WRF-Var System Overview

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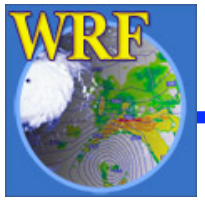
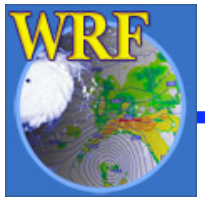
Michael Duda

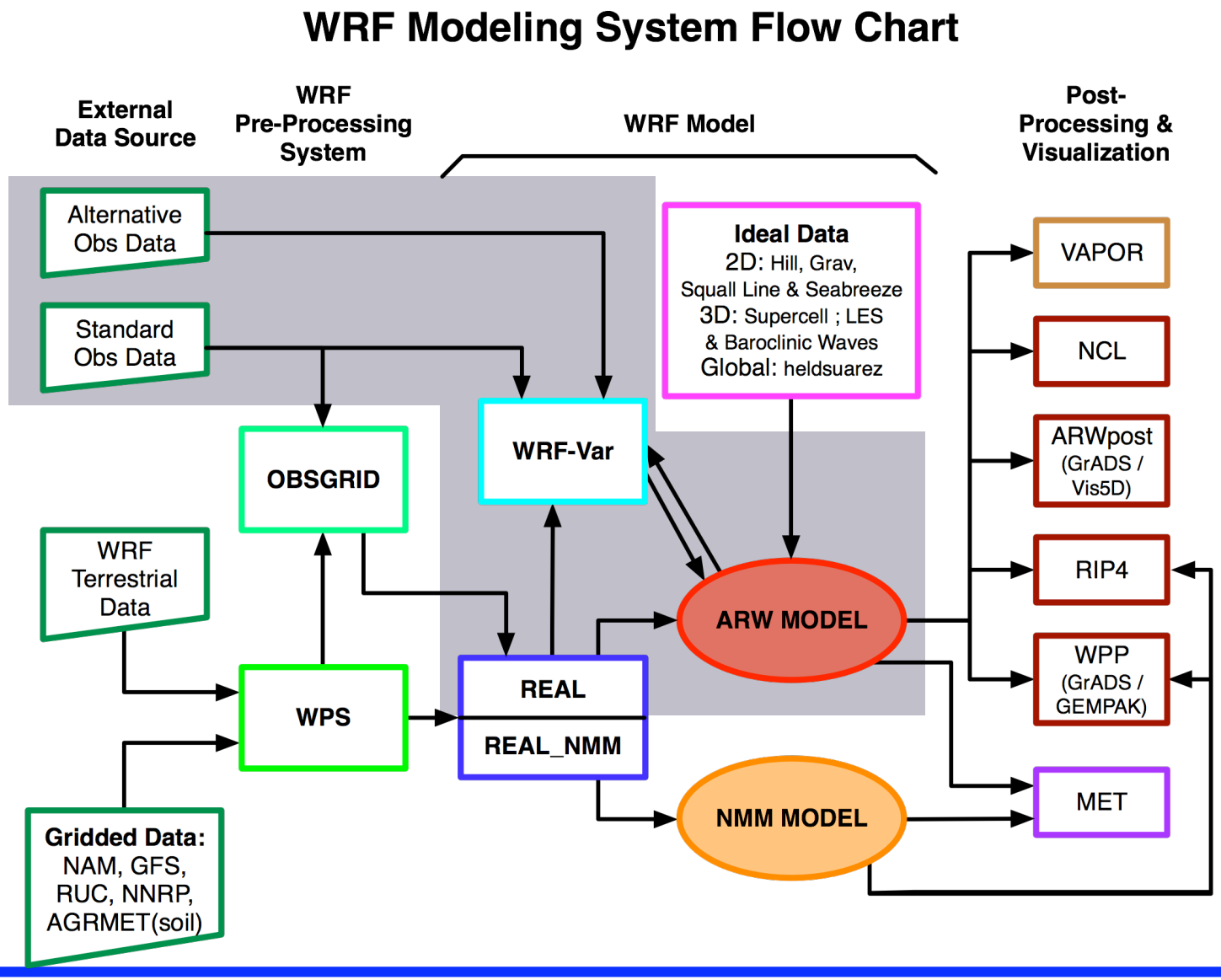


Outline

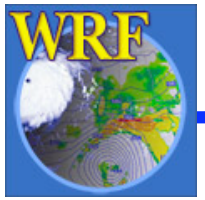
1. WRF-Var in the WRF Modeling System
2. WRF-Var Implementation
3. WRF-Var Software



WRF-Var in the WRF Modeling System



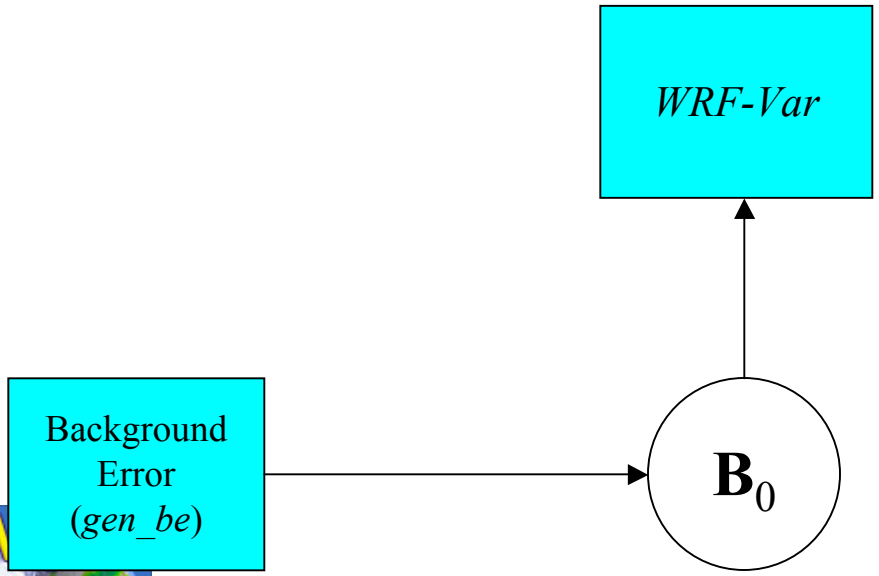
WRF-Var in the WRF Modeling System



Blue --> Supported by WRF-Var Team

WRF-Var in the WRF Modeling System

1. Prepare BE data



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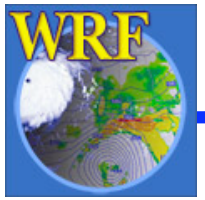
Prepare BE statistics

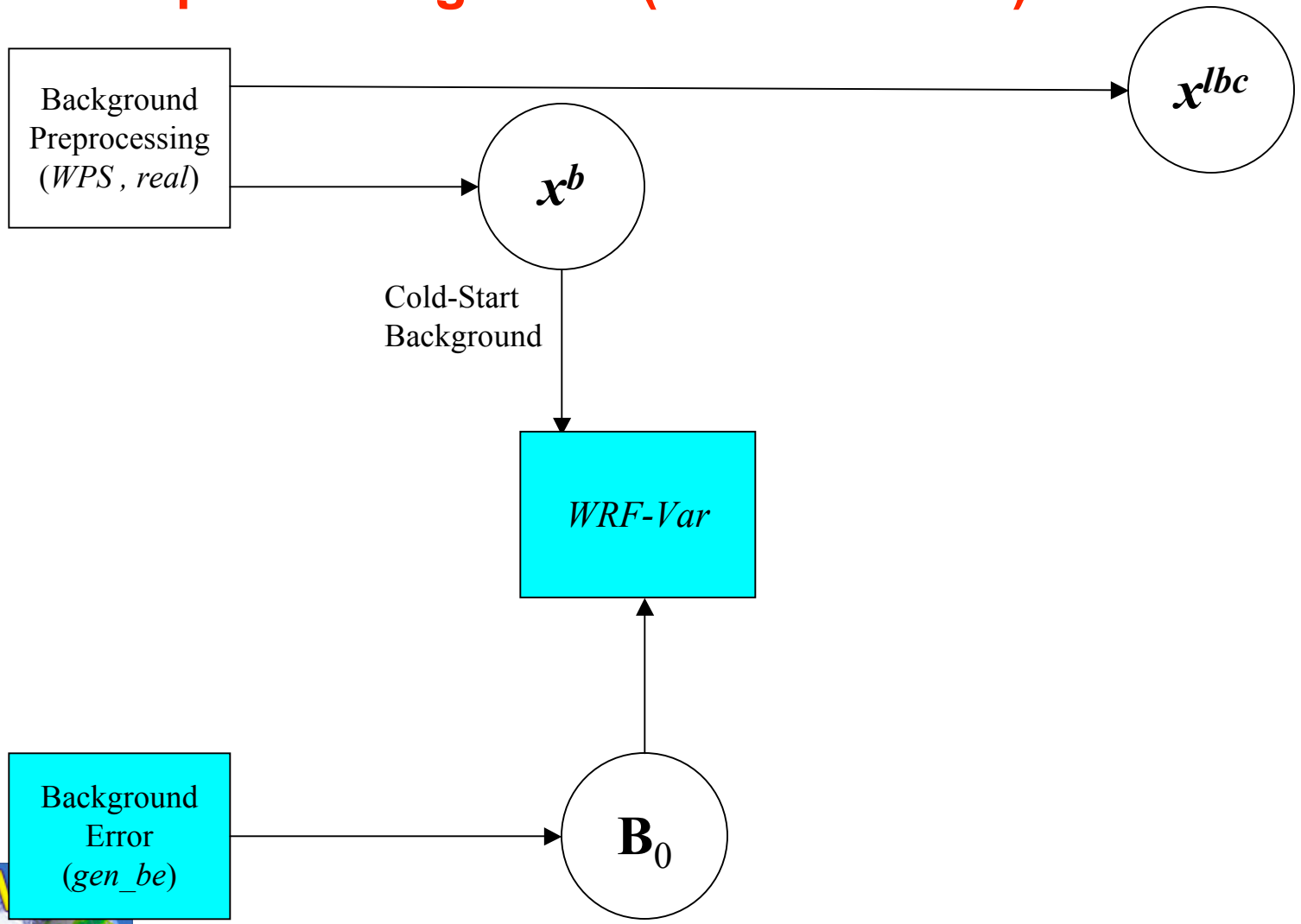
$$J(\mathbf{x}) = {}^{1}/_{2}(\mathbf{x} - \mathbf{x}^{b})^{T}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^{b}) + {}^{1}/_{2}(\mathbf{y}^{o} - H(\mathbf{x}))^{T}\mathbf{R}^{-1}(\mathbf{y}^{o} - H(\mathbf{x}))$$

- 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

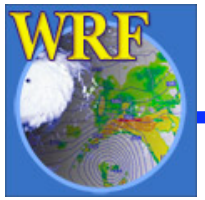
2. Prepare background (WPS and real)



Prepare background

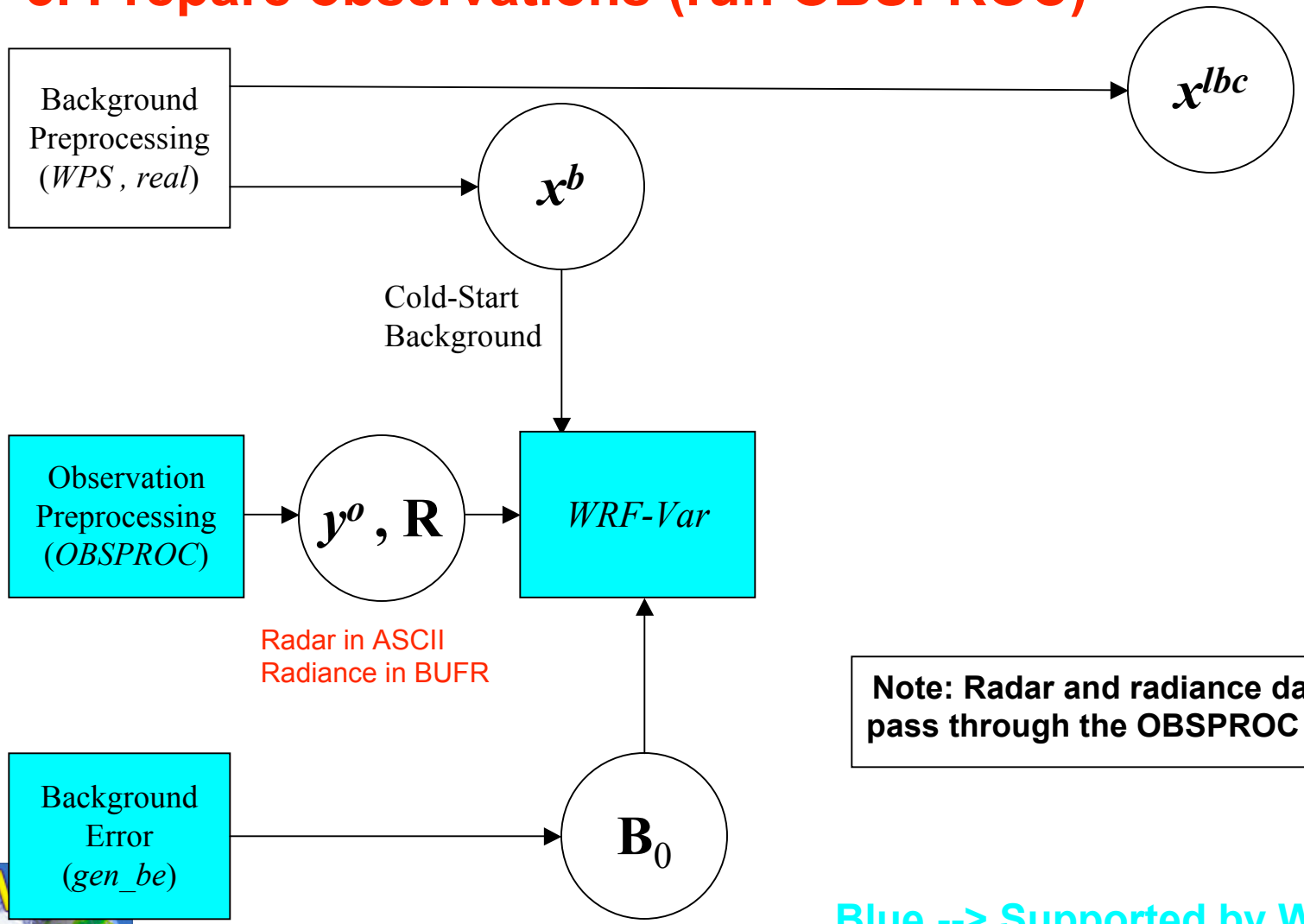
$$J(\mathbf{x}) = {}^{1}/_{2}(\mathbf{x} - \mathbf{x}^{b})^{T}\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^{b}) + {}^{1}/_{2}(\mathbf{y}^{o} - H(\mathbf{x}))^{T}\mathbf{R}^{-1}(\mathbf{y}^{o} - H(\mathbf{x}))$$

- 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)



Note: Radar and radiance data do not pass through the OBSPROC program!

