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WRF Variational Data Assimilation System (WRF-Var) Tutorial

Presentation for the FORMOSAT-3/COSMIC Science Summer Camp

June 3rd 2005 at the Central Weather Bureau, Taipei, Taiwan

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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. The WRF-Var Algorithm.
3. Observations (focus on GPS).
4. Current Status and Future Plans.

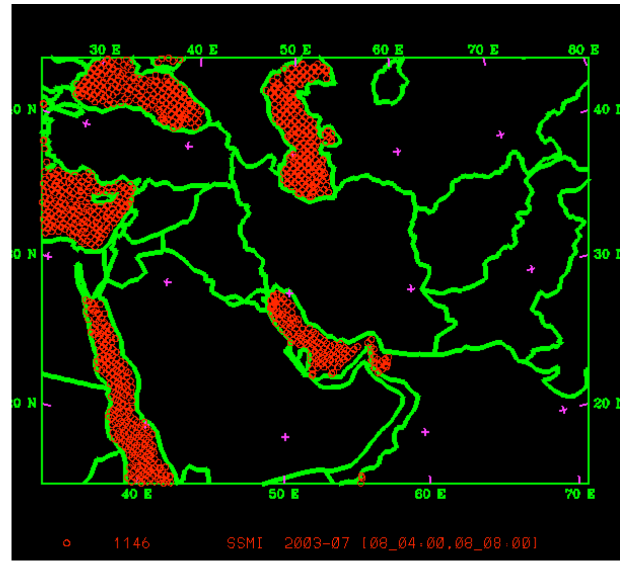
1. What is WRF-Var?

…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….

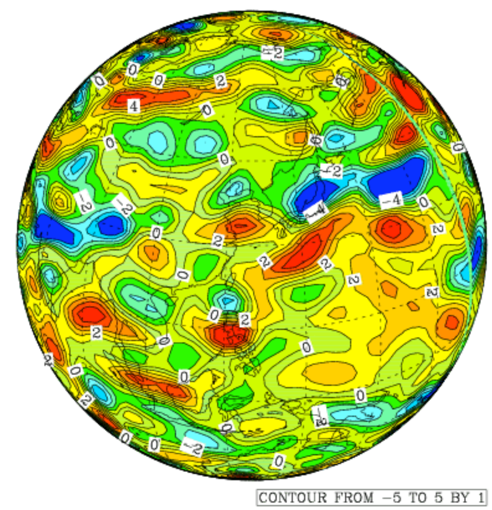
What Do We Mean By "Unified"

- 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:



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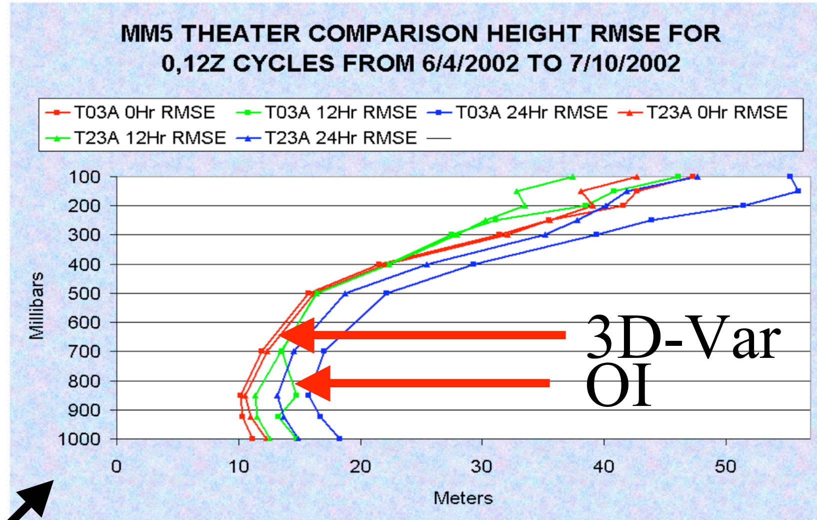
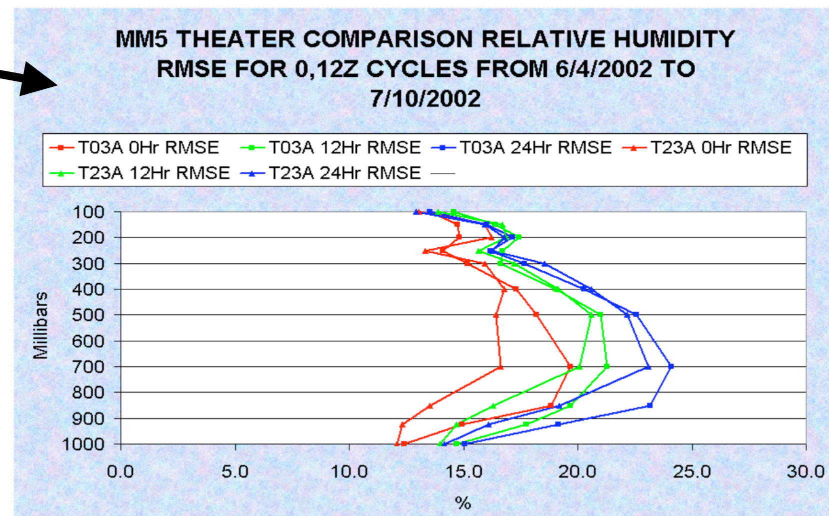
WRF Variational Data Assimilation (WRF-Var) History

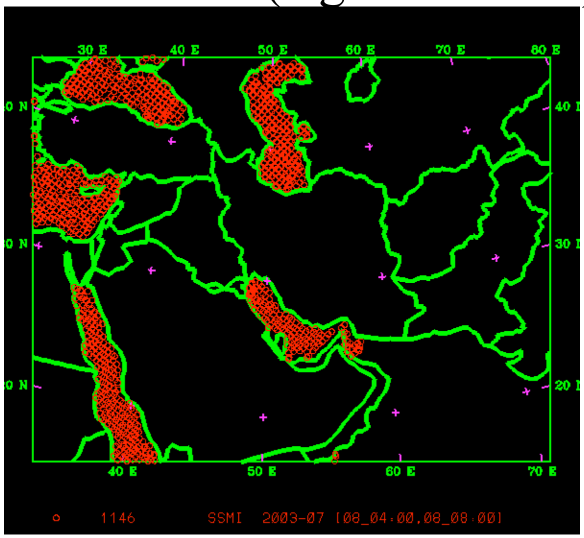
- **Late 1999:** Begin development of MM5 3D-Var.
- **June 2001:** MM5-3DVar adopted as starting point for WRF 3D-Var.
- **May 2002:** MM5/WRF 3D-Var operational at Taiwanese CAA.
- **September 2002:** MM5/WRF 3D-Var operational in 45km domains at AFWA.
- **June 2003:** WRF 3D-Var V1.0 release.
- **May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



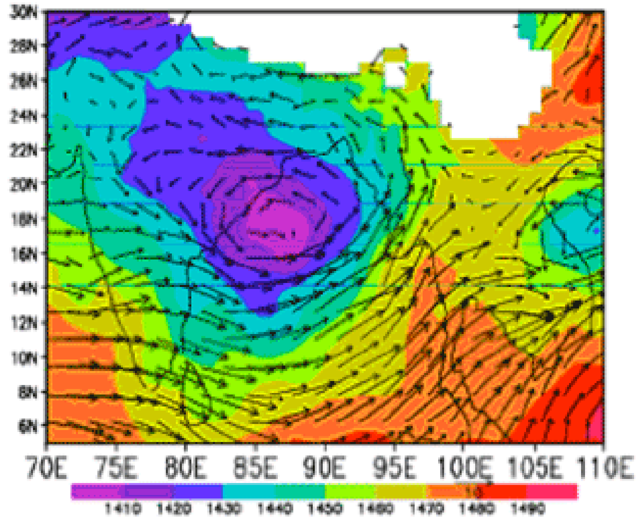


WRF-Var Operational Applications: June 2005

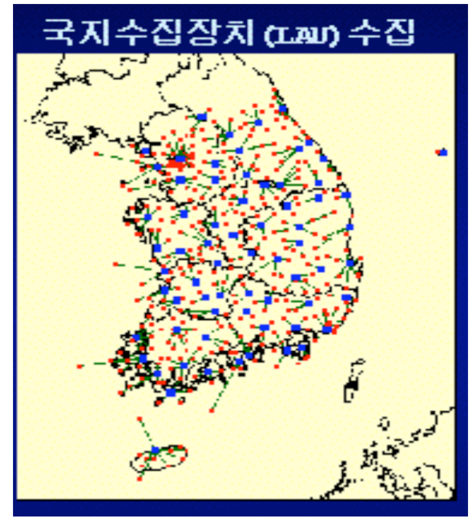
AFWA 15km (e.g. S-W Asia):



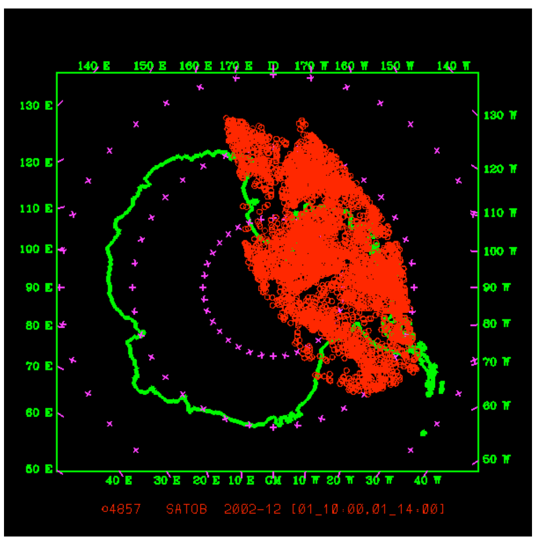
Indian NCMRWF 30km:



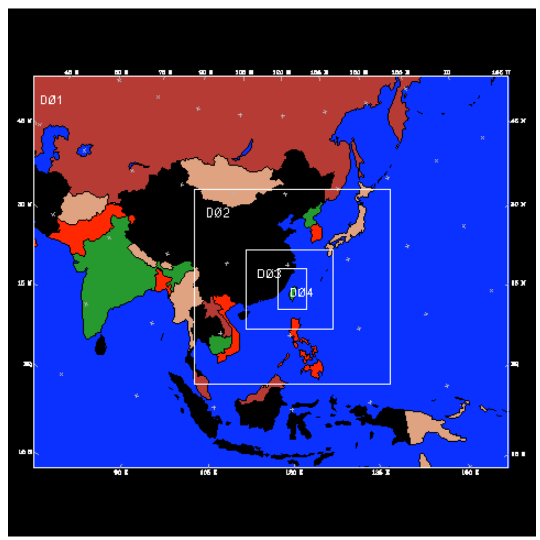
Korean 10km:



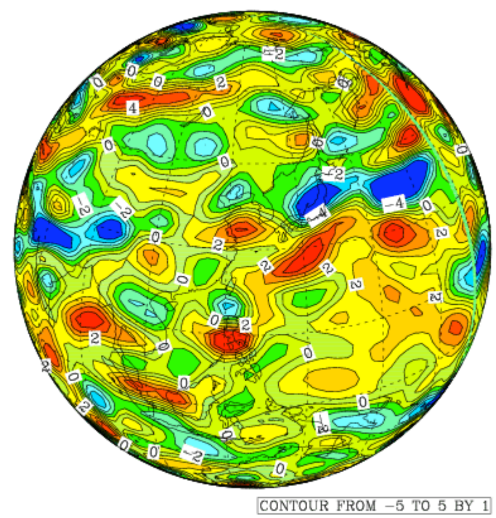
AMPS 30km:



Taiwanese CAA 135/45/15km:



Korean T213/T426:



2. The WRF-Var Algorithm

Data Assimilation Overview

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

- Assume error probability $P(\boldsymbol{x})$ is Gaussian then

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

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

- ***Error covariances:***

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

- Practical implementation requires numerous assumptions and approximations.

