

WRF Data Assimilation System

Xin Zhang Xiang-Yu Huang

NCAR Earth System Laboratory

April 16, 2011
5th East Asia WRF Tutorial

NCAR is sponsored by the National Science Foundation

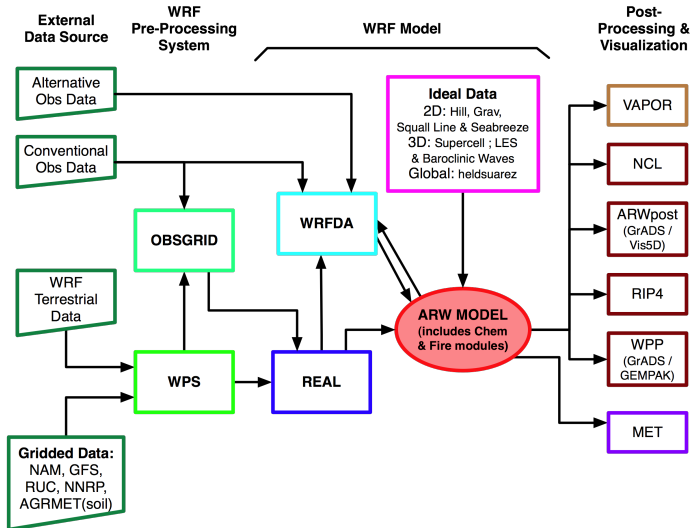


What is WRFDA ?

- WRFDA : A Data Assimilation system for WRF (ARW) model
 - Variational and Ensemble methods
 - Used for both research and operational data analysis
- It is a supported community model, i.e. a free and shared resource with distributed development and centralized support



WRF Modeling System Flow Chart



WRFDA formulation

$$J = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}[\mathbf{y}_o - H(\mathbf{x})]^T \mathbf{R}^{-1}[\mathbf{y}_o - H(\mathbf{x})]$$

Define the first guess of the n^{th} outer loop: $\mathbf{x}_{n-1}$, note: $\mathbf{x}_0 = \mathbf{x}_b$

$$J = \frac{1}{2}(\mathbf{x}_n - \mathbf{x}_{n-1} + \mathbf{x}_{n-1} - \mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}_n - \mathbf{x}_{n-1} + \mathbf{x}_{n-1} - \mathbf{x}_b) \\ + \frac{1}{2}[\mathbf{y}_o - H(\mathbf{x}_n)]^T \mathbf{R}^{-1}[\mathbf{y}_o - H(\mathbf{x}_n)]$$

Define analysis increment of n^{th} outer loop: $\delta \mathbf{x}_n = \mathbf{x}_n - \mathbf{x}_{n-1}$

$$J = \frac{1}{2}(\delta \mathbf{x}_n + \mathbf{x}_{n-1} - \mathbf{x}_b)^T \mathbf{B}^{-1}(\delta \mathbf{x}_n + \mathbf{x}_{n-1} - \mathbf{x}_b) \\ + \frac{1}{2}[\mathbf{y}_o - H(\mathbf{x}_{n-1} + \delta \mathbf{x}_n)]^T \mathbf{R}^{-1}[\mathbf{y}_o - H(\mathbf{x}_{n-1} + \delta \mathbf{x}_n)]$$



Define innovation : $\mathbf{d}_n = \mathbf{y}_o - \mathbf{H}_{n-1}(\mathbf{x}_{n-1})$

$$J = \frac{1}{2}(\delta\mathbf{x}_n + \mathbf{x}_{n-1} - \mathbf{x}_b)^T \mathbf{B}^{-1}(\delta\mathbf{x}_n + \mathbf{x}_{n-1} - \mathbf{x}_b) \\ + \frac{1}{2}[\mathbf{d}_n - \mathbf{H}_{n-1}(\delta\mathbf{x}_n)]^T \mathbf{R}^{-1}[\mathbf{d}_n - \mathbf{H}_{n-1}(\delta\mathbf{x}_n)]$$

$\mathbf{H}_{n-1} = \frac{\partial \mathbf{H}_{n-1}}{\partial \mathbf{x}_{n-1}}$ is the tangent linear observational operator
To find the $\delta\mathbf{x}_n$ which lead J to minimum:

$$\nabla_{\delta\mathbf{x}_n} J = 0$$

$$\nabla_{\delta\mathbf{x}_n} J = \mathbf{B}^{-1}(\delta\mathbf{x}_n + \mathbf{x}_{n-1} - \mathbf{x}_b) - \mathbf{H}_{n-1}^T \mathbf{R}^{-1}(\mathbf{d}_n - \mathbf{H}_{n-1}(\delta\mathbf{x}_n))$$