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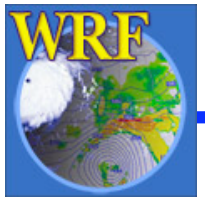
Prepare observations (y^0)

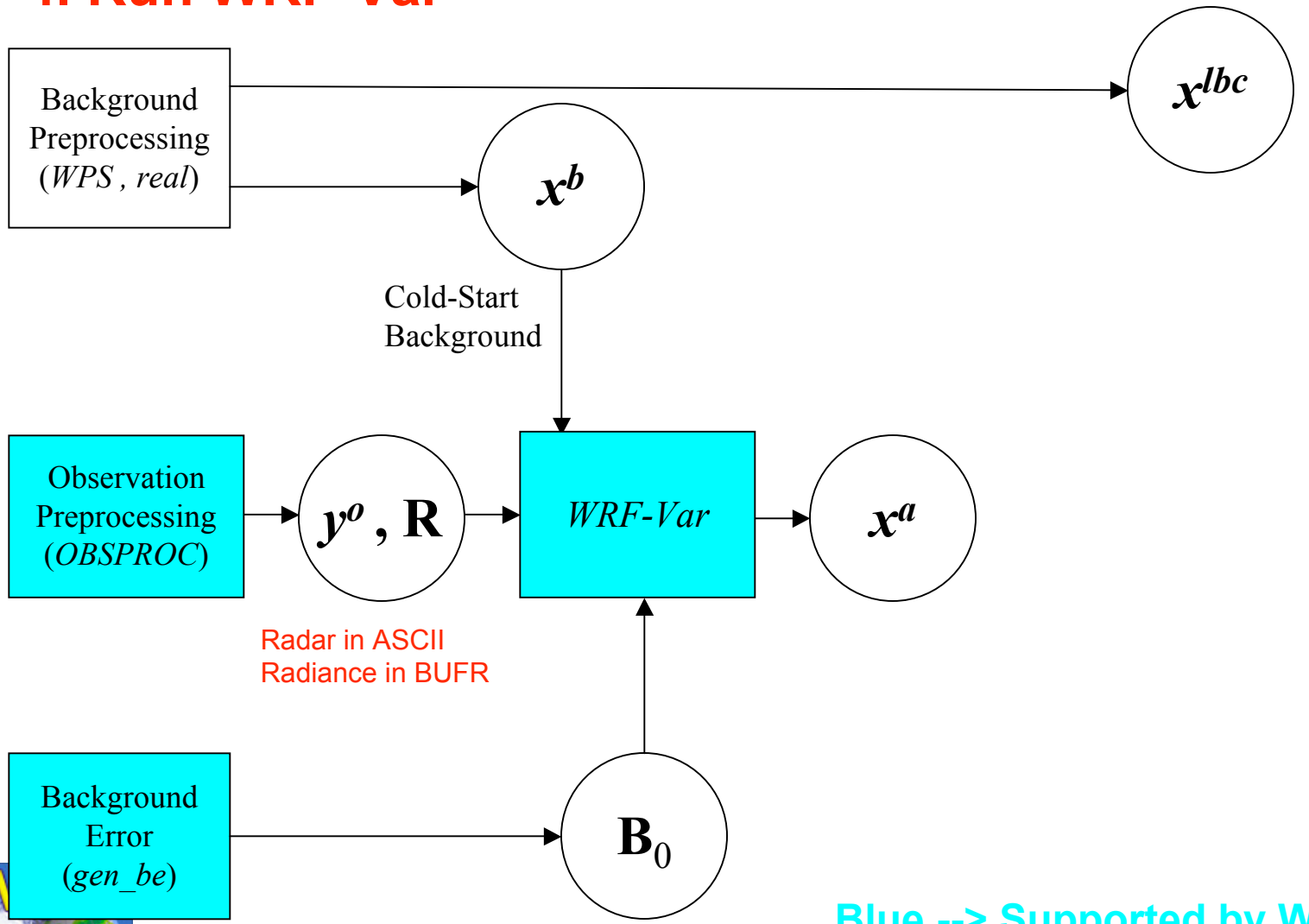
$$J(\mathbf{x}) = {}^1/_2(\mathbf{x} - \mathbf{x}^b)^T\mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b) + {}^1/_2(\mathbf{y}^o - H(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y}^o - H(\mathbf{x}))$$

- Observation input for WRF-Var is supplied through observation preprocessor, OBSPROC
  - Except radar and satellite radiances
- 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



WRF-Var in the WRF Modeling System

4. Run WRF-Var



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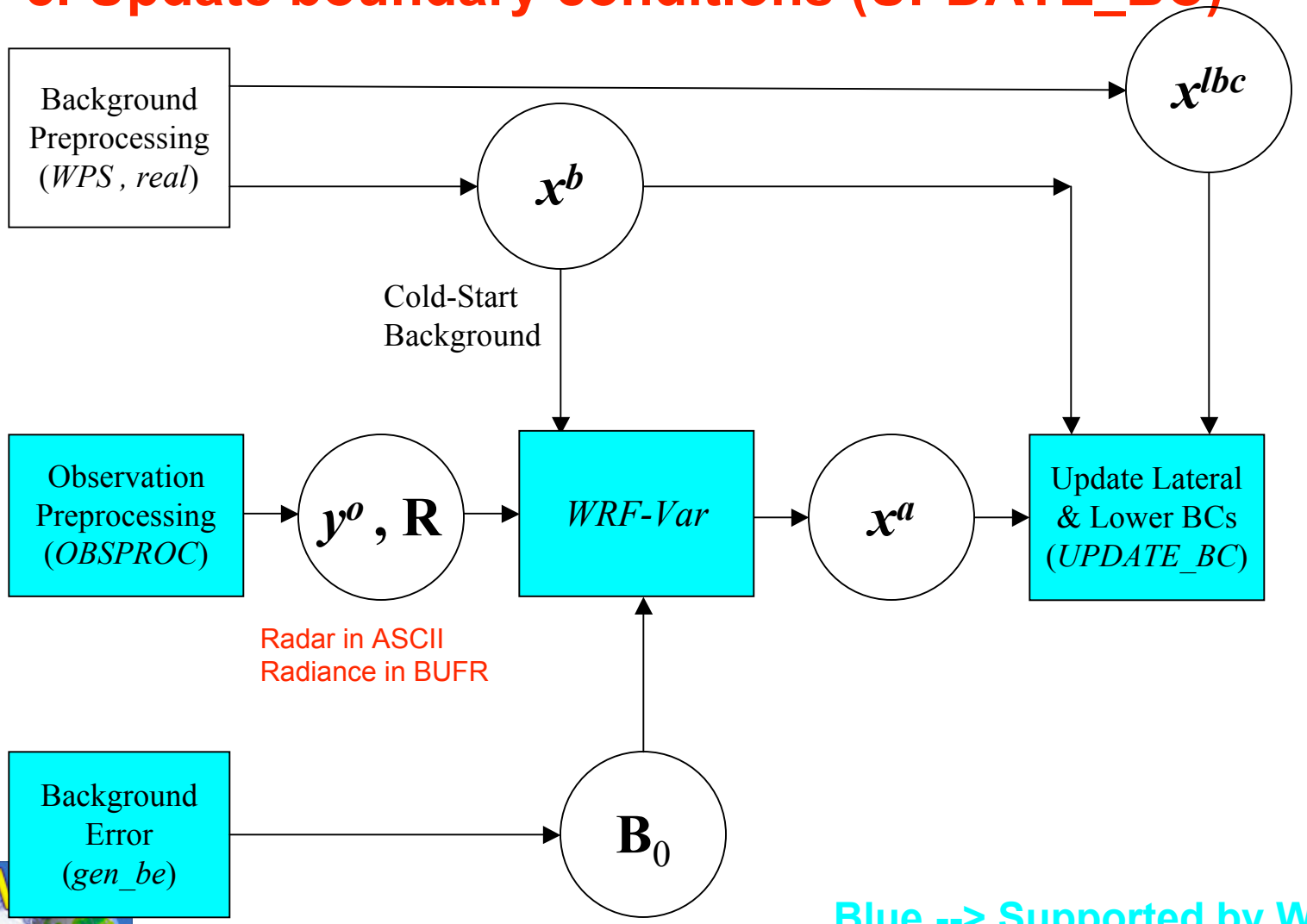
WRF-Var in the WRF Modeling System

5. Update boundary conditions (UPDATE_BC)



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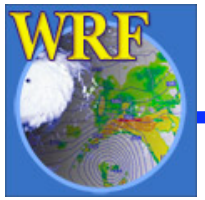
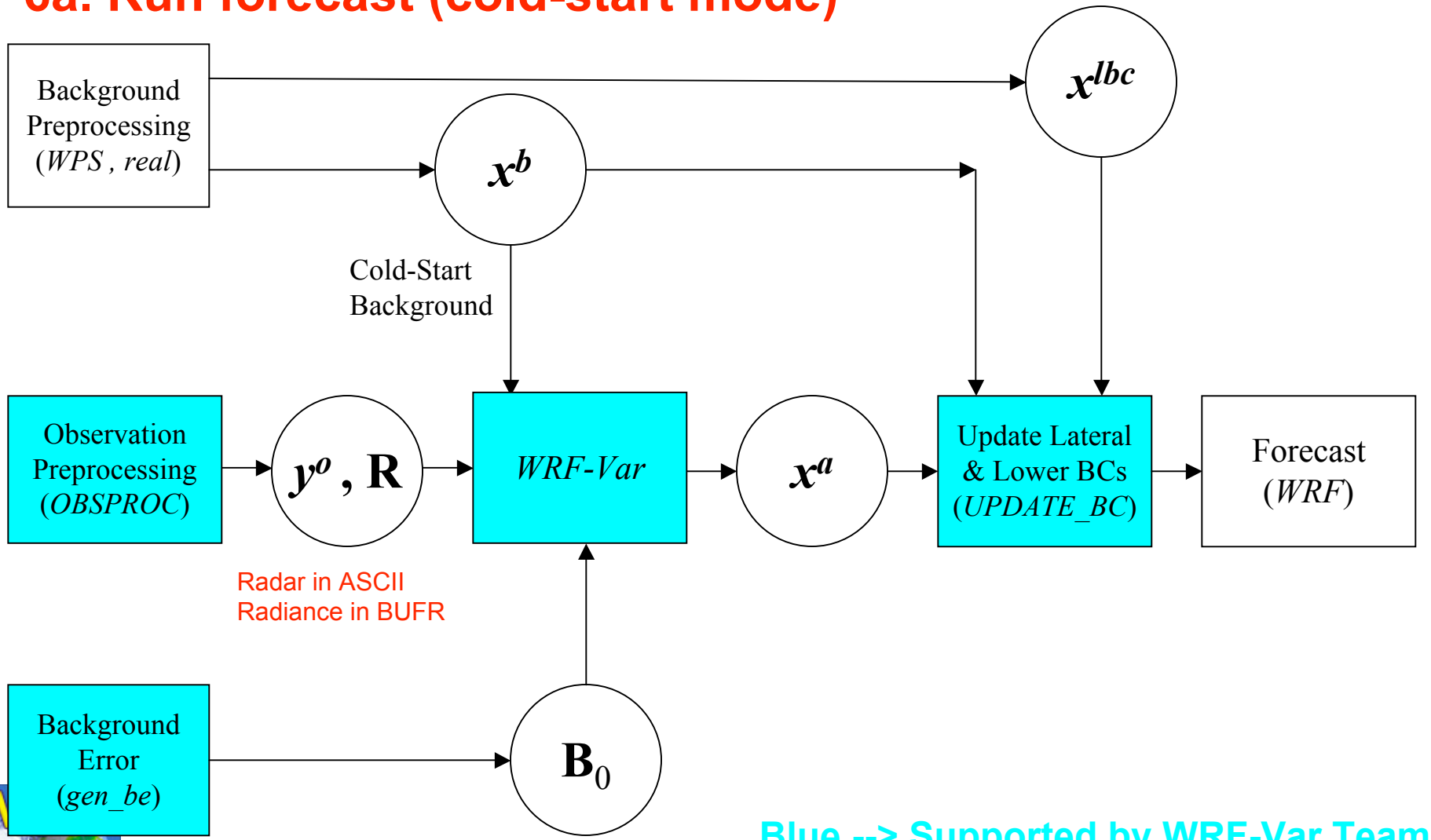
Update boundary conditions

- 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)