Incremental WRF-Var and Preconditioning

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

- *Solve **incremental*** cost function (with uncorrelated obs. errors):

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

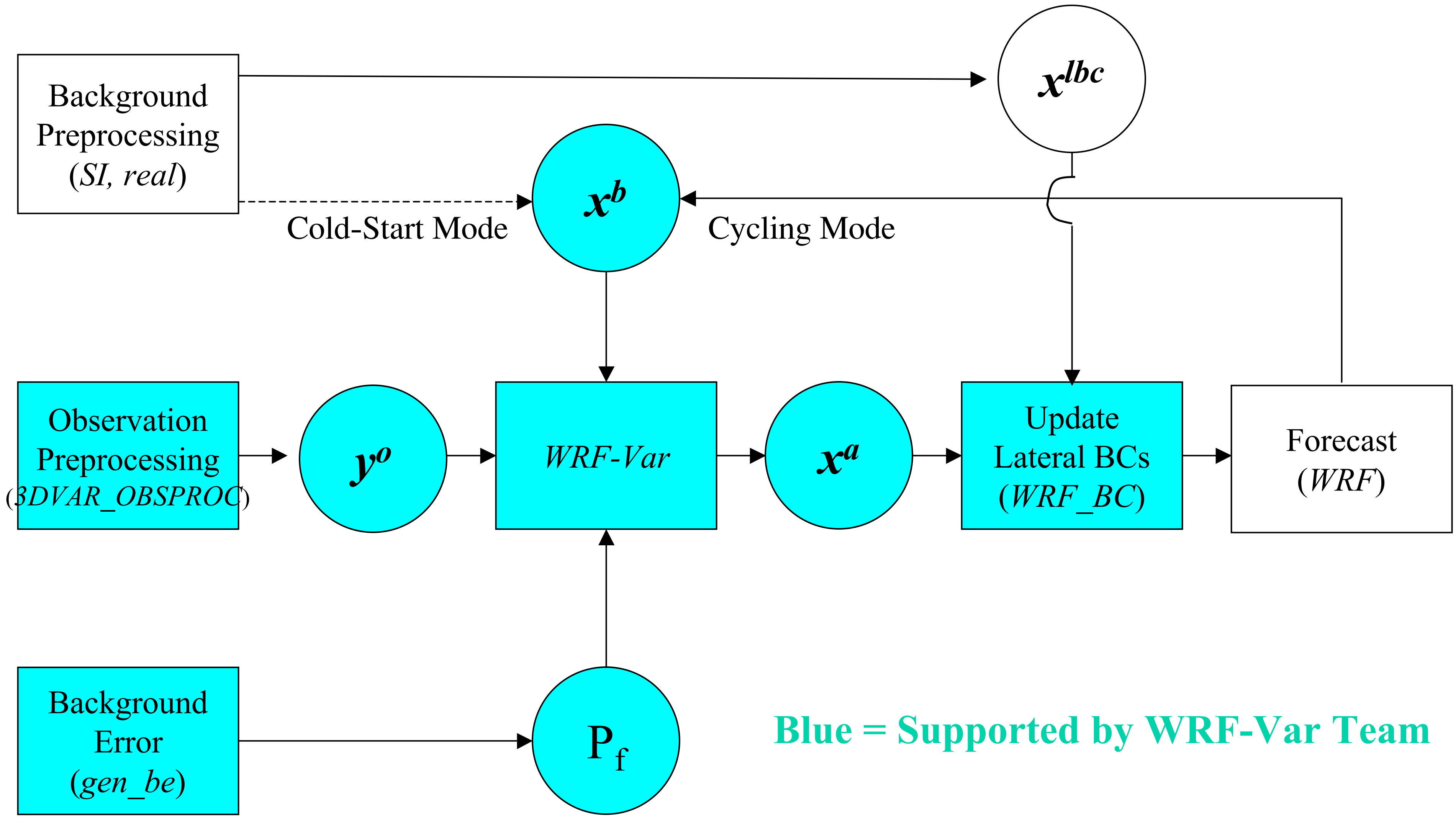
where $\boldsymbol{y}' = \mathbf{H}\boldsymbol{x}'$, $\boldsymbol{d} = \boldsymbol{y} - H(\boldsymbol{x}^b)$

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

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

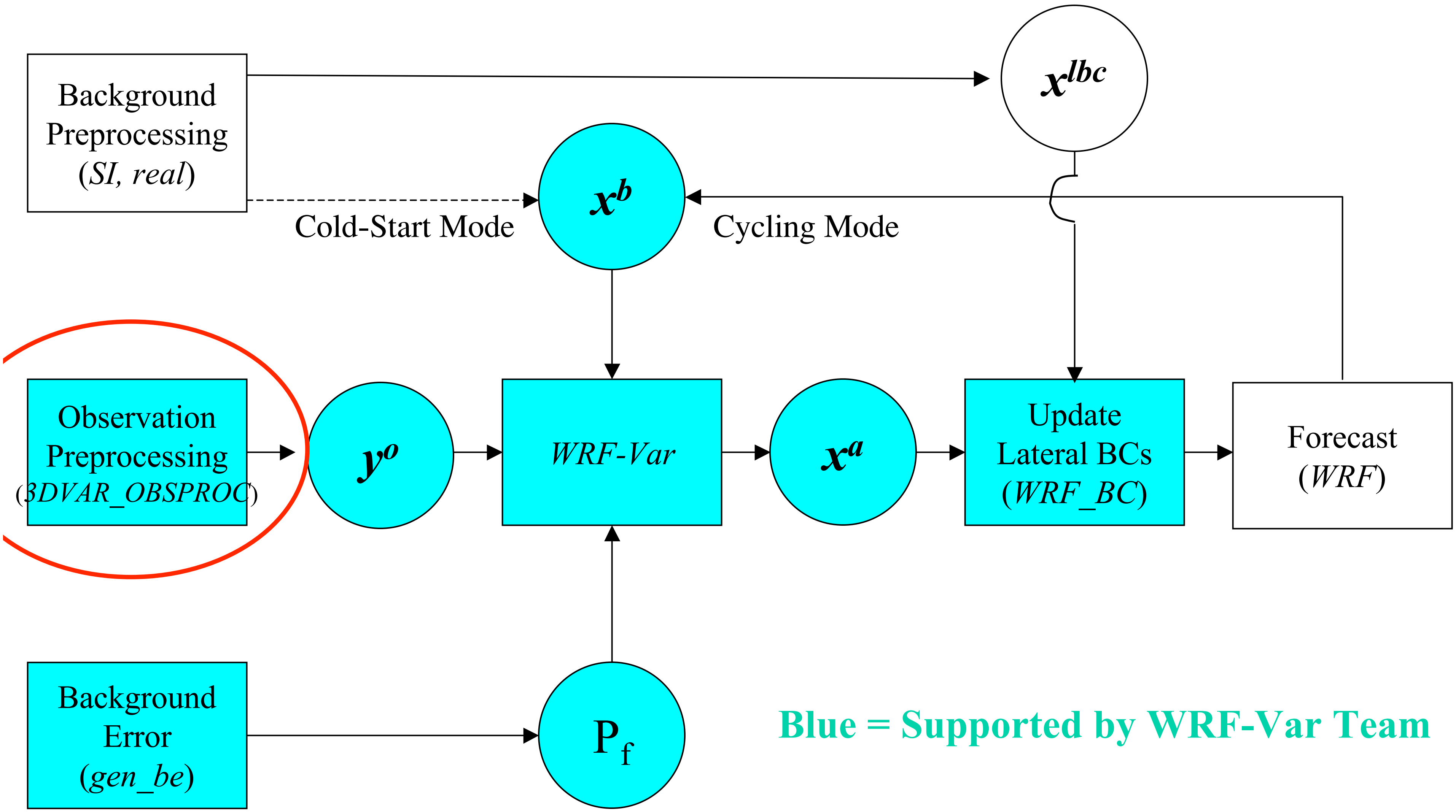
$$J(\boldsymbol{x}) = \frac{1}{2} \sum_i v_i^2 + \frac{1}{2} \sum_n \left[\boldsymbol{d} - \boldsymbol{y}'\right]_n^2 / \sigma_{on}^2$$

WRF-Var in the WRF Modeling System



Blue = Supported by WRF-Var Team

WRF-Var in the WRF Modeling System



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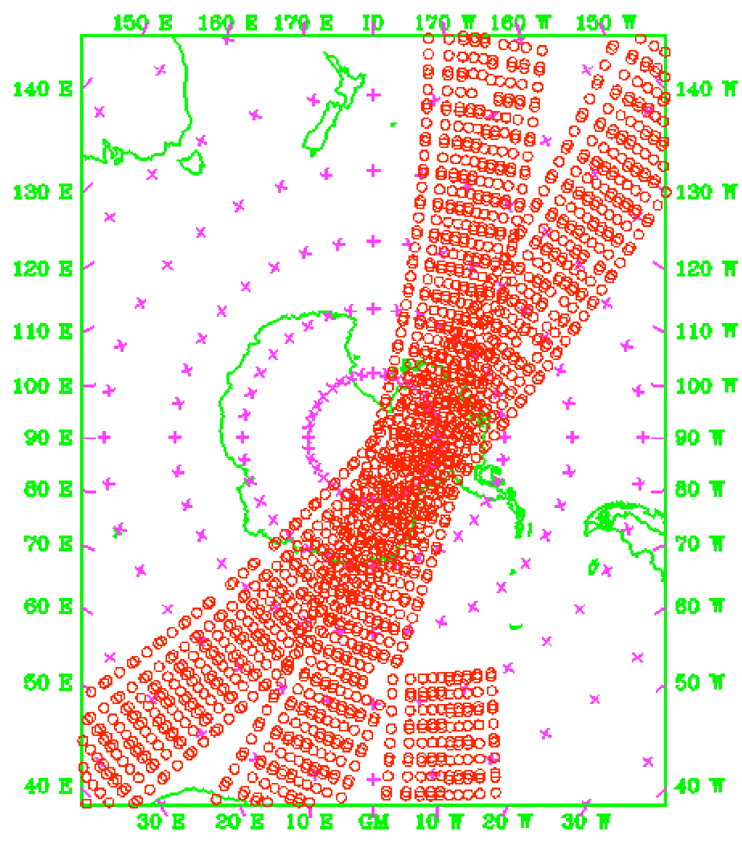
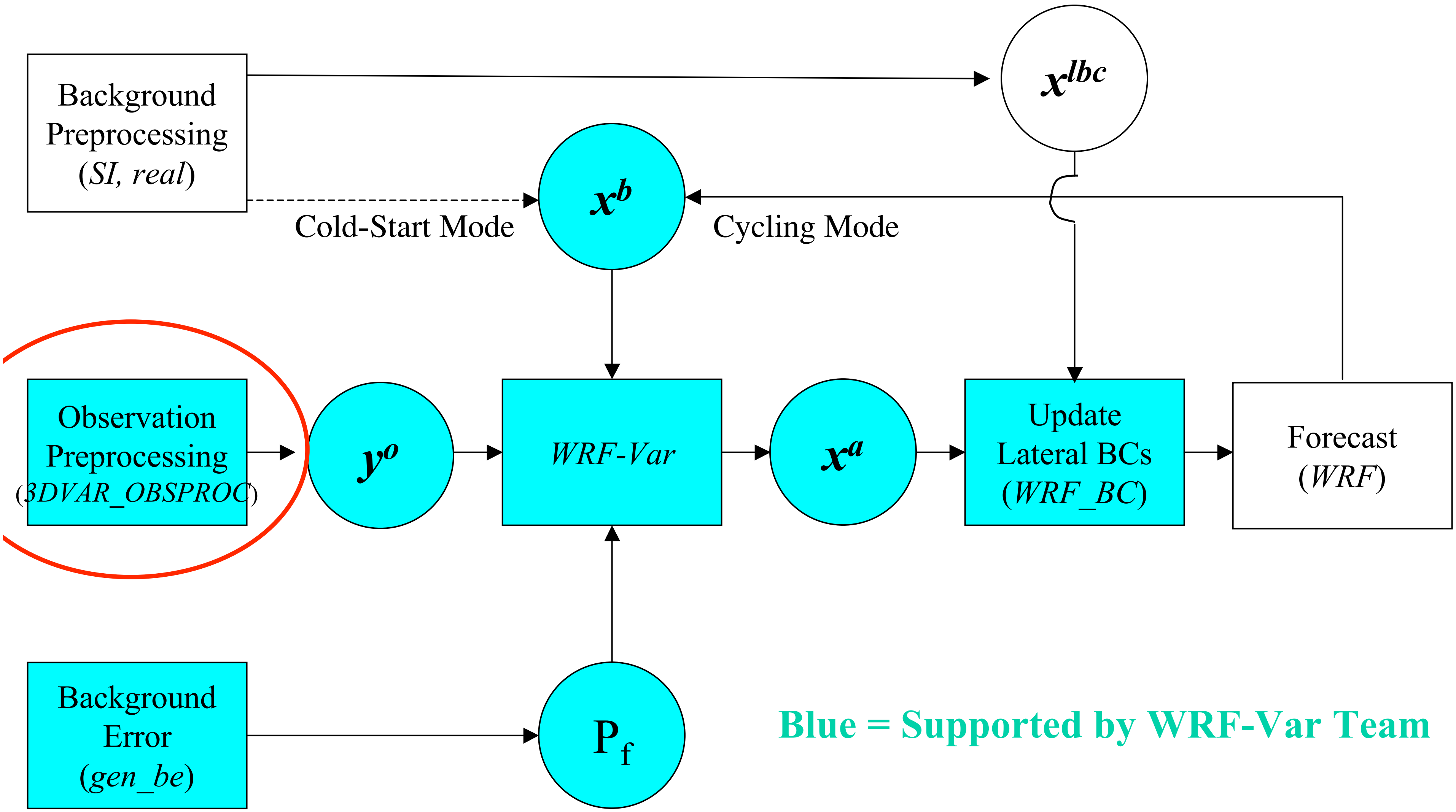
Observation Preprocessing (*3DVAR_OBSPROC*)

- Reads in observation files from decoders/GTS.
- Performs gross QC, e.g. domain/time, consistency, duplicate, merging.
- Simple thinning option.
- Outputs in text "3D-Var format" for further QC and assimilation in WRF-Var.
- Assign observation errors.
- Plots observation distributions.
- Note: Work under way to convert to BUFR, rather than text files.