At the minimum, $\nabla_{\delta \mathbf{x}_n} J$ vanishes:

$$(\mathbf{B}^{-1} + \mathbf{H}_{n-1}^T \mathbf{R}^{-1} \mathbf{H}_{n-1}) \delta \mathbf{x}_n = \mathbf{H}_{n-1}^T \mathbf{R}^{-1} \mathbf{d}_n - \mathbf{B}^{-1}(\mathbf{x}_{n-1} - \mathbf{x}_b)$$

Then

$$\delta \mathbf{x}_n = (\mathbf{B}^{-1} + \mathbf{H}_{n-1}^T \mathbf{R}^{-1} \mathbf{H}_{n-1})^{-1} [\mathbf{H}_{n-1}^T \mathbf{R}^{-1} \mathbf{d}_n - \mathbf{B}^{-1}(\mathbf{x}_{n-1} - \mathbf{x}_b)]$$

With the Woodbury Matrix Identity formulation:

$$(\mathbf{A} + \mathbf{UCV})^{-1} = \mathbf{A}^{-1} - \mathbf{A}^{-1} \mathbf{U} (\mathbf{C}^{-1} + \mathbf{VA}^{-1} \mathbf{U})^{-1} \mathbf{VA}^{-1}$$

$$(\mathbf{B}^{-1} + \mathbf{H}_{n-1}^T \mathbf{R}^{-1} \mathbf{H}_{n-1})^{-1} = \mathbf{B} - \mathbf{B} \mathbf{H}_{n-1}^T (\mathbf{R} + \mathbf{H}_{n-1} \mathbf{B} \mathbf{H}_{n-1}^T)^{-1} \mathbf{H}_{n-1} \mathbf{B}$$



$$\delta \mathbf{x}_n = [\mathbf{B} - \mathbf{B}\mathbf{H}_{n-1}^T(\mathbf{R} + \mathbf{H}_{n-1}\mathbf{B}\mathbf{H}_{n-1}^T)^{-1}\mathbf{H}_{n-1}\mathbf{B}]$$

$$[\mathbf{H}_{n-1}^T\mathbf{R}^{-1}\mathbf{d}_n - \mathbf{B}^{-1}(\mathbf{x}_{n-1} - \mathbf{x}_b)]$$

$$\delta \mathbf{x}_n = \mathbf{B}\mathbf{H}_{n-1}^T(\mathbf{R} + \mathbf{H}_{n-1}\mathbf{B}\mathbf{H}_{n-1}^T)^{-1}[\mathbf{d}_n + \mathbf{H}_{n-1}(\mathbf{x}_{n-1} - \mathbf{x}_b)]$$

$$- (\mathbf{x}_{n-1} - \mathbf{x}_b)$$

Please note that the new analysis is :

$$\mathbf{x}_a = \delta \mathbf{x} + \mathbf{x}_{n-1}$$



For one outer loop, $\mathbf{x}_0 = \mathbf{x}_b$ and $\mathbf{d} = \mathbf{y}_o - H(\mathbf{x}_b)$

$$J = \frac{1}{2} \delta \mathbf{x}^T \mathbf{B}^{-1} \delta \mathbf{x} + \frac{1}{2} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})^T \mathbf{R}^{-1} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})$$

$$\nabla_{\delta \mathbf{x}} J = \mathbf{B}^{-1} \delta \mathbf{x} - \mathbf{H}^T \mathbf{R}^{-1} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})$$

$$\delta \mathbf{x} = \mathbf{B} \mathbf{H}^T (\mathbf{R} + \mathbf{H} \mathbf{B} \mathbf{H}^T)^{-1} \mathbf{d}$$

Prepare the BE

$$J = \frac{1}{2} \delta \mathbf{x}^T \mathbf{B}^{-1} \delta \mathbf{x} + \frac{1}{2} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})^T \mathbf{R}^{-1} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})$$

- Nominally, **B** is the background error covariance
- For initial testing, default background error statistics may be used
 - be.dat file (CV option 5) from test case tar file can **only be used with the case of online tutorial**
 - be.dat.cv3 (CV option 3) from source code tar file can be used for general test domains, **tuning is still needed for satisfied performance**
- Ultimately, **B** should be specific to the particular model domain (and season)



Prepare the Background

$$J = \frac{1}{2} \delta \mathbf{x}^T \mathbf{B}^{-1} \delta \mathbf{x} + \frac{1}{2} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})^T \mathbf{R}^{-1} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})$$

$$\delta \mathbf{x} = \mathbf{x} - \mathbf{x}_b$$

- In cold-start mode: accomplished by running the WPS and real programs
 - The background is the wrfinput_d01 file
- In cycling mode: the output of the WRF model
 - WRF can output wrfinput-formatted files used for cycling



Prepare the Observations & Errors

$$J = \frac{1}{2} \delta \mathbf{x}^T \mathbf{B}^{-1} \delta \mathbf{x} + \frac{1}{2} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})^T \mathbf{R}^{-1} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})$$

$$\mathbf{d} = \mathbf{y} - H(\mathbf{x}_b)$$

- Conventional observation input for WRFDA is supplied through
 - Little_R format, observation preprocessor, OBSPROC
 - Prepbufr format data directly
- Observation error covariance also provided by OBSPROC (R is a diagonal matrix)
- Separate input file (ASCII) for radar, both reflectivity and radial velocity
- Separate input file for satellite radiances, BUFR format



Run WRFDA

$$J = \frac{1}{2} \delta \mathbf{x}^T \mathbf{B}^{-1} \delta \mathbf{x} + \frac{1}{2} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})^T \mathbf{R}^{-1} (\mathbf{d} - \mathbf{H} \delta \mathbf{x})$$

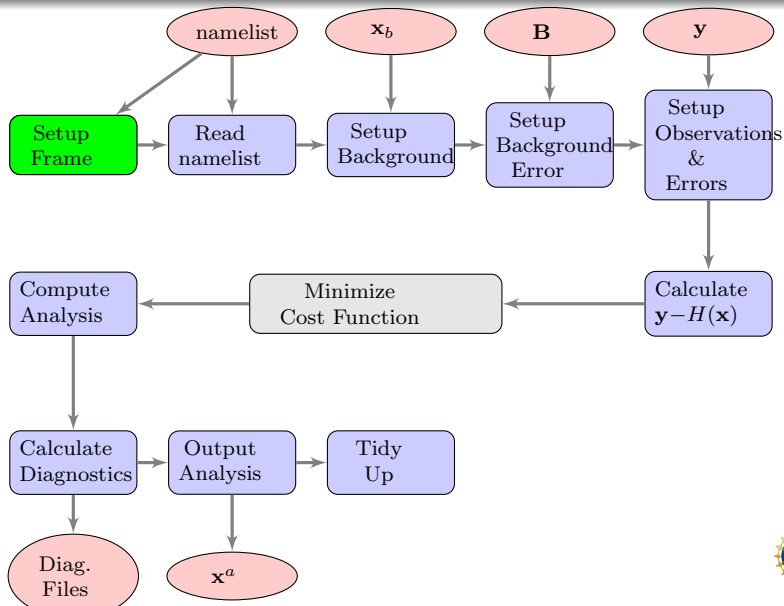
- H is the observational operator, which calculate the counterpart of observations in model space
- Conjugate gradient method
- Try to find a $\delta \mathbf{x}^a$, which minimizes J and then $\mathbf{x}^a = \mathbf{x}^b + \delta \mathbf{x}^a$



Update Boundary Condition

- After creating an analysis, $\mathbf{x}^a$, we have changed the initial conditions for the model
- However, tendencies in wrfbdy_d01 file are valid for background, $\mathbf{x}_b$
- The update_bc program adjusts these tendencies based on the difference $\mathbf{x}^a - \mathbf{x}_b$
- Of course, if $\mathbf{x}^a$ was produced for reasons other than running WRF, there is probably not a need to update boundary conditions

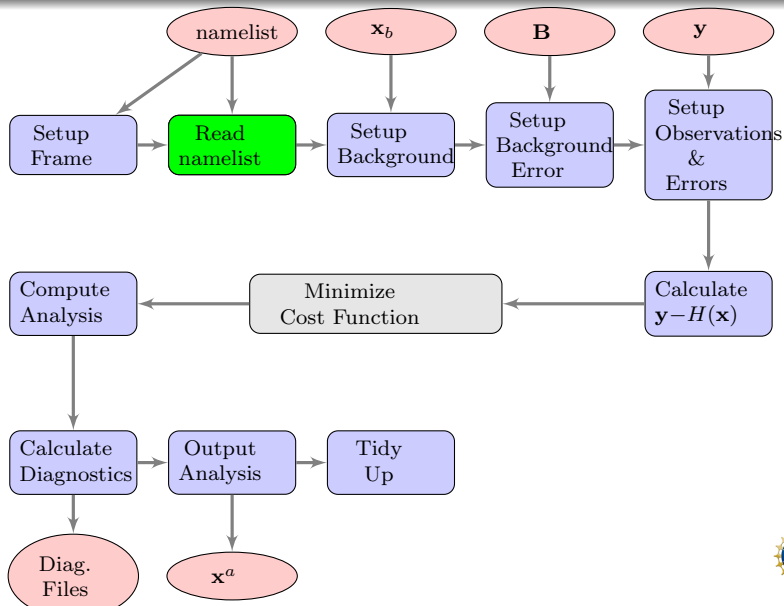




Setup Frame

- Reads grid dimensions from *namelist.input* file
- Use WRF framework distributed memory capability to initialize tile, memory, patch dimensions, etc.

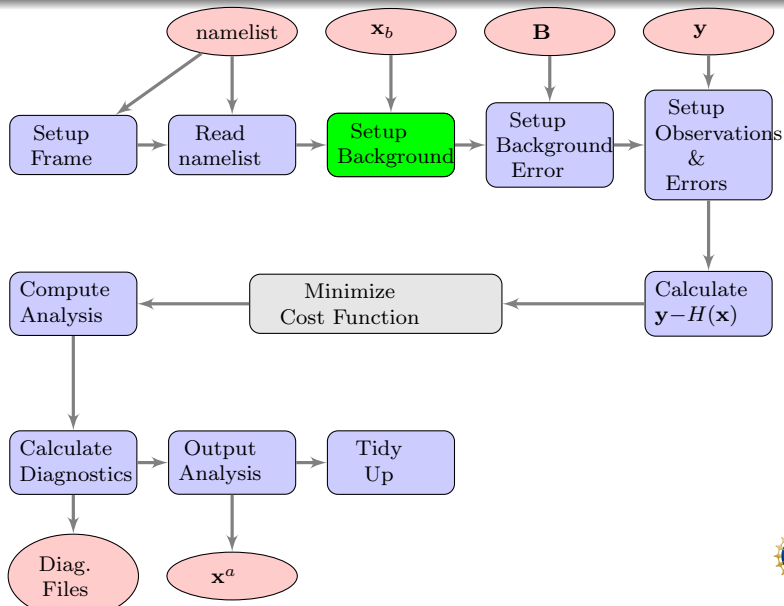




Read namelist

- Reads WRFDA data assimilation options from namelist.input file
- Performs consistency checks between namelist options.

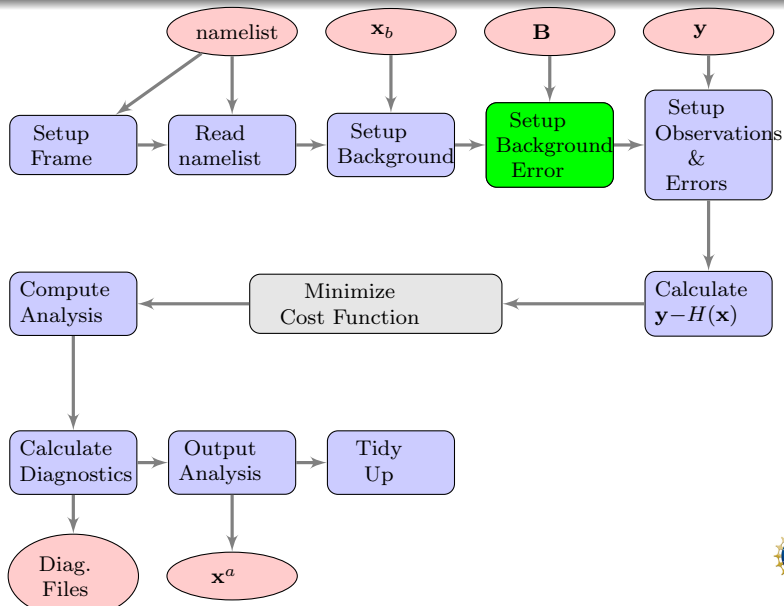




Setup Background

- Reads the first-guess file
- Extracts fields used by WRFDA
- Creates background FORTRAN 90 derived data type *xb* etc.

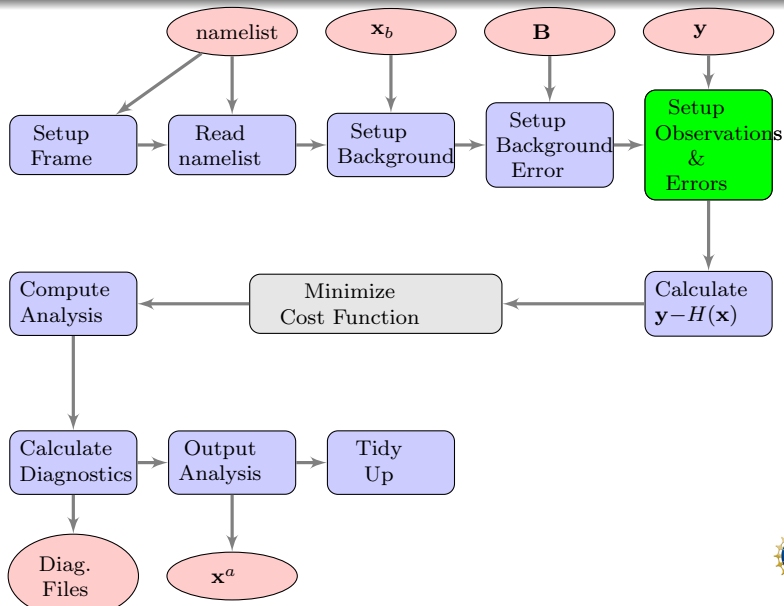




Setup Background Error

- Reads in background error statistics
- Extracts necessary quantities: eigenvectors, eigenvalues, lengthscales, regression coefficients, etc.
- Creates background error FORTRAN 90 derived data type *be*
- Reference : **Online BE Documents**

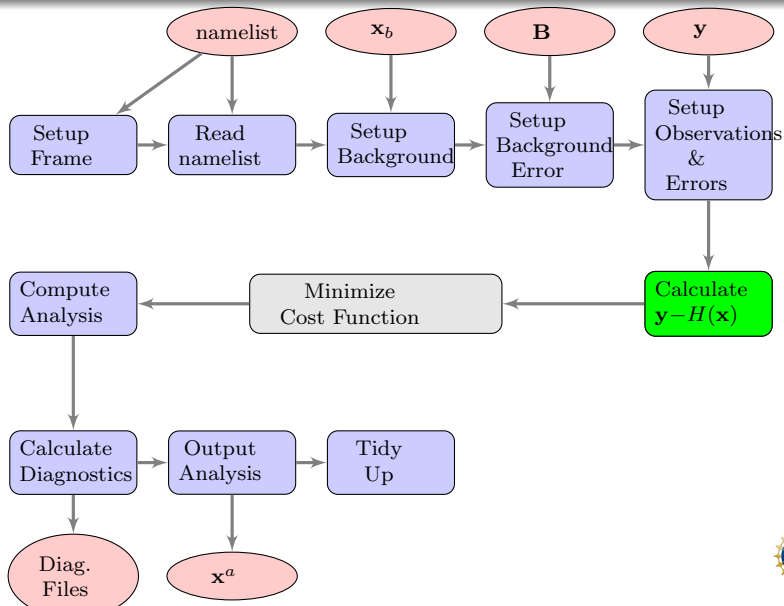




Setup Observations & Errors

- Reads in observations
- Assign observational error
- Creates observation FORTRAN 90 derived data type *ob*
- Domain and time check

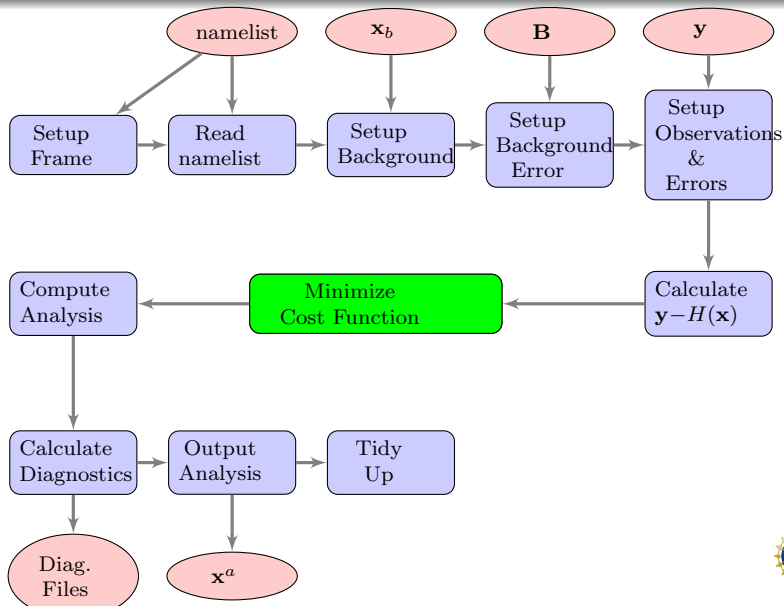




Calculate Innovation

- Calculates model equivalent of observations through interpolation and change of variable
- Computes observation minus first guess ($\mathbf{y} - H(\mathbf{x})$) value
- Creates innovation vector FORTRAN 90 derived data type *iv*



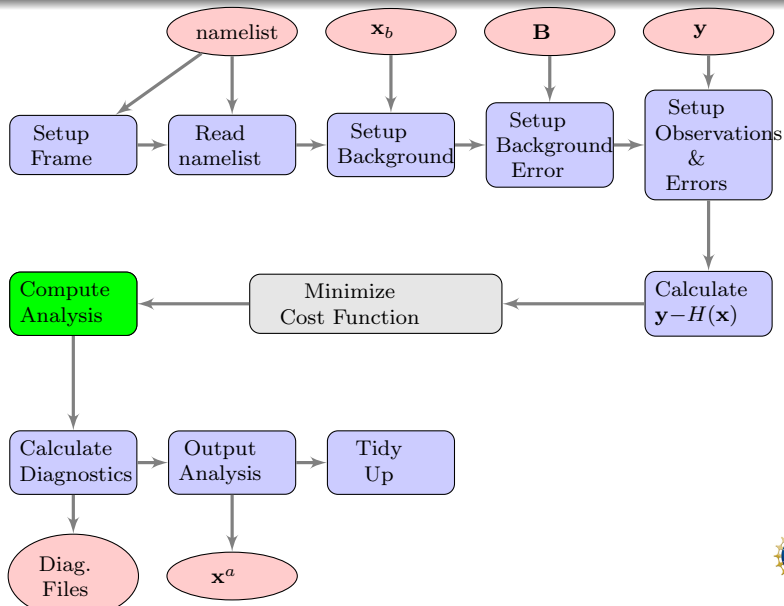


Minimization

Use conjugate gradient method

- Initializes analysis increments to zero
- Computes cost function (if desired)
- Computes gradient of cost function
- Uses cost function and gradient to calculate new value of analysis control variable

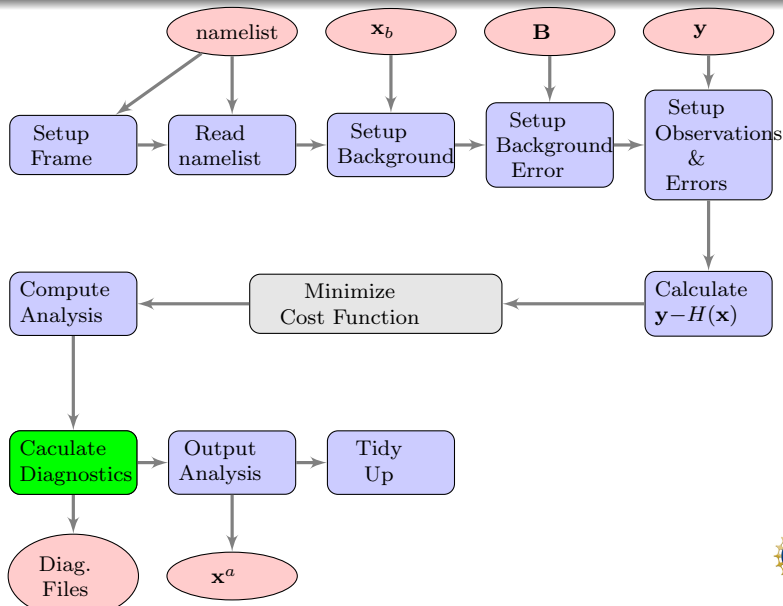




Compute Analysis

- Once WRFDA has found a converged control variable, convert control variable to model space analysis increments
- Calculate:
analysis = first-guess + analysis increment
- Performs consistency checks, e.g., remove negative humidity etc.
- Optionally, do outer loop

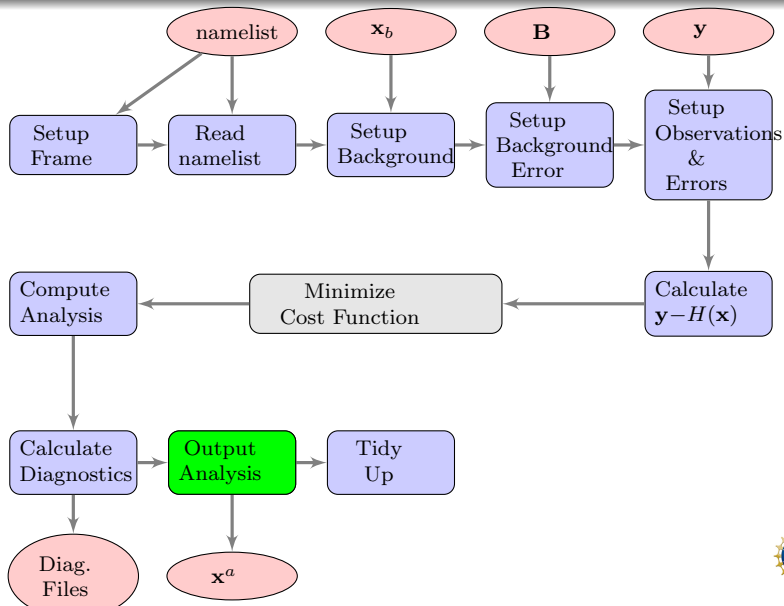




Calculate Diagnostics

- Output $\mathbf{y} - H(\mathbf{x}_b)$, $\mathbf{y} - H(\mathbf{x}^a)$ statistics for all observation types and variables
- Compute $\mathbf{x}^a - \mathbf{x}_b$ (analysis increment) statistics for all model variables and levels
- Statistics include minimum, maximum (and their locations), mean and standard deviation.

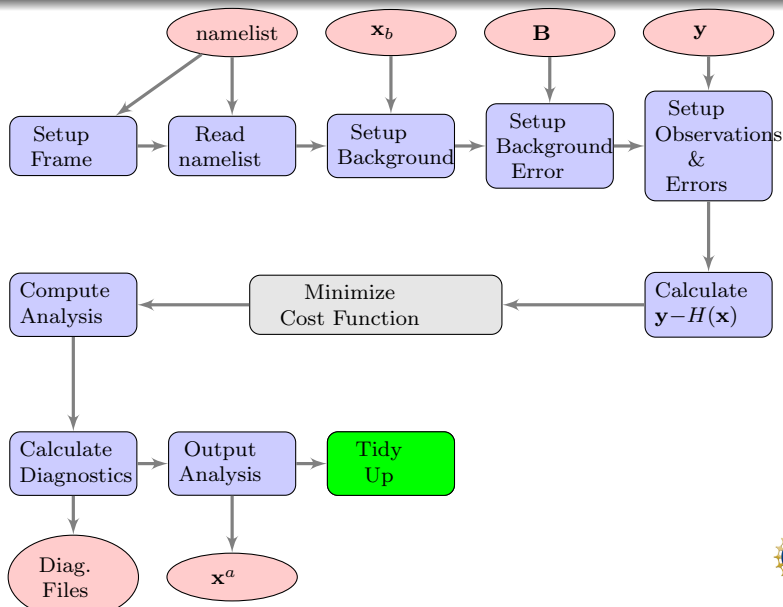




Output Analysis

- Outputs analysis in native model format.



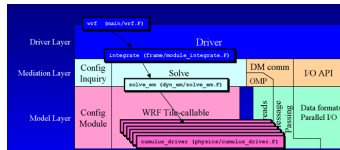


Tidy Up

- Deallocate dynamically-allocated arrays, structures, etc.
- Timing information
- Clean end to WRFDA



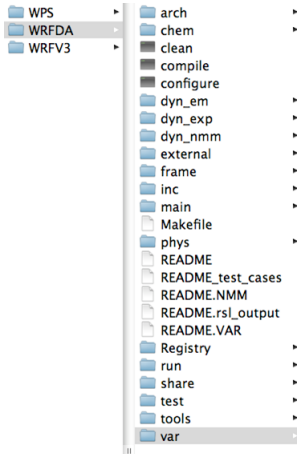
WRFDA Software Framework



- WRFDA relies on the WRF Software framework for
 - Distributed memory parallelism (halo exchanges, etc.)
 - Input/Output of first guess and analysis files
 - Parallel transposes
- WRFDA also uses
 - The WRF Registry mechanism to handle definitions of fields, halos, type, package and transposes ([Registry.wrfvar](#))
 - The WRF build system (clean, configure, compile)



WRFDA Code Organization

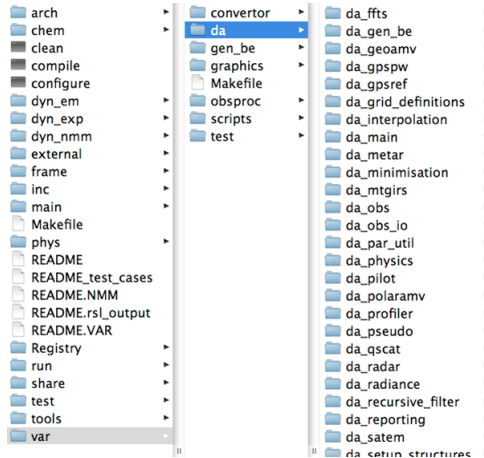


Remarks

Besides the directories for WRF, the WRFDA tar file contains a *var* directory, which holds all of the WRFDA code



WRFDA Code Organization

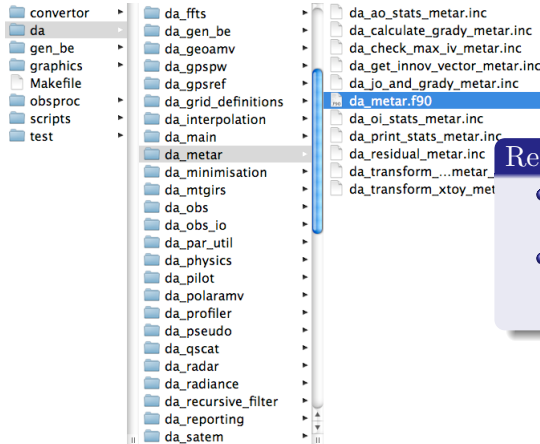


Remarks

Generally, each subdirectory of *da* contains a Fortran module with the same name



WRFDA Code Organization



Remarks

- da_metar.f90 contains a Fortran module
- Each .inc file corresponds to a subroutine within the module

Quick Start

- Supported compilation mechanisms
 - Serial
 - Distributed-memory(dm)
 - Shared-memory(sm) (use with cautions, thread safe compiler only-IBM XLF)
 - hybrid (dm+sm) (use with cautions)
- Supported platforms
 - IBM: XLF
 - Linux: PGI, IFORT, GFORTRAN (higher version needed,V4.4.0 tested)
 - Macintosh intel: PGI, G95, GFORTRAN (higher version needed,V4.4.0 tested)
- Included libraries
 - CRTM 2.0.2
 - BUFR, BLAS and LAPACK



- Install NetCDF (V3.6 above) with **THE SAME COMPILER** you will choose to compile WRFDA codes.
- Setup the environmental variable
 - `csh, tcsh` : `setenv NETCDF your_netcdf_path`
 - `bash, ksh` : `export NETCDF=your_netcdf_path`
- `cd WRFDA`
- `./clean -a`
- `./configure (-d) wrfda (-d : compile with debug mode)`
- `./compile all_wrfvar`
- 41 executables should be generated under `var/build` directory



Upgraded to Mac OS X Snow Leopard Users

- PGI (v10.3.0, 64-bit), G95(v4.0.3, 32-bit), GFORTRAN(v4.4.0, default is 32-bit, '-m64' needed for 64-bit) have been tested.
- gcc, g++ are version 4.2.1, default is 64-bit, '-m32' needed for 32-bit.
- NetCDF library should be re-install with appropriate compiler and option.
- V3.3 configure is able to produce configure.wrf for PGI and G95.
- For GFORTRAN compiler, '-m64' should be added to SFC, SCC, CCOMP in configure.wrf manually.
- Prepbufr and Bufr format data have problem to be read on Snow Leopard system.



Online WRFDA Resources

WRFDA has a dedicated page, similar to the ARW Users page:
WRFDA User Page

WRFDA USERS PAGE

Home Analysis System User Support Download Bug / Patches Links Users Forum

Search

wrf-model.org
Public Domain Notice
Contact WRF Support

WRF Data Assimilation System Users Page

Welcome to the users home page for the Weather Research and Forecasting (WRF) model data assimilation system (WRFDA). The WRFDA system is in the public domain and is freely available for community use. It is designed to be a flexible, state-of-the-art atmospheric data assimilation system that is portable and efficient on available parallel computing platforms. WRFDA is suitable for use in a broad range of applications across scales ranging from kilometers of regional mesoscale to thousands of kilometers of global scales.

The Mesoscale and Microscale Meteorology Division of NCAR is currently maintaining and supporting a subset of the overall WRF code (Version 3) that includes:

- WRF Software Framework (WRF)
- Advanced Research WRF (ARW) dynamic solver, including one-way, two-way nesting and moving nests, grid and observation nudging
- WRF Pre-Processing System (WPS)
- WRF Data Assimilation System (WRFDA)
- Numerous physics packages contributed by WRF partners and the research community

Other components of the WRF system will be supported for community use in the future, depending on interest and available resources.

updated Wed, 01 Apr 2009 17:24:21 GMT

ANNOUNCEMENTS

New WRF tutorial: July 13 - 24, 2009, Boulder, Colorado. Registration not yet open.

[WRF Version 3.1.1 Release Information](#)

[WRF Version 3.0.1.1 Release](#)
August 22, 2008

[WRF Var Version 3.0.1.1 Release](#)
August 28, 2008

New 'Known Problems' posts for V3
[WRF](#) (1/6/08) and [WPS](#) (6/4/08)

The 9th WRF Users' Workshop was held June 23 - 27, 2008 in Boulder, Colorado. [Workshop Presentations](#) is now online.

[MET 1.1 Release](#): The Model Evaluation Tools (July, 2008)

[Online Tutorial](#) (updated on Oct 2008)

Online Resources

From the WRFDA page, one can access:

Analysis System	User Support	Download	Doc / Pub
Downloads Overview			
WRFDA			
TESTDATA			
WRFNL			
WRFPLUS			
TOOLS			
Input Data from NCAR			
NCEP ftp			

WRFDA Source Code

Before you download, please take a look at the [Domain Notice](#), and [Users'](#) below. This registration form is prompted by the download. It also **subscribes** you to the WRF news email list. We are using this list to broadcast any messages regarding the WRFDA project.

Analysis System	User Support	Download	Doc / Pub
System Overview			
WRF-Var V3.1			
WRF-Var Online Tutorial			
WRF-Var Tools			
Data assimilation and their requirements			
state. Variational Data Assimilation			
Differences between the analysis and observation			
difference between three-dimensional (3D) and two-dimensional (2D) analysis			

Features in WRF-Var V3.1

Release Updates

How to Compile

How to Run

Known Problems and Fixes

Namelist

Analysis System	User Support	Download	Doc / Pub	Links
Documents & Publications				
References:				
Barker, D. M., W. Huang, Y.-R. Guo, and A. Bourgeois, 2003: A Three-Dimensional Variational (3DVAR) Data Assimilation System For Use With MM5. NCAR/TN-453+STR, 68 pp. (Available from UCAR Communications)				



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

