WRF Variational Data Assimilation System (WRF-Var) Overview

WRF Tutorial Presentation

NCAR, Boulder, Colorado

July 26th 2007

Dale Barker (dmbarker@ucar.edu)

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) Background Error Modeling.

4) Observational Issues.

5) Current Status and Future Plans.

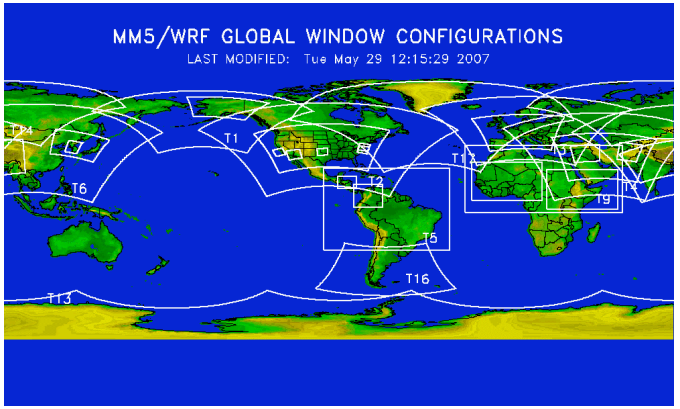
1. What is WRF-Var?

…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….

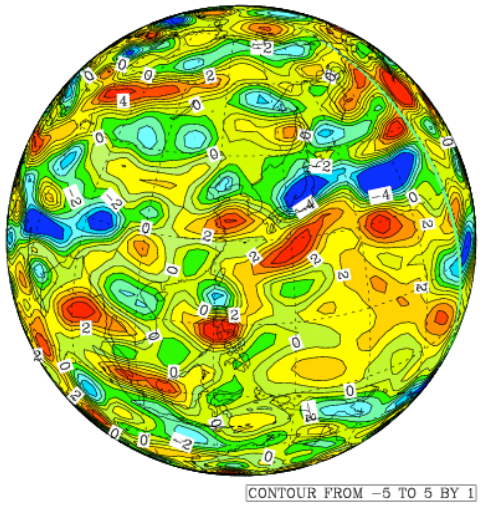
WRF-Var Data Assimilation Overview

- **Techniques:** 3D-Var, 4D-Var (regional), Hybrid Variational/Ensemble DA.
- **Software Engineering:** WRF framework.
- **Multiple Models:** Runs with WRF, MM5, KMA global model, etc.
- **Support:** MMM Division, NCAR.
- **Applications:** Regional/global, Research/Operational, Deterministic/Ensemble,

AFWA Worldwide Theaters

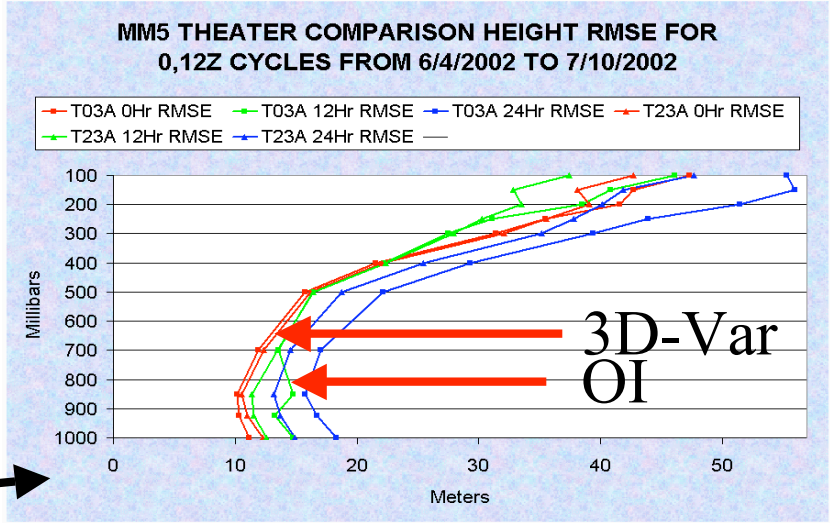


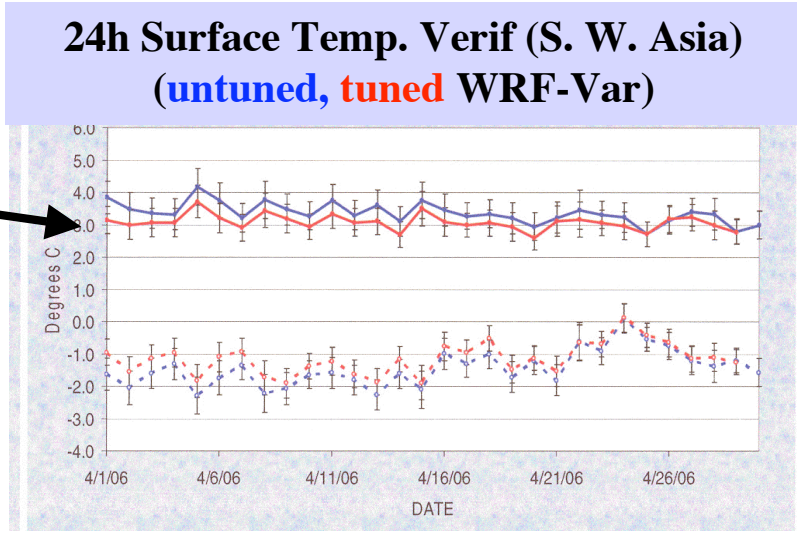
KMA T213/426 Global:



WRF Variational Data Assimilation (WRF-Var) History

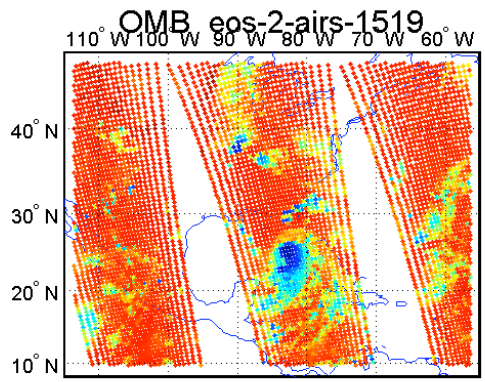
- **June 2001:** MM5-3DVar adopted as starting point for WRF 3D-Var.
- **May 2002:** MM5/WRF 3D-Var operational in Taiwan.
- **September 2002:** MM5/WRF 3D-Var operational in 45km domains at AFWA.
- **June 2003:** First public release of WRF-Var.
- **July 2006:** WRF-ARW/WRF-Var operational in AFWA 15km domains.
- **May 2007:** WRF-Var/ARW operational in Korea 10km domain
- **March 2008:** WRF-Var/WRF V3.0

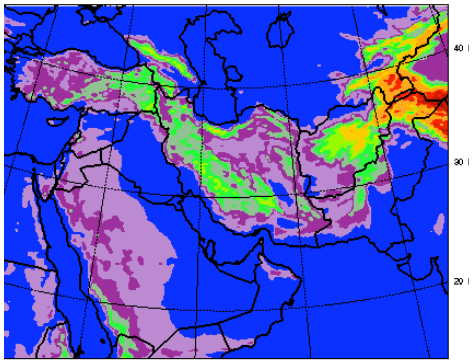


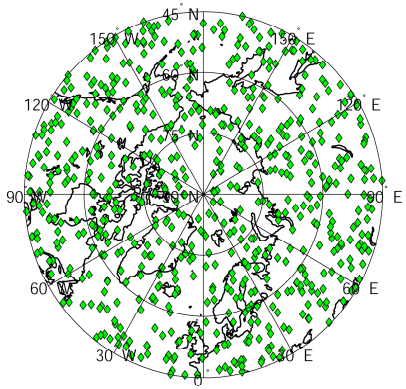


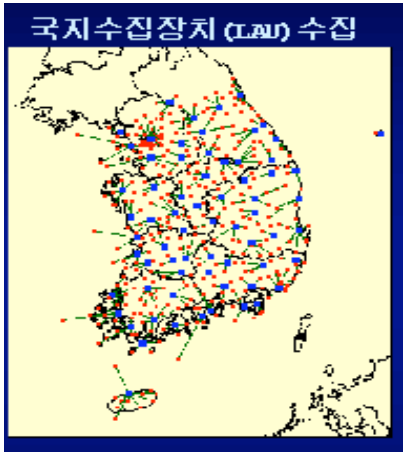
The WRF-Var Program

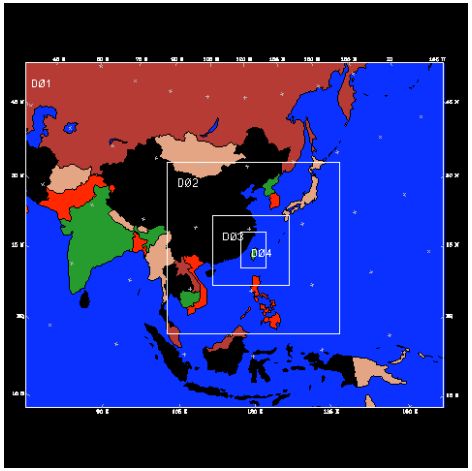
- NCAR staff: 23FTE, ~12 projects.
- Non-NCAR collaborators (AFWA, KMA, etc): ~10FTE.
- Community users: ~30 (more in 4000 general WRF downloads?).

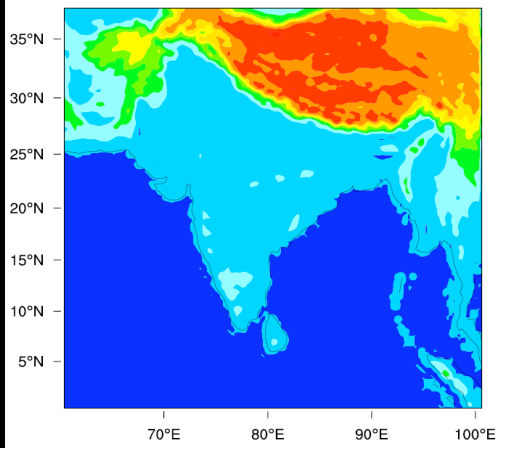


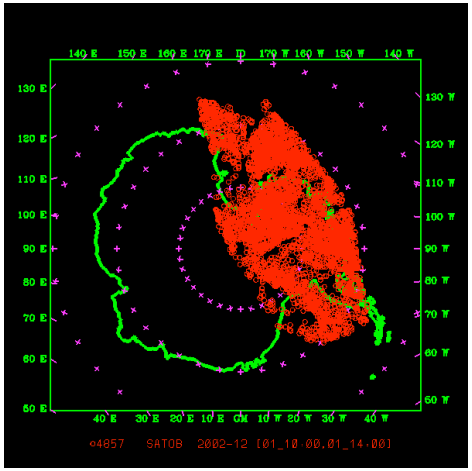


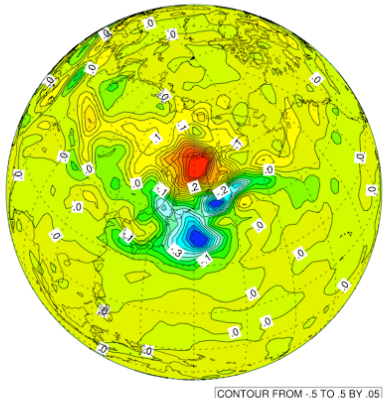








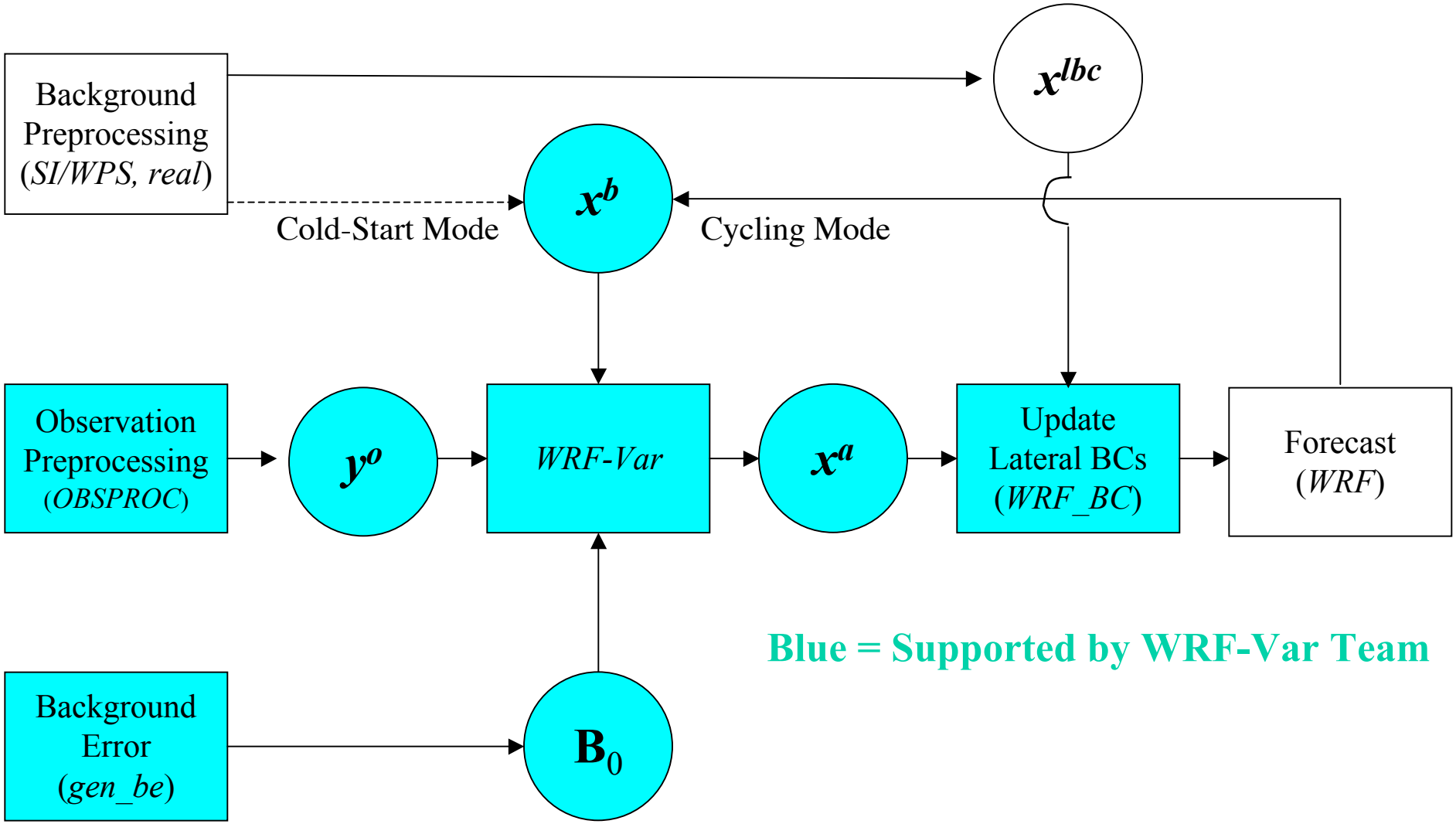




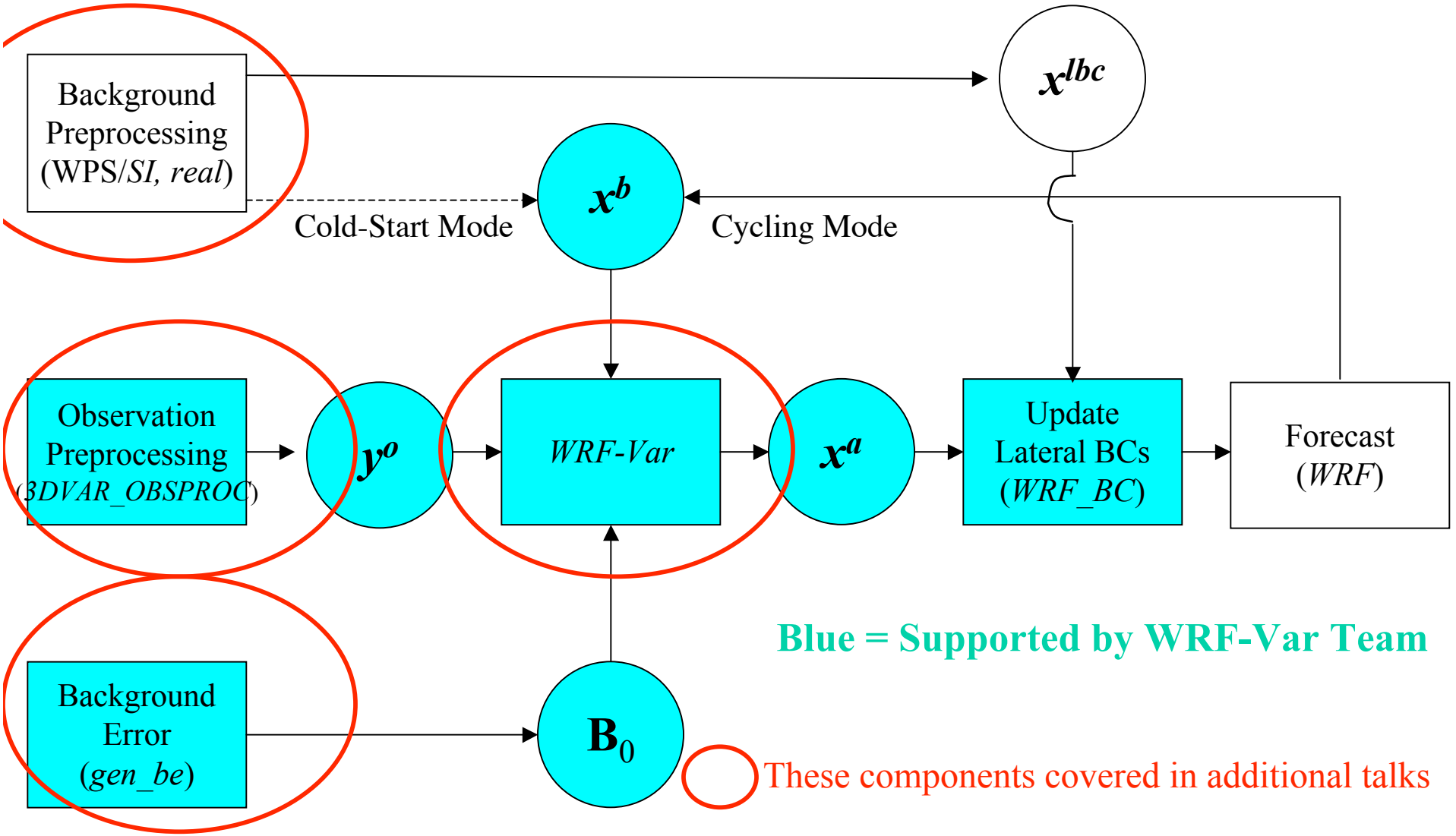
New Features Of WRF-Var Version 2.1 (Release July 2005)

- 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-Var in the WRF Modeling System



WRF-Var in the WRF Modeling System

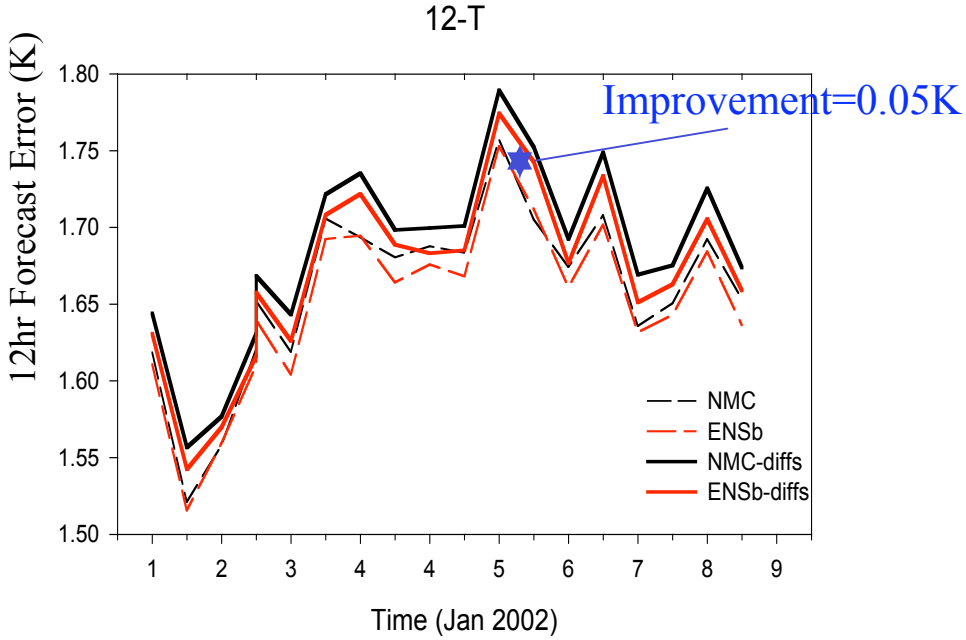


Importance of Data Assimilation For General WRF Development/Testing

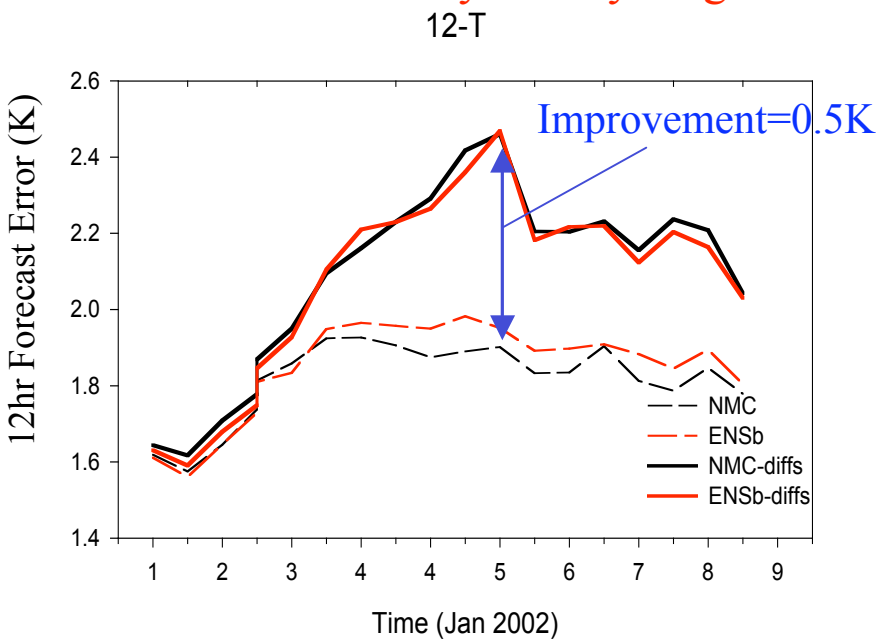
Experiment (Mi-Seon Lee, KMA):

- Test undisclosed change to WRF modeling system.
- 40km WRF CONUS application. Solid = Control, Dashed = Test.
- Use January 2002 conventional data for cycling.

Without DA Cycling



With 12hourly DA Cycling



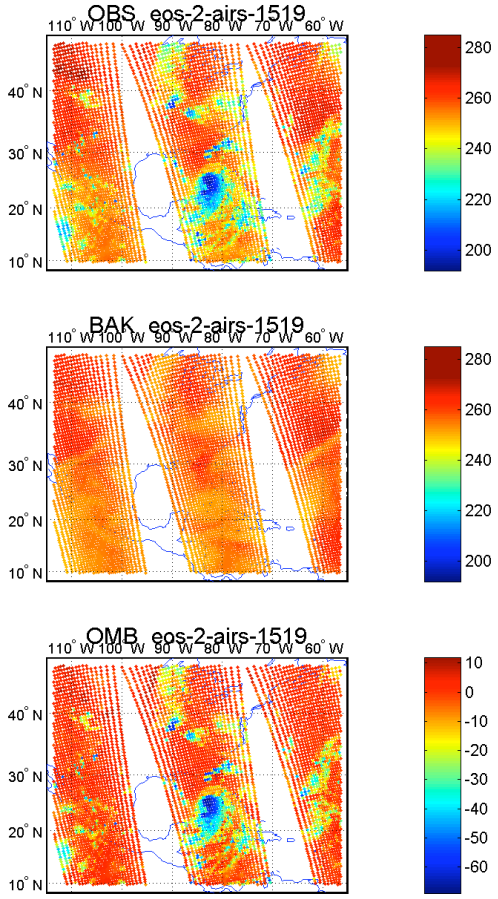
2. Practical Variational Data Assimilation

What Is Data Assimilation?

- Assimilation system combines:
  - Observations - $\boldsymbol{y^o}$
  - Previous forecast ("background field $\boldsymbol{x^b}$)
  - Estimate of observations/forecast errors.
  - Laws of physics.

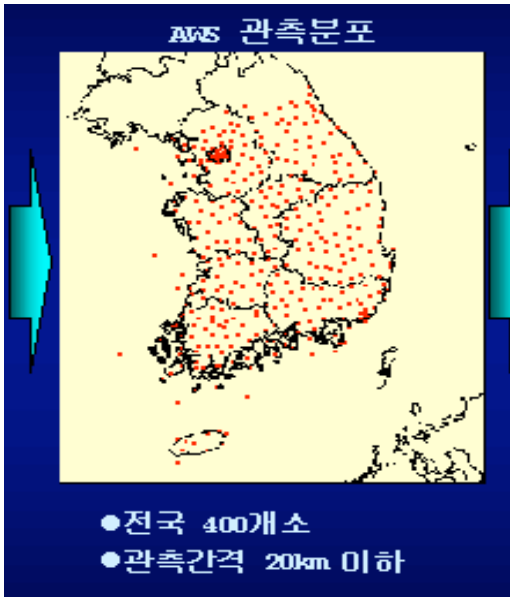
- Assimilation system outputs an "analysis".

- Analysis used in a number of ways:
  - Initial conditions for numerical forecasts.
  - Climatology - reanalyses.
  - Observing system design (e.g. OSSEs).



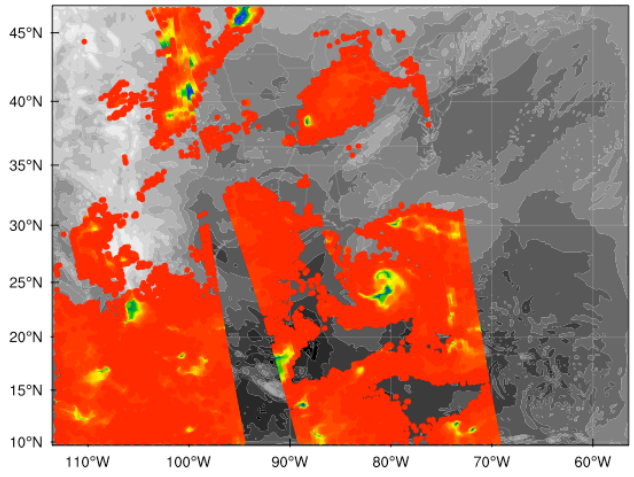
Need For Data Assimilation in NWP

Fact: There are never enough good observations!!



- Consider NWP model:
  - Typical global model – 425 * 325 * 50 = 7 million gridpts.
  - Minimum number of 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.
  - Use previous forecast to propagate past observations.
  - Use approximate physical balance relationships.
  - More/better observations!

Variational Data Assimilation

• Variational data assimilation systems attempt to find an analysis $\boldsymbol{x}^a$ that minimizes a cost-function

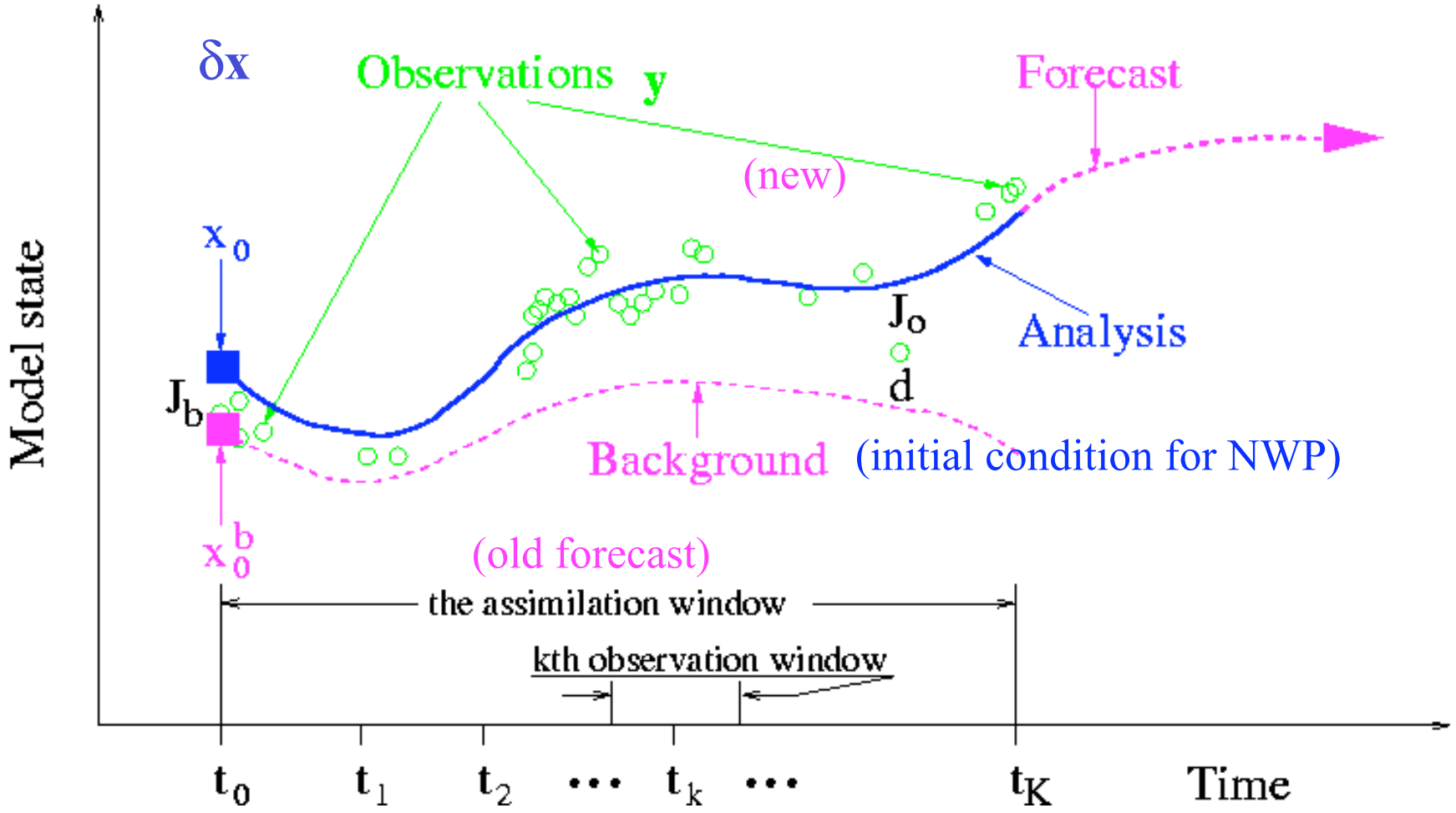
$$J = J_b + J_o$$

• Three-Dimensional Variational Data Assimilation = 3D-Var (first implemented at NCEP - Parrish and Derber 1992).

• Four-Dimensional Variational Data Assimilation = 4D-Var. First implemented at ECMWF - Rabier et al. 2000).

•4D-Var includes the time dimension by including the forecast model as part of the data assimilation system.

4D Variational Data Assimilation



Variational Data Assimilation

- The components J_b and J_o of the cost function are defined as

$$J_b\left[\mathbf{x}\left(t_0\right)\right] = \frac{1}{2}\left[\mathbf{x}\left(t_0\right) - \mathbf{x}^b\left(t_0\right)\right]^T \mathbf{B}_o^{-1}\left[\mathbf{x}\left(t_0\right) - \mathbf{x}^b\left(t_0\right)\right]$$

$$J_o\left[\mathbf{x}\left(t_0\right)\right] = \frac{1}{2}\sum_{i=0}^{n}\left[\mathbf{y}_i - \mathbf{y}_i^o\right]^T \mathbf{R}_i^{-1}\left[\mathbf{y}_i - \mathbf{y}_i^o\right]$$

- $\mathbf{B_0}$ is an *a priori* weight matrix estimating the error covariance of $\mathbf{x^b}$.

- $\mathbf{R_i}$ is the observation error covariance matrix at time *i*.

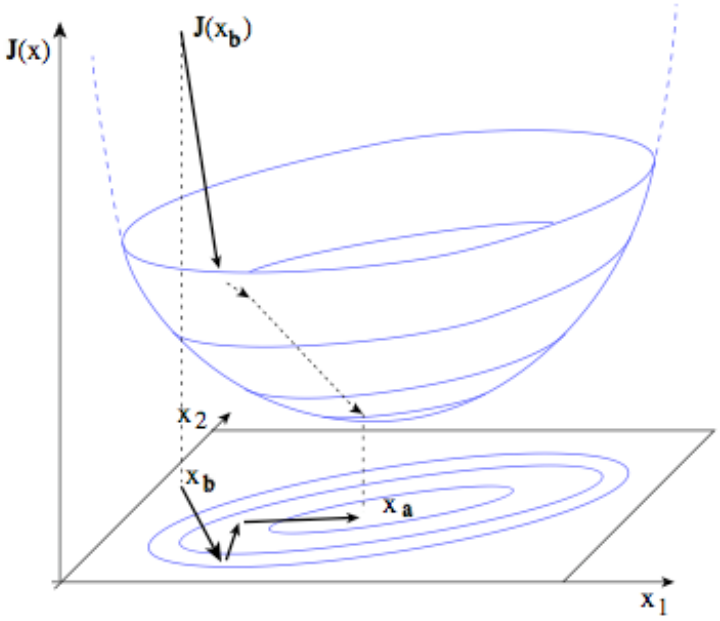
- Direct calculation of J_b and J_o impossible for NWP problems ($\mathbf{B_0}$, $\mathbf{R}$ are matrices of dimension 10^7). Therefore many practical simplifications required.

- *Incremental Var* produces analysis increments that are added back to a *first guess* field $\mathbf{x^g}$ to produce the analysis, i.e.

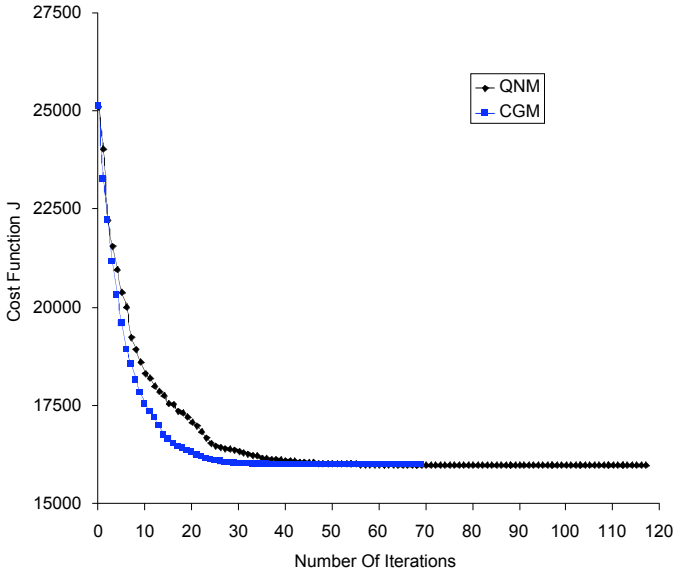
$$\mathbf{x}^a\left(t_0\right) \equiv \mathbf{x}^g\left(t_0\right) + \delta\mathbf{x}\left(t_0\right)$$

Minimization Of The Cost Function

- Minimization of the cost function proceeds iteratively.



From Bouttier and Courtier (1999)



From WRF-Var tutorial

- "Convergence" achieved when either 1) Maximum iterations reached, 2) Ratio final/initial gradient hits a specified criterion.

3. Background Error Modeling

Incremental WRF-Var J_b Preconditioning

$$J_b\left[\delta\mathbf{x}(t_0)\right] = \frac{1}{2}\left\{\delta\mathbf{x}(t_0) - \left[\mathbf{x}^b(t_0) - \mathbf{x}^g(t_0)\right]\right\}^T \mathbf{B}_o^{-1}\left\{\delta\mathbf{x}(t_0) - \left[\mathbf{x}^b(t_0) - \mathbf{x}^g(t_0)\right]\right\}$$

- *Define* ***preconditioned control variable*** ***v*** space transform

$$\delta\mathbf{x}(t_0) = \mathbf{U}\mathbf{v}$$

where **U** transform CAREFULLY chosen to satisfy $\mathbf{B_o} = \mathbf{U}\mathbf{U}^T$.

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

$$J_b\left[\delta\mathbf{x}(t_0)\right] = \frac{1}{2}\sum_n v_n^2$$

- where n~number pieces of independent information.

WRF-Var Background Error Modeling

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	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	RF	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	
Horizontal Correlations	U_h	RF		Spectral	RF
Control Variables	$\mathbf{v}$	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

$$\delta\mathbf{x}(t_0) = \mathbf{U}\mathbf{v} = \mathbf{U}_p\mathbf{U}_v\mathbf{U}_h\mathbf{v}$$

Up: Change of variable, impose balance.

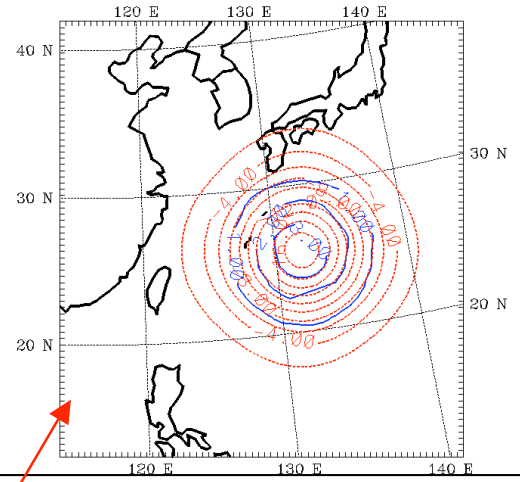
Uv: Vertical correlations EOF Decomposition

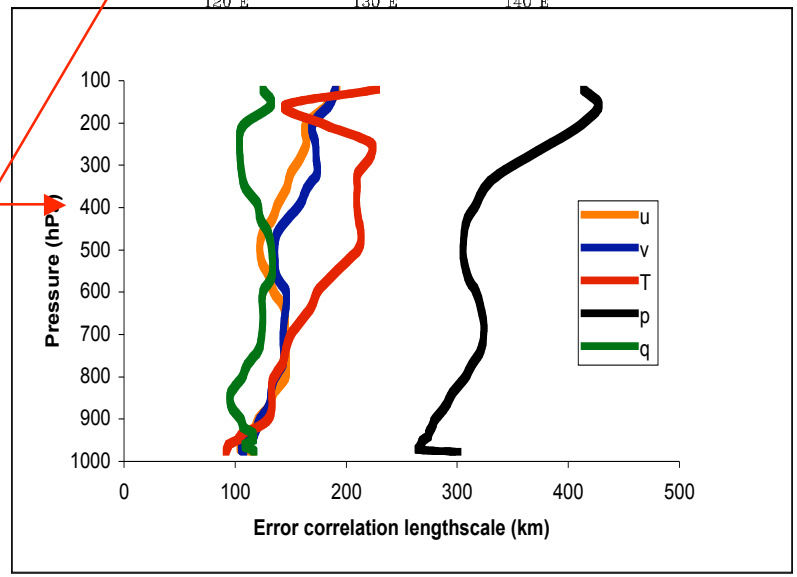
RF = Recursive Filter, e.g. Purser et al 2003

WRF-Var Background Error Modeling

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	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	RF	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	
Horizontal Correlations	U_h	RF		Spectral	RF
Control Variables	$\mathbf{v}$	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

$$\delta\mathbf{x}(t_0) = \mathbf{U}\mathbf{v} = \mathbf{U}_p\mathbf{U}_v\mathbf{U}_h\mathbf{v}$$

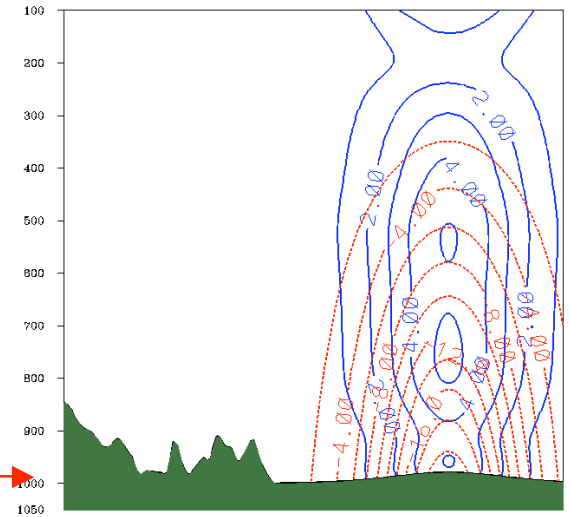


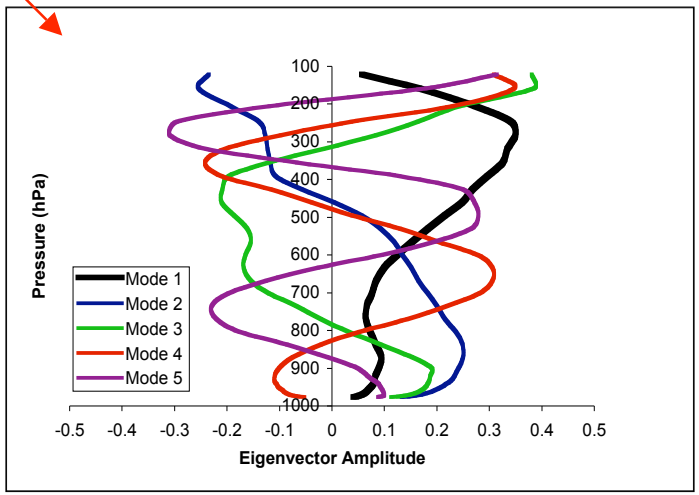


WRF-Var Background Error Modeling

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	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	RF	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	
Horizontal Correlations	U_h	RF		Spectral	RF
Control Variables	$\mathbf{v}$	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

$$\delta\mathbf{x}(t_0) = \mathbf{U}\mathbf{v} = \mathbf{U}_p\mathbf{U}_v\mathbf{U}_h\mathbf{v}$$





WRF-Var Background Error Modeling

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	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	RF	$\mathbf{B} = \mathbf{E}\Lambda\mathbf{E}^{\mathrm{T}}$	
Horizontal Correlations	U_h	RF		Spectral	RF
Control Variables	$\mathbf{v}$	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

$$\delta\mathbf{x}(t_0) = \mathbf{U}\mathbf{v} = \mathbf{U}_p\mathbf{U}_v\mathbf{U}_h\mathbf{v}$$

Define control variables:

$$\psi'$$

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

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

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

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

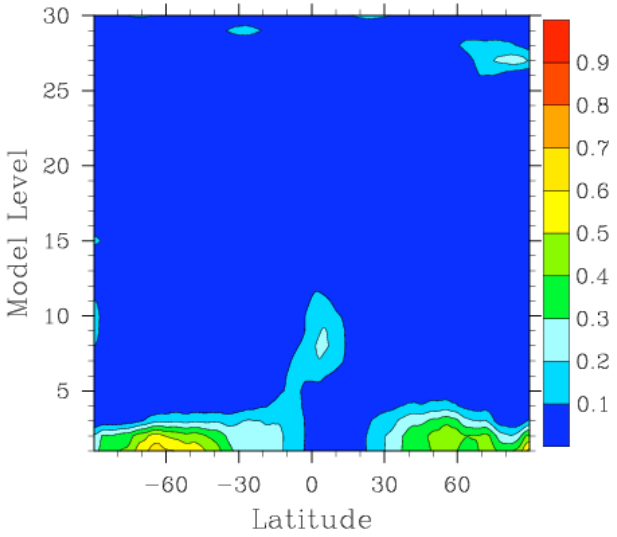
WRF-Var Statistical Balance Constraints

- Define statistical balance after Wu et al (2002):

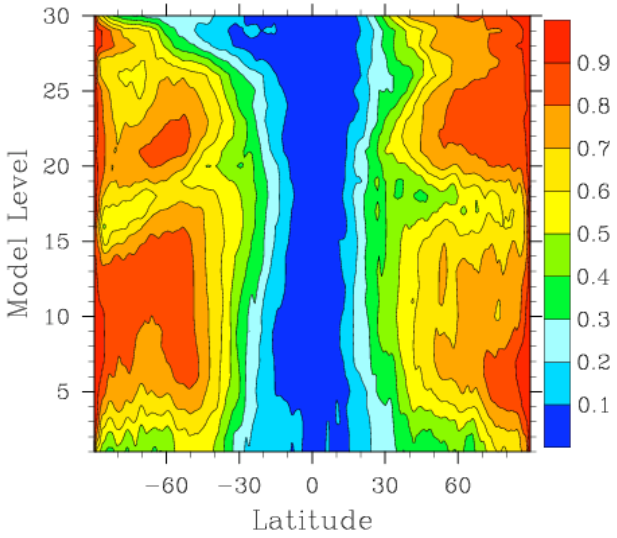
$$\chi_b^{'} = c\psi^{'} \quad T_b^{'}(k) = \sum_{k1} G(k,k1)\psi^{'}(k1) \quad p_{sb}^{'} = \sum_{k} W(k)\psi^{'}(k)$$

- How good are these balance constraints? Test on KMA global model data. Plot correlation between "Full" and balanced components of field:

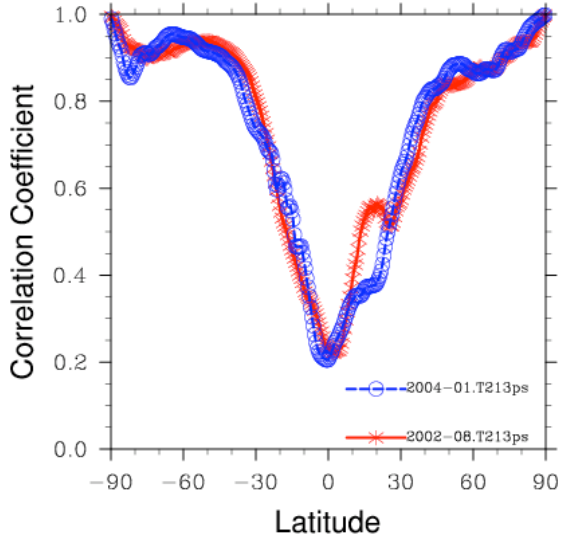
$\langle \chi_b \bullet \chi \rangle / \langle \chi \bullet \chi \rangle$



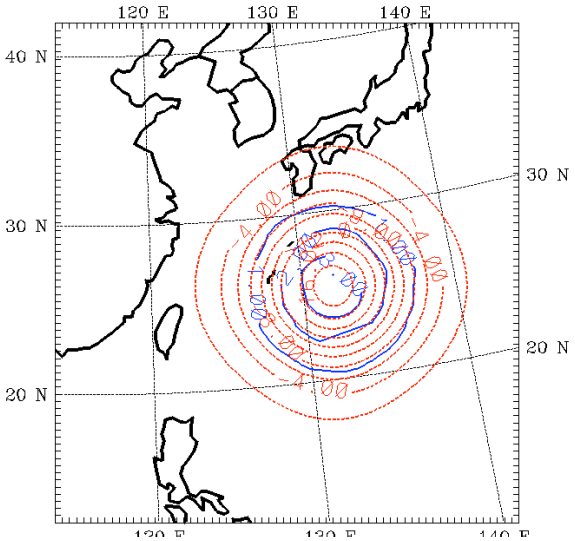
$\langle T_b \bullet T \rangle / \langle T \bullet T \rangle$



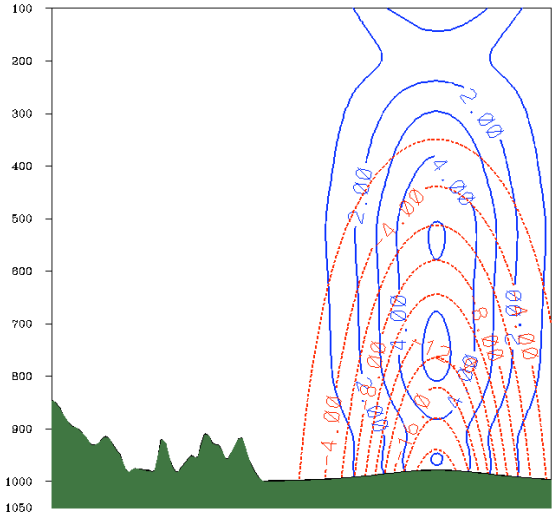
$\langle p_{sb} \bullet p_s \rangle / \langle p_s \bullet p_s \rangle$

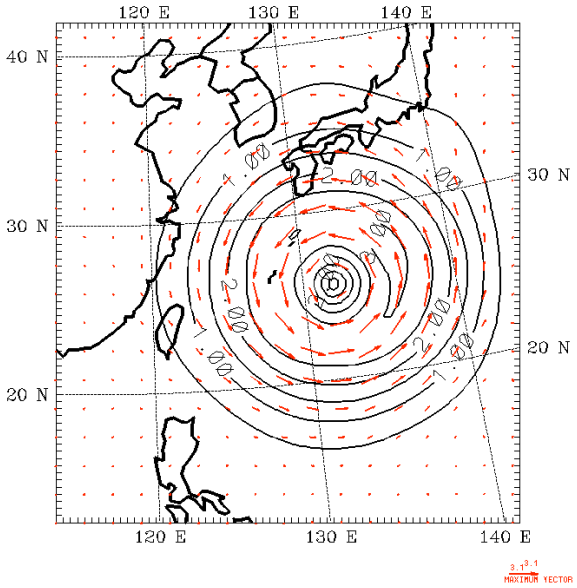


3D-Var response to a single P_s Observation

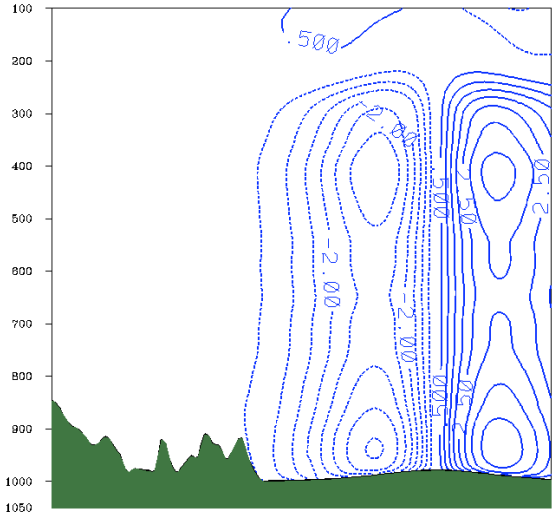


Pressure,
Temperature





Wind Speed,
Vector,
v-wind component.

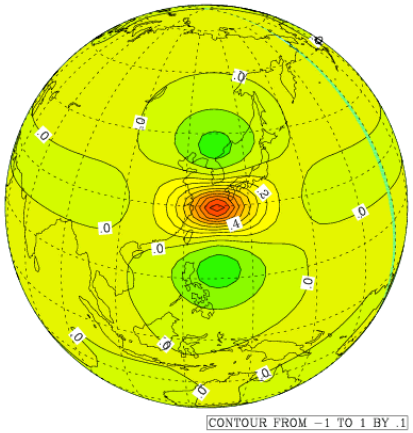


Global Applications of WRF-Var

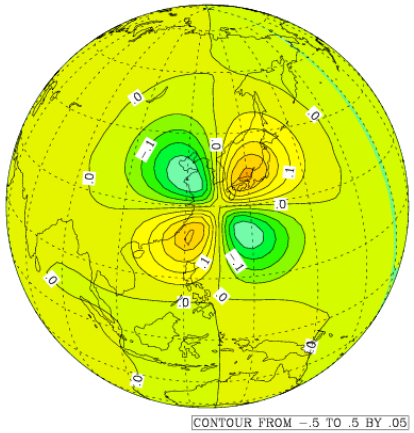
Major technical changes to regional system are

1. Periodic boundary conditions.
2. New global WRF Registry created.
3. Minor changes to treat pole as a special point.
4. Spectral-Grid transformation for horizontal error correlations (FFTPACK).

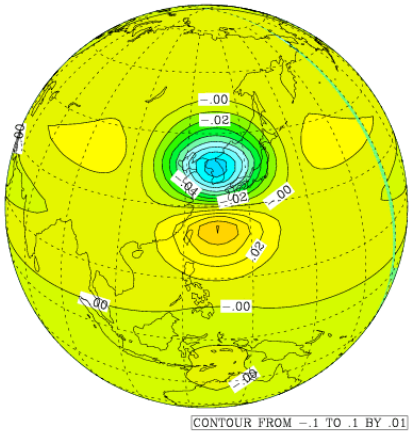
U-wind Observation (O-B = 1m/s, s_o = 1m/s) at 120E, 45N, level 15:



U



V

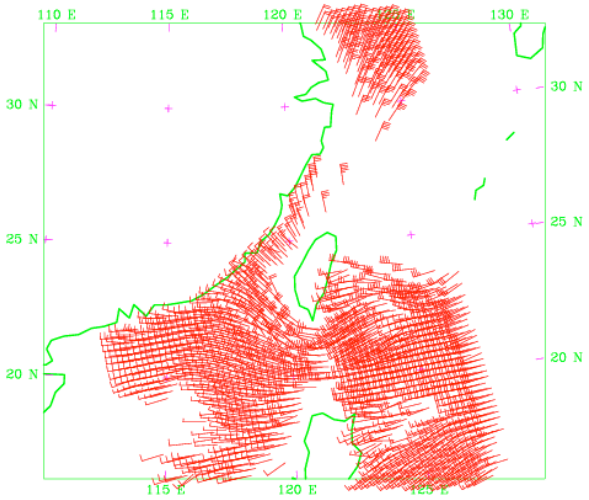


T

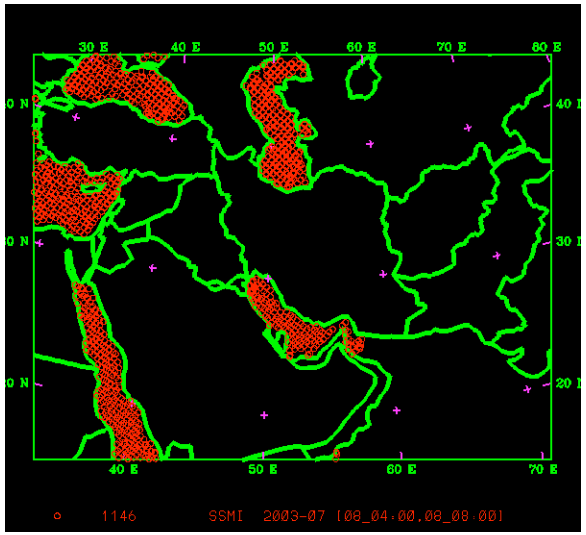
4. Observational Issues

WRF-Var Observations (August 2005, V2.1 Release)

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

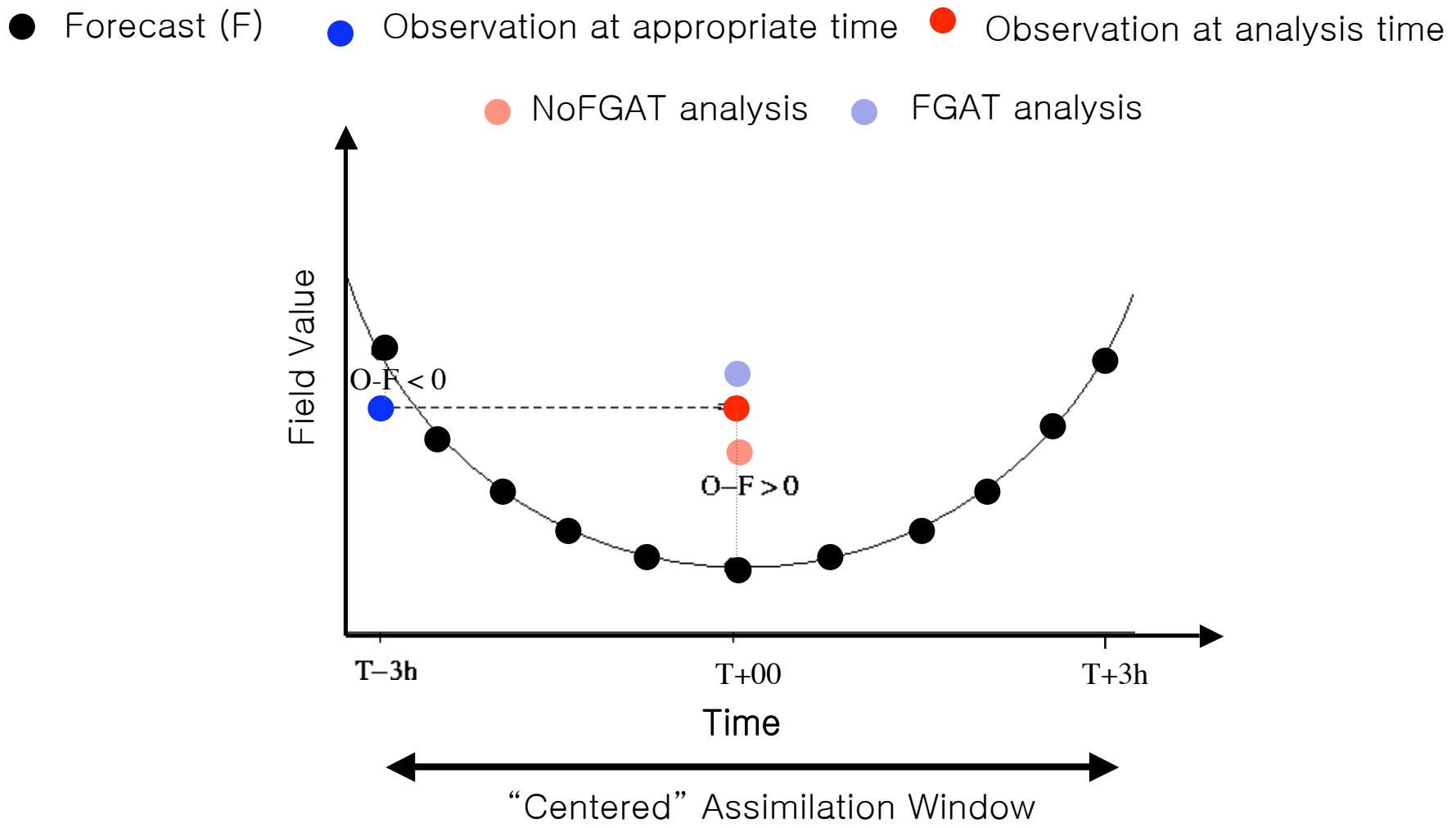


- Remotely sensed retrievals:
  - Atmospheric Motion Vectors (SATOBS, MODIS
  - Ground-based GPS Total Precipitable Water.
  - SSM/I oceanic surface wind speed and TPW.
  - Scatterometer (Quikscat) oceanic surface winds.
  - Wind Profiler.
  - **Radar radial velocity and reflectivity.**
  - ATOVS/AIRS/MODIS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



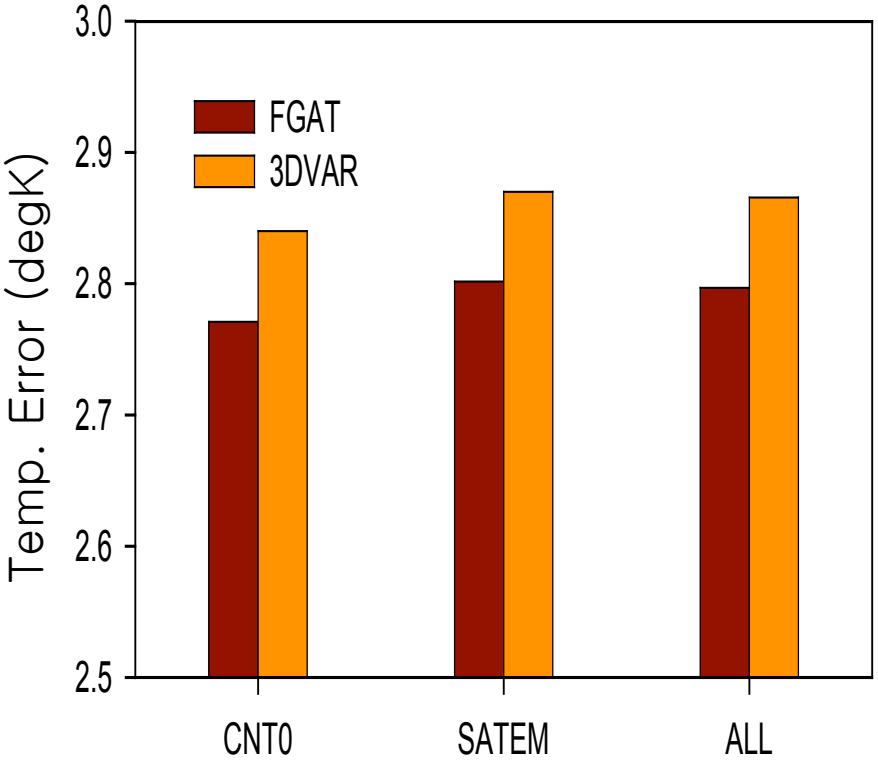
- Radiances:
  - SSM/I brightness temperatures (Shu-Hua Chen).

3D-Var FGAT: First Guess at Appropriate Time

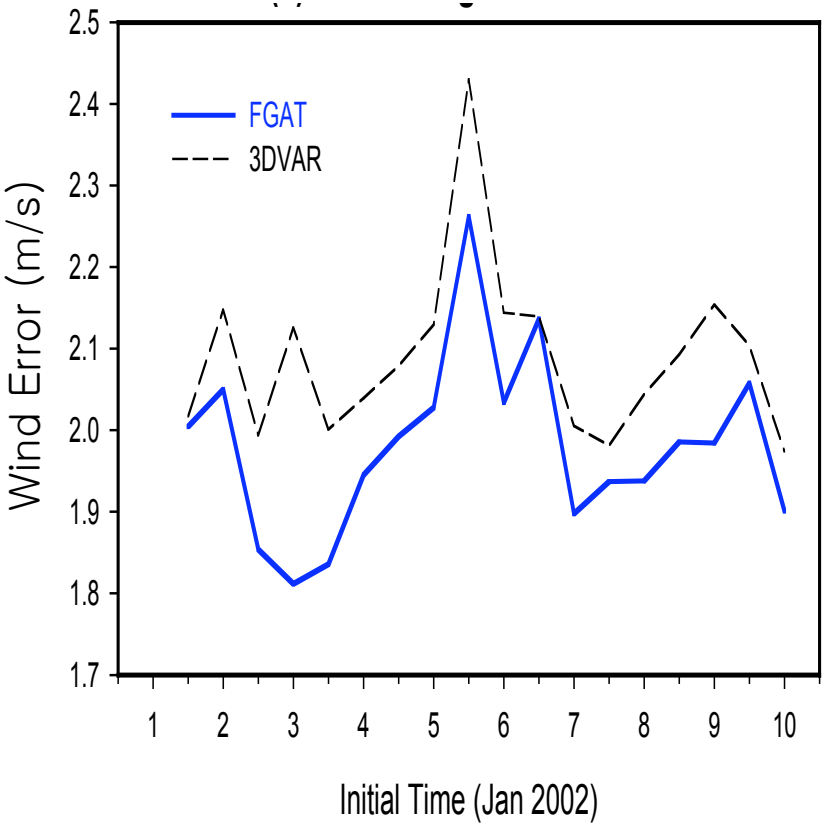


3D-Var-FGAT Forecast Impact

6hr Forecast T Error



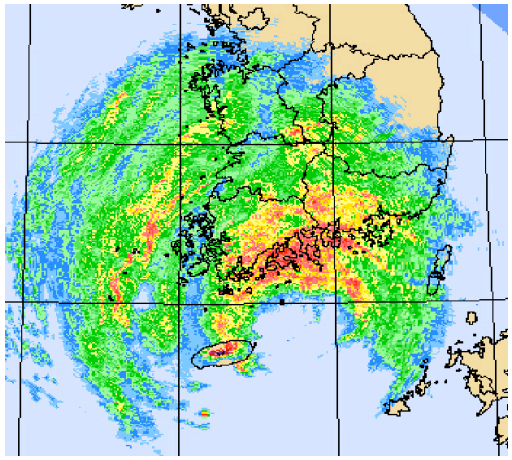
12hr Forecast U Error



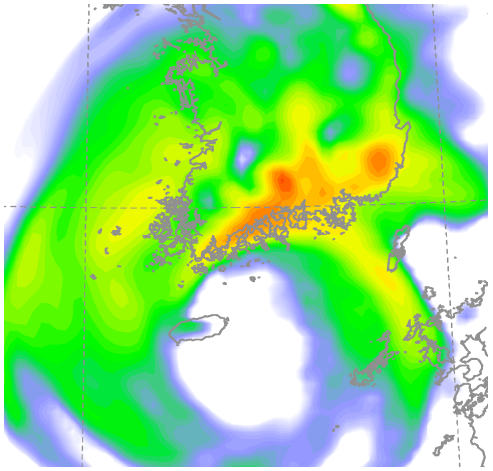
Korean Radar Data Assimilation in WRF-Var

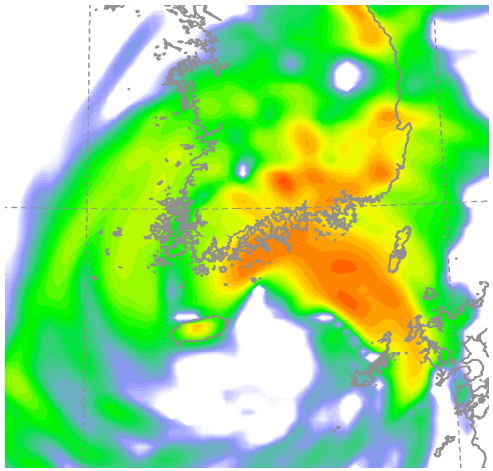
Typhoon Rusa Test Case 3hr Precip:

Obs (03Z, 31/08)

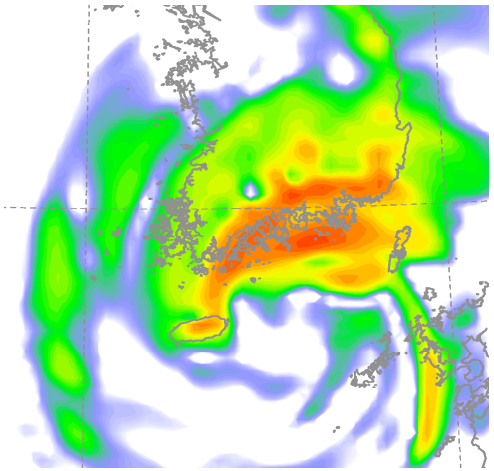


No Radar



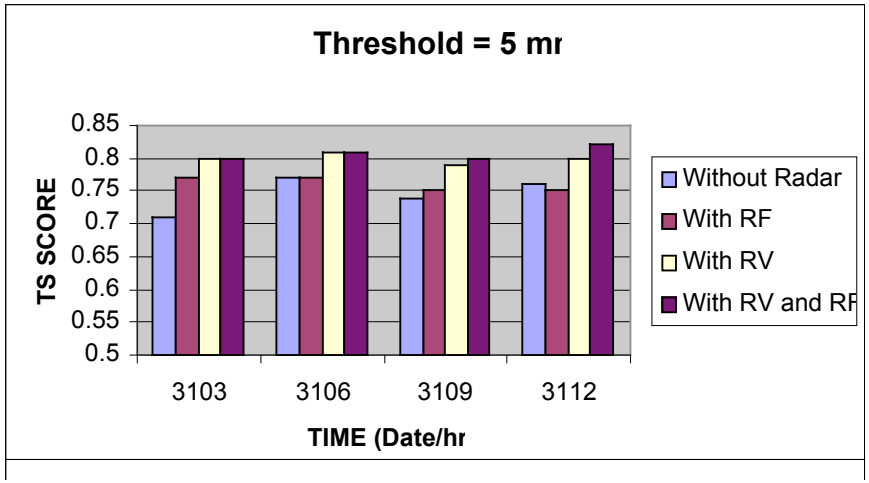


Radar RV



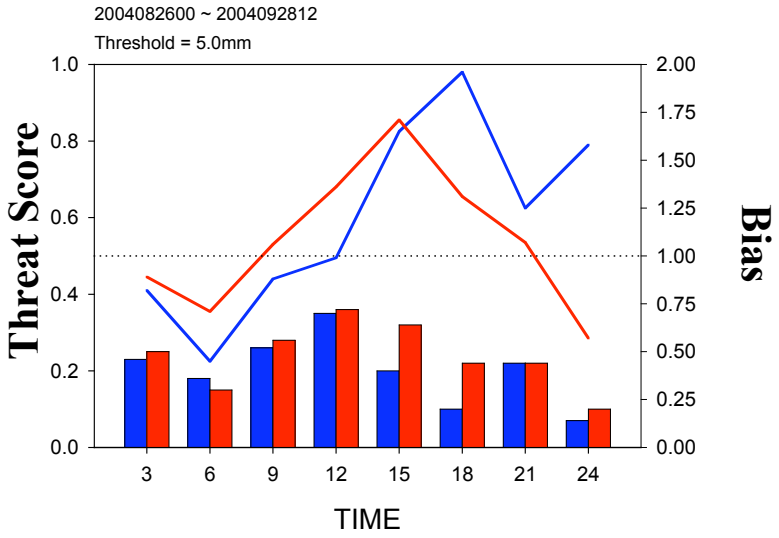
Radar RV+RF

Typhoon Rusa 3hr Precip. Verification:

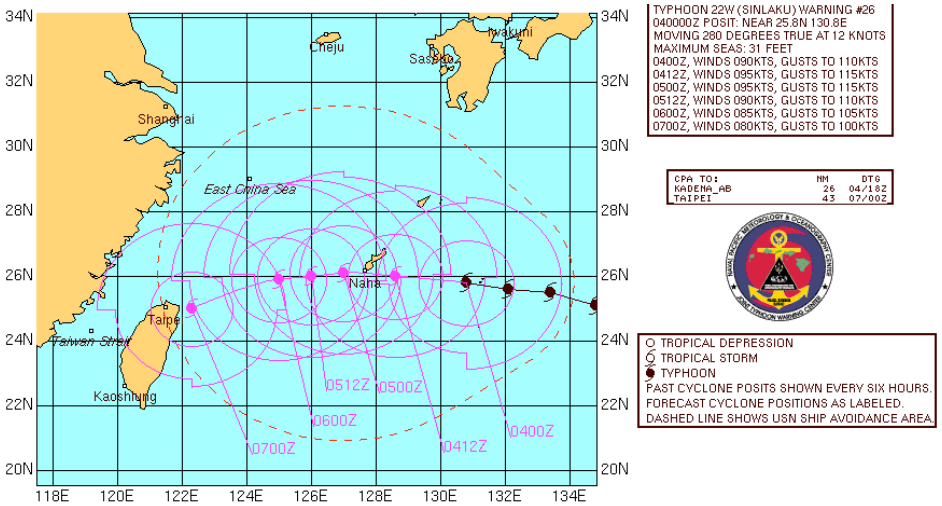


KMA Pre-operational Verification:

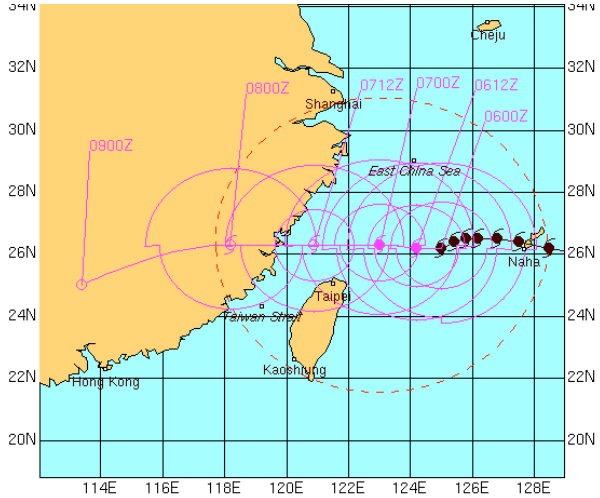
(no radar: blue, with radar: red)



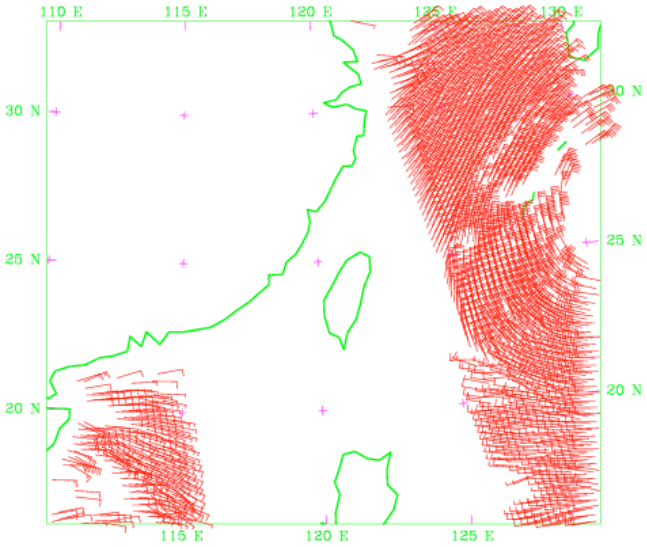
Typhoon Sinlaku: Quikscat Data



00Z September 4th 2002

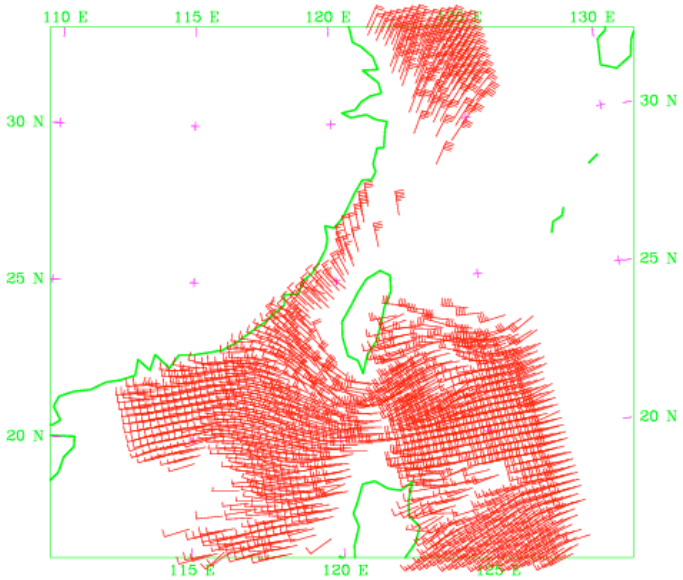


00Z September 6th 2002

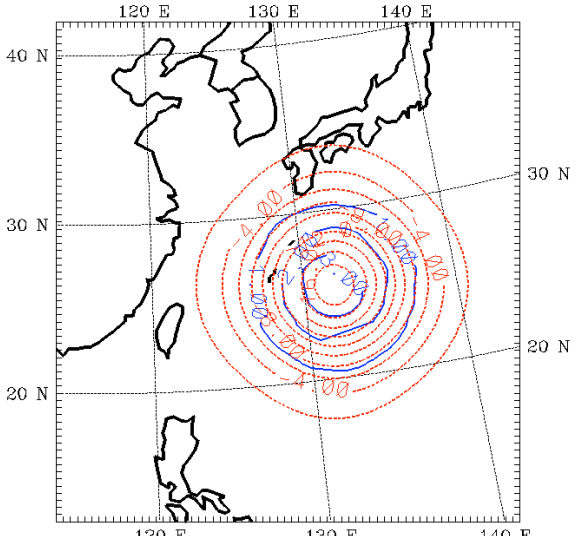


Quikscat Data

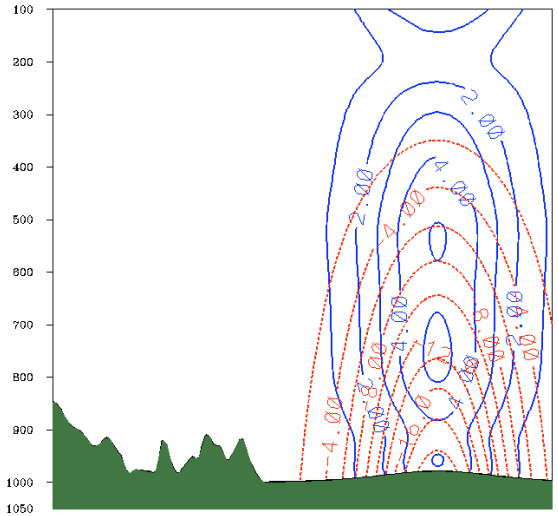
Barker et al (2004)

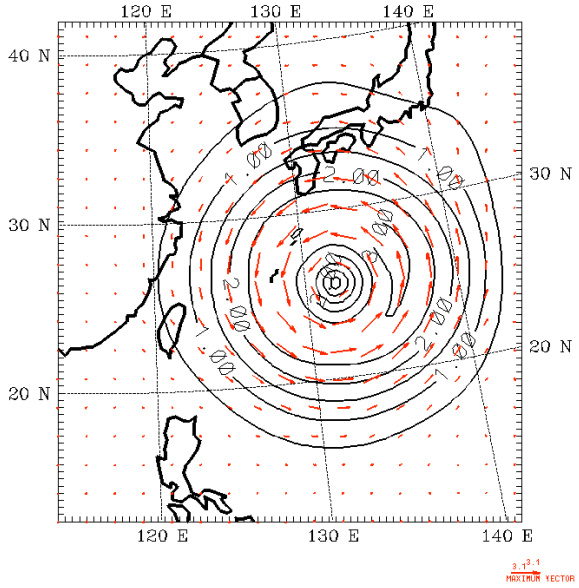


WRF-Var Sinlaku Bogus:Analysis Increments

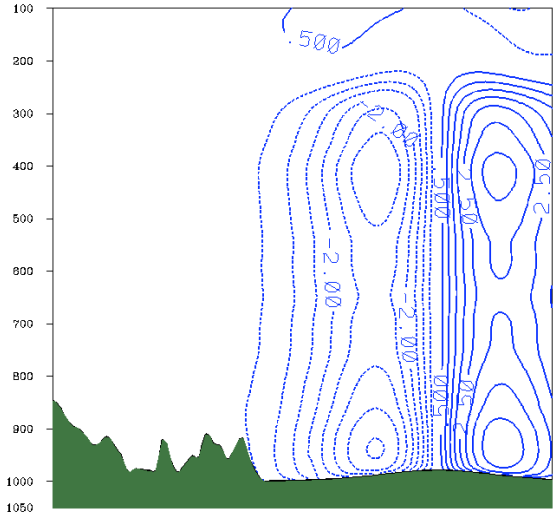


Pressure,
Temperature

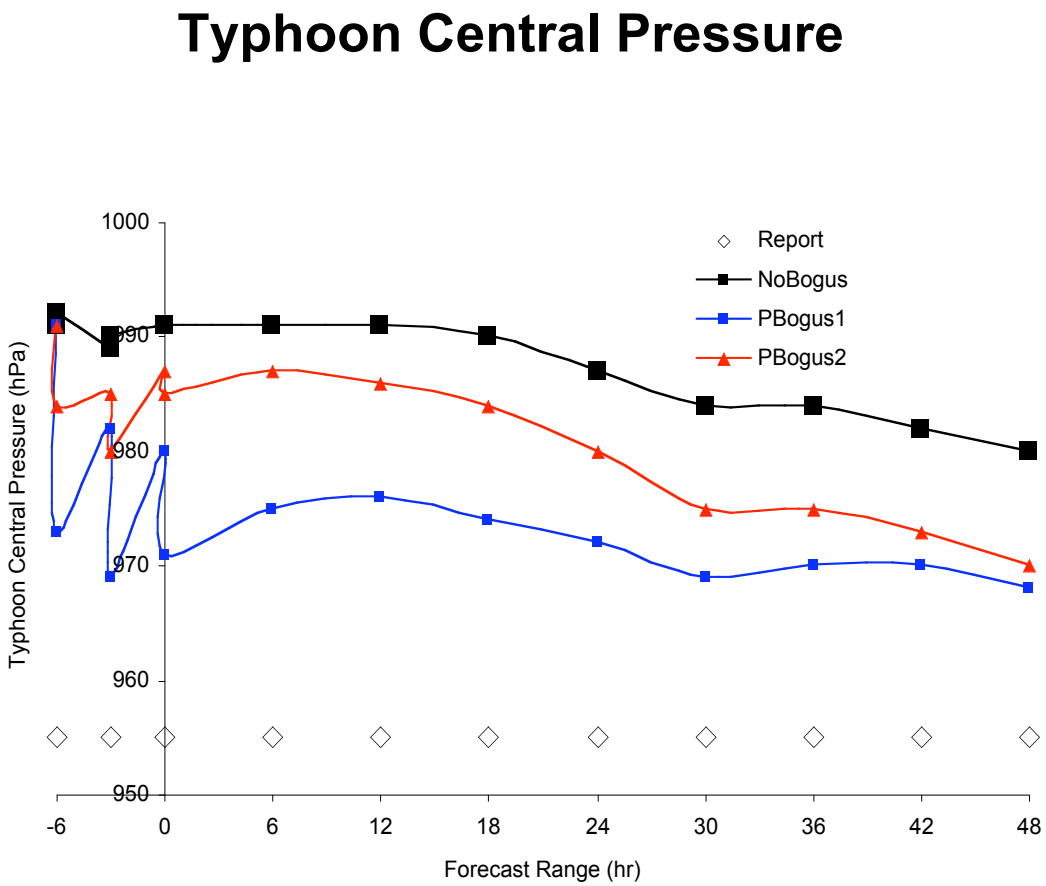




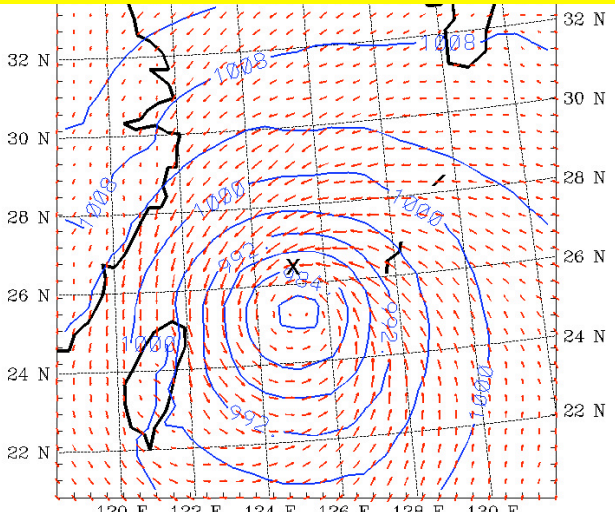
Wind Speed,
Vector,
v-wind component.



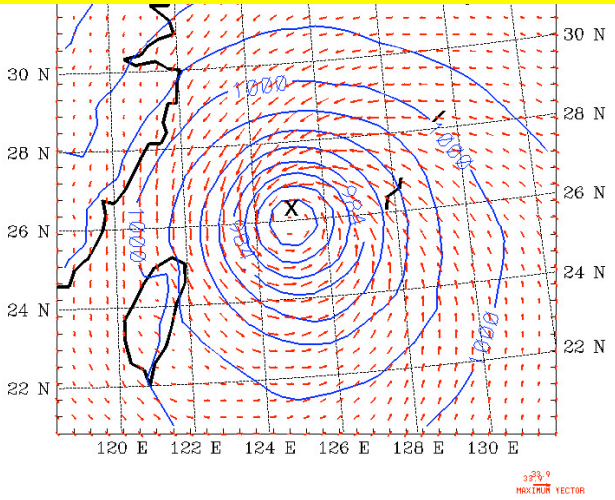
Single Surface Pressure Bogus: Forecast Impact



48hr Forecast (NoBogus)



48hr Forecast (PBogus1)

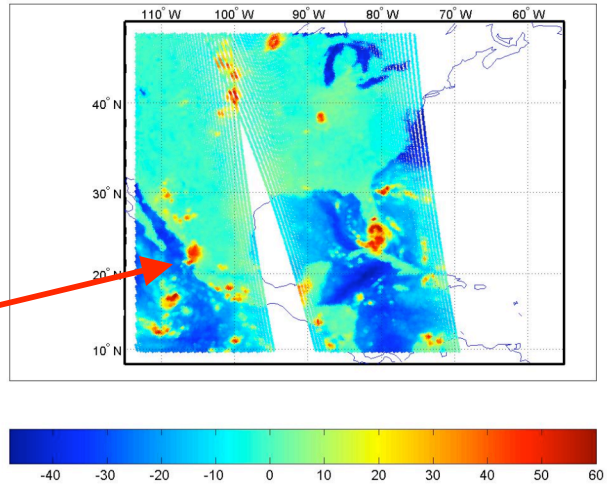


5. Current Status and Future Plans

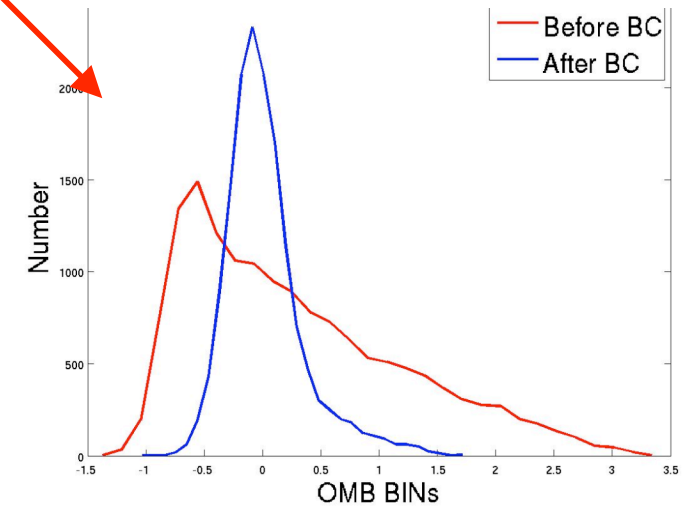
WRF-Var Radiance Assimilation Status

- BUFR Data interface for a number of satellites
- RTM interface: RTTOV8_5 or CRTM
- Currently only assimilating clear-sky radiances
- NESDIS Microwave surface emissivity model
- Quality Control for AMSU-A/B, AIRS
- Bias Correction (Scan Angle + Air Mass)
- Innovation output and Statistics Diagnosis
  - O-B, O-A, counting number of observation
- Observation error tuning
- FGAT(First Guess at Appropriate Time)
- Parallel: MPI (regional, not yet global)
- Flexible design to easily add new satellite sensor

AMSU-B Scatter Index > 3K



Air Mass Bias Correction: AMSU-A

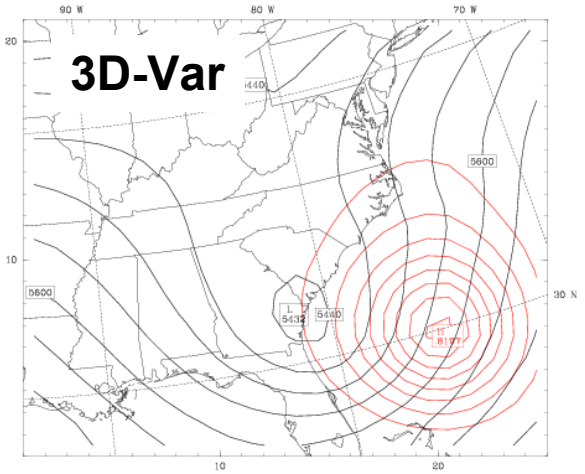


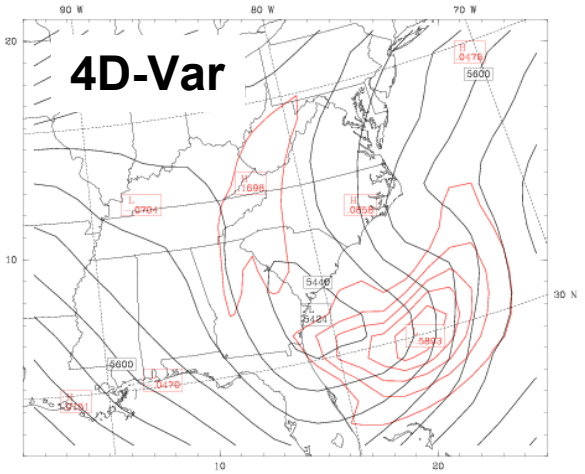
WRF-(4D)Var Summary

1. WRF-(4D)Var AFWA project: 2004-2007.

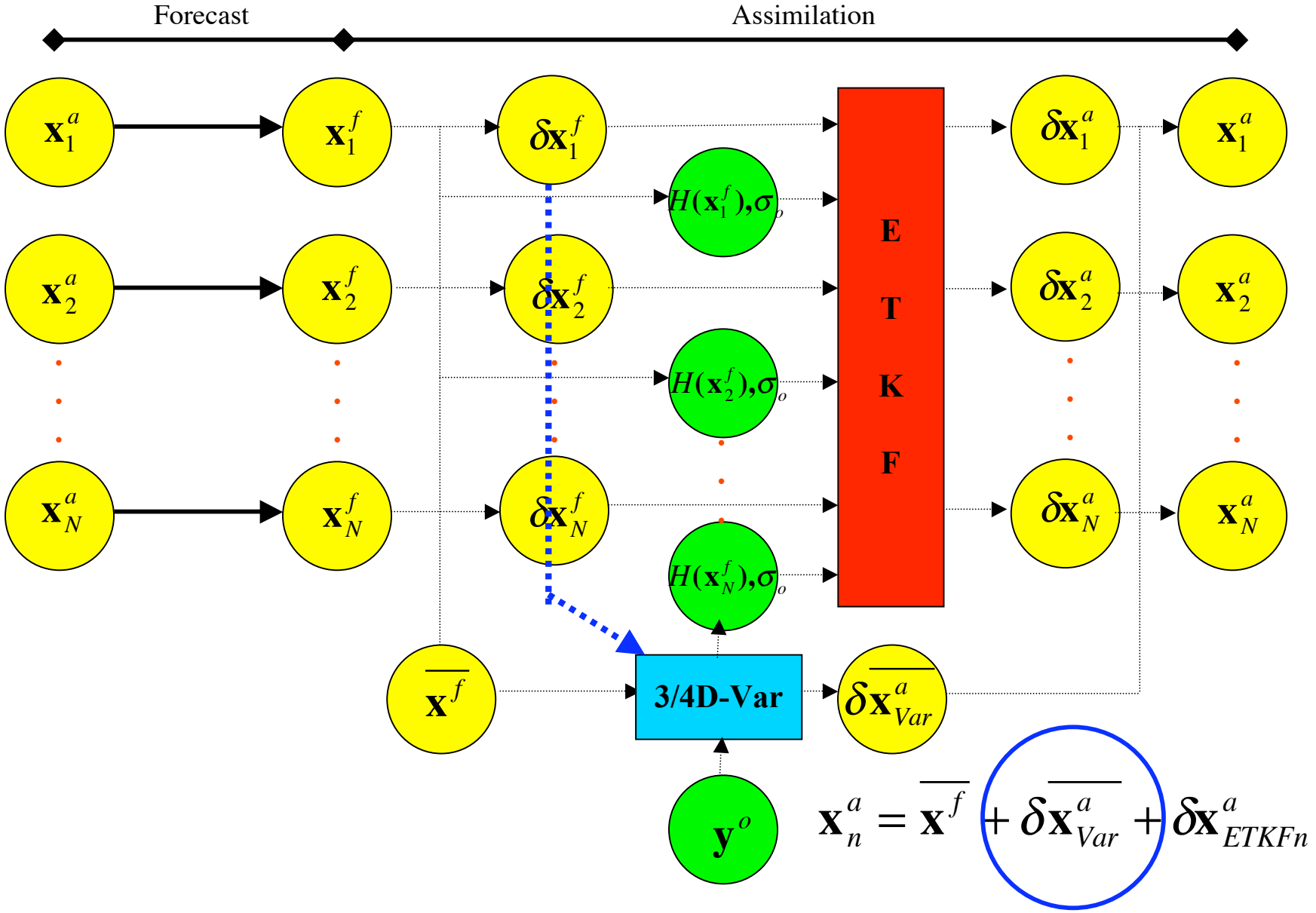
2. Formulation: Built within WRF-Var, using ARW dynamic core.

3. Status:
   - Prototype built (parallel, JcDFI, limited physics).
   - Prototypes delivered to AFWA in 2006 and 2007.
   - Current focus: Testing, more physics, optimization.





Cycling WRF/WRF-Var/ETKF System (Hybrid DA)

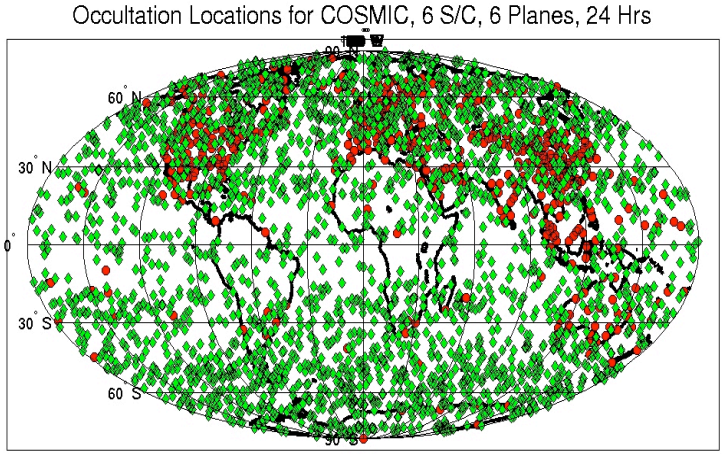


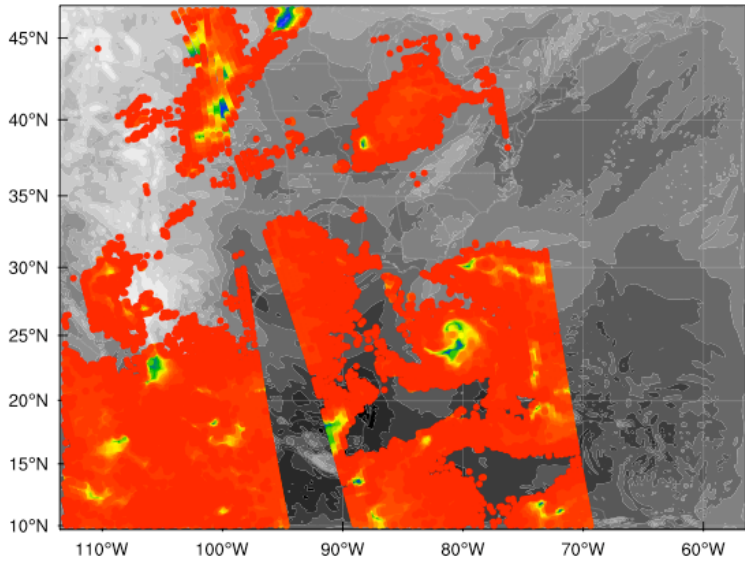
WRF-Var Observations (July 2007)

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

- Remotely sensed retrievals:
  - Atmospheric Motion Vectors (geo/polar).
  - Ground-based GPS Total Precipitable Water.
  - SSM/I oceanic surface wind speed and TPW.
  - Scatterometer oceanic surface winds.
  - Wind Profiler.
  - Radar radial velocity and reflectivity.
  - Satellite temperature/humidities.
  - GPS refractivity (e.g. COSMIC).

- Radiances:
  - SSM/I brightness temperatures.
  - Direct radiance assimilation (SSM/I, TMI, AMSU, AIRS).





WRF-Var/WRF Version 3.0 (March 2008)

- Major new features/improvements (provisional):
  - Radiance data assimilation via CRTM/RTTOV.
  - Hybrid variational/ensemble DA.
  - Ensemble Transform Kalman Filter (ETKF).
  - Enhanced gen_be utility (EPS-based stats., efficiency).
  - Major software engineering reorganization.
  - Option to use [PREP]BUFR for observation ingest.
  - Remove obsolete features (e.g. MM5/GFS-based errors).
- Unify code management (process, regression testing, SE framework) for WRF/WRF-Var.
- NOT included: 4D-Var.

Future Plans

General Goals:

- Research: Focus on high-resolution (1-10km).
- Development: Unified DA system (3/4D-Var, EnKF).
- Community Model: Retain flexibility for research.
- Leverage international WRF community efforts.
- Work to eliminate **unnecessary** diversity.

WRF-Var Development (MMM Division):

- 4D-Var (physics, optimization).
- Adjoint Sensitivities.
- EnKF within WRF-Var.
- Instrument-specific radiance QC, bias correction.

Data Assimilation Extended-Period Testing (DATC):

- Technique intercomparison: 3/4D-Var, EnKF, Hybrid.
- System studies: WRF-Var, GSI, DART.
- Obs. impact: AMSU, AIRS, COSMIC, SSMI/S.
- New Regional testbeds: Korea, India, CONUS.

Air Mass Bias Correction: AMSU-A