Example thinned AIRS distribution 00 UTC 15th May 2004 (+/-2hrs):



WRF-Var in the WRF Modeling System



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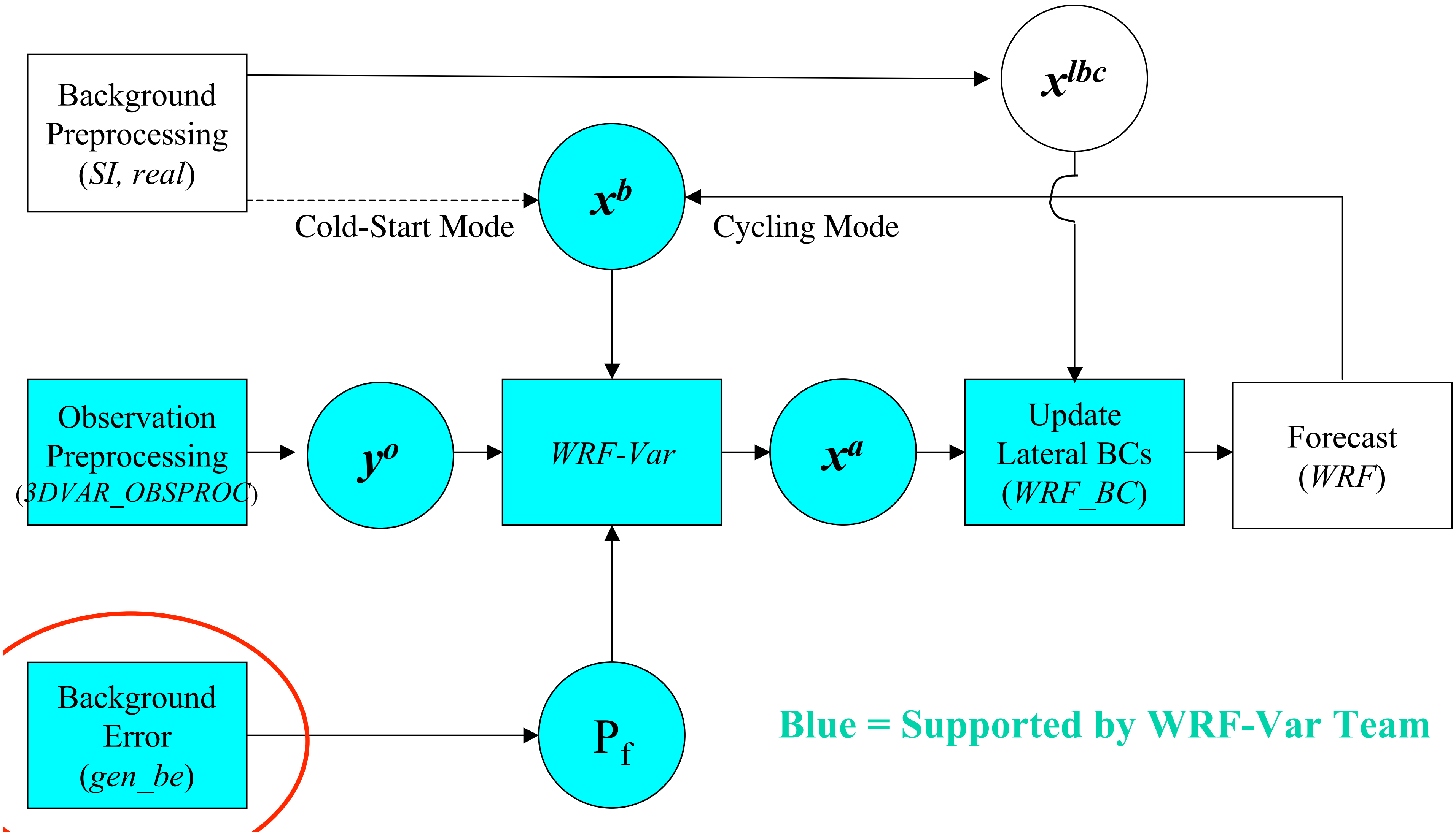
WRF-Var in the WRF Modeling System



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Background Error Estimation (*gen_be*)

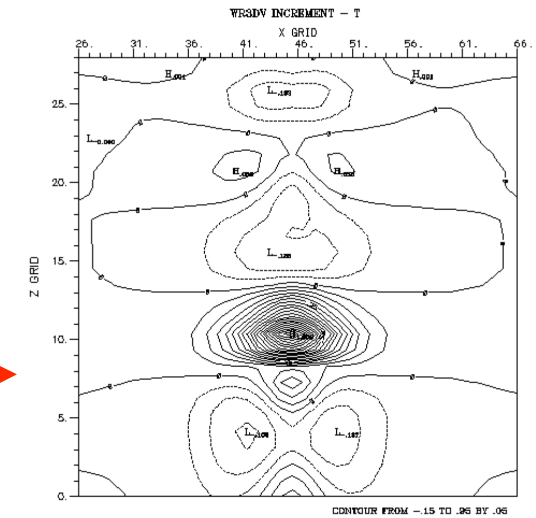
- Assume background error covariance estimated by model perturbations ***x'*** :

$$\mathbf{P}_f = \overline{(\boldsymbol{x}^b - \boldsymbol{x}^t)(\boldsymbol{x}^b - \boldsymbol{x}^t)^T} \approx \overline{\boldsymbol{x}'\boldsymbol{x}'^T}$$

Two ways of defining ***x'*** in utility *gen_be*:

- The NMC-method (Parrish and Derber 1992):

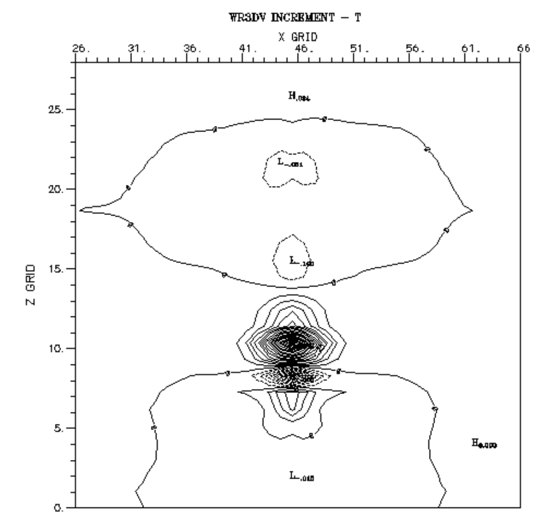
$$\mathbf{P}_f = \overline{\boldsymbol{x}'\boldsymbol{x}'^T} \approx A\overline{(\boldsymbol{x}^{t2} - \boldsymbol{x}^{t1})(\boldsymbol{x}^{t2} - \boldsymbol{x}^{t1})^T}$$



where e.g. t2=24hr, t1=12hr forecasts…

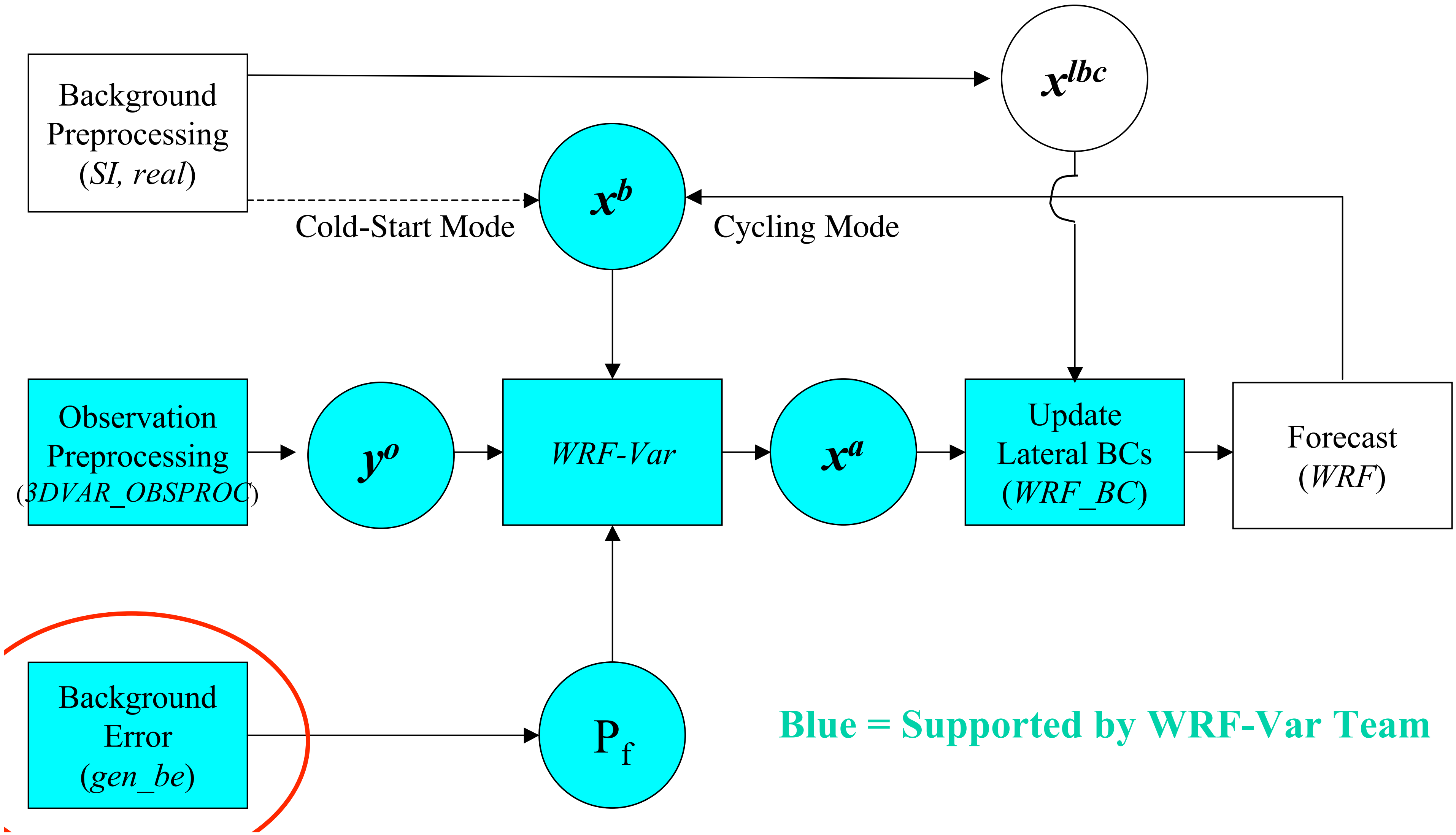
- …or ensemble perturbations:

$$\mathbf{P}_f = \overline{\boldsymbol{x}'\boldsymbol{x}'^T} \approx C\overline{(\boldsymbol{x}^{k} - \langle \boldsymbol{x} \rangle)(\boldsymbol{x}^{k} - \langle \boldsymbol{x} \rangle)^T}$$