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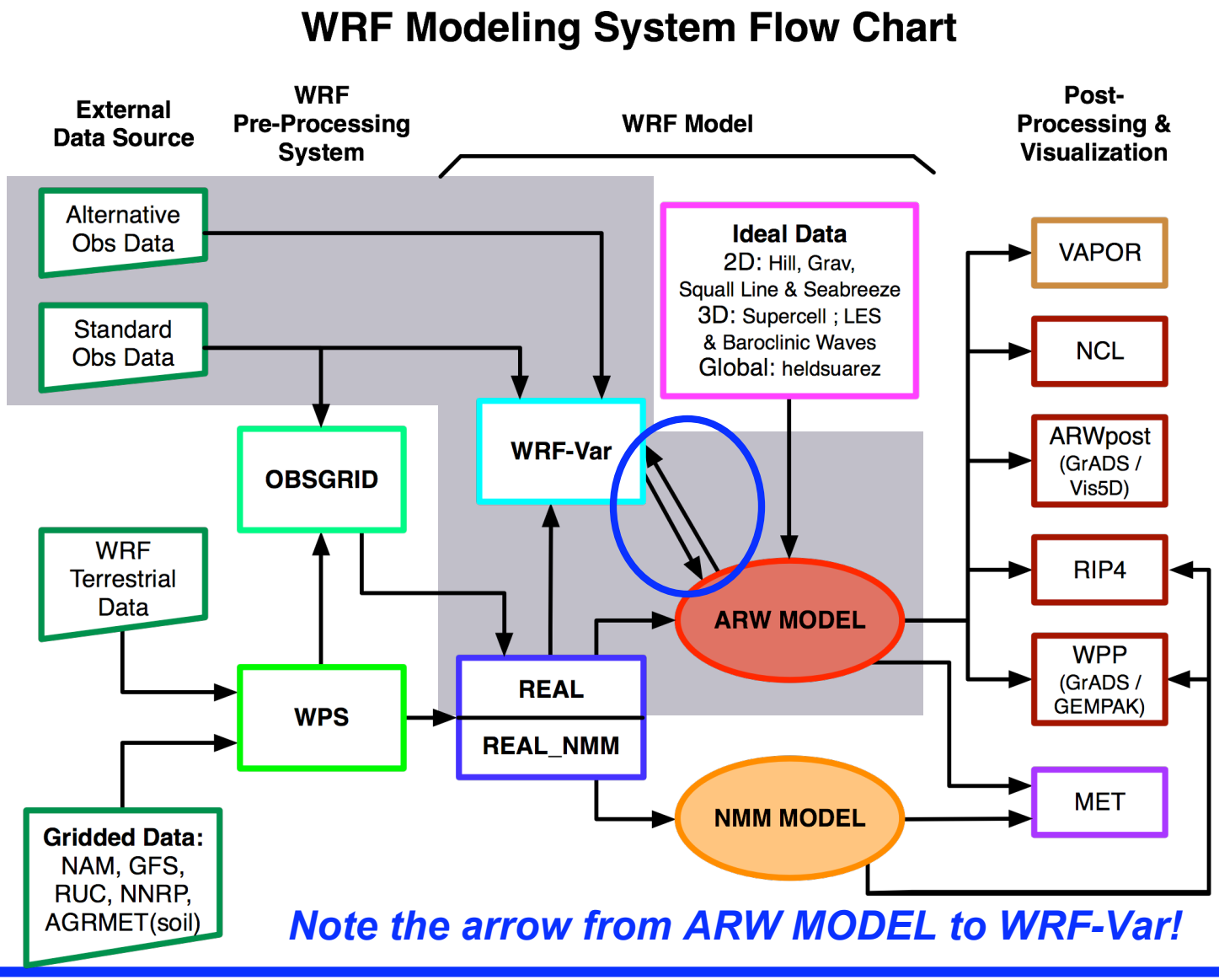
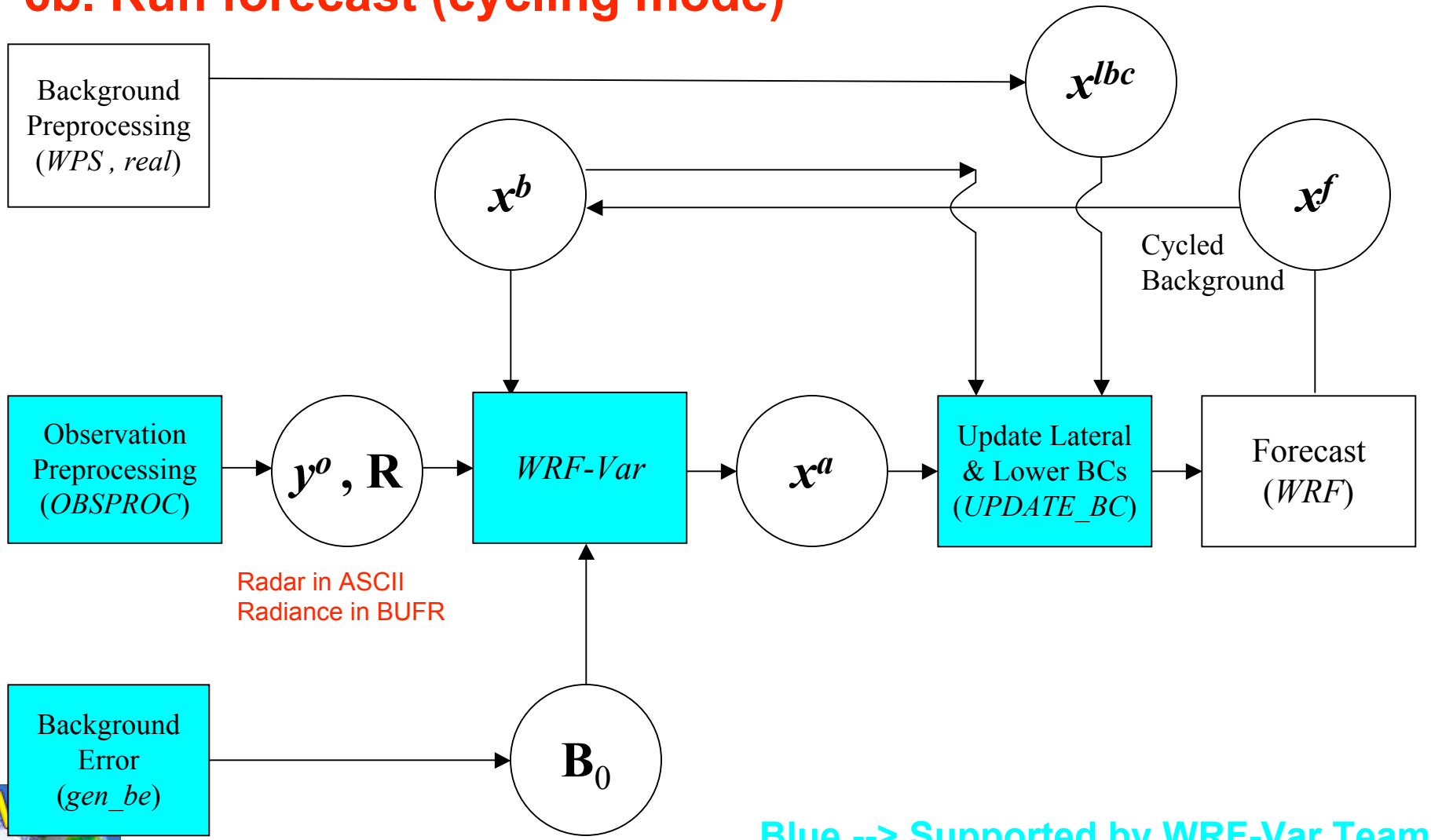
WRF-Var in the WRF Modeling System



Note the arrow from ARW MODEL to WRF-Var!

WRF-Var in the WRF Modeling System

6b. Run forecast (cycling mode)



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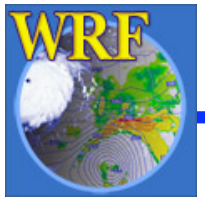
Background Error (BE) for WRF-Var

One important question from WRF-Var users is

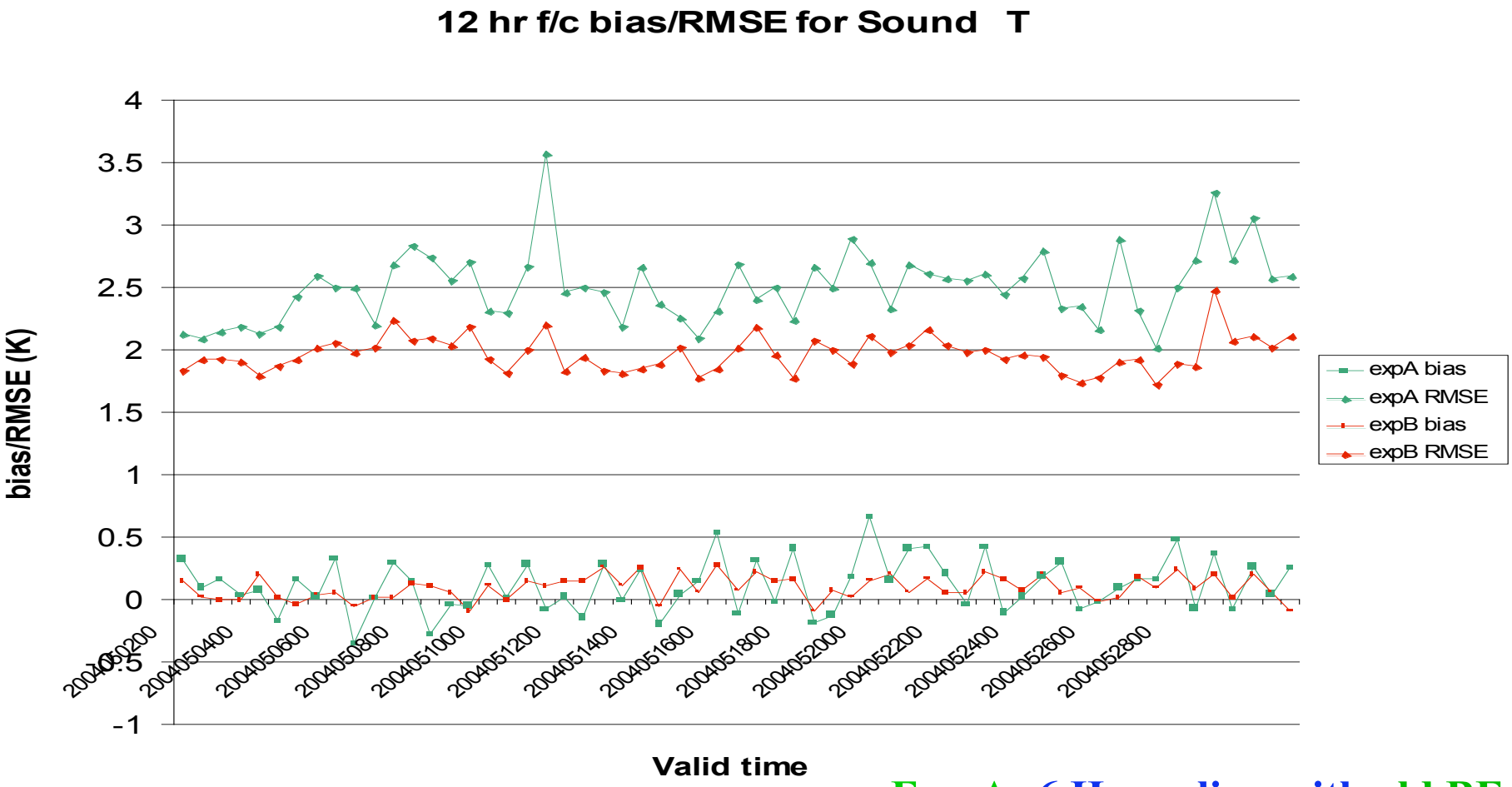
"What background errors are best for my application?"

- 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

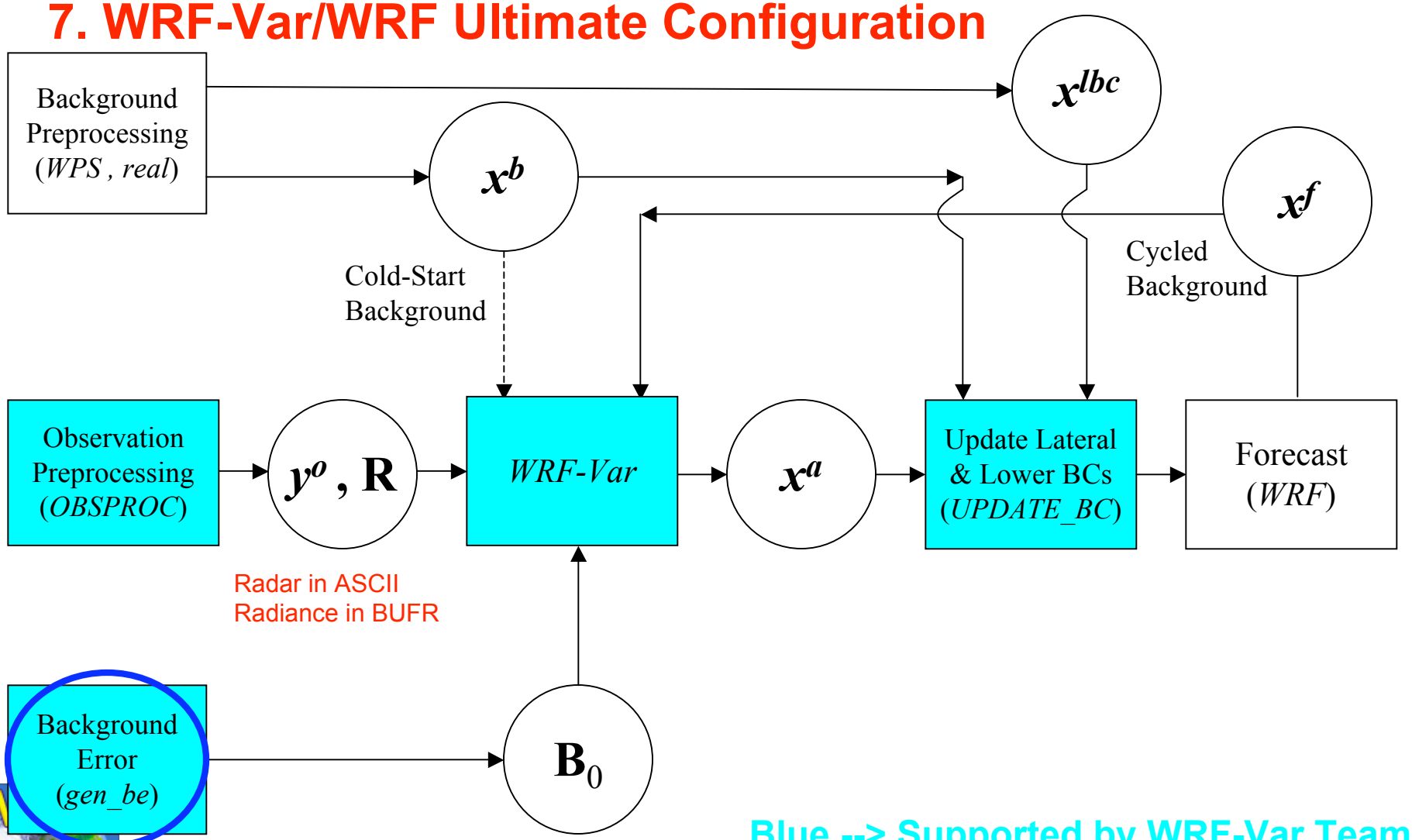


Exp A: 6 Hr cycling with old BE

Exp B: 6 Hr cycling with new BE

WRF-Var in the WRF Modeling System

7. WRF-Var/WRF Ultimate Configuration



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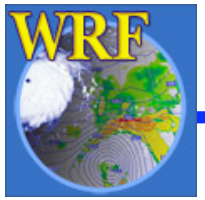
WRF-Var Implementation



WRF-Var Formulation

3D-Var:

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

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

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

$$\delta\mathbf{x} = \mathbf{x}-\mathbf{x}^{\mathrm{g}} \qquad \mathbf{d} = \mathbf{y}-H\left(\mathbf{x}^{\mathrm{g}}\right) \quad H\left(\mathbf{x}\right)-H\left(\mathbf{x}^{\mathrm{g}}\right) \approx \mathbf{H}\delta\mathbf{x}$$

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

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

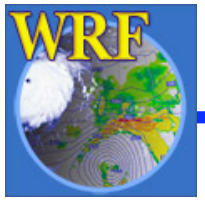
$$J = \frac{1}{2}\delta\mathbf{x}^{T}\mathbf{B}^{-1}\delta\mathbf{x}+\frac{1}{2}\left(\mathbf{d}-\mathbf{H}\delta\mathbf{x}\right)^{T}\mathbf{R}^{-1}\left(\mathbf{d}-\mathbf{H}\delta\mathbf{x}\right)$$

Outer-loop:

d (and QC, etc) … nonlinear!

