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The Weather Research and Forecasting Model Based 4-dimensional Variational Data Assimilation System

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1. Introduction

The 4-dimensional variational data assimilation (4DVAR) idea (Le Dimet and Talagrand, 1986; Lewis and Derber, 1985) has been pursued actively by research community and operational centers over the past two decades. The 5th generation Pennsylvania State University – National Center for Atmospheric Research mesoscale model (MM5) based 4DVAR (Zou *et al.* 1995; Ruggiero *et al.* 2005), for example, has been widely used for more than 10 years. There are also many successful operational implementations of 4DVAR (e.g. Rabier *et al.* 2000). The 4DVAR systems have a number of advantages including the abilities to:

1) Use observations over a time interval, which suits most asynoptic data,
2) Implicitly use flow-dependent background errors, which ensures the analysis quality for fast developing weather systems, and
3) Use a forecast model as a constraint, which ensures the dynamic balance of the final analysis.

The last mentioned advantage also implies that the current Weather Research and Forecasting model (WRF) based 3-dimensional variational data assimilation system (WRF-3DVAR), which is developed from MM5-3DVAR (Barker *et al.* 2004), should be enhanced with a 4-dimensional capability, using the WRF forecast model as a constraint, in order to provide the best initial conditions for the WRF model.

The WRF based 4DVAR system has been under extensive development since 2004. The development effort has been primarily supported by the Air Force Weather Agency (AFWA).

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The unified WRF-based 3/4DVAR system is named **WRF-Var** which includes the WRF model and WRF-3DVAR as its basic components. Its prototype will be ready in 2005 and its basic version should be constructed in 2006. In this paper, we present the formulation, system design, working plan and current status of WRF-Var.

2. WRF-Var

The WRF-Var follows closely the incremental 4DVAR formulation of Courtier *et al.* (1994), Veersé and Thépaut (1998), and Lorenc (2003). The data flow and program structure of WRF-Var is given in Fig.1.

The input to WRF-Var is the following. The observations are grouped into K window, $\mathbf{y}_k$ (k=1,K). A short-range forecast is used as a background, $\mathbf{x^b}$. Assume the background error covariance matrix, **B**, and the observation error covariance matrix, **R**, are known. For integrating the WRF model over a time interval lateral boundaries, WRFBDY, are required. The 3DVAR option of WRF-Var, is obtained by setting K=1 and removing WRF model related components.

WRF-Var allows outer-loops and inner-loops. The outer-loops deal with nonlinear aspects of the assimilation problem while the inner-loops run a minimization algorithm for a quadratic problem. Using superscript **n** for the outer-loop index the analysis vector, $\mathbf{x^n}$, is the final output of WRF-Var.

For the inner-loops, the minimization starts from a guess vector, $\mathbf{x^{n-1}}$ (the analysis vector from the previous outer-loop). For the first outer-loop, **n**=1, $\mathbf{x^b}$ is normally taken as the guess vector, $\mathbf{x^0}$. It should be stressed that in the incremental 3/4DVAR formulation the background vector and the guess vector should not be mixed. They are the same only during the first outer-loop.

Mathematically WRF-Var minimizes a cost function *J*, using its gradient *J'* with respect to the control variable, $\chi^{\mathbf{n}}$:

$$J'(\boldsymbol{\chi}^{\mathbf{n}}) = \boldsymbol{\chi}^{\mathbf{n}} + \sum_{i=1}^{n-1} \boldsymbol{\chi}^{\mathbf{i}} + \mathbf{U}^{-\mathbf{T}}\mathbf{S}_{\mathbf{V-W}}^{\mathbf{T}} \sum_{k=1}^{K} \mathbf{M}_{\mathbf{k}}^{\mathbf{T}}\mathbf{S}_{\mathbf{W-V}}^{\mathbf{T}}\mathbf{H}_{\mathbf{k}}^{\mathbf{T}}\mathbf{R}^{-1}\left\{\mathbf{H}_{\mathbf{k}}\mathbf{S}_{\mathbf{W-V}}\mathbf{M}_{\mathbf{k}}\mathbf{S}_{\mathbf{V-W}}\mathbf{U}^{-1}\boldsymbol{\chi}^{\mathbf{n}} + H_k\left[M_k\left(\mathbf{x}^{\mathbf{n-1}}\right)\right] - \mathbf{y}_{\mathbf{k}}\right\} \quad (1)$$

and the preconditioning is through a variable transform,

$$\boldsymbol{\chi}^{\mathbf{n}} = \mathbf{U}\left(\mathbf{x}^{\mathbf{n}} - \mathbf{x}^{\mathbf{n-1}}\right) \quad (2)$$