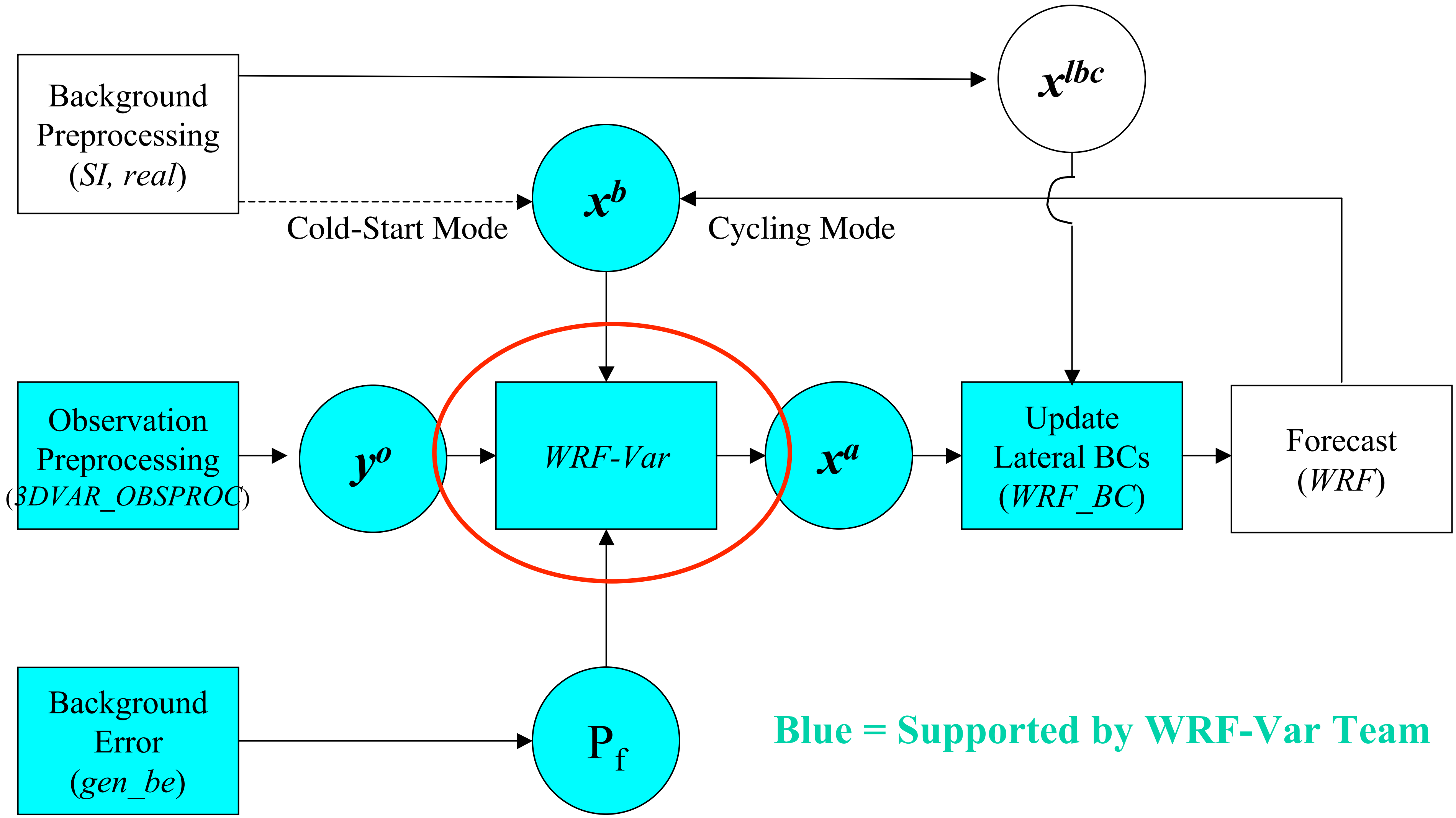


- Tuning via innovation vector statistics (H&L86) and variational methods (Desroziers & Ivanov 2001)

WRF-Var in the WRF Modeling System



WRF-Var in the WRF Modeling System



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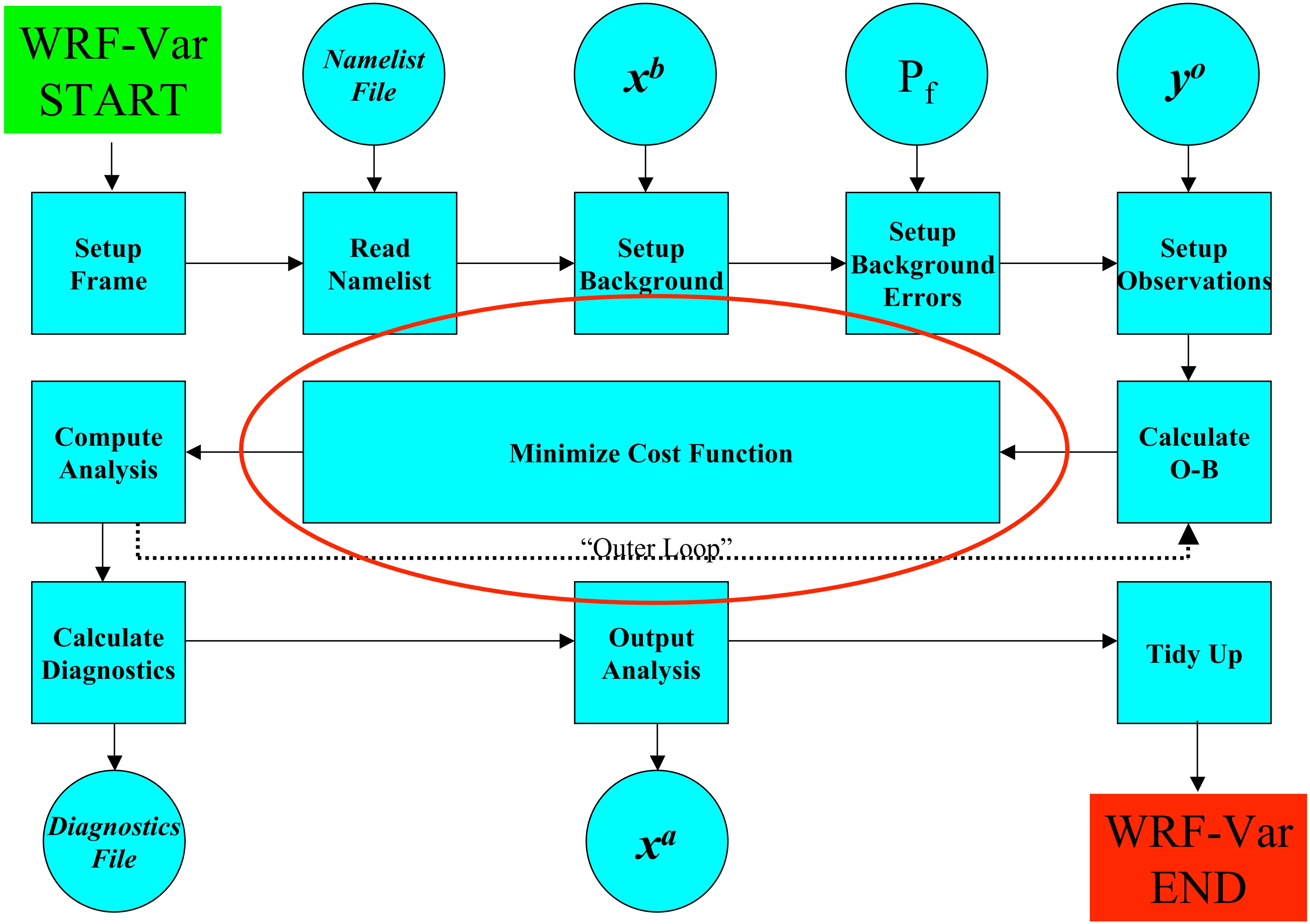
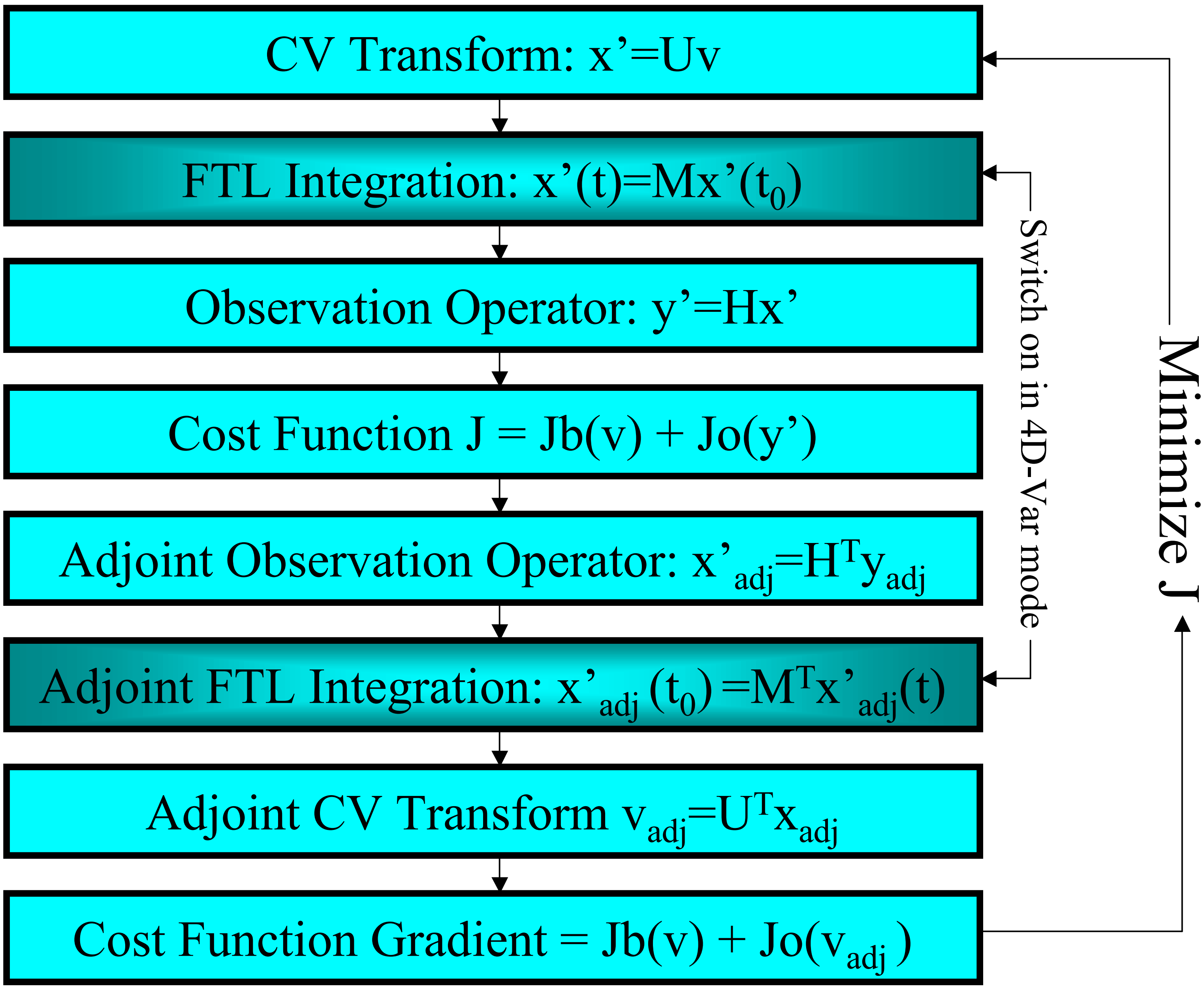
WRF-Var


