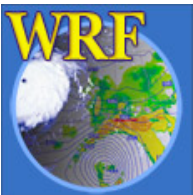


WRF-Var System Overview

Xin Zhang, Yong-Run Guo,
Syed R-H Rizvi, Hans Huang, and
Michael Duda



WRFDA Tutorial, 1-3 February 2010

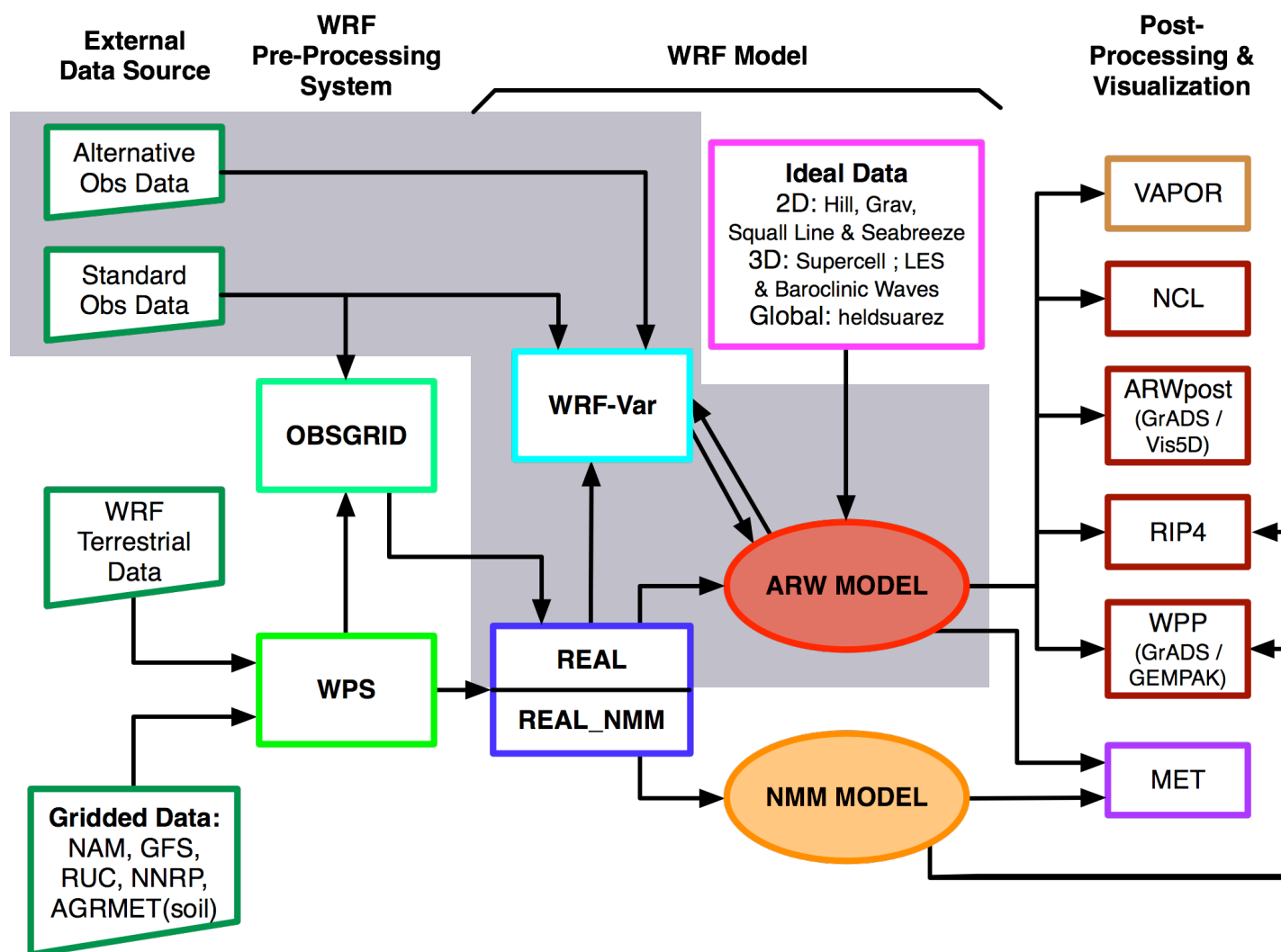
Outline

1. WRF-Var in the WRF Modeling System
2. WRF-Var Implementation
3. WRF-Var Software



WRF-Var in the WRF Modeling System

WRF Modeling System Flow Chart



WRF-Var in the WRF Modeling System

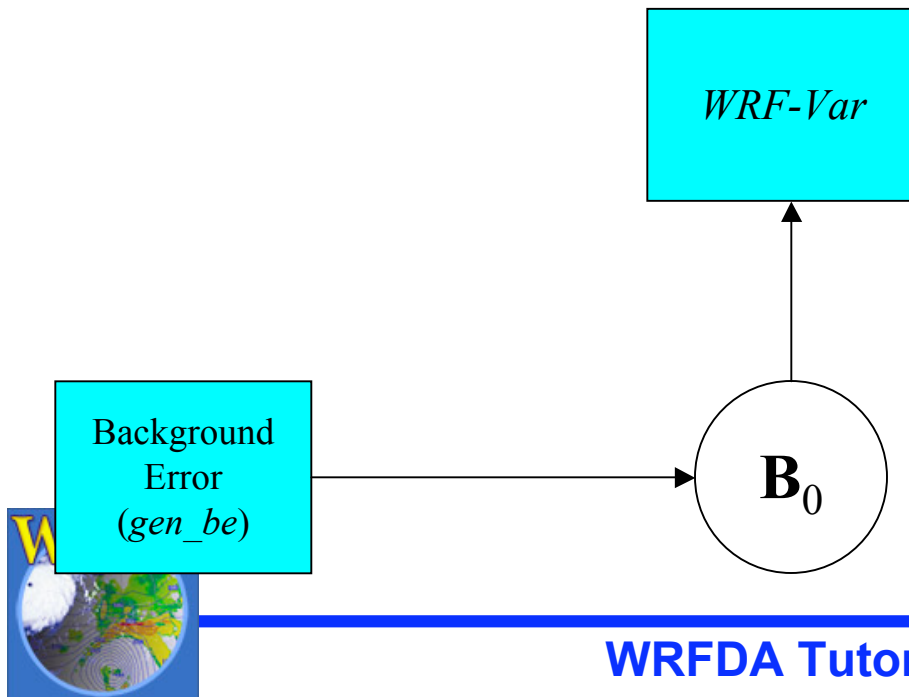
WRF-Var



Blue --> Supported by WRF-Var Team

WRF-Var in the WRF Modeling System

1. Prepare BE data

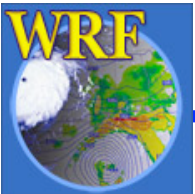


Blue --> Supported by WRF-Var Team

Prepare BE statistics

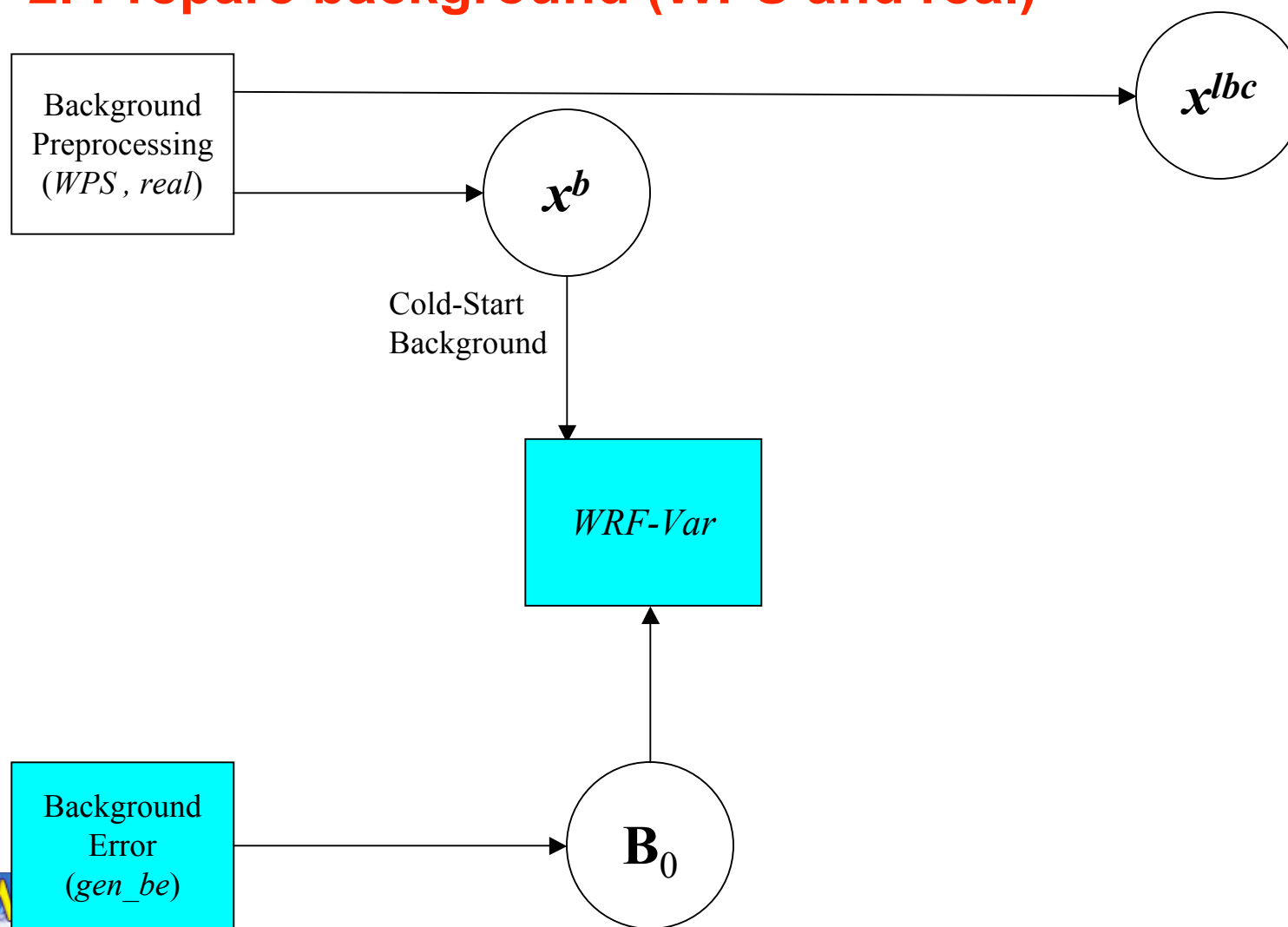
$$J(\mathbf{x}) = 1/2(\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b) + 1/2(\mathbf{y}^o - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y}^o - H(\mathbf{x}))$$

- 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 domain from online tutorial
 - be.dat.cv3 (CV option 3) from source code tar file can be used for general test domains
- Ultimately, these should be specific to the particular model domain (and season)
- See lecture “WRF-Var Background Error Estimations”



WRF-Var in the WRF Modeling System

2. Prepare background (WPS and real)



Prepare background

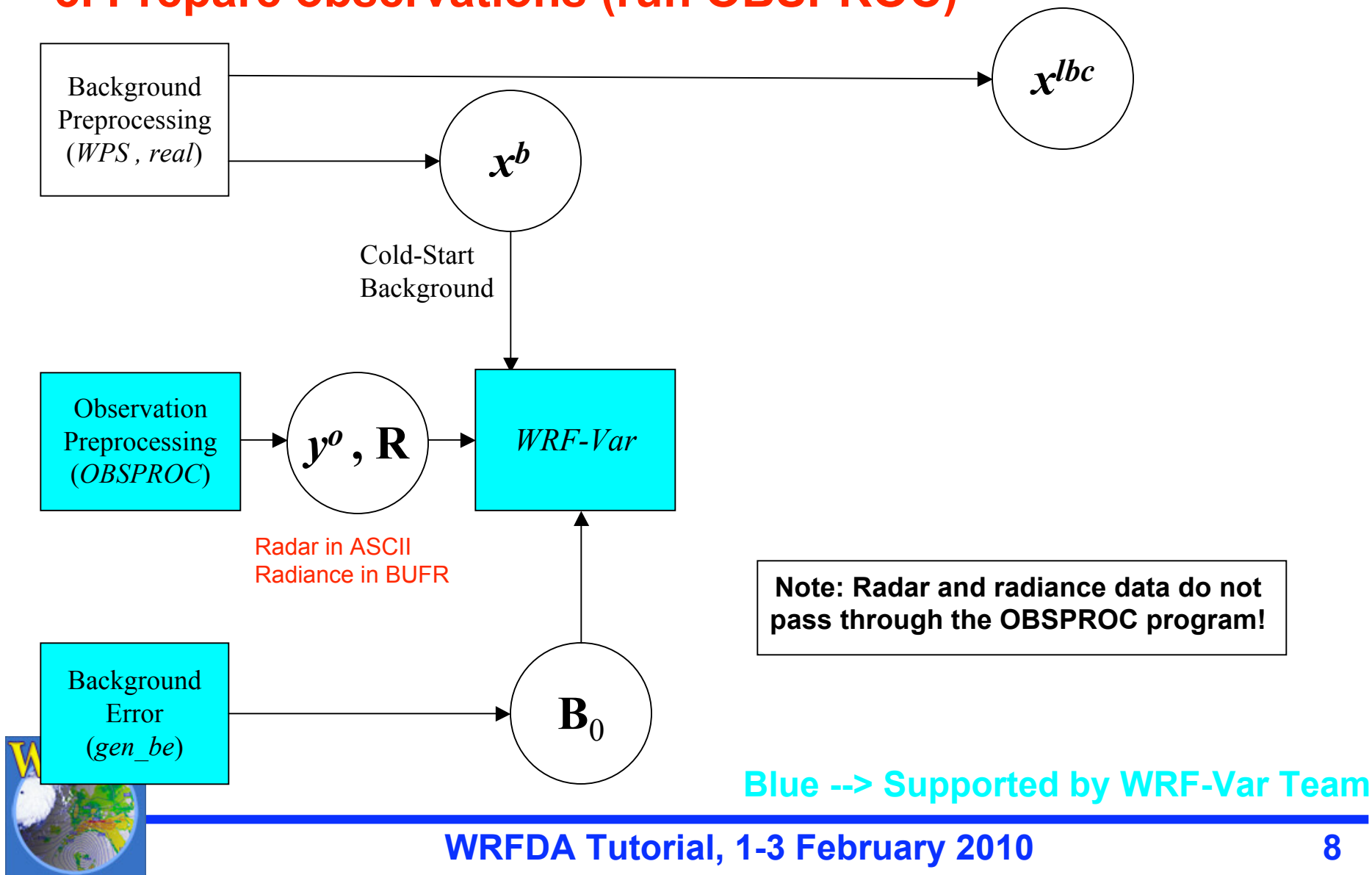
$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b) + \frac{1}{2}(\mathbf{y}^o - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y}^o - H(\mathbf{x}))$$

