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Mesoscale & Microscale Meteorology @ NCAR

WRF Variational Data Assimilation System (WRF-Var) Overview

WRF Tutorial Presentation

NCAR, Boulder, Colorado: July 28th 2005

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Acknowledge:

NCAR/MMM Division Staff

USWRP, NSF-OPP, NCAR Data Assimilation Initiative

US Air Force Weather Agency, Korean Meteorological Administration,

Taiwanese Central Weather Bureau, Civil Aeronautics Administration,

Outline of Talk

1. What is WRF-Var?
2. Practical Variational Data Assimilation.
3. The WRF-Var Algorithm.
4. Background Error Modeling.
5. Observational Issues.
6. Current Status and Future Plans.

1. What is WRF-Var?

…WRF-Var is a **unified** variational data assimilation system built within the software framework of the Weather Research and Forecasting (WRF) model, used for application in both research and operational environments….

What Do We Mean By "Unified"

•Regional (worldwide applicability) / global.

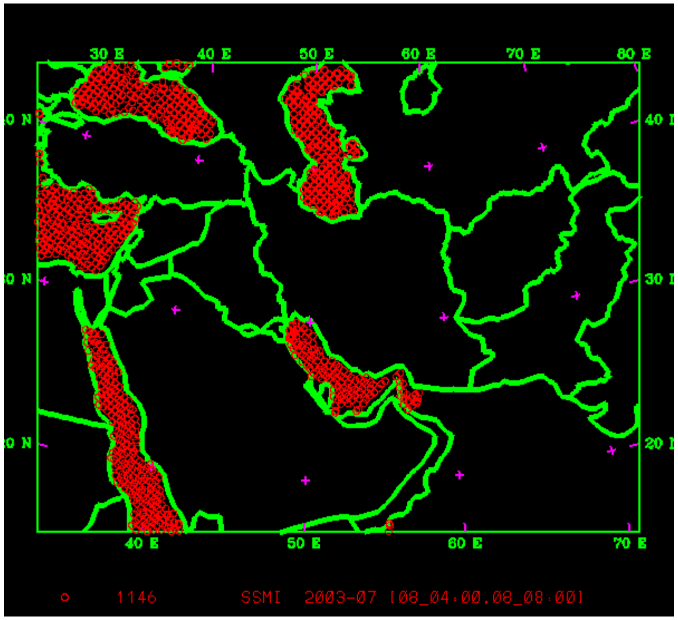
•Run-time configurable 3/4D-Var.

•Single code (WRF-Var) for development, release. Supported by NCAR/MMM.

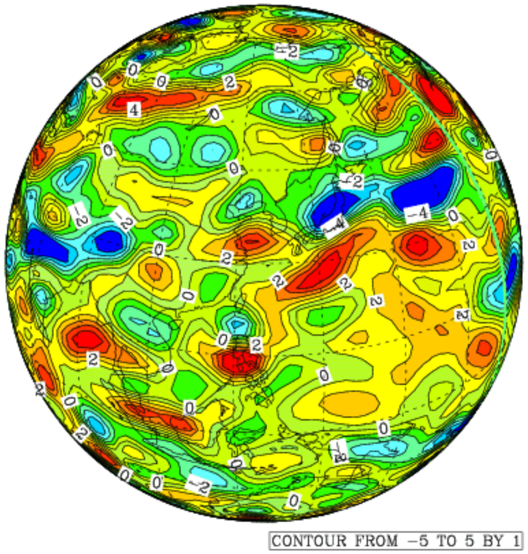
•Embedded within WRF framework.

•Multi-model: WRF/MM5/KMA/NFS/…

AFWA 15km S-W Asia:

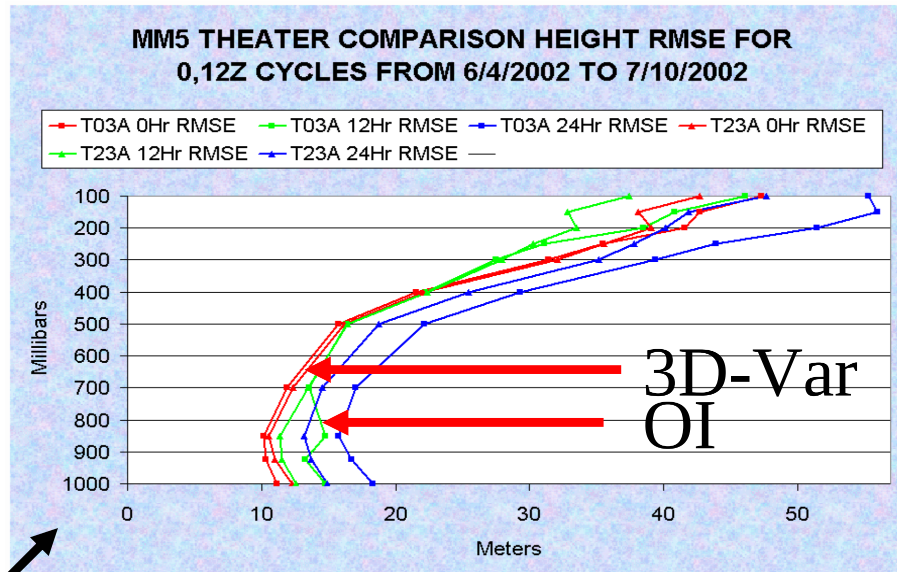


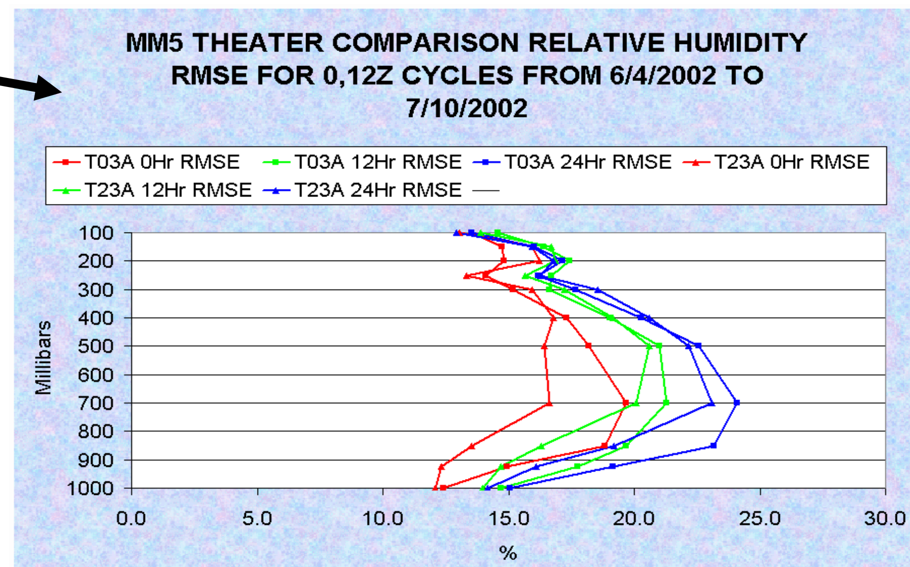
KMA T213 Global:



WRF Variational Data Assimilation (WRF-Var) History

- **Late 1999:** Begin development of MM5 3D-Var.
- **June 2001:** MM5-3DVar adopted as starting point for WRF 3D-Var.
- **May 2002:** MM5/WRF 3D-Var operational at Taiwanese CAA.
- **September 2002:** MM5/WRF 3D-Var operational in 45km domains at AFWA.
- **June 2003:** WRF 3D-Var V1.0 release.
- **May 2004:** WRF 3D-Var V2.0 release.
- **July 2005:** WRF-Var V2.1 release.





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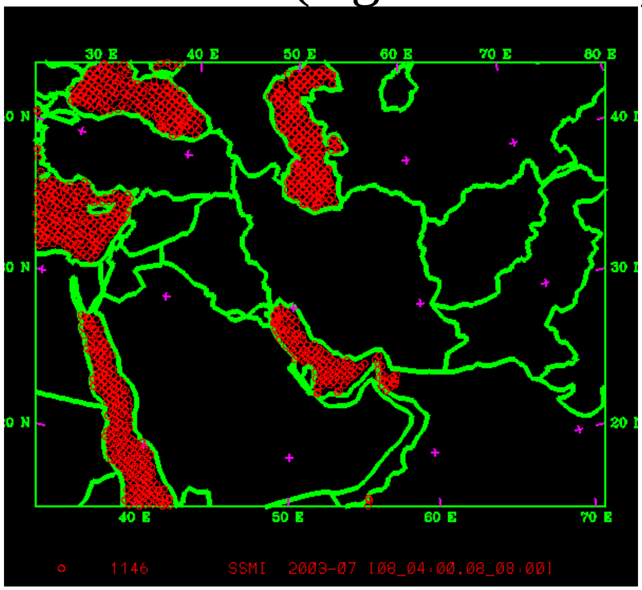
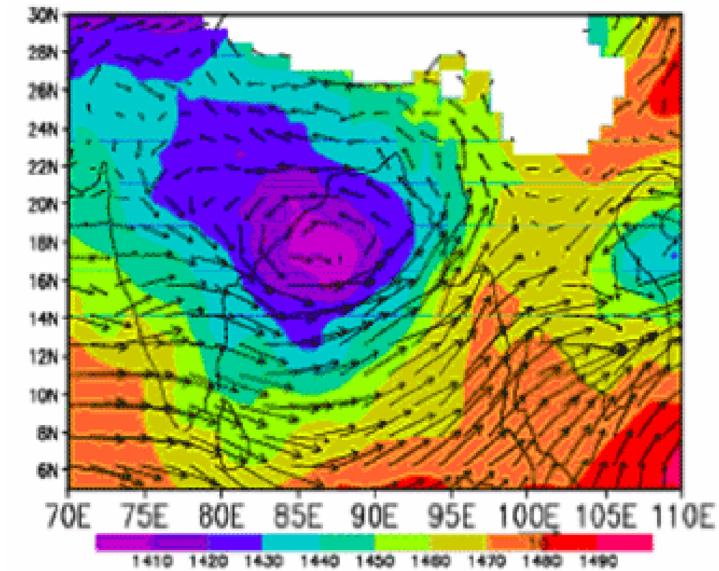
WRF-Var Operational Applications: June 2005

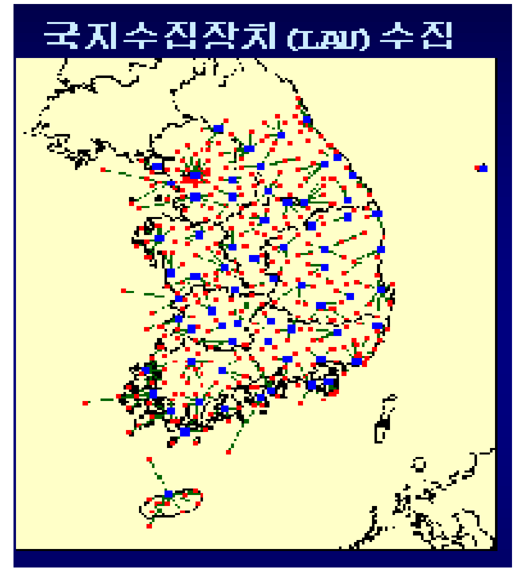
AFWA 15km (e.g. S-W Asia):



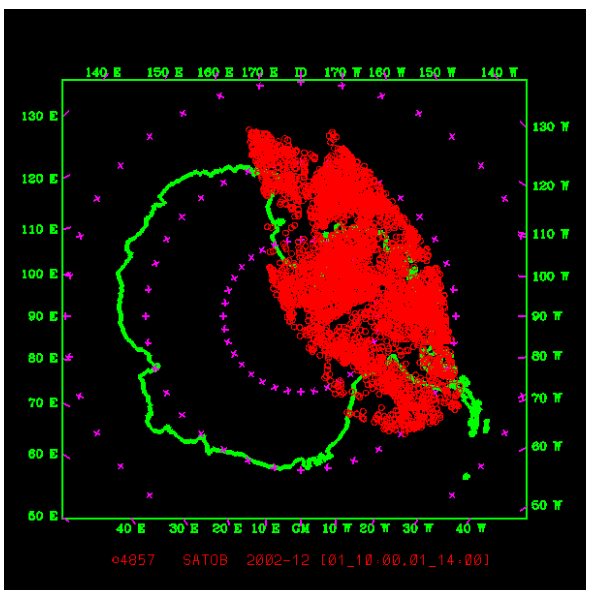
Indian NCMRWF 30km:



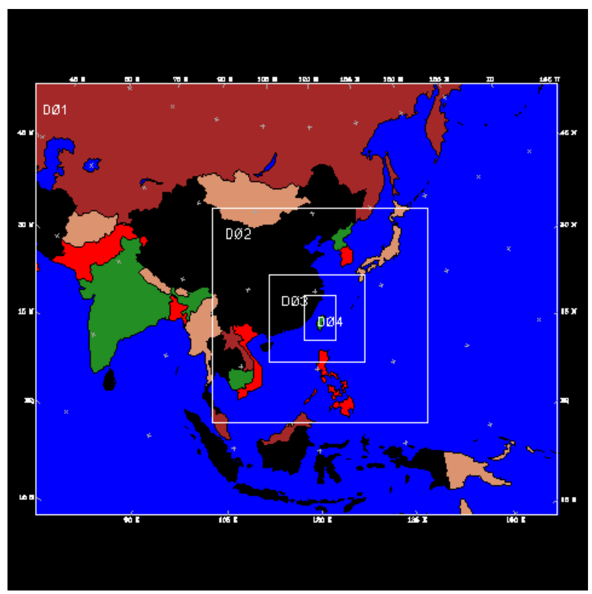
Korean 10km:



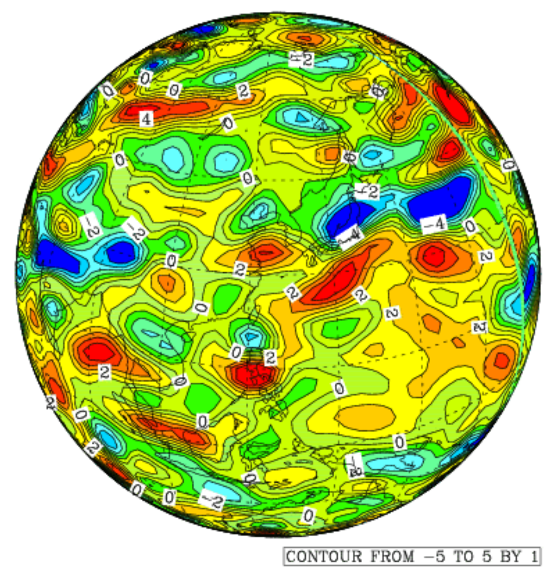
AMPS 30km:



Taiwanese CAA 135/45/15km:



Korean T213/T426:



2. Practical Variational Data Assimilation

Data Assimilation Overview 1

- Assimilation system combines all sources of information:
  - Observations - y^o
  - Background field - x^b
  - Estimate of observation/background errors.
  - Laws of physics.
- Output of the assimilation system is the “analysis”.
- Analysis used in a number of ways:
  - Initial conditions for numerical forecasts.
  - Climatology - reanalyses.
  - Observing system justification (e.g. OSEs, OSSEs).

Data Assimilation Overview 2

There are never enough good observations!!

- Consider NWP model:
  - Typical global model – 425 * 325 * 50 = 6.9 million gridpoints.
  - Minimum number of prognostic variables = 6 *(u, v, w, T, p, q).*
  - Number of degrees of freedom = 41.4 million.

- Typical number of observations = few x 10^6 but:
  - Inhomogeneous distribution of data.
  - Observations not always in sensitive areas.
  - Observations have errors.

- Solutions:
  - Use sophisticated (variational/ensemble) techniques (can use "exotic" obs).
  - Use previous forecast to propagate obs. info from previous times.
  - Use approximate physical balance relationships.
  - More/better observations!