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

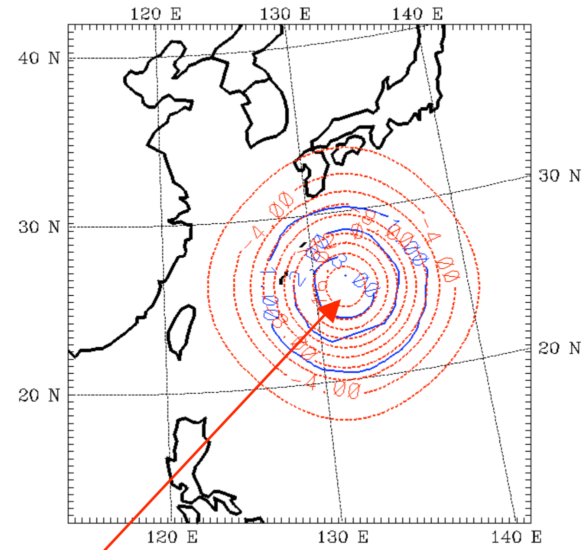
WRF-Var "Inner Loop"

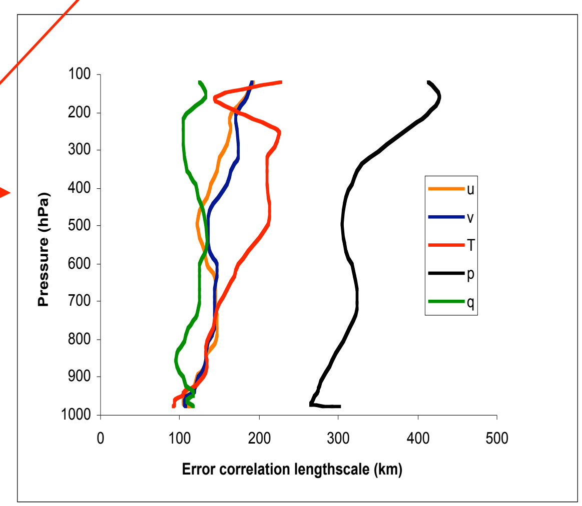


WRF-Var Control Variable Transform

$$x' = \mathbf{U}v = \mathbf{U}_p\mathbf{U}_v\mathbf{U}_h v$$

		Global	**Regional**	*MM5*
Model Variables	x'	$u',v',T',q',p_s'(i,j,k)$		
Change of variable	U_p	$\psi',\chi_u',T_u',\tilde{r}',p_{su}'(i,j,k)$		$\psi',\chi',p_u',q'(i,j,k)$
Vertical Transform	U_v	EOF Decomposition: $\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^T$		
Horizontal Transform	U_h	Spectral Transform	Recursive Filter	
Control Variables	v	$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$	

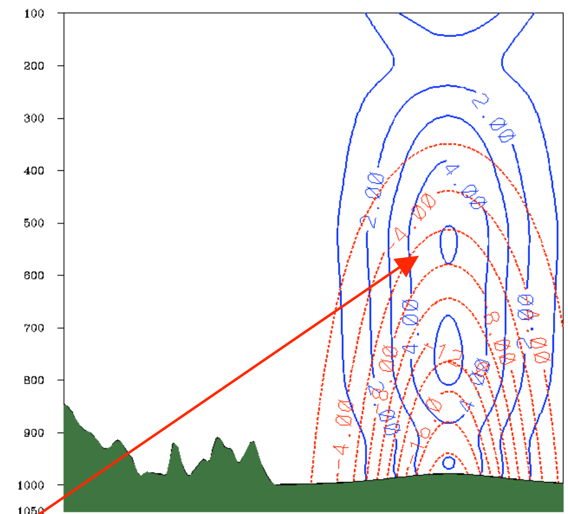


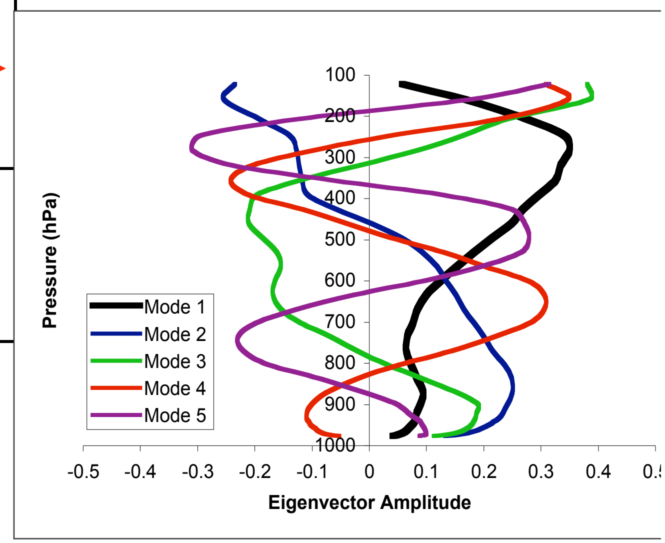


WRF-Var Control Variable Transform

$$x' = Uv = U_p U_v U_h v$$

		Global	Regional	MM5
Model Variables	x'	$u',v',T',q',p_s'(i,j,k)$		
Change of variable	U_p	$\psi',\chi_u',T_u',\tilde{r}',p_{su}'(i,j,k)$		$\psi',\chi',p_u',q'(i,j,k)$
Vertical Transform	U_v	EOF Decomposition: $\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^T$		
Horizontal Transform	U_h	Spectral Transform	Recursive Filter	
Control Variables	v	$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$	





WRF-Var Control Variable Transform

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

		Global	Regional	*MM5/UKMO*
Model Variables	x'	$u',v',T',q',p_s'(i,j,k)$		
Change of variable	U_p	$\psi',\chi_u',T_u',\tilde{r}',p_{su}'(i,j,k)$		$\psi',\chi',p_u',q'(i,j,k)$
Vertical Transform	U_v	EOF Decomposition: $\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^T$		
Horizontal Transform	U_h	Spectral Transform	Recursive Filter	
Control Variables	v	$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$	

Define statistical balance e.g.

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

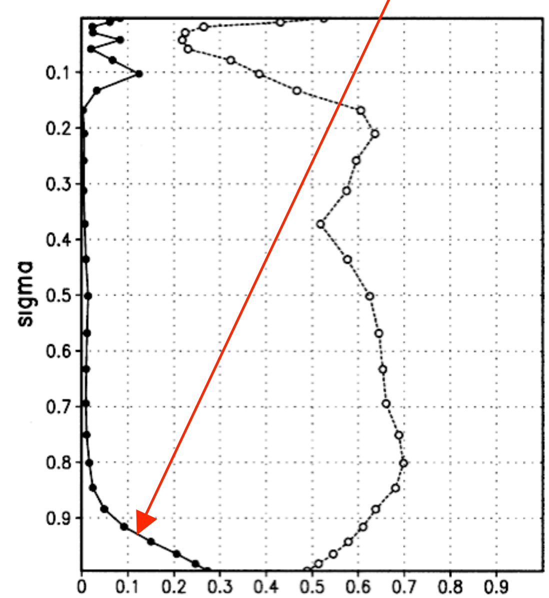


FIG. 1. Global-mean fraction of explained covariance of the balanced part of temperature (open circles) and velocity potential (closed circles).

from Wu et al (2002)

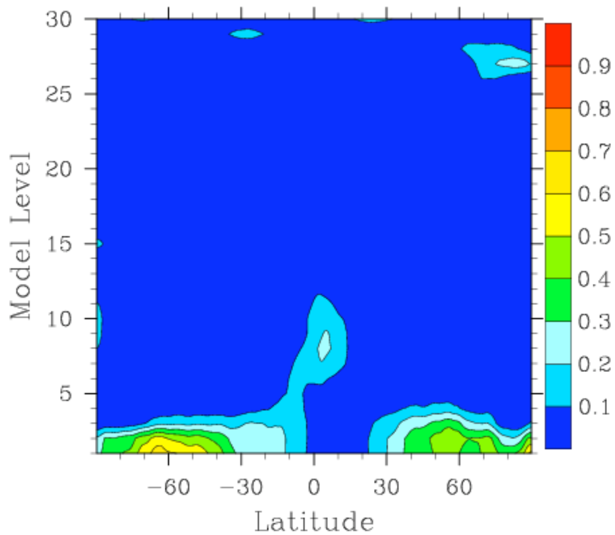
Stage2: Global model (KMA) data

Regression Coefficients after Wu et al (2002):

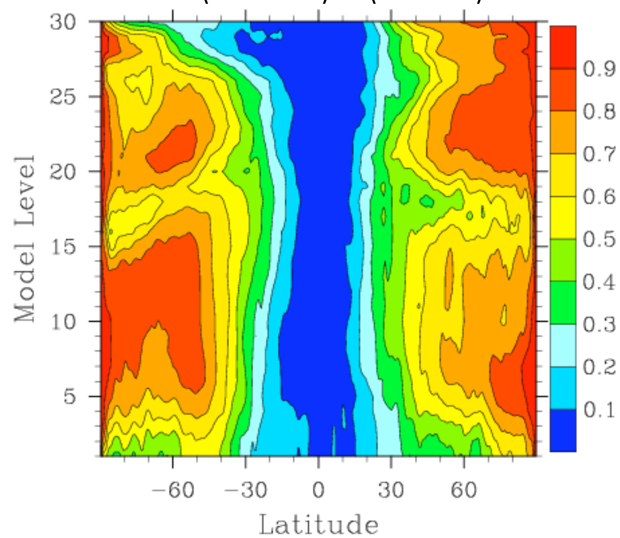
$$\chi_b' = c\psi' \qquad T_b'(k) = \sum_{k1} G(k,k1)\psi'(k1) \qquad p_{sb}' = \sum_k W(k)\psi'(k)$$

Explained covariance due to balance constraints (Jan 2004 data - NMC-method applied):

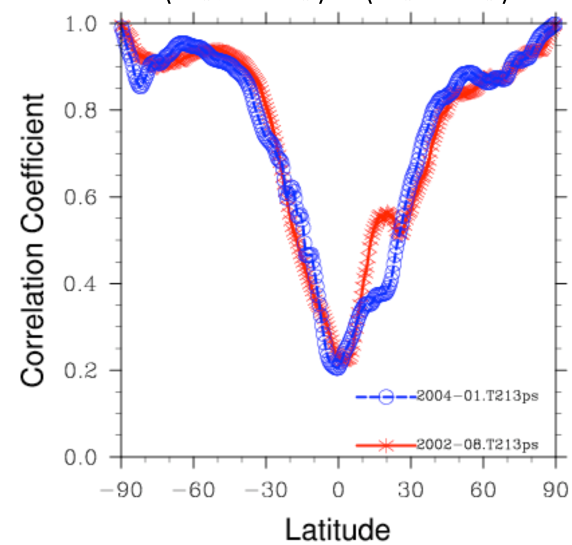
$\langle \chi_b \bullet \chi \rangle / \langle \chi \bullet \chi \rangle$