where $\mathbf{U} = \mathbf{B}^{1/2}$ (Barker *et al.* 2004); superscripts -1 and T denote inverse and adjoint of a matrix or a linear operator; H_k, $\mathbf{H_k}$ and $\mathbf{H^T}_k$ are nonlinear, tangent linear and adjoint observation operators over observation window k, which transform atmospheric variables between the gridded analysis space and observation space; M_k, $\mathbf{M_k}$ and $\mathbf{M^T}_k$ are nonlinear, tangent linear and adjoint models, which propagate in time the guess vector $\mathbf{x^{n-1}}$, analysis increments $\mathbf{U^{-1}}\boldsymbol{\chi}^{\mathbf{n}}$ and analysis residual, {.} in Equation (1), respectively; $\mathbf{S_{W\text{-}V}}$, $\mathbf{S_{V\text{-}W}}$, $\mathbf{S_{W\text{-}V}}^{\mathbf{T}}$ and $\mathbf{S_{V\text{-}W}}^{\mathbf{T}}$ are the WRF-Var specific operators which transform variables (e.g. between T and θ) and grids (between A-grid and C-grid) between VAR and WRF$^+$.

WRF+, VAR and COM are the three major components of WRF-Var from a program structure point of view (Fig.1):

I. WRF$^+$

WRF$^+$ is an extension of WRF model under the same framework. It contains, in addition to the original WRF nonlinear model (renamed here as WRF_NL), the WRF tangent linear model (WRF_TL), the WRF adjoint model (WRF_AD) and a simplified WRF nonlinear model (WRF_SN, not shown in Fig.1 as it is only used for testing and developing WRF_TL and WRF_AD).

II. VAR

VAR contains all the components of WRF 3DVAR (Barker *et al.* 2004) plus the 4-dimensional related enhancements. Among the enhancements are the grouping of observations (break $\mathbf{y}$ into $\mathbf{y_k}$) and their related calculations (replace H, $\mathbf{H}$ and $\mathbf{H^T}$ by H_k, $\mathbf{H_k}$ and $\mathbf{H_k}^{\mathbf{T}}$) according to the observation windows (k); the calls to WRF_NL, WRF_TL and WRF_AD; and the grid/variable transform operators.

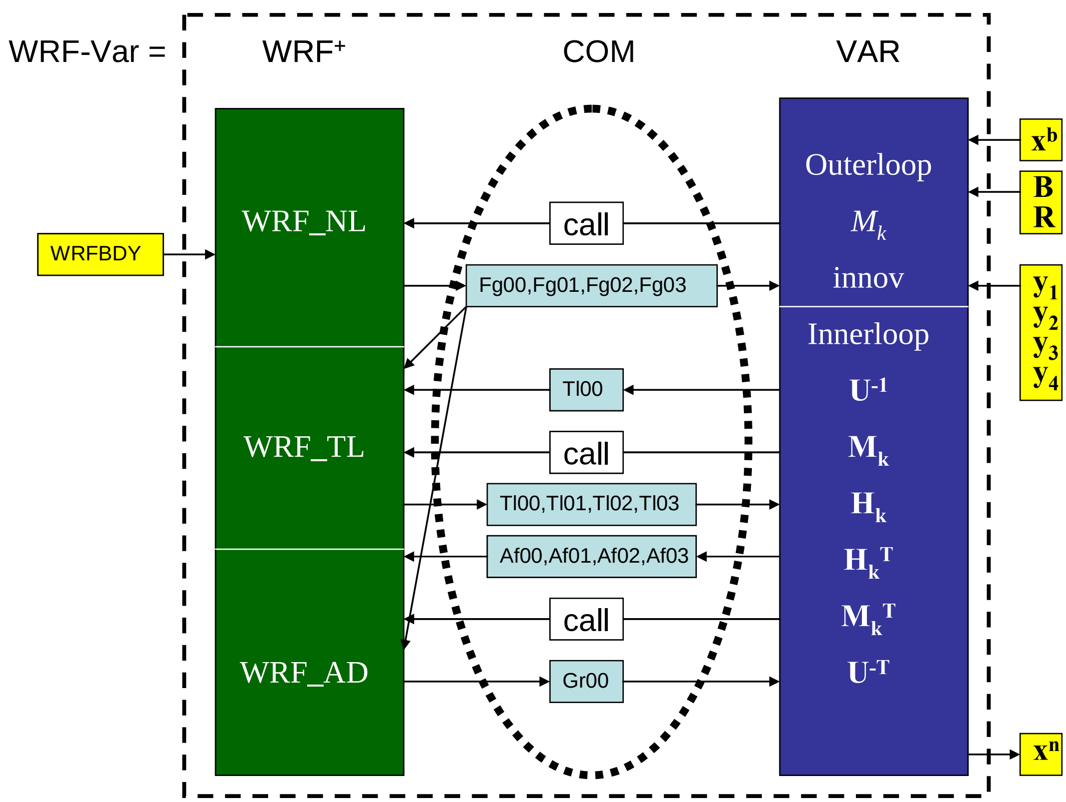

Figure 1. The data flow and program structure of WRF-Var.