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



WRF-Var in the WRF Modeling System

3. Prepare observations (run OBSPROC)



Prepare observations (y^0)

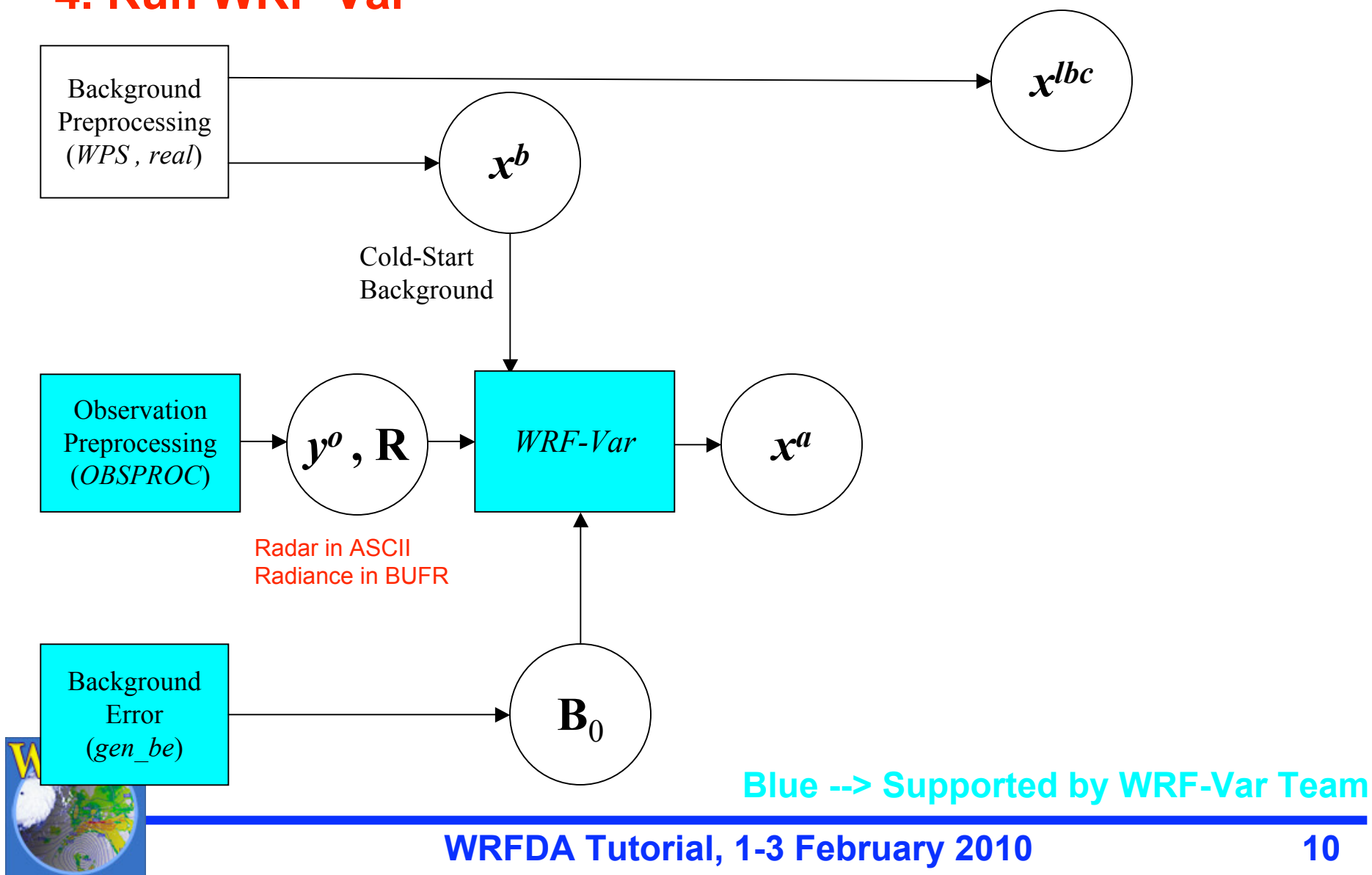
$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b) + \frac{1}{2}(\mathbf{y}^o - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y}^o - H(\mathbf{x}))$$

- Observation input for WRF-Var is supplied through observation preprocessor, OBSPROC
 - Except radar and satellite radiances
- Observation error covariance also provided by OBSPROC ($\mathbf{R}$ is a diagonal matrix)
- Separate input file (ASCII) for radar, both reflectivity and radial velocity.
- Separate input file for satellite radiances



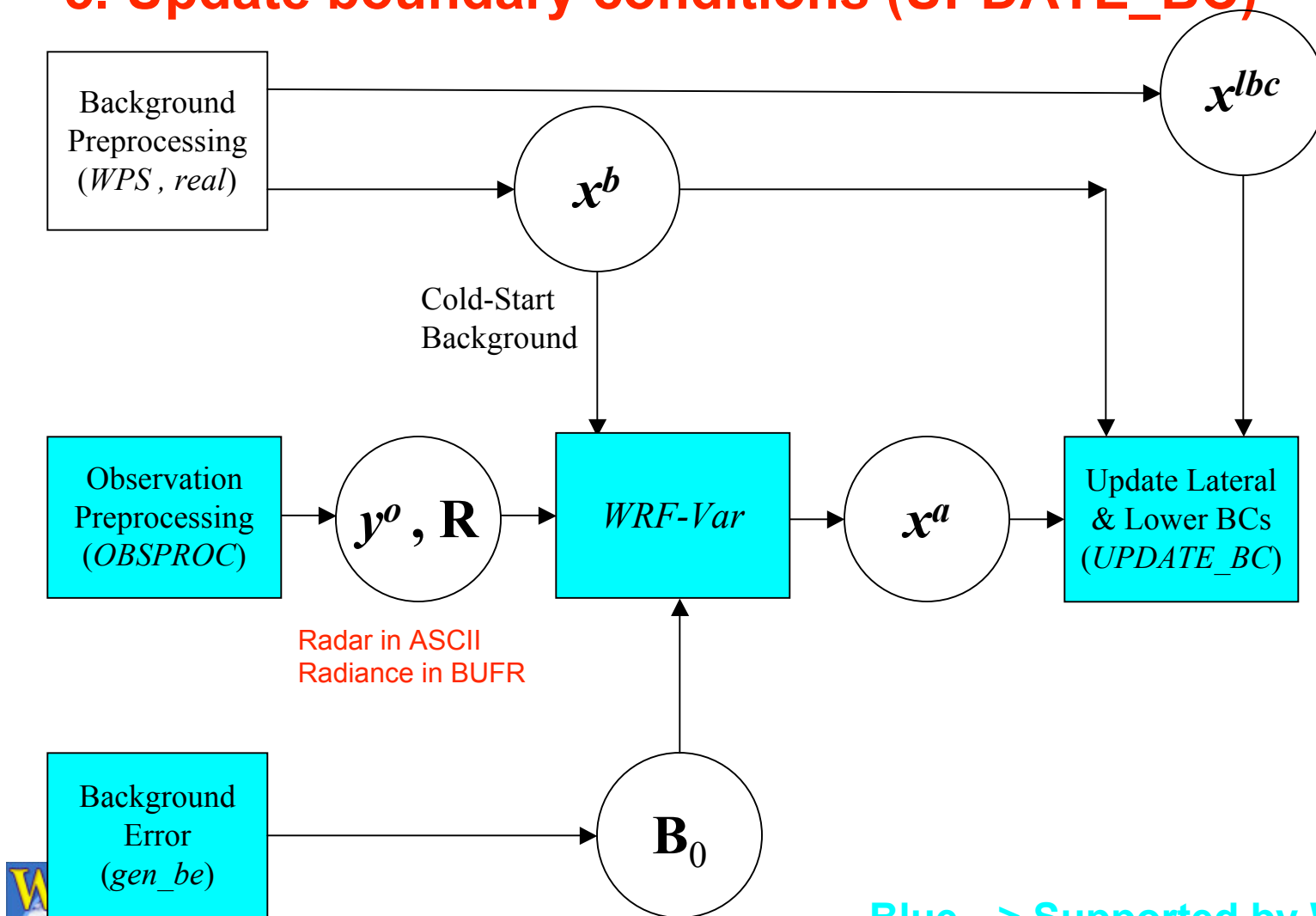
WRF-Var in the WRF Modeling System

4. Run WRF-Var



WRF-Var in the WRF Modeling System

5. Update boundary conditions (UPDATE_BC)



Blue --> Supported by WRF-Var Team

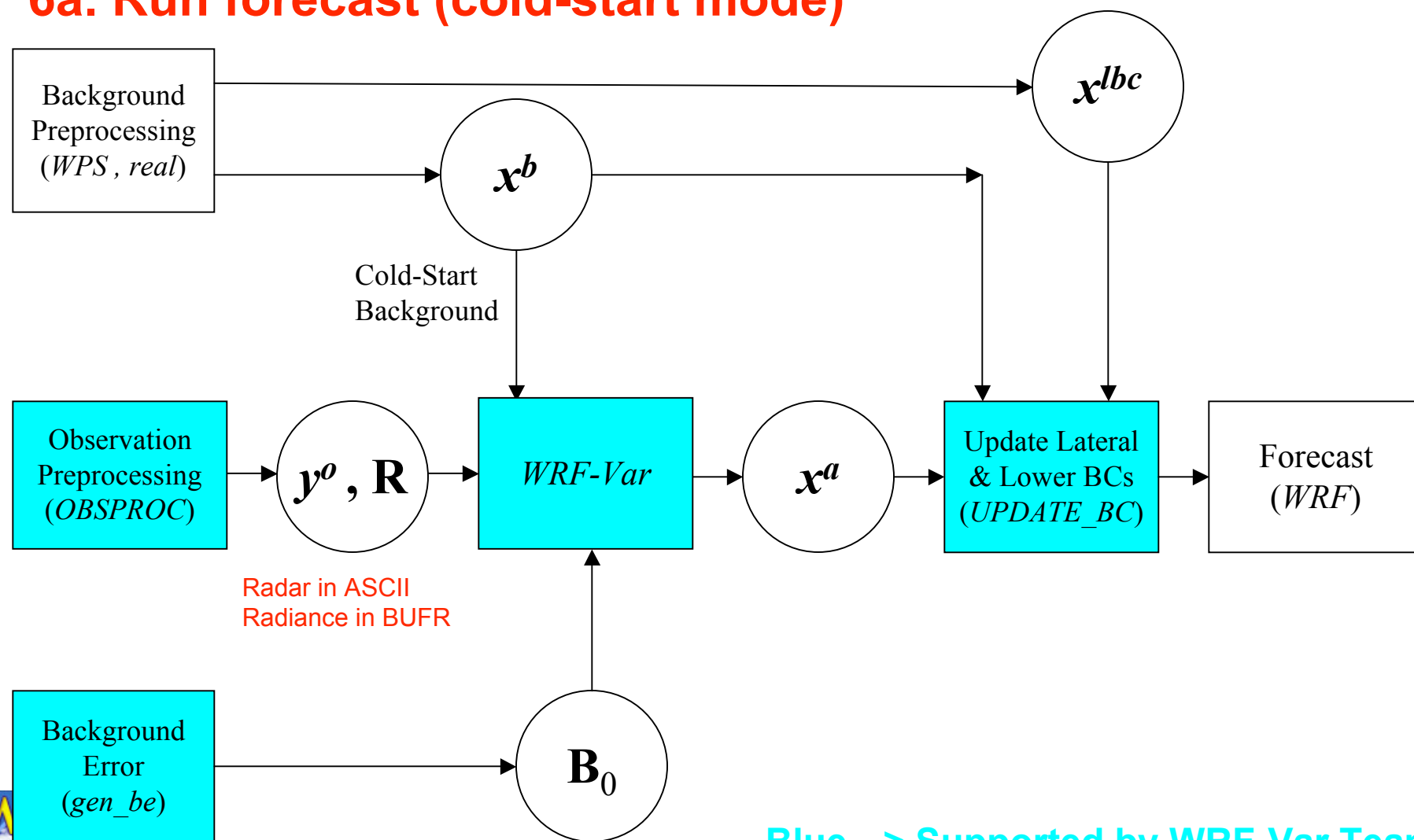
Update boundary conditions

- After creating an analysis, $\mathbf{x}^a$, we have changed the initial conditions for the model
 - However, tendencies in wrfbdy_d01 (and possibly wrflbdy) 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