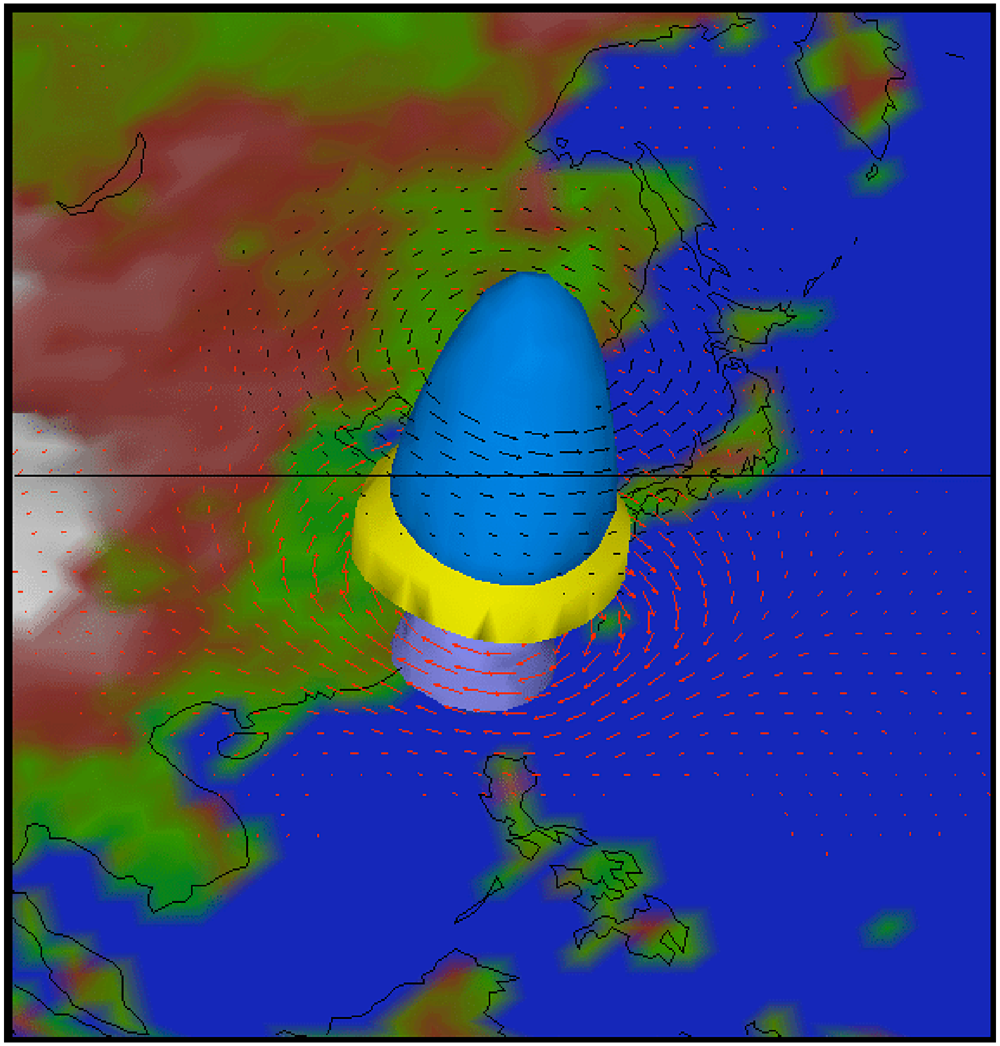
$\langle T_b \bullet T \rangle / \langle T \bullet T \rangle$



$\langle p_{sb} \bullet p_s \rangle / \langle p_s \bullet p_s \rangle$



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).

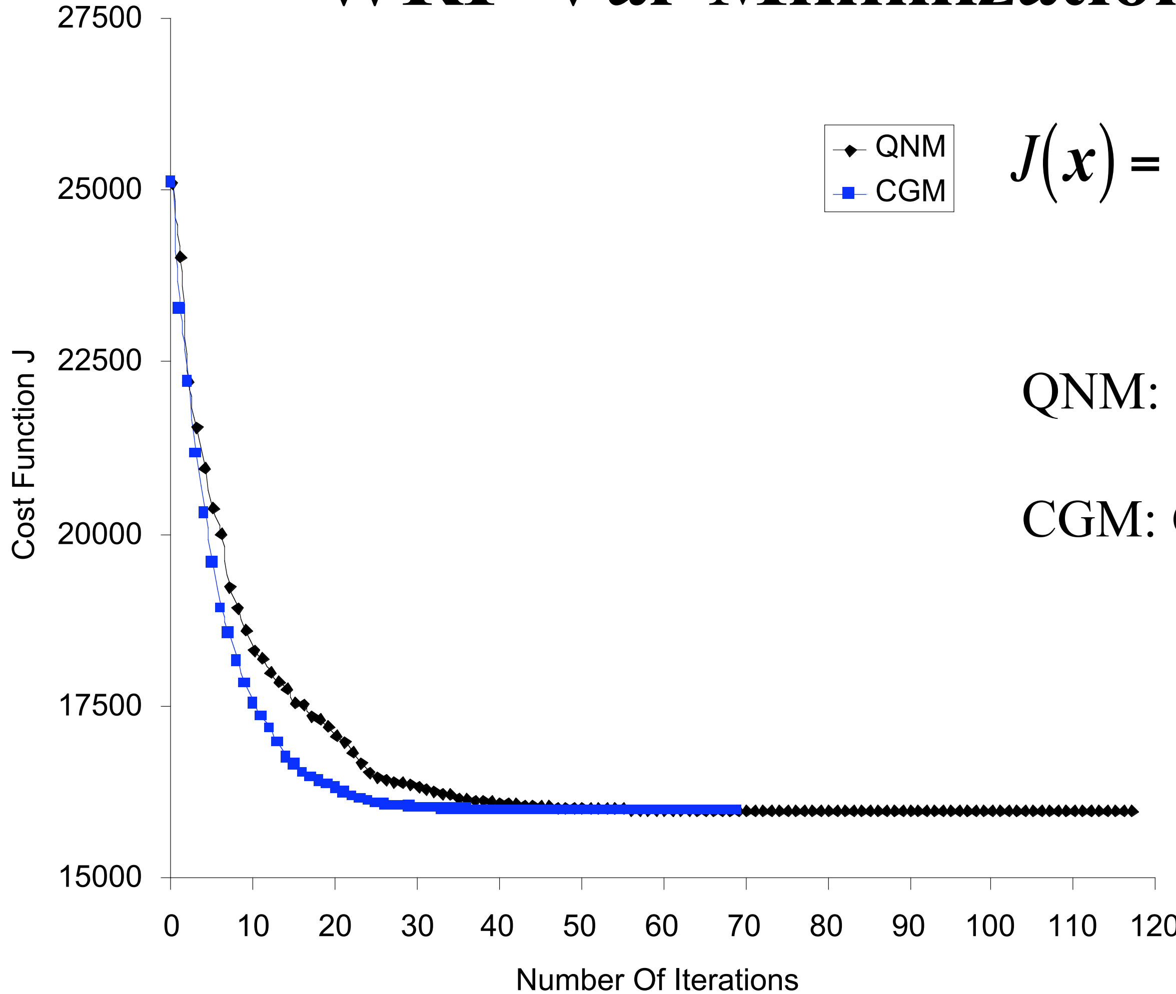
Yellow = T (1K).

Purple=Pressure(1hPa).

Red = Wind Circulation at k=5.

Black = Wind Circulation at k=25.

WRF-Var Minimization Example



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

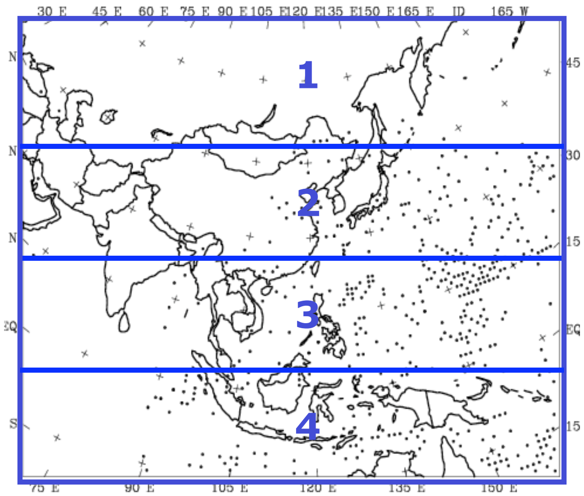
QNM: Quasi-Newton Method.

CGM: Conjugate Gradient Method.

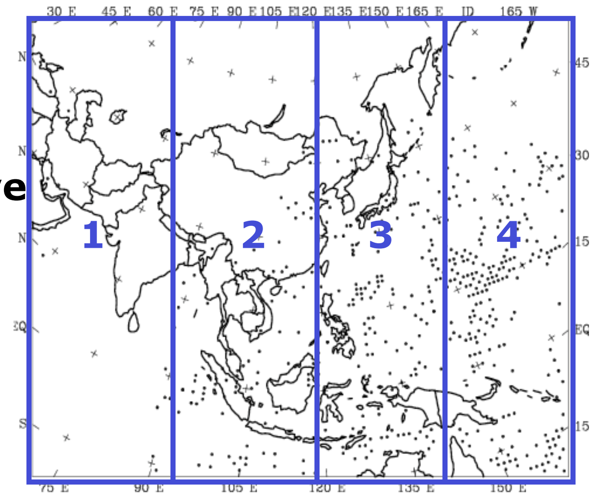
Convergence obtained when gradient < 0.001starting gradient.

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

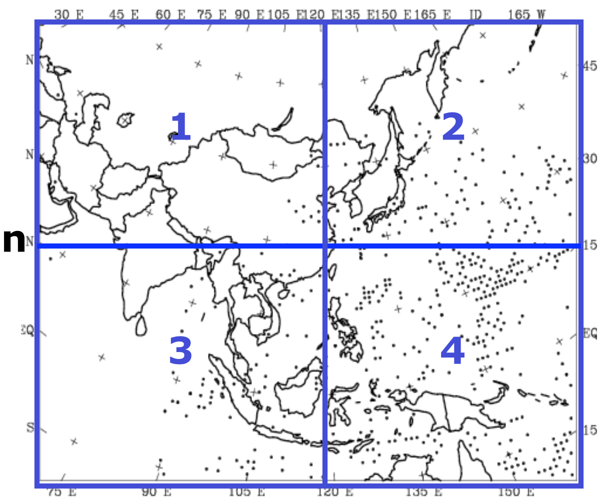
WRF-Var Multi-Processor Decomposition (e.g. np=4)

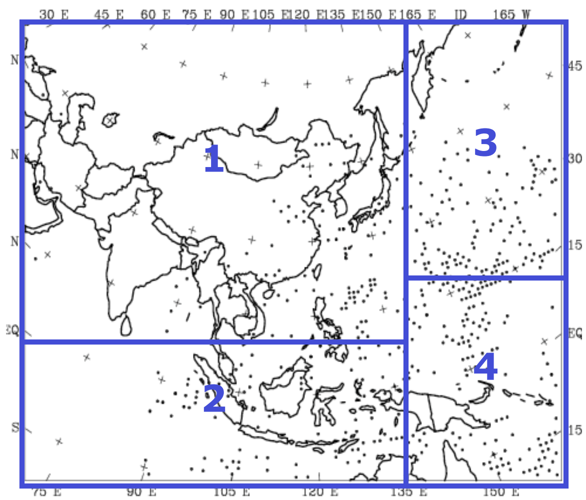


Recursive Filter and FFTs



Minimization and Forecast Model





Observation Operators

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.)

3. Observations

WRF-VAR Observations Used (May 2005)

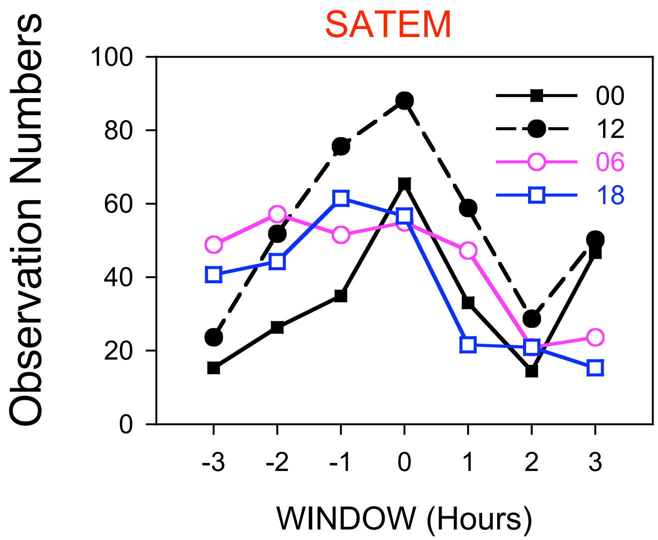
- Conventional:
  - Surface (SYNOP, METAR, SHIP, BUOY).
  - Upper air (TEMP, PIBAL, AIREP, ACARS).