Inner-loop: minimization

update $\mathbf{x}^{\mathrm{g}}$



B in WRF-Var

- Partly for preconditioning reasons:

  $\mathbf{B} = \mathbf{U}\,\mathbf{U}^{T}$ with $\mathbf{U} = \mathbf{U_p U_v U_h}$

- Horizontal transformation ($\mathbf{U_h}$) is via

  Regional - recursive filters

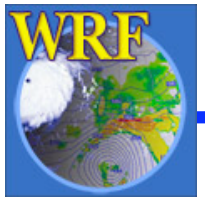
  Global - power spectrum

- 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

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

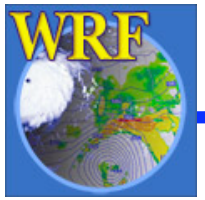
  - **v** is the analysis increment in control variable space
    - WRF-Var control variables: streamfunction, unbalanced velocity potential, unbalanced temperature, RH, and unbalanced surface pressure
  - **B** is approximated by $\mathbf{U}\mathbf{U}^T$

- WRF-Var actually minimizes

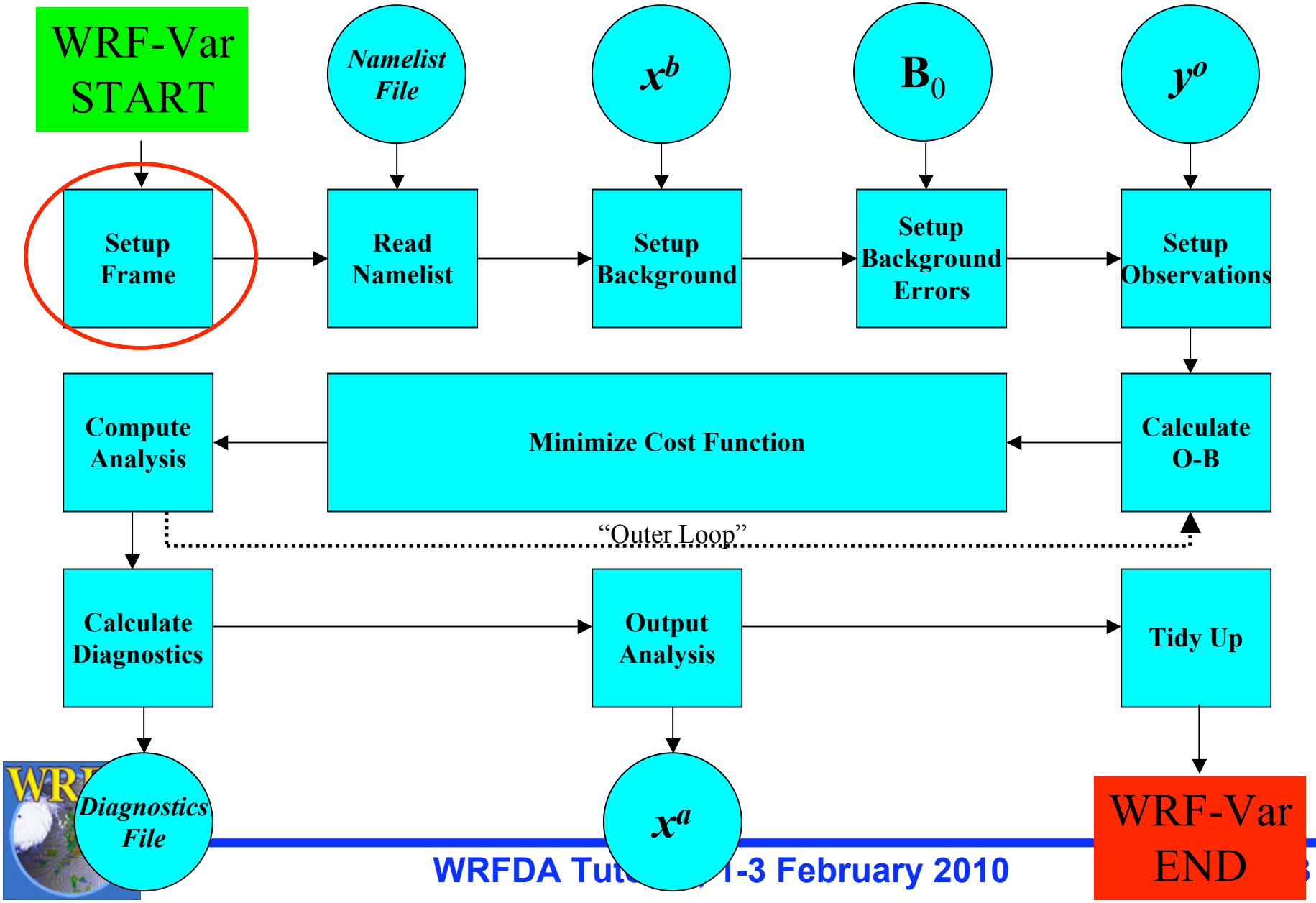
$$J(\mathbf{v}) = \frac{1}{2}\mathbf{v}^T\mathbf{v} + \frac{1}{2}(\mathbf{d} - \mathbf{H}\mathbf{U}\mathbf{v})^T\mathbf{R}^{-1}(\mathbf{d} - \mathbf{H}\mathbf{U}\mathbf{v})$$

- After minimization, the analysis, $\mathbf{x}^a$, is given by

$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{U}\mathbf{v}$$

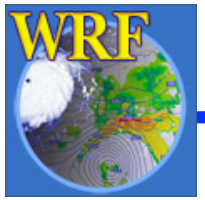


WRF-Var

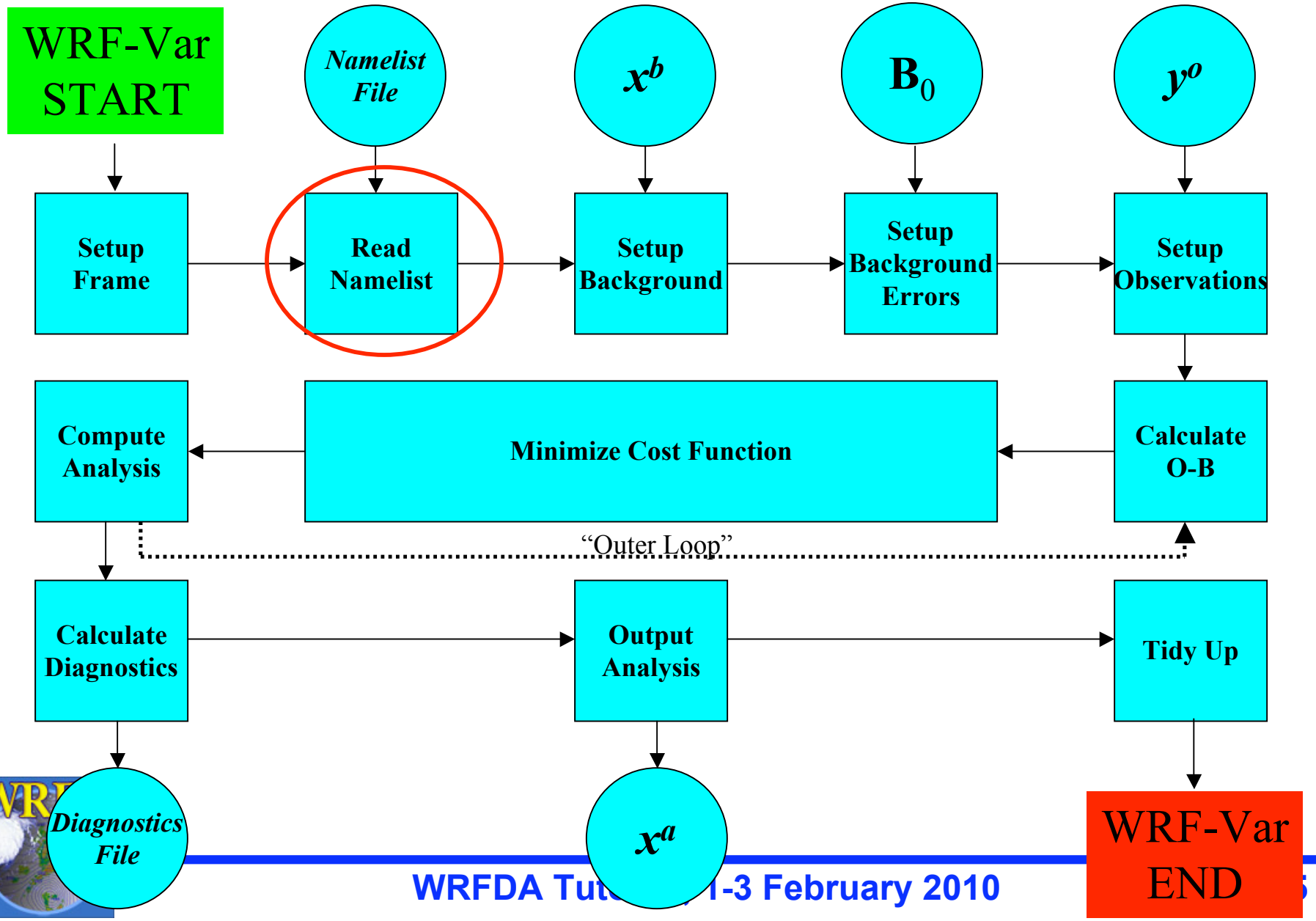

WRF-Var START
Namelist File
x^b
B_0
y^o
Setup Frame
Read Namelist
Setup Background
Setup Background Errors
Setup Observations
Compute Analysis
Minimize Cost Function
Calculate O-B
"Outer Loop"
Calculate Diagnostics
Output Analysis
Tidy Up
Diagnostics File
x^a
WRF-Var END

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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Namelist File
x^b
B_0
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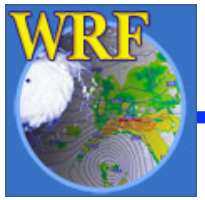
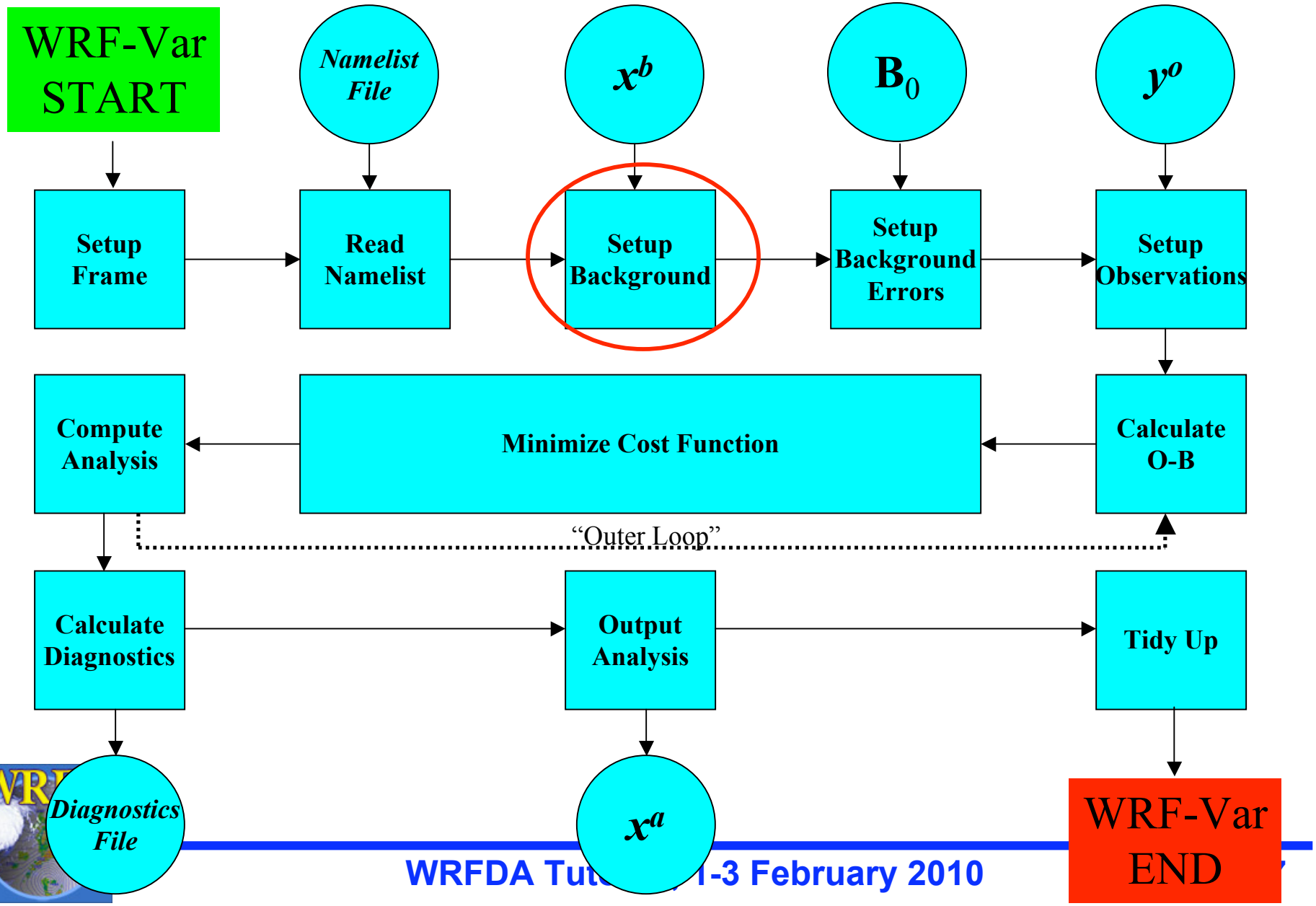
x^a
WRF-Var END