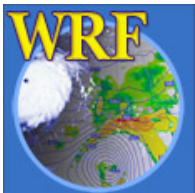
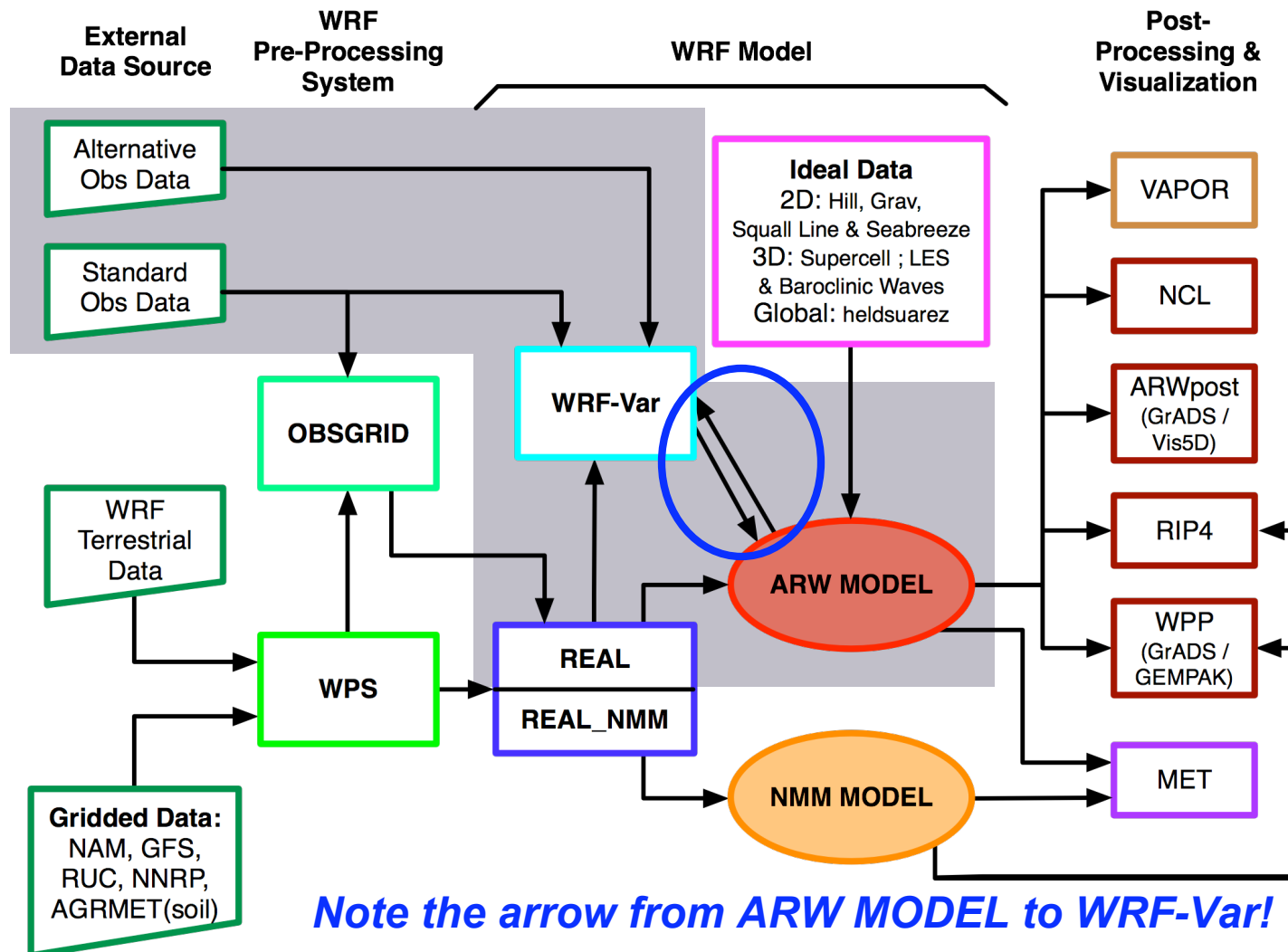
WRF-Var in the WRF Modeling System

6a. Run forecast (cold-start mode)



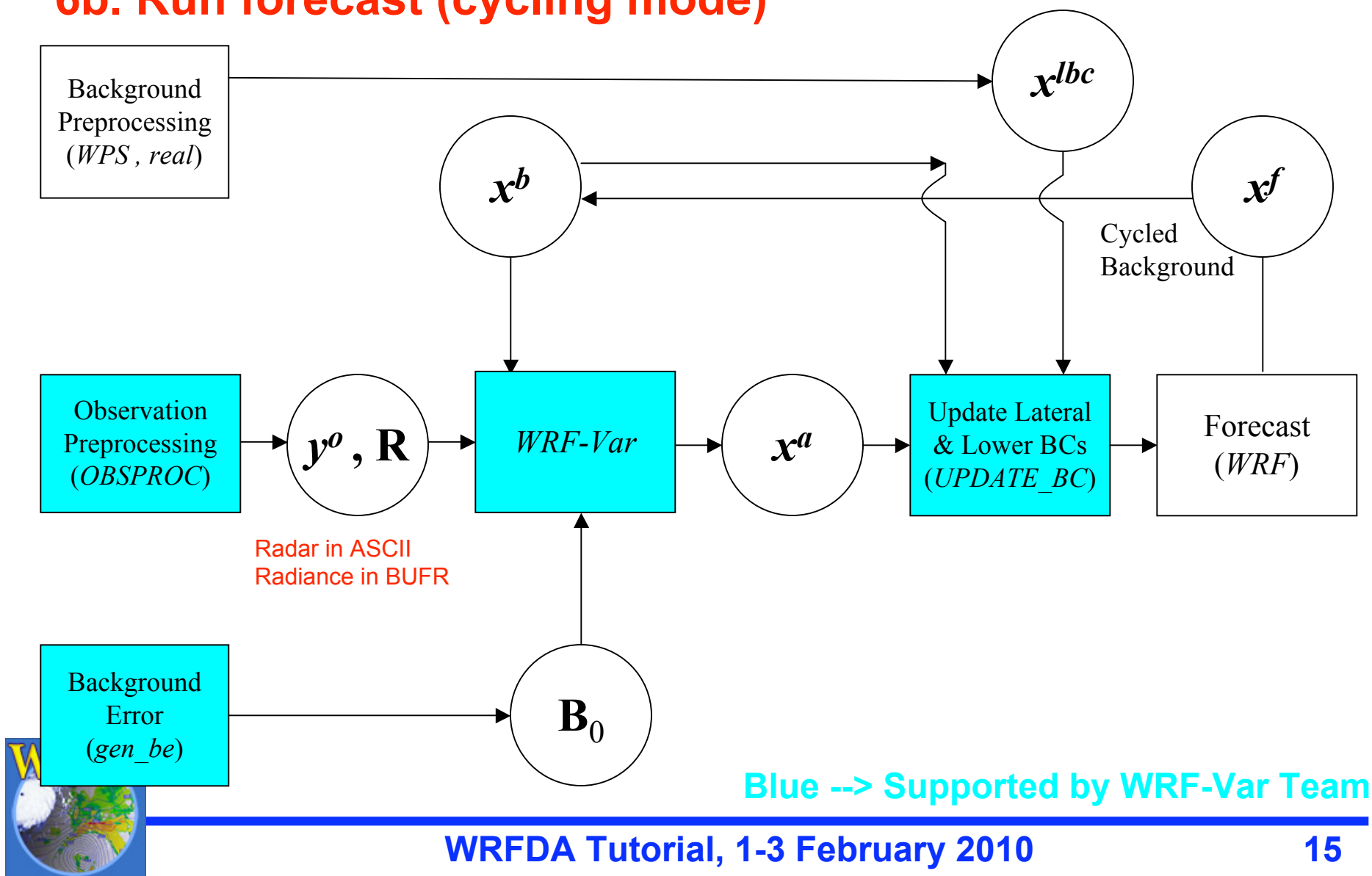
WRF-Var in the WRF Modeling System

WRF Modeling System Flow Chart



WRF-Var in the WRF Modeling System

6b. Run forecast (cycling mode)

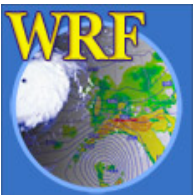


Background Error (BE) for WRF-Var

One important question from WRF-Var users is
“What background errors are best for my application?”

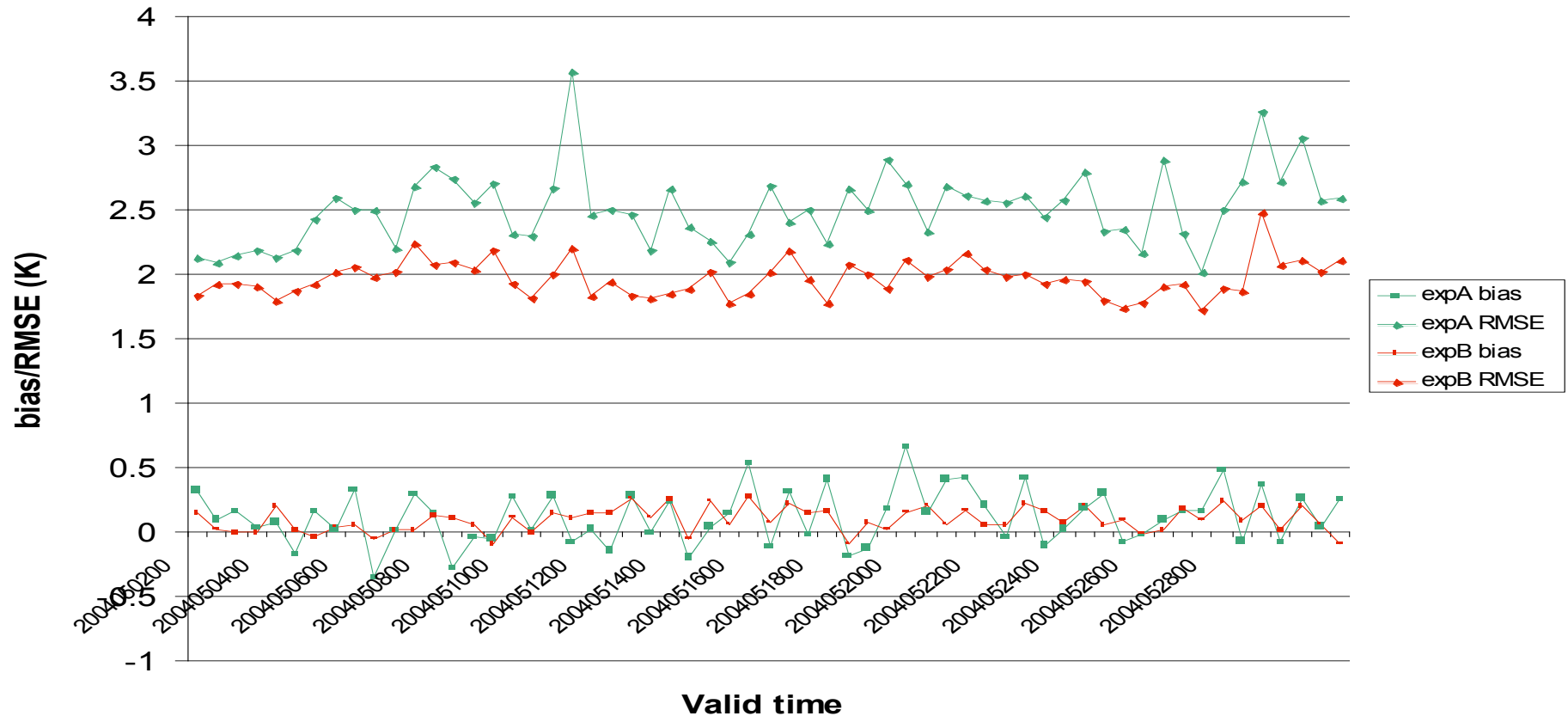
- Create your own once you have run your system for a few weeks to a month
- Implement, tune, and iterate

*The utility **gen_be** has been developed at NCAR for use in calculating these BEs*



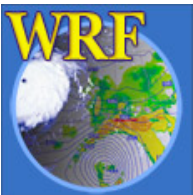
Impact of BE on Forecasts

12 hr f/c bias/RMSE for Sound T



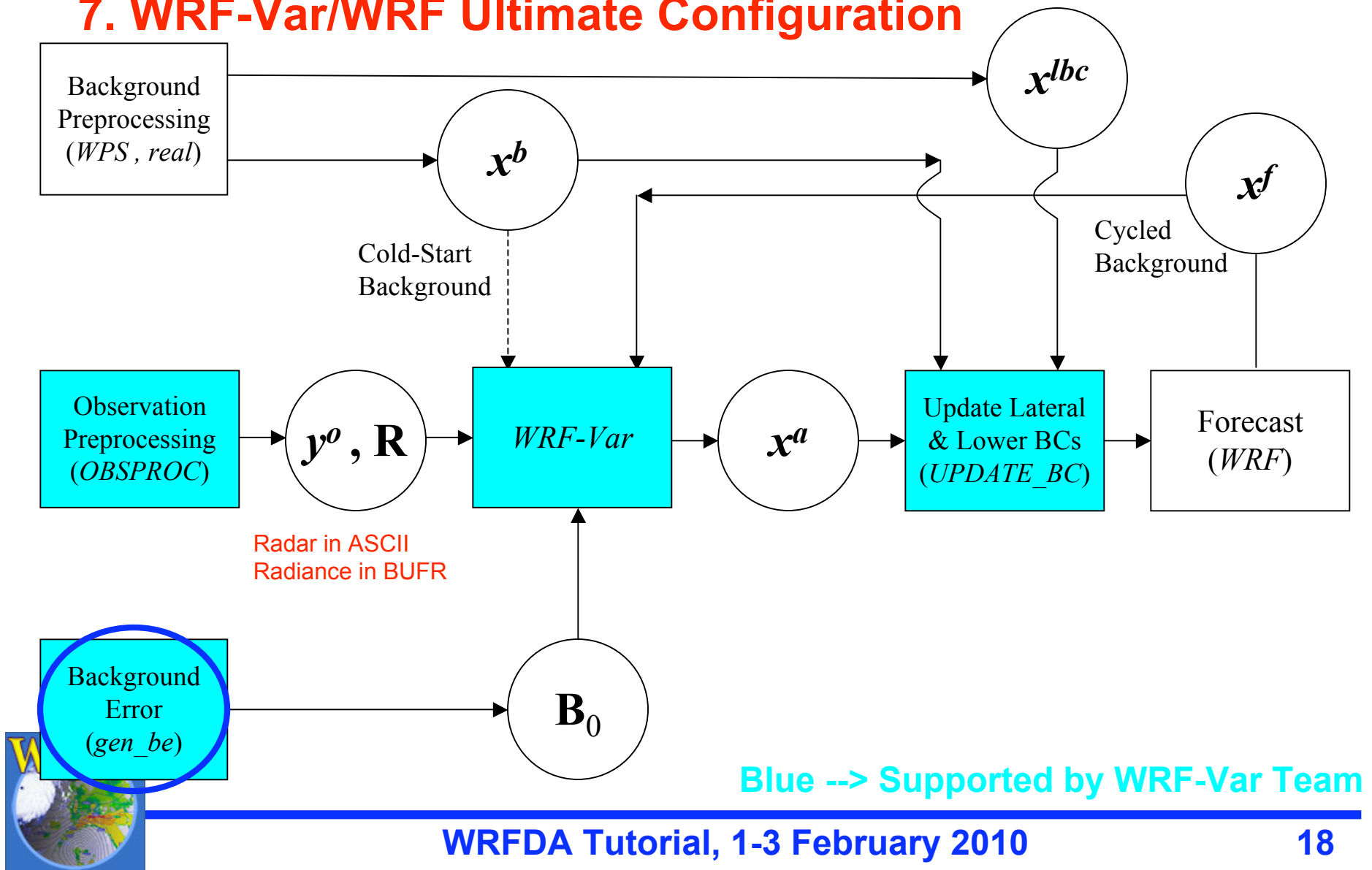
Exp A: 6 Hr cycling with old BE

Exp B: 6 Hr cycling with new BE



WRF-Var in the WRF Modeling System

7. WRF-Var/WRF Ultimate Configuration



WRF-Var Implementation



WRF-Var Formulation

3D-Var:
$$J = \frac{1}{2}(\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b) + \frac{1}{2}(\mathbf{y} - H(\mathbf{x}))^T \mathbf{R}^{-1}(\mathbf{y} - H(\mathbf{x}))$$

The incremental formulation (in the general form, $\mathbf{x}^g \neq \mathbf{x}^b$!)