Alternative Formulations of Advanced DA

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

- Minimization implies gradient of cost function is zero. Leads to **information** or **analysis space** formulation (applied in ECMWF, Met. Office, HIRLAM, etc…):

$$\mathbf{x}^a - \mathbf{x}^b = \left[\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H} + \mathbf{P_b}^{-1}\right]^{-1}\mathbf{H}^T\mathbf{R}^{-1}\left[\mathbf{y}-H(\mathbf{x}^b)\right]$$

- Alternatively, application of the "Sherman-Morrison-Woodbury" formula leads to the **error** or **observation** space formulation (NAVDAS, PSAS):

$$\mathbf{x}^a - \mathbf{x}^b = \mathbf{P_b}\mathbf{H}^T\left[\mathbf{H}\mathbf{P_b}\mathbf{H}^T + \mathbf{R}^{-1}\right]^{-1}\left[\mathbf{y}-H(\mathbf{x}^b)\right]$$

- Both can be written in terms of a "Kalman Gain" **K**

$$\mathbf{x}^a - \mathbf{x}^b = \mathbf{K}\left[\mathbf{y}-H(\mathbf{x}^b)\right]$$

Good reference: NAVDAS Source Book (Daley and Barker, 2001, NRL)

Variational Data Assimilation

- **Variational** analysis $\boldsymbol{x}^{\boldsymbol{a}}$ is minimum $\boldsymbol{x}$ of cost-function J = -ln ($P(\boldsymbol{x})$)
- Assume error probability $P(\boldsymbol{x})$ is Gaussian then

$$J(\mathbf{x}) = J_{\mathbf{b}} + J_o = \frac{1}{2}\left[\mathbf{x} - \mathbf{x}^b\right]^T \mathbf{P}_{\mathbf{b}}^{-1}\left[\mathbf{x} - \mathbf{x}^b\right] + \frac{1}{2}\left[\boldsymbol{y} - H(\mathbf{x})\right]^T \mathbf{R}^{-1}\left[\boldsymbol{y} - H(\mathbf{x})\right]$$

- $\boldsymbol{x}^{\boldsymbol{b}}$ is the *background*. H is the (possibly nonlinear) *observation operator*.
- ***Error covariances:***

  $\mathbf{P_b}$ = Background (previous forecast) error covariance matrix.
  $\mathbf{R}$ = Observation error covariance matrix (includes instrumental and representiveness error).

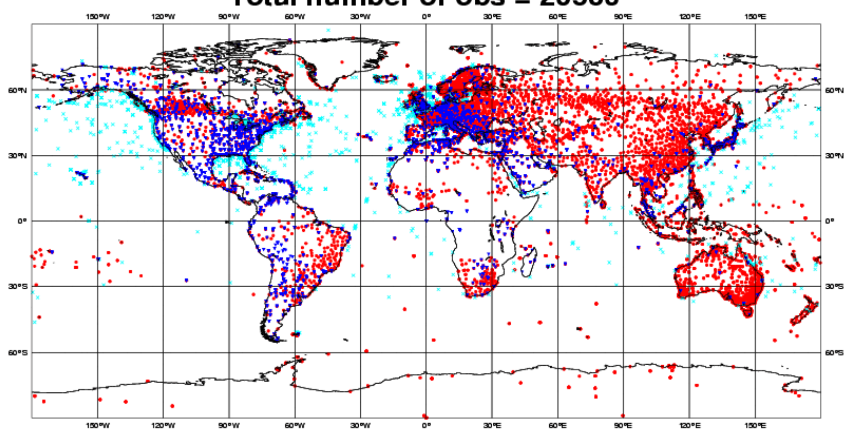
- Practical implementation requires numerous assumptions and approximations……consider first the observations…..

ECMWF Global Observations 1

Obs Type

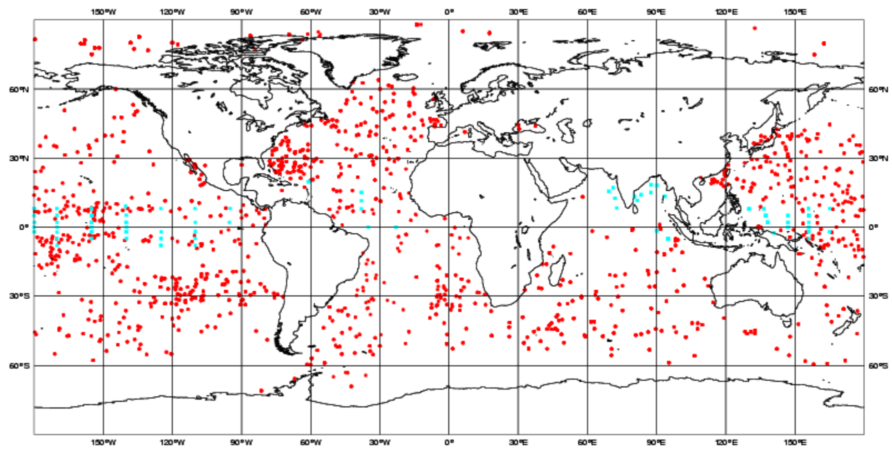
15161 SYNOP · 1940 SHIP · 9479 METAR

ECMWF Data Coverage (All obs) - SYNOP/SHIP
25/JUL/2005; 00 UTC
Total number of obs = 26580



Obs Type

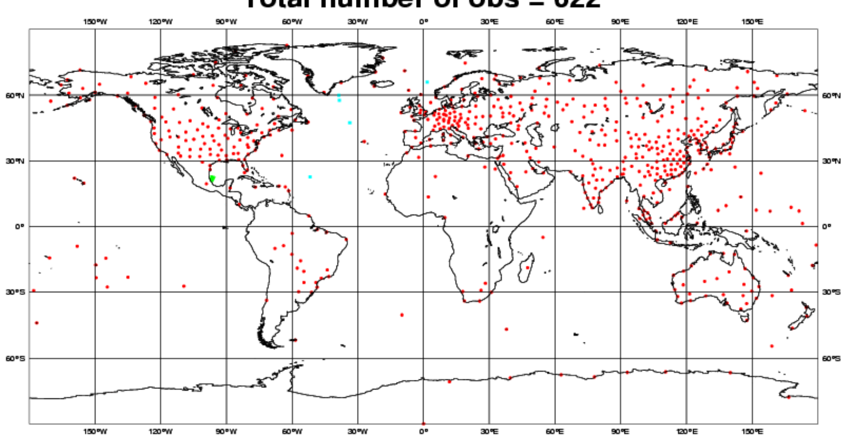
ECMWF Data Coverage (All obs) - BUOY
25/JUL/2005; 00 UTC
Total number of obs = 4095



Obs Type

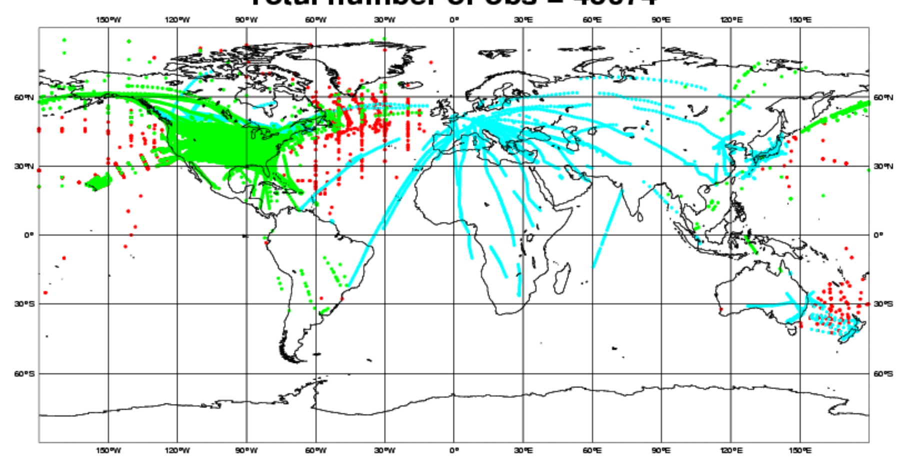
608 LAND · 5 SHIP · 9 DROPSONDE

ECMWF Data Coverage (All obs) - TEMP
25/JUL/2005; 00 UTC
Total number of obs = 622



Obs Type

ECMWF Data Coverage (All obs) - AIRCRAFT
25/JUL/2005; 00 UTC
Total number of obs = 45074

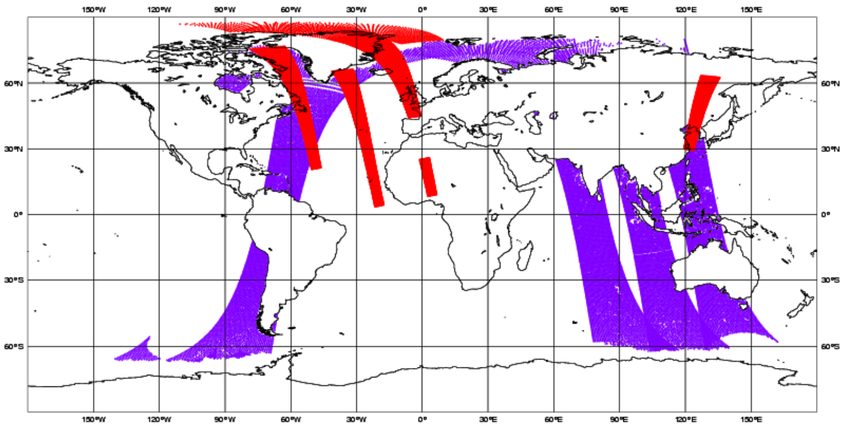


ECMWF Global Observations 2

Obs Type

26336 SCAT 25270 ERS-2

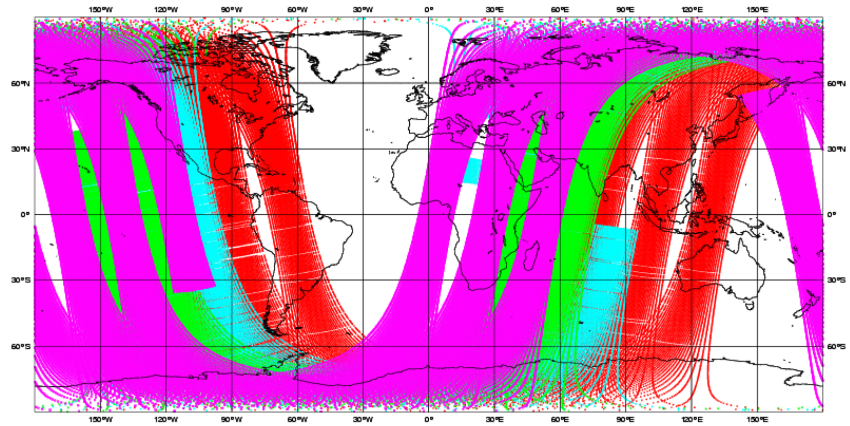
ECMWF Data Coverage (All obs) - SCAT
25/JUL/2005; 00 UTC
Total number of obs = 51606



Obs Type

81790 N15-AMSUA 83065 N16-AMSUA 0 N17-AMSUA
41837 N18-AMSUA 72450 AQUA-AMSU

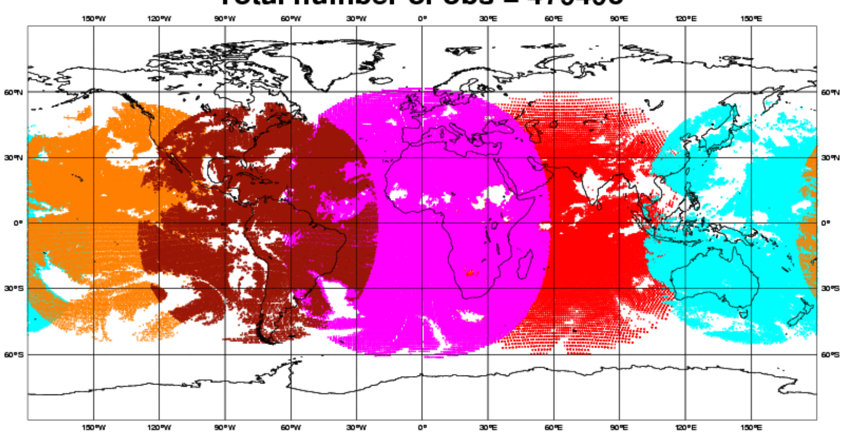
ECMWF Data Coverage (All obs) - ATOVS
25/JUL/2005; 00 UTC
Total number of obs = 279142



Obs Type

73379 MET5 171623 MET8 95147 GOES9 78684 GOES10
60662 GOES12

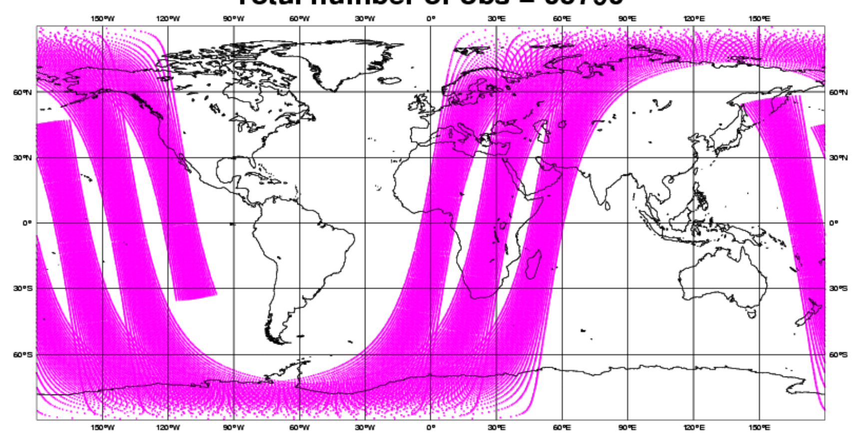
ECMWF Data Coverage (All obs) - GRAD
25/JUL/2005; 00 UTC
Total number of obs = 479495



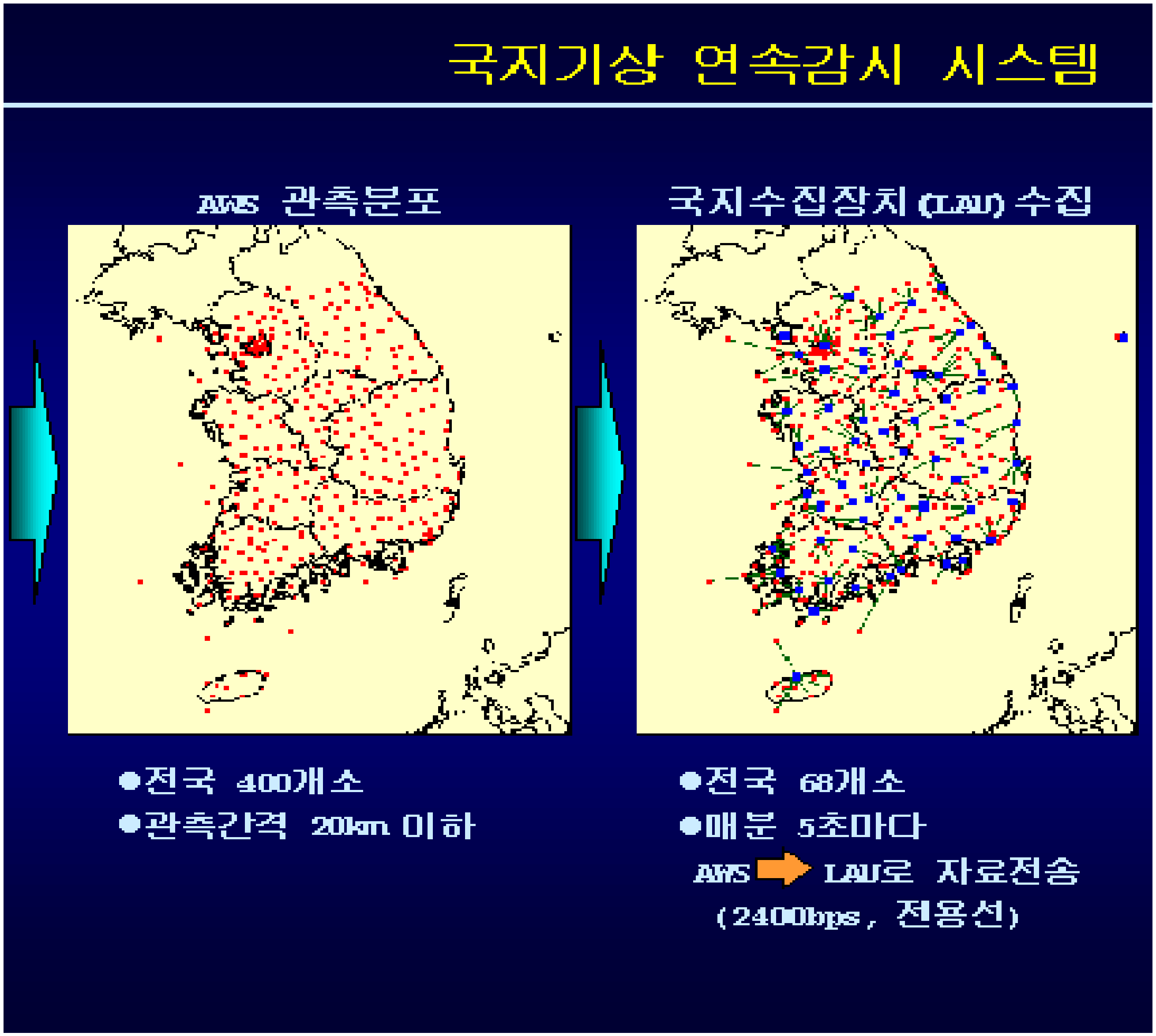
Obs Type

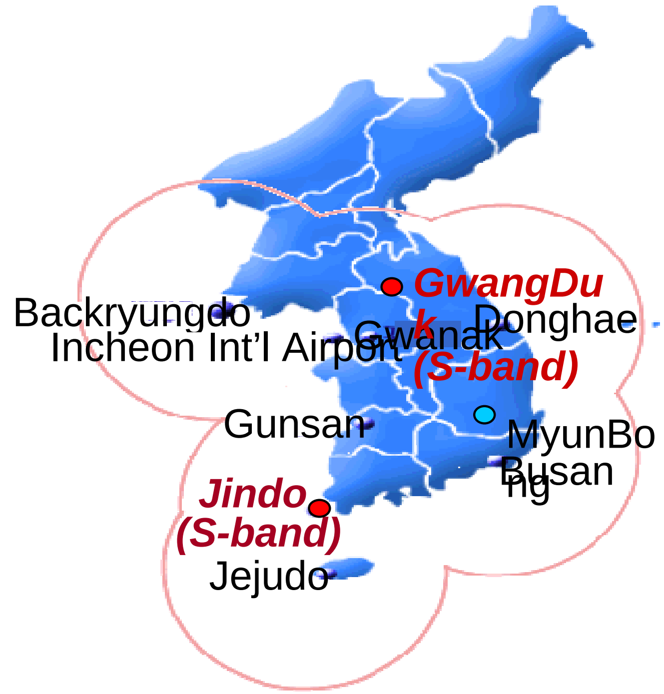
0 TERRA 68796 AQUA

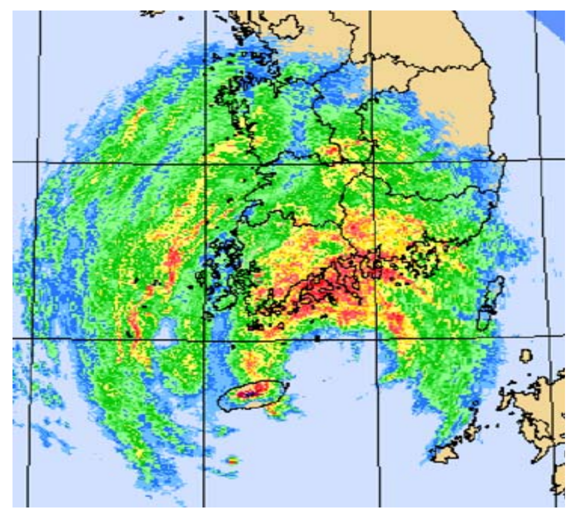
ECMWF Data Coverage (All obs) - AIRS
25/JUL/2005; 00 UTC
Total number of obs = 68796