III. COM

As WRF⁺ and VAR are separate components, communications between them are needed. COM manages this communication. The implementation of COM is hidden from the other two components, allowing the movement of data to be handled either through disk I/O or, for maximum efficiency, through memory.

3. Working plan and progress

The WRF-Var development started in 2004 and was planned for 3 years in 4 stages.

Stage I. Prepare the components: (WRF⁺ and VAR)

The major effort in 2004 was devoted to the WRF⁺ development. The strategy for building WRF⁺ and its current status of development are reported by Xiao *et al.* (2005). Here only a brief description is given.

WRF⁺ comprises 4 models -- WRF_NL, WRF_TL, WRF_AD and WRF_SN -- under the same framework. Significant time was spent on selecting a simplified subset, WRF_SN, of the WRF model, referred to here as WRF_NL. WRF_SN, contains the full dynamics of WRF_NL plus a minimal set of physics. It has been shown to produce reasonable short-range forecasts compared to WRF_NL (Xiao *et al.* 2005).

The Transformation of Algorithms in Fortran (TAF) is used to construct WRF_TL and WRF_AD. Most of the TAF generated code passed the standard gradient tests and TL/AD tests following Zou *et al.* (1997). Several bugs were removed from the TAF generated code. The debugging work is expected to be finished before the end of 2005.

One of the major tasks in 2005 is to extend WRF-3DVAR to VAR. The breakup of tangent linear and adjoint observation operators closely followed the structure of nonlinear observation operators, which were prepared for WRF-3DVAR the First Guess at the Appropriate Time (FGAT) system (e.g. Lee *et al.* 2004).

At this stage we have tried to avoid merging WRF⁺ and VAR. Rather, they execute as separate programs, interacting as necessary through COM. The VAR code controls the overall execution of the assimilation system, using calls to UNIX "system" library routine to invoke WRF_NL, WRF_TL and WRF_AD when they are needed.

The WRF model variables and WRF-3DVAR variables are different and are on different grids. The current strategy is to use transform operators between WRF⁺ and VAR. The operators were made and tested, but refinements are still needed.

Stage II. Build the prototype: (WRF⁺ + VAR)

Another major task in 2005 is to construct a prototype 4DVAR capability for WRF-Var. The prototype is almost completed and it has been tested with most of the WRF_TL and WRF_AD components switched off. Refinements are still needed. The main features of the prototype are:

1) It runs as separate WRF⁺ and VAR executables (wrfplux.exe and var.exe),
2) It uses calls to "system" to invoke wrfplus.exe from var.exe, and
3) Data move between WRF⁺ and VAR through disk I/O using the NETCDF format.

To use disk I/O is one option of COM. It enables WRF-Var to run on computers with limited memory, though at a cost of slowing performance.

With the WRF-Var prototype it is possible to conduct single-observation experiments and case studies. Preliminary results will be reported in autumn 2005.

Stage III. Build the basic system: (WRF-Var)

The WRF-Var basic system will be built on the prototype in 2006. The main features of the basic system include:

1) A single executable, wrfvar.exe, which integrates WRF⁺ and VAR, and
2) A new option for communication between WRF⁺ and VAR using memory.

The WRF-Var basic system is expected to be computationally efficient as the program structure of WRF model and WRF-3DVAR will be maintained. Cycling experiments will be conducted using the basic system.

Stage IV. Enhance the performance

Efforts in 2006 will focus on improving the performance of the WRF-Var system both meteorologically and computationally. More physics will be incorporated into the tangent linear and adjoint models. Testing and further development of the multi-incremental formulation will be performed. Work on the parallelization and optimization on the COM component and the enhanced basic system will also be carried out. At this stage, extensive experiments will be carried out to assess the performance of WRF-Var.

To control the gravity wave generated during the minimization iterations a penalty term based on the Digital Filter Initialization, JcDFI (Wee and Kuo, 2004), may need to be implemented.

4. The current status

There are some overlaps among the stages. We are currently finishing the work planned for Stage I and in the middle of Stage II.

We are still working on the solver routine in WRF_AD, solve_em_ad.F, and moving towards the first complete WRF$^+$. As the VAR and COM I/O option can now be used, we have made some test of the full system with both solve_em_tl.F (the solver routine in WRF_TL) and solve_em_ad.F replaced by an identity operator. With this setup the analysis increments remain the same for all observation windows but the forcing terms are added up during the WRF_AD integration. This is in fact an option of First Guess at the Appropriate Time (FGAT). Different from other FGAT implementations (e.g. Lee *et al.* 2004) the WRF-Var-FGAT has observations on one side of analysis time and therefore allows the WRF nonlinear model integrations in the outer-loops of the minimization process. In this way the model dynamics can, to some extent, be taken into account. Experiments with WRF-FGAT have been planned and will be reported in the near future.

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