WRF-VAR Overview

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Outline of Talk

1) Introduction to data assimilation.
2) Basics of modern data assimilation.
3) Demonstration with a simple system.
4) WRF-Var.
5) Important issues.

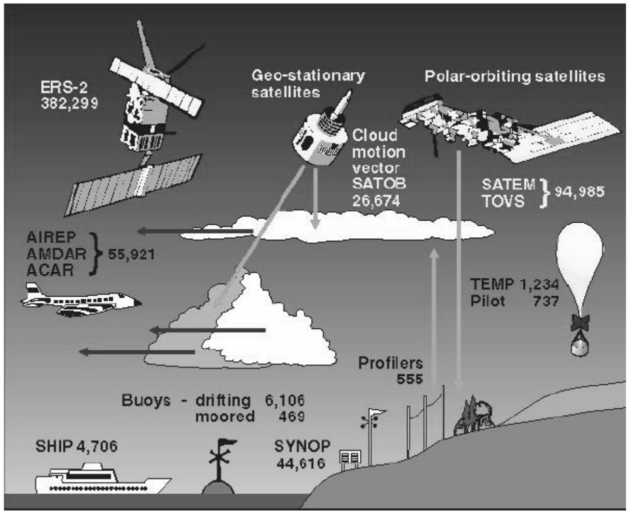
1. Introduction to data assimilation

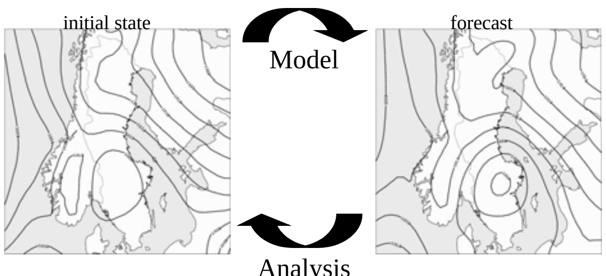
Modern weather forecast (Bjerknes,1904)

- A sufficiently accurate knowledge of the state of the atmosphere at the initial time
- A sufficiently accurate knowledge of the laws according to which one state of the atmosphere develops from another.

Vilhelm Bjerknes (1862–1951)

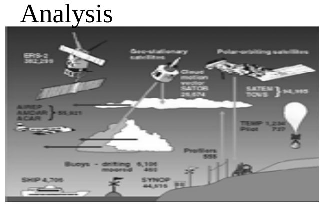
- Analysis: using observations and other information, we can specify the atmospheric state at a given initial time: “Today’s Weather”
- Forecast: using the equations, we can calculate how this state will change over time: “Tomorrow’s Weather”





Model state
x, $\sim 10^7$

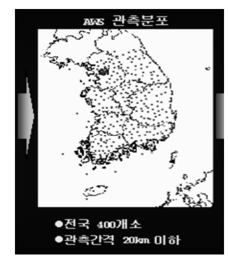
Observations
y^o, $\sim 10^5$-10^6

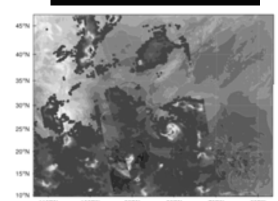


Need For Data Assimilation in NWP

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!





Assimilation methods

- Empirical methods
  - Successive Correction Method (SCM)
  - Nudging
  - Physical Initialisation (PI), Latent Heat Nudging (LHN)
- Statistical methods
  - Optimal Interpolation (OI)
  - 3-Dimensional VARiational data assimilation (3DVAR)
  - 4-Dimensional VARiational data assimilation (4DVAR)
- Advanced methods
  - Extended Kalman Filter (EKF)
  - Ensemble Kalman Filter (EnFK)

2. Basics of modern data assimilation

The analysis problem for a given time

Consider a scalar x.

The background (normally a short-range forecast):

$$x^b = x^t + b.$$

The observation:

$$x^r = x^t + r.$$

The error statistics are assumed to be known:

$$\begin{aligned} <b> &= 0, && \textit{mean error (unbiased)},\\ <r> &= 0, && \textit{mean error (unbiased)},\\ <b^2> &= B, && \textit{background error variance},\\ <r^2> &= R, && \textit{observation error variance},\\
 &= 0, && \textit{nocorrelation between } b \textit{ and } r, \end{aligned}$$

where $< . >$ is ensemble average.

BLUE: the Best Linear Unbiased Estimate

The analysis: $x^a = x^t + a$.
Search for the best estimate: $x^a = \alpha x^b + \beta x^r$

Substitute the definitions, we have:

$$\alpha + \beta = 1.$$

$$< a > = 0$$

The variance:

$$A = < a^2 > = B - 2\beta B + \beta^2 (B + R)$$

To determine β: $\frac{dA}{d\beta} = -2B + 2\beta(B + R) = 0$
we have

$$\beta = \frac{B}{B + R}.$$

$$A^{-1} = B^{-1} + R^{-1}$$

The analysis: $x^a = x^b + \frac{B}{B+R}\left(x^r - x^b\right)$.

"3DVAR"

The analysis is obtained by minimizing the cost function J, defined as:

$$J = \frac{1}{2}\left(x - x^b\right)^T B^{-1}\left(x - x^b\right) + \frac{1}{2}\left(x - x^r\right)^T R^{-1}\left(x - x^r\right).$$

The gradient of J with respect to x:

$$J' = B^{-1}\left(x - x^b\right) + R^{-1}\left(x - x^r\right).$$

At the minimum, $J' = 0$, we have:

$$x^a = x^b + \frac{B}{B+R}\left(x^r - x^b\right),$$

the same as BLUE.

Sequential data assimilation (I)

$$\begin{array}{lcl} \textit{True states} & : & \ldots,\ x^t_{i-1},\ x^t_i,\ x^t_{i+1},\ \ldots \\ \textit{Observations} & : & \ldots,\ x^r_{i-1},\ x^r_i,\ x^r_{i+1},\ \ldots \\ \textit{Forecasts} & : & \ldots,\ x^f_{i-1},\ x^f_i,\ x^f_{i+1},\ \ldots \\ \textit{Analyses} & : & \ldots,\ x^a_{i-1},\ x^a_i,\ x^a_{i+1},\ \ldots \end{array}$$

Sequential data assimilation (II)

Forecast model:

$$x^t_{i+1} = M(x^t_i) + q_i,$$

where q_i is the model error.

As q_i is unknown and x^a_i is the best estimate of x^t_i, the forecast model usually takes the form:

$$x^f_{i+1} = M(x^a_i).$$

OI (and 3DVAR):

$$x^a_i = x^f_i + \frac{B}{B+R}\left(x^r_i - x^f_i\right).$$

Sequential data assimilation (III)

4DVAR

4DVAR analysis is obtained by minimizing the cost function J, defined as:

$$J(x_i) = \frac{1}{2}\left(x_i - x^f_i\right)^T B^{-1}\left(x_i - x^f_i\right) + \frac{1}{2}\sum_{k=0}^{K}\left[M_{k-1}(x_i) - x^r_{i+k}\right]^T R^{-1}\left[M_{k-1}(x_i) - x^r_{i+k}\right]$$

where, K is the assimilation window and

$$\begin{array}{lcl} M_{-1}(x_i) & = & x_i \\ M_0(x_i) & = & M(x_i) \\ M_{k-1}(x_i) & = & \underbrace{M(M(\ldots M}_{k}(x_i)\ldots)) \end{array}$$

Sequential data assimilation (IV)

4DVAR (continue)

The gradient of J with respect to x:

$$J = B^{-1}\left(x_i - x_i^f\right) + \sum_{k=0}^{K}\prod_{j=0}^{k-1}\mathbf{M}_{i+j}^T R^{-1}\left[M_{k-1}(x_i) - x_{i+k}^r\right]$$

where, $\mathbf{M}_{i+j}^T$ is the adjoint model of M at time step $i + j$.

Sequential data assimilation (V)

Extended Kalman Filters:

True states: $x_{i+1}^t = M(x_i^t) + q_i$

Model states: $x_{i+1}^f = M(x_i^a)$

Forecast error: $x_{i+1}^f - x_{i+1}^t = M(x_i^a) - M(x_i^t) - q_i$

A major assumption in KF:

$$M(x_i^a) - M(x_i^t) \approx \mathbf{M}_i(x_i^a - x_i^t)$$

Sequential data assimilation (VI)

Extended Kalman Filters (continue):

Forecast error covariance matrix:

$$P_{i+1}^f = \left\langle \left(x_{i+1}^f - x_{i+1}^t\right)\left(x_{i+1}^f - x_{i+1}^t\right)^T \right\rangle$$

$$\approx \mathbf{M}_i \left\langle \left(x_i^a - x_i^t\right)\left(x_i^a - x_i^t\right)^T \right\rangle \mathbf{M}_i^T + \left\langle q_i q_i^T \right\rangle$$

$$= \mathbf{M}_i P_i^a \mathbf{M}_i^T + Q_i$$

Sequential data assimilation (VII)

Extended Kalman Filters (continue):

For the analysis step:

$$K_i = P_i^f \left(P_i^f + R\right)^{-1}$$

$$x_i^a = x_i^f + K_i(x_i^r - x_i^f)$$

$$P_i^a = (I - K_i)P_i^f$$

For the forecast step:

$$x_{i+1}^f = M(x_i^a)$$

$$P_{i+1}^f = \mathbf{M}_i P_i^a \mathbf{M}_i^T + Q_i$$

Sequential data assimilation (VIII)

From scalar to vector:

Number of grid points $\approx 10^7$:

$$x \rightarrow \mathbf{x}$$

$$x^b \rightarrow \mathbf{x}^{\mathbf{b}}$$

Dimension of $\mathbf{B}$, $\mathbf{P} \approx 10^7 \times 10^7$.

Number of observations, 10^6:

$$x^r \rightarrow \mathbf{y}^{\mathbf{o}}$$

$$x - x^r \rightarrow H(\mathbf{x}) - \mathbf{y}^{\mathbf{o}}$$

Dimension of $\mathbf{R} \approx 10^6 \times 10^6$.

Sequential data assimilation (IX)

OI:

$$\mathbf{x}_i^a = \mathbf{x}_i^f + \mathbf{B}\mathbf{H}^T \left(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right)^{-1} \left[\mathbf{y}^{\mathbf{o}} - H(\mathbf{x}_i^f)\right]$$

$$\mathbf{x}_{i+1}^f = M(\mathbf{x}_i^a)$$

4DVAR:

$$J(\mathbf{x}_i) = \frac{1}{2}\left(\mathbf{x}_i - \mathbf{x}_i^f\right)^T \mathbf{B}^{-1} \left(\mathbf{x}_i - \mathbf{x}_i^f\right)$$

$$+\frac{1}{2}\sum_{k=0}^{K} \left[H\left(M_{k-1}\left(\mathbf{x}_i\right)\right) - \mathbf{y}^{\mathbf{o}}{}_{i+k}\right]^T \mathbf{R}^{-1} \left[H\left(M_{k-1}\left(\mathbf{x}_i\right)\right) - \mathbf{y}^{\mathbf{o}}{}_{i+k}\right]$$

$$J' = \mathbf{B}^{-1}\left(\mathbf{x}_i - \mathbf{x}_i^f\right) + \sum_{k=0}^{K}\prod_{j=0}^{k-1} \mathbf{M}_{i+j}^T \mathbf{H}^T \mathbf{R}^{-1} \left[H\left(M_{k-1}\left(\mathbf{x}_i\right)\right) - \mathbf{y}^{\mathbf{o}}{}_{i+k}\right]$$

Sequential data assimilation (X)

The Extended Kalman Filter:

For the analysis step i:

$$\mathbf{K}_i = \mathbf{P}_i^f \mathbf{H}_i^T \left(\mathbf{H}_i \mathbf{P}_i^f \mathbf{H}_i^T + \mathbf{R}\right)^{-1}$$

$$\mathbf{x}_i^a = \mathbf{x}_i^f + \mathbf{K}_i \left[\mathbf{y}^{\mathbf{o}} - H(\mathbf{x}_i^f)\right]$$

$$\mathbf{P}_i^a = (\mathbf{I} - \mathbf{K}_i \mathbf{H}_i)\mathbf{P}_i^f$$

For the forecast step, from i to $i+1$:

$$\mathbf{x}_{i+1}^f = M(\mathbf{x}_i^a)$$

$$\mathbf{P}_{i+1}^f = \mathbf{M}_i \mathbf{P}_i^a \mathbf{M}_i^T + \mathbf{Q}_i$$

Issues on data assimilation

- Observations $\mathbf{y}^o$
- Observation operator H
- Observation errors $\mathbf{R}$
- Background $\mathbf{x}^b$
- Size of $\mathbf{B}$: statistical model and tuning
- $\mathbf{M}$ and $\mathbf{M}^T$: development and validity
- Minimization algorithm (Quasi-Newton; Conjugate Gradient; ...)
- Model errors $\mathbf{Q}$
- Size of $\mathbf{P}^f$ and $\mathbf{P}^a$: simplifications

3. Demonstration with a simple system

The Lorenz 1964 equation

Nonlinear equation (NL):

$$x_{i+1} = ax_i - x_i^2 = M(x_i).$$

Depending on a, three types of solution are found: steady state; limited cycle; chaotic.

Tangent Linear equations (TL):

$$x_{i+1}^{tl} = \left(a - 2x_i^{bs}\right) x_i^{tl} = \mathrm{M}_i x_i^{tl}.$$

(linearized around basic state x_i^{bs})
Adjoint equation (AD):

$$x_i^{ad} = \left(a - 2x_i^{bs}\right) x_{i+1}^{ad} = \mathrm{M}_i^T x_{i+1}^{ad}.$$

Note here for this simple case we have

$$\mathrm{M}_i = \mathrm{M}_i^T = \left(a - 2x_i^{bs}\right).$$

Issues on data assimilation for the system based on the Lorenz 64 eqation

- Observation operator $H = \mathbf{H} = \mathbf{H}^T = 1$
- Estimate of the true states - generated (with model error!)
- Observation error $x^o - x^t = \sigma_o G$
- Size of $\mathbf{B}$ is 1, but $B = \sigma_b^2$ still needs attention
- Model errors $\mathbf{Q}$: $q_i = \sigma_m G$ when "true" states are generated; but we assume $Q = B/4$
- Size of $\mathbf{P}^f$ or $\mathbf{P}^a$ is 1.
- M and M^T: no e ort in development but their validity is still a major problem
  (model, assimilation window length, ...)
- Gaussian statistics

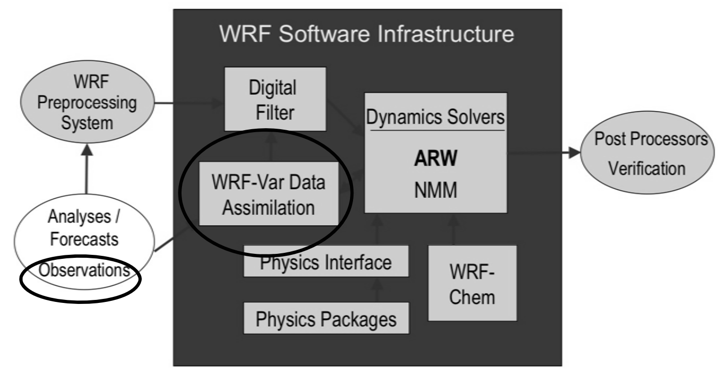
Too simple?

Try: Lorenz63 model
Try: 1-D advection equation
Try: 2-D shallow water equation
…
Try: ARW!!!

4. WRF-Var

…WRF-Var is a **Var**iational data assimilation system built within the software framework of **WRF**, used for application in both research and operational environments….

WRF Modeling System



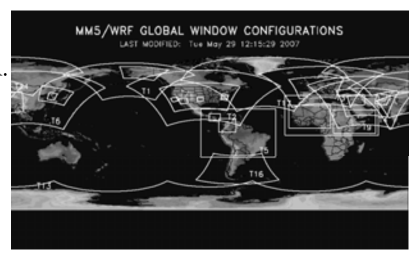
ARW = Advanced Research WRF (NCAR) Core

NMM = Nonhydrostatic Mesoscale Model (NCEP) Core

WRF-Var (WRFDA) Data Assimilation Overview

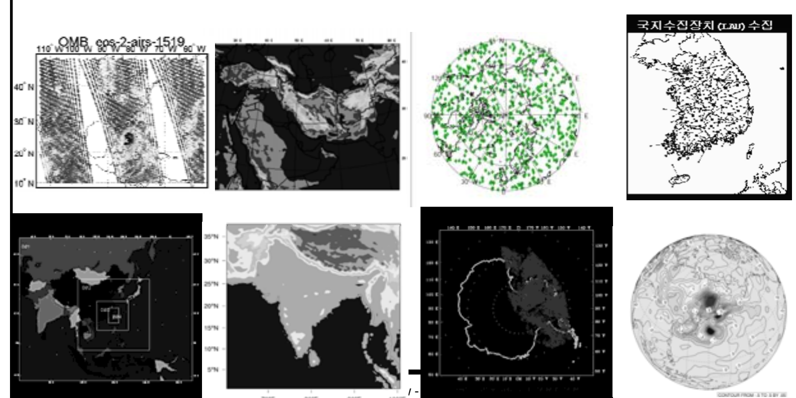
- **Goal:** Community WRF DA system for regional/global, research/operations, and deterministic/probabilistic applications.
- **Techniques:**
  - 3D-Var
  - 4D-Var (regional)
  - Ensemble DA,
  - Hybrid Variational/Ensemble DA.
- **Models:** WRF, MM5, KMA global.
- **Support:**
  - NCAR/ESSL/MMM/DAG
  - NCAR/RAL/JNT/DATC
- **Observations:** Conv.+Sat.+Radar

AFWA Theaters:



The WRF-Var Program

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



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).
  - Verification package
  - Utilization of observations packed in NCEP PREPBUFR format
  - Inclusion of various scripts and NCL based graphics
- Unified WRF/WRF-Var code repository.
- Unified WRF/WRF-Var namelist
- Extended wiki-based documentation.

WRF-Var Version 3.0 (Release April 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).
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- Unified WRF/WRF-Var code repository.
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- Extended wiki-based documentation.

Not included in public release due to lack of funding.

Collaborations welcome!

Future Plans

General Goals:

- Unified, multi-technique WRF DA system.
- Retain flexibility for research, multi-applications.
- Leverage international WRF community efforts.

WRF-Var Development (MMM Division):

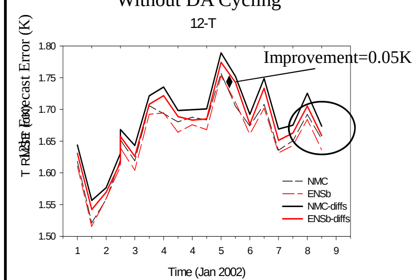
- 4D-Var (additional physics, optimization).
- Sensitivities tools (adjoint, ensemble, etc.).
- EnKF within WRF-Var -> WRFDA.
- Instrument-specific radiance QC, bias correction, etc.

Data Assimilation Testbed Center (DATC):

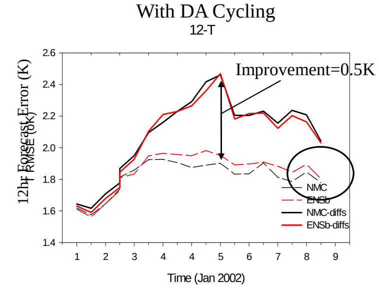
- Technique intercomparison: 3/4D-Var, EnKF, Hybrid
- Obs. impact: AIRS, TMI, SSMI/S, METOP.
- New Regional testbeds: US, India, Arctic, Tropics.

Importance of Data Assimilation For General WRF Development/Testing

Without DA Cycling



With DA Cycling



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

Experiment (Mi-Seon Lee, KMA)

5. Important issues covered by this tutorial

- y^o observations - collection, quality control, bias correction, thinning, …
- *H* observation operator, including the tangent linear operator **H** and the adjoint operator $\mathbf{H}^T$.
- *M* forecast model, including the tangent linear model **M** and adjoint model $\mathbf{M}^T$.
- **B** background error covariance (~ 10^7x10^7).
- **R** observation error covariance which includes the representative error (10^6x10^6).
- Minimization algorithm
- $\mathbf{P}^a$ and $\mathbf{P}^f$ analysis and forecast error covariances

Observation Pre-processing

Observation Pre-processor for WRF-Var

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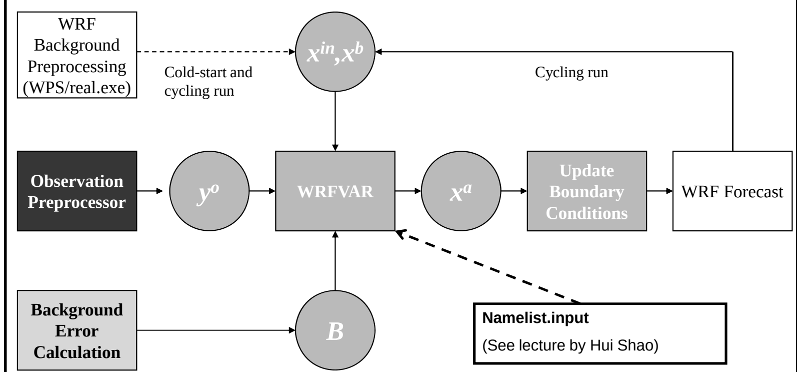
Presented in WRFVar Tutorial, 2 February 2009

Thanks to everyone in NCAR/MMM/WRFDA group, especially to

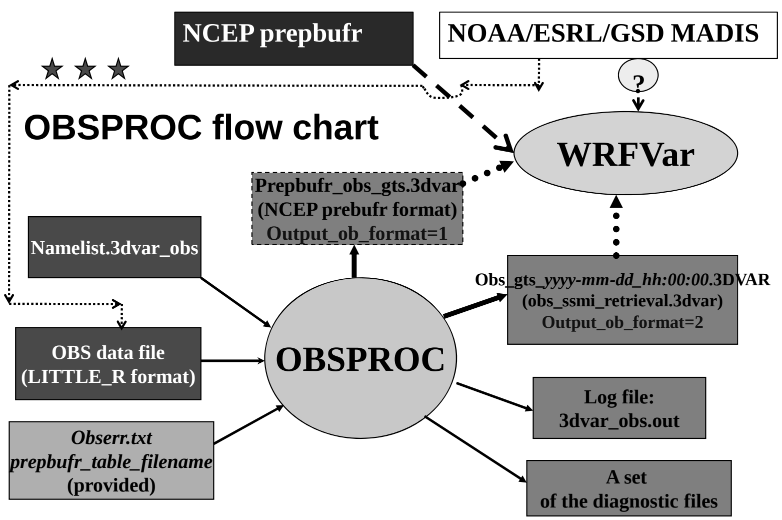
Hui-Chuan Lin, Zhiquan Liu, Hans Huang, and Jim Bresch

WRF-Var in the WRF Modeling System



The observations are one of the important input files for WRF-Var, no observations will be no data assimilation.

* In certain cases, no obs WRF-Var run is still useful (e.g. using *RIP4 diff* to plot increments when cycling run conducted).



There are 3 observation data sources available:

- NCEP prepbufr files: real-time and archived;
  Not fully tested (ob_format=1)
- NOAA/ESRL/GSD MADIS files: real-time and archived;
  Not fully tested (ob_format=3 ?)
- NCAR archived observation data files (LITTLE_R format) via obsproc (ob_format=2)

The impact of the different observation data sources on the final analysis should be investigated.

prepbufr observation data from NCEP ftp site:

You can download the NCEP real-time prepbufr observation data from

ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/

The NCEP GDAS archived prepbufr data can be downloaded from

http://nomads.ncdc.noaa.gov/data/gdas

Or you can download the archived prepbufr observation data from NCAR MSS:

mss:/LIUZ/GDAS/*yyyymm*/*yyyymmddhh*/gdas1.t*hh*z.prepbufr.unblok.nr
(using var/obsproc/lib/cwordsh/cwordsh to add the blocking informationto the BUFR file in the little-endian (Linux/PGI) system) or

mss:/LIUZ/GDAS/*yyyymm*/*yyyymmddhh*/gdas1.t*hh*z.prepbufr.nr
(can be directly used in big-endian machine, such as IBM)

The archived data are available starting from **20060718Z** to date, every 6 hours.

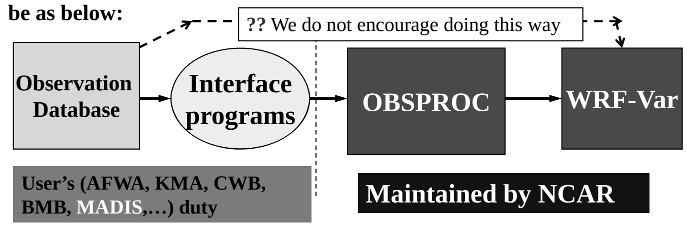
NOAA/ESRL/GSD MADIS files available back to **July 1, 2001**

The interface program to ingest the MADIS data to WRF-Var was developed by Michael F. Barth, NOAA/GSD. The information for MADIS data can be found from

http://madis.noaa.gov/

NCAR is merging the code to WRFDA released code as ob_format=3, but it is still in testing.

The better way to ingest OBS data from a database to WRF-Var should be as below:



NCAR archived observation files

- The NCEP ADP observation data (upper air from **20 December 1972** to 28 February 2007 and surface data from **10 February 1975** to 28 February 2007) may also be downloaded.
  http://www.mmm.ucar.edu/mm5/mm5v3/data/free_data.html

  Then use a MM5 utility FETCH (http://www.mmm.ucar.edu/mm5/src/) to convert these ADP data to LITTLE_R format data (Recently we did not try this procedure, and not sure if it is still working properly).

- Conventional observation data can also be downloaded from NCAR MSS:

  mss:/BRESCH/RT/DATA/*yyyymm*/obs.*yyyymmddhh*.gz (available starting from **2003040800Z**, every 6 hours)

  mss:/RTFCST/ARCHIVE/RAIN/init.*yyyymmddhh*.tar (available starting from **1999012400Z to 2004072612Z**, every 12 hours)

Why do we need the OBS preprocessor?

To ingest the *intermediate format (LITTLE_R)* OBS data file and prepare the *OBS data file suitable for WRF-Var* needs (3DVAR, FGAT, 4DVAR, etc.)

- **Screening of the conventional observations (time window, domain, duplication, etc.), and keep the necessary information for WRF-Var assimilation**
- **Assign the observation errors to each of the observations**
- **Do the basic quality control (gross check and consistent check)**
- **Can save the OBS data processing time, *one OBS file* can be repeatedly used for multiple times of WRF-Var experiments.**

Input files to obsproc LITTLE_R format

- The ***input file*** to 3DVAR_OBSPROC is the LITTLE_R format (see below)

  This is a report-based format, so all types of the observation data can be easily '*cat*'ted together to form a monolithic file.

  It is easily to read, edit,…. with an ASCII file.
- Users' duty is just to convert their own observations in any format to the (ASCII) LITTLE_R format. The LITTLE_R obs data can be processed by OBSPROC, and an observation file suitable for assimilation with WRF-Var is created.
- The available observation data with LITTLE_R format have the longest archive history: 1972 upper air, and 1975 surface.

Structure of the input OBS (LITTLE_R) file

- *OBS decoded file* in LITTLE_R format containing *Reports*
- *Report* containing *Records (header, data,…, and ending) and 3 tail integers* (3I7)
- *Record* containing *fields*
  - The *fields* in the *header record* (Fortran format in parenthesis)
  - The *fields* in the *data record* (Fortran format in parenthesis)
  - The *fields* in the *ending record*

The details for each of records are described below:

The fields in the header record:

No	Field	No	Filed	No	Field
1	Latitude (f20.5)	2	Longitude (f20.5)	3	ID (a40)
4	Name (a40)	5	Platform (a40)	6	Source (a40)
7	Elevation (f20.5)	8	Num_vld_fld (i10)	9	Num_error (i10)
10	Num_warning (i10)	11	Seq_num (i10)	12	Num_dupd (i10)
13	Is_sound (L10)	14	Bogus (L10)	15	Discard (L10)
16	Valid_time%sut (i10)	17	Valid_time%julian (i10)	18	Valid_time%date_char(a20)
19	Slp%data (f13.5)	20	Slp%qc (i7)	21	Ref_pres%data (f13.5)
22	Ref_pres%qc (i7)	23	Ground_t%data (f13.5)	24	Ground_t%qc (i7)
25	SST%data (f13.5)	26	SST%qc (i7)	27	Psfc%data (f13.5)
28	Psfc%qc (i7)	29	Precip%data (f13.5)	30	Precip%qc (i7)
31	T_max%data (f13.5)	32	T_max%qc (i7)	33	T_min%data (f13.5)
34	T_min%qc (i7)	35	T_min_night%data (f13.5)	36	T_min_night%qc (i7)
37	P_tend03%data (f13.5)	38	P_tend03%qc (i7)	39	P_tend24%data (f13.5)
40	P_tend24%qc (i7)	41	Cloud_cvr%data (f13.5)	42	Cloud_cvr%qc (i7)
43	Celling%data (f13.5)	44	Celling%qc (i7)	45	Pw%data (f13.5)
46	Pw%qc (i7)	47	Tb19v%data (f13.5)	48	Tb19v%qc (i7)
49	Tb19h%data (f13.5)	50	Tb19h%qc (i7)	51	Tb22v%data (f13.5)
52	Tb22v%qc (i7)	53	Tb37v%data (f13.5)	54	Tb37v%qc (i7)
55	Tb37h%data (f13.5)	56	Tb37h%qc (i7)	57	Tb85v%data (f13.5)
58	Tb85v%qc (i7)	59	Tb85h%data (f13.5)	60	Tb85h%qc

The fields in the data record (Fortran format in parenthesis)

No	Field	No	Field
1	Pressure%data (f13.5)	2	Pressure%qc (i7)
3	Height%data 9f13.5)	4	Height%qc (i7)
5	Temperature%data (f13.5)	6	Temperature%qc (i7)
7	Dew_point%data (f13.5)	8	Dew_point%qc (i7)
9	Speed%data (f13.5)	10	Speed%qc (i7)
11	Direction%data (f13.5)	12	Direction%qc (i7)
13	U%data (f13.5)	14	U%qc (i7)
15	V%data (f13.5)	16	V%qc (i7)
17	RH%data (f13.5)	18	RH%qc (i7)
19	Thickness%data (f13.5)	20	Thickness%qc (i7)

The fields in the ending record

No	field	No	field	No	field	No	field
1	-777777.00000	2	0	3	-777777.00000	4	0
5	-888888.00000	6	0	7	-888888.00000	8	0
9	-888888.00000	10	0	11	-888888.00000	12	0
13	-888888.00000	14	0	15	-888888.00000	16	0
17	-888888.00000	18	0	19	-888888.00000	20	0

Remarks

1. The tail fields in the header record are not need to all filled in. For example, if no SSMI Tb (brightness temperature) available, the header record may only have 46 fields.
2. For certain type of observations, the some of the fields in data record are just used as the storage, not the actual data as the field's name. For example, for QuikScat SeaWind, the fields: U%data and V%data are the observation errors of speed and direction, respectively.
3. For certain types of observations, such as GPSREF, etc., the observation data are not the wind, temperature, moisture, etc., so specific arrangements are made with the fields to hold the refractivity, perigee point location, etc.

GPS RO data format

Content of the level record in little_r file:

Press.	Geo height	Temp.	Dew-p	speed	Dir.	u	v	rh	thick
Miss.	height	miss	Refractivity	Impact parameter	Azimuth angle	latitude	longitude	Bending angle	Opt. bending

The units of parameters for GPSRO data in little_r file:

press	latitude	longitude	height	temp	Refractivity	Azimuth angle	Impact parameter *1.e-3	Bending angle*1.e7
Ref. Atmos	N	E	m	miss	N	Deg.		rad

Output WRFDA/var/obsproc

1. **NCEP prepBUFR format (not fully tested yet!)**

In obsproc namelist.3dvar_obs

&record9

prepbufr_output_filename='*prepbufr_obs_gts.3dvar*'

prepbufr_table_filename='*prepbufr_table_filename*'

output_ob_format=1 (or 3)

In WRFVar namelist.input,

&wrfvar3

ob_format=1,

The prepbufr file is a binary file, and an endian dependent. See

http://www.nco.ncep.noaa.gov/sib/decoders/BUFRLIB/toc/cwordsh/

2, ASCII format --- Easy to manipulate: read, edit, etc. and *endian* independent (fully supported)

In obsproc namelist.3dvar_obs

```
&record9
 output_ob_format=2 (or 3)
;    Select the obs_gts (ASCII) files used for 3DVAR, FGAT,
       and 4DVAR:
 use_for          = '3DVAR',  ; '3DVAR' obs file, same as
                              before, default
                              ; 'FGAT ' obs files for FGAT
                              ; '4DVAR' obs files for 4DVAR
;     num_slots_past and num_slots_ahead are used ONLY for
FGAT   and 4DVAR:
num_slots_past   = 3, ; the number of time slots before
                      time_analysis
num_slots_ahead  = 3, ; the number of time slots after
                      time_analysis
```

In WRFVar namelist.input,

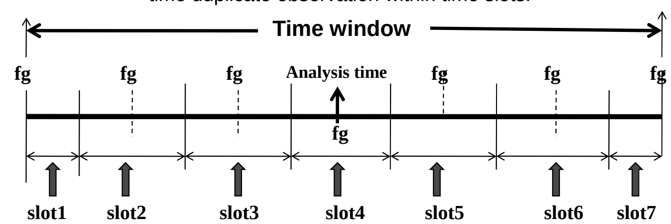
```
&wrfvar3
ob_format=2,
```

3DVAR, FGAT, and 4DVAR have the different requirements:

3DVAR ---- not allowed the time duplicate observation within time window

FGAT ---- multiple time slots within the time window, but not allowed the time duplicate observation within time window *(First Guess at Appropriate Time)*

4DVAR ---- multiple time slots within the time window, but not allowed the time duplicate observation within time slots.



Output filenames for WRFVar

For 3DVAR,

obs_gts_yyyy-mm-dd_hh:00:00.3DVAR

For FGAT,

obs_gts_yyyy-mm-dd_hh:00:00.FGAT

For 4DVAR,

obs_gts_yyyy-mm-dd_hh:00:00.4DVAR

Types of observations to be processed

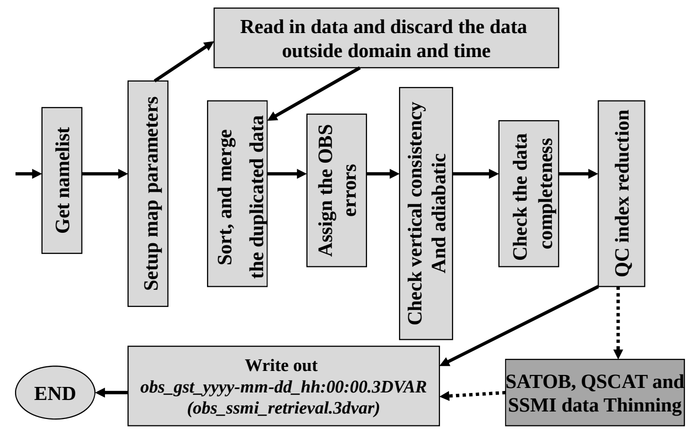
→18 types (SYNOP, SHIPS, METAR, TEMP , AIREP, PILOT , AMDAR, PROFL, SATOB, SATEM, SSMT1, SSMT2, SSMI, GPSPW/GPSZD, GPSRF, QSCAT, BOGUS)

Each type of the observations is identified by its WMO code in WRF-Var. If the standard WMO code is not available to a new data type, user should assign a 3-digit code to that data type.

WMO code for each type of observations

Name	WMO code	WMO code name
SYNOP	12, 14	SYNOP, SYNOP MOBIL
SHIP	13	SHIP
METAR	15, 16	METAR, SPECI
PILOT	32, 33, 34	PILOT, PILOT SHIP, PILOT MOBIL
SOUND	35, 36, 37, 38	TEMP, TEMP SHIP, TEMP DROP, TEMP MOBIL
AMDAR	42	AMDAR
SATEM	86	SATEM
SATOB	88	SATOB
AIREP	96, 97	AIREP
GPSPW	111	GPSPW (Ground-based GPS precipitable water)
GPSZD	114	GPSZD (Ground-based GPS Zenith Total Delay)
GPSRF	116	GPSRF (Space-based GPS Refractivity)
SSMT1	121	SSMT1
SSMT2	122	SSMT2
SSMI	125	SSMI
PROFL	132	WIND PROFILER
BOGUS	135	TCBOU (Typhoon bogus), BOGUS (other bogus)
QSCAT	281	Quik SCAT level-2B SeaWind
OTHER		UNKNOWN

Flow chart of OBS preprocessor



Tasks of the OBS preprocessor: obsproc

1, To perform a time-windowed and, in case of regional application (domain_check_h = .TRUE.), geographically-filtered dump of the ingested observations

Currently, there is *no time-check for observation data in WRF-Var assimilation code*, so to select the observation data within a suitable time-window must be performed in OBSPROC.

For the regional application with the IPROJ = 1 (Lambert conformal), 2 (Polar Stereographic), or 3 (Mercator), there is a geographic-filtered performed based on the model domain settings. For the global application of WRF-Var, it should set IPROJ = 0 and no geographic-filtered is performed.

Gross check during the data ingestion:

- Ignore the data with the invalid WMO code.
- Any data values in header record > 888887 or < -888887 or pressure%data <= 0.0, etc., will be regarded as missing.
- Elevations for SHIP and BUOY data outside the Great Lakes are always set to zero. If the pressure < 85,000 Pa for SHIP and BUOY, the data are tossed out.
- Gross pressure/height consistent check based on the reference atmosphere defined by namelist variables: base_pres, base_temp, and base_lapse
- If both pressure and height are missing, the whole data are discarded.
- ………………………………………………………………………………….

Tasks of the OBS preprocessor: 3DVAR_OBSPROC (cont.)

2, Sort and merge the duplicated data

- To retrieve the pressure or height based on the observed information with the hydrostatic assumption
- To remove the duplicate reports of observations:
  for 3DVAR and FGAT only observations nearest to the analysis time are kept, for 4DVAR, the observations nearest to the central time of each of the time slots are kept.
- To re-order (from bottom to top) and merge the data reports with the same platform, time, and location based on the pressure.

Tasks of the OBS preprocessor: 3DVAR_OBSPROC (cont.)

3, To assign the observation errors to the different types of observations

Observations errors
→ Directly from the observation reports (GPS PW/ZTD, QSCAT,etc.)
→ US Air Force (AFWA) OBS error file
→ NCEP OBS error (Parrish and Derber 1992)

4, To perform the quality control (QC) for soundings

- Vertical consistency check: super adiabatic check and wind shear check
- Dry convective adjustment
- To discard the data above the model top ($p<p_{top}$) in the upper-air observations (remove_above_lid = .TRUE.)

Tasks of the OBS preprocessor: 3DVAR_OBSPROC (cont.)

8, To complete thinning with the SATOB, SSMI, and QSCAT data

The data points nearest to the model grid-points will be picked up for assimilation for SATOB, SSMI, and QSCAT.

9, To write out the OBS files in ASCII format as the WRF-Var input

→ GTS data (*obs_gts_yyyy-mm-dd_hh:00:00.3DVAR*): pressure, Wind, height, temperature, dew-point, RH, thickness, etc.
→ SSMI data (*obs_ssmi_retrieval.3dvar*): PW and surface wind speed

10, To plot the distribution for each type of observations

→MAP_plot

Output files

1, *Obs_gts_yyyy-mm-dd_hh:00:00.3DVAR* and *obs_ssmi_retrieval.3dvar*

Header: the information for this OBS file and data format

Data : *header* record and *data* records for each of levels

- These are the OBS input file to WRF-Var program
- obs_ssmi_retrieval.3dvar needed only when SSMI retrieval data available
- These files can be used as input to MAP_plot to obtain the gmeta plot file with NCAR GRAPHICS

2, 3dvar_obs.out ---- a program execution log file

The printing out from the program execution. It can used to monitor the execution and to identify the troubles if any

3, Diagnostic files depended on the print switches in namelist

3dvar_obs.exe >&! 3dvar_obs.out

File: *obs_gts_yyyy-mm-dd_hh:00:00.3DVAR*

```
TOTAL =   8169, MISS. =-888888.,
SYNOP =   1432, METAR =    164, SHIP  =     86, BUOY  =      0, TEMP  =    179, AMDAR =      0,
AIREP =    265, PILOT =      0, SATEM =      0, SATOB =   6043, GPSPW =      0, SSMT1 =      0,
SSMT2 =      0, TOVS  =      0, QSCAT =      0, PROFL =      0, OTHER =      0,
PHIC  =  28.50, XLONC = 116.00, TRUE1 =  10.00, TRUE2 =  45.00, XIM11 =   1.00, XJM11 =   1.00,
TS0   = 275.00, TLP   =  50.00, PTOP  =  7000., PS0   =100000.,
IXC   =     67, JXC   =     81, IPROJ =      1, IDD   =      1, MAXNES=     10,
NESTIX=     67,     67,     67,     67,     67,     67,     67,     67,     67,     67,
NESTJX=     81,     81,     81,     81,     81,     81,     81,     81,     81,     81,
NUMC  =      1,      1,      1,      1,      1,      1,      1,      1,      1,      1,
DIS   = 135.00,   0.00,   0.00,   0.00,   0.00,   0.00,   0.00,   0.00,   0.00,   0.00,
NESTI =      1,      1,      1,      1,      1,      1,      1,      1,      1,      1,
NESTJ =      1,      1,      1,      1,      1,      1,      1,      1,      1,      1,
INFO  = PLATFORM, DATE, NAME, LEVELS, LATITUDE, LONGITUDE, ELEVATION, ID.
SRFC  = SLP, PW (DATA,QC,ERROR).
EACH  = PRES, SPEED, DIR, HEIGHT, TEMP, DEW PT, HUMID (DATA,QC,ERROR)*LEVELS.
INFO_FMT = (A12,1X,A19,1X,A40,1X,I6,3(F12.3,11X),6X,A5)
SRFC_FMT = (F12.3,I4,F7.2,F12.3,I4,F7.2)
EACH_FMT = (3(F12.3,I4,F7.2),11X,3(F12.3,I4,F7.2),11X,1(F12.3,I4,F7.2)))
#------------------------------------------------------------------------------#
FM-35 TEMP   1999-08-19_11:00:00  AHMADABAD / INDIA                 17     23.070        72.630        55.000        42647
 -888888.000 -88 200.00 -888888.000 -88   0.20
  100000.000   0 100.00       3.000   0   1.10     225.000   0   5.00        53.000   0   7.00     305.550   0   1.00     298.550   0   1.00        65.984   0  15.00
   92500.000   0 100.00       3.000   0   1.10     220.000   0   5.00       745.000   0   7.48     300.550   0   1.00     295.550   0   1.00        73.714   0  12.60
   91600.000   0 100.00 -888888.000 -88   1.10 -888888.000 -88   5.00       830.000   0   7.54     300.150   0   1.00     295.150   0   1.00        73.653   0  12.30
   87300.000   0 100.00 -888888.000 -88   1.10 -888888.000 -88   5.00      1251.000   0   7.84     297.350   0   1.00     291.350   0   1.00        68.712   0  10.82
   85000.000   0 100.00       6.000   0   1.10     250.000   0   5.00      1498.000   0   8.00     295.350   0   1.00     290.750   0   1.00        74.809   0  10.00
   79200.000   0 100.00 -888888.000 -88   1.13 -888888.000 -88   5.00      2104.000   0   8.22     290.750   0   1.00     288.550   0   1.00        86.755   0  10.00
   78000.000   0 100.00 -888888.000 -88   1.18 -888888.000 -88   5.00      2238.000   0   8.27     292.950   0   1.00     281.950   0   1.00        48.599   0  10.00
   70700.000   0 100.00 -888888.000 -88   1.39 -888888.000 -88   5.00      3076.000   0   8.57     289.950   0   1.00     268.950   0   1.00        23.245   0  10.00
   70000.000   0 100.00       2.000   0   1.40      30.000   0   5.00      3168.000   0   8.60 -888888.000 -11   1.00 -888888.000 -11   1.00   -888888.000 -11  10.00
   61100.000   0 100.00 -888888.000 -88   1.76 -888888.000 -88   5.00      4312.000   3  10.01     282.350   0   1.00     271.350   0   1.00        45.937   0  10.00
   60000.000   0 100.00 -888888.000 -88   1.80 -888888.000 -88   5.00      4463.000   3  10.20     281.350   0   1.00     272.350   0   1.00        52.920   0  10.00
   57400.000   0 100.00 -888888.000 -88   1.90 -888888.000 -88   5.00      4828.000   3  10.66     279.150   0   1.00     274.150   0   1.00        70.188   0  10.00
   52700.000   0 100.00 -888888.000 -88   2.14 -888888.000 -88   5.00      5526.000   3  11.55     275.550   0   1.00     272.650   0   1.00        81.128   0  10.00
   50300.000   0 100.00 -888888.000 -88   2.28 -888888.000 -88   5.00      5902.000   3  12.04     273.350   0   1.00     269.650   0   1.00        76.187   0  10.00
   50200.000   0 100.00 -888888.000 -88   2.29 -888888.000 -88   5.00      5918.000   3  12.06     273.150   0   1.00     269.450   0   1.00        76.157   0  10.00
   50000.000   0 100.00       3.000   0   2.30      95.000   0   5.00      5950.000   0  12.10     272.850   0   1.00     269.250   0   1.00        76.682   0  10.00
   46900.000   0 100.00       2.000   0   2.42     100.000   0   5.00      6461.000   3  12.90     270.450   0   1.00     266.250   0   1.00        72.904   0  10.00
FM-35 TEMP   1999-08-19_11:00:00  BOMBAY / SANTACRUZ / INDIA         25     19.120        72.850        14.000        430
..................................................................
```

← # of observations

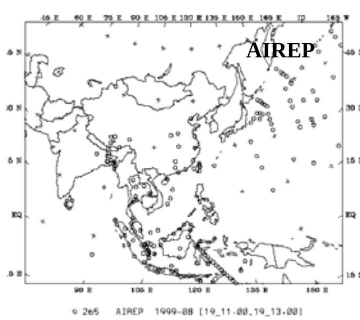
← Model domain information

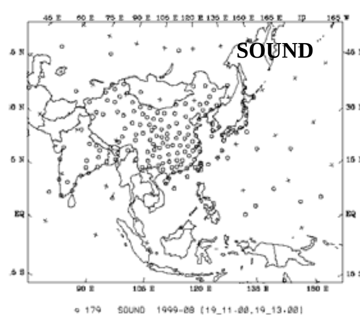
← Data format

How to plot the OBS distribution?

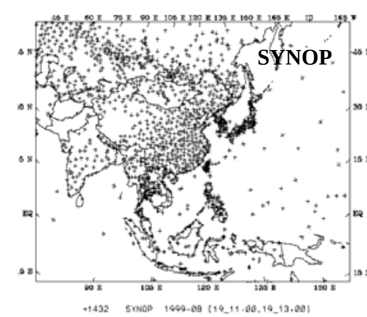
- Go to the directory *var/obsproc/MAP_plot*
- Modify the shell script *Map.csh*
  - » To fill in *TIME_ANALYSIS*, etc., and *OBSDATA* file name
- Run shell script *Map.csh*
  - » You will have a gmeta file: *gmeta.${TIME_ANALYSIS}* to show the the distribution of observations contained in *OBSDATA* file.

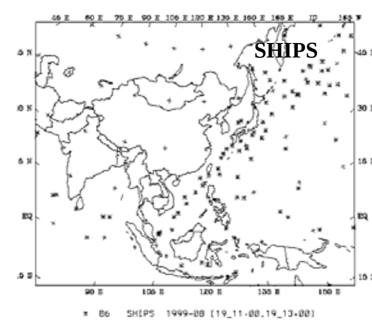
Distribution for each type of observations



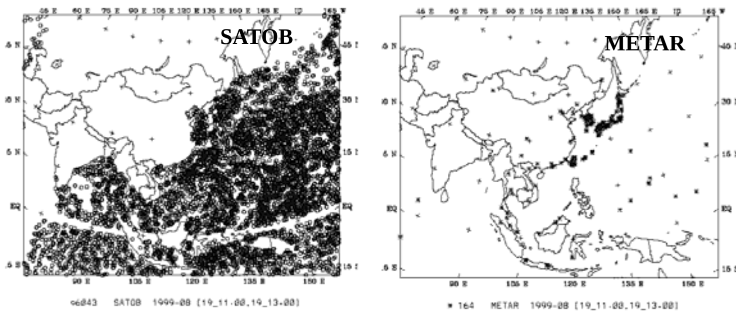


Distribution for each type of observations





Distribution for each type of observations



Introduction to run *obsproc*

- Compiling the obsproc

    cd var/obsproc

    make

- **Edit the namelist.3dvar_obs**
- Run obsproc

    3dvar_obs.exe >&! 3dvar_obs.out

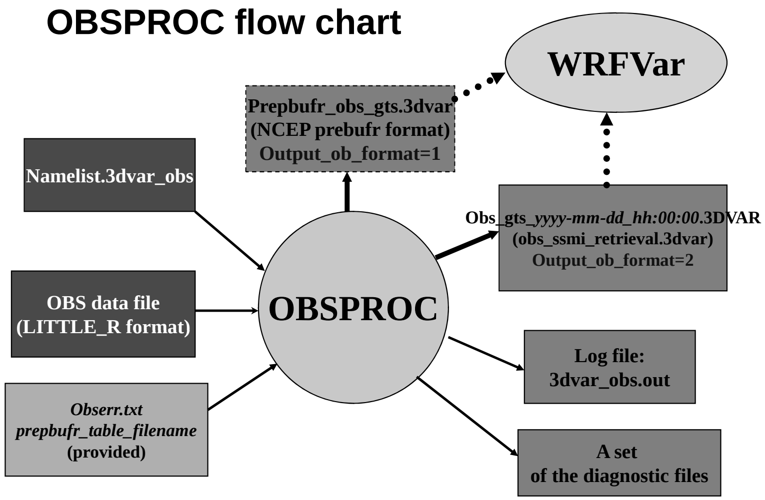
- Plot the horizontal distribution of the observations

    cd MAP_plot

    make

    edit MAP.csh

OBSPROC flow chart



- **Input files for OBS preprocessor (obsproc)**

  3 *Input files*

  - **OBS decoded file (Reports) in little_r format**

    A report (F90 pointer linking structure)

    - **header record (fields)**
    - **Level*1* data record (fields)**
    - **…………………**
    - **Level*n* data record (fields)**
    - **Ending record (fields)**
    - **3 Integers in format(3i7)**

  - **Namelist file (*namelist.3dvar_obs*) (See: README.namelist)**

    Record1: input file names
    Record2: analysis times
    Record3: Maximum number of observations allowed
    Record4: quality control switches
    Record5: print switches
    Record6: define the reference state: ptop, etc.
    Record7: Geographic parameters
    Record8: Domain settings
    Record9: Output format: prebufr, ascii, or both

  - **AFWA OBS errors file: *obserr.txt* (provided by 3DVAR system)**
  - **Prebufr table file: *prepbufr_table_filename***

OBSPROC namelist variables.

&record1

`obs_gts_filename`	name and path of decoded observation file
`fg_format`	'MM5' for MM5 application, 'WRF' for WRF application
`obserr.txt`	name and path of observational error file
`first_guess_file`	name and path of the first guess file (Only for MM5 application)

&record2

`time_window_min`	Beginning of time window (included) as ccyy-mm-dd_hh:mn:ss
`time_analysis`	Ananlysis time as ccyy-mm-dd_hh:mn:ss
`time_window_max`	End of time window (included) as ccyy-mm-dd_hh:mn:ss ** Note : Only observations between [time_window_min, time_window_max] will kept.

&record3

`max_number_of_obs`	Maximum number of observations to be loaded, ie in domain and time window, this is independent of the number of obs actually read.
`fatal_if_exceed_max_obs`	.TRUE.: will stop when more than max_number_of_obs are loaded .FALSE.: will process the first max_number_of_obs loaded observations.

&record4

`qc_test_vert_consistency`	.TRUE. will perform a vertical consistency quality control check on sounding
`qc_test_convective_adj`	.TRUE. will perform a convective adjustment quality control check on sounding
`qc_test_above_lid`	.TRUE. will flag the observation above model lid
`remove_above_lid`	.TRUE. will remove the observation above model lid
`domain_check_h`	.TRUE. will discard the observations outside the domain
`Thining_SATOB`	.FALSE.: no thinning for SATOB data. .TRUE.: thinning procedure applied to SATOB data.
`Thining_SSMI`	.FALSE.: no thinning for SSMI data. .TRUE.: thinning procedure applied to SSMI data.
`Thining_QSCAT`	.FALSE.: no thinning for SATOB data. .TRUE.: thinning procedure applied to SSMI data.

&record6

`x_left`	West border of sub-domain, not used
`x_right`	East border of sub-domain, not used
`y_bottom`	South border of sub-domain, not used
`y_top`	North border of sub-domain, not used
`ptop`	Reference pressure at model top
`ps0`	Reference sea level pressure
`base_pres`	Same as ps0. User must set either ps0 or base_pres.
`ts0`	Mean sea level temperature
`base_temp`	Same as ts0. User must set either ts0 or base_temp.
`tlp`	Temperature lapse rate
`base_lapse`	Same as tlp. User must set either tlp or base_lapse.
`pis0`	Tropopause pressure, the default = 20000.0 Pa
`base_tropo_pres`	Same as pis0. User must set either pis0 or base_tropo_pres
`tis0`	Isothermal temperature above tropopause (K), the default = 215 K.
`base_start_temp`	Same as tis0. User must set either tis0 or base_start_temp.

&record7

`IPROJ`	Map projection (0 = Cylindrical Equidistance, 1 = Lambert Conformal, 2 = Polar stereographic, 3 = Mercator)
`PHIC`	Central latitude of the domain
`XLONC`	Central longitude of the domain
`TRUELAT1`	True latitude 1
`TRUELAT2`	True latitude 2
`MOAD_CEN_LAT`	The central latitude for the Mother Of All Domains
`STANDARD_LON`	The standard longitude (Y-direction) of the working domain.

&record8

`IDD`	Domain ID (1=< ID =< MAXNES), Only the observations geographically located on that domain will be processed. For WRF application with XLONC /= STANDARD_LON, set IDD=2, otherwise set 1.
`MAXNES`	Maximum numbe of domains as needed.
`NESTIX`	The I(y)-direction dimension for each of the domains
`NESTJX`	The J(x)-direction dimension for each of the domains
`DIS`	The grid size for each of the domains. For WRF application, always set NESTIX(1),NESTJX(1), and DIS(1) based on the infomation in wrfinput.
`NUMC`	The mother domain ID number for each of the domains
`NESTI`	The I location in its mother domain of the nest domain's low left corner -- point (1,1)
`NESTJ`	The J location in its mother domain of the nest domain's low left corner -- point (1,1). For WRF application, NUMC(1), NESTI(1), and NESTJ(1) are always set to be 1.

&record9

`prepbufr_output_filename`	Name of the prebufr OBS file.
`prepbufr_table_filename`	'prepbufr_table_filename' ; not change
`output_ob_format`	output 1, prebufr OBS file only; 2, ASCII OBS file only; 3, Both prebufr and ASCII OBS files.
`use_for`	'3DVAR' obs file, same as before, default 'FGAT ' obs files for FGAT '4DVAR' obs files for 4DVAR
`num_slots_past`	the number of time slots before time_analysis
`num_slots_ahead`	the number of time slots after time_analysis
`write_synop`	If keep synop obs in obs_gts (ASCII) files.
`write_ship`	If keep ship obs in obs_gts (ASCII) files.
`write_metar`	If keep metar obs in obs_gts (ASCII) files.
`write_buoy`	If keep buoy obs in obs_gts (ASCII) files.
`write_pilot`	If keep pilot obs in obs_gts (ASCII) files.
`write_sound`	If keep sound obs in obs_gts (ASCII) files.
`write_amdar`	If keep amdar obs in obs_gts (ASCII) files.
`write_satem`	If keep satem obs in obs_gts (ASCII) files.
`write_satob`	If keep satob obs in obs_gts (ASCII) files.
`write_airep`	If keep airep obs in obs_gts (ASCII) files.
`write_gpspw`	If keep gpspw obs in obs_gts (ASCII) files.
`write_gpsztd`	If keep gpsztd obs in obs_gts (ASCII) files.
`write_gpsref`	If keep gpsref obs in obs_gts (ASCII) files.
`write_gpseph`	If keep gpseph obs in obs_gts (ASCII) files.

`write_ssmt1`	If keep ssmt1 obs in obs_gts (ASCII) files.
`write_ssmt2`	If keep ssmt2 obs in obs_gts (ASCII) files.
`write_ssmi`	If keep ssmi obs in obs_gts (ASCII) files.
`write_tovs`	If keep tovs obs in obs_gts (ASCII) files.
`write_qscat`	If keep qscat obs in obs_gts (ASCII) files.
`write_profl`	If keep profile obs in obs_gts (ASCII) files.
`write_bogus`	If keep bogus obs in obs_gts (ASCII) files.
`write_airs`	If keep airs obs in obs_gts (ASCII) files.

WRF-Var System

WRF-Var System Overview

WRF-Var Tutorial
February 2 - 4, 2008

Xin Zhang and Syed RH Rizvi
Michael Duda

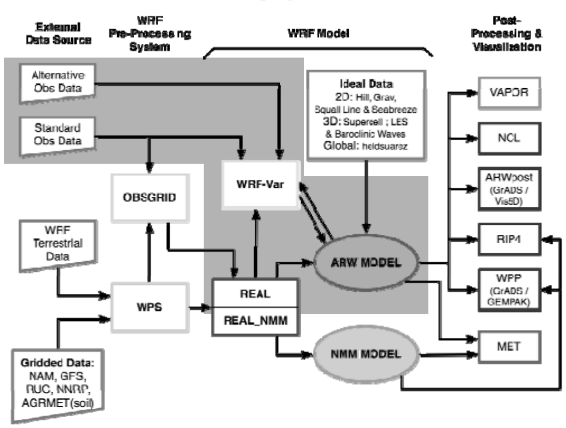
Outline

- WRF-Var in the WRF Modeling System
- WRF-Var Software
- WRF-Var Implementation

1

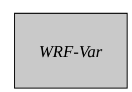
WRF-Var in the WRF Modeling System

WRF Modeling System Flow Chart



2

WRF-Var in the WRF Modeling System

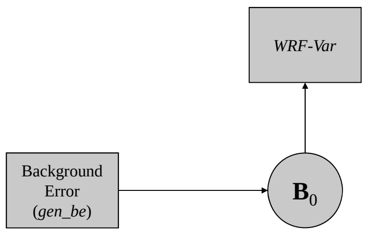


Blue --> Supported by WRF-Var Team

3

WRF-Var in the WRF Modeling System

1. Prepare BE data



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4

Prepare BE statistics

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

- For initial testing, the default background error statistics may be used
- Ultimately, these should be specific to the particular model domain (and season)
- See "WRF-Var Background Error Estimation" (Syed Rizvi)

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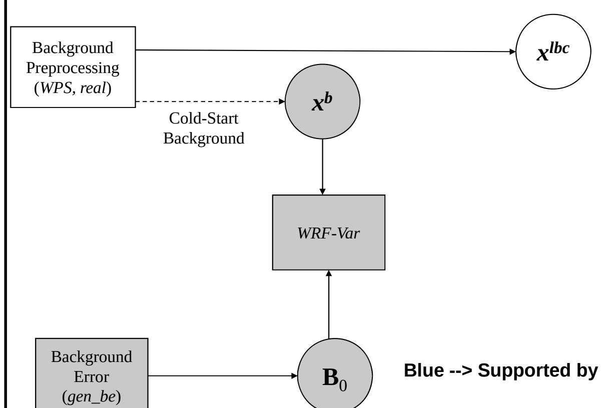
WRF-Var in the WRF Modeling System

2. Prepare background (WPS and real)



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Prepare background

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

- In "cold-start" mode: accomplished by running the WPS and *real* programs
  - The background is essentially the wrfinput_d01 file
- In "cycling" mode: the output of the WRF model
  - WRF can output wrfinput-formatted files used for cycling

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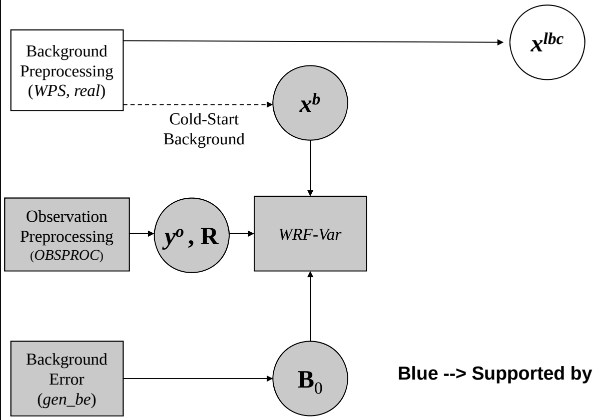
WRF-Var in the WRF Modeling System

3. Prepare observations (run OBSPROC)



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Prepare observations (y^0)

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

- Observation input for WRF-Var is supplied through observation preprocessor, OBSPROC
- Observation error covariance also provided by OBSPROC (**R** is a diagonal matrix)
- Separate input file (ASCII) for Radar, both reflectivity and radial velocity.
- See “Observation Pre-Processing” (Yong-Run Guo)

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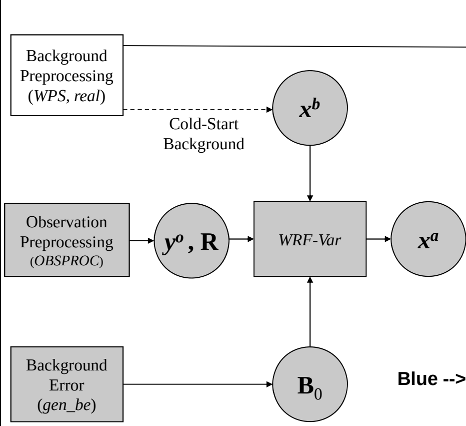
WRF-Var in the WRF Modeling System

4. Run WRF-Var



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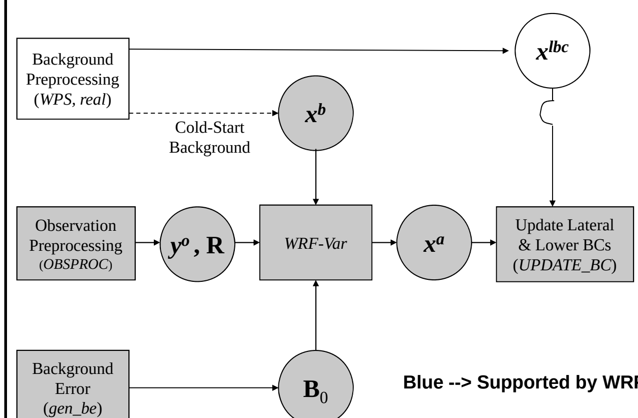
WRF-Var in the WRF Modeling System

5. Update boundary conditions (UPDATE_BC)



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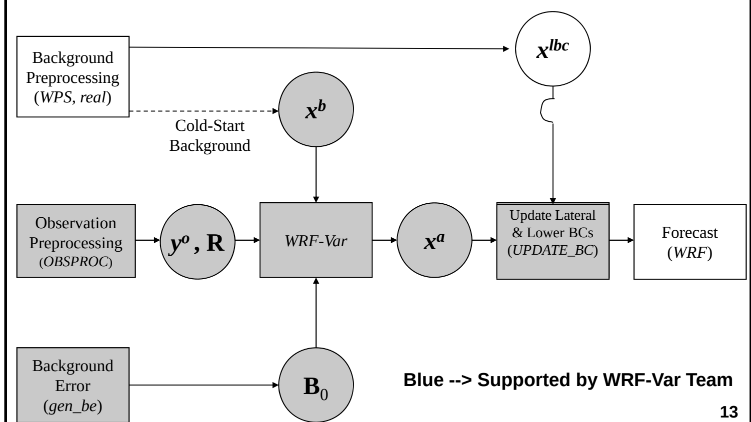
Update boundary conditions

- After creating an analysis, $\mathbf{x^a}$, we have changed the initial conditions for the model
  - However, tendencies in wrfbdy_d01 (and possibly wrflbdy) file are valid for background, $\mathbf{x^b}$
- The update_bc program adjusts these tendencies based on the difference $\mathbf{x^a - x^b}$
- Of course, if $\mathbf{x^a}$ was produced for reasons other than running WRF, there is probably not a need to update boundary conditions

WRF-Var in the WRF Modeling System

6a. Run forecast (cold-start mode)



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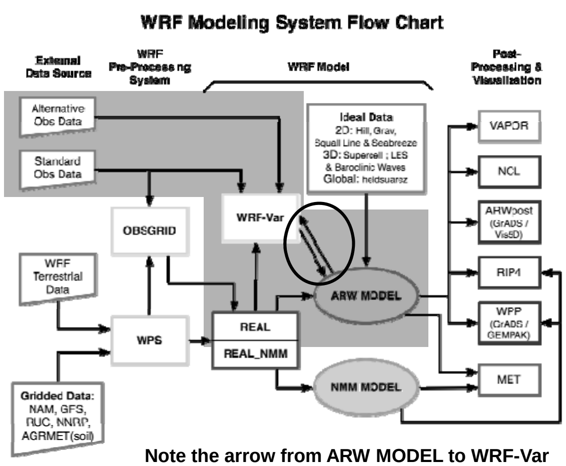
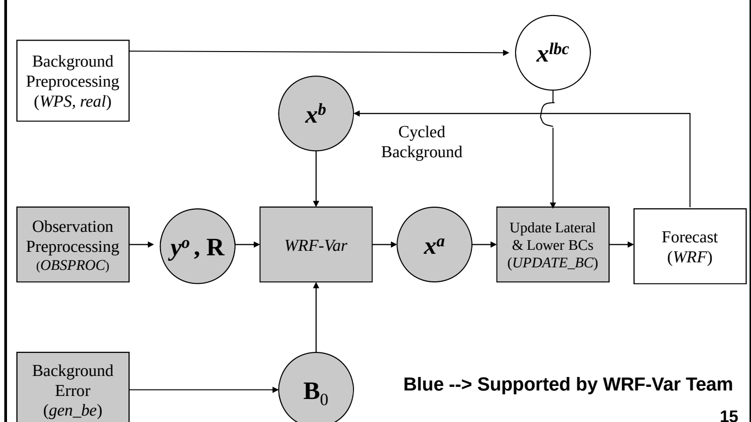
WRF-Var in the WRF Modeling System



Note the arrow from ARW MODEL to WRF-Var

WRF-Var in the WRF Modeling System

6b. Run forecast (cycling mode)



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Background Error (BE) for WRF-Var

The number 1 question from WRF-Var users is
"What background error are best for my application?"

- Create your own once you have run your system for a few weeks to a month
- Implement, tune, and iterate

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

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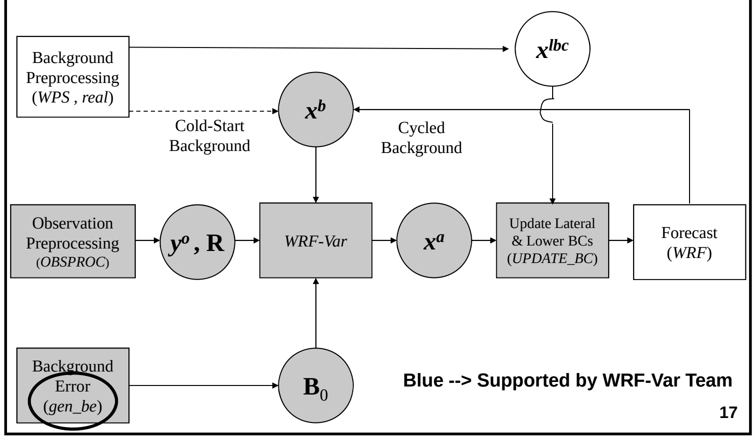
WRF-Var in the WRF Modeling System

7. WRF-Var/WRF Ultimate Configuration



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WRF-Var Software

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Supported Platforms and Compilers

Generally speaking, the following should work "out of the box" :

- IBM (AIX/xlf)
- PC (Linux/PGI, Linux/ifort, Linux/g95)
- Macintosh (OS X/PGI, OS X/g95)
- SGI (IRIX/ifort) *(tested by 3rd party)*

<u>Only serial and dmpar are supported!</u>

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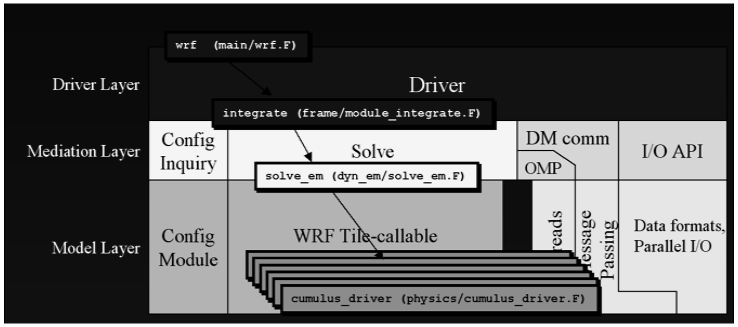
Use of the WRF Software Framework



WRF ⟶ **WRF-Var**
Integrate ⟶ **da_wrfvar_interface**
Solve_em ⟶ **da_solve**
Cumulus_driver ⟶ **obs. (da_ships) or da_minimisation etc.**

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WRF-Var Code Organization

…
- configure
- dyn_em
- dyn_exp
- dyn_nmm
- external
- frame
- inc
- main

…
- Registry
- run
- share
- test
- tools
- var

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

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WRF-Var Code Organization

- var
  - convertor
  - da
  - gen_be
  - graphics
  - Makefile
  - obsproc
  - scripts
  - test

- da
  - da_airep
  - da_airsr
  - da_bogus
  - da_buoy
  - da_control
  - da_define_structures
  - …
  - da_metar
  - da_minimisation
  - da_mtgirs
  - da_obs
  - …
  - da_setup_structures
  - da_ships
  - da_sound

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

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WRF-Var Code Organization

- da_metar
  - da_ao_stats_metar.inc
  - da_calculate_grady_metar.inc
  - da_check_max_iv_metar.inc
  - da_get_innov_vector_metar.inc
  - da_jo_and_grady_metar.inc
  - da_metar.f90
  - da_oi_stats_metar.inc
  - da_print_stats_metar.inc
  - da_residual_metar.inc
  - da_transform_xtoy_metar_adj.inc
  - da_transform_xtoy_metar.inc

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

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WRF-Var Registry

- "Active data-dictionary" for managing WRF-Var data structures
  - Database describing attributes of model state, intermediate, and configuration data
    - » Dimensionality, number of time levels, staggering
    - » Association with physics
    - » I/O classification (history, initial, restart, boundary)
    - » Communication points and patterns
    - » Configuration lists (e.g. namelists)
  - Program for auto-generating sections of WRF from database:
    - » Argument lists for driver layer/mediation layer interfaces
    - » Interprocessor communications: Halo and periodic boundary updates, transposes
    - » Code for defining and managing run-time configuration information
- Automates time consuming, repetitive, error-prone programming
- Insulates programmers and code from package dependencies
- Allow rapid development
- Documents the data

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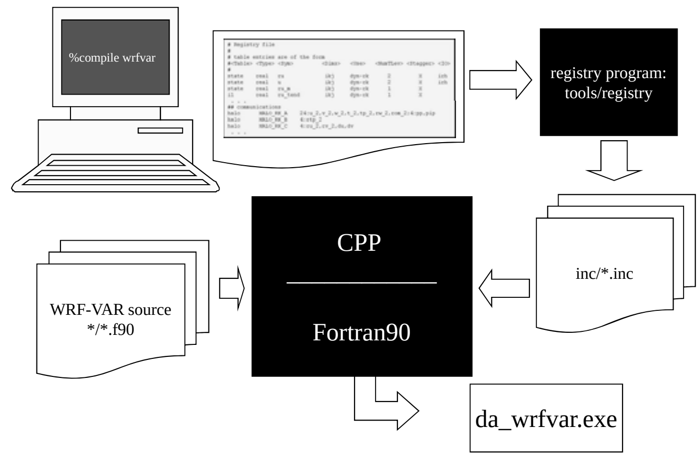
Registry Mechanics



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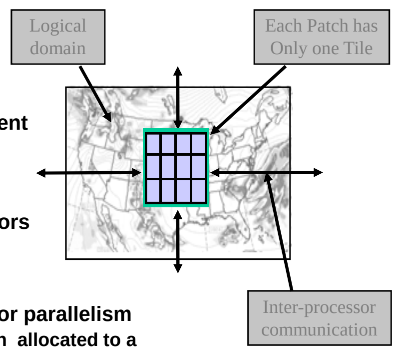
Parallelism in WRF-Var: MPI Decomposition



Single version of code for efficient execution on:
- **Distributed-memory**
- **Vector and microprocessors**

Model domain is decomposed for parallelism

Patch: **section of model domain allocated to a distributed memory node**

Tile: **same as patch in WRF-Var**

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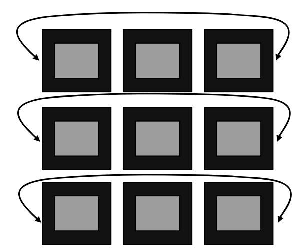
Distributed Memory Communications

- Halo updates
- Periodic boundary updates (only needed for global 3dvar)



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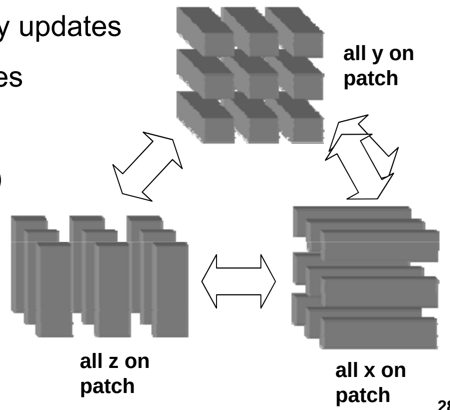
Distributed Memory Communications

- Halo updates
- Periodic boundary updates
- Parallel transposes
- "nproc_x = 1"
  (for global option)



WRF-Var Implementation

WRF-Var Formulation

- WRF-Var actually uses an incremental formulation of the 3DVAR problem

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

- Define the increment $\mathbf{x}' = \mathbf{x} - \mathbf{x}^b$
- Also, if $\mathbf{x}'$ is small, $H(\mathbf{x}) = H(\mathbf{x}^b + \mathbf{x}') \approx H(\mathbf{x}^b) + \mathbf{H}\mathbf{x}'$ where $\mathbf{H}$ is the linearization of H
- Then, the problem becomes

  $J(\mathbf{x}') = (\mathbf{x}')^T\mathbf{B}^{-1}(\mathbf{x}') + (\mathbf{y}^{o\prime} - \mathbf{H}\mathbf{x}')^T\mathbf{R}^{-1}(\mathbf{y}^{o\prime} - \mathbf{H}\mathbf{x}')$

  with $\mathbf{y}^{o\prime} = \mathbf{y}^o - H(\mathbf{x}^b)$

WRF-Var Formulation

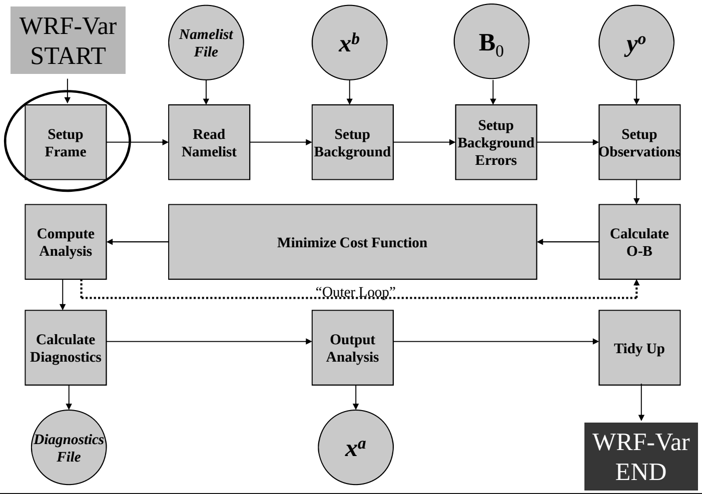
- Next, define the *control variable transform* **U** such that $\mathbf{x}' = \mathbf{U}\mathbf{v}$.
  - $\mathbf{v}$ is the analysis increment in control variable space
  - $\mathbf{B}$ is approximated by $\mathbf{U}\mathbf{U}^T$
- WRF-Var actually minimizes

  $J(\mathbf{v}) = \mathbf{v}^T\mathbf{v} + (\mathbf{y}^{o\prime} - \mathbf{H}\mathbf{U}\mathbf{v})^T\mathbf{R}^{-1}(\mathbf{y}^{o\prime} - \mathbf{H}\mathbf{U}\mathbf{v})$

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

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

WRF-Var



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Setup Frame

- Reads grid dimensions from "namelist.input" file.
- Use WRF framework's distributed memory capability to initialize tile, memory, patch dimensions, etc.

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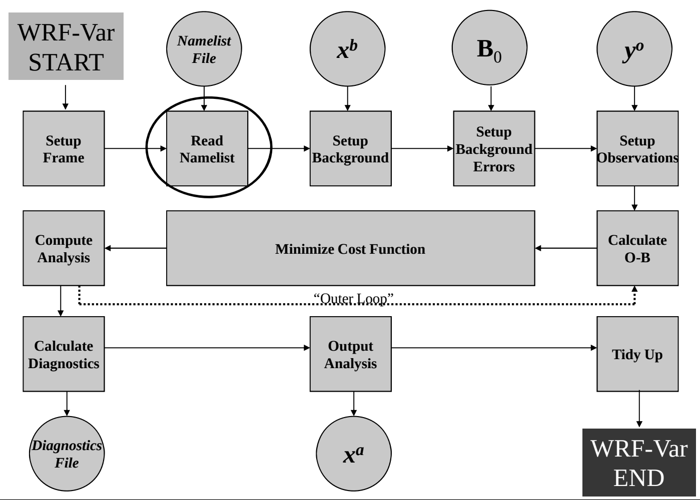
WRF-Var



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Read Namelist

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

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namelist.input

```
&wrfvar1
var4d=true,
multi_inc=0,
var4d_coupling=2,
global=false,
/
&wrfvar2
/
&wrfvar3
ob_format=2,
num_fgat_time=7,
/
&wrfvar4
use_synopobs=true,
use_shipsobs=true,
use_metarobs=true,
use_soundobs=true,
use_pilotobs=true,
use_airepobs=true,
use_geoamvobs=true,
use_polaramvobs=true,
use_bogusobs=true,
use_buoyobs=true,
use_profilerobs=true,
use_satemobs=true,
use_gpspwobs=true,
use_gpsrefobs=true,
use_qscatobs=true,
use_radarobs=false,
use_radar_rv=false,
use_radar_rf=false,
/
&wrfvar5
check_max_iv=true,
/
&wrfvar6
ntmax=100,
/
&wrfvar7
/
&wrfvar8
/
&wrfvar9
/
&wrfvar10
/
&wrfvar11
cv_options_hum=1,
check_rh=2,
seed_array1=2007081421,
seed_array2=2007081421,
/
&wrfvar12
/
&wrfvar13
/
&wrfvar14
/
&wrfvar15
/
&wrfvar16
/
&wrfvar17
analysis_type="3D-VAR",
/
&wrfvar18
analysis_date="2007-08-
14_21:00:00.0000",
/
&wrfvar19
/
&wrfvar20
/
&wrfvar21
time_window_min="2007-08-
14_21:00:00.0000",
/
&wrfvar22
time_window_max="2007-08-
15_03:00:00.0000",
/
&wrfvar23
jcdfi_use=false,
jcdfi_io=false,
jcdfi_tauc=21600,
jcdfi_gama=0.1,
jcdfi_error_wind=3.0,
jcdfi_error_t=1.0,
jcdfi_error_q=0.001,
jcdfi_error_mu=1000.,
/
&time_control
run_hours=27,
run_minutes=0,
run_seconds=0,
start_year=2007,
start_month=08,
start_day=14,
start_hour=21,
start_minute=00,
start_second=00,
end_year=2007,
end_month=08,
end_day=15,
end_hour=03,
end_minute=00,
end_second=00,
interval_seconds=21600,
input_from_file=true,
frames_per_outfile=1,
debug_level=0,
history_interval_s=10800,
inputout_interval_s=3600,
auxinput3_interval_s=3600,
inputout_begin_h=6,
inputout_begin_m=0,
inputout_begin_s=0,
inputout_end_h=6,
inputout_end_m=0,
inputout_end_s=0,
input_outname="wrfinput_d<domain
>_<date>",
write_input=true,
/
&fdda
/
&domains
time_step=240,
e_we=123,
e_sn=111,
e_vert=27,
num_metgrid_levels=27,
p_top_requested=5000,
interp_type=1,
t_extrap_type=1,
dx=45000,
dy=45000,
i_parent_start=0,
j_parent_start=0,
smooth_option=0,
nproc_x=0,
eta_levels= 1.000, 0.990, 0.978,
0.964, 0.946, 0.922, 0.894, 0.860,
0.817, 0.766, 0.707, 0.644, 0.576,
0.507, 0.444, 0.380, 0.324, 0.273,
0.228, 0.188, 0.152, 0.121, 0.093,
0.069, 0.048, 0.029, 0.014, 0.000,
/
&physics
mp_physics=3,
ra_lw_physics=1,
ra_sw_physics=1,
radt=45,
sf_sfclay_physics=1,
sf_surface_physics=1,
bl_pbl_physics=1,
cu_physics=1,
cudt=1,
num_soil_layers=5,
mp_zero_out=0,
co2tf=0,
/
&dynamics
w_damping=1,
diff_opt=1,
km_opt=1,
dampcoef=0.0,
time_step_sound=4,
base_temp=290.0,
/
&bdy_control
specified=true,
real_data_init_type=3,
/
&grib2
/
```

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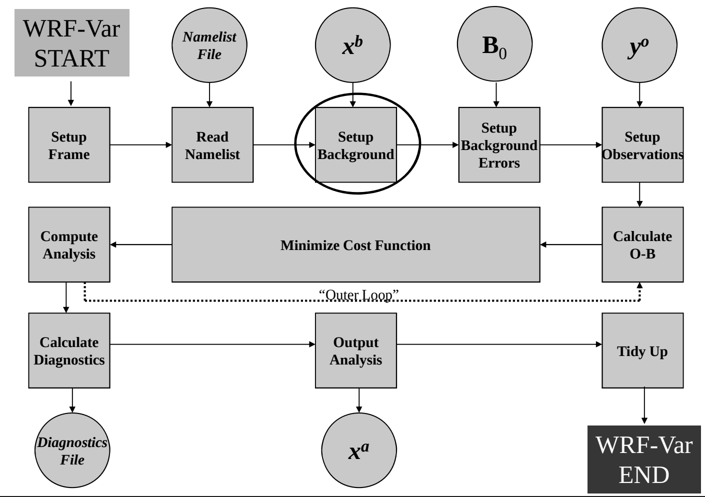
WRF-Var



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Setup Background (First-guess)

- Reads in the first-guess field.
- Format depends on namelist option : “fg_format” ; 1= WRF, etc.
- Extracts necessary fields.
- Creates background FORTRAN 90 derived data type “xb” e.g. xb % mix, xb % u(:,:,:), ….

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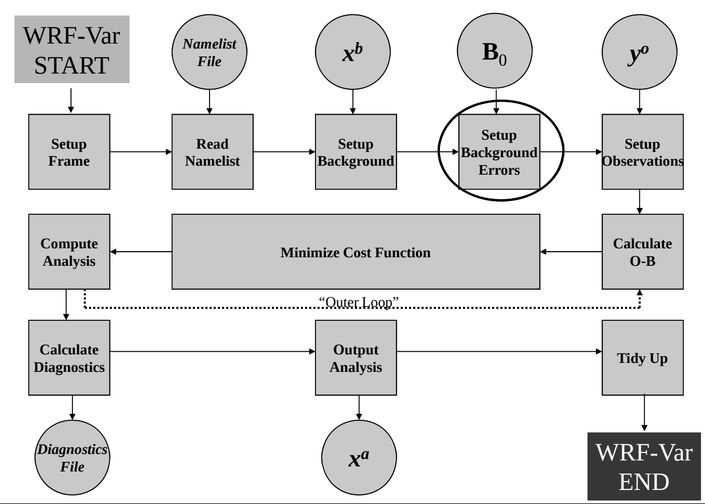
WRF-Var



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Setup Background Errors (BE)

- Reads in background error statistics.
- Extracts necessary quantities – eigenvectors, eigenvalues, lengthscales, regression coefficients, etc (see “WRF-Var Background Error Estimation”).
- Creates background error FORTRAN 90 derived data type “be” e.g. be % v1 % evec(:,:), be % v2 % eval(:), etc, ….

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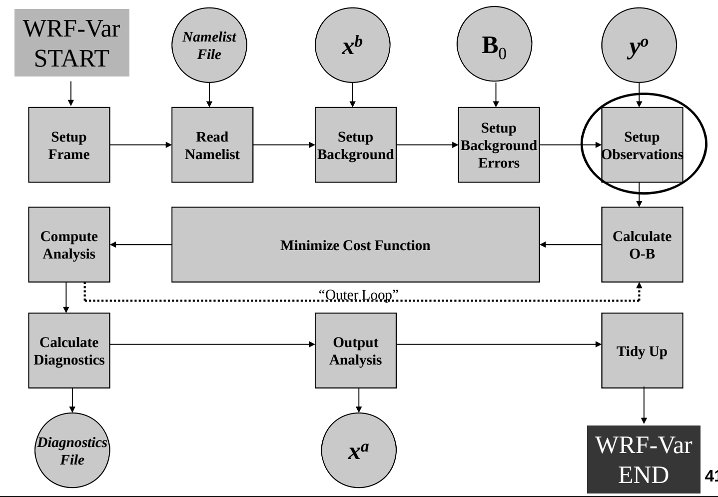
WRF-Var



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Setup Observations

- Reads in observations.
- Format depends on namelist variable “ob_format”

  1 = BUFR, 2 = ASCII “WRF-Var” format.
- Creates observation FORTRAN 90 derived data type “ob” e.g. ob % metar(:), ob % sound(:) % u(:), etc, ….
- Identifies Obs outside/inside the domain

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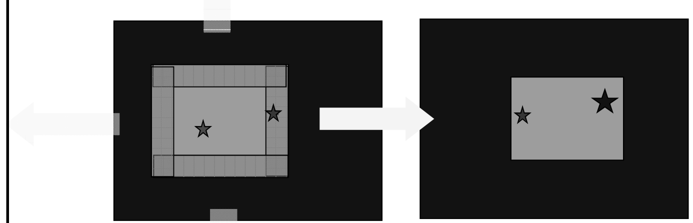
Observations in Distributed Memory

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



Obs. on one processor’s halo **Obs. on neighboring processor**

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