Korean AWS/Radar Observations







Observation Cost Function (Jo) Implementation

$$J(\mathbf{x}) = J_{\mathbf{b}} + J_o = \frac{1}{2}\left[\mathbf{x} - \mathbf{x}^b\right]^T \mathbf{P}_{\mathbf{b}}^{-1}\left[\mathbf{x} - \mathbf{x}^b\right] + \frac{1}{2}\left[\mathbf{y} - H(\mathbf{x})\right]^T \mathbf{R}^{-1}\left[\mathbf{y} - H(\mathbf{x})\right]$$

- Observation error correlations increase computational cost of second term (also hard to determine), so…

- Assume observation errors uncorrelated (specified by std. dev. σ_o^2):

$$J(\mathbf{x}) = \frac{1}{2}\left[\mathbf{x} - \mathbf{x}^b\right]^T \mathbf{P}_{\mathbf{b}}^{-1}\left[\mathbf{x} - \mathbf{x}^b\right] + \frac{1}{2}\sum_n \left[\mathbf{y} - H(\mathbf{x})\right]_n^2 / \sigma_{on}^2$$

- Assumption motivates move towards assimilation of "raw" observations e.g. radiances, rather than retrievals.

- Use of "super observations" makes assumption better (and reduces cost still further).

Background Cost Function (Jb) Implementation

$$J(\mathbf{x})=\frac{1}{2}\left[\mathbf{x}-\mathbf{x}^{b}\right]^{T}\mathbf{P_b}^{-1}\left[\mathbf{x}-\mathbf{x}^{b}\right]+\frac{1}{2}\sum_{n}\left[\mathbf{y}-H(\mathbf{x})\right]_{n}^{2}/\sigma_{on}^{2}$$

The Incremental formulation:

- *Define* ***analysis increments:*** $x^a = x^b + I\,x'$

- *Solve* ***incremental*** cost function:

$$J(\mathbf{x})=\frac{1}{2}x'^{T}\mathbf{P_b}^{-1}\mathbf{x}'+\frac{1}{2}\sum_{n}\left[\mathbf{d}-\mathbf{y}'\right]_{n}^{2}/\sigma_{on}^{2}$$

where $y' = \mathbf{H}x'$, $\mathbf{d}=\mathbf{y}-H(\mathbf{x}^{b})$

Incremental WRF-Var Preconditioning

$$J(\mathbf{x}) = \frac{1}{2} x'^T \mathbf{P_b}^{-1} \mathbf{x}' + \frac{1}{2} \sum_n [\mathbf{d} - \mathbf{y}']_n^2 / \sigma_{on}^2$$

- *Define **preconditioned control variable*** $\mathbf{v}$ space transform $\mathbf{x}'=\mathrm{U}\mathbf{v}$ where U transform CAREFULLY chosen to satisfy $\mathbf{P_b} = \mathrm{UU}^T$.

- Choose (at least assume) control variable components with uncorrelated errors:

$$J(\mathbf{x}) = \frac{1}{2} \sum_i v_i^2 + \frac{1}{2} \sum_n [\mathbf{d} - \mathbf{y}']_n^2 / \sigma_{on}^2$$

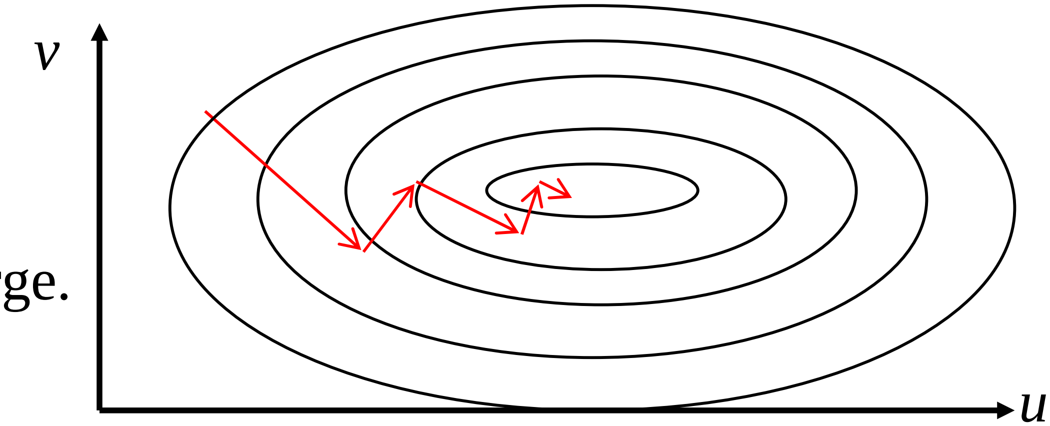
- where

  i~number pieces of independent information.
  n~number of thinned, quality controlled observations.

Minimization Basics

$$J = u^2/a^2 + v^2/b^2$$

- Suppose want to minimize J by iteration:

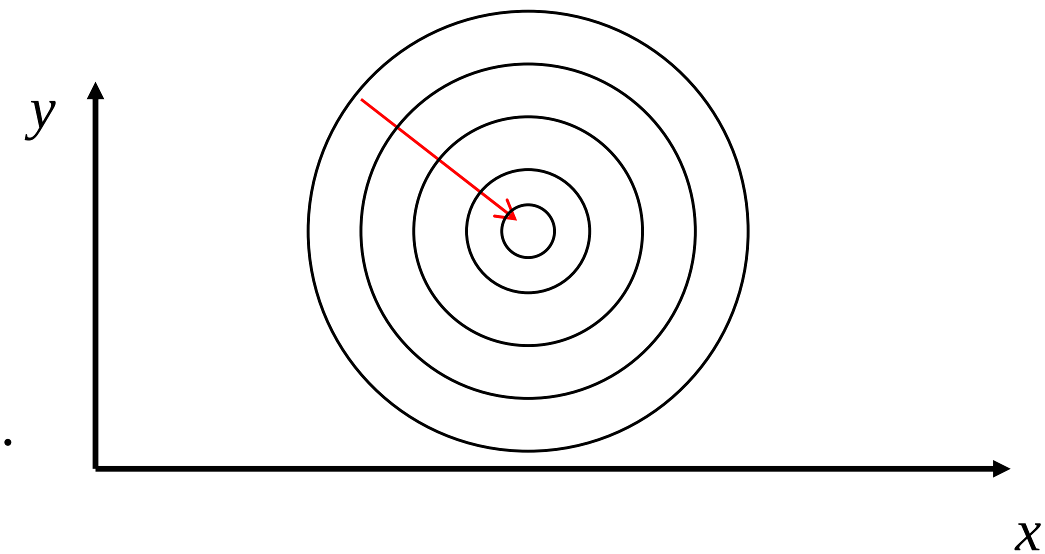


Steepest descent: many interations to converge.

- Write transformation

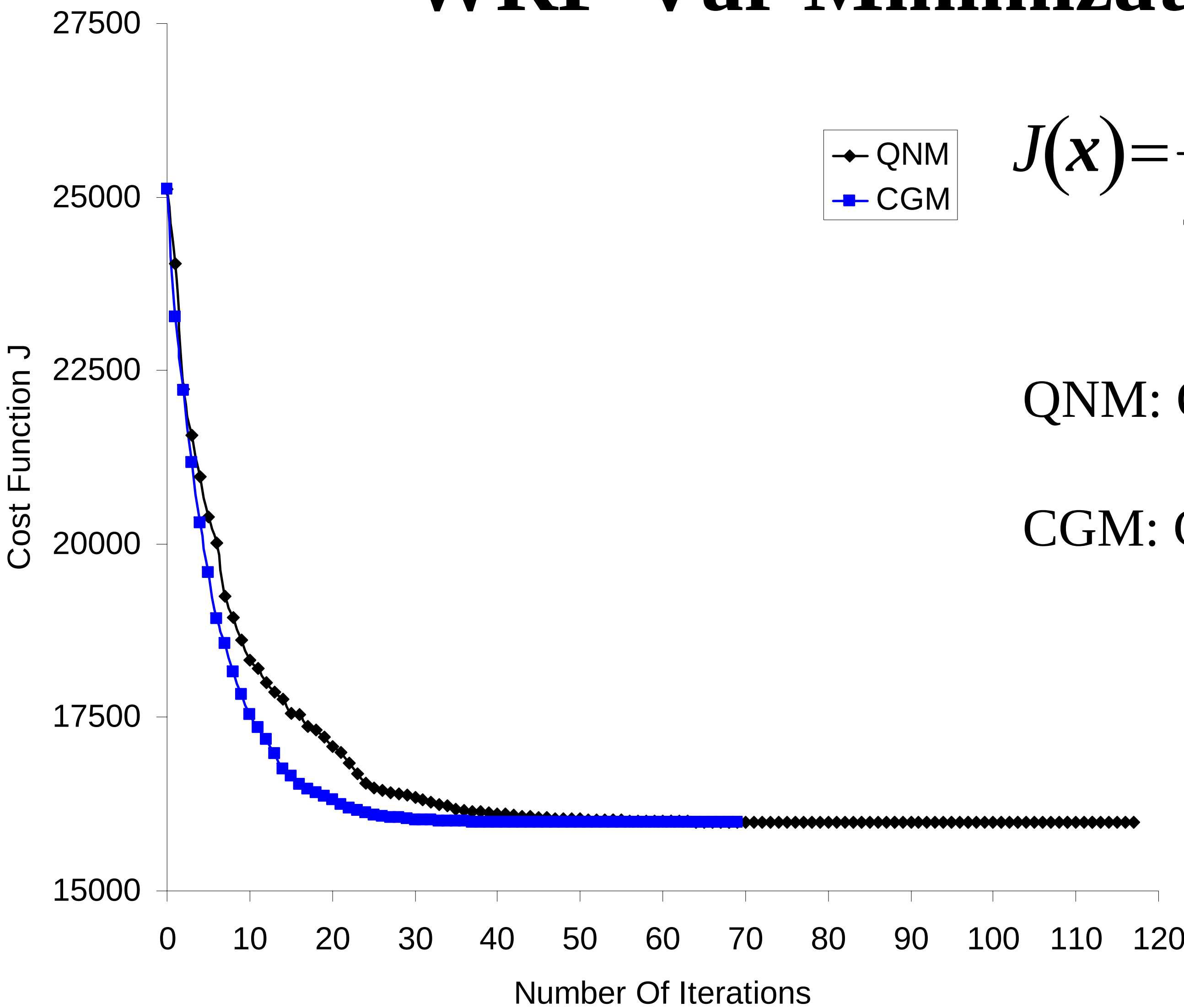
$$(x, y) = (u/a, v/b), \qquad J = x^2 + y^2$$

Steepest descent: one iteration to convergence.



In VAR, precondition and use e.g. Quasi-Newton, Conjugate Gradient methods.

WRF-Var Minimization Example



$$J(\boldsymbol{x}) = \frac{1}{2}\sum_i v_i^2 + \frac{1}{2}\sum_n [\boldsymbol{d} - \boldsymbol{y}']_n^2 / \sigma_{on}^2$$

QNM: Quasi-Newton Method.

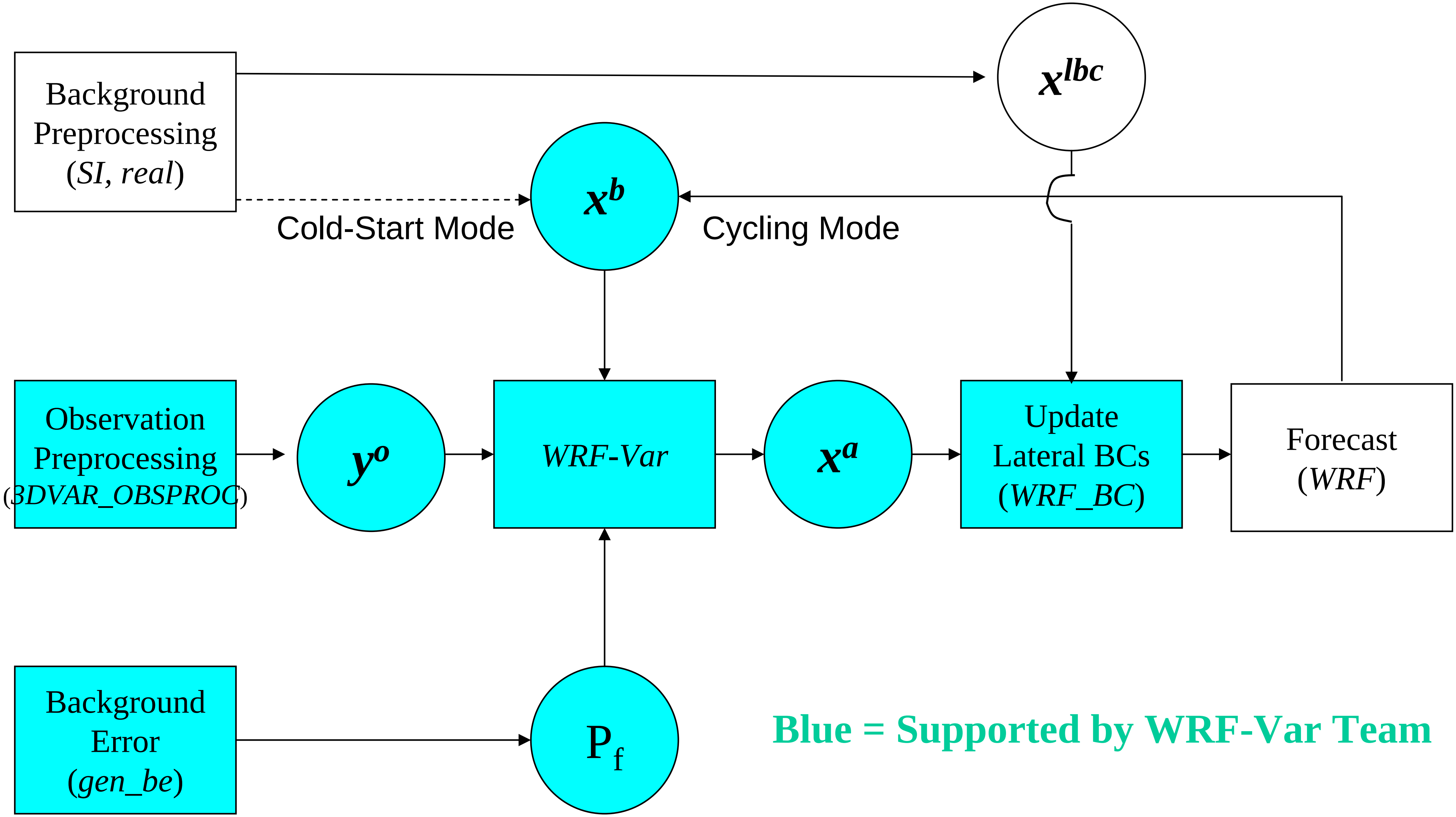
CGM: Conjugate Gradient Method.