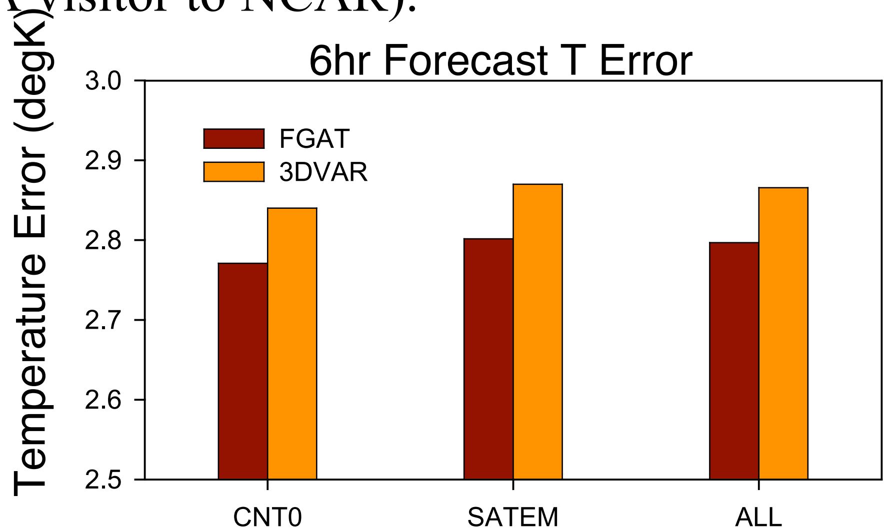
- Remotely sensed retrievals:
  - Atmospheric Motion Vectors (SATOBS, MODIS).
  - Ground-based GPS TPW/ZTD.
  - SSM/I oceanic surface wind speed and TPW.
  - Scatterometer (Quikscat) oceanic surface winds.
  - Wind Profiler.
  - Radar radial velocity and reflectivity.
  - ATOVS/AIRS/MODIS temperature/humidities (SATEMs).
  - GPS "local" refractivity.

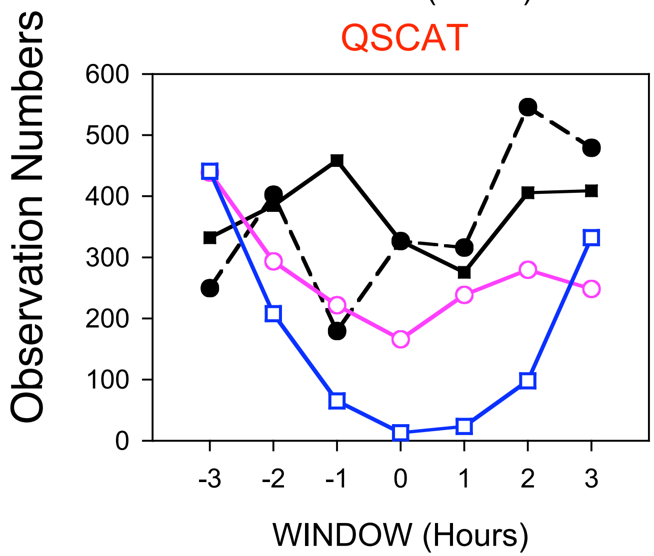
- Radiances:
  - SSM/I brightness temperatures (Shu-hua Chen).
  - AMSU/GOES/AIRS (under development).

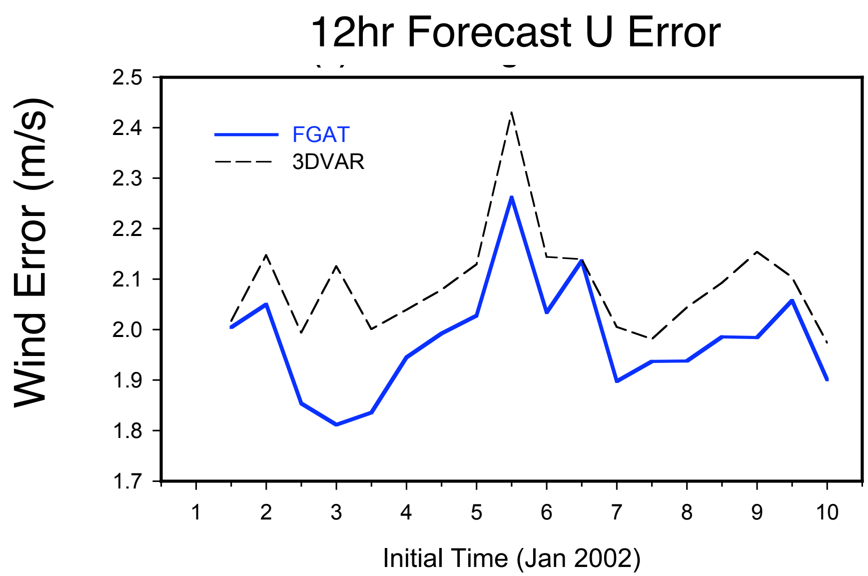
First Guess at Appropriate Time (FGAT)

- Principle: Compare observations with first guess forecast valid at time of observation
- Results courtesy of Mi-Seon Lee (KMA visitor to NCAR).









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”*

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

Combines thermodynamic, continuity and hydrostatic equations….

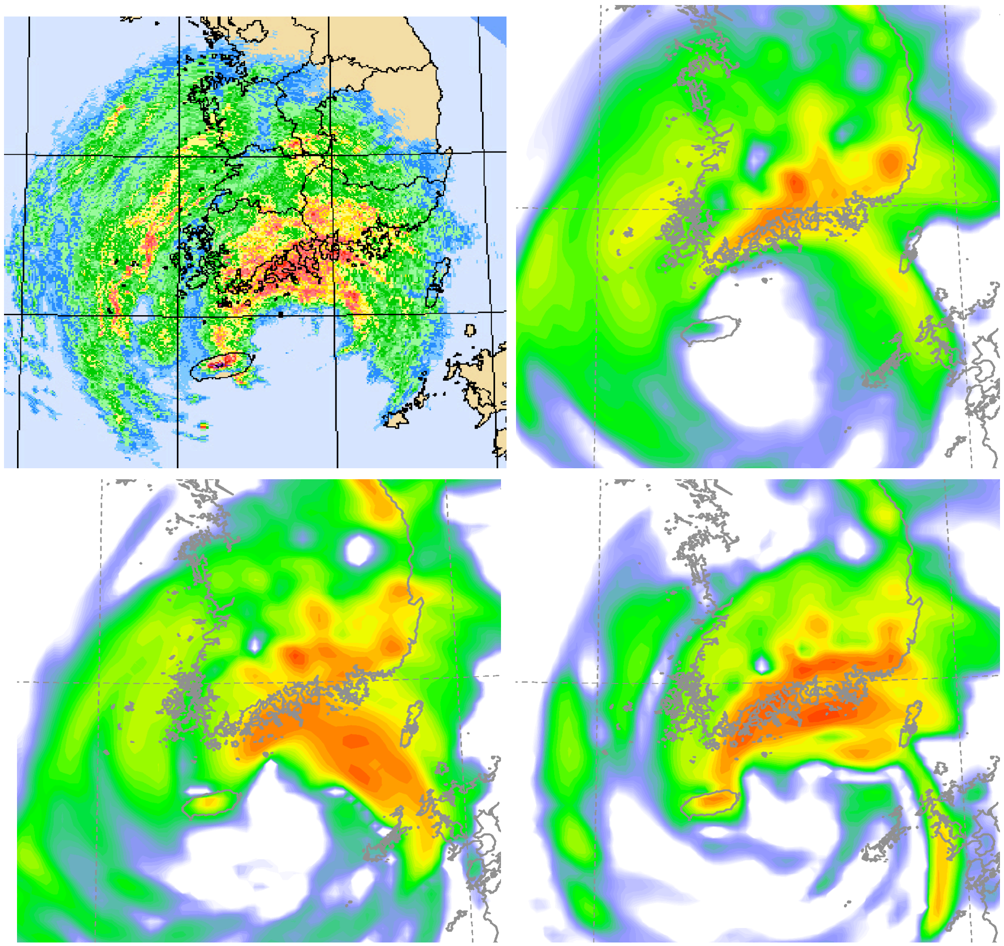
- *Linearize continuous eqn., then discretize (assume Q=0 for now):*

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

Korean Radar Data Assimilation in WRF 3D-Var

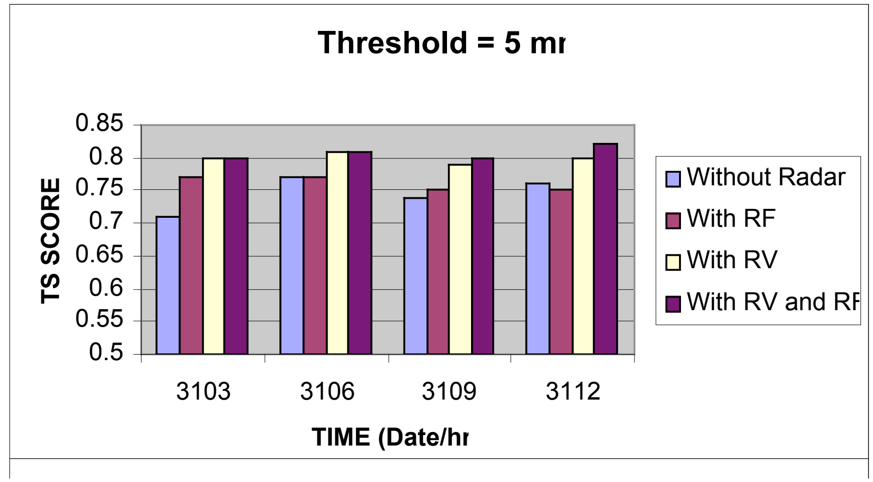
Typhoon Rusa Test Case 3hr Precip:

Obs (03Z, 31/08) No Radar

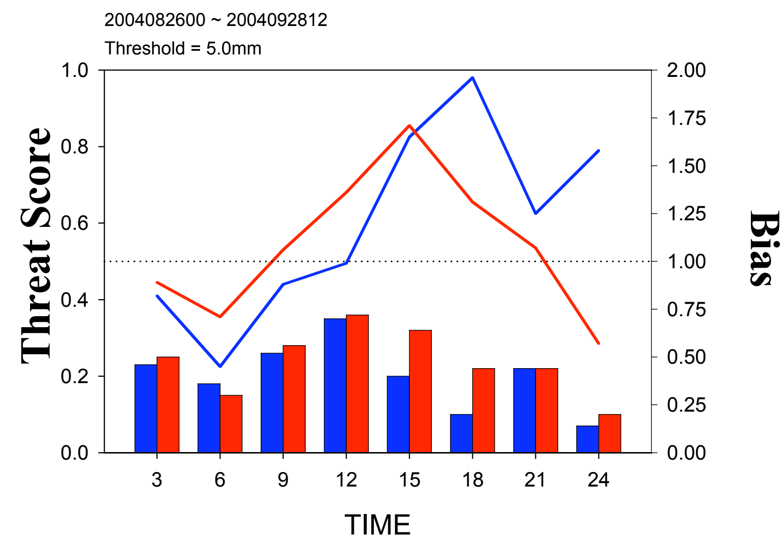


Radar RV Radar RV+RF

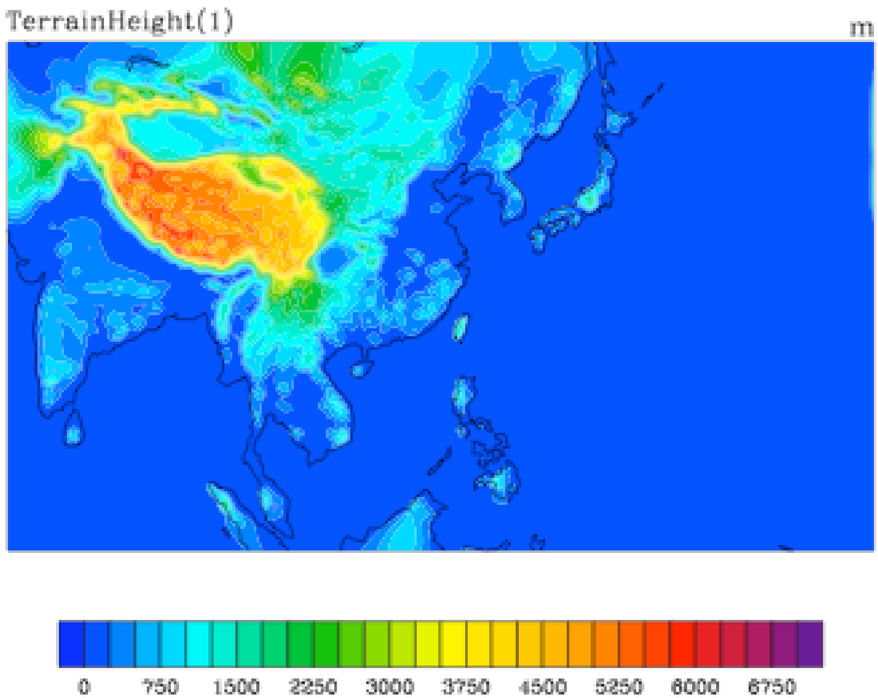
Typhoon Rusa 3hr Precip. Verification:



KMA Pre-operational Verification:
(no radar: blue, with radar: red)



Typhoon Dujuan GPS Refractivity Assimilation (preliminary results from Yong-Run Guo NCAR/MMM)



WRF Domain Info:

- 222x128x31 gridpoints.
- Resolution=45km.
- dt=270 sec.