Read Namelist

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



WRF-Var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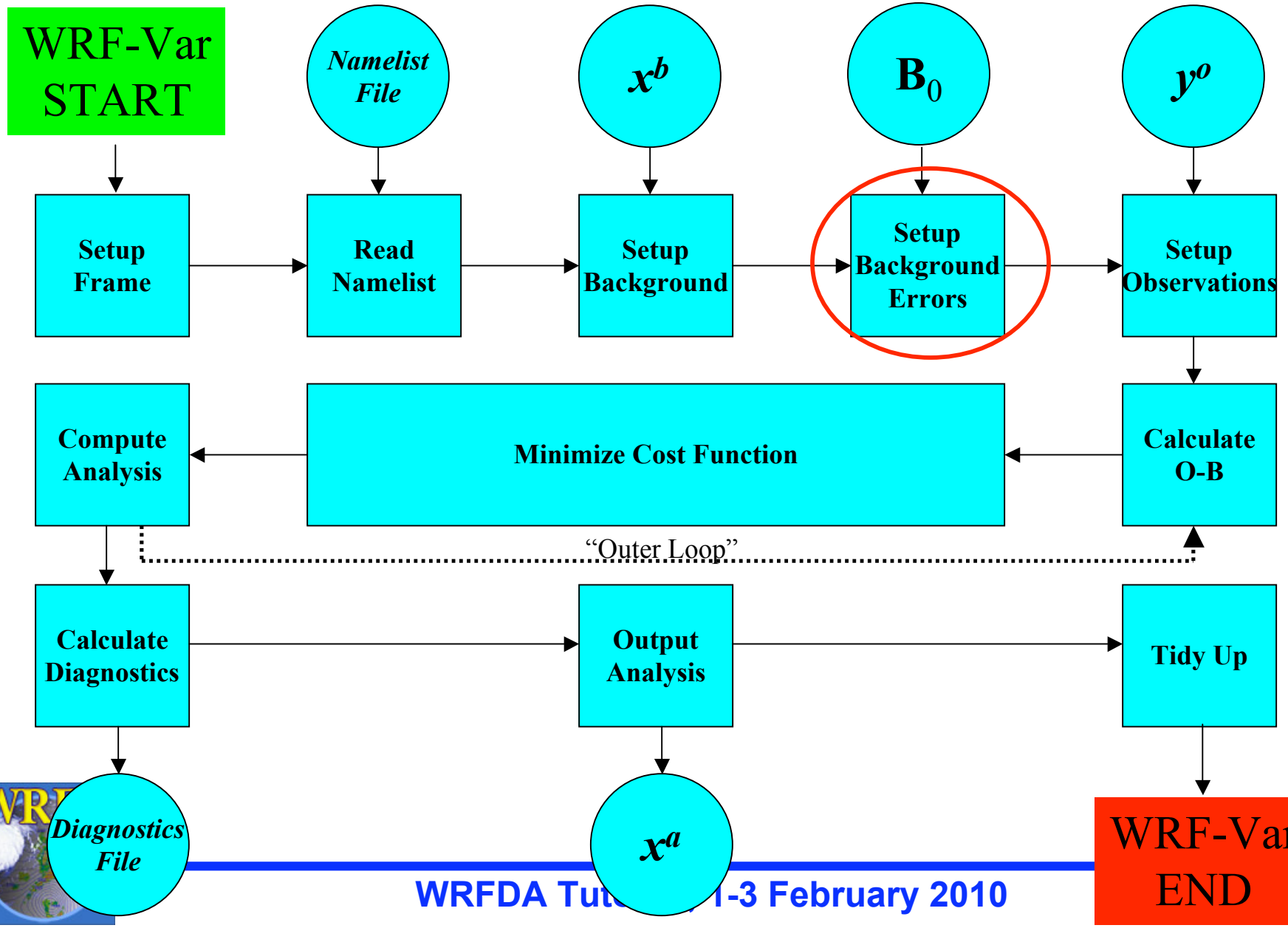
x^a
WRF-Var END

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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Namelist File
x^b
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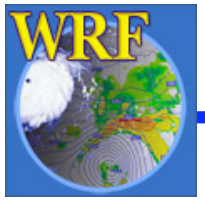
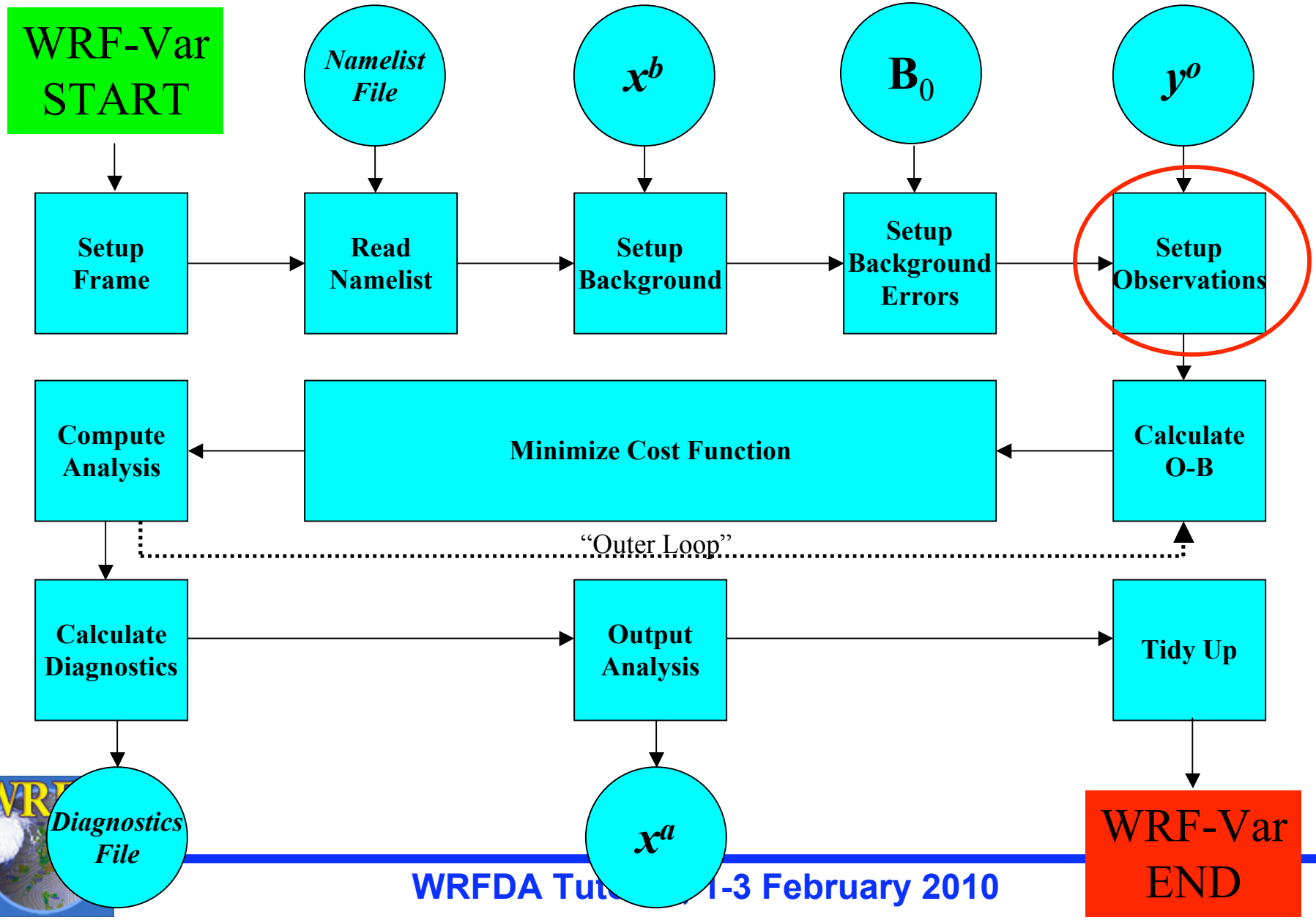
WRF-Var END

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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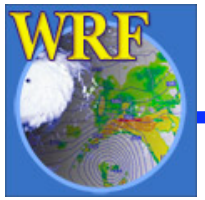
Diagnostics File
x^a
WRF-Var END

Setup Observations

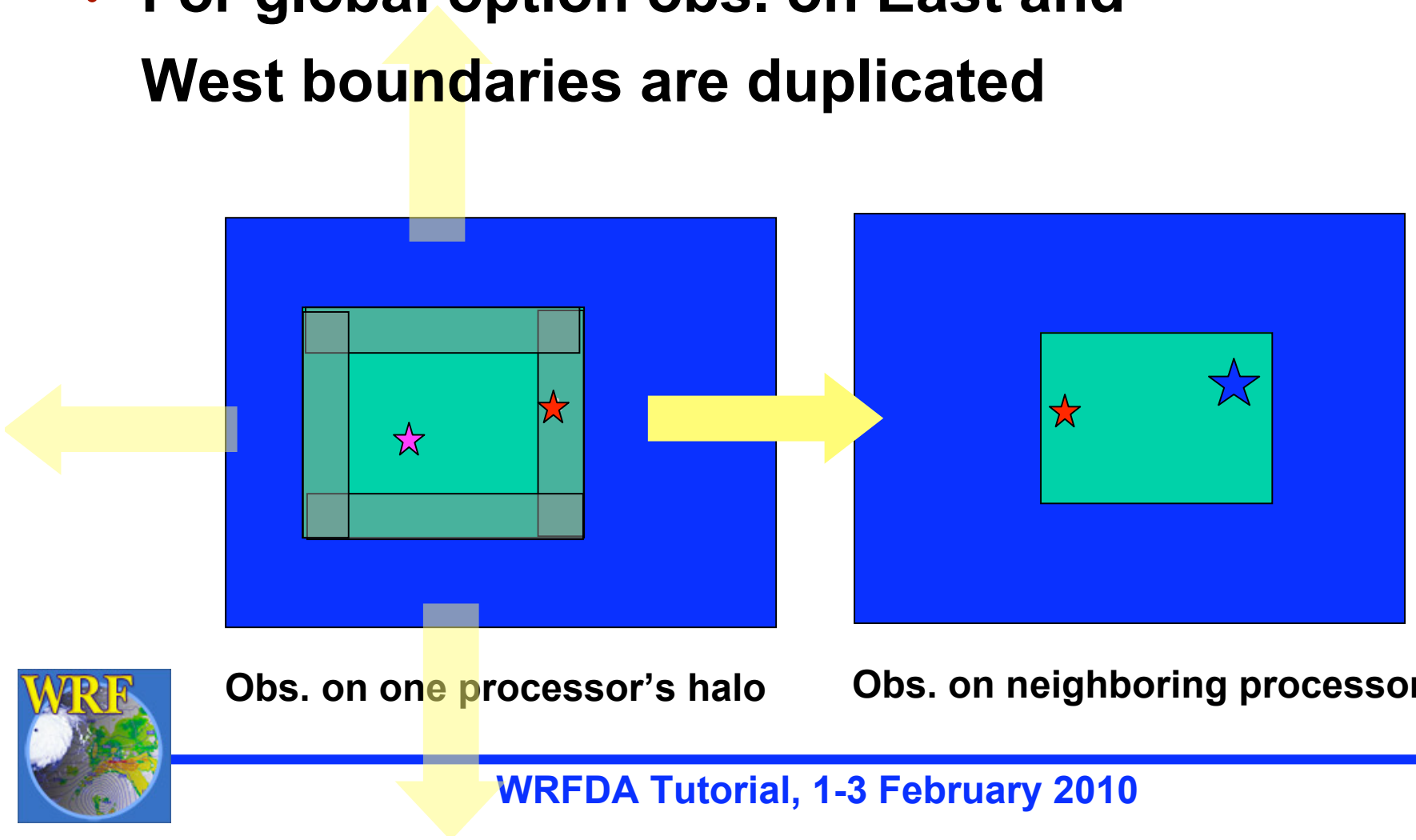
- Reads in observations.
- Format depends on namelist variable "ob_format"

  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

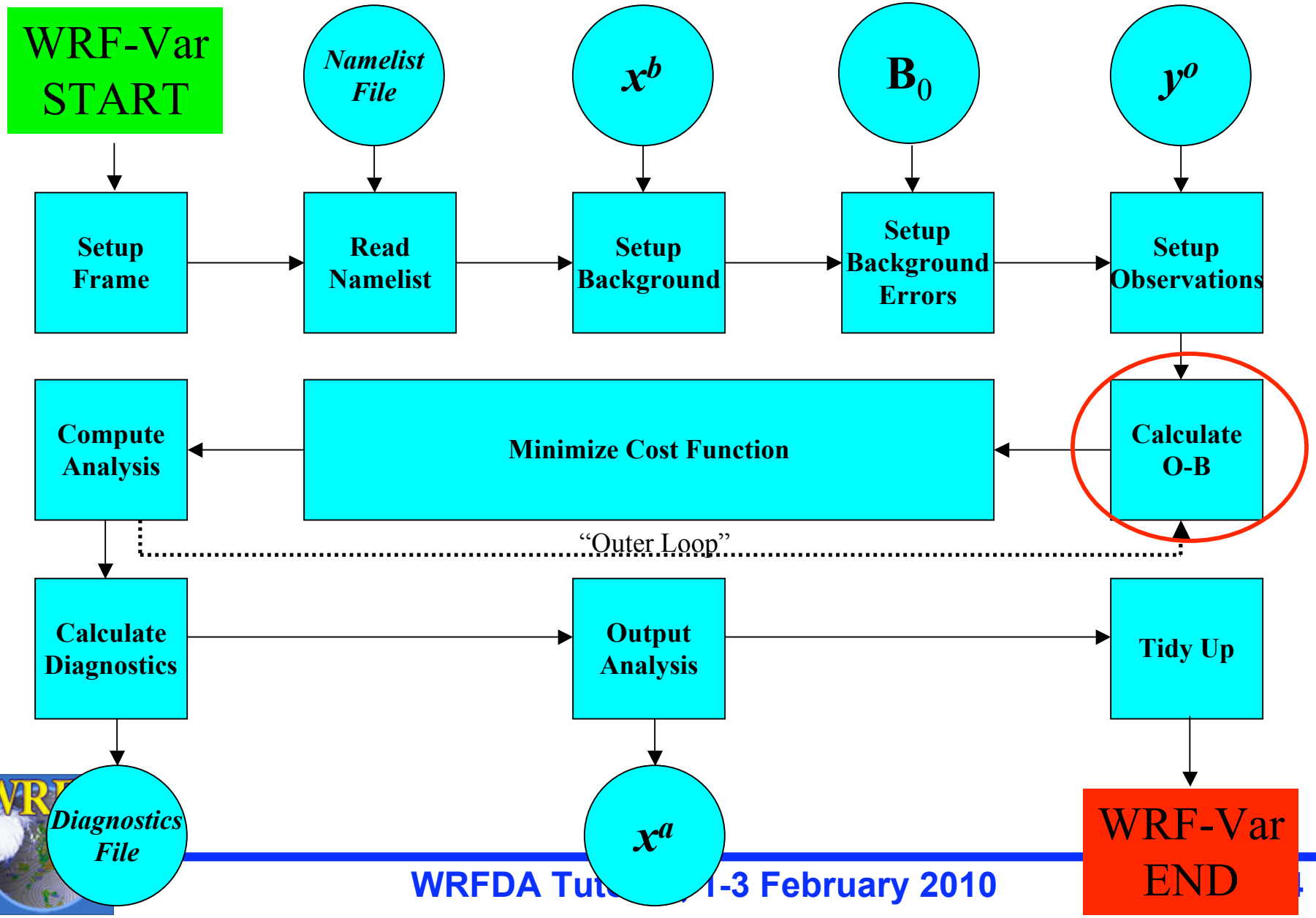
- **Halo Region Observation**
- **For global option obs. on East and West boundaries are duplicated**