Convergence obtained when gradient < 0.001starting gradient.

Here, CGM -> ~40% reduction in 3DVAR run-time.

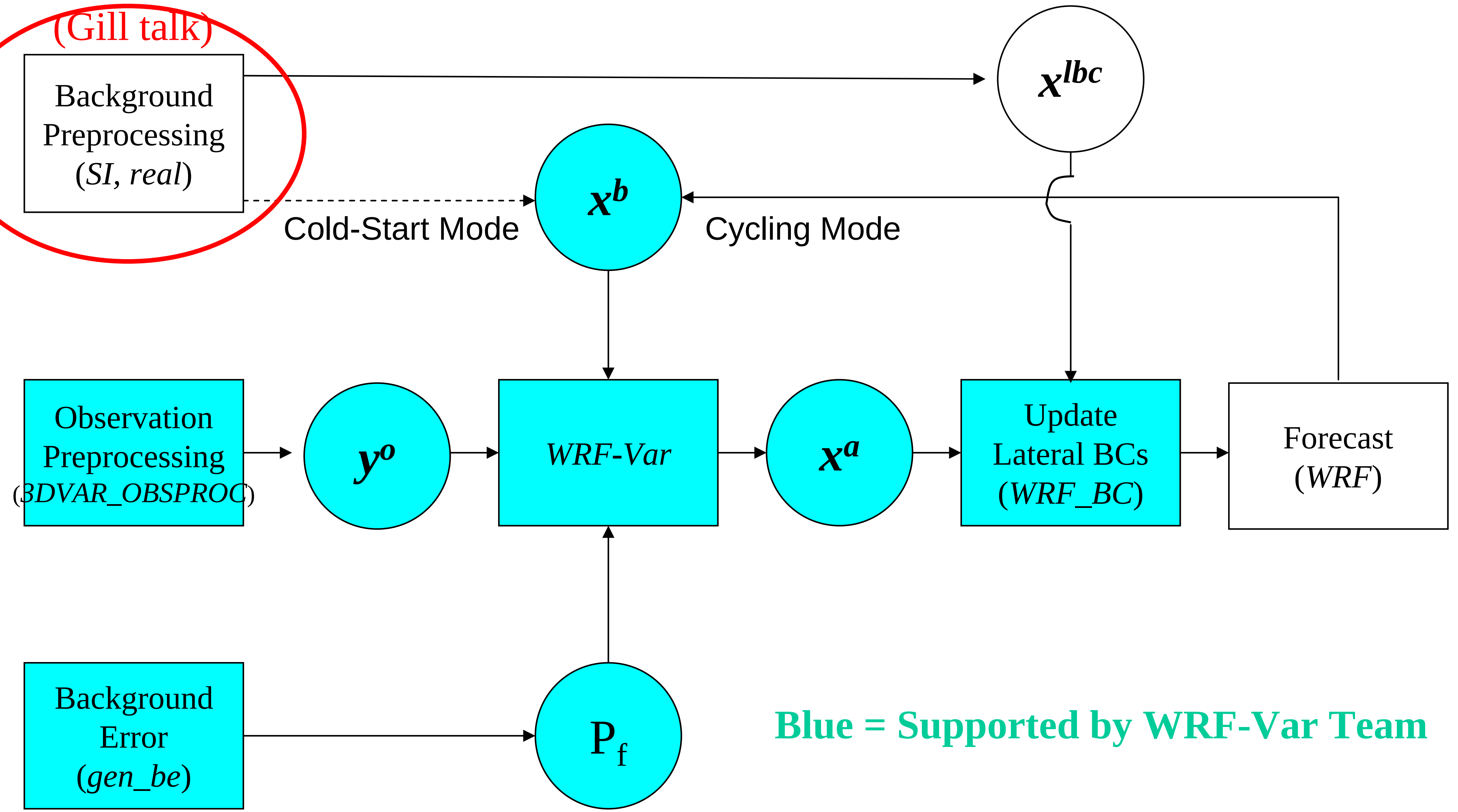
3. The WRF-Var Algorithm

WRF-Var in the WRF Modeling System

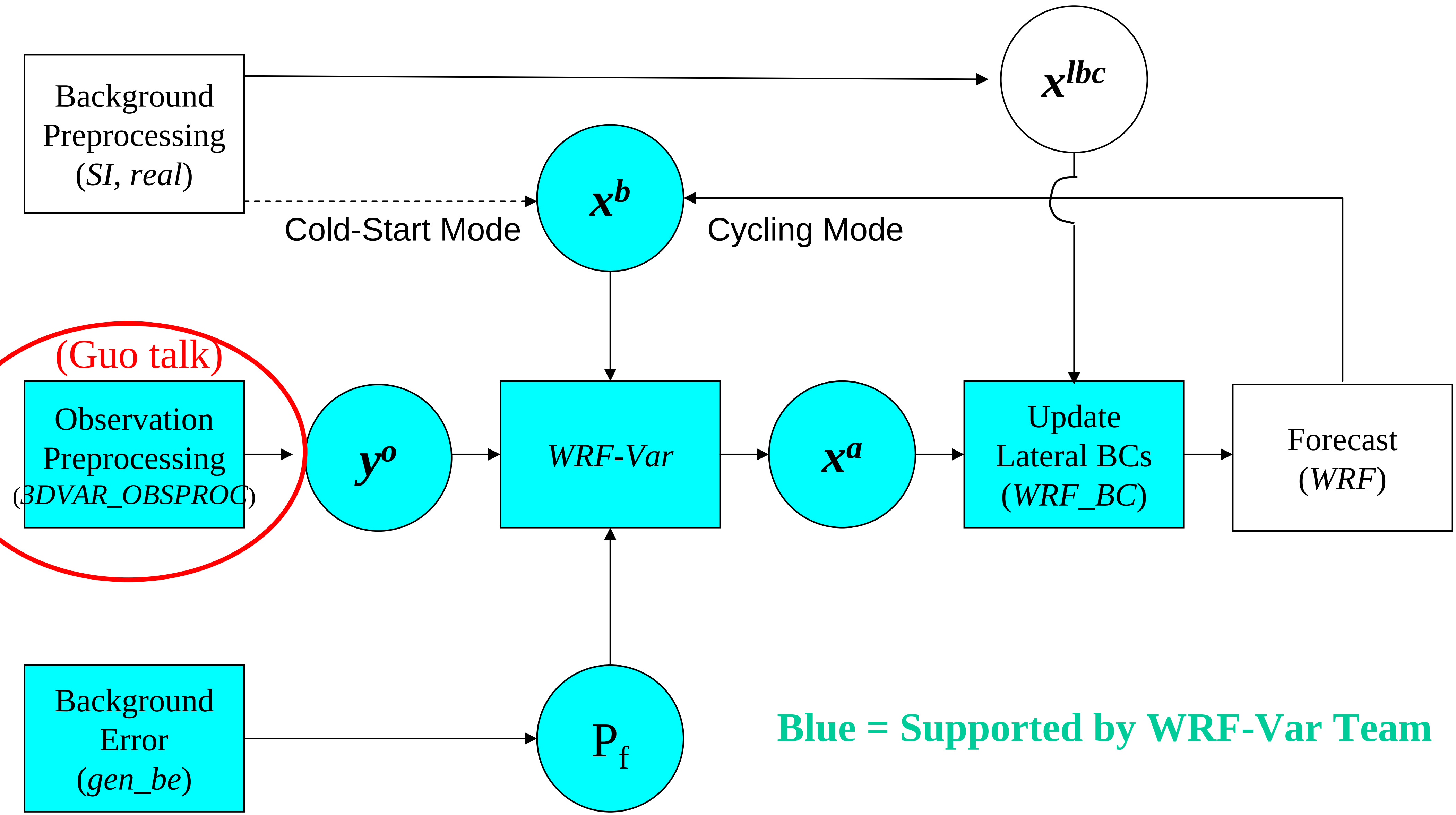


Blue = Supported by WRF-Var Team

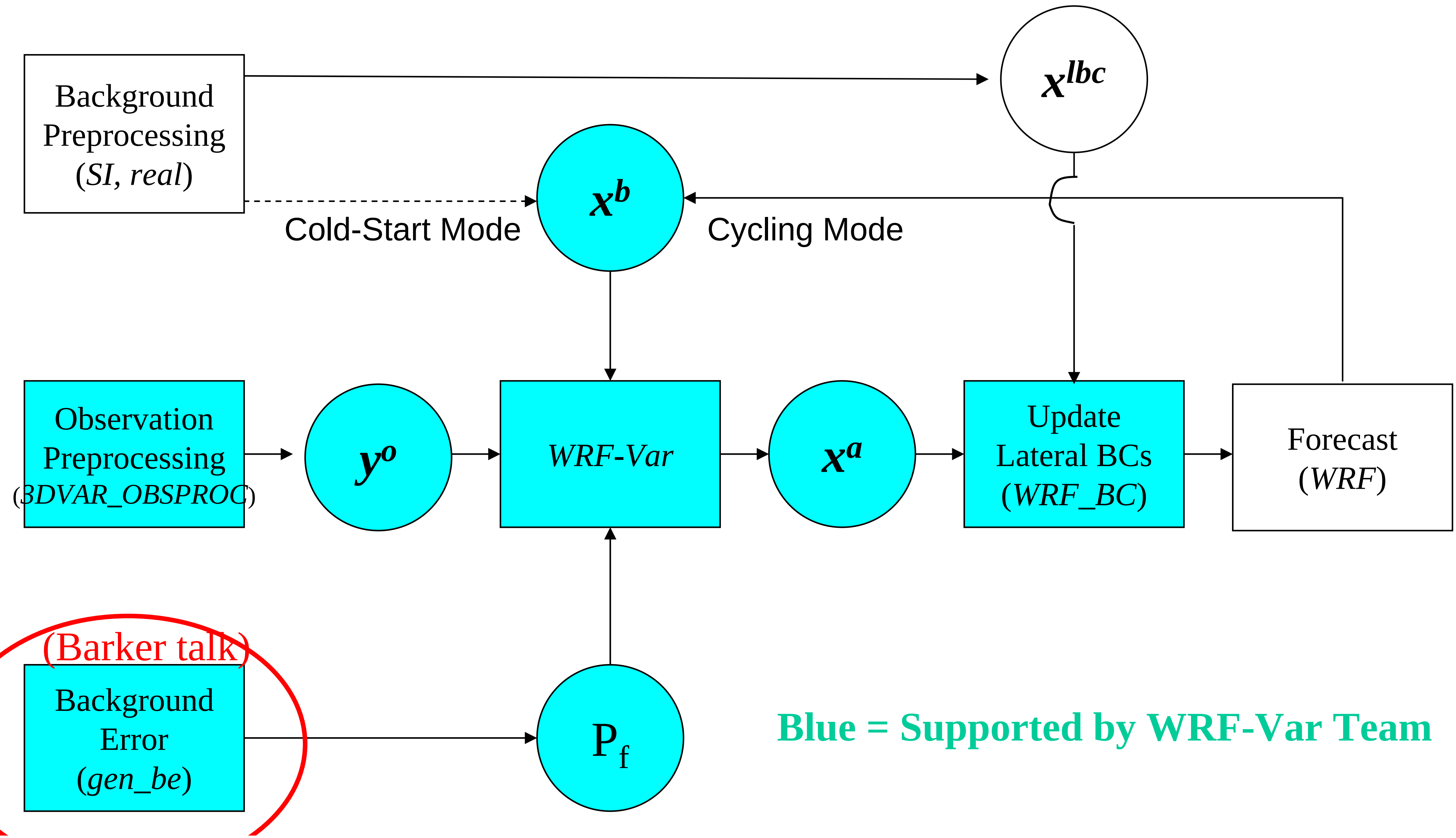
WRF-Var in the WRF Modeling System



WRF-Var in the WRF Modeling System



WRF-Var in the WRF Modeling System



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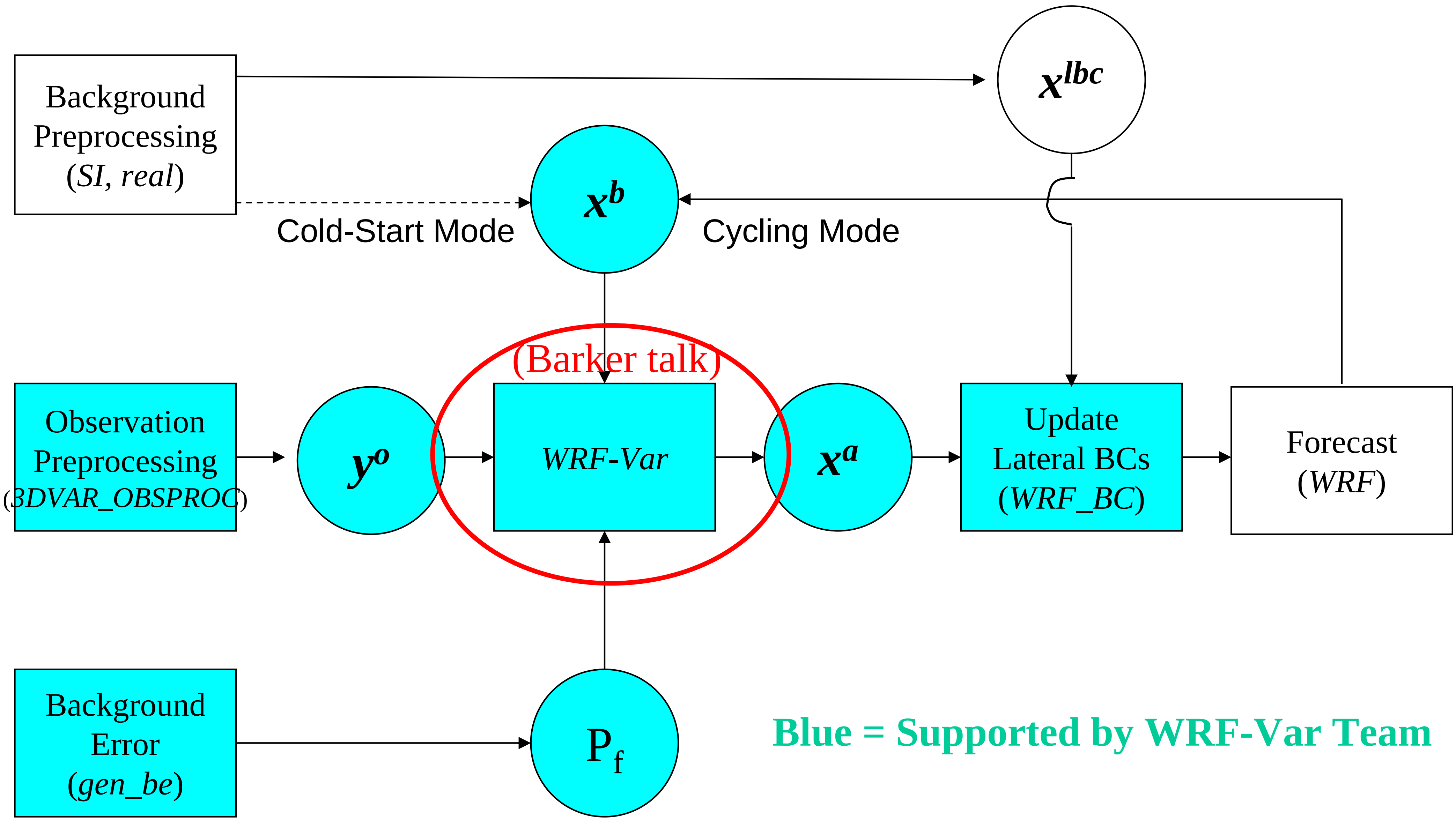
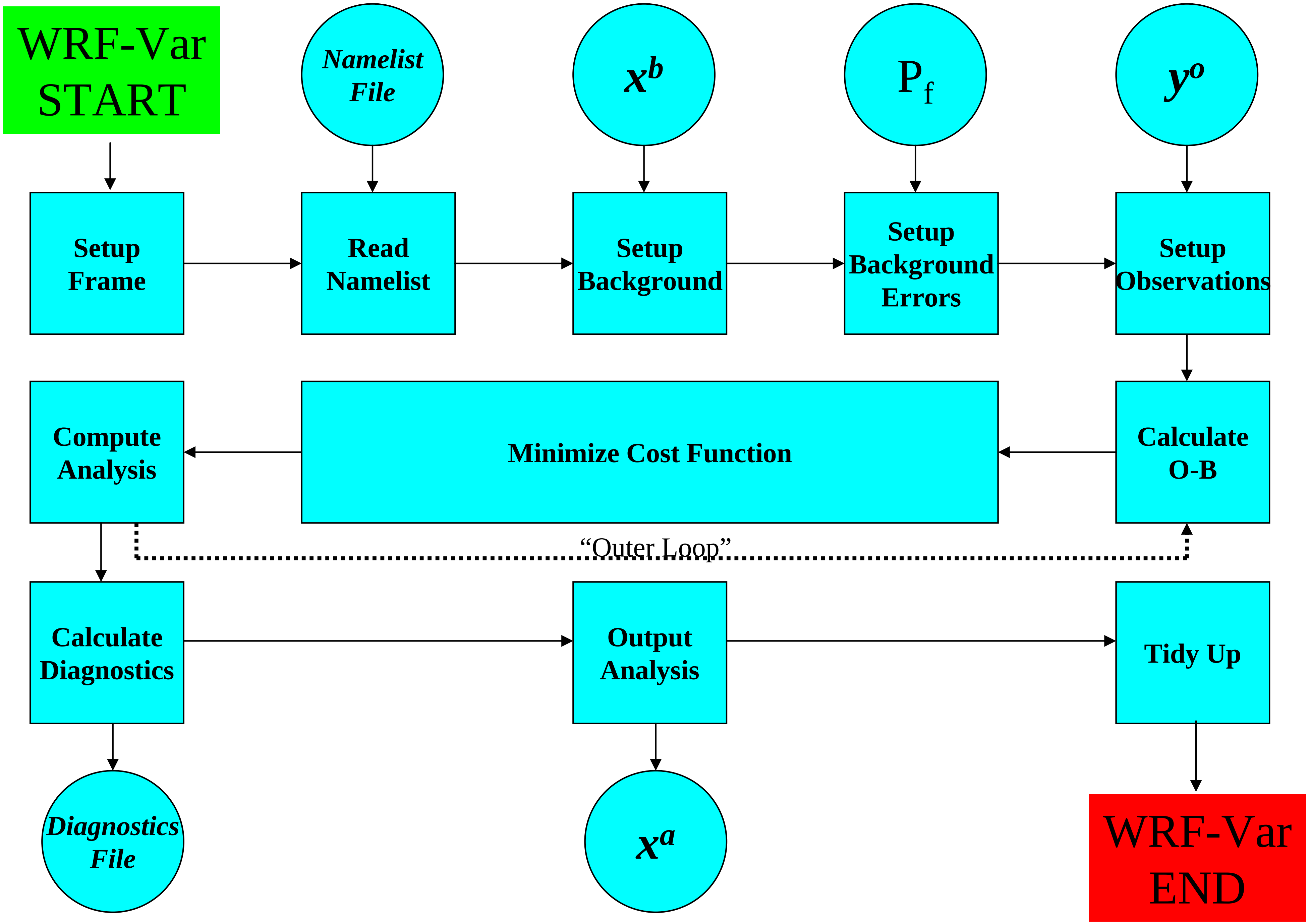
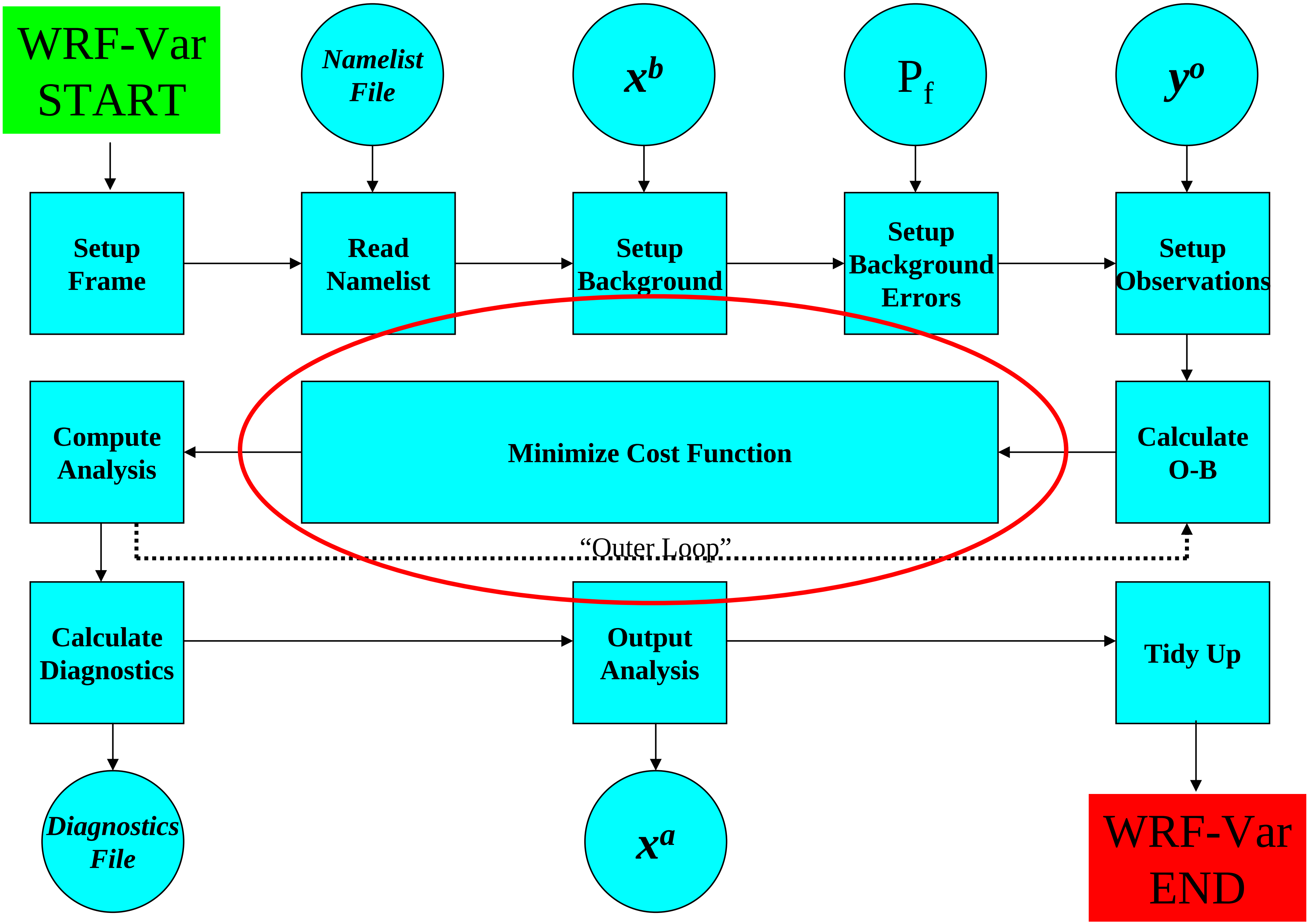
WRF-Var in the WRF Modeling System



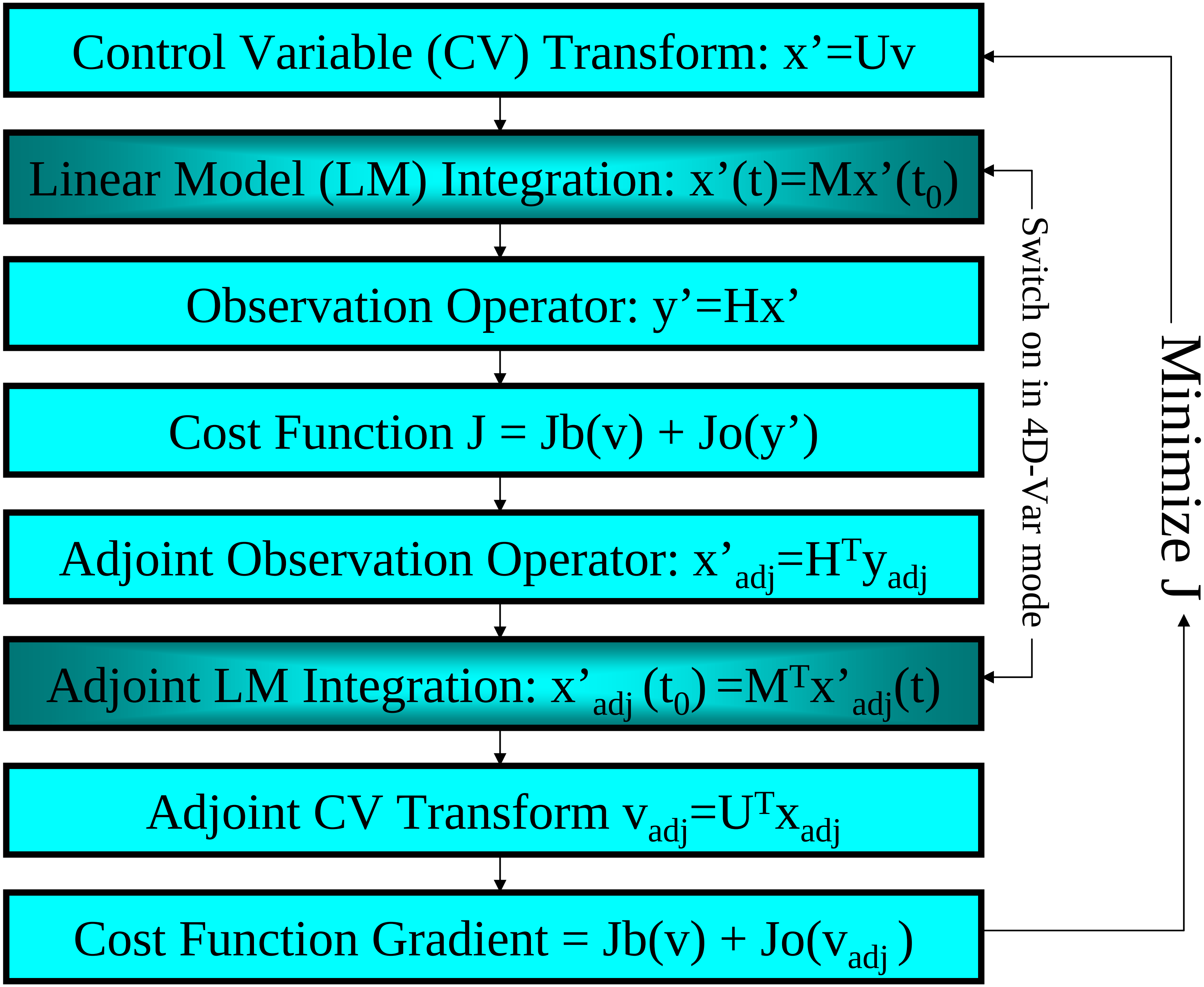
WRF-Var


WRF-Var START
Namelist File
x^b
P_f
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

WRF-Var


WRF-Var START
Namelist File
x^b
P_f
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

WRF-Var “Inner Loop”

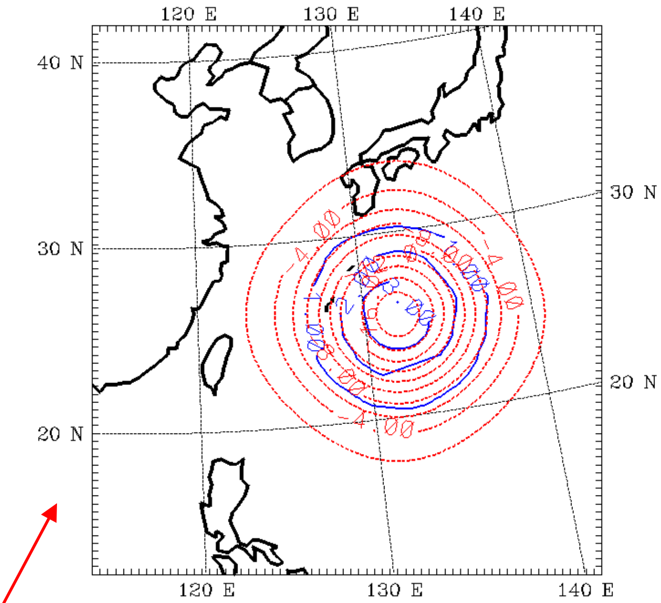


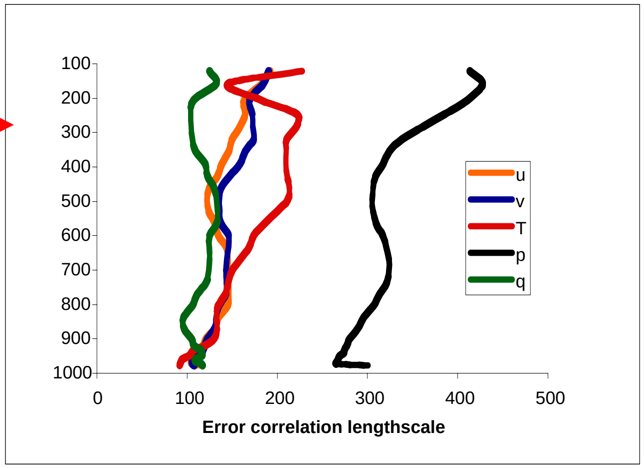
4. Background Error Modelling

WRF-Var Control Variable Transform

$$\mathbf{x}' = U\mathbf{v} = U_p U_v U_h \mathbf{v}$$

cv_options		2 (original MM5)	3(GSI)	4 (Global)	5(regional)
Analysis increments	x'	$u', v', T', q', p_s'(i,j,k)$			
Change of Variable	U_p	$\psi', \chi', p_u', q'(i,j,k)$	$\psi', \chi_u', T_u', \tilde{r}', p_{su}'(i,j,k)$		