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

$\delta\mathbf{x} = \mathbf{x} - \mathbf{x}^g$ $\mathbf{d} = \mathbf{y} - H(\mathbf{x}^g)$ $H(\mathbf{x}) - H(\mathbf{x}^g) \approx \mathbf{H}\delta\mathbf{x}$

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

The first outer-loop: $\mathbf{x}^g = \mathbf{x}^b$

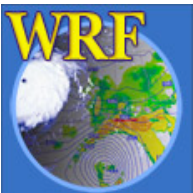
$$J = \frac{1}{2}\delta\mathbf{x}^T \mathbf{B}^{-1}\delta\mathbf{x} + \frac{1}{2}(\mathbf{d} - \mathbf{H}\delta\mathbf{x})^T \mathbf{R}^{-1}(\mathbf{d} - \mathbf{H}\delta\mathbf{x})$$

Outer-loop:

$\mathbf{d}$ (and QC, etc) ... **nonlinear!**

Inner-loop: minimization

update $\mathbf{x}^g$



B in WRF-Var

- Partly for preconditioning reasons:

$$\mathbf{B} = \mathbf{U} \mathbf{U}^T \quad \text{with} \quad \mathbf{U} = \mathbf{U}_p \mathbf{U}_v \mathbf{U}_h$$

- Horizontal transformation ($\mathbf{U}_h$) is via
Regional - recursive filters
Global - power spectrum
- Vertical transformation ($\mathbf{U}_v$) is
cv3 - recursive filters
cv5 - via EOF
- Physical transformation ($\mathbf{U}_p$) depends upon the choice of
the analysis control variable



WRF-Var Formulation

- $\mathbf{U}_p$ defines the *control variable transform*, so that

$$\delta \mathbf{x} = \mathbf{U} \mathbf{v}$$

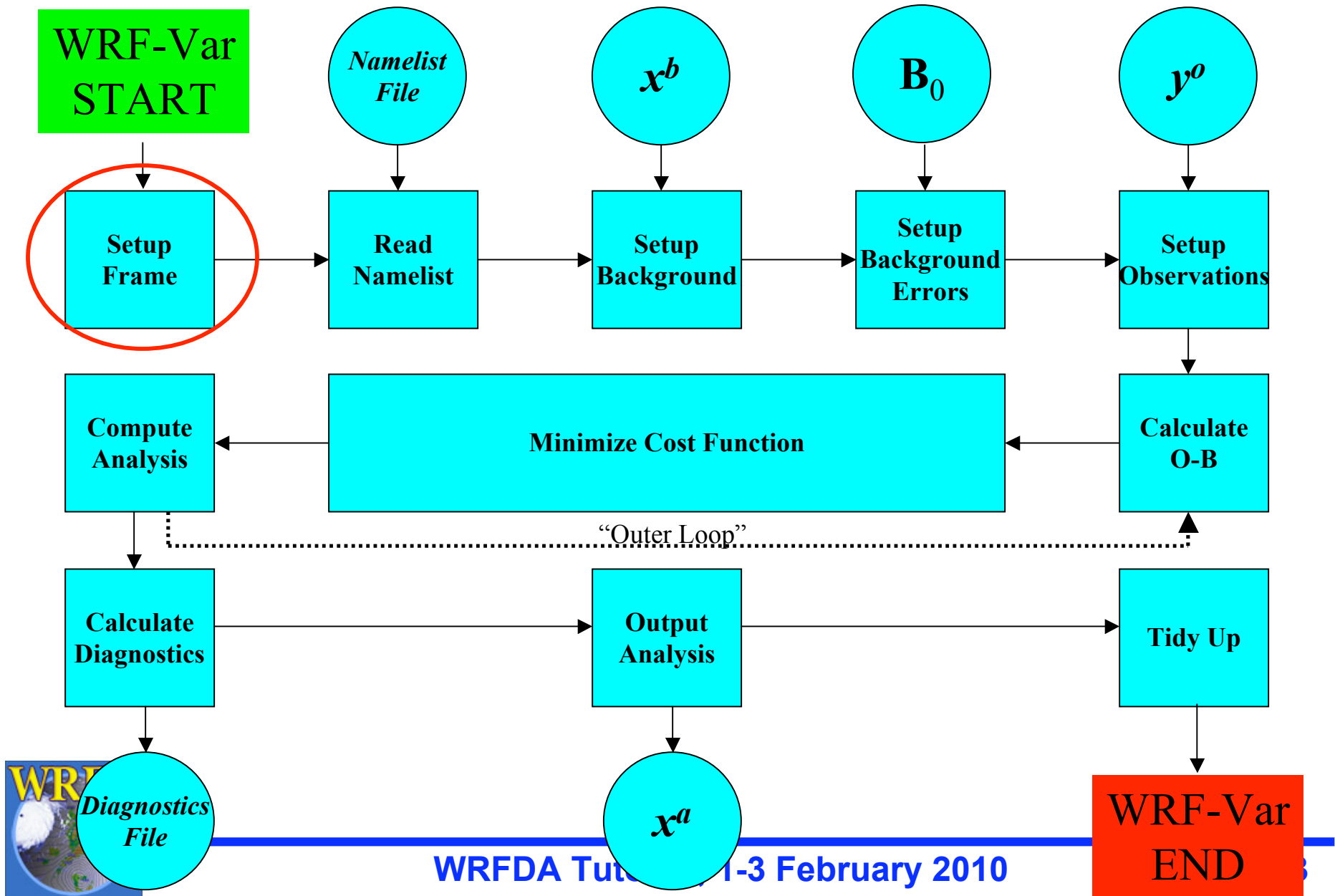
- $\mathbf{v}$ is the analysis increment in control variable space
 - WRF-Var control variables: streamfunction, unbalanced velocity potential, unbalanced temperature, RH, and unbalanced surface pressure
- $\mathbf{B}$ is approximated by $\mathbf{U} \mathbf{U}^T$
- WRF-Var actually minimizes

$$J(\mathbf{v}) = \frac{1}{2} \mathbf{v}^T \mathbf{v} + \frac{1}{2} (\mathbf{d} - \mathbf{H} \mathbf{U} \mathbf{v})^T \mathbf{R}^{-1} (\mathbf{d} - \mathbf{H} \mathbf{U} \mathbf{v})$$

- After minimization, the analysis, $\mathbf{x}^a$, is given by
$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{U} \mathbf{v}$$



WRF-Var

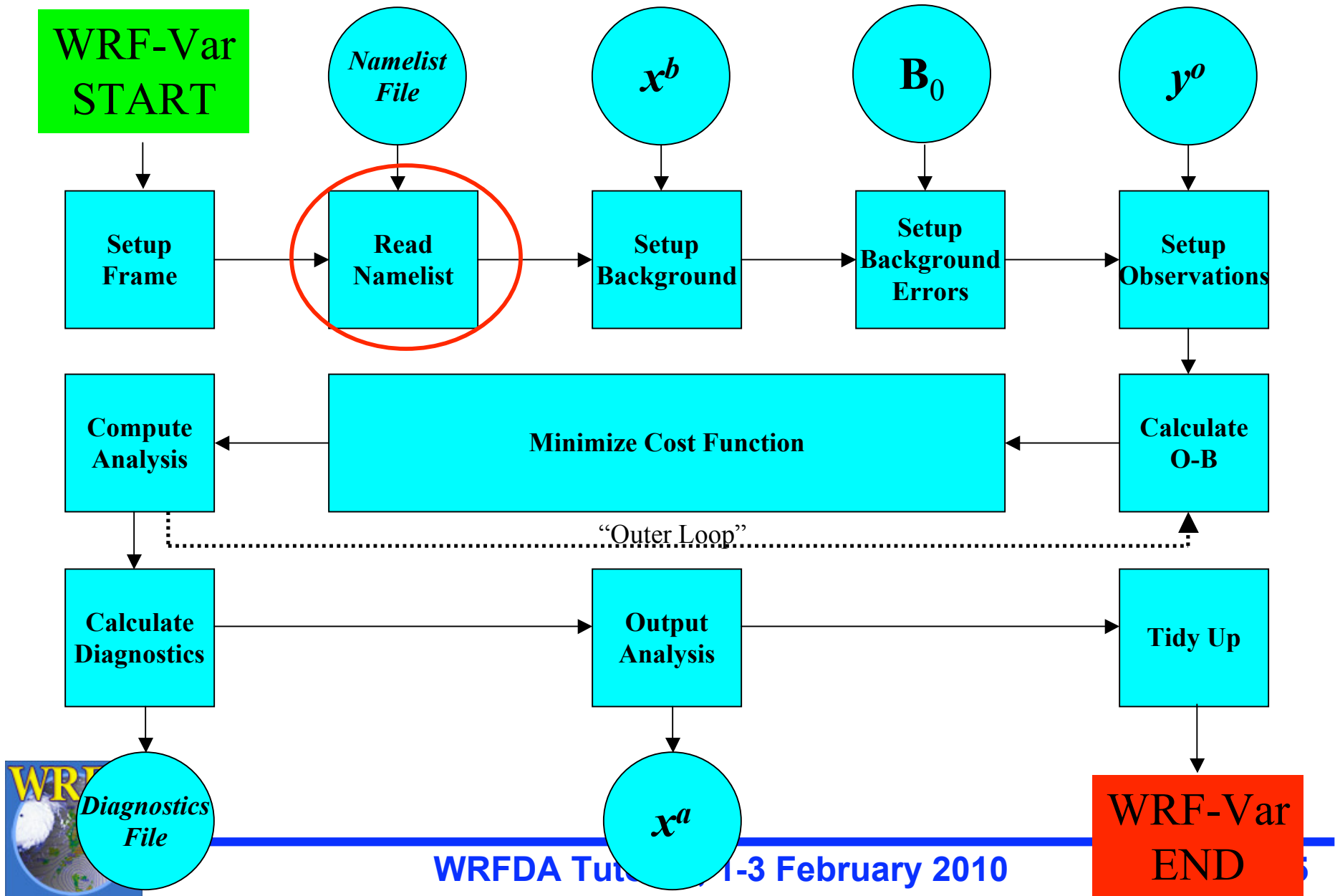


Setup Frame

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



WRF-Var

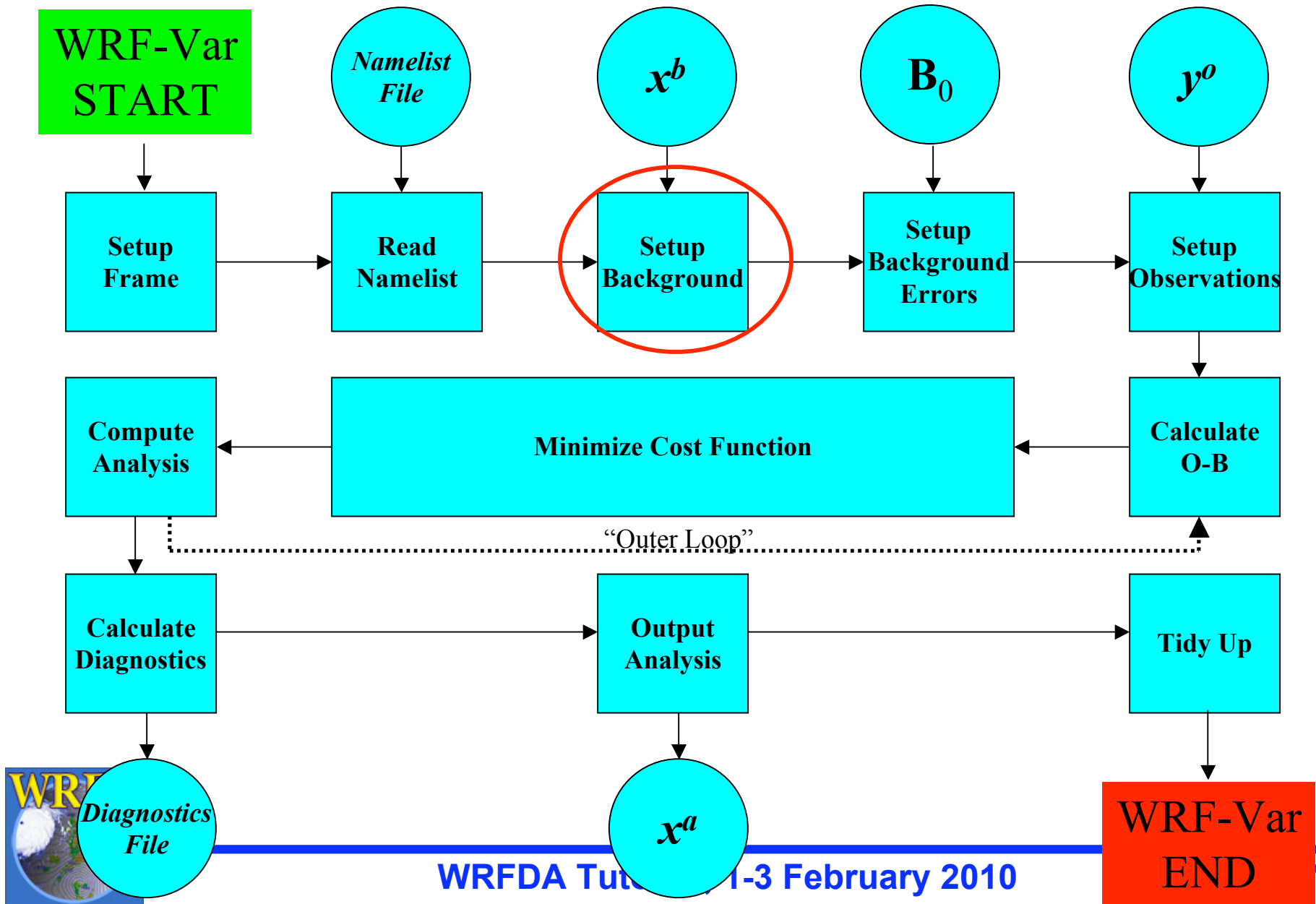


Read Namelist

- Reads WRF-Var data assimilation options from “namelist.input” file.
- Performs consistency checks between namelist options.