Obs. on one processor's halo

Obs. on neighboring processor

WRF-Var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x^a
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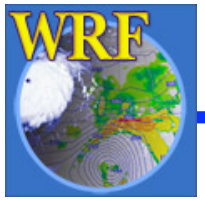
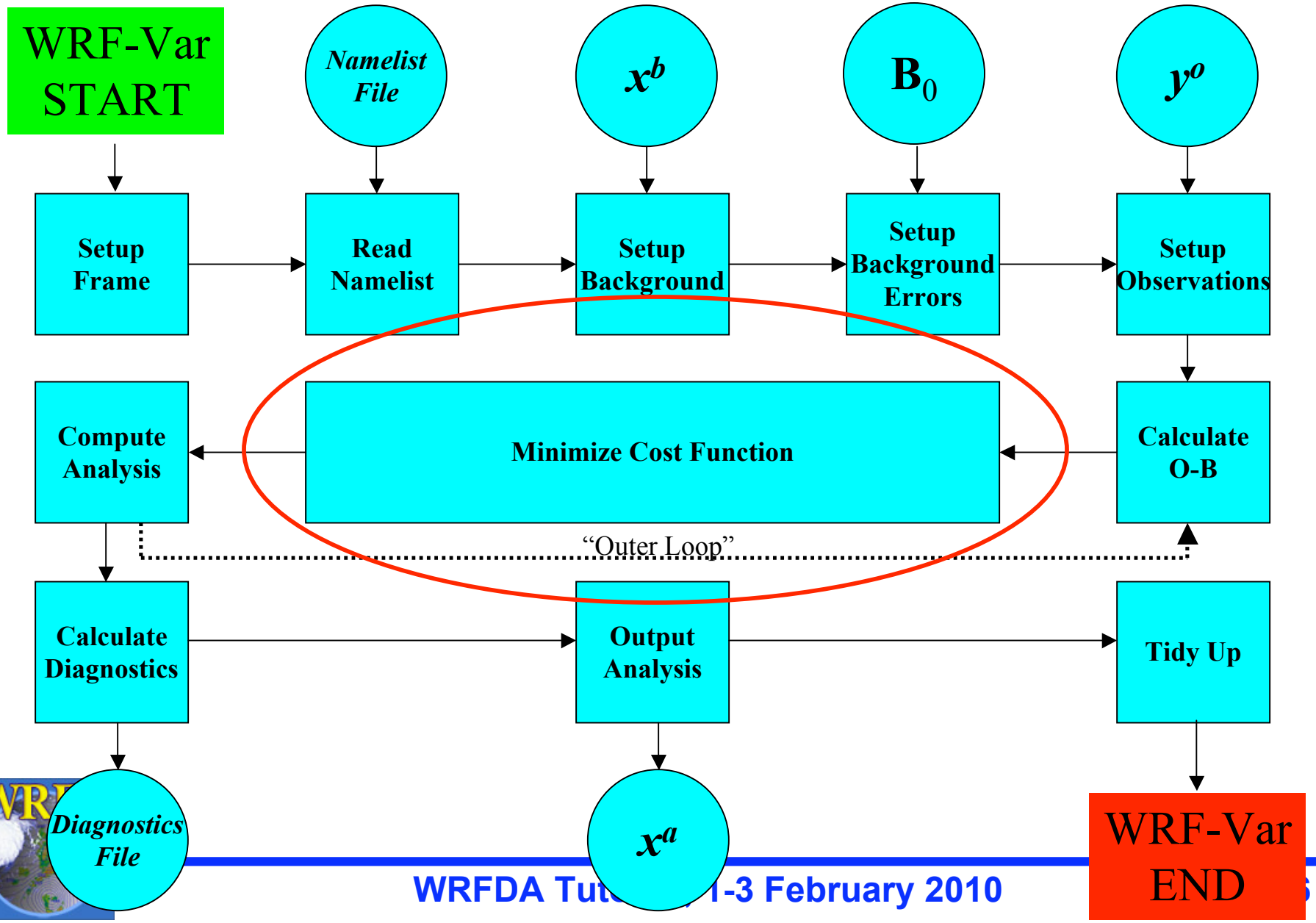
Calculate Innovation Vector (O-B)

- 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


WRF-Var START
Namelist File
x^b
B_0
y^o
Setup Frame
Read Namelist
Setup Background
Setup Background Errors
Setup Observations
Compute Analysis
Minimize Cost Function
Calculate O-B
"Outer Loop"
Calculate Diagnostics
Output Analysis
Tidy Up
Diagnostics File
x^a
WRF-Var END

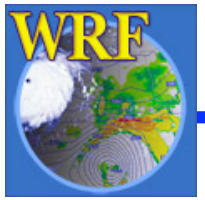
Minimize Cost Function

Use conjugate gradient method

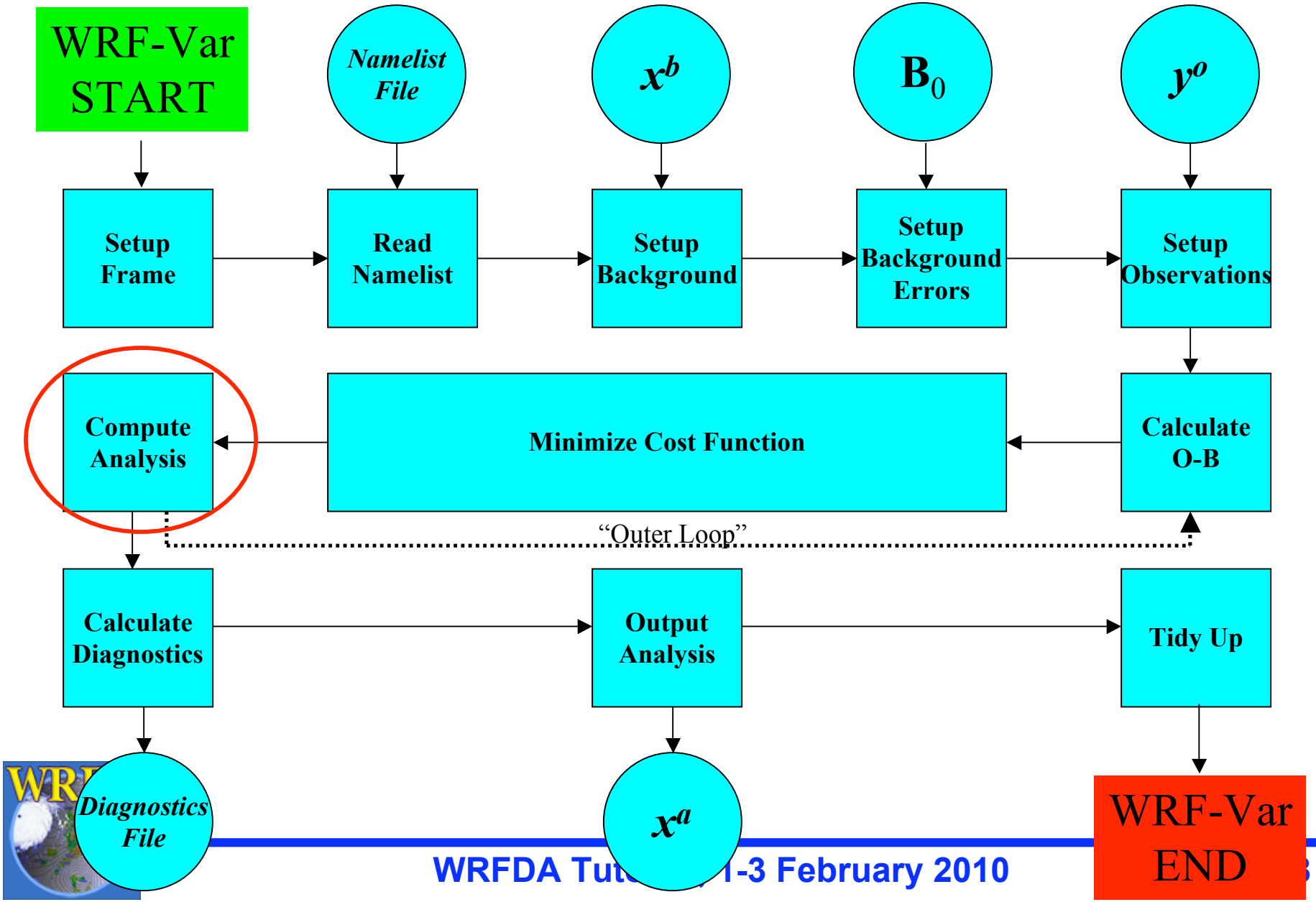
- (a) Initializes analysis increments to zero.
- (b) Computes cost function (if desired).
- (c) Computes gradient of cost function.
- (d) Uses cost function and gradient to calculate new value of analysis control variable, **v**

Iterate (b) to (d) to minimize

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



WRF-Var


WRF-Var START
Namelist File
x^b
B_0
y^o
Setup Frame
Read Namelist
Setup Background
Setup Background Errors
Setup Observations
Compute Analysis
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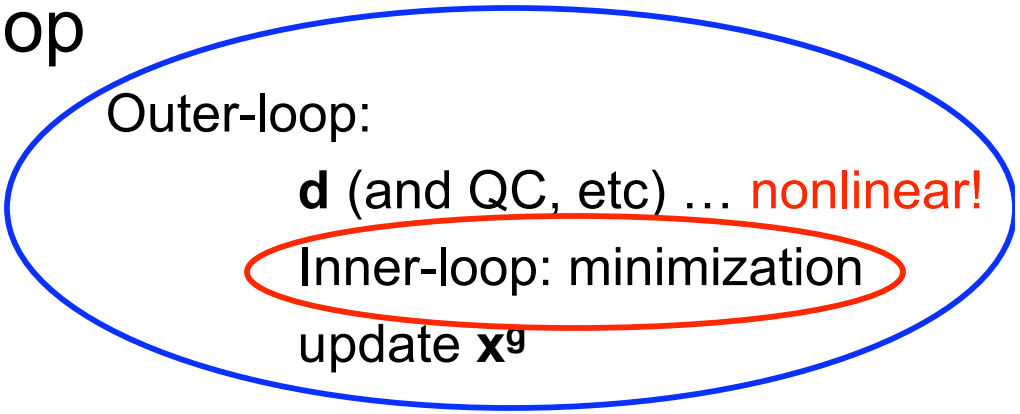
Diagnostics File
x^a
WRF-Var END

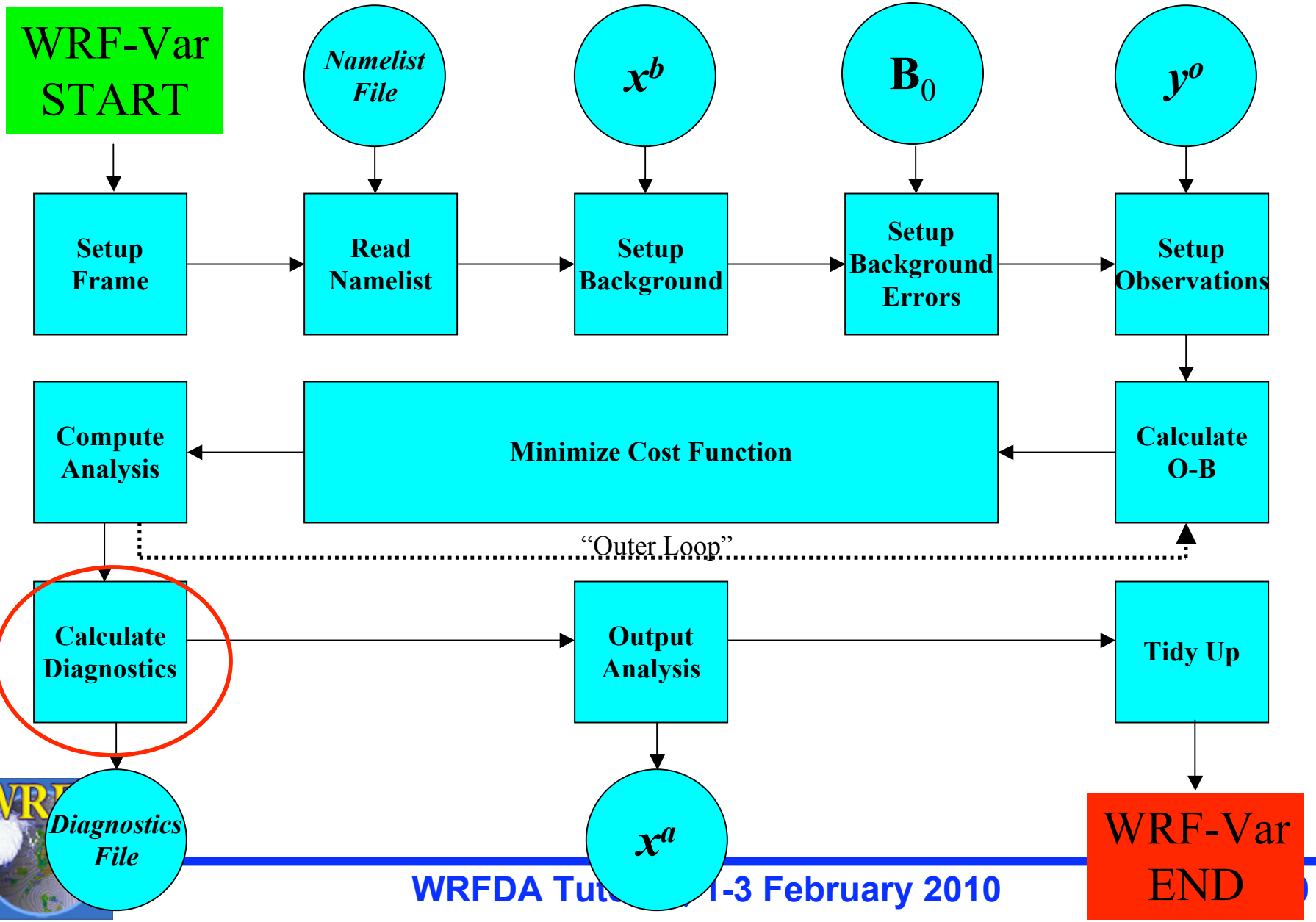
Compute Analysis

- 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



WRF-Var


WRF-Var START
Namelist File
x^b
B_0
y^o
Setup Frame
Read Namelist
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Compute Analysis
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"Outer Loop"
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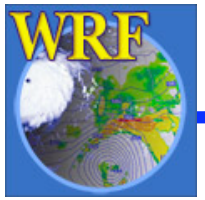
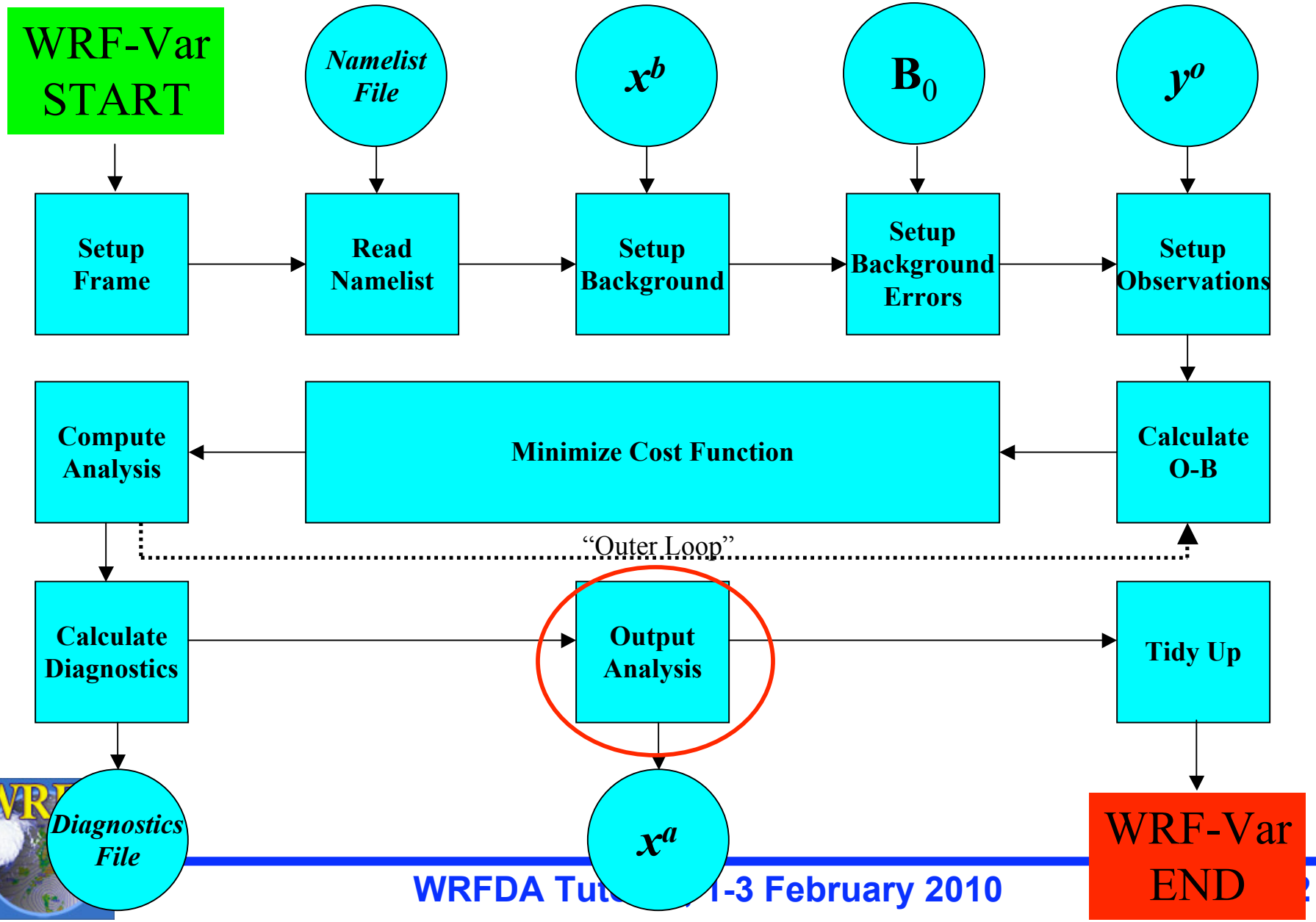
Diagnostics File
x^a
WRF-Var END

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


WRF-Var START
Namelist File
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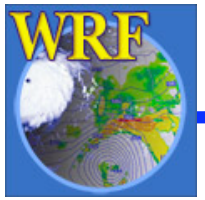
Diagnostics File
x^a
WRF-Var END

Output Analysis

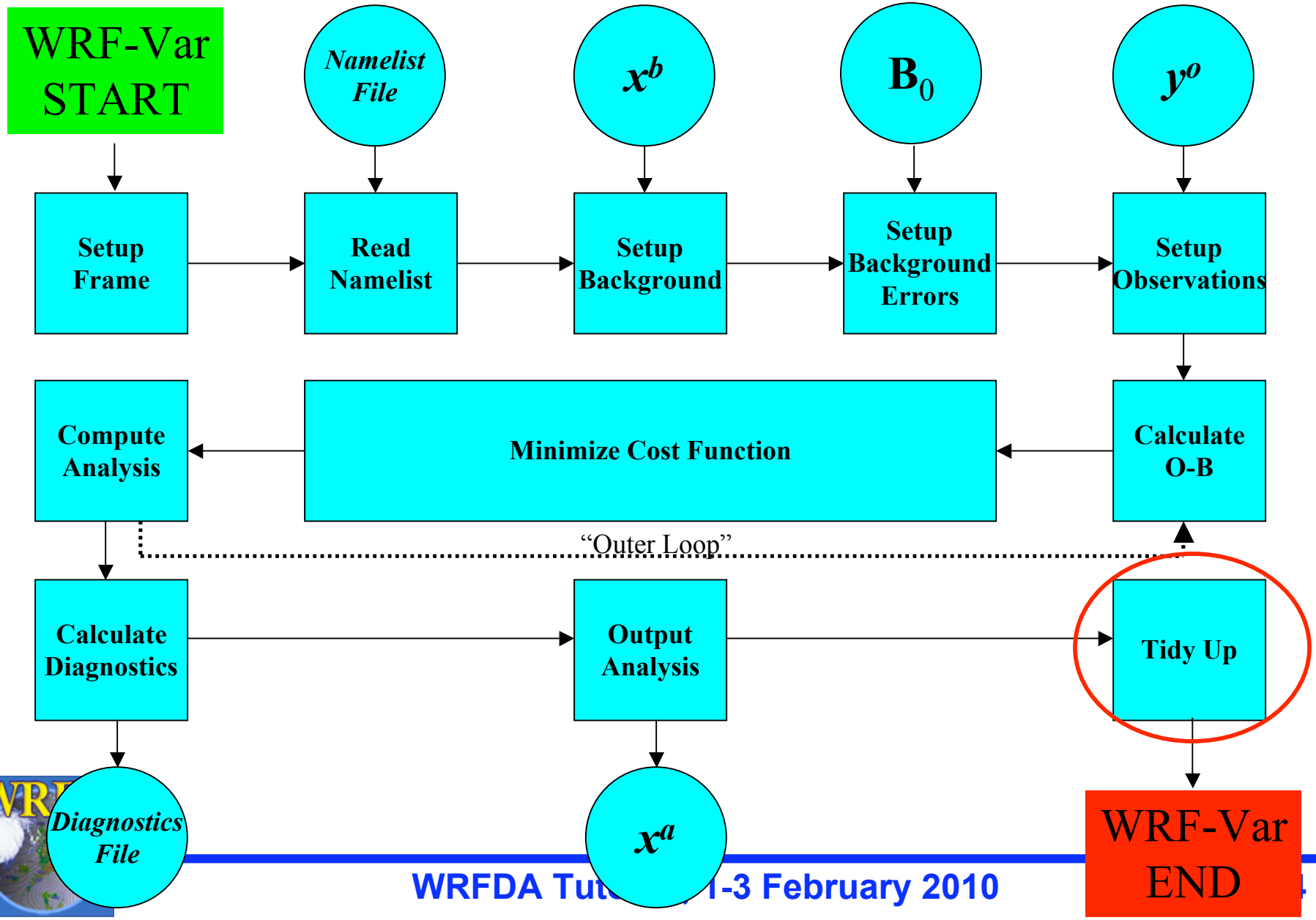
- Outputs analysis in native model format. Choice is made through namelist option "fg_format"

  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


WRF-Var START
Namelist File
x^b
B_0
y^o
Setup Frame
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Compute Analysis
Minimize Cost Function
Calculate O-B
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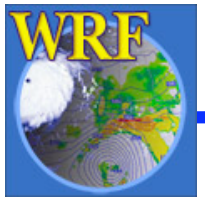
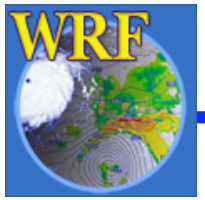
Tidy Up
Diagnostics File
x^a
WRF-Var END

Tidy Up

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

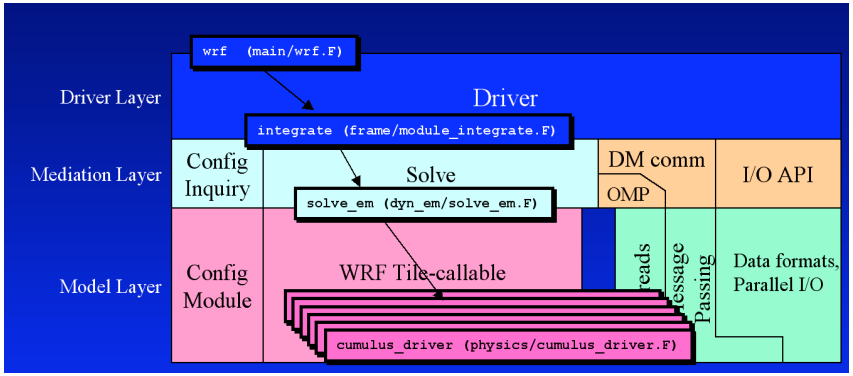


WRF-Var Software

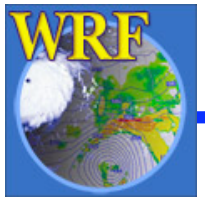


Use of the WRF Software Framework

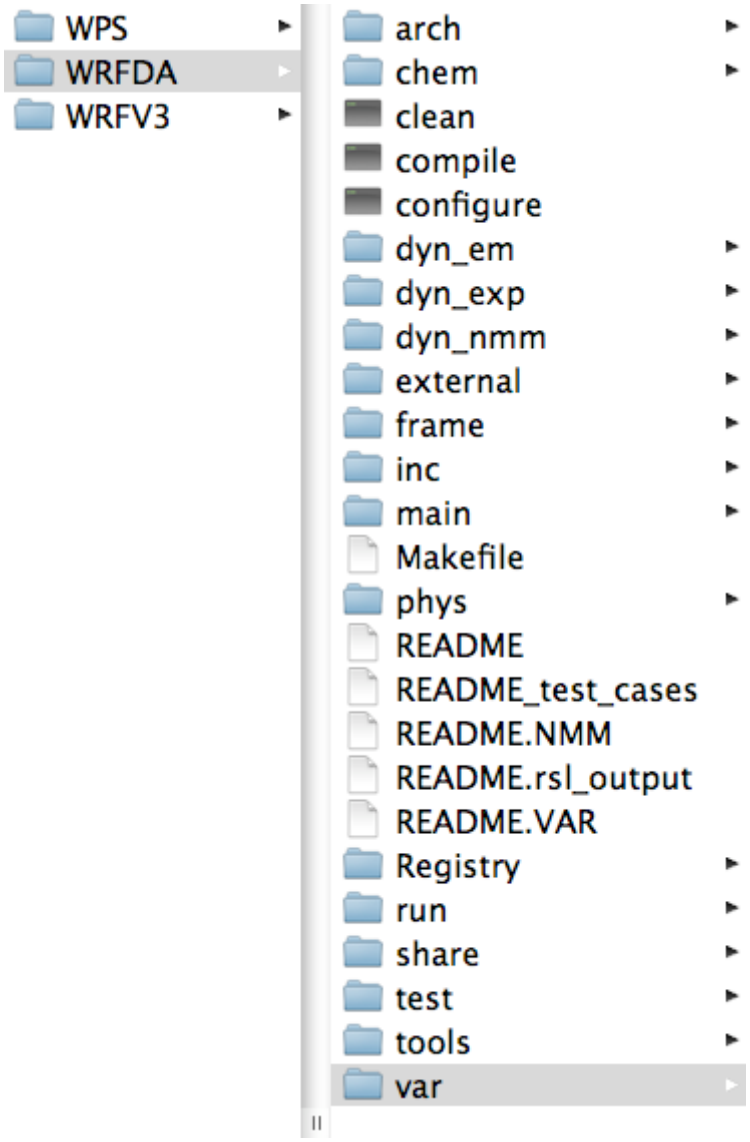
- WRF-Var relies on the WRF Software framework for
  - Distributed memory parallelism (halo exchanges, etc.)
  - Input/Output of first guess and analysis files
  - Parallel transposes



- WRF-Var also uses
  - The WRF Registry mechanism to handle definitions of fields, halos, and transposes
  - The WRF build system (clean, configure, compile)