Vertical Covariances	U_v	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^T$	RF	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^T$	
Horizontal Correlations	U_h	RF		Spectral	RF
Control Variables	v	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

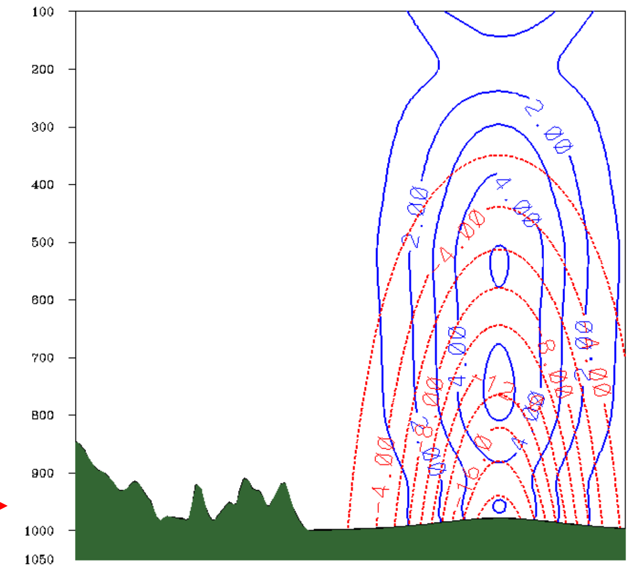


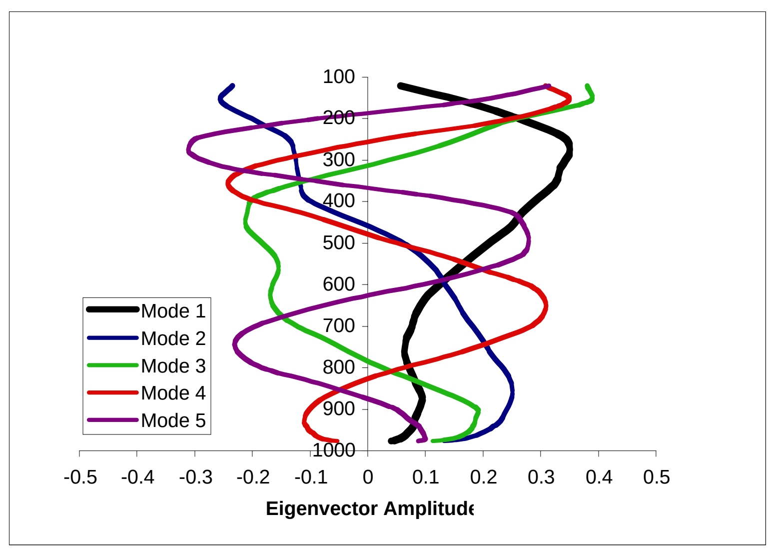


WRF-Var Control Variable Transform

cv_options		2 (original MM5)	3(GSI)	4 (Global)	5(regional)
Analysis increments	x'	$u',v',T',q',p_s'(i,j,k)$			
Change of Variable	U_p	$\psi',\chi',p_u',q'(i,j,k)$	$\psi',\chi_u',T_u',\tilde{r}',p_{su}'(i,j,k)$		
Vertical Covariances	U_v	$\mathbf{B}=\mathbf{E}\Lambda\mathbf{E}^T$	RF	$\mathbf{B}=\mathbf{E}\Lambda\mathbf{E}^T$	
Horizontal Correlations	U_h	RF		Spectral	RF
Control Variables	v	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

$$\boldsymbol{x}' = U\boldsymbol{v} = U_p U_v U_h \boldsymbol{v}$$





WRF-Var Control Variable Transform

$$\mathbf{x}' = U\mathbf{v} = U_p U_v U_h \mathbf{v}$$

cv_options		2 (original MM5)	3(GSI)	4 (Global)	5(regional)
Analysis increments	$\mathbf{x}'$	$u',v',T',q',p_s'(i,j,k)$			
Change of Variable	U_p	$\psi',\chi',p_u',q'(i,j,k)$	$\psi',\chi_u',T_u',\tilde{r}',p_{su}'(i,j,k)$		
Vertical Covariances	U_v	$\mathbf{B}=\mathbf{E}\Lambda\mathbf{E}^T$	RF	$\mathbf{B}=\mathbf{E}\Lambda\mathbf{E}^T$	
Horizontal Correlations	U_h	RF		Spectral	RF
Control Variables	$\mathbf{v}$	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

