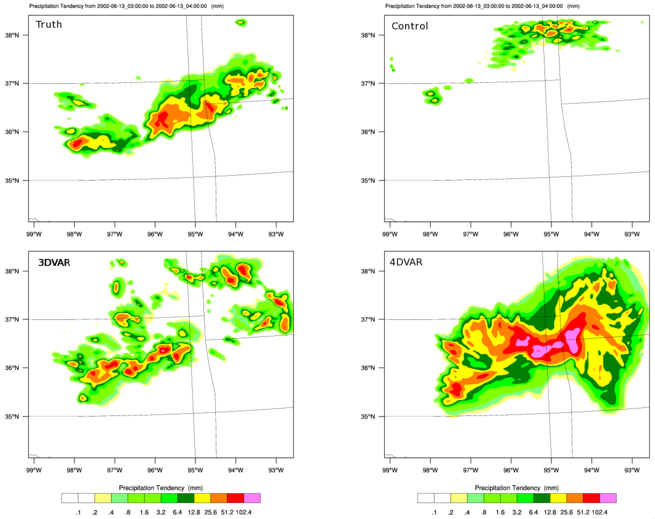
- 4DVAR —— 4DVAR analysis at 2002061301Z used as initial condition, and boundary condition from NCEP GFS. The radar radial velocity at 4 times: 200206130100, 05, 10, and 15, are assimilated (total data points = 384,304), 3 outer loops.

OSSE 3rd hour precipitation simulation



Discussion

- Obviously, 4DVAR reproduce the best squall line precipitation band.
- However, the coverage and intensity of 3rd hour precipitation forecasted 4DVAR are more than the observation.
- Possible reason: The new WRFPLUS is a dynamic-only model, PBL and microphysics are needed.

Summary

- The single executable WRF 4DVar system was developed.
- Parallelization of WRF tangent linear code has been done.
- 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

- Add simplified physics packages into WRFPLUS: surface drag, large scale condensation, a simplified moist cumulus scheme, as well as a radiation scheme.
- Parallelization of WRF adjoint codes.

Quick Start

Install WRFPLUS and WRFPLUS

- 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
```

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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