WRF Variational Data Assimilation System (WRF-Var) Overview

WRF Tutorial Presentation

NCAR, Boulder, Colorado

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Taiwanese Central Weather Bureau, Civil Aeronautics Administration

Outline of Talk

1) What is WRF-Var?

2) Practical Variational Data Assimilation.

3) Forecast Error Estimation.

4) Forecast 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….

WRF-Var Data Assimilation Overview

- **Techniques:** 3D-Var, 4D-Var (regional), Hybrid Variational/Ensemble DA.

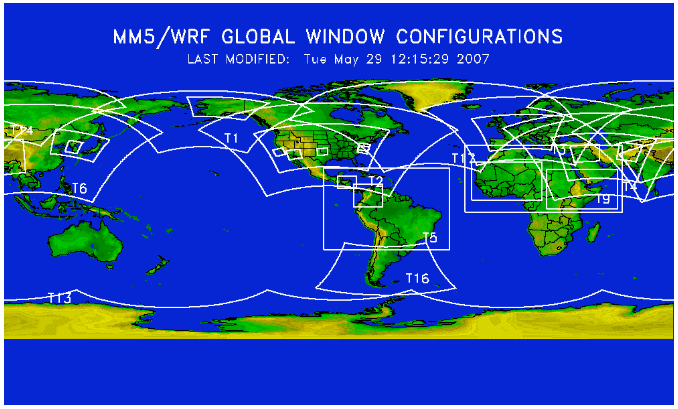
- **Software Engineering:** WRF framework.

- **Multiple Models:** Runs with WRF, MM5, KMA global model, etc.

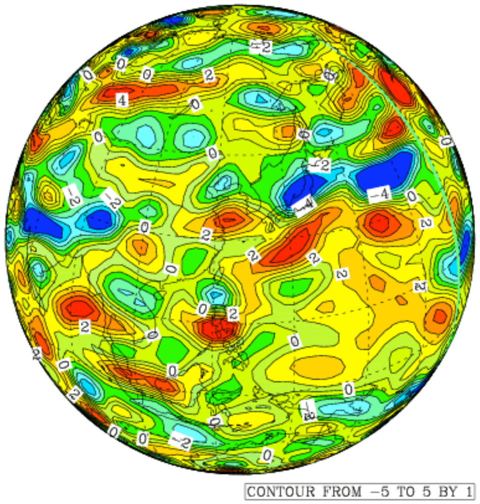
- **Support:** MMM Division, NCAR.

- **Applications:** Regional/global, Research/Operational, Deterministic/Ensemble,

AFWA Worldwide Theaters

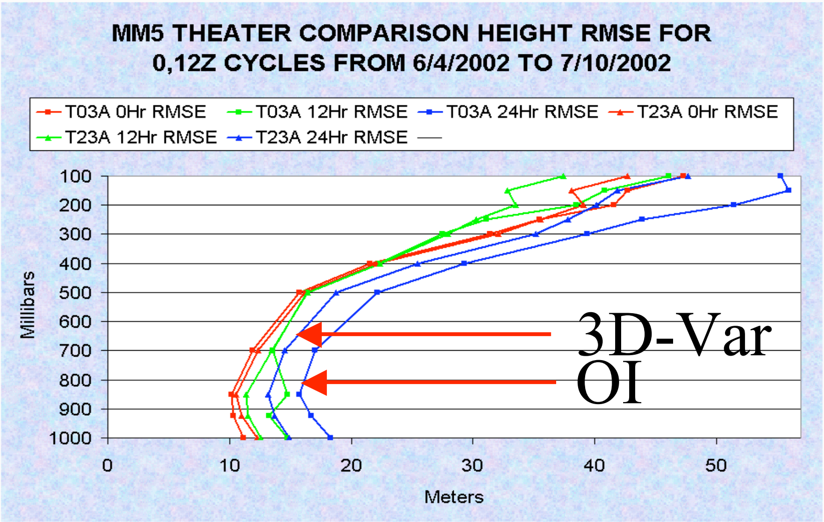


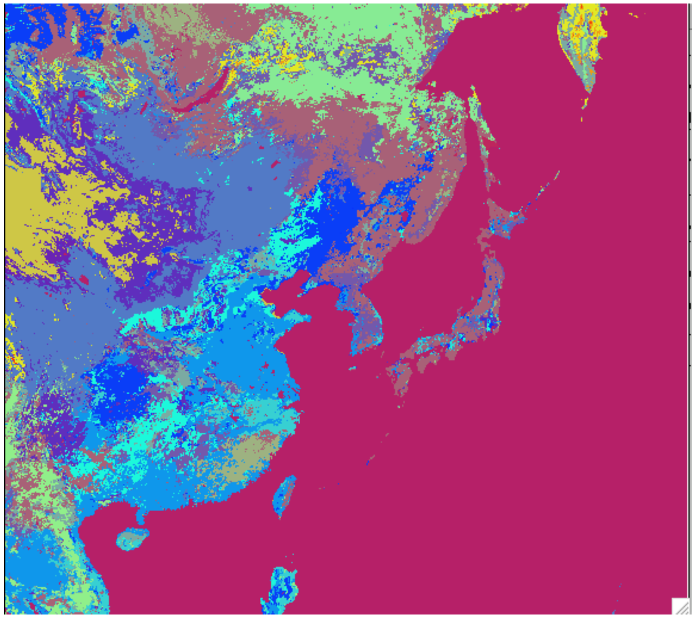
KMA T213/426 Global:



WRF Variational Data Assimilation (WRF-Var) History

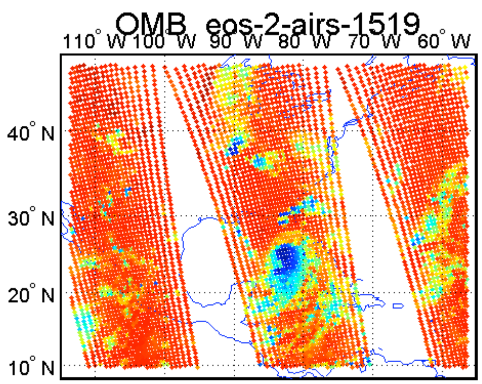
- **June 2001:** MM5-3DVar adopted as starting point for WRF 3D-Var.
- **2002:** MM5/WRF 3D-Var operational in Taiwan and at AFWA.
- **June 2003:** First public release of WRF-Var.
- **July 2006:** WRF-ARW/WRF-Var operational in AFWA 15km domains.
- **May 2007:** WRF-Var/ARW operational in Korea 10km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

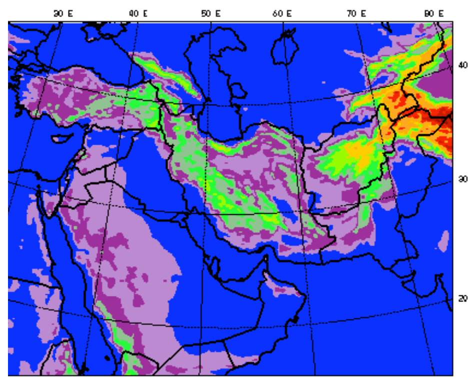


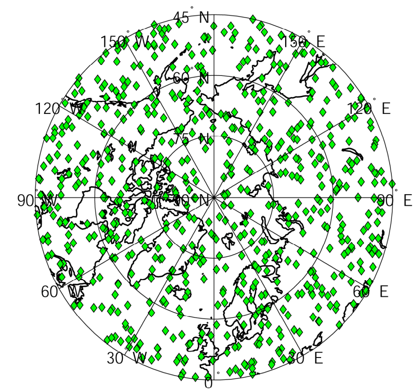


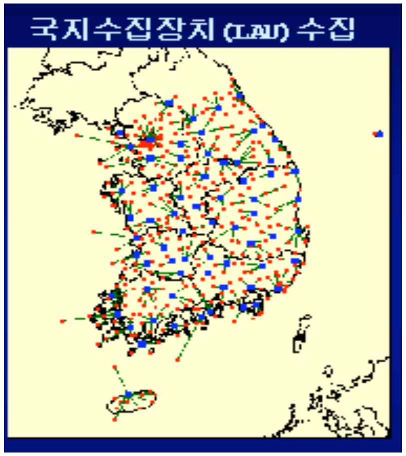
The WRF-Var Program

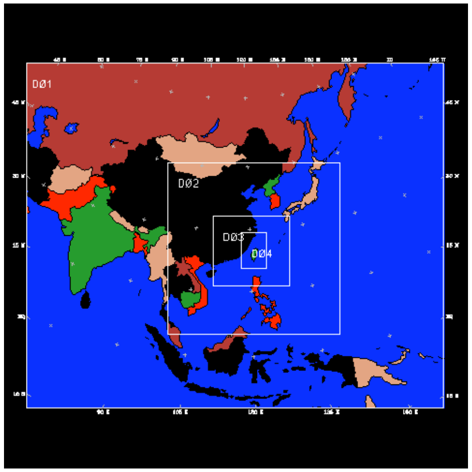
- NCAR staff: 23FTE, ~12 projects.
- Non-NCAR collaborators (AFWA, CWB, etc): ~10FTE.
- Community users: ~30 (more in 4000 general WRF downloads?).

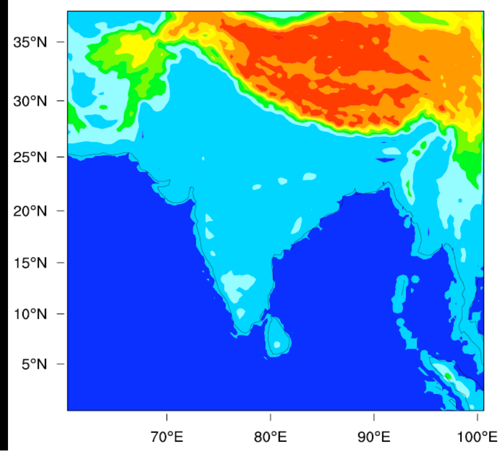


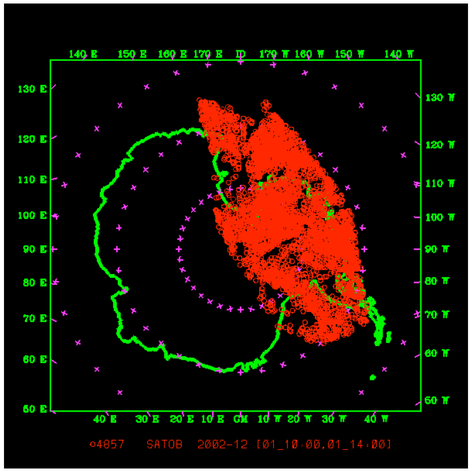


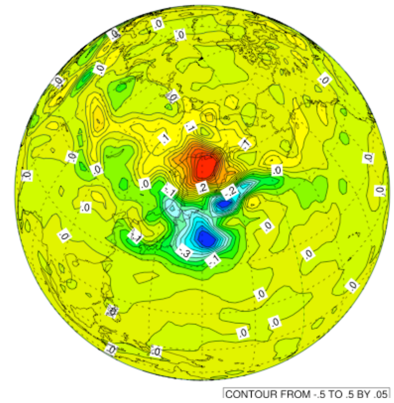




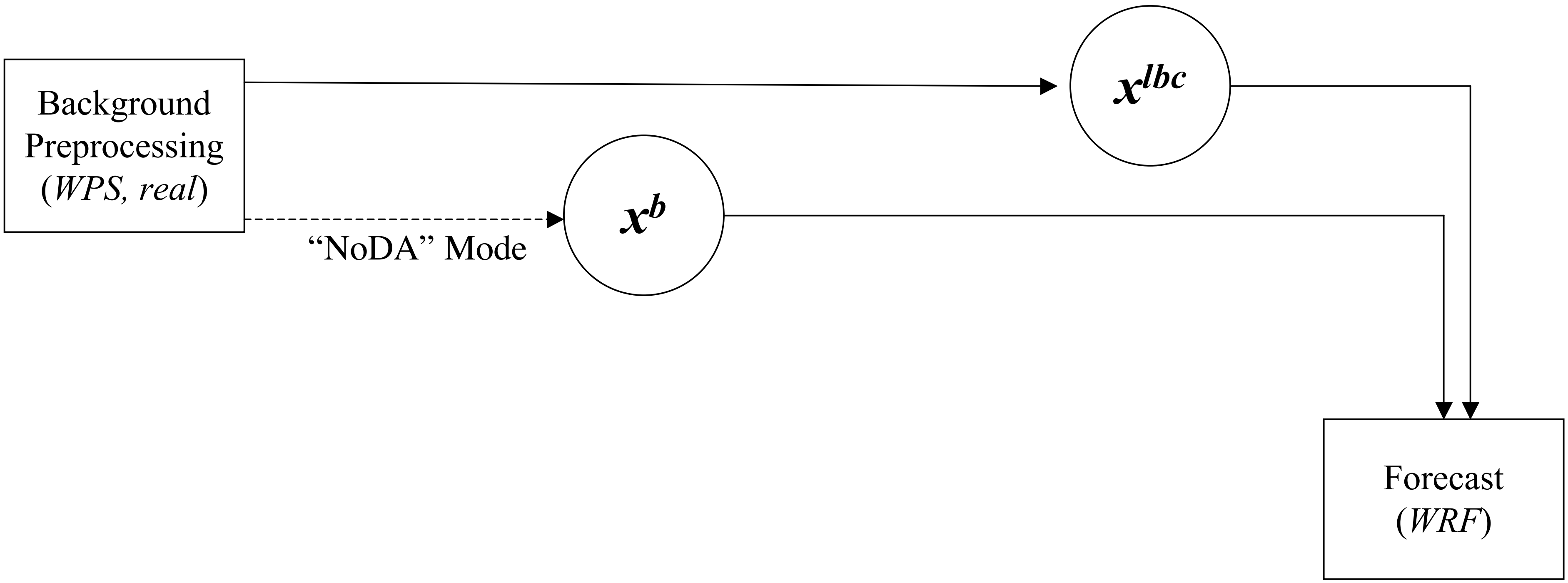




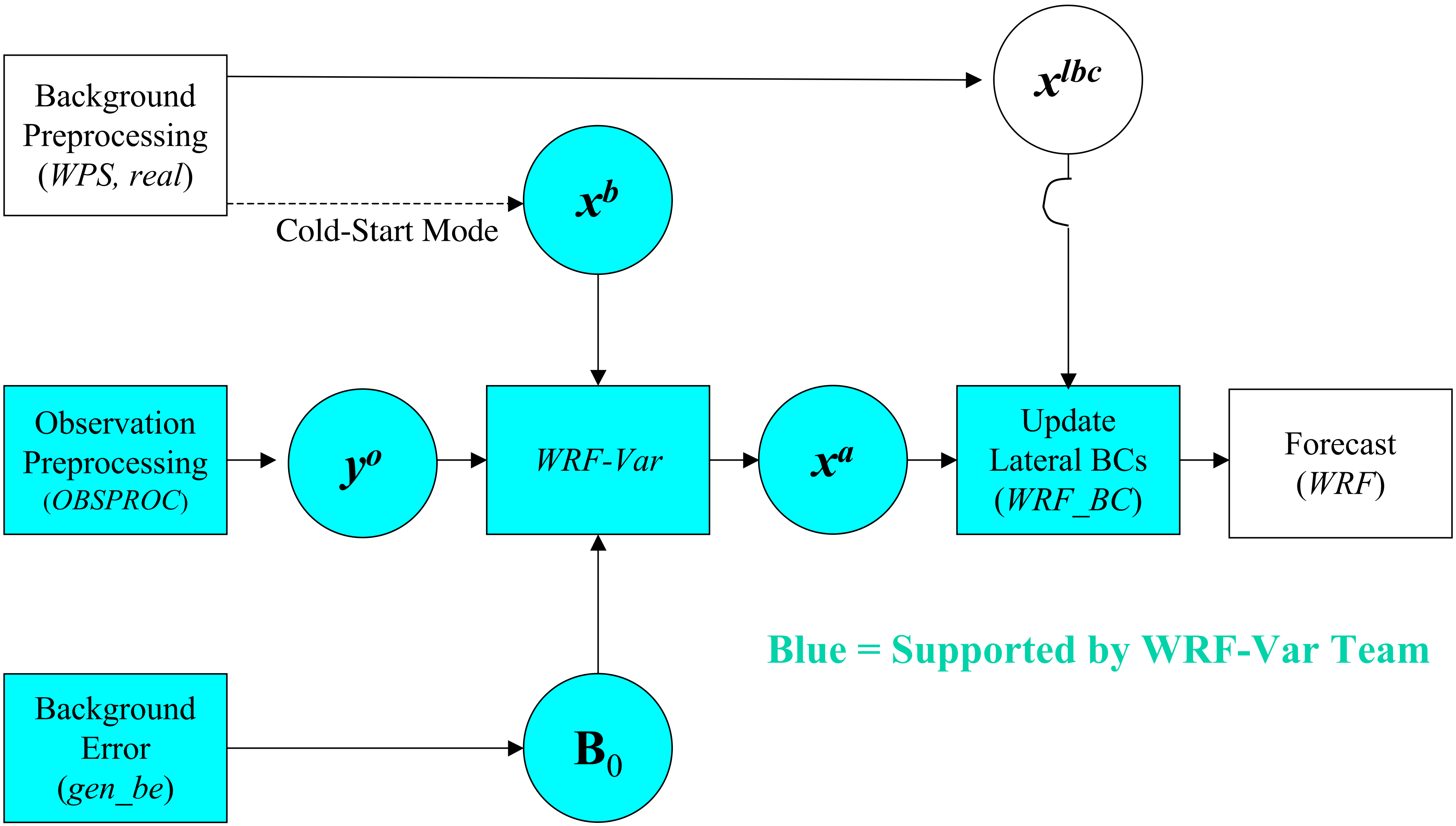




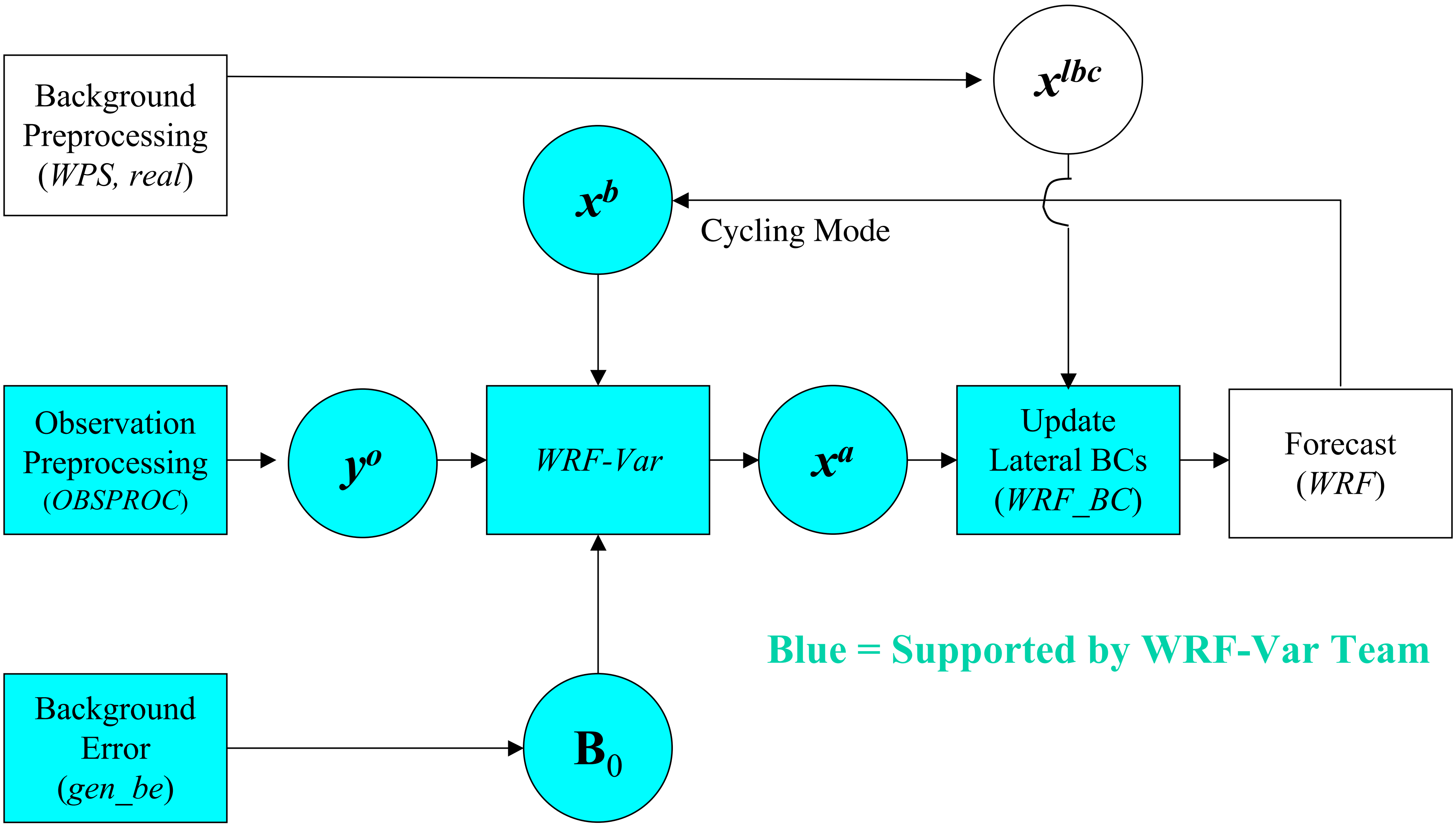
WRF-Var [not] in the WRF Modeling System



WRF-Var in the WRF Modeling System



WRF-Var in the WRF Modeling System



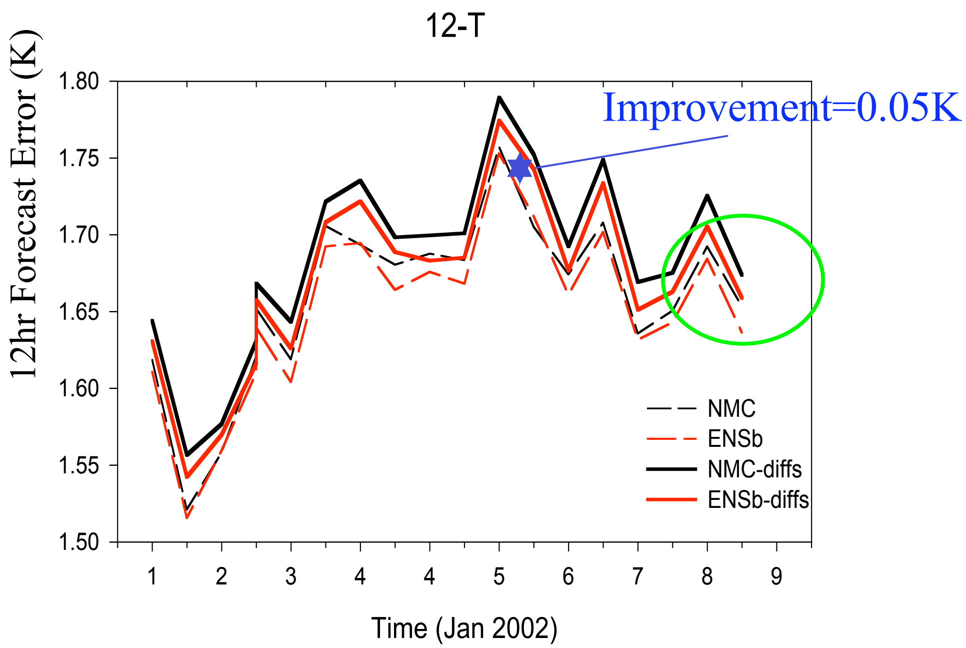
Blue = Supported by WRF-Var Team

Importance of Data Assimilation For General WRF Development/Testing

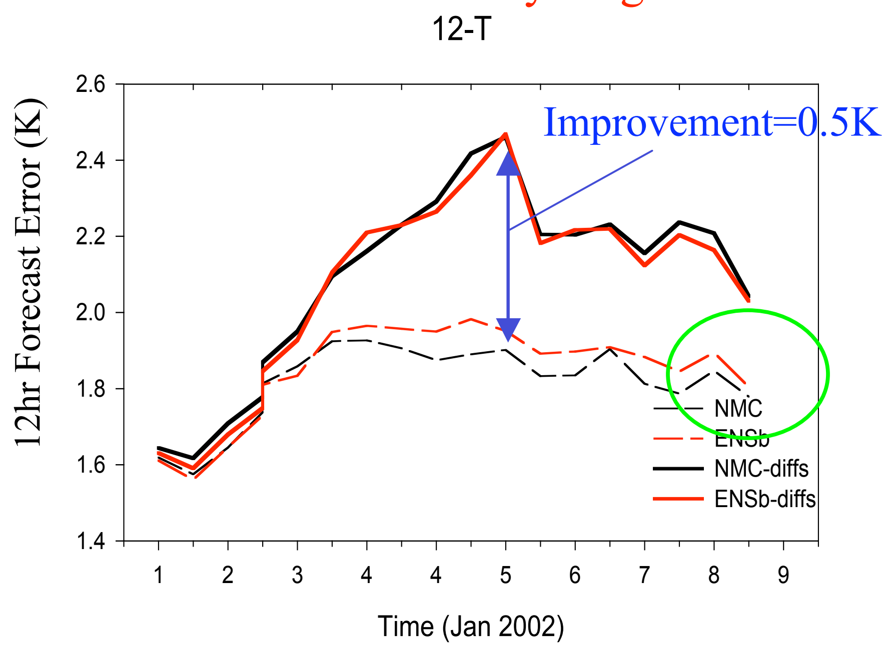
Experiment (Mi-Seon Lee, KMA):

- 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

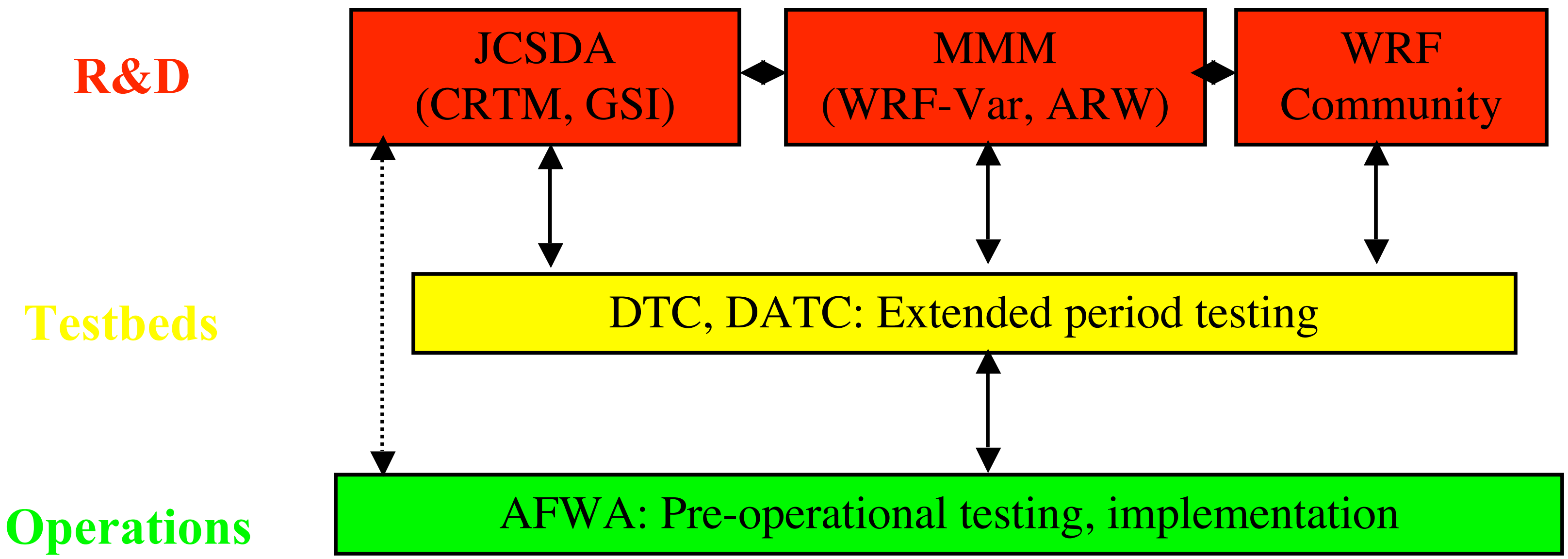


With DA Cycling



Warning: Cycling with insufficient observations leads to degradation (1.8K vs. 1.7K)

WRF DA Research To Operations



- NCAR/AFWA DA Program initiated in August 2006.
- MMM Division responsible for WRF-Var development and initial testing.
- JCSDA provides Community Radiative Transfer Model (CRTM), etc.
- WRF Community contributions include radar, radiance (RTTOVS).
- DATC responsible for extended-period testing of DA updates.

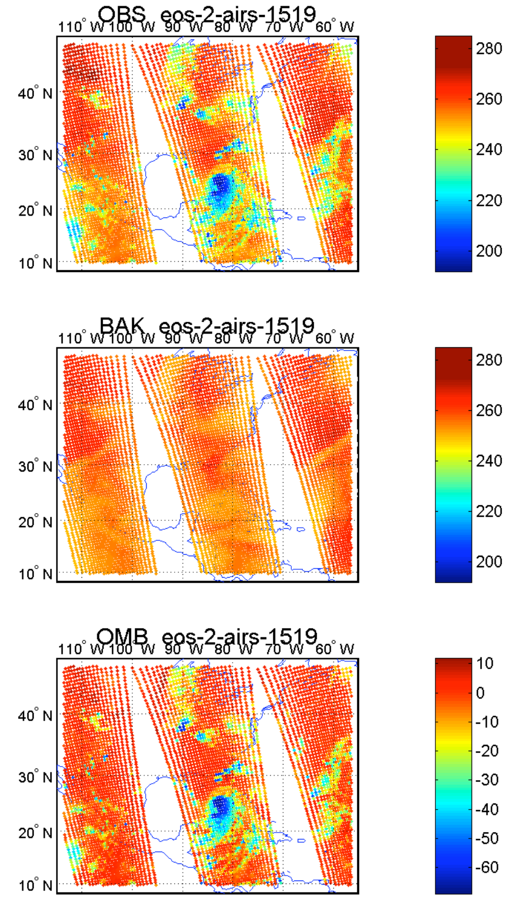
2. Practical Variational Data Assimilation

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.

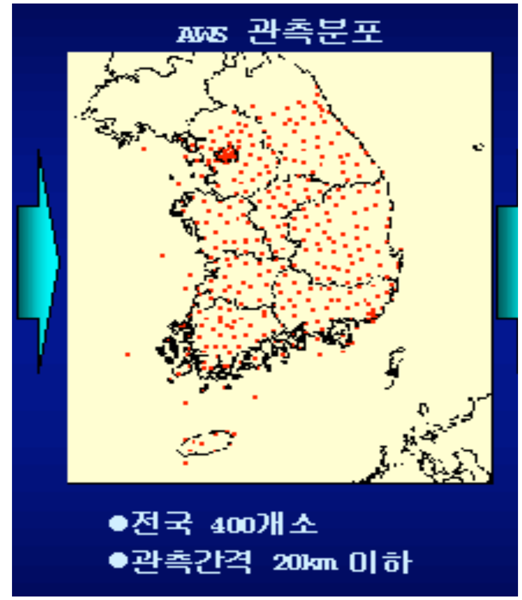
- Assimilation system outputs an “analysis”.

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



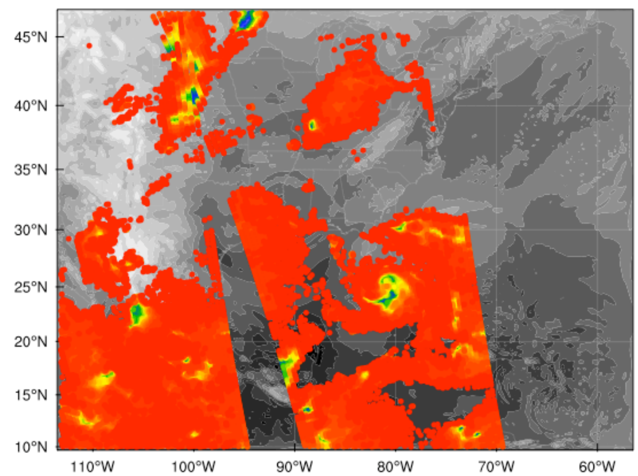
Need For Data Assimilation in NWP

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

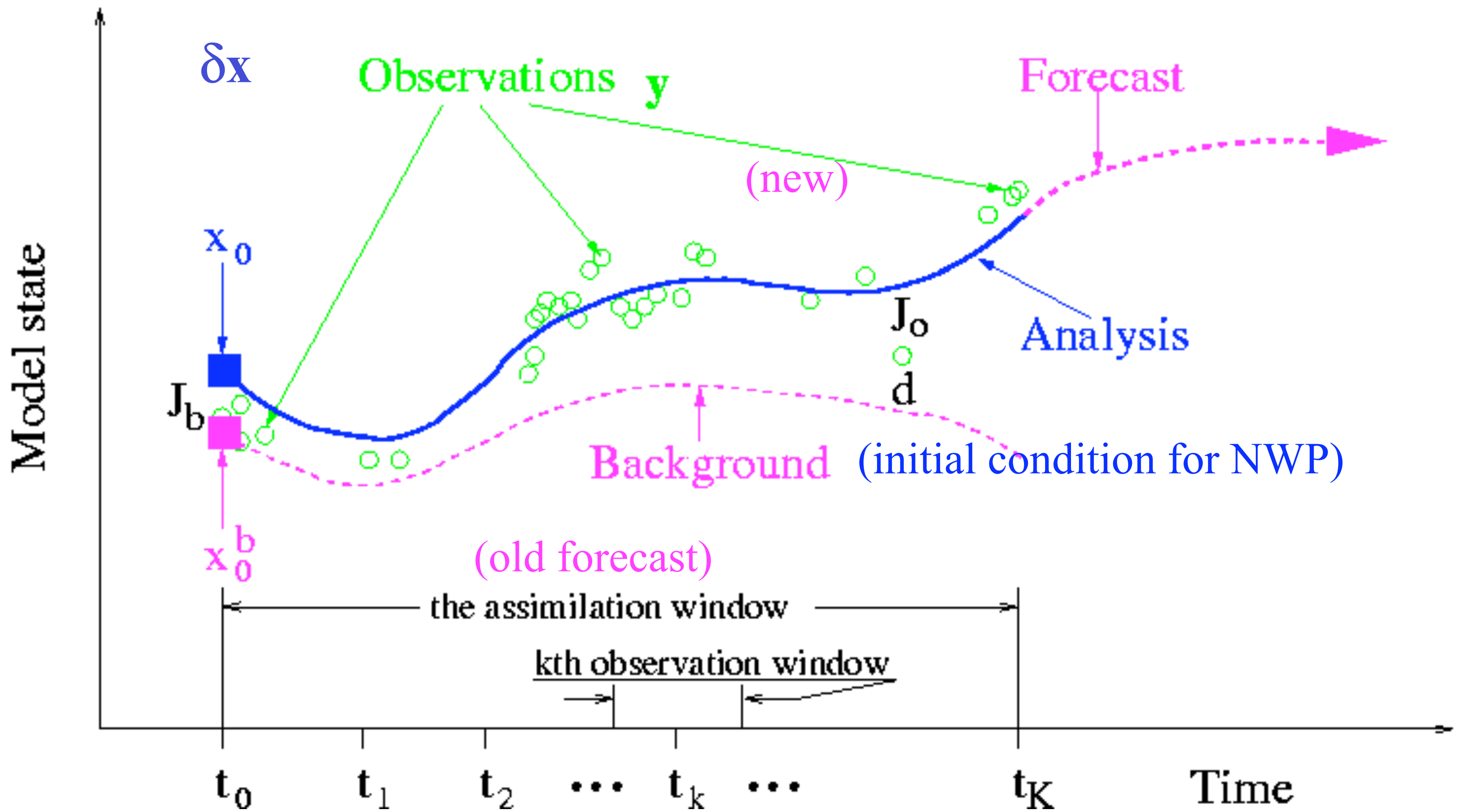
$$J = J_b + J_o$$

• 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

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

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

- $\mathbf{B_0}$ 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*.

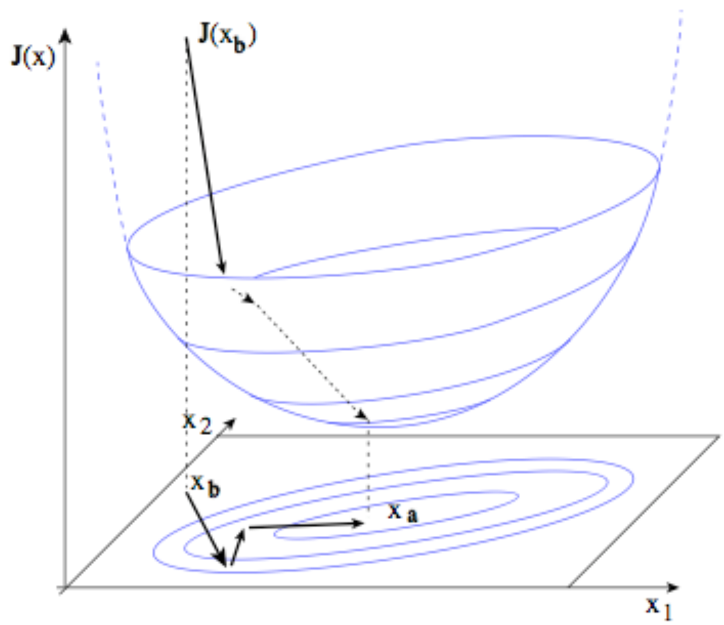
- Direct calculation of J_b and J_o impossible for NWP problems ($\mathbf{B_0}$, $\mathbf{R}$ are matrices of dimension 10^7). Therefore many practical simplifications required.

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

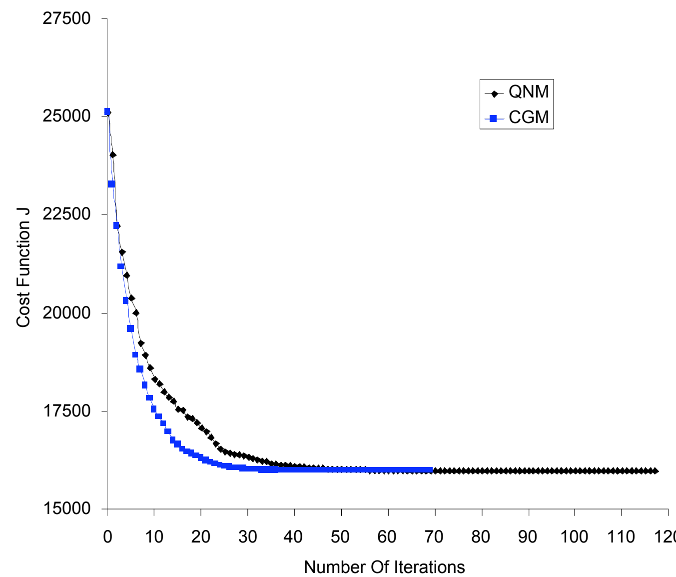
$$\mathbf{x}^a(t_0) \equiv \mathbf{x}^g(t_0) + \delta\mathbf{x}(t_0)$$

Minimization Of The Cost Function

- Minimization of the cost function proceeds iteratively.



From Bouttier and Courtier (1999)



From WRF-Var tutorial

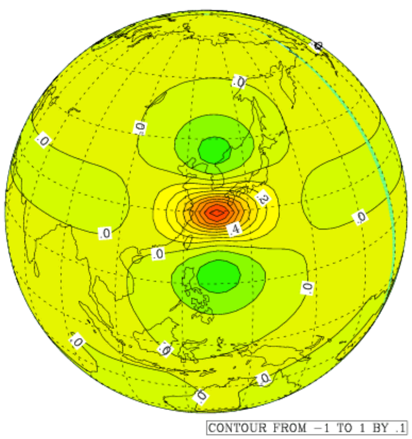
- "Convergence" achieved when either 1) Maximum iterations reached, 2) Ratio final/initial gradient hits a specified criterion.

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:



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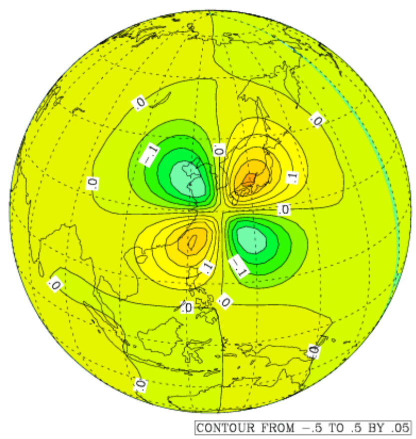

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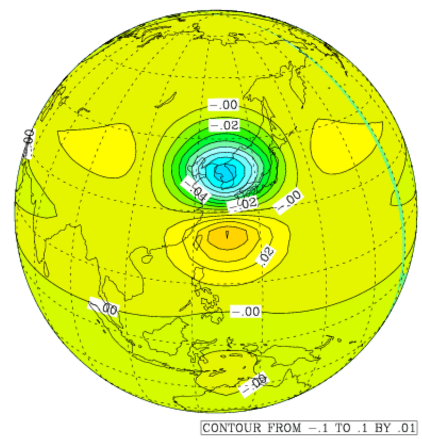

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3. Forecast Error Estimation

Background Error (BE) Estimation in WRF-Var

The number 1 question from WRF-Var users is

“What background error covariances are best for my application?”.

Procedure:

1. Use default statistics files supplied with code (MM5, GFS-based).
2. Create you own, once you have run your system for ~a few weeks.
3. Implement, tune, and iterate.

A new utility *gen_be* has been developed at NCAR to calculate BEs.

Model-Based Estimation of Climatological Background Errors

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

$$\mathbf{B}_0 = \overline{(\boldsymbol{x}^b - \boldsymbol{x}^t)(\boldsymbol{x}^b - \boldsymbol{x}^t)^T} \approx \overline{\boldsymbol{x}'\boldsymbol{x}'^T}$$

Two ways of defining $\boldsymbol{x}'$:

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

$$\mathbf{B}_0 = \overline{\boldsymbol{x}'\boldsymbol{x}'^T} \approx A\overline{(\boldsymbol{x}^{t2} - \boldsymbol{x}^{t1})(\boldsymbol{x}^{t2} - \boldsymbol{x}^{t1})^T}$$

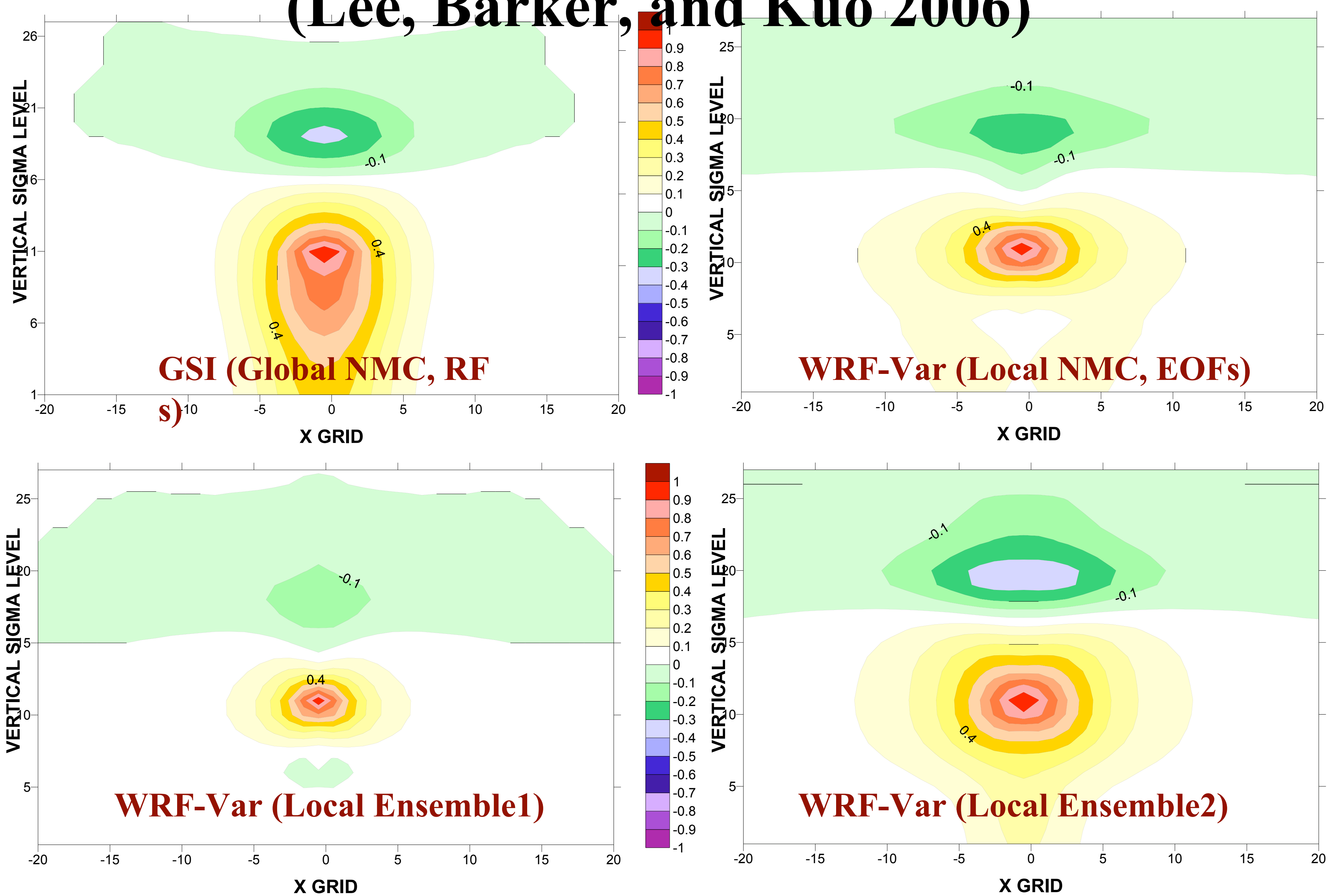
  where e.g. t2=24hr, t1=12hr forecasts…

- …or ensemble perturbations (Fisher 2003):

$$\mathbf{B}_0 = \overline{\boldsymbol{x}'\boldsymbol{x}'^T} \approx C\overline{(\boldsymbol{x}^k - \langle \boldsymbol{x} \rangle)(\boldsymbol{x}^k - \langle \boldsymbol{x} \rangle)^T}$$

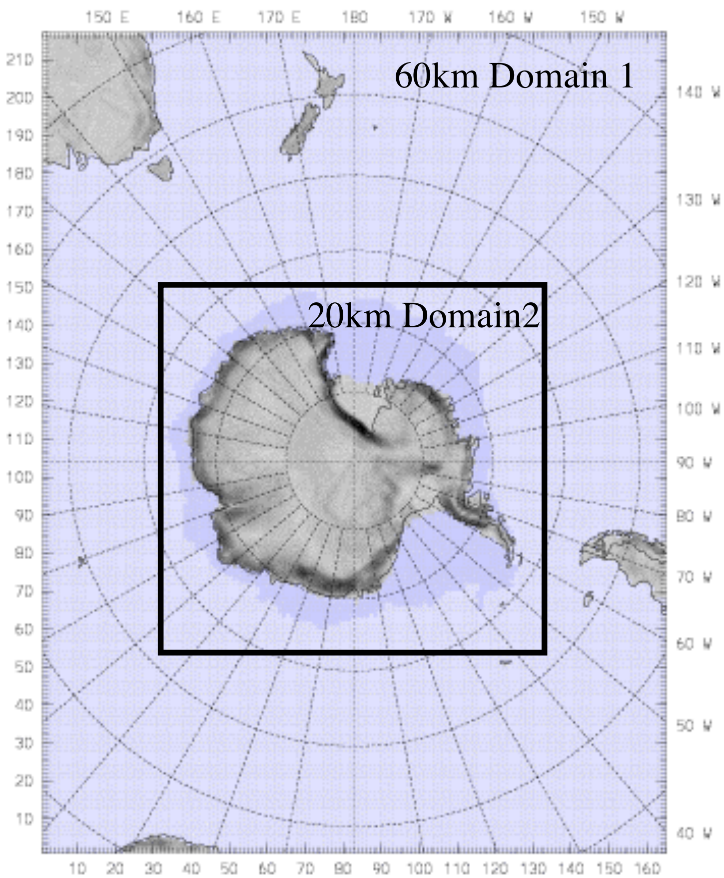
- Tuning via innovation vector statistics and/or variational methods.

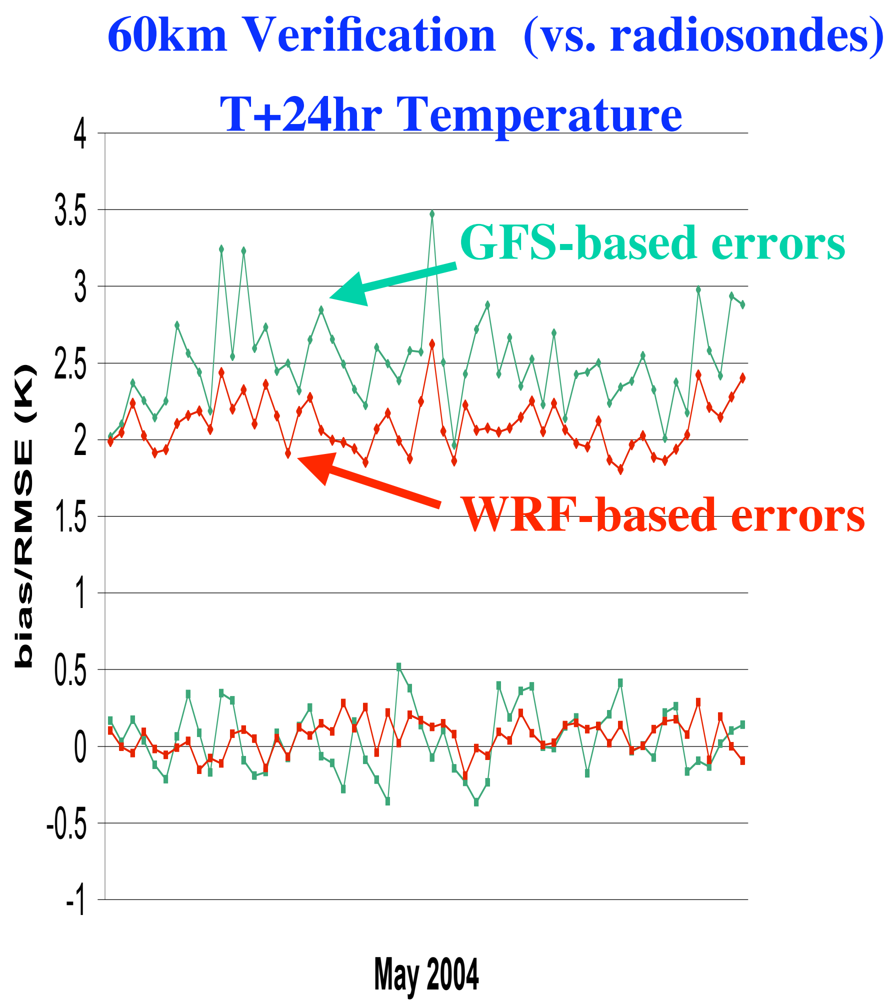
Analysis Sensitivity to Background Error Model (Lee, Barker, and Kuo 2006)



T increments : T Observation (1 Deg , 0.001 error around 850 hPa)

Sensitivity to Forecast Error Covariances in Antarctica (Rizvi et al 2006)





4. Forecast 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*** $\boldsymbol{v}$ space transform

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

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

- 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	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	$\mathbf{v}(i,j,m)$		$\mathbf{v}(l,n,m)$	$\mathbf{v}(i,j,m)$

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

Up: Change of variable, impose balance.

Uv: Vertical correlations EOF Decomposition

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

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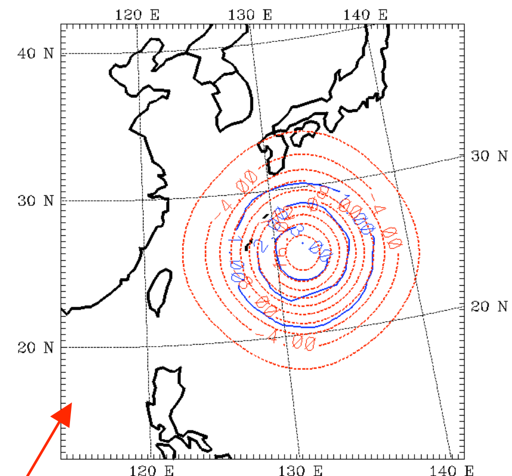

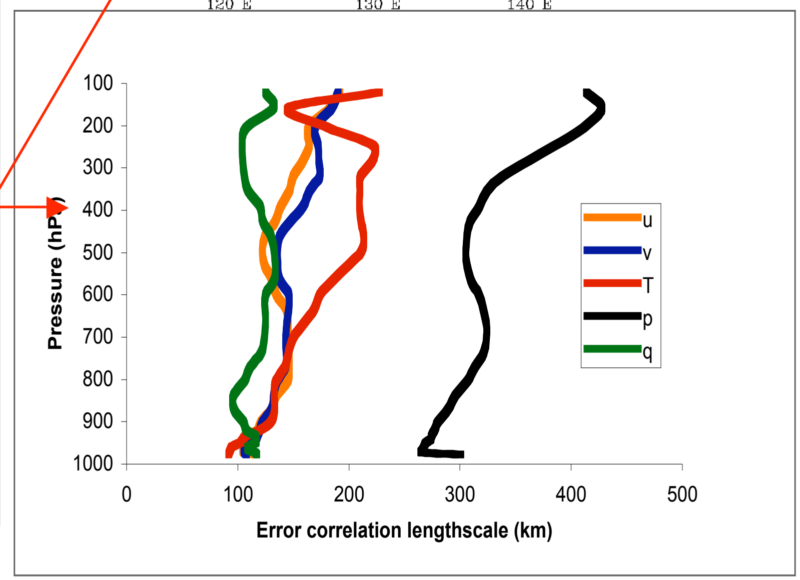

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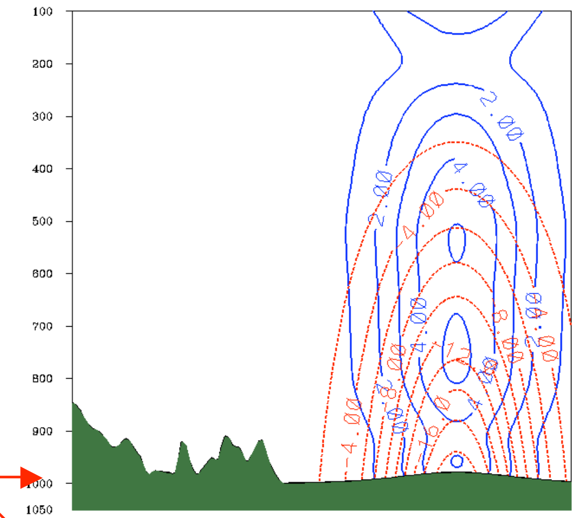
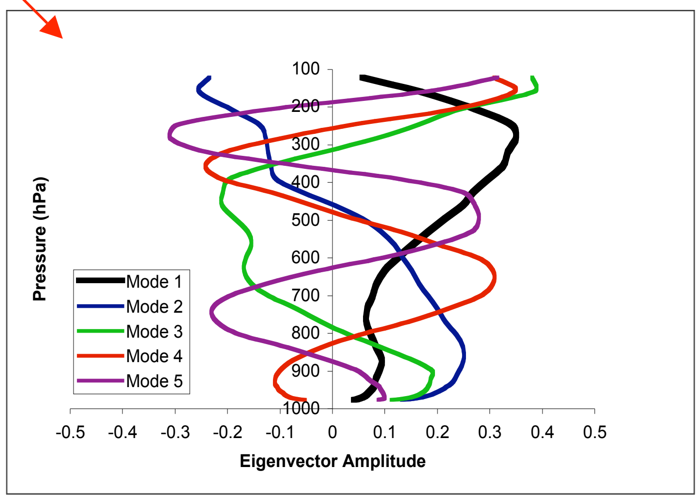




WRF-Var Background Error Modeling

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:

$$\psi'$$

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

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

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

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

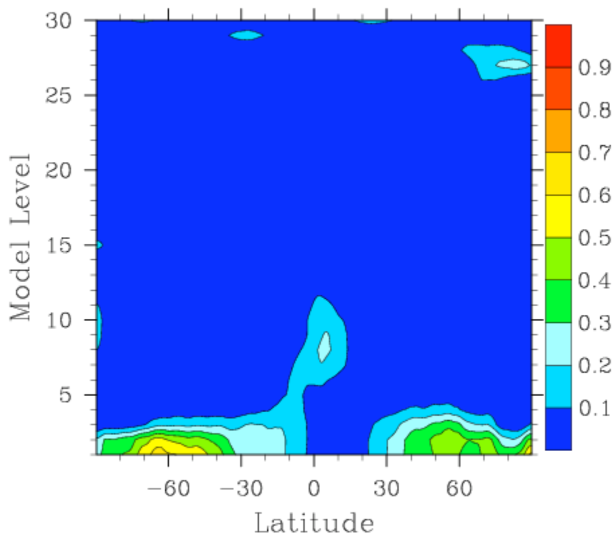
WRF-Var Statistical Balance Constraints

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

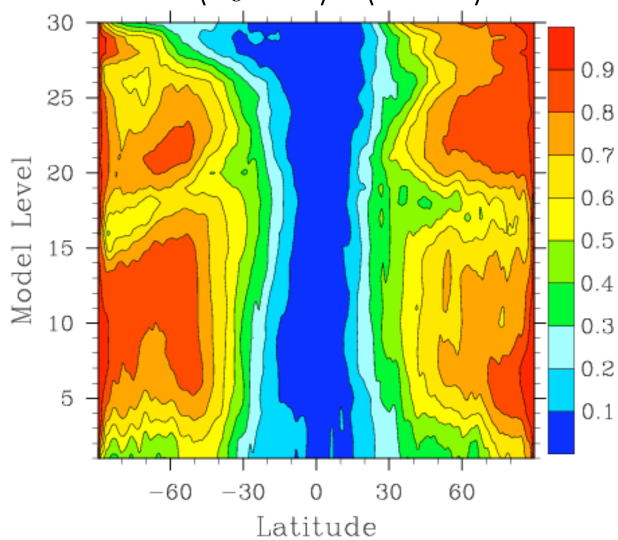
$$\chi_b' = c\psi' \quad T_b'(k) = \sum_{k1} G(k,k1)\psi'(k1) \quad p_{sb}' = \sum_{k} W(k)\psi'(k)$$

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

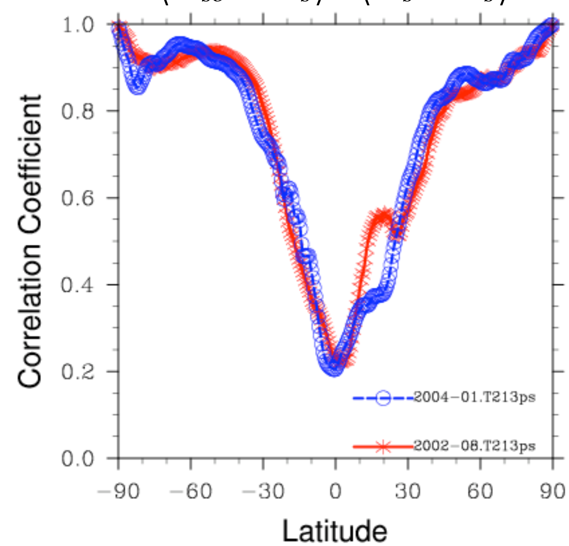
$\langle \chi_b \bullet \chi \rangle / \langle \chi \bullet \chi \rangle$



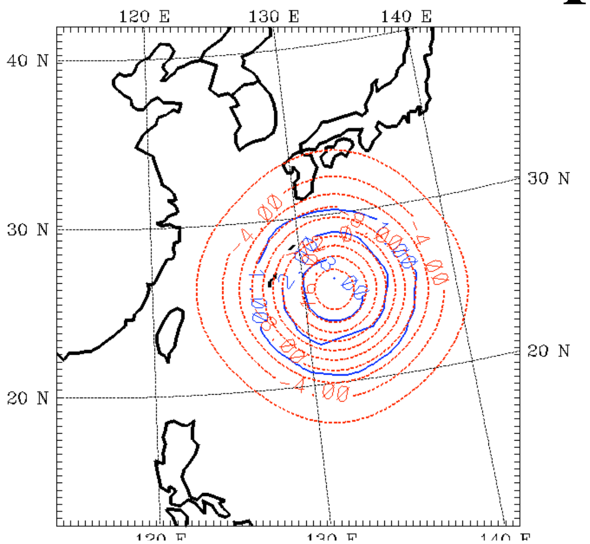
$\langle T_b \bullet T \rangle / \langle T \bullet T \rangle$



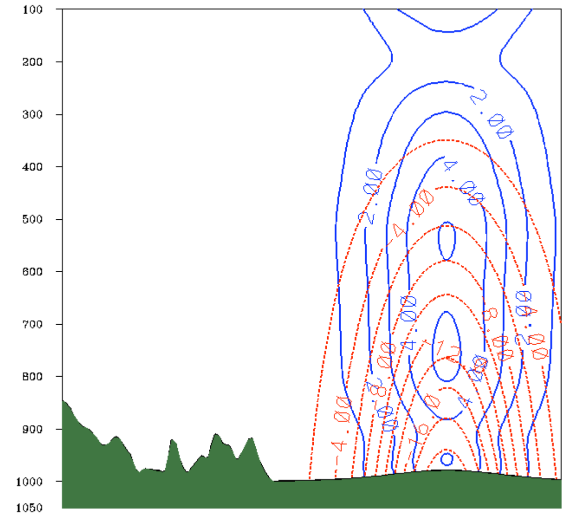
$\langle p_{sb} \bullet p_s \rangle / \langle p_s \bullet p_s \rangle$

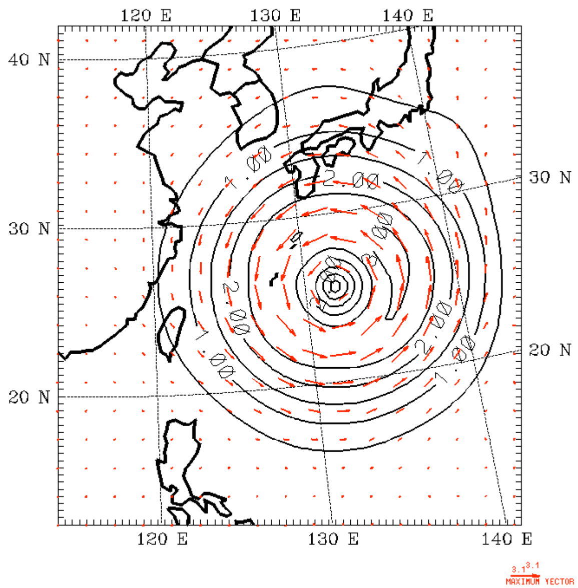


3D-Var response to a single P_s Observation

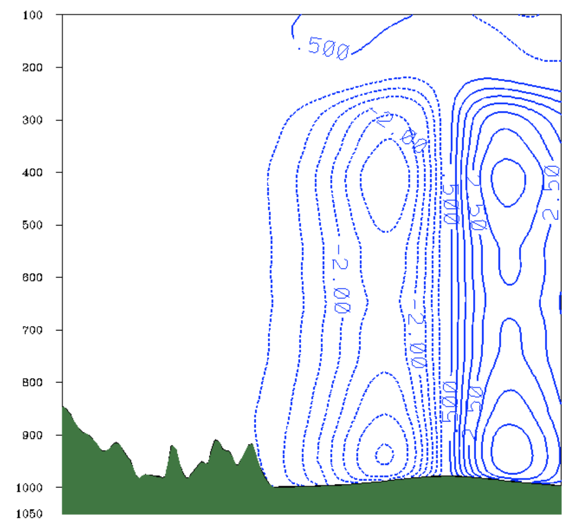


Pressure,
Temperature





Wind Speed,
Vector,
v-wind component.

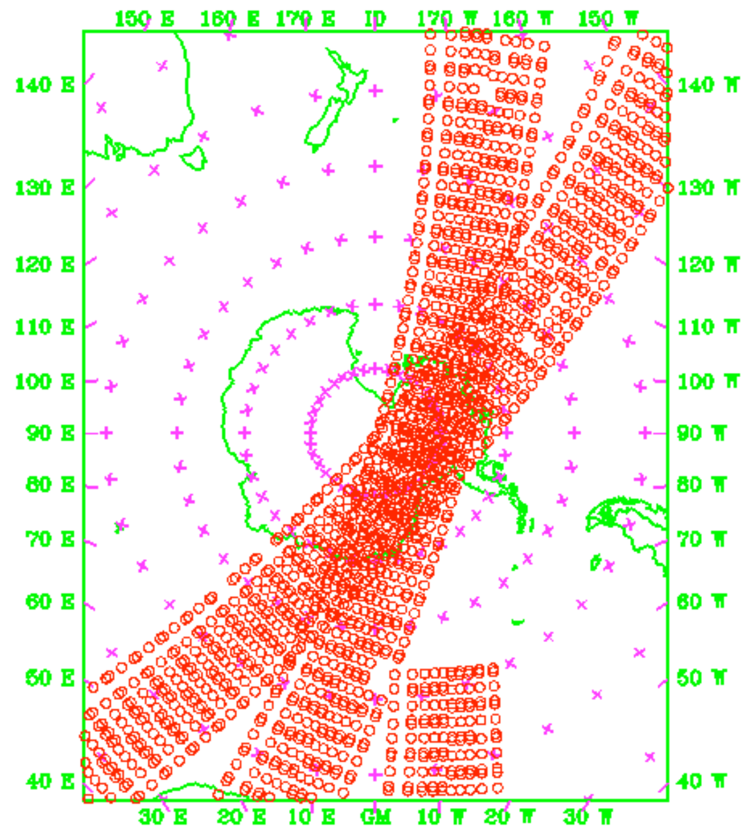


5. Observational Issues

Observation Preprocessing (*OBSPROC*)

- Reads in conventional observation files from decoders/GTS.
- Performs gross QC, e.g. domain/time, consistency, duplicate, merging.
- Simple thinning option.
- Assigns observation errors.
- Outputs in ascii “3D-Var format” for further QC and input to WRF-Var.
- Plots observation distributions.

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

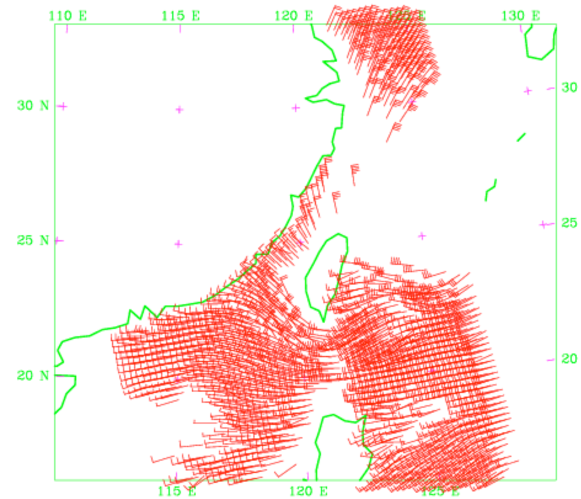


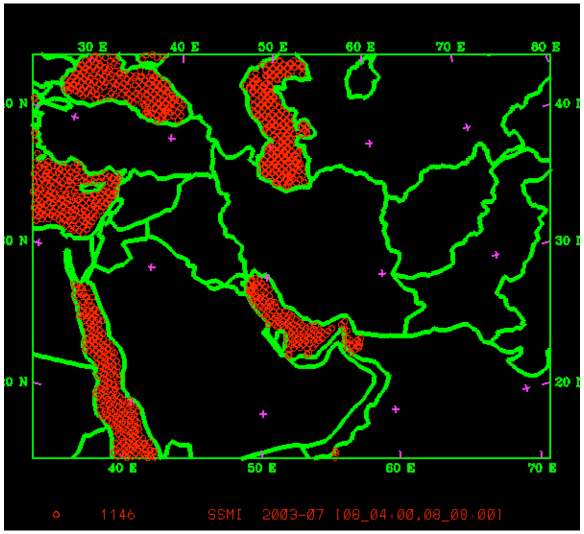
WRF-Var Observations (August 2005, V2.1 Release)

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

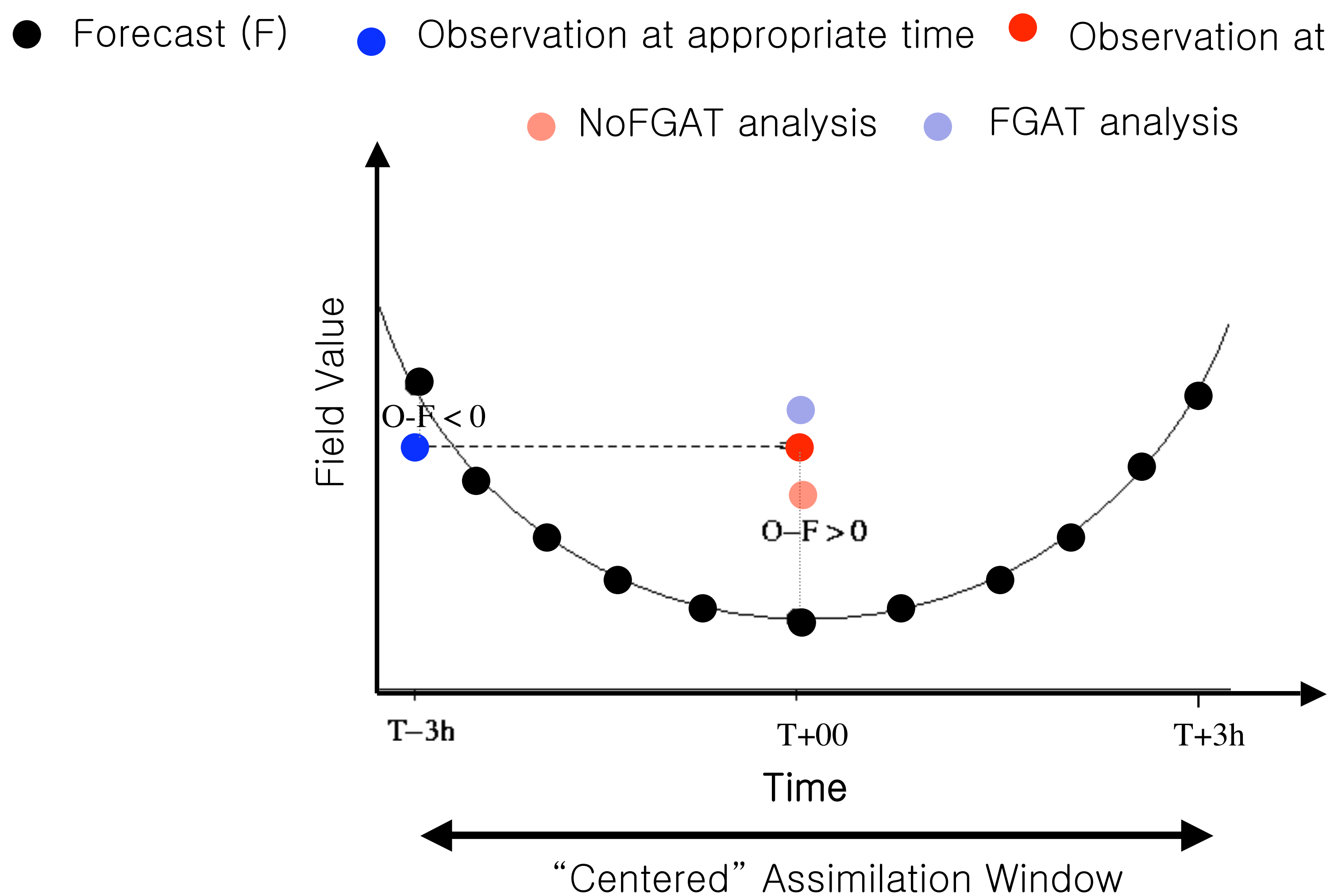
- Remotely sensed retrievals:
  - Atmospheric Motion Vectors (SATOBS, MODIS
  - Ground-based GPS Total Precipitable Water.
  - SSM/I oceanic surface wind speed and TPW.
  - Scatterometer (Quikscat) oceanic surface winds.
  - Wind Profiler.
  - **Radar radial velocity and reflectivity.**
  - ATOVS/AIRS/MODIS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

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



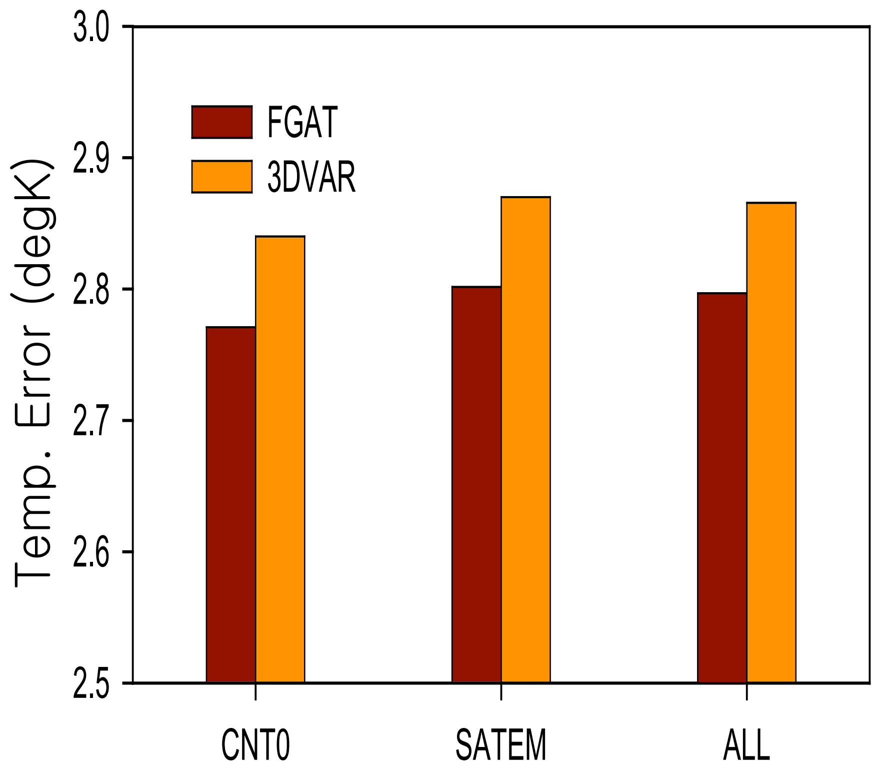


3D-Var FGAT: First Guess at Appropriate Time

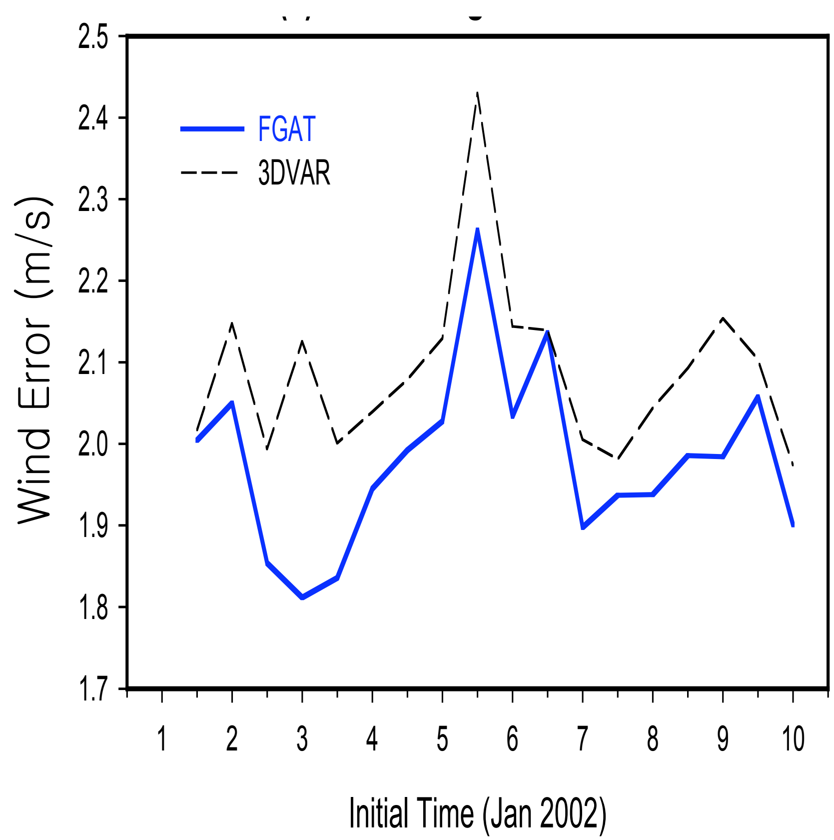


3D-Var-FGAT Forecast Impact

6hr Forecast T Error



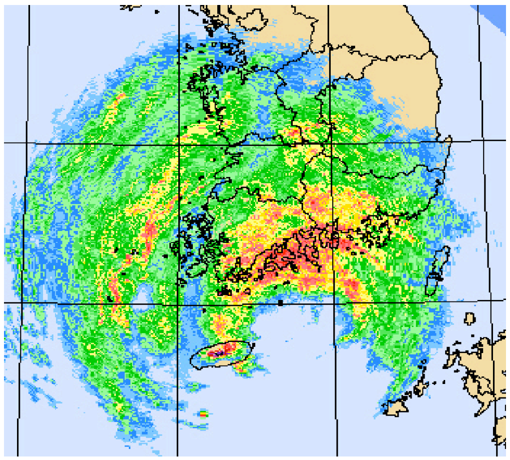
12hr Forecast U Error



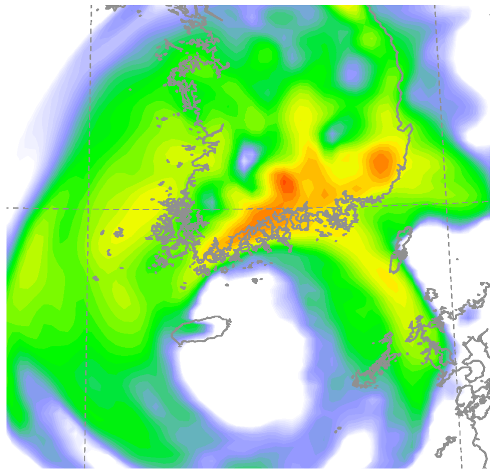
Korean Radar Data Assimilation in WRF-Var

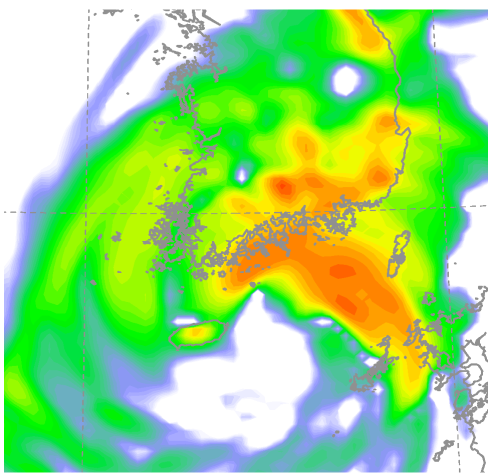
Typhoon Rusa Test Case 3hr Precip:

Obs (03Z, 31/08)

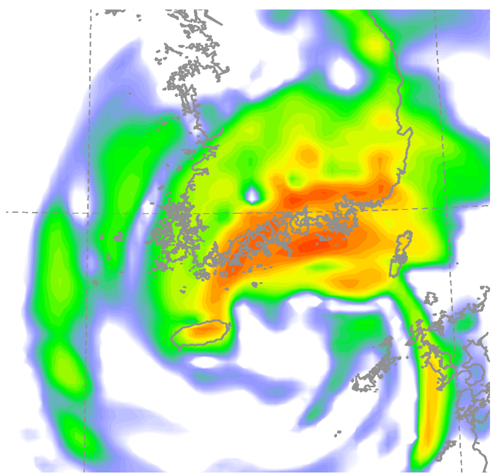


No Radar



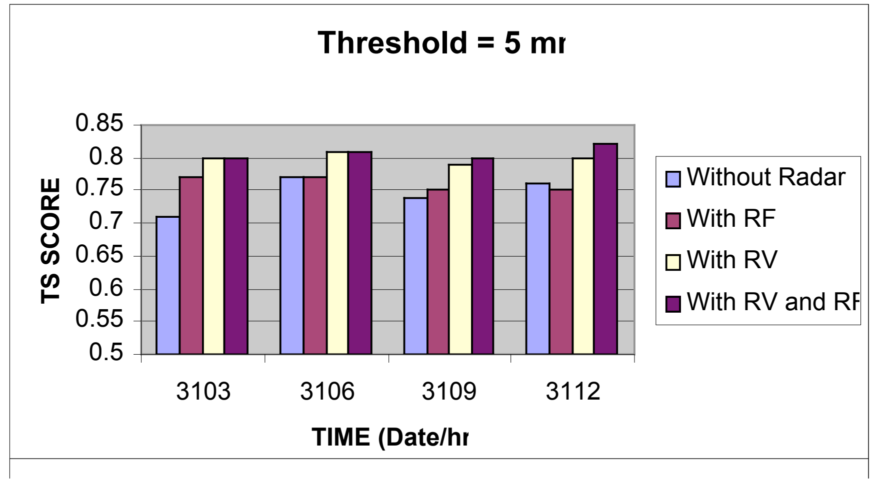


Radar RV

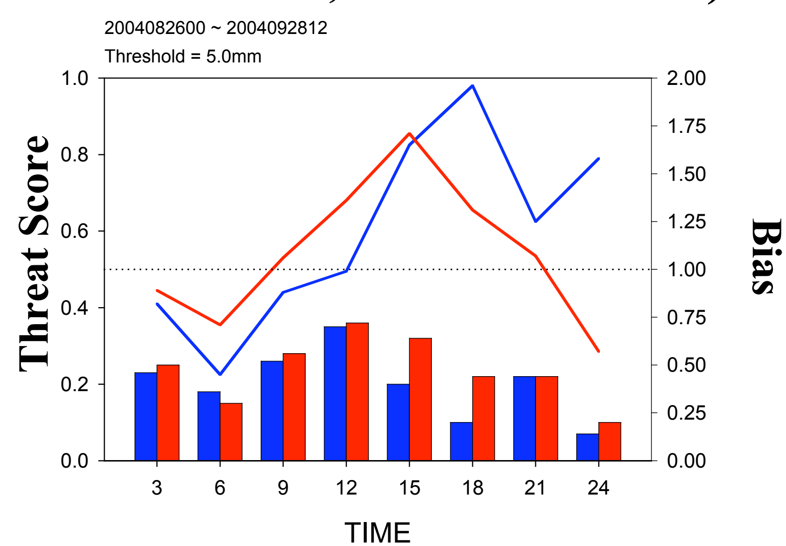


Radar RV+RF

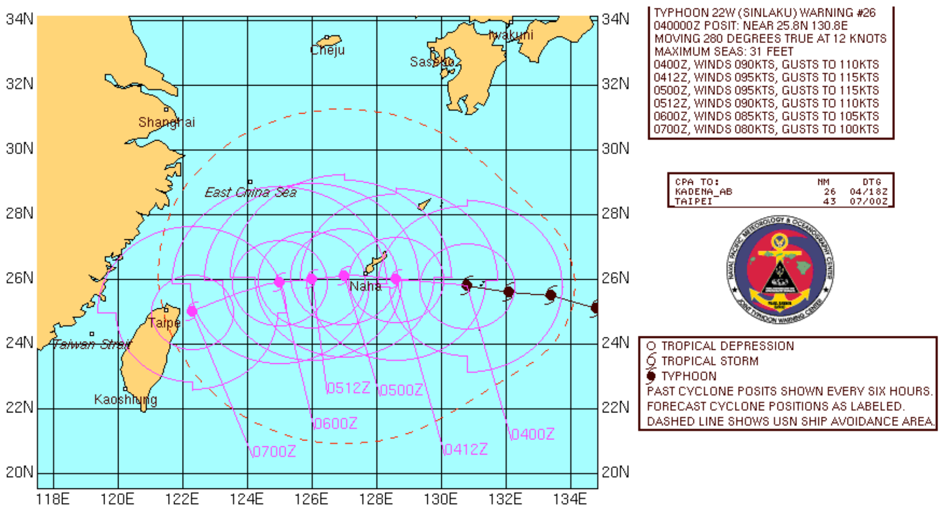
Typhoon Rusa 3hr Precip. Verification:



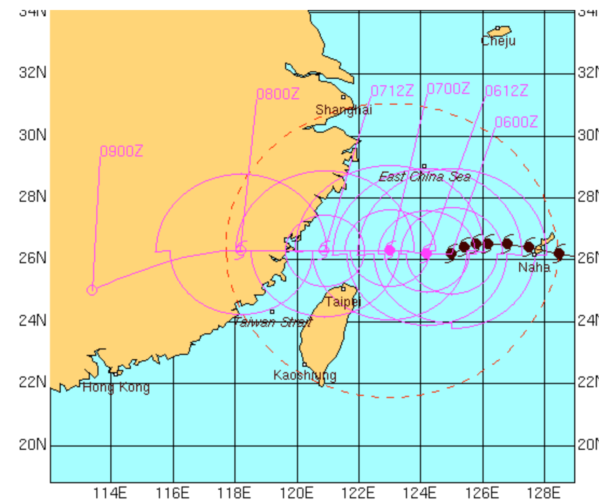
KMA Pre-operational Verification:
(no radar: blue, with radar: red)



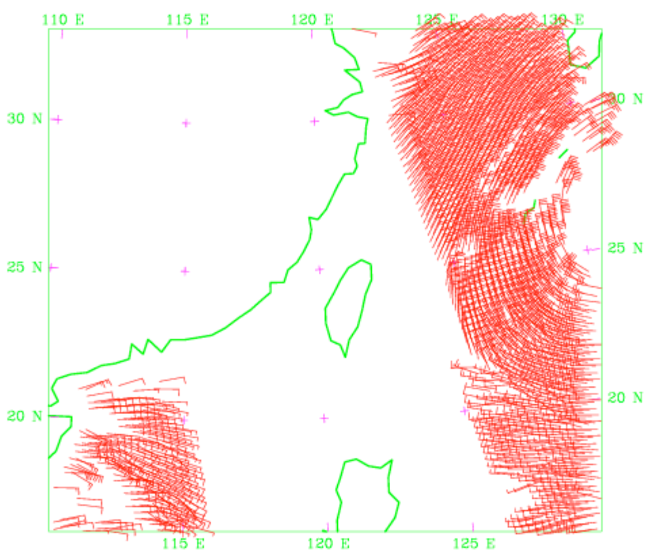
Typhoon Sinlaku: Quikscat Data



00Z September 4th 2002

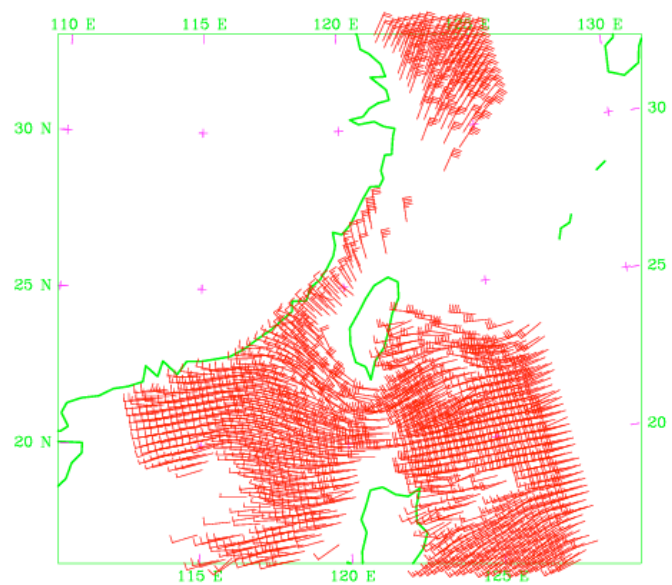


00Z September 6th 2002

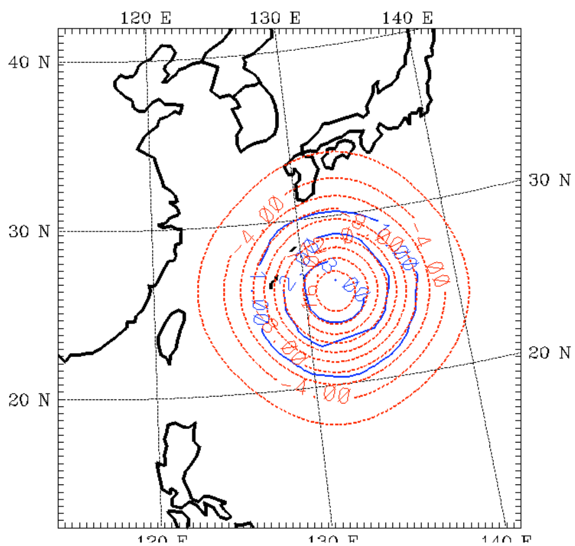


Quikscat Data

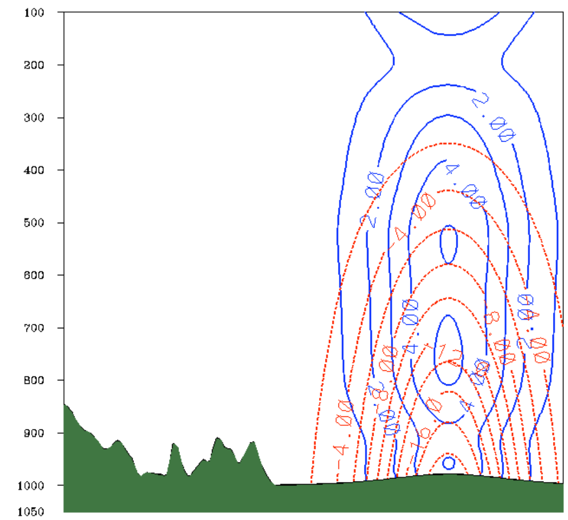
Barker et al (2004)

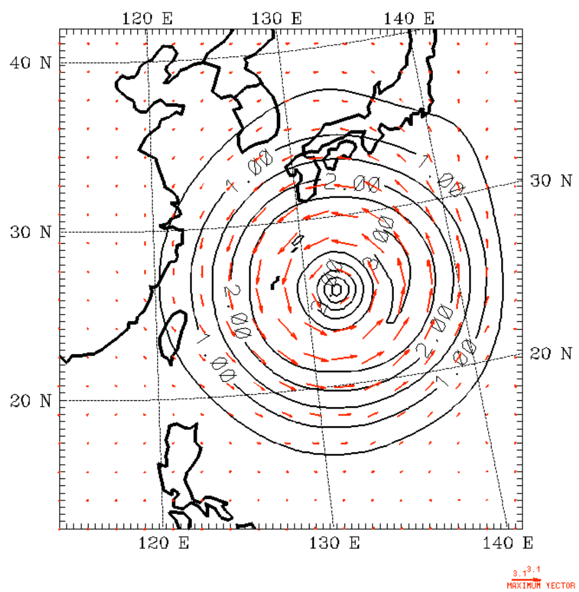


WRF-Var Sinlaku Bogus:Analysis Increments

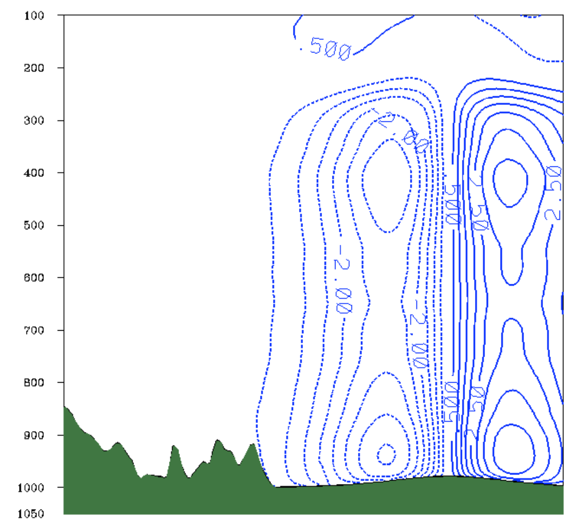


Pressure,
Temperature



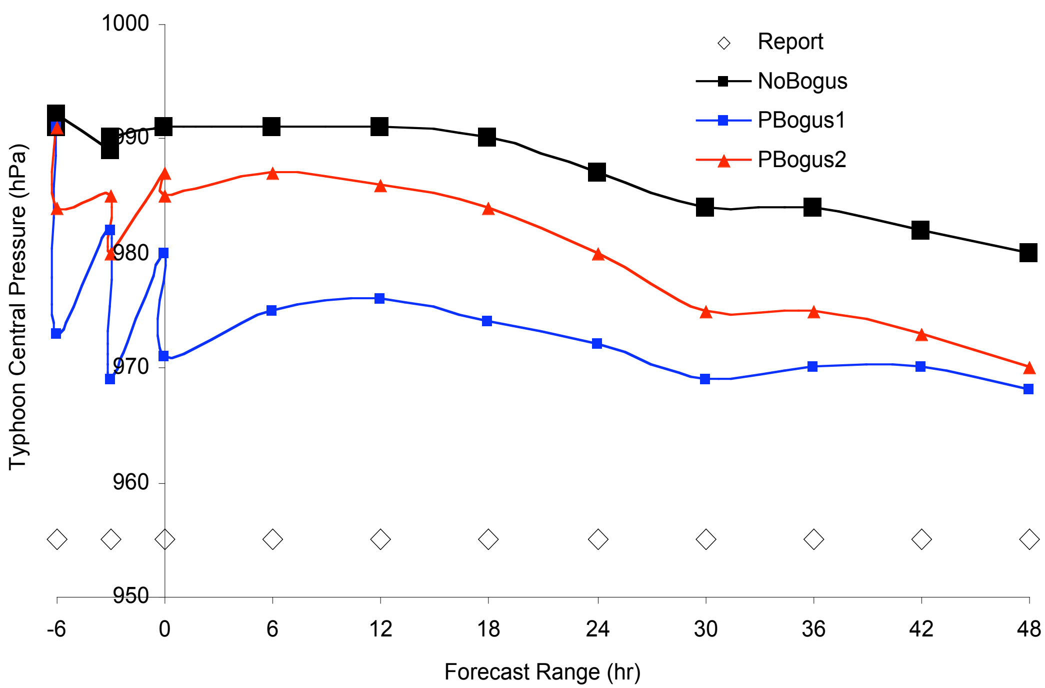


Wind Speed,
Vector,
v-wind component.

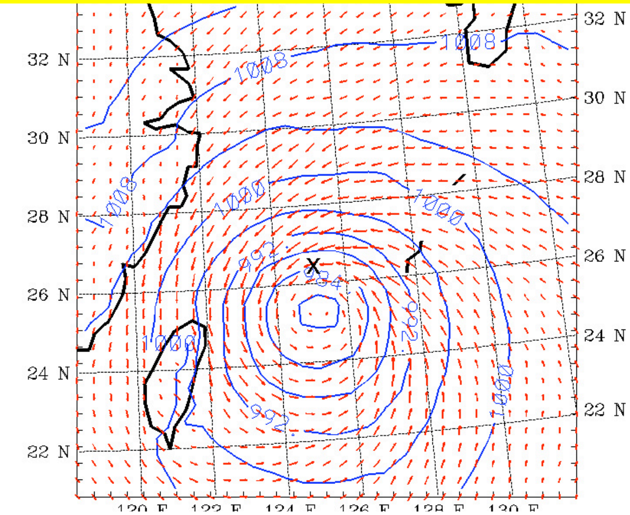


Single Surface Pressure Bogus: Forecast Impact

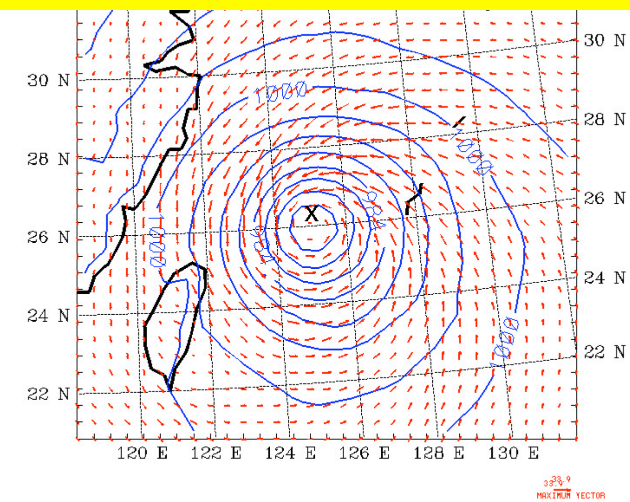
Typhoon Central Pressure



48hr Forecast (NoBogus)



48hr Forecast (PBogus1)



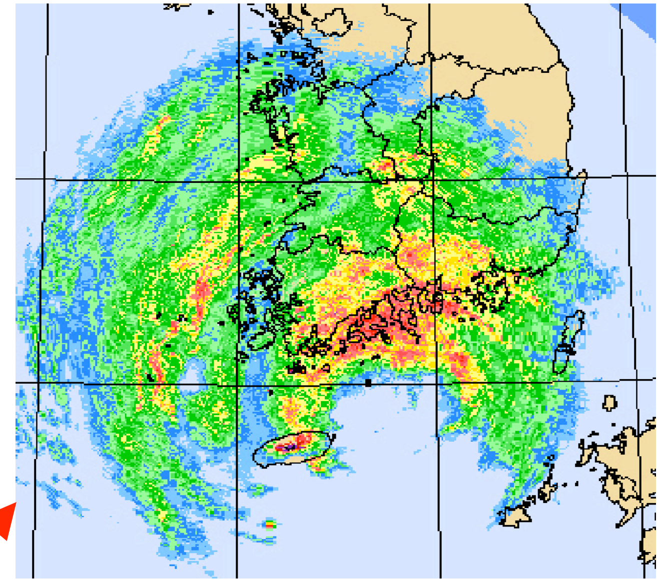
6. Current Status and Future Plans

WRF-Var Observations

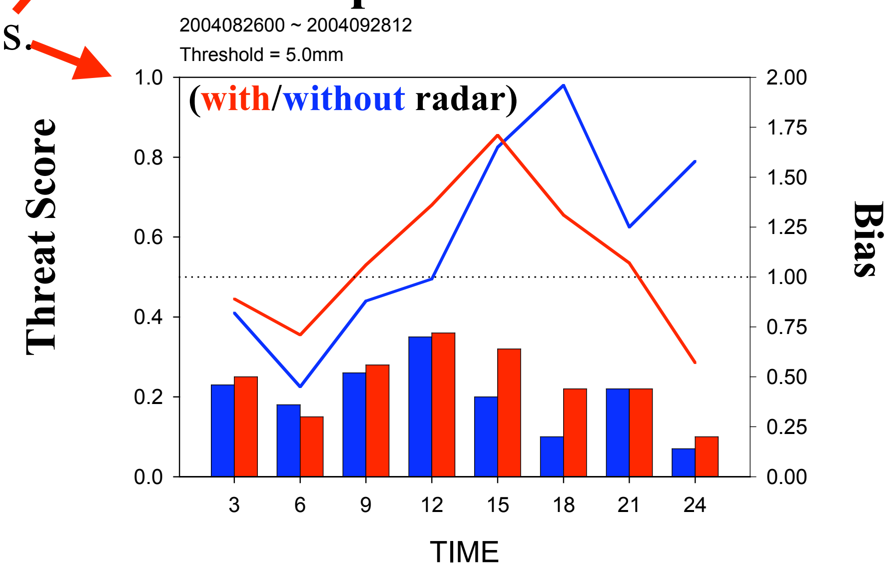
- **In-Situ:**
  - Surface (SYNOP, METAR, SHIP, BUOY).
  - Upper air (TEMP, PIBAL, AIREP, ACARS).

- **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 velocities and reflectivities.
  - Satellite temperature/humidities.
  - GPS refractivity (e.g. COSMIC).

- **Radiative Transfer:**
  - RTTOVS (EUMETSAT).
  - CRTM (JCSDA).

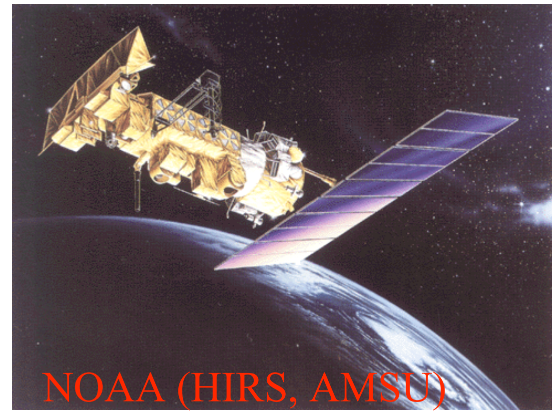


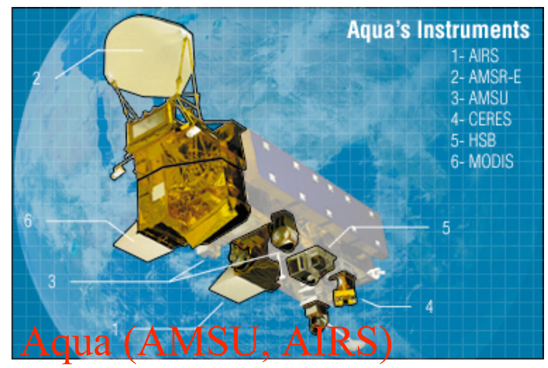
KMA Pre-operational Verification:



WRF-Var Radiance Assimilation Status

- BUFR 1b radiance ingest.
- RTM interface: RTTOV8_5 **or** CRTM
- NESDIS microwave surface emissivity model
- Range of monitoring diagnostics.
- Quality Control for HIRS, AMSU, AIRS, SSMI/S.
- Bias Correction (Adaptive, *Variational in 2008*)
- Variational observation error tuning
- Parallel: MPI
- Flexible design to easily add new satellite sensors

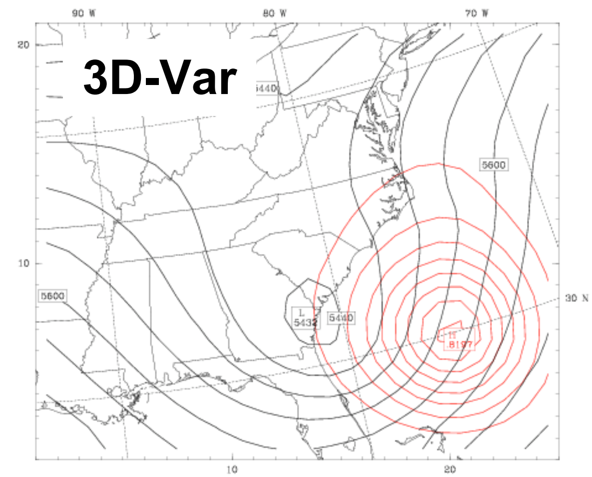

NOAA (HIRS, AMSU)



Aqua (AMSU, AIRS)


DMSP(SSMI/S)

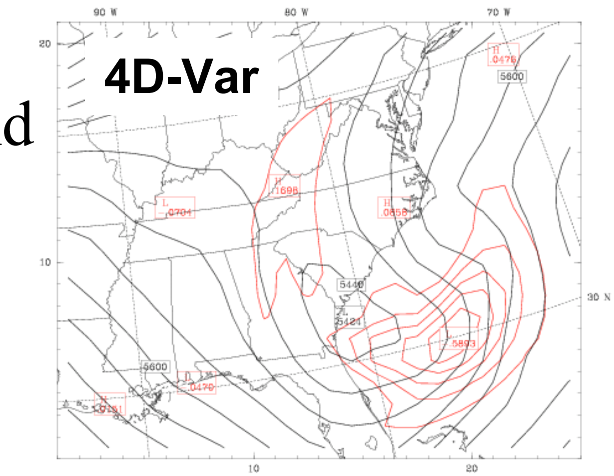
WRF-(4D)Var Summary



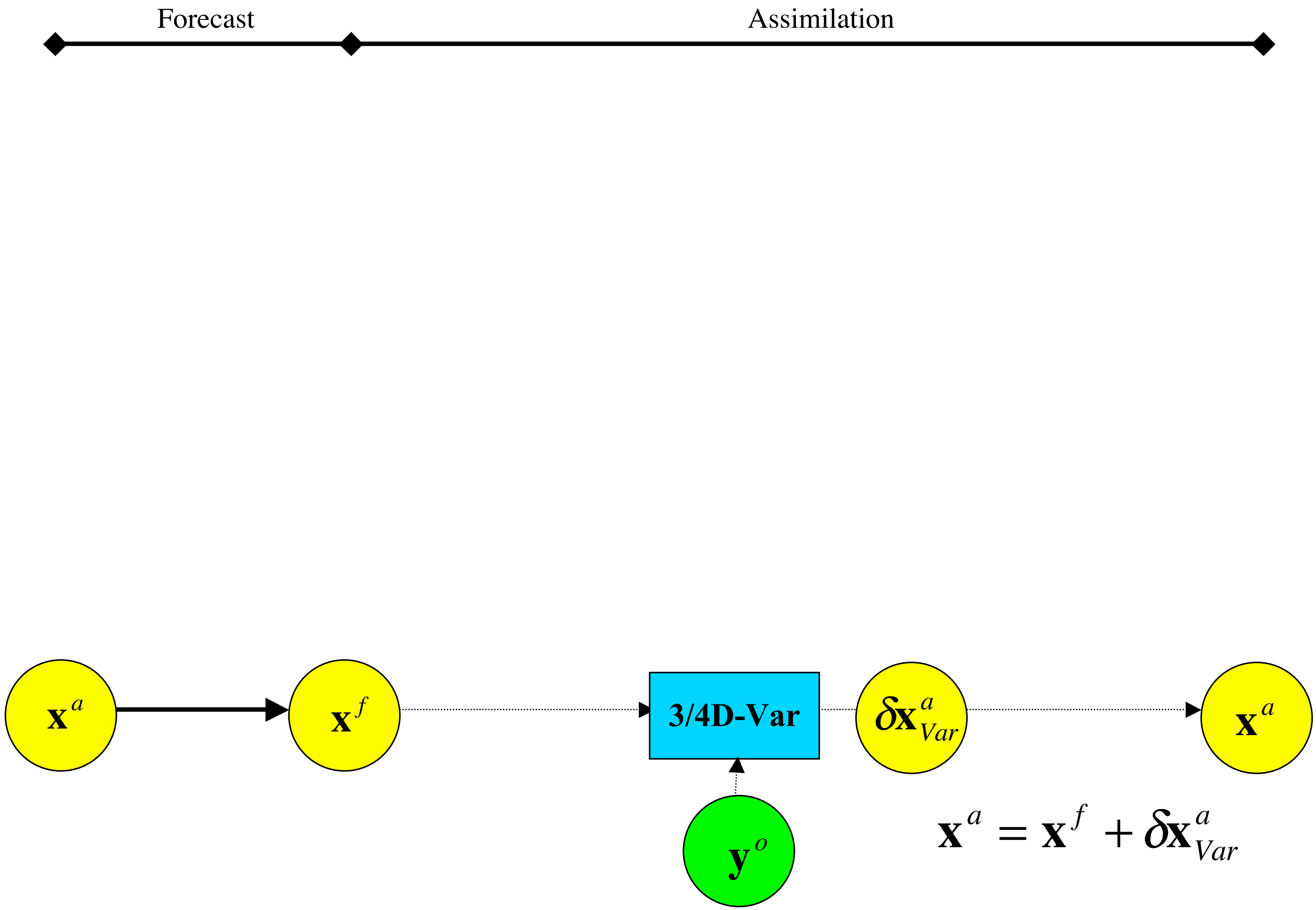
1. WRF-(4D)Var AFWA project: 2004-2007.

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.

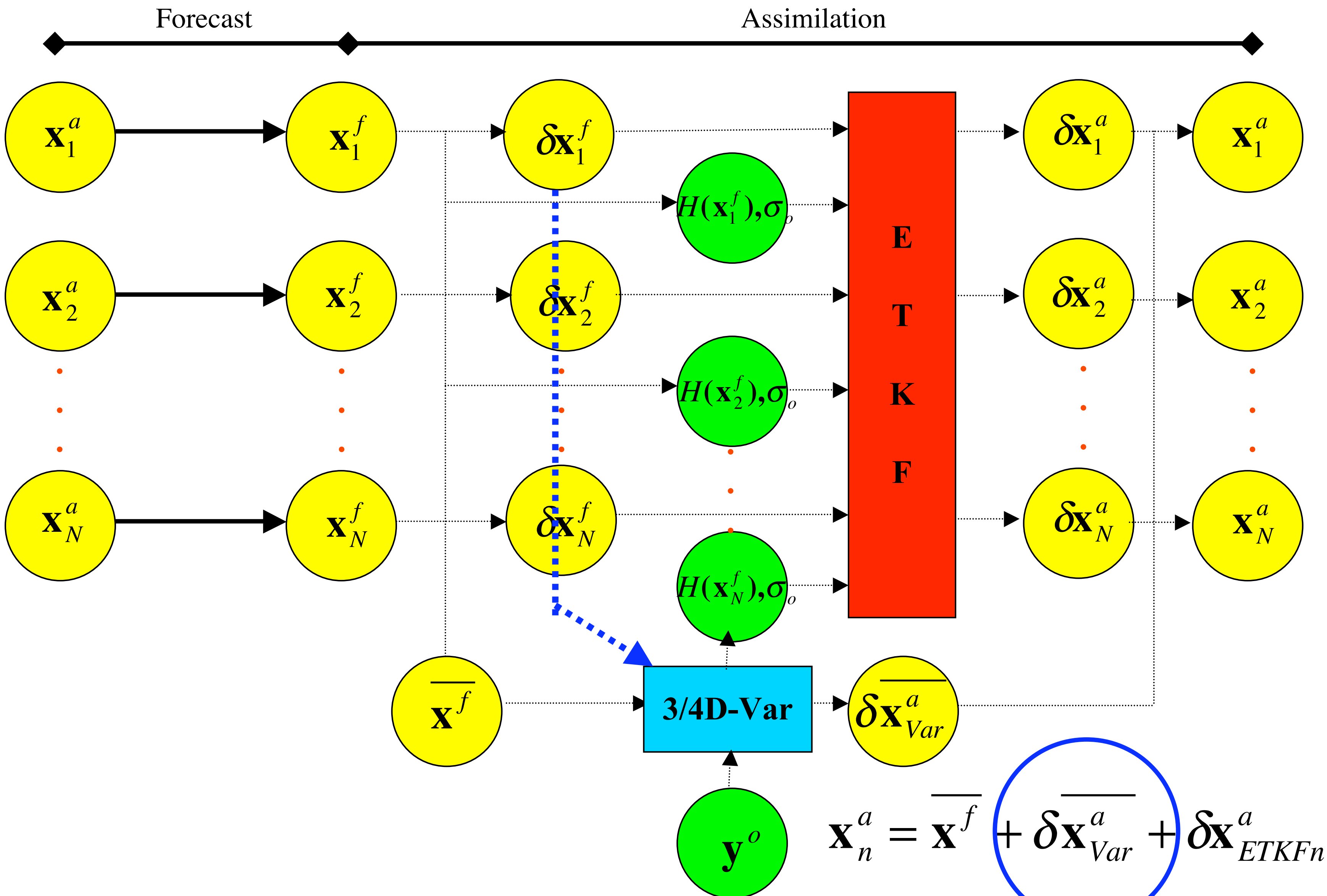


Deterministic Cycling NWP System



$$\mathbf{x}^a = \mathbf{x}^f + \delta\mathbf{x}^a_{Var}$$

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



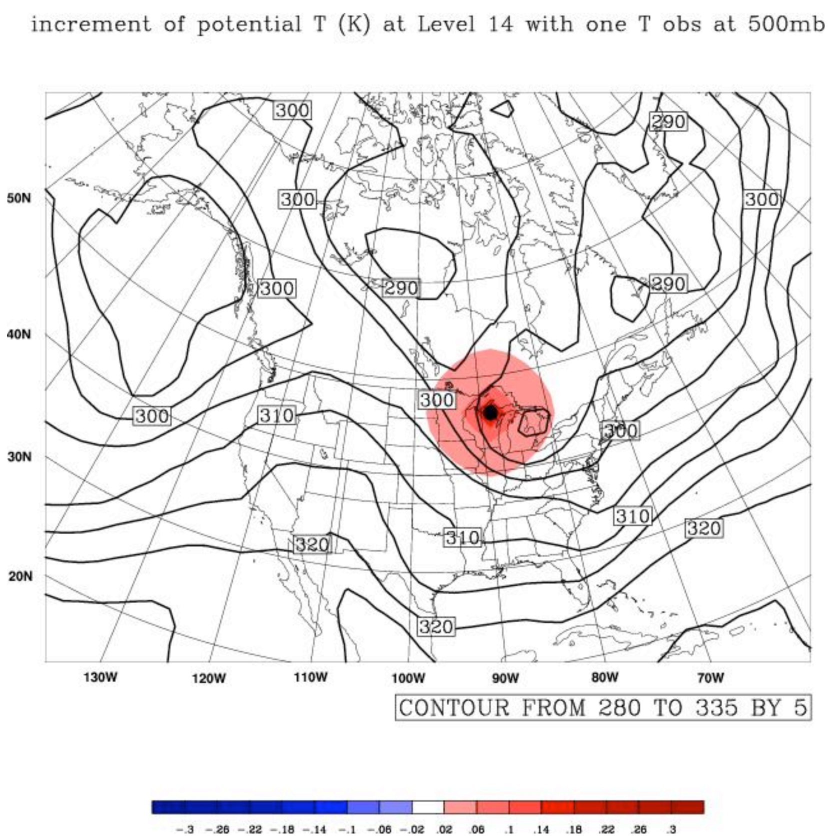
$$\mathbf{x}_n^a = \overline{\mathbf{x}^f} + \delta\overline{\mathbf{x}_{Var}^a} + \delta\mathbf{x}_{ETKFn}^a$$

Motivation: Leverage existing 3/4D-Var framework to implement ensemble DA.

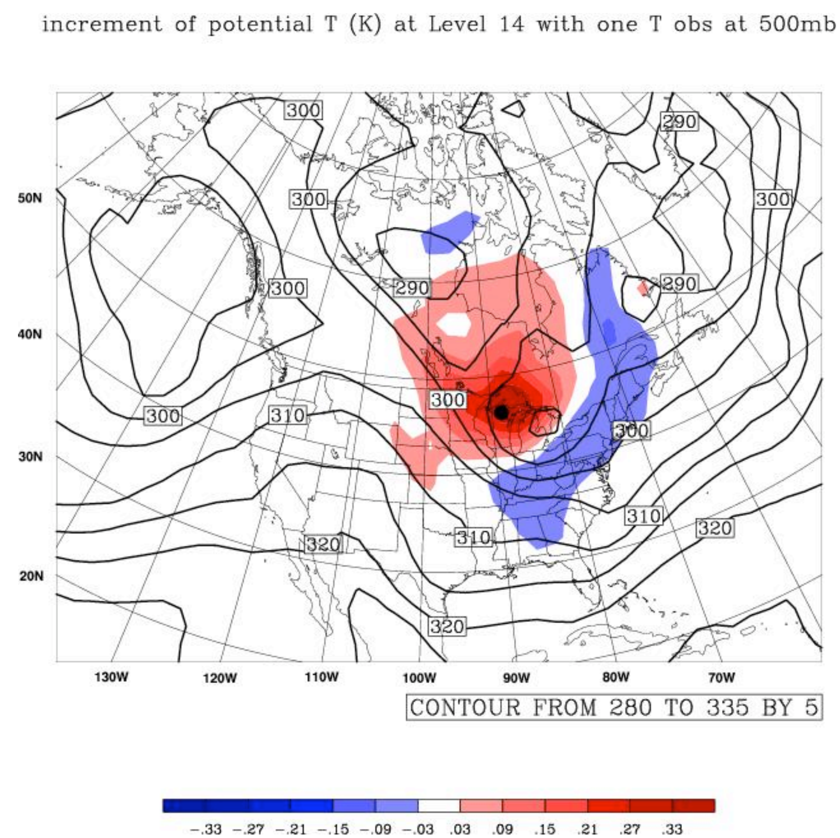
Hybrid DA (Regional) Single Observation Test

Analysis increment

Pure 3D-Var Covariance



Pure Ensemble Covariance



Flow-dependent ETKF ensemble covariance is successfully incorporated in WRF-Var

WRF-Var Version 2.1
(Release July 2005)

- Three-dimensional variational data assimilation (3D-Var).

- Conventional and radar (radial velocity and reflectivity) observations.

- Other new obs: GPS refractivity, MODIS Feature Track Winds.

- 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 (Latest Code)

- Major new features:

  - Direct assimilation of satellite radiances (AMSU, AIRS, SSMI/S, etc.).
  - Four-Dimensional Variational Data Assimilation (4D-Var).
  - Ensemble Transform Kalman Filter (ETKF).
  - Hybrid variational/ensemble DA.
  - Enhanced forecast error covariances (e.g. ensemble-based).
  - Major software engineering reorganization.
  - Remove obsolete features (e.g. MM5/GFS-based errors).

- Unified WRF/WRF-Var code repository.

- Extended wiki-based documentation.

WRF-Var Version 3.0 (Release March 2008)

- Major new features:

    - Direct assimilation of satellite radiances (AMSU, AIRS, SSMI/S, etc.).
    - Four-Dimensional Variational Data Assimilation (4D-Var).
    - Ensemble Transform Kalman Filter (ETKF).
    - Hybrid variational/ensemble DA.
    - Enhanced forecast error covariances (e.g. ensemble-based).
    - Major software engineering reorganization.
    - Remove obsolete features (e.g. MM5/GFS-based errors).

- Unified WRF/WRF-Var code repository.

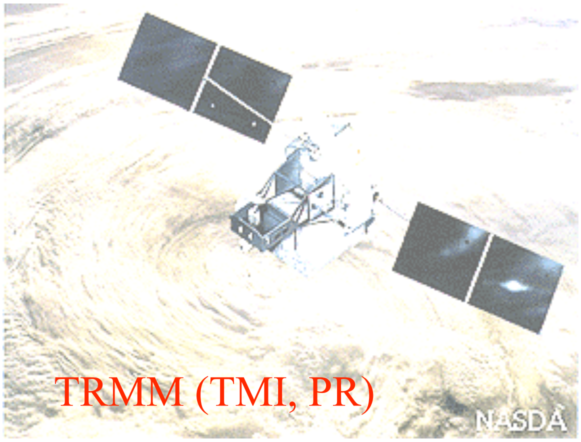
- Extended wiki-based documentation.

Not included in public release due to lack of funding

Future Plans

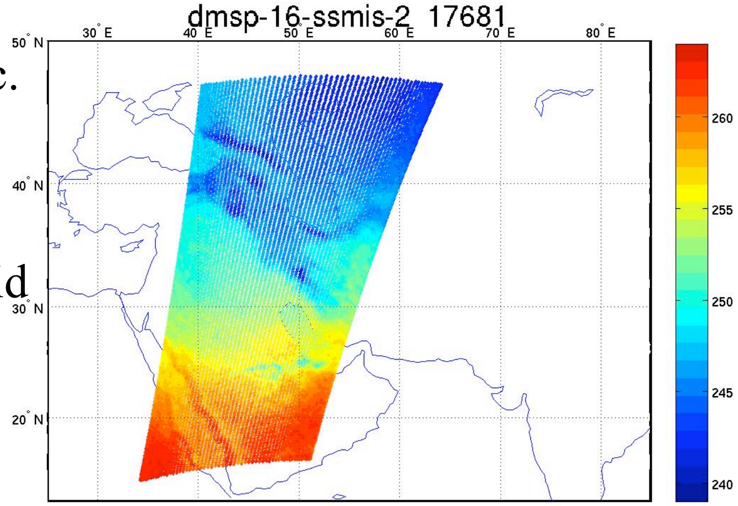
General Goals:

- Unified, multi-technique WRF DA system.
- Retain flexibility for research, multi-applications.
- Leverage international WRF community efforts.
- Work to eliminate **unnecessary** diversity.



WRF-Var Development (MMM Division):

- 4D-Var (additional physics, optimization).
- Sensitivities tools (adjoint, ensemble, etc.).
- EnKF within WRF-Var -> WRF-DAS.
- Instrument-specific radiance QC, bias correction, etc.



Data Assimilation Testbed Center (DATC):

- Technique intercomparison: 3/4D-Var, EnKF, Hybrid
- Obs. impact: AIRS, TMI, SSMI/S, METOP.
- New Regional testbeds: US, India, Arctic, Tropics.