Define control variables:

$$\psi'$$

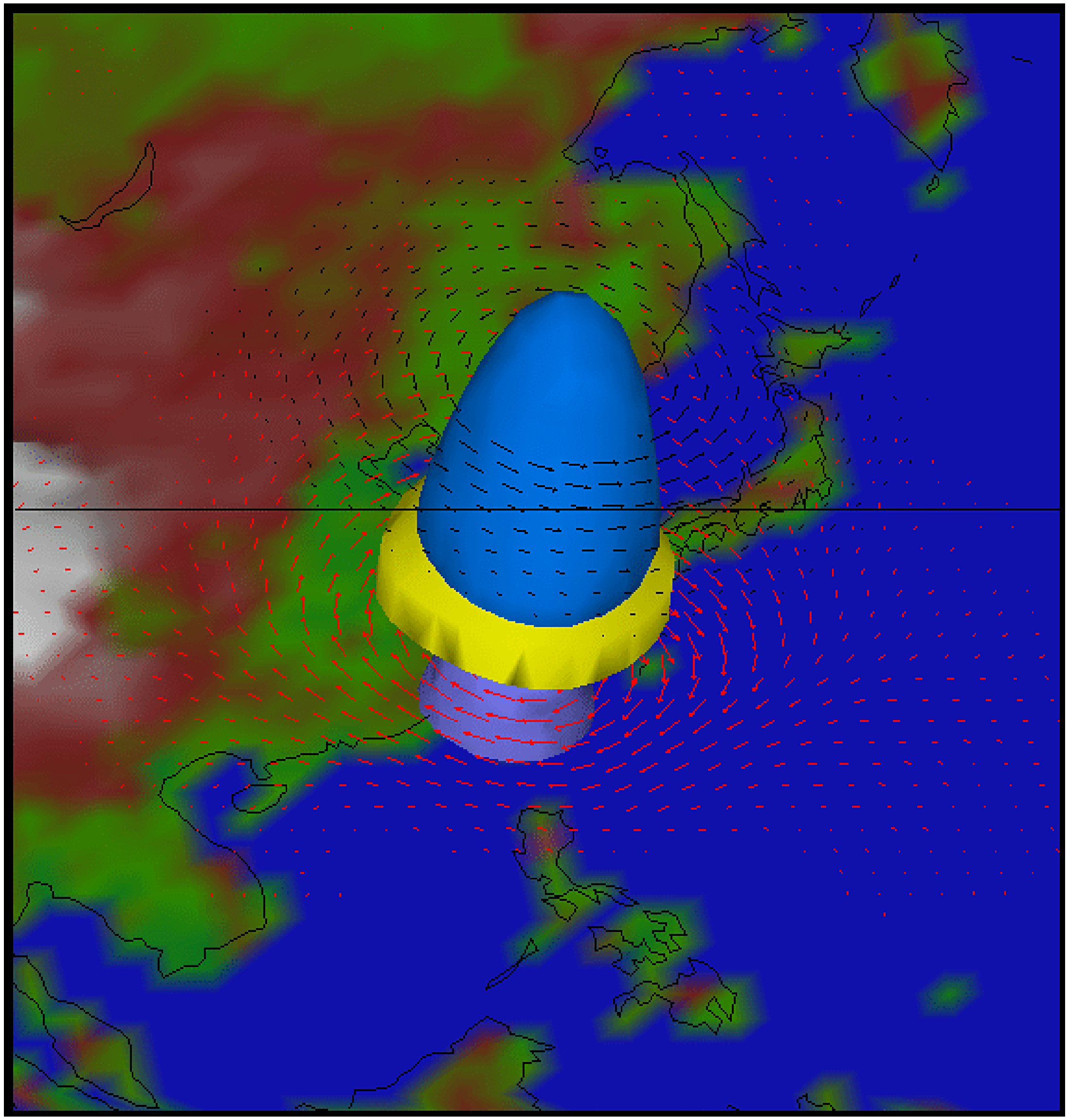
$$r' = q'/q_s(T_b, q_b, p_b)$$

$$\chi' = \chi_u' + \chi_b'(\psi')$$

$$T' = T_u' + T_b'(\psi')$$

$$p_s' = p_{su}' + p_{sb}'(\psi')$$

WRF-Var: Analysis Increment of Single GPS TPW Observation



The plot at left shows the combined response of WRF-Var to a single TPW observation O-B=1mm located at Taipei.

Analysis Increment Isosurfaces:

Blue = q (1g/kg).

Yellow = T (1K).

Purple=Pressure(1hPa).

Red = Wind Circulation at k=5.

Black = Wind Circulation at k=25.

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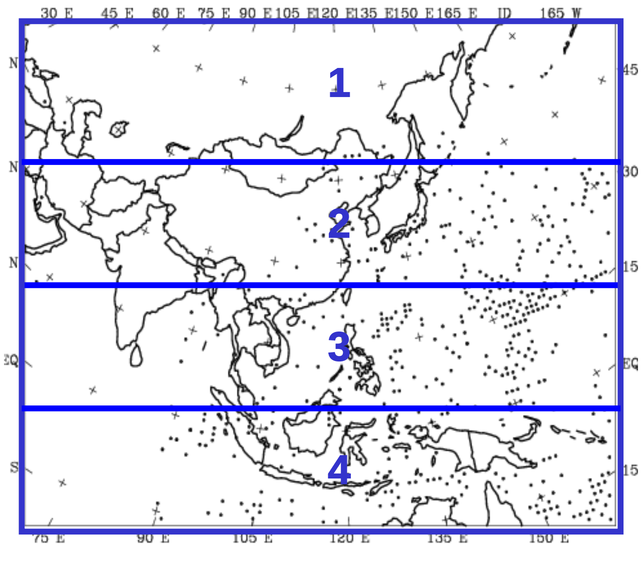
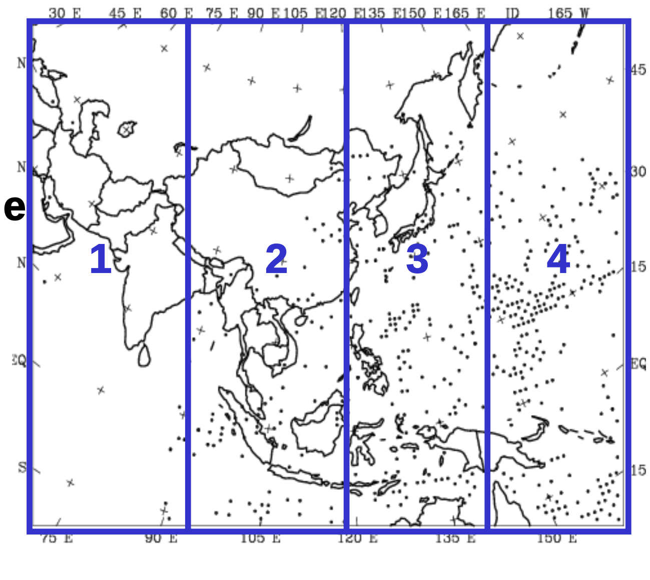
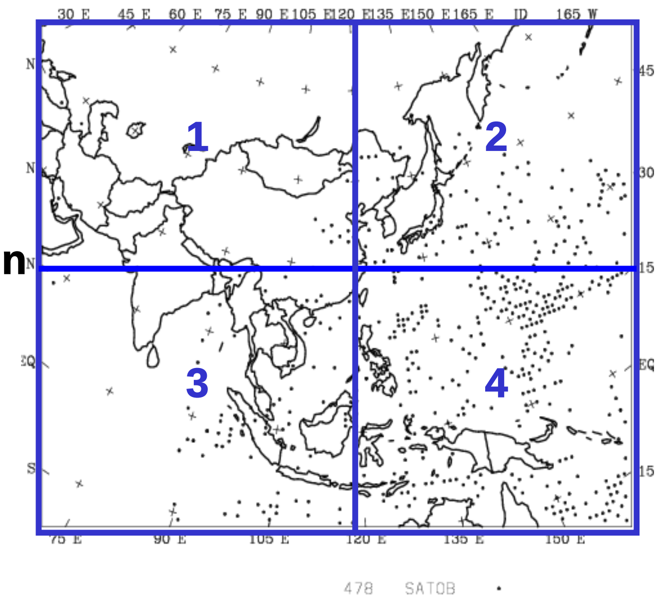
WRF-Var Multi-Processor Decomposition (e.g. np=4)

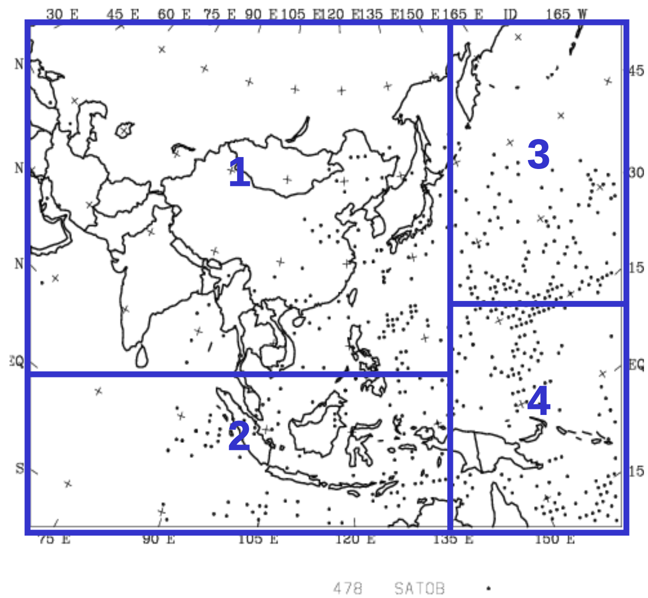


Recursive Filter and FFTs



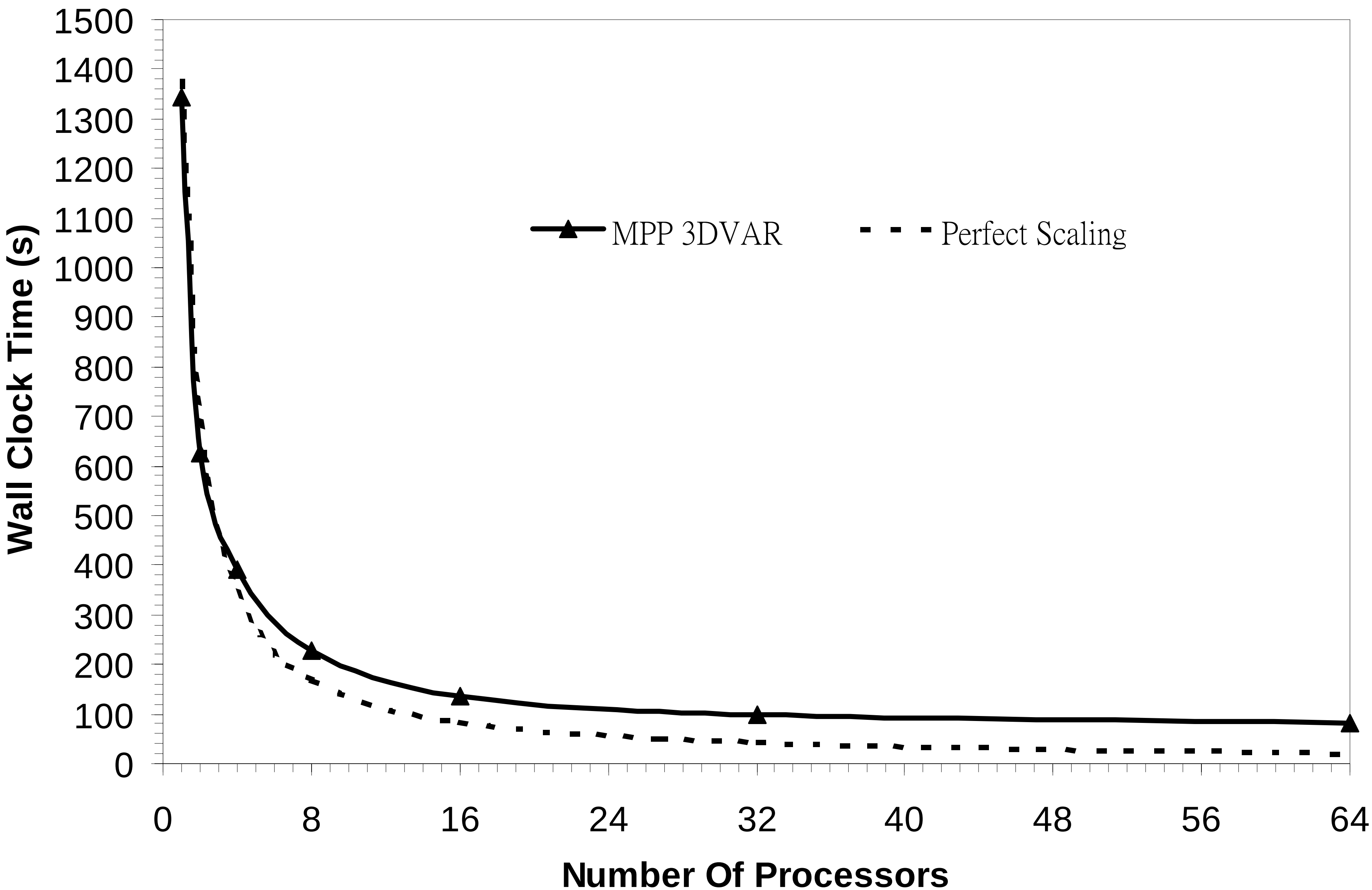
Minimization and Forecast Model





Observation Operators

MPP Scalability – NCAR IBM-SP



- **Test Case: 140x150x41 AFWA 45km "T4 theater" – 25th Jan 2002.**
- **Background error tuning – Old Its = 98, New = 49 (64PE = 58s).**

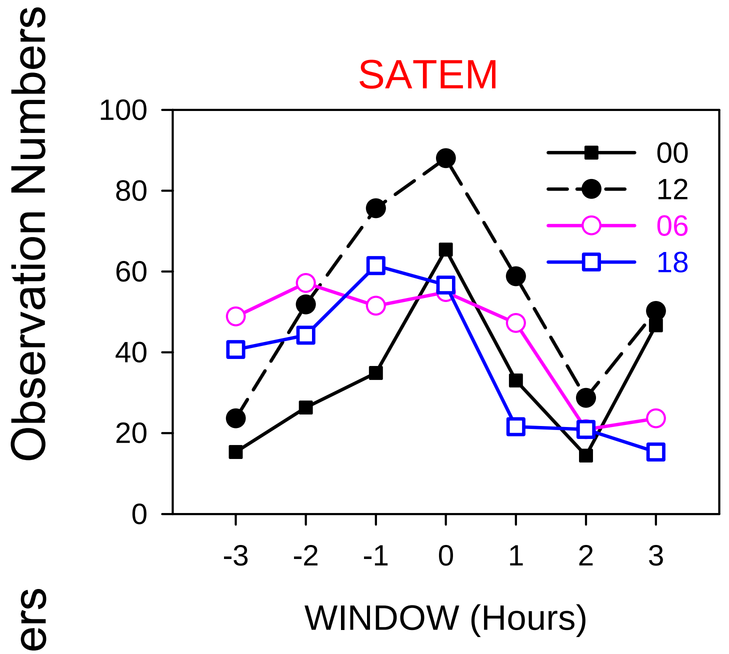
5. Observational Issues

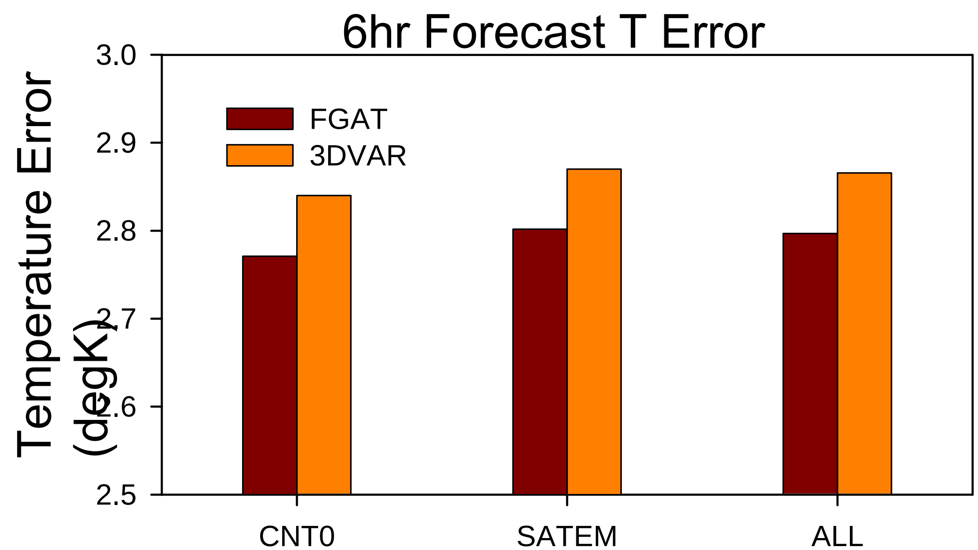
WRF-Var Observations Used (July 2005)