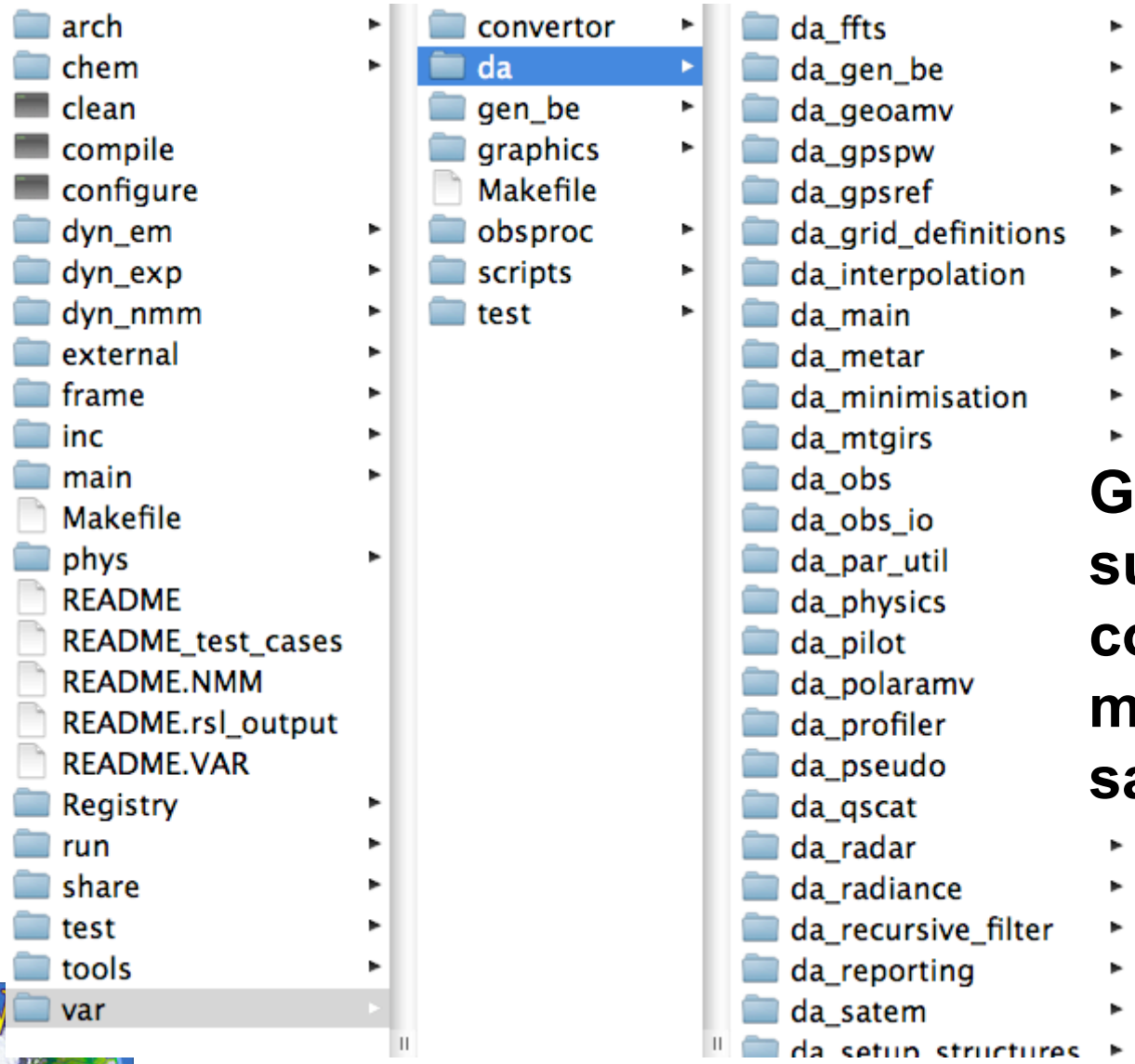


WRF-Var Code Organization



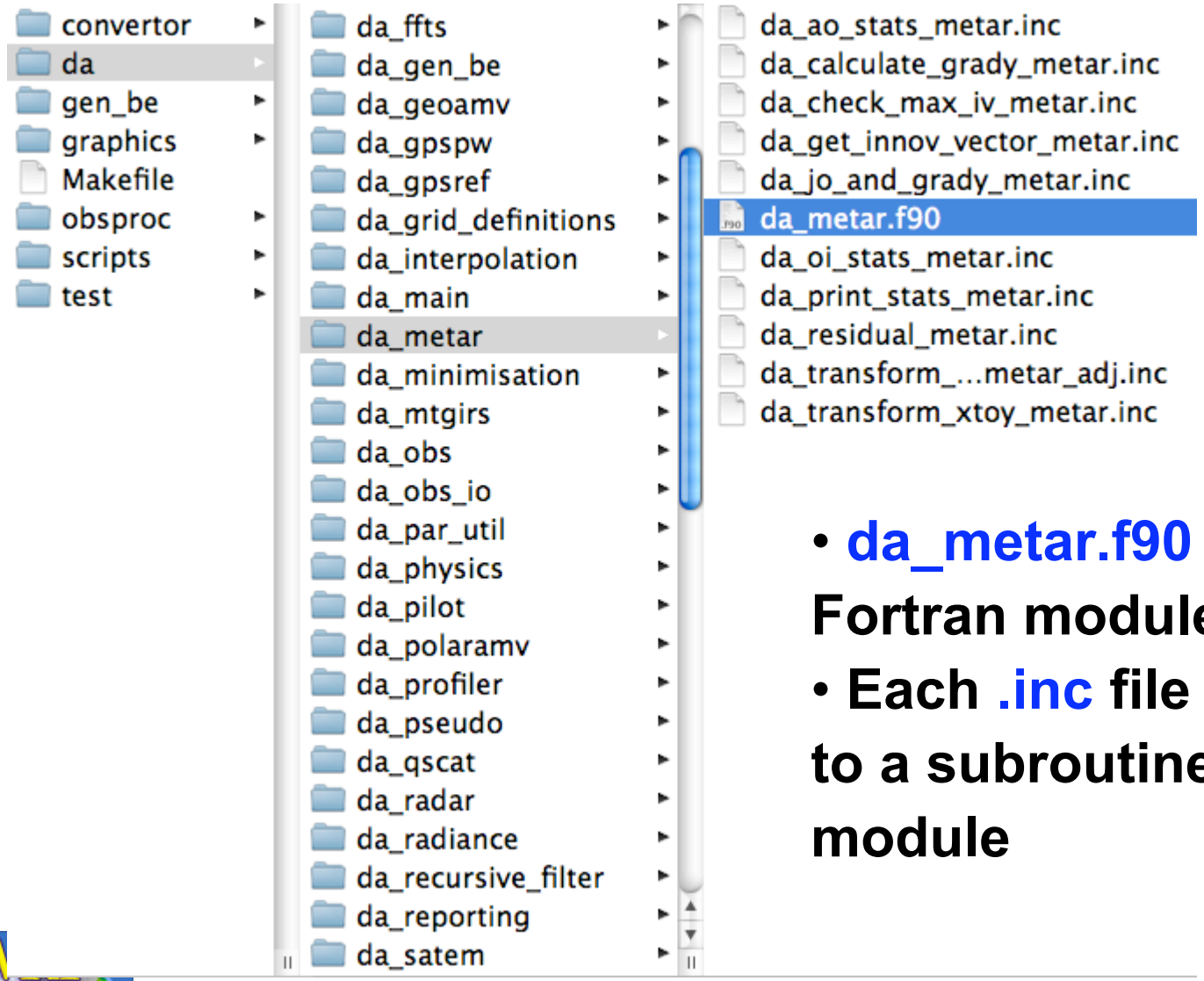
Besides the directories for WRF, the WRFDA tar file contains a "var" directory, which holds all of the WRF-Var code

WRF-Var Code Organization

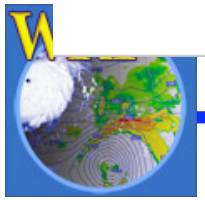


Generally, each subdirectory of "da" contains a Fortran module with the same name

WRF-Var Code Organization

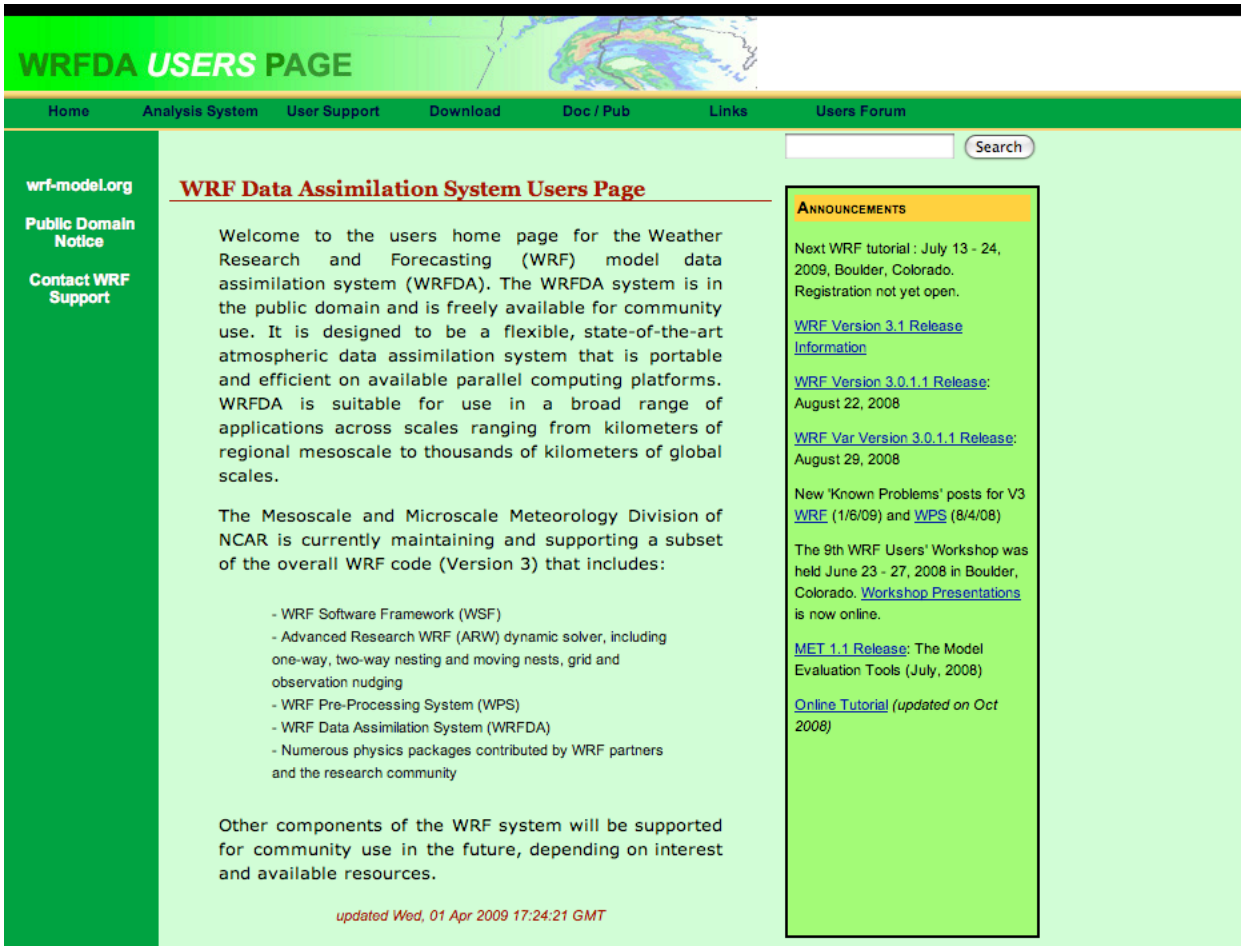


- **da_metar.f90 contains a Fortran module**
- **Each .inc file corresponds to a subroutine within the module**



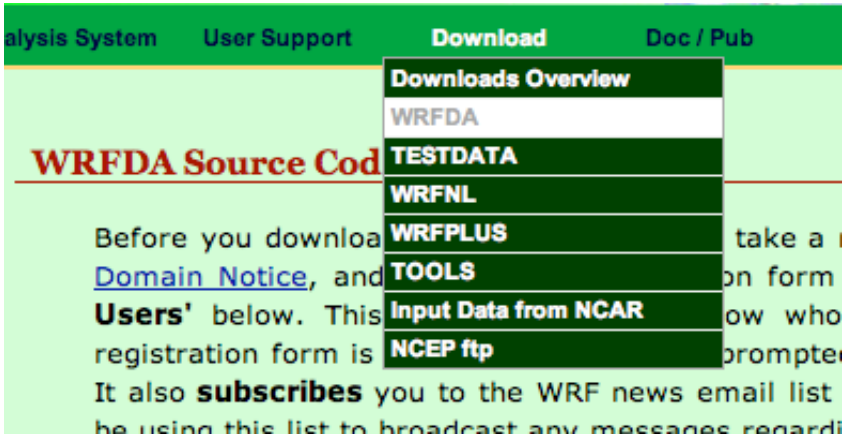
Online WRFDA Resources

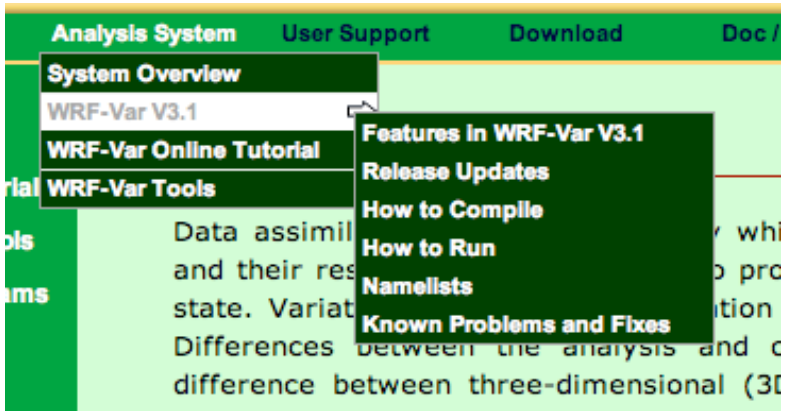
WRFDA has a dedicated page, similar to the ARW Users' page:
http://www.mmm.ucar.edu/wrf/users/wrfda/



Online WRFDA Resources

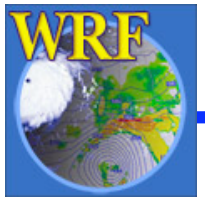
From the WRFDA page, one can access:





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?