WRF-Var

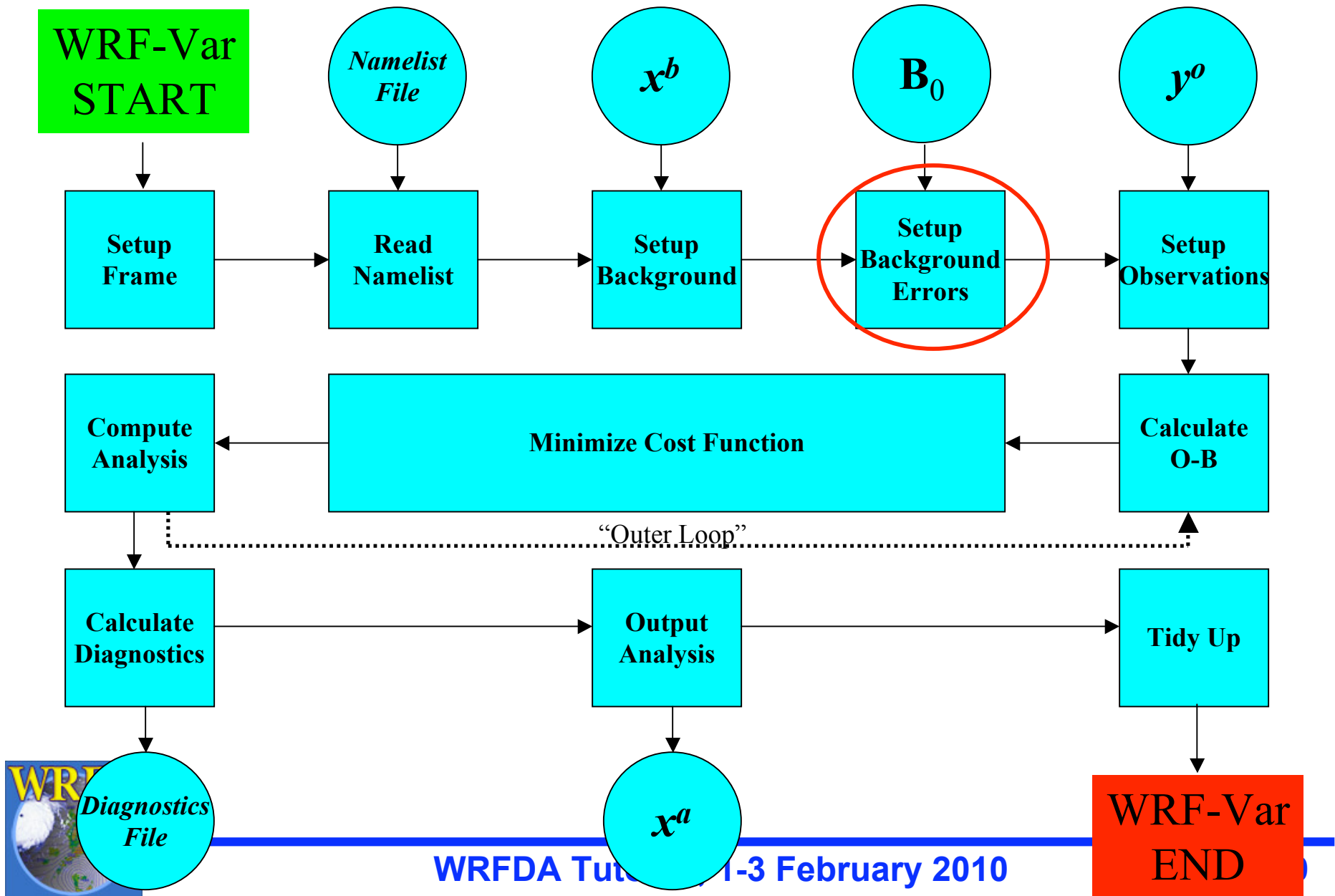


Setup Background (First-guess)

- Reads the first-guess file
- Format depends on namelist option :
“fg_format” ; 1= WRF, etc.
- Extracts fields used by WRF-Var
- Creates background FORTRAN 90 derived data type “xb” e.g. xb%mix(:, :, :), xb%u(:, :, :), etc.



WRF-Var

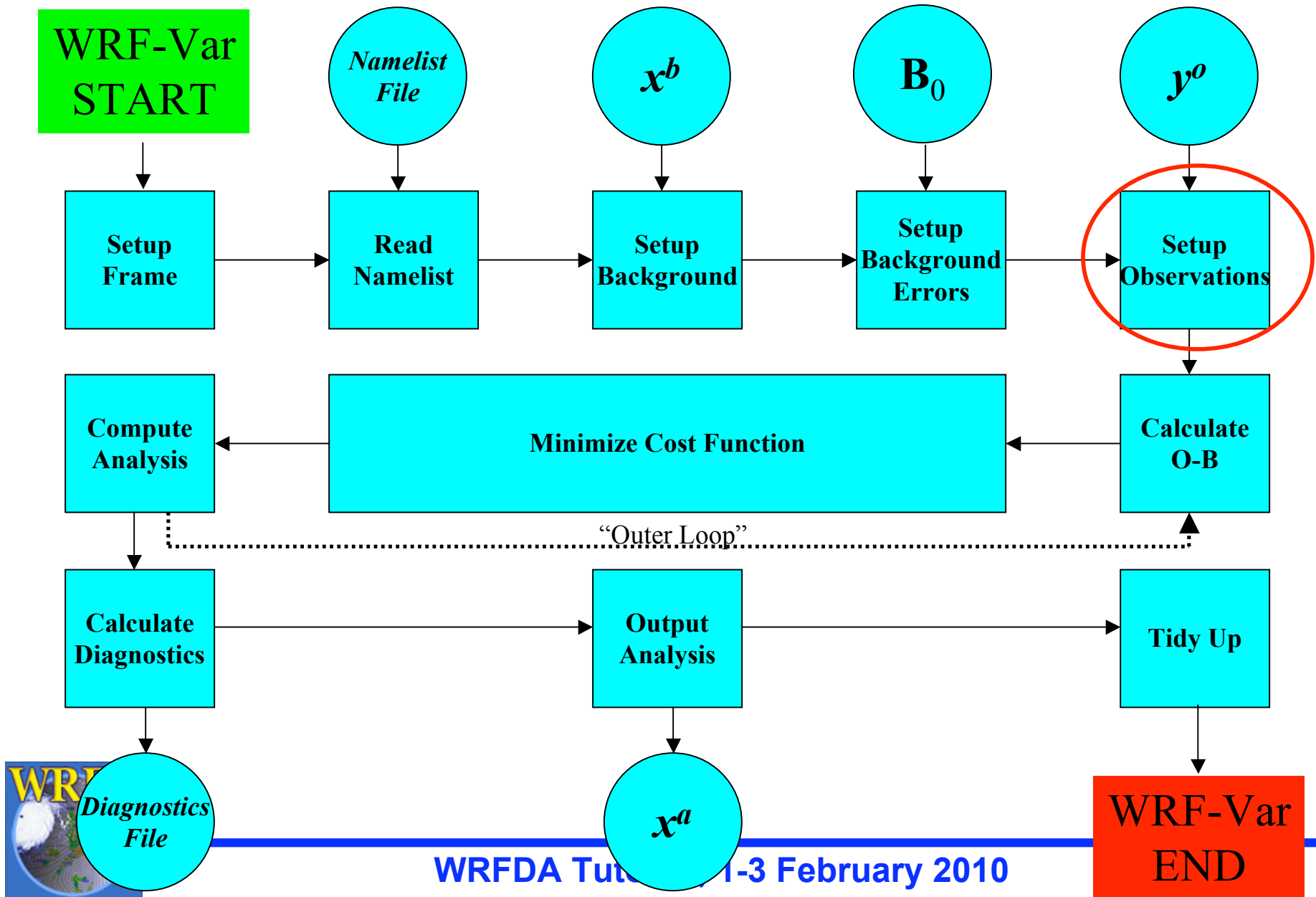


Setup Background Errors (BE)

- Reads in background error statistics.
- Extracts necessary quantities – eigenvectors, eigenvalues, lengthscales, regression coefficients, etc. (see “WRF-Var Background Error Estimation”).
- Creates background error FORTRAN 90 derived data type “be”
 - e.g. `be % v1 % evec(:,:), be % v2 % eval(:,:), etc.`



WRF-Var



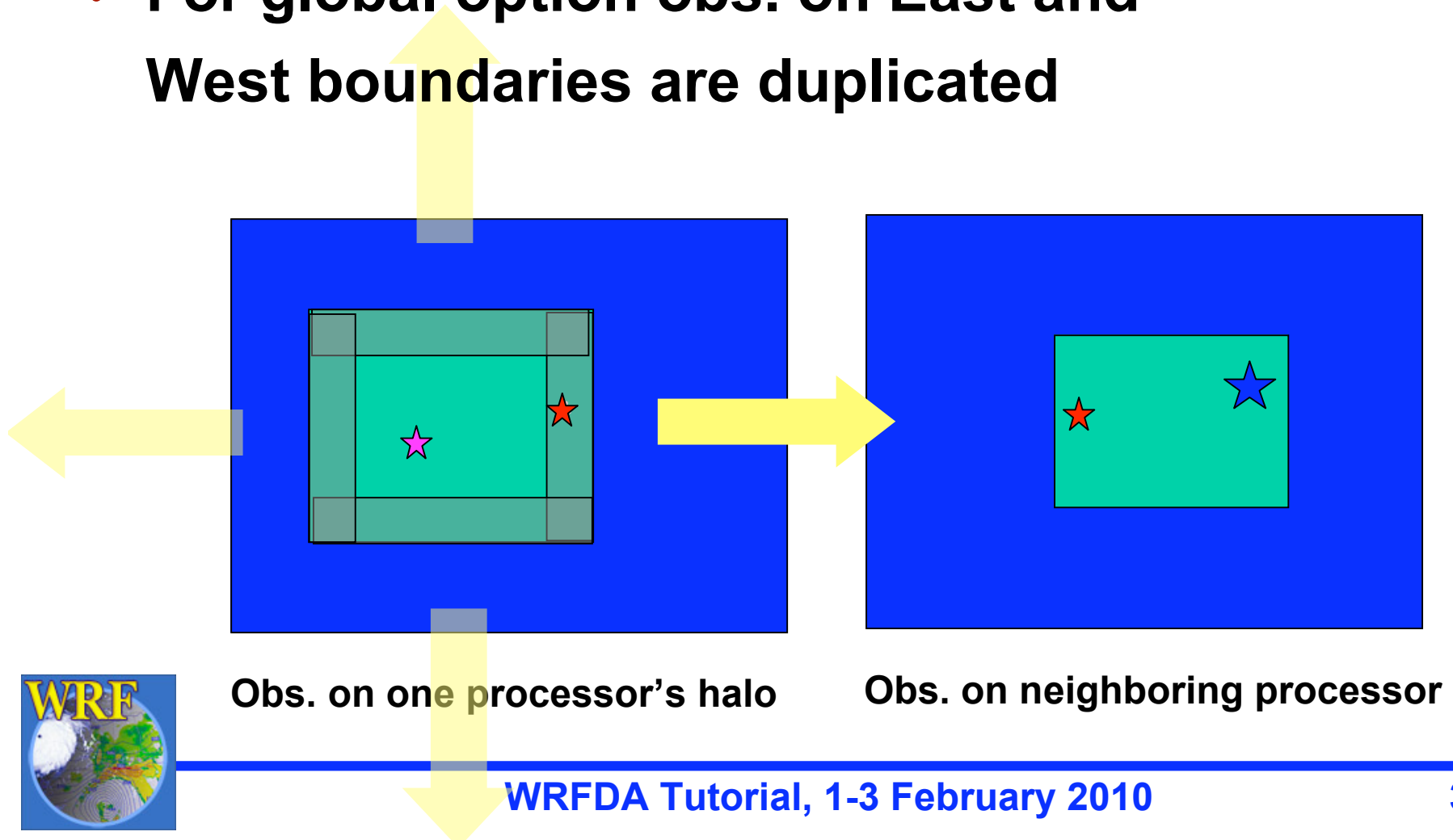
Setup Observations

- Reads in observations.
- Format depends on namelist variable “ob_format”
 - 1 = BUFR, 2 = ASCII “WRF-Var” format.
- Creates observation FORTRAN 90 derived data type “ob”
 - e.g. ob % metar(:), ob % sound(:) % u(:), etc,
- Identifies Obs outside/inside the domain

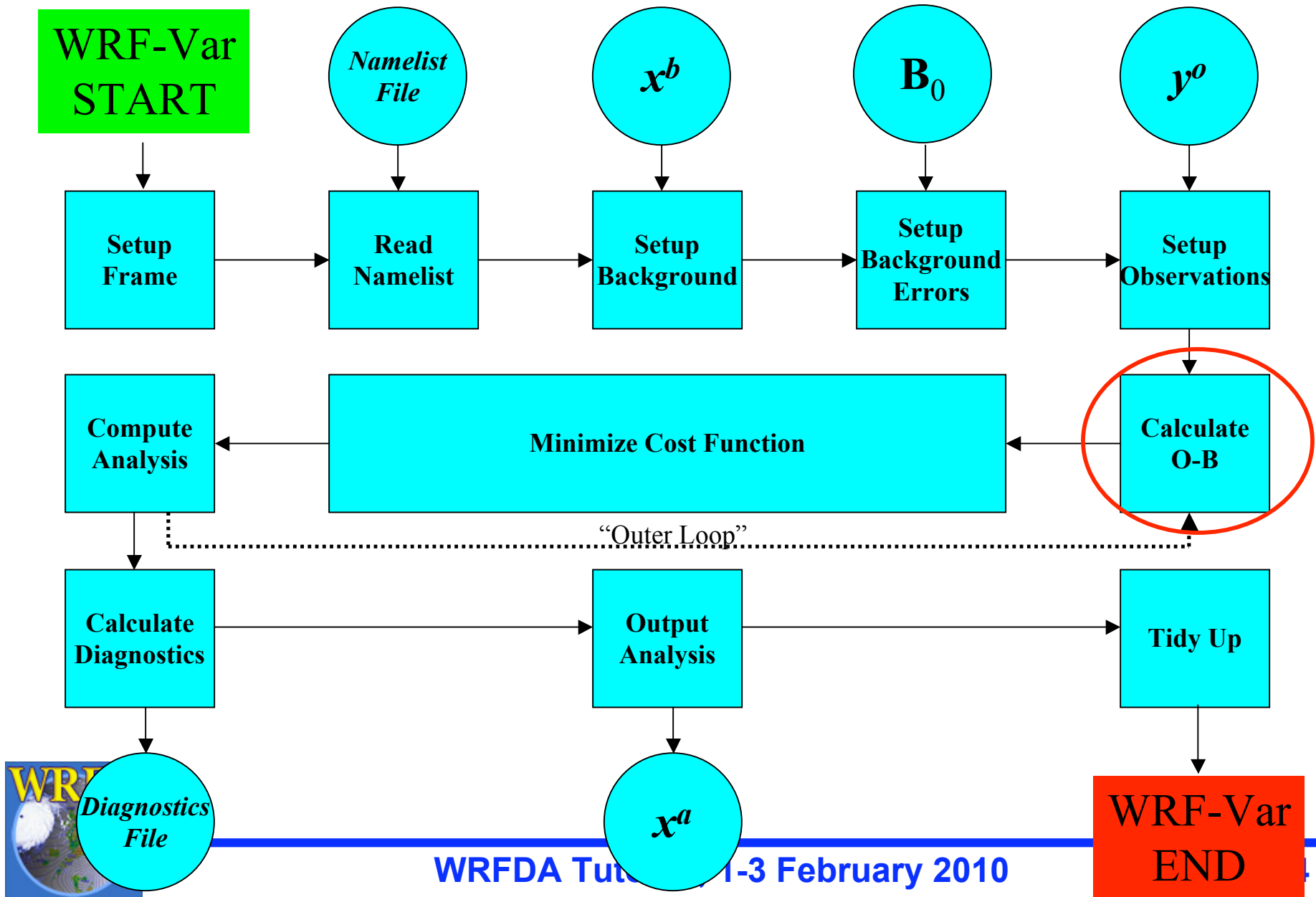


Observations in Distributed Memory

- Halo Region Observation
- For global option obs. on East and West boundaries are duplicated

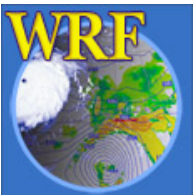


WRF-Var

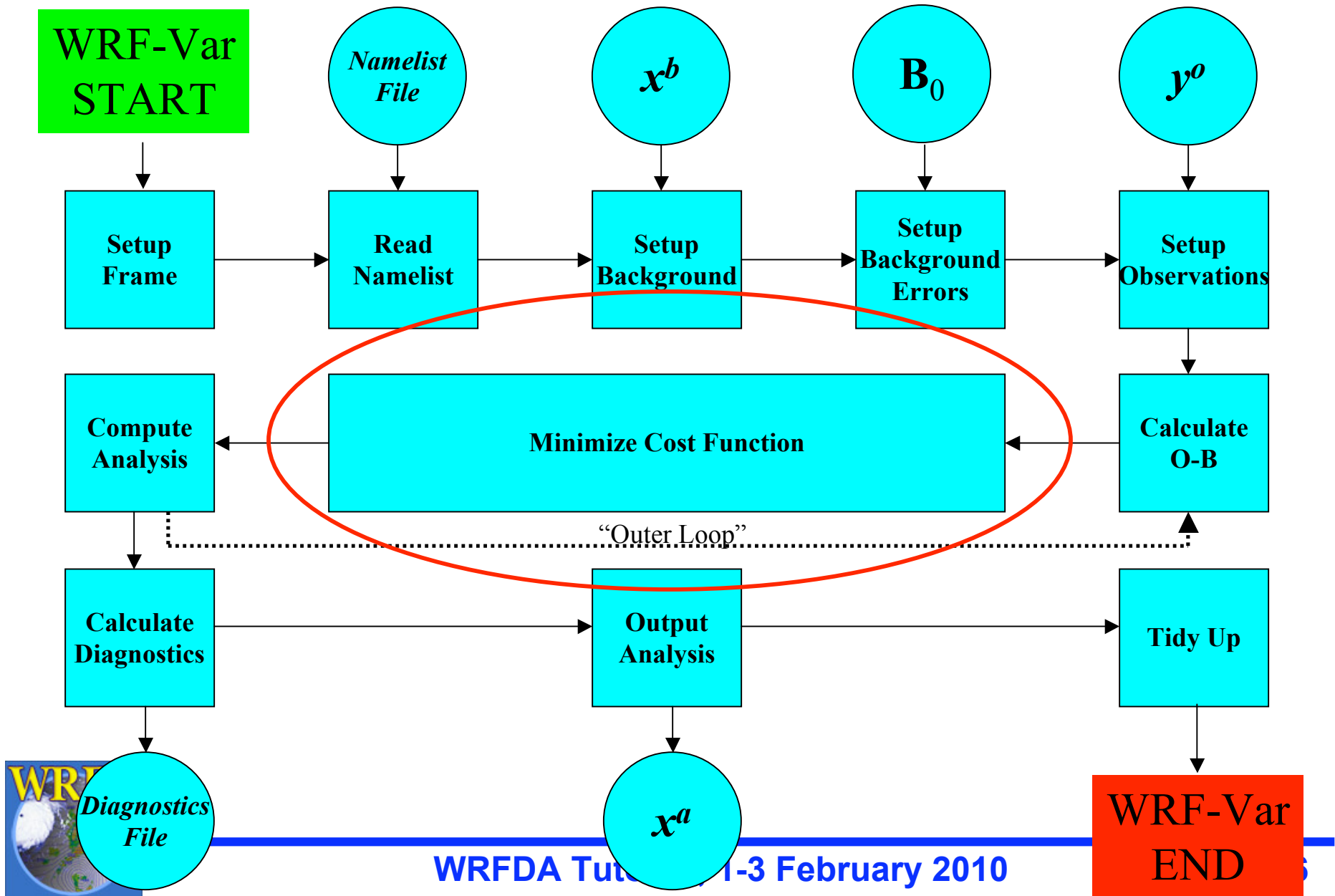


Calculate Innovation Vector (O-B)

- Calculates “model equivalent” of observations through interpolation and change of variable.
- Computes observation minus first guess (O-B) value.
- Creates innovation vector FORTRAN 90 derived data type “iv”
 - e.g. `iv % metar(:), iv % qscat(:) % u, iv % sound(:) % u(:), etc ....`



WRF-Var



Minimize Cost Function

Use conjugate gradient method

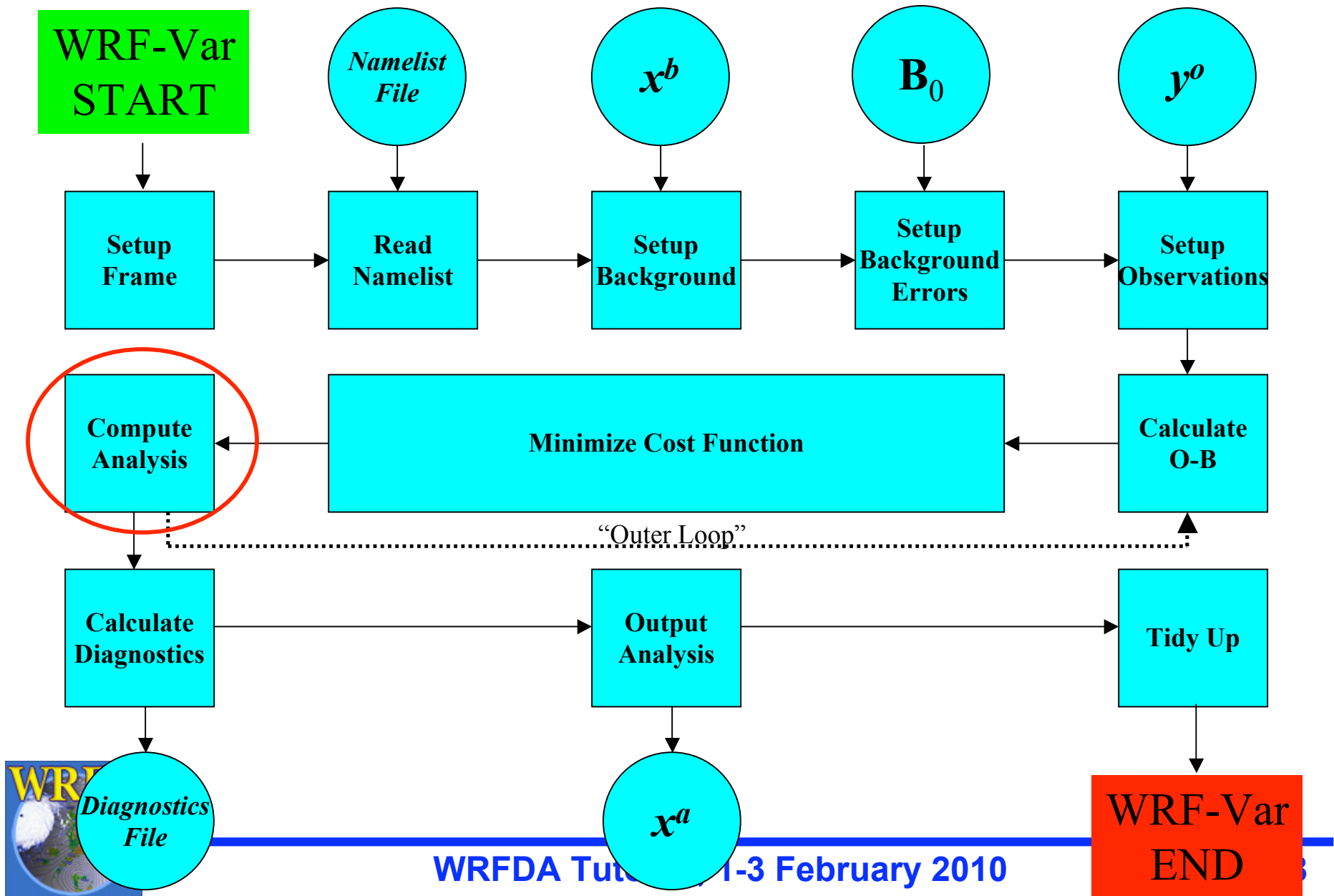
- (a) Initializes analysis increments to zero.
- (b) Computes cost function (if desired).
- (c) Computes gradient of cost function.
- (d) Uses cost function and gradient to calculate new value of analysis control variable, $\mathbf{v}$

Iterate (b) to (d) to minimize

$$J(\mathbf{v}) = \frac{1}{2}\mathbf{v}^T\mathbf{v} + \frac{1}{2}(\mathbf{d} - \mathbf{H}\mathbf{U}\mathbf{v})^T\mathbf{R}^{-1}(\mathbf{d} - \mathbf{H}\mathbf{U}\mathbf{v})$$



WRF-Var



Compute Analysis

- Once WRF-Var 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

Outer-loop:

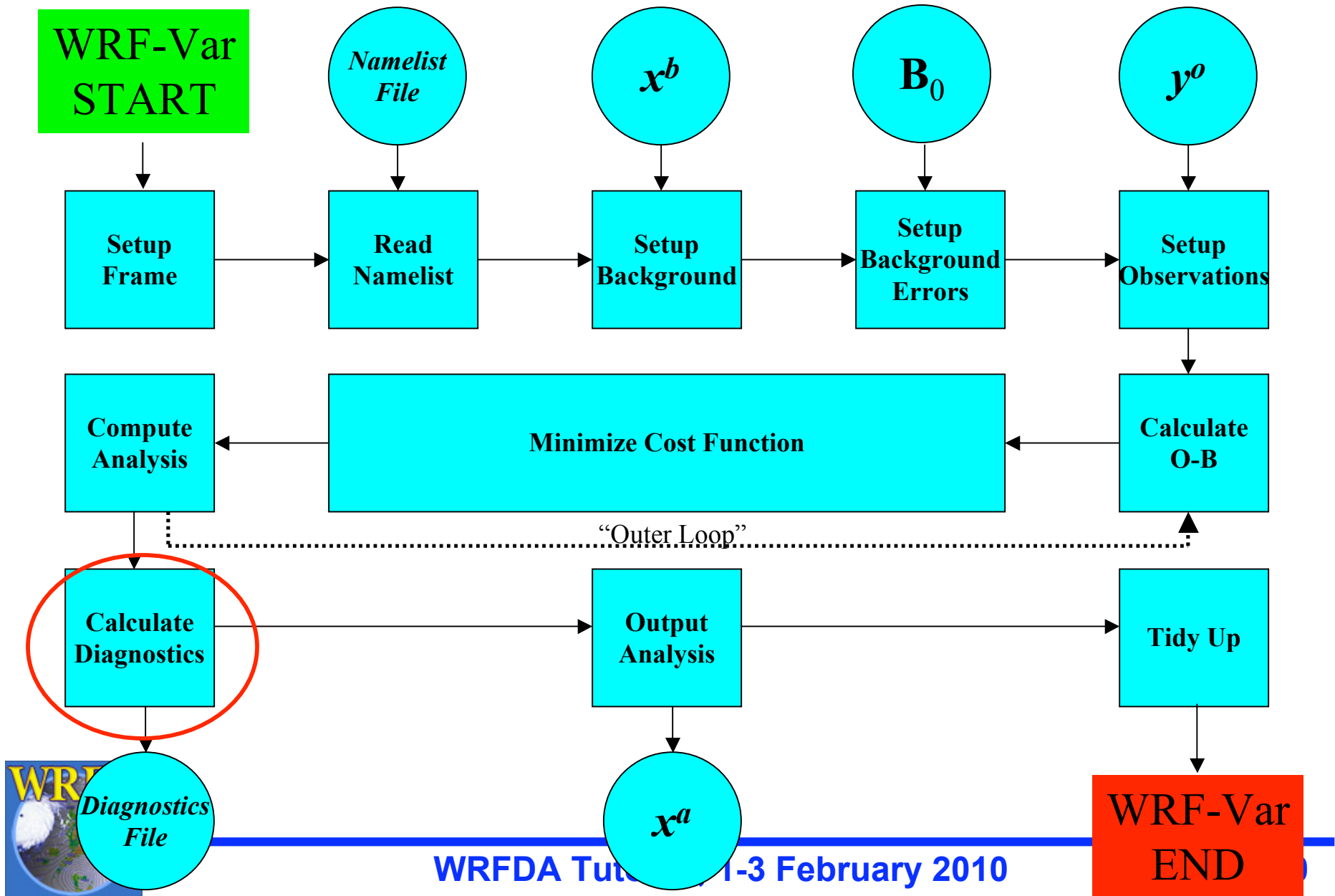
d (and QC, etc) ... **nonlinear!**

Inner-loop: minimization

update $\mathbf{x}^g$



WRF-Var

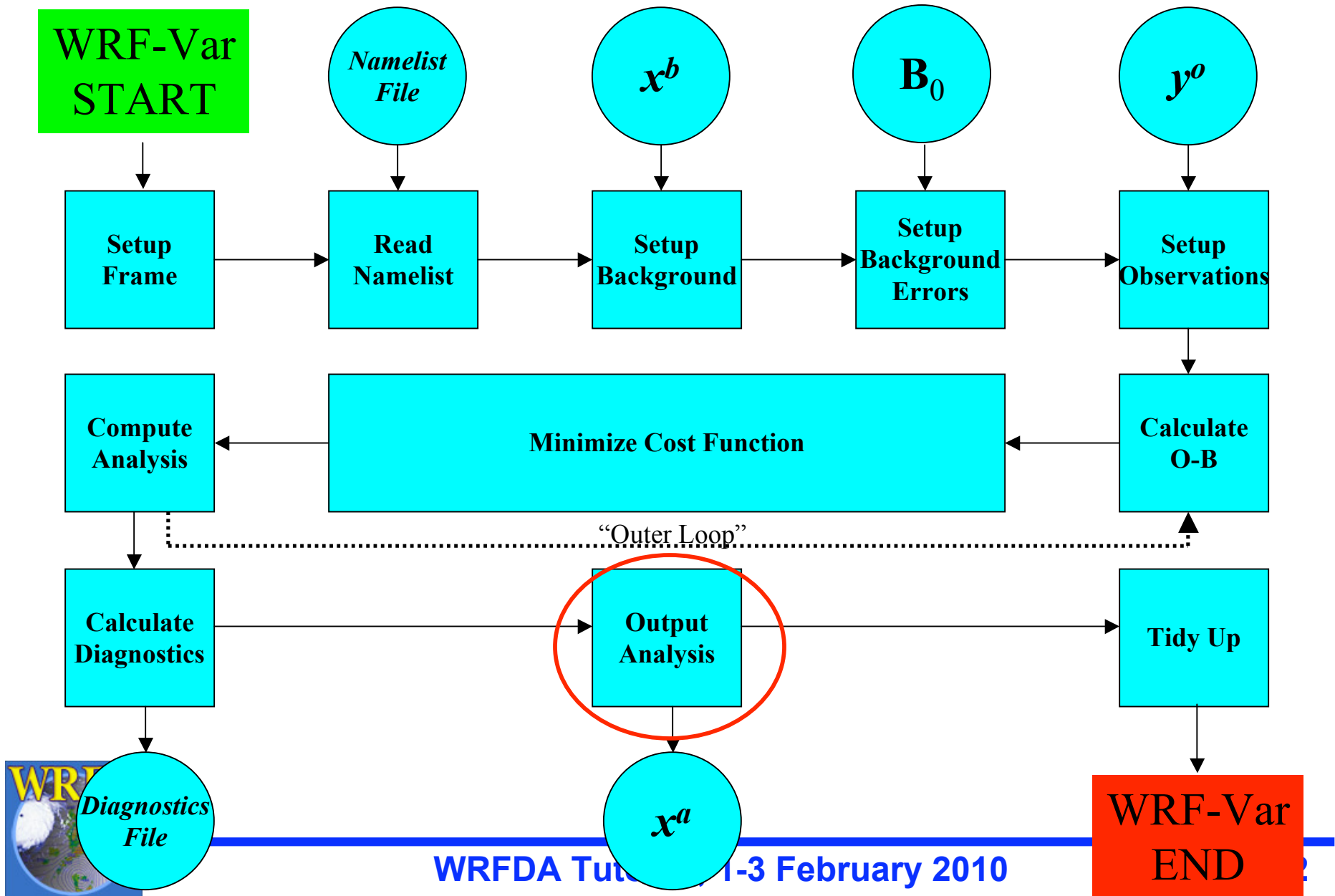


Compute Diagnostics

- Compute O-B, O-A statistics for all observation types and variables.
- Compute A-B (analysis increment) statistics for all model variables and levels.
- Statistics include minimum, maximum (and their locations), mean and standard deviation.



WRF-Var

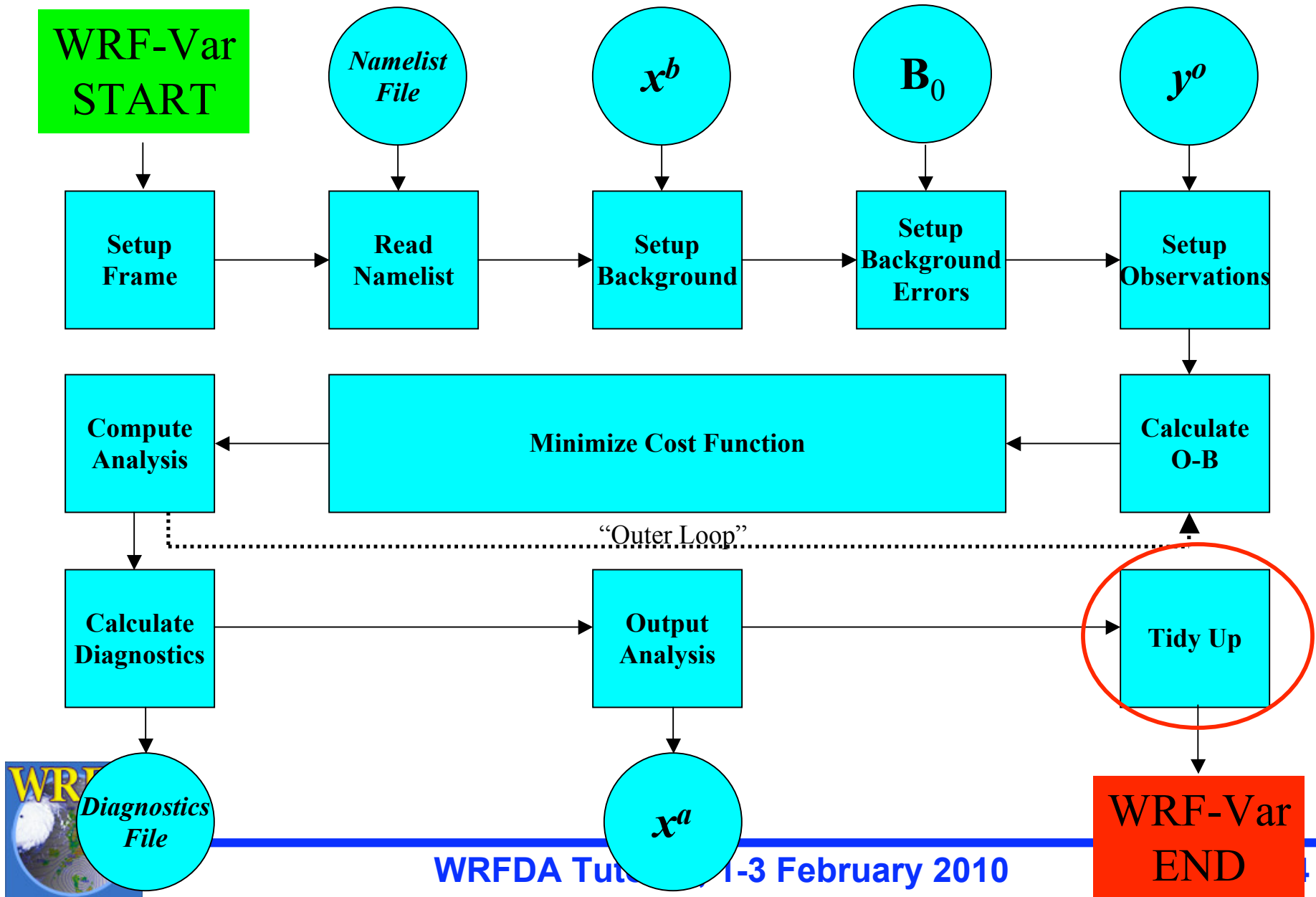


Output Analysis

- Outputs analysis in native model format. Choice is made through namelist option “fg_format”
1 = WRF, etc.
- Also output analysis increments (for diagnostic purposes) in native model format. Switch off by setting WRITE_INCREMENTS = .FALSE. in namelist.input.



WRF-Var

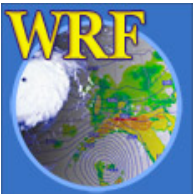


Tidy Up

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

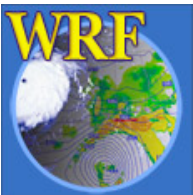
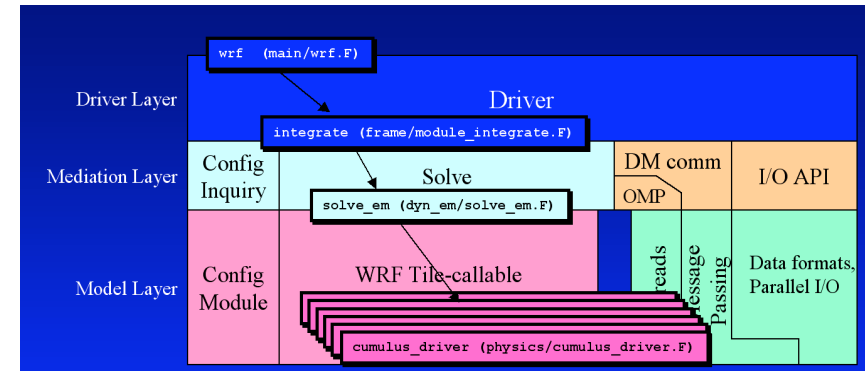


WRF-Var Software

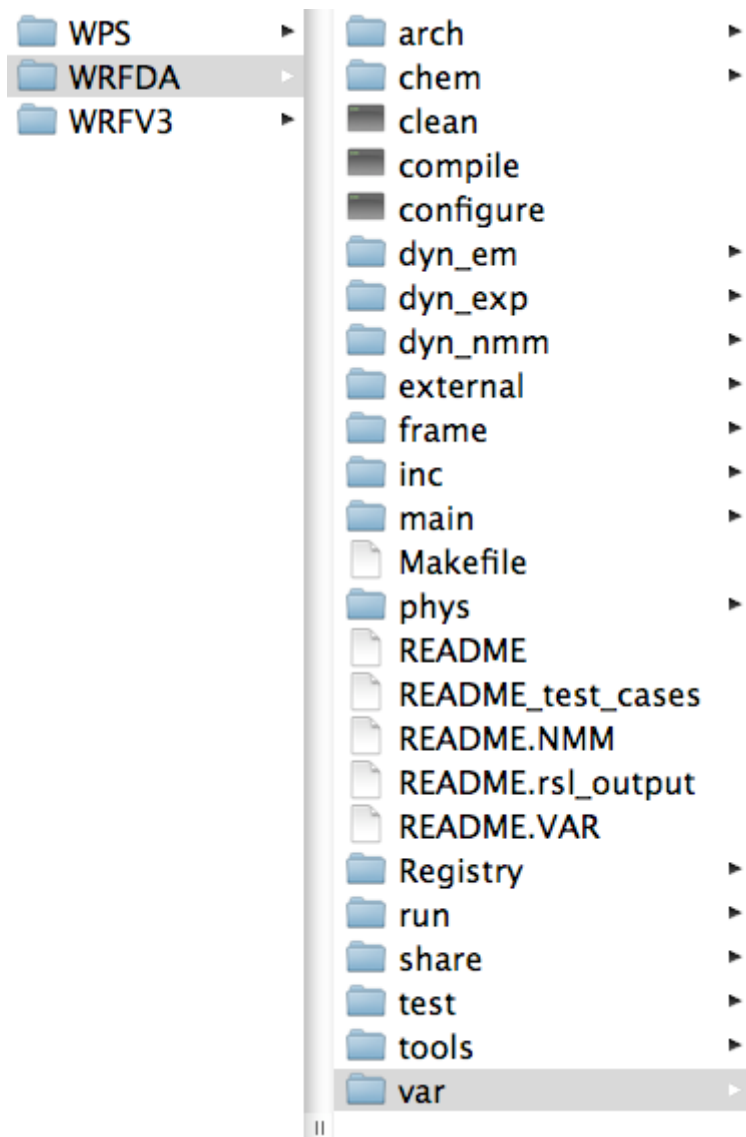


Use of the WRF Software Framework

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



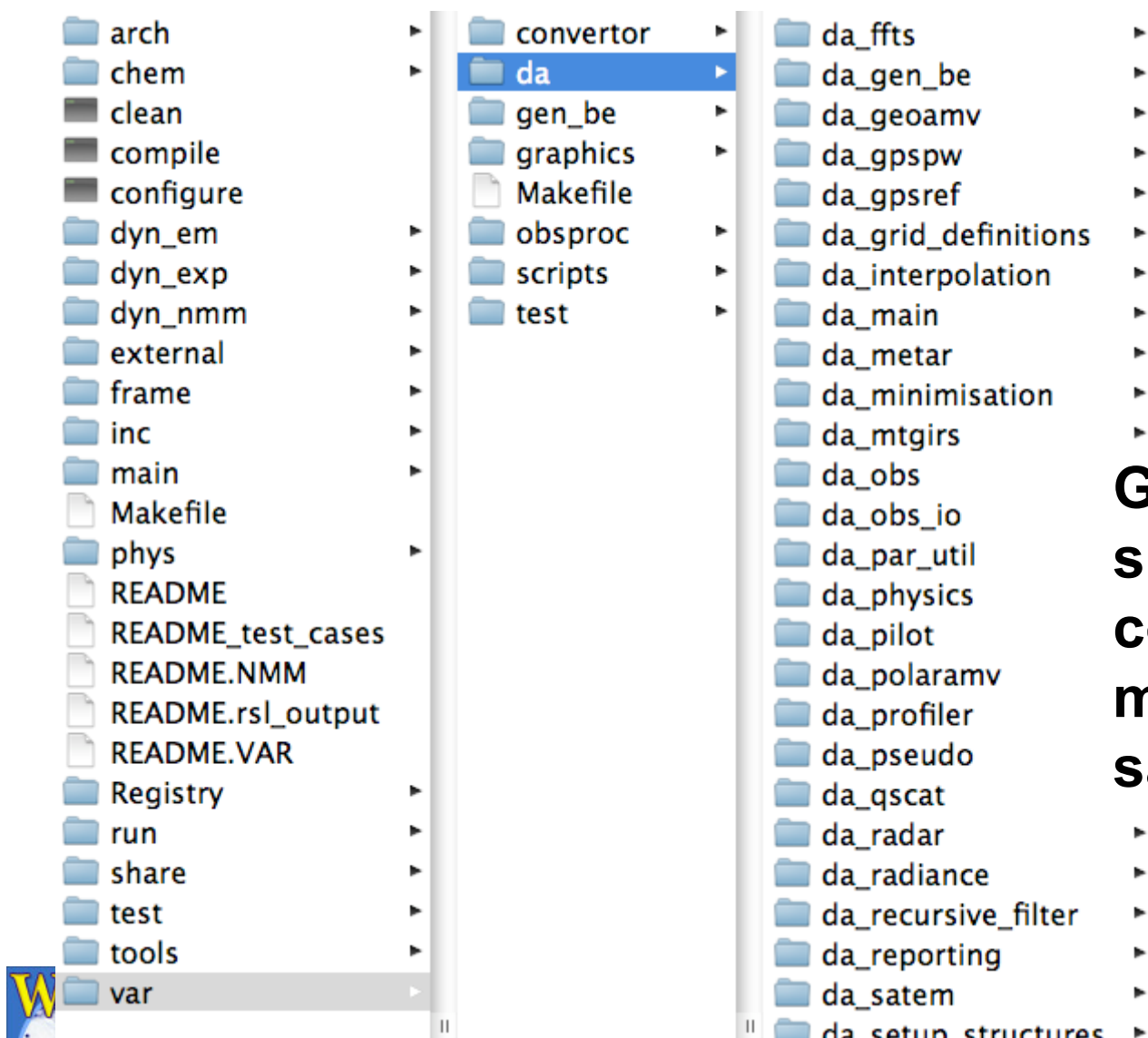
WRF-Var Code Organization



Besides the directories for WRF, the WRFDA tar file contains a “var” directory, which holds all of the WRF-Var code



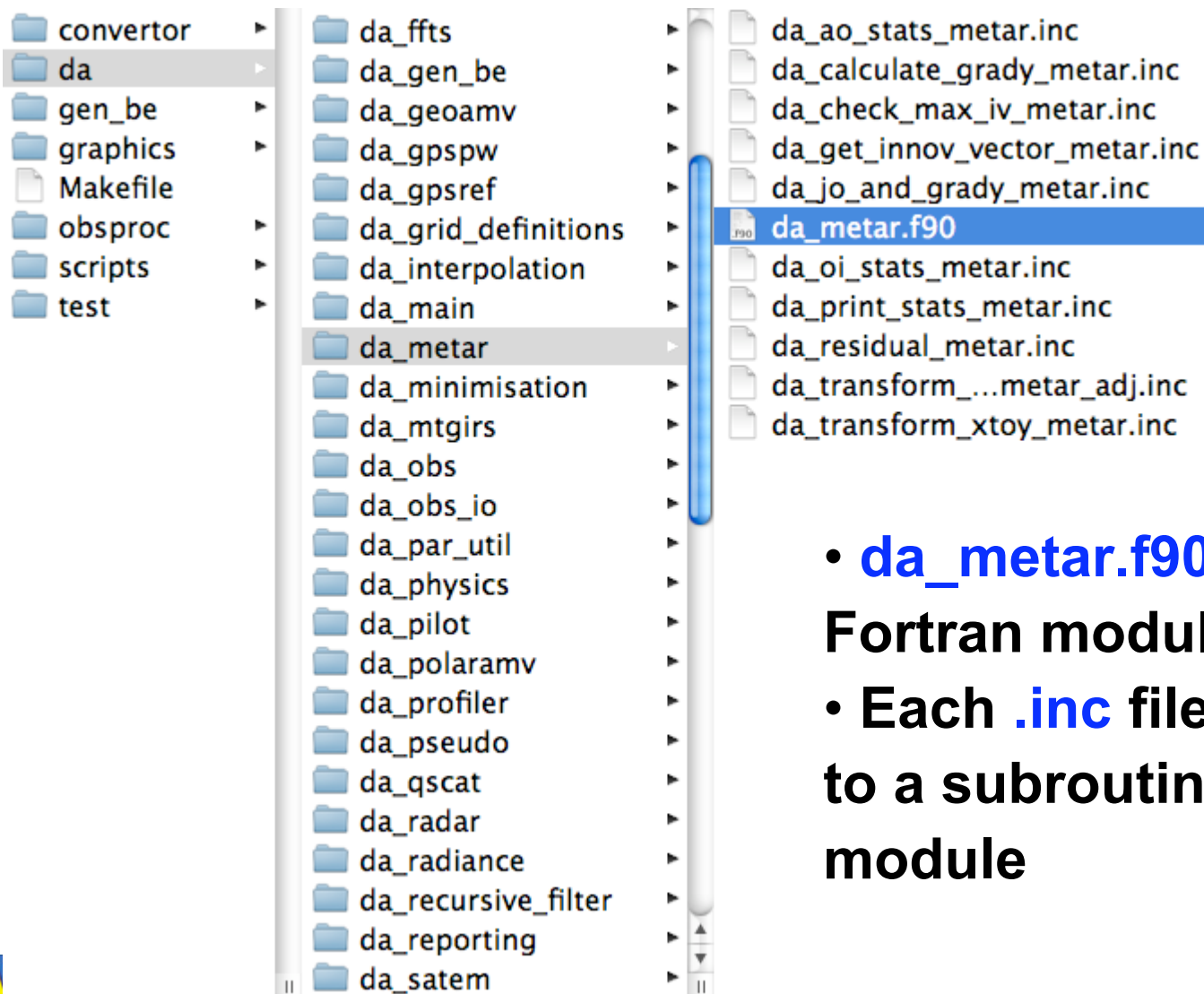
WRF-Var Code Organization



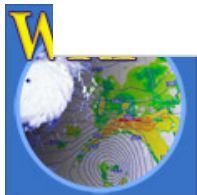
Generally, each subdirectory of “da” contains a Fortran module with the same name



WRF-Var Code Organization



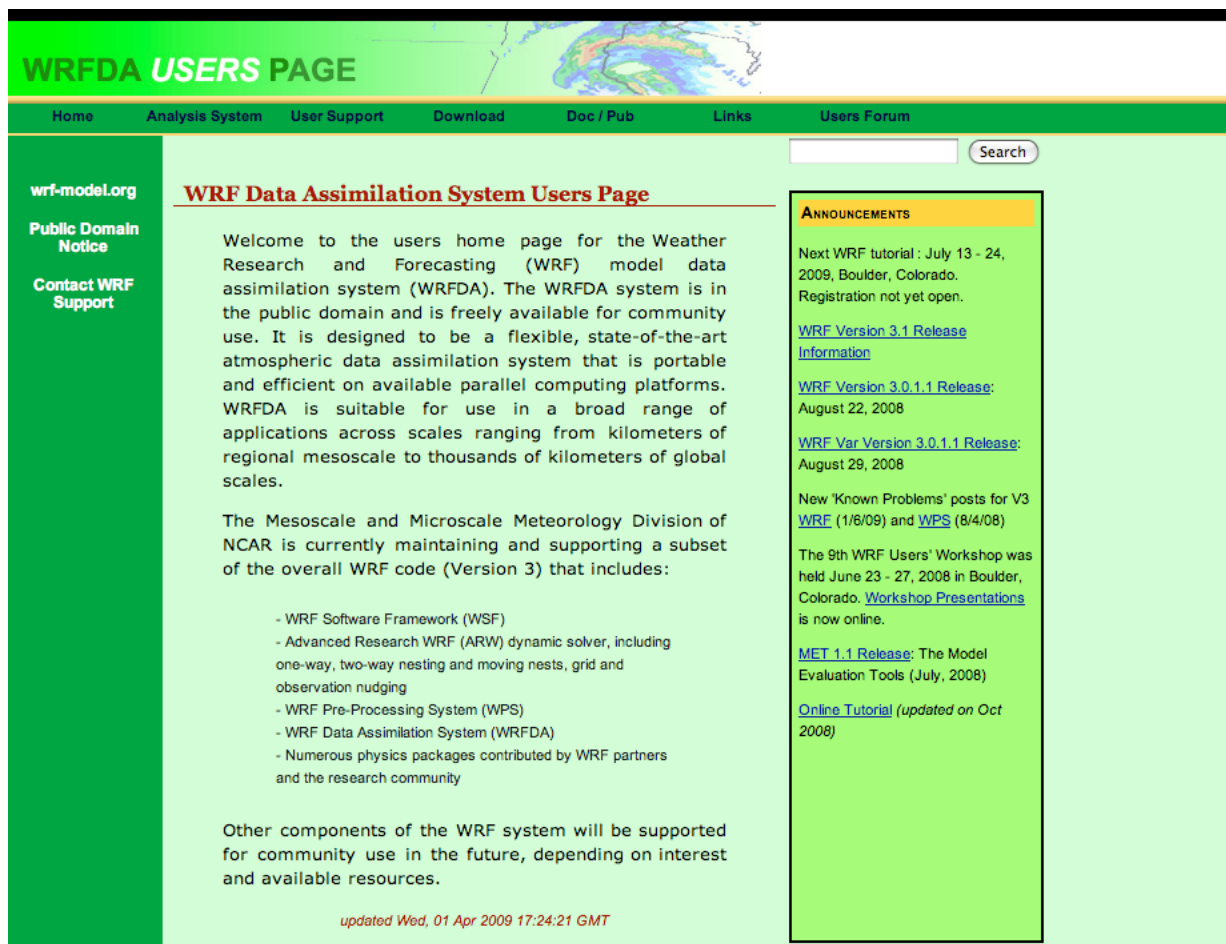
- **da_meteor.f90** contains a Fortran module
- Each **.inc** file corresponds to a subroutine within the module



Online WRFDA Resources

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

<http://www.mmm.ucar.edu/wrf/users/wrfda/>



The screenshot shows the 'WRFDA USERS PAGE' with a green header and navigation bar. The main content area is white with a green sidebar on the left. The sidebar contains links: 'wrf-model.org', 'Public Domain Notice', and 'Contact WRF Support'. The main content area has a title 'WRF Data Assimilation System Users Page' and a welcome message. It lists the components of the WRF system: WRF Software Framework (WSF), Advanced Research WRF (ARW) dynamic solver, WRF Pre-Processing System (WPS), WRF Data Assimilation System (WRFDA), and various physics packages. It also mentions the 9th WRF Users' Workshop and provides links to 'WRF Version 3.1 Release Information', 'WRF Version 3.0.1.1 Release', 'WRF Var Version 3.0.1.1 Release', 'MET 1.1 Release', and 'Online Tutorial'. A search bar is located in the top right corner. The page is updated as of Wed, 01 Apr 2009 17:24:21 GMT.

WRFDA USERS PAGE

Home Analysis System User Support Download Doc / Pub 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 (WSF)
- 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

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

[WRF Version 3.1 Release Information](#)

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

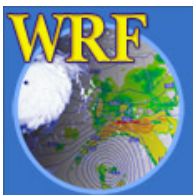
[WRF Var Version 3.0.1.1 Release:](#)
August 29, 2008

New 'Known Problems' posts for V3 [WRF](#) (1/6/09) and [WPS](#) (8/4/08)

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

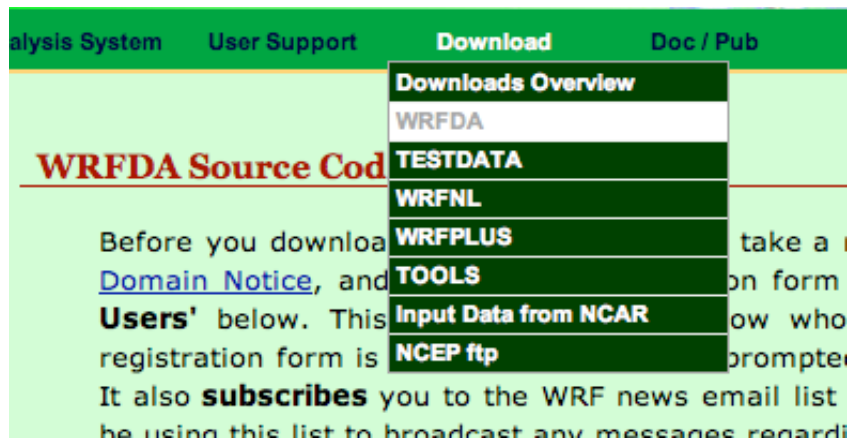
[MET 1.1 Release:](#) The Model Evaluation Tools (July, 2008)

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

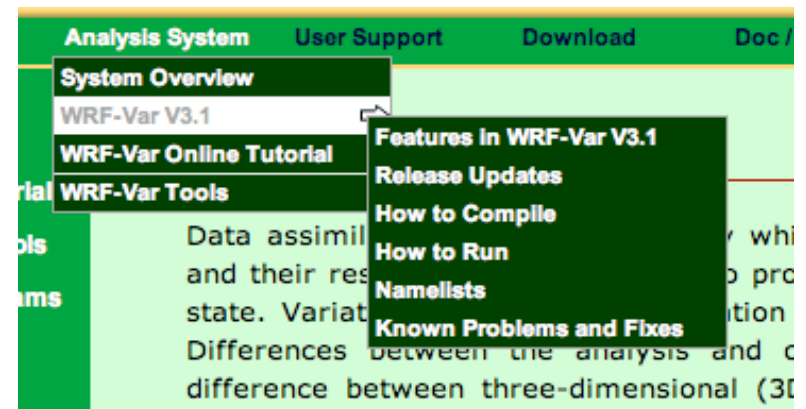


Online WRFDA Resources

From the WRFDA page, one can access:



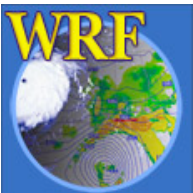
This screenshot shows the 'Download' menu of the WRFDA website. The menu is open, displaying a list of download options: Downloads Overview, WRFDA, TESTDATA, WRFNL, WRFPLUS, TOOLS, Input Data from NCAR, and NCEP ftp. To the left of the menu, there is a section titled 'WRFDA Source Code' with text explaining that users should read the 'Domain Notice' and 'Users' before downloading, and that the site also subscribes users to the WRF news email list.



This screenshot shows the 'WRF-Var V3.1' menu. The menu is open, displaying a list of options: System Overview, WRF-Var V3.1, WRF-Var Online Tutorial, and WRF-Var Tools. To the right of the menu, there is a section titled 'Features In WRF-Var V3.1' with a list of features: Release Updates, How to Compile, How to Run, Namelists, and Known Problems and Fixes. Below the menu, there is text describing the system's capabilities, including data assimilation and its use with MM5.



This screenshot shows the 'Documents & Publications' page of the WRFDA website. The page has a green header with navigation links: Analysis System, User Support, Download, Doc / Pub, Links, and Us. The 'Doc / Pub' menu is open, showing 'Pubs & Docs Overview', 'Tech Notes', and 'WRFDA User's Guide'. The main content area is titled 'Documents & Publications' and includes a 'References:' section. The first reference listed is: Barker, D. M., W. Huang, Y.-R. Guo, and A. Bourgeois, 2003: A TH Variational (3DVAR) Data Assimilation System For Use With MM5. NCAR/TN-453+STR, 68 pp. (Available from UCAR Communications).



Other WRFDA Resources

- **Online WRF-Var Tutorial**
 - <http://www.mmm.ucar.edu/wrf/users/wrfda/tutorial.html>
- **WRF-Var chapter of Users' Guide**
 - http://www.mmm.ucar.edu/wrf/users/wrfda/Docs/user_guide_V3.1.1/users_guide_chap6.htm
- **If further help is needed, try the WRF Users' Forum**
<http://forum.wrfforum.com/> or ask questions via wrfhelp@ucar.edu



Questions?