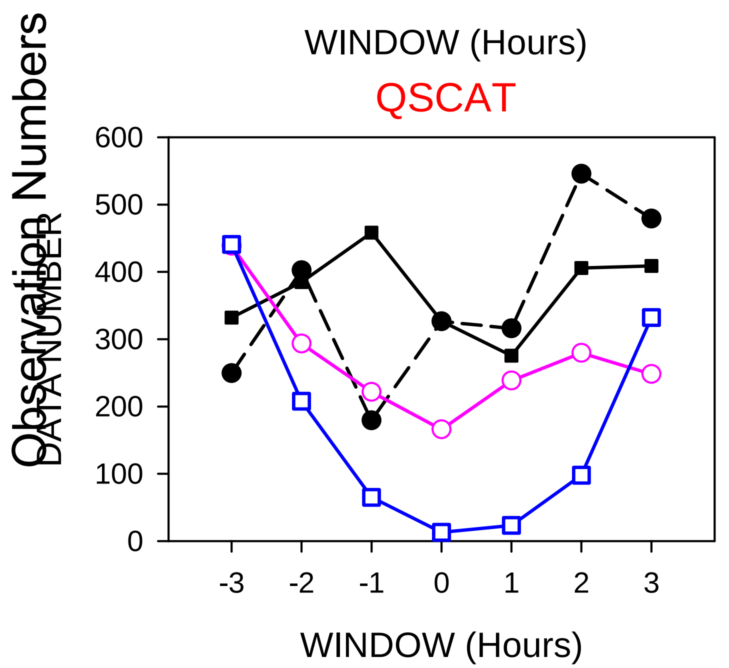
- Conventional:
  - Surface (SYNOP, METAR, SHIP, BUOY).
  - Upper air (TEMP, PIBAL, AIREP, ACARS).
- Remotely sensed retrievals:
  - Atmospheric Motion Vectors (SATOBS, MODIS).
  - Ground-based GPS Total Precipitable Water.
  - SSM/I oceanic surface wind speed and TPW.
  - Scatterometer (Quikscat) oceanic surface winds.
  - Wind Profiler.
  - Radar radial velocity and reflectivity.
  - ATOVS/AIRS/MODIS temperature/humidities.
  - GPS “local” refractivity.
- Radiances:
  - SSM/I brightness temperatures (Shu-Hua Chen).
  - AMSU/GOES/AIRS (under development).

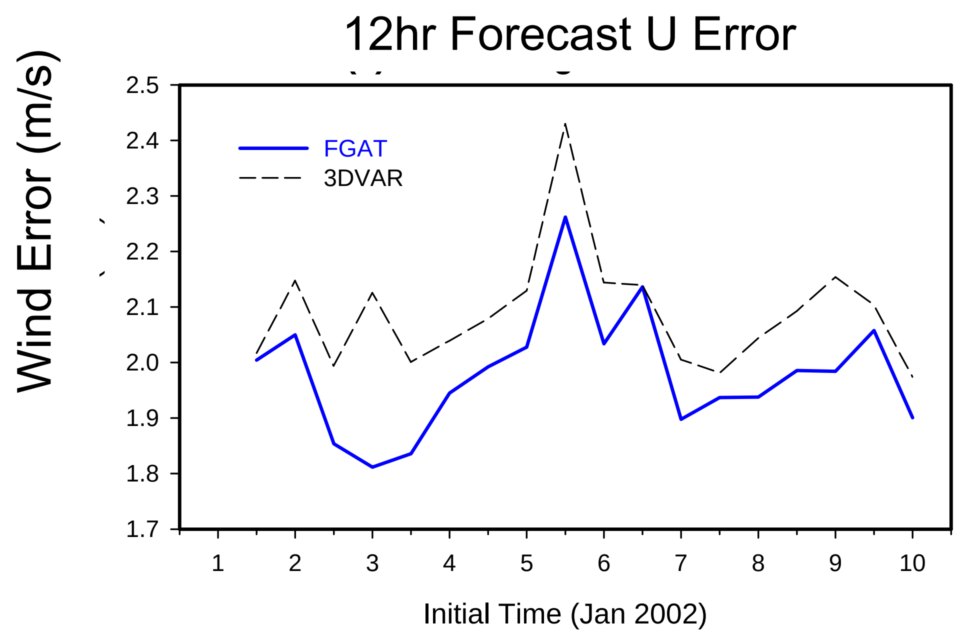
First Guess at Appropriate Time (FGAT)

• Principle: Compare observations with first guess forecast valid at time of observation









Radar Radial Velocity Observation Operator

•Observation operator (Sun and Crook 1998):

$$V_r = u\frac{x-x_i}{r_i} + v\frac{y-y_i}{r_i} + (w-v_T)\frac{z-z_i}{r_i}$$

•Terminal velocity a function of rain concentration:

$$v_T = 5.40a \cdot q_r^{\ 0.125}$$

$$a = (p_0/\overline{p})^{0.4}$$

•Require addition of hydrometeor variables to WRF-Var.

Radar Data Assimilation

- *Purpose: Can we assimilate radar radial velocity (and reflectivity) in 3D-Var to produce superior forecasts?*

- *Quality control/preprocessing crucial.*

- *Diagnose/analyze vertical velocity via "Richardson equation"*

$$\gamma p \frac{\partial w}{\partial z} = \gamma p \left[\frac{Q}{Tc_p} - \nabla_z \bullet v \right] - v \bullet \nabla_z p + g \int_z^{\infty} \nabla_z \bullet (\rho v) dz$$

Combines thermodynamic, continuity and hydrostatic equations….

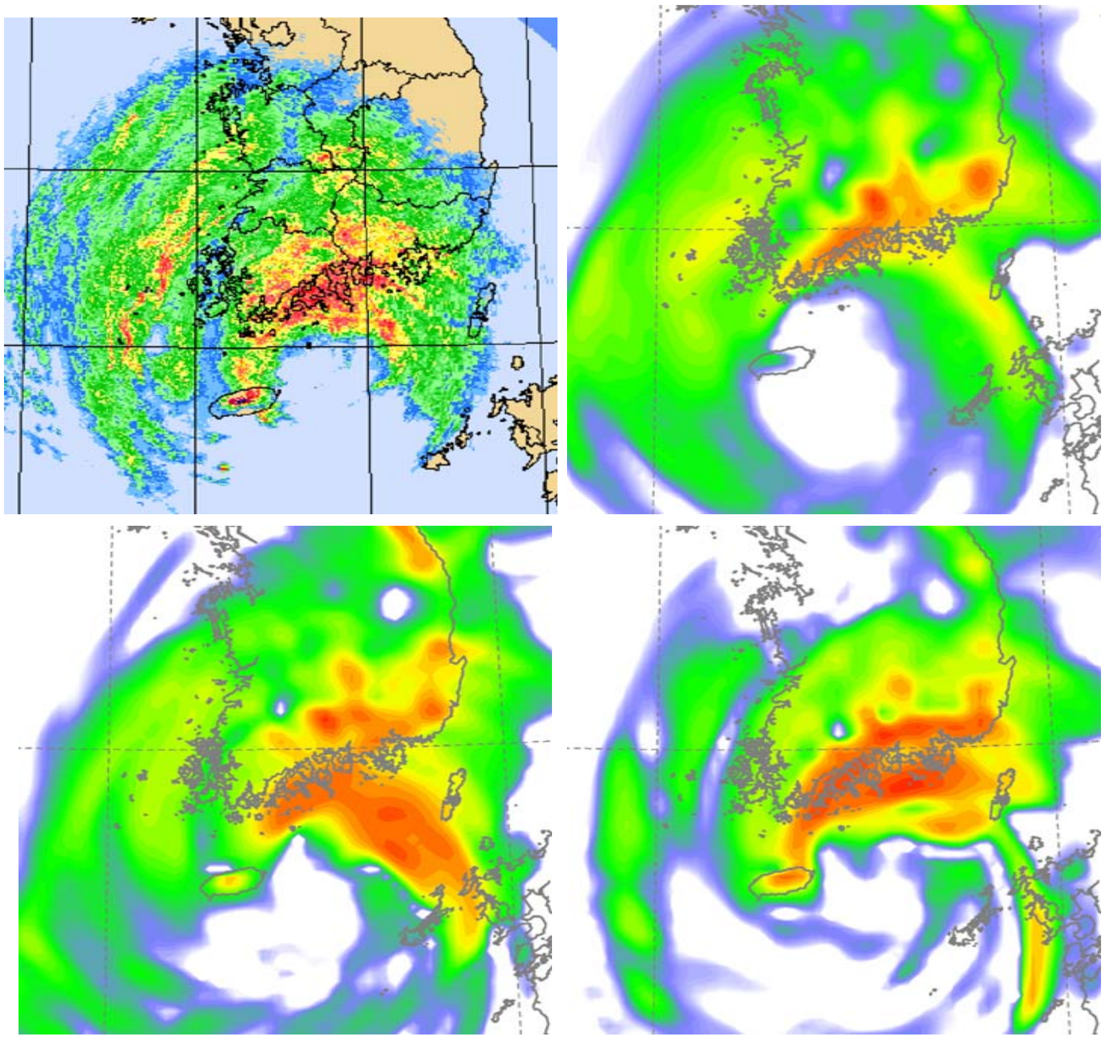
- *Linearize continuous eqn., then discretize (assume Q=0 for now):*

$$\gamma \bar{p} \frac{\partial w'}{\partial z} = -\gamma p' \frac{\partial \bar{w}}{\partial z} - \gamma \bar{p} \nabla \cdot \vec{v}'_h - \gamma p' \nabla \cdot \bar{\vec{v}}_h - \bar{\vec{v}}_h \nabla p'$$
$$- \vec{v}' \nabla \bar{p} + g \int_z^{\infty} \nabla \cdot (\rho \vec{v}'_h) dz + g \int_z^{\infty} \nabla \cdot (\rho' \bar{\vec{v}}_h) dz$$

Korean Radar Data Assimilation in WRF 3D-Var

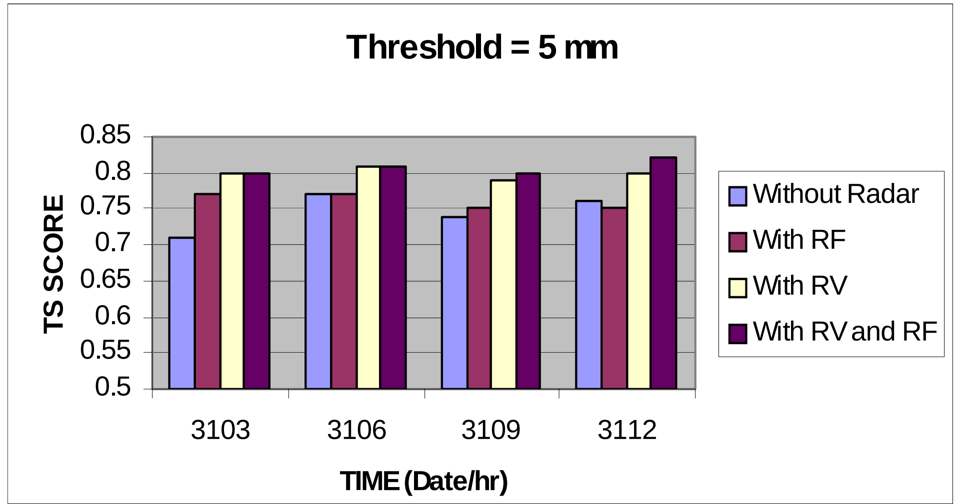
Typhoon Rusa Test Case 3hr Precip:

Obs (03Z, 31/08) No Radar



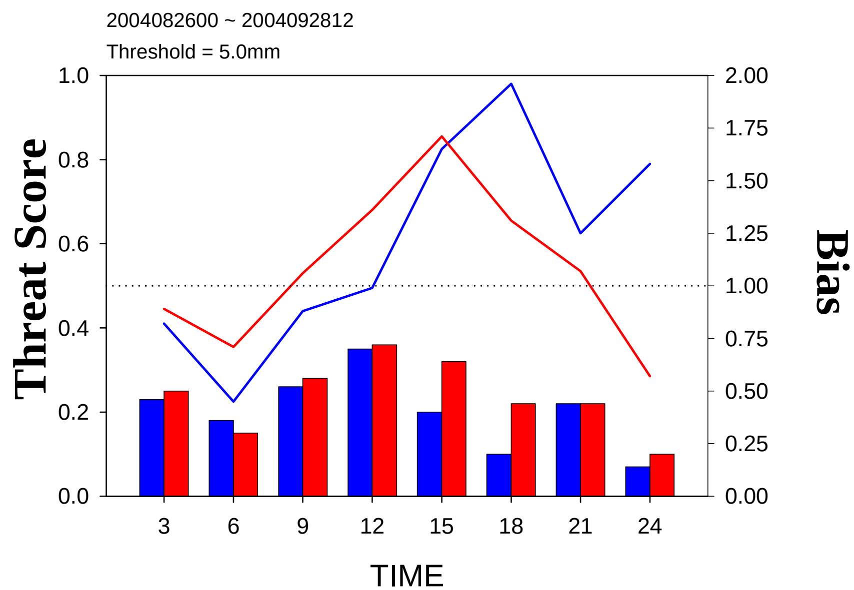
Radar RV Radar RV+RF

Typhoon Rusa 3hr Precip. Verification:



KMA Pre-operational Verification:

(no radar: blue, with radar: red)



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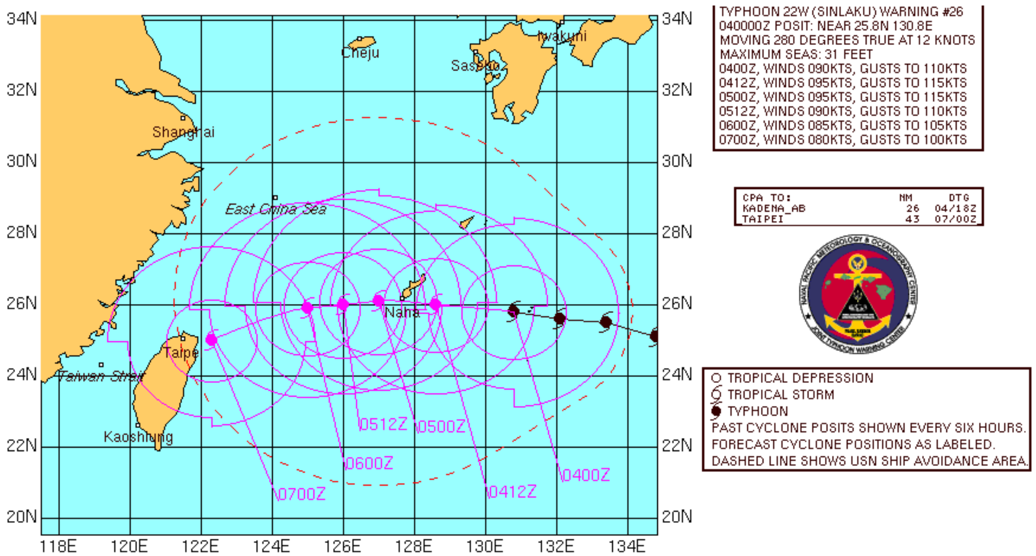
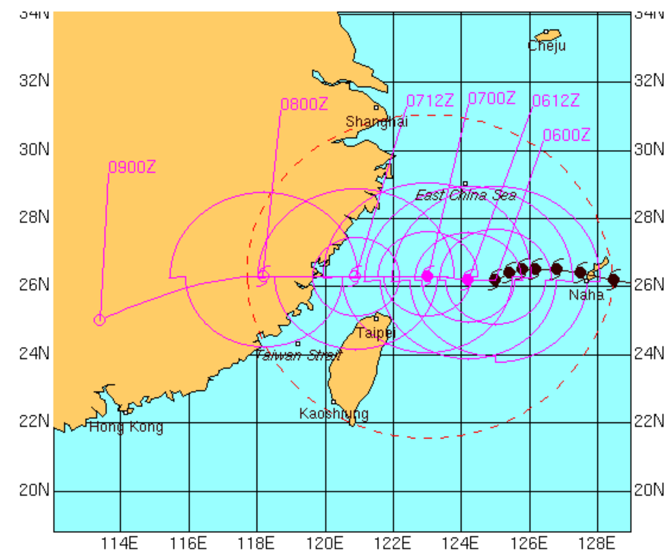
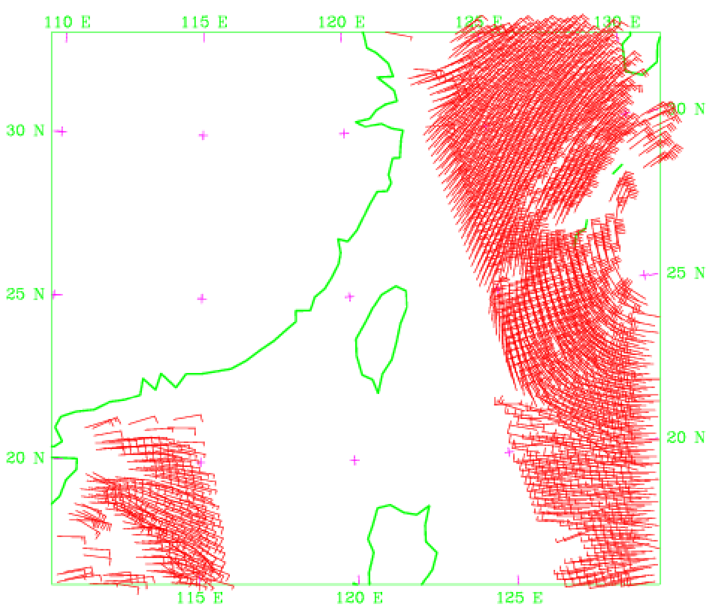
Typhoon Sinlaku WRF-Var Bogussing