Observations:

- Conventional + CHAMP level2 wetPrf data within 6 hour time window centered at 1200 UTC 30 and 1200 UTC 31 August 2003.

GPS Local Refractivity Observation Operator

The refractivity N is

$$N = 77.6 \times \frac{p}{T} + 3.73 \times 10^{5} \times \frac{pq}{T^{2}\left(0.622 + 0.378q\right)}$$

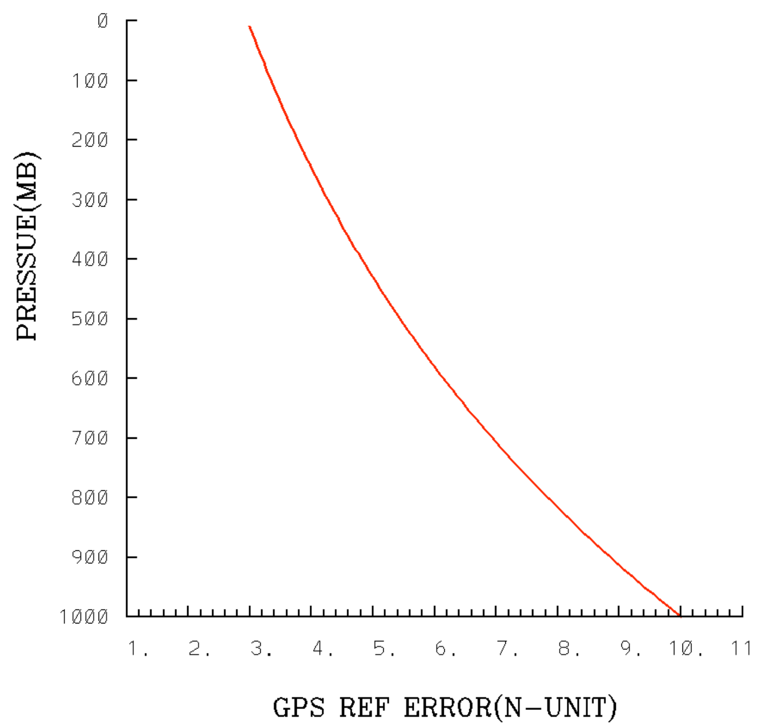
where p is the pressure in mb, T in the temperature in K, and q is the specific humidity in kg/kg (Zou et al 1995).

GPS Local Refractivity Observation Errors

- GPS local refractivity observation error based on Huang et al (2004)

$$Error = N\_bottom \times e^{\left(\frac{p-p_0}{a}\right)}$$

$$a = \frac{p_t - p_0}{\log\left(\frac{N\_top}{N\_bottom}\right)}$$



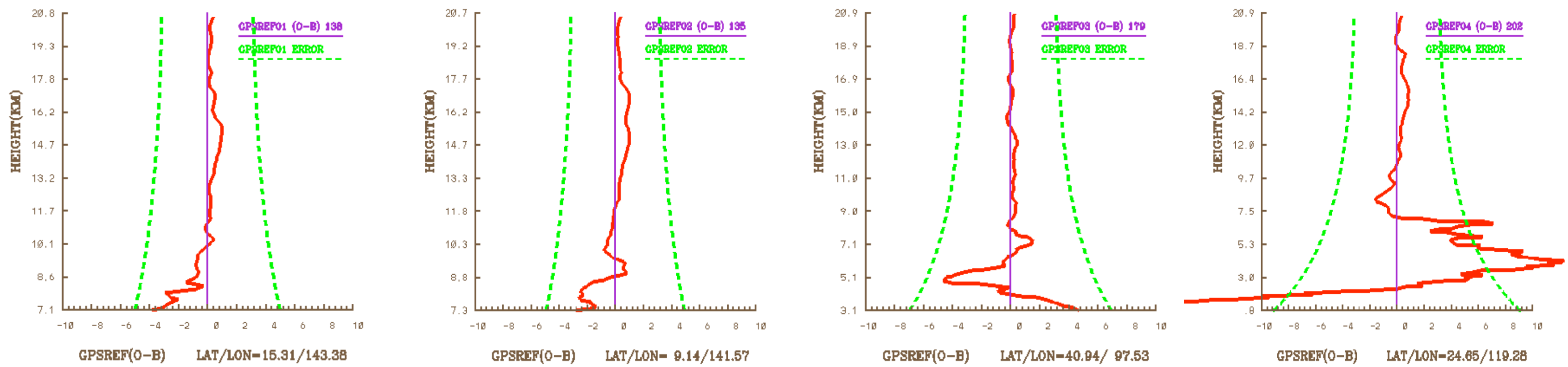
where *N_bottom* = 10 and *N_top* = 3 N-units. p_0 = 1000mb, p_t = 10mb, and *p* is the pressure at the observed level.

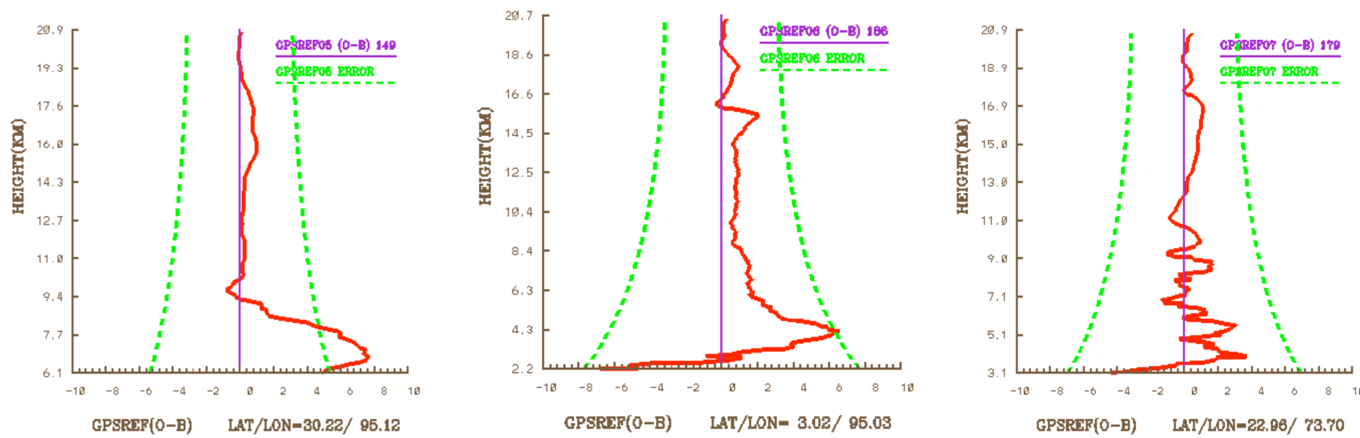
Future work: Refine the ***N*** error specification varying with the latitude, altitude, and season, etc (Kuo et al 2004).

NCAR

Mesoscale & Microscale Meteorology @ NCAR

- **Innovations (O-B) of GPS refractivity with NCEP analysis as the first guess and the observation errors**





- In most cases, the innovations are less than the observation errors.
- The large (O-B) values located below 8-km.

WRF 3D-Var experiments for Typhoon Dujuan

CNTRL : No assimilation, initiated with NCEP AVN analysis
3DREF : Assimilation of GPS Refractivity only
3DCWB : Assimilation of CWB observations (SOUND, AIREP, SYNOP. SHIPS, PILOT, SATOB, SATEM, METAR).
3DCWBREF : Assimilation of CWB observations + GPS refractivity.

Physics:
WSM 3-class simple ice scheme,
RRTM for long wave radiation
Dudhia scheme for short wave radiation,
MOnin-Obukhov surface layer
Thermal diffusion land-surface
YSU PBL
Kain-Fritsch (new Eta) scheme

WRF-Var FirstGuess = NCEP Analysis.

Background Error Statistics = "Global" default values derived from NCEP GFS forecasts and NMC-method.

Initial times are 1200 UTC 30 and 1200 UTC 31 August 2003.

Typhoon Dujuan Track Forecast Errors

Experiment	2003083012Z			2003083112Z		
	24-h(km)	48-h(km)	72-h(km)	24-h(km)	48-h(km)	72-h(km)
CNTRL	69.2	**67.1**	221.1	110.2	115.7	_
3DREF	69.8	85.8	**214.2**	115.1	120..7	_
3DCWB	58.5	89.3	259.1	**103.6**	**104.9**	_
3DCWBREF	**52.5**	79.8	260.0	105.6	108.1	_

This table shows the averaged track forecast errors for three 24-h periods ending at 24, 48, and 72 h. We have 3-hourly forecast positions for Typhoon Dujuan, so in each of 24-h periods, there are 8 forecast positions. The values shown in Table are obtained by averaging over eight 3-h errors. Except the 48-h initiated at 2003083012Z, the 3D-Var experiments gave better results than control.

Dale: Statistical Significance? Need more cases, and cycling.

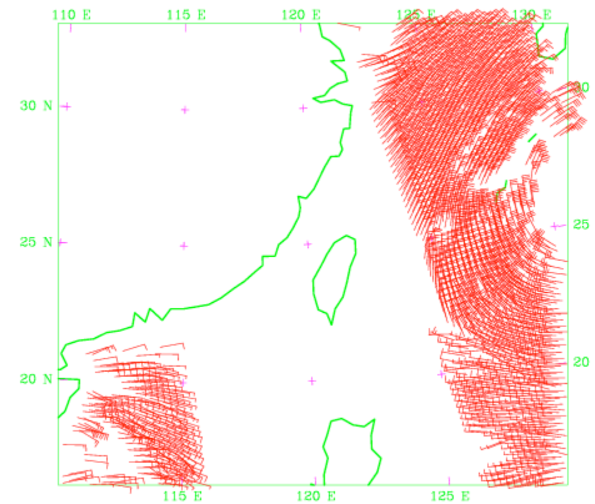
Also more sophisticated error specification, “nonlocal” operator.

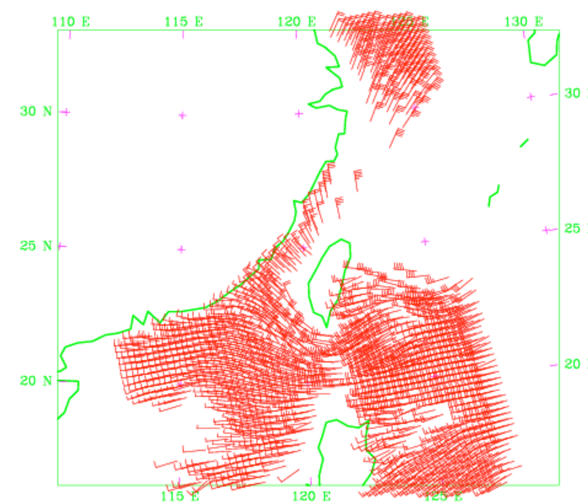
4. Current Status and Future Plans

WRF-Var Version 2.1 (Release June 2005)

- First Guess at Appropriate Time (FGAT).
- New obs: Radar reflectivity, GPS refractivity, AIRS/MODIS temperature retrievals, MODIS atmospheric motion vectors.
- Global 3D-Var capability.
- New utility *gen_be* to calculate local background error statistics.
- Platforms: IBM-SP, DEC, Linux (Alpha, PC), SGI, Cray X1, Mac G4/G5.
- Initial WRF 4D-Var modifications.

MMM WRF Data Assimilation Plans





WRF-Var:

- Further development of radar, GPS refractivity assimilation.
- Initial 4D-Var capability for AFWA (October 2005).
- AMSU radiance assimilation (December 2005).
- Operational global application at KMA (June 2006).
- 4D-Var operational at AFWA (October 2007).

EnKF:

- Assimilation of reflectivity (particularly low reflectivity).
- Case-studies, particularly including mesoscale predictability.
- Further comparison of EnKF and variational schemes.
- Assimilation of hurricane position.

Unified WRF Data Assimilation System:

- Combines variational and ensemble-based techniques.
- Leverages satellite radiance expertise of JCSDA, universities.
- Suitable for MMM research, operations, and university community use.