00Z September 4th 2002

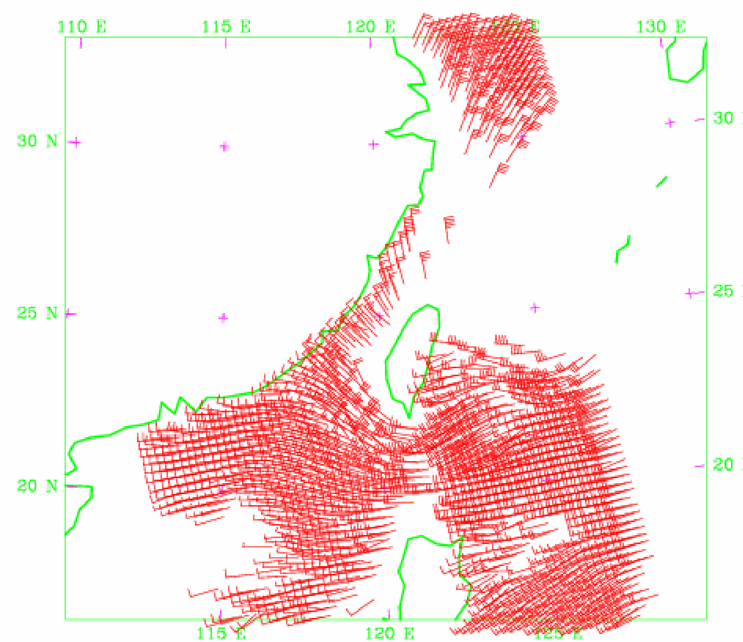


00Z September 6th 2002

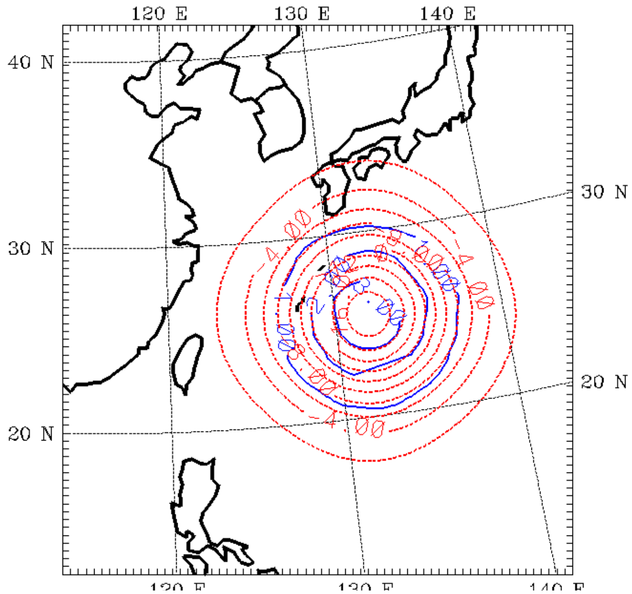


Quikscat Data

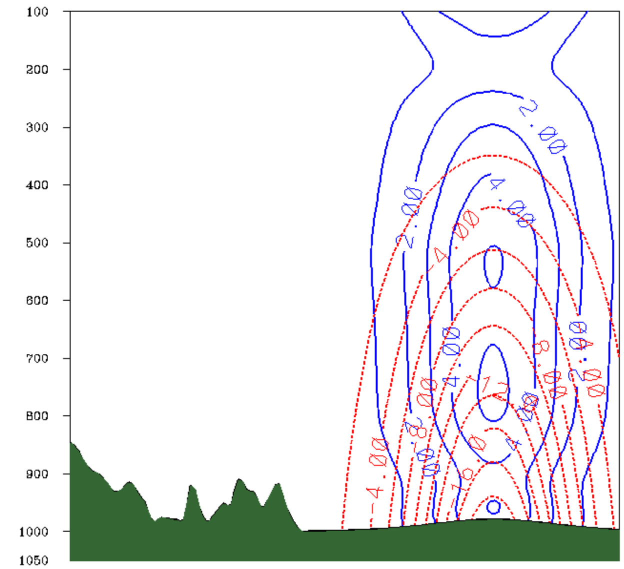
Barker et al (2004)

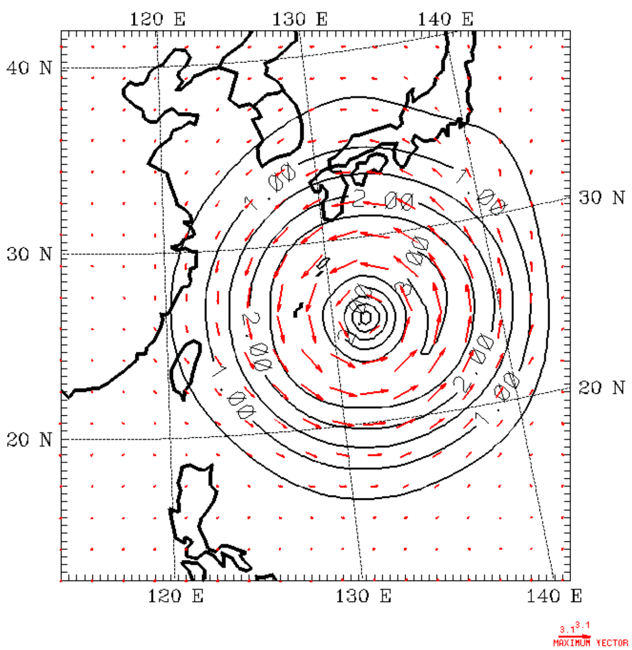


WRF-Var bogus:Analysis Increments

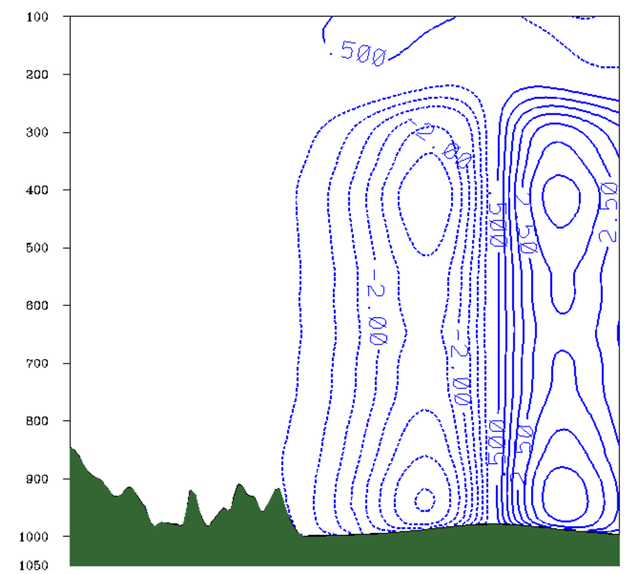


Pressure,
Temperature



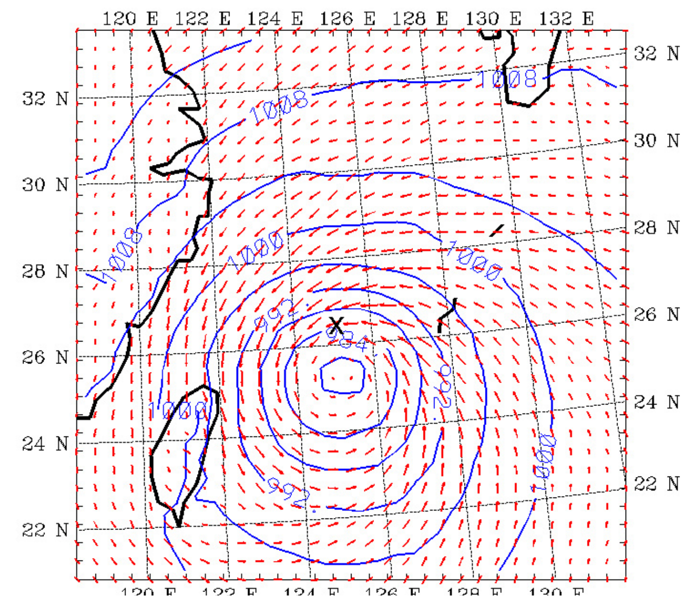


Wind Speed,
Vector,
v-wind component.

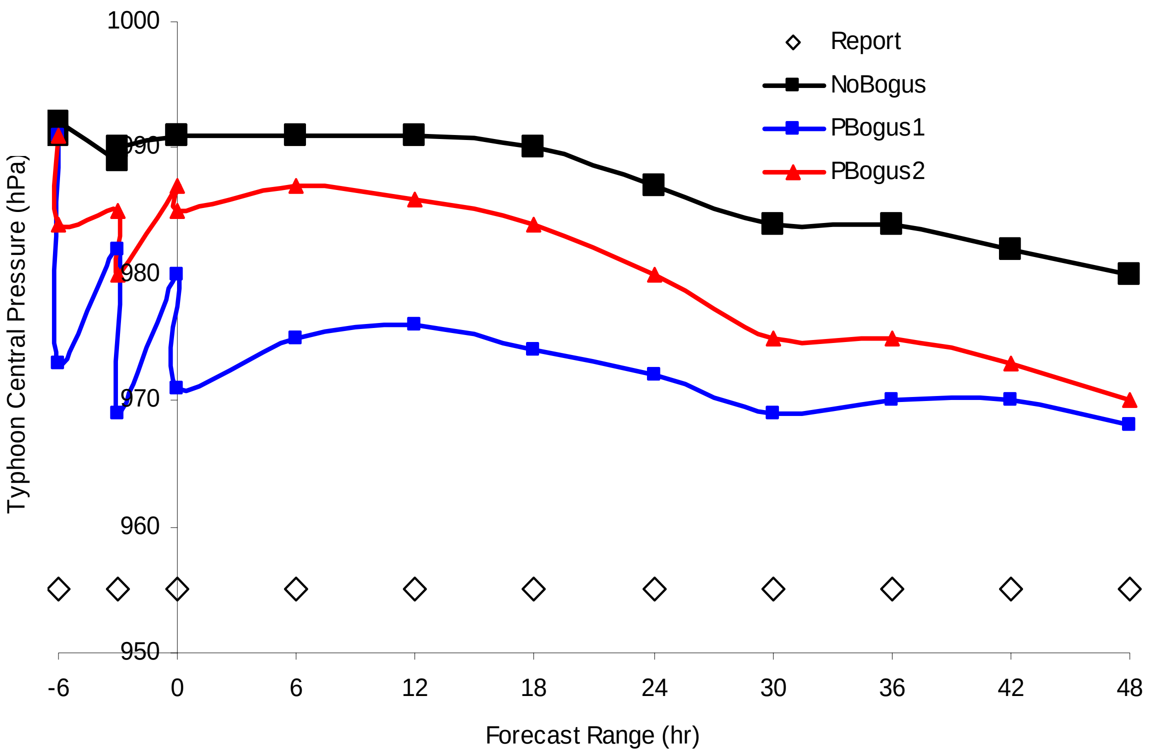


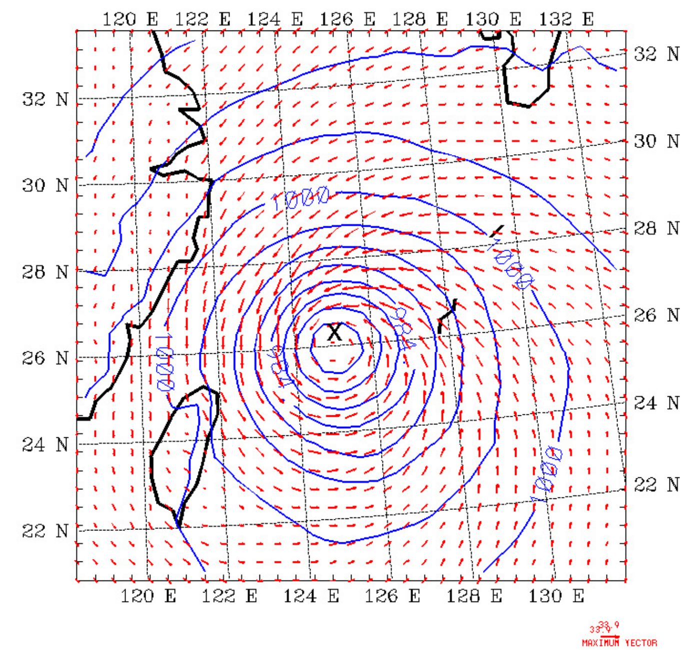
WRF-Var bogus: Impact on forecast

48hr Forecast (NoBogus)->



Typhoon Central Pressure





48hr Forecast (PBogus1)->

4. Current Status and Future Plans

WRF-Var Version 2.1 (Release July 2005)

- First Guess at Appropriate Time (FGAT).
- Radar reflectivity.
- Other new obs: GPS refractivity, MODIS AMVs.
- Platforms: IBM-SP, DEC, Linux, SGI, Cray X1, Apple G4/G5.
- Initial 4D-Var modifications.
- New utility *gen_be* to calculate local background error statistics.
- Global 3D-Var capability.

WRF 4DVAR project

Supported by AFWA

The team: Dale, Hans, John, Qingnong, Wei Huang

Schedule

- FY04: prepare. (wrf model, simplified model, testing TAF on wrf subroutines.)
- FY05: construct. (4DVAR framework, basic (dry) wrf TL and AD components, initial experiments.)
- FY06: refine. (more physics, parallel code, extensive testing.)

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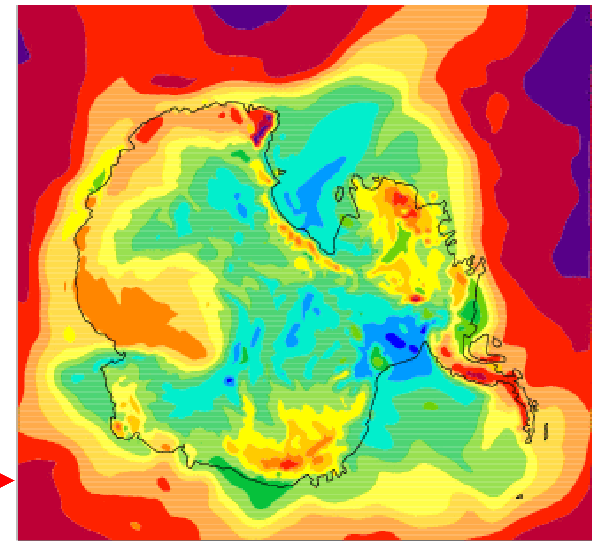
NCAR/MMM WRF Advanced Data Assimilation (WG10) Plans

WRF-Var:

- Further development of radar, GPS refractivity assimilation.
- Initial 4D-Var capability for AFWA (Oct. 2005).
- 4D-Var operational at AFWA (October 2007).
- Initial radiance capability (AMSU /RTTOVS) (Dec. 2005).
- Global 3D-Var operational at KMA (2006/2007).
- Applications (US, Korea, Taiwan, India, Antarctica).
- Flow-dependent covariances (Alpha CV, 4D-Var).

WRF 20km Antarctica:



Unified WRF Data Assimilation System (WADAS?):

- Further comparison of EnKF and variational schemes.
- Combined variational and ensemble-based techniques.
- Leverages satellite radiance expertise of JCSDA, EUMETSAT, universities, etc.
- Suitable for MMM research, operations, and academic community use.

Alpha CV: T response to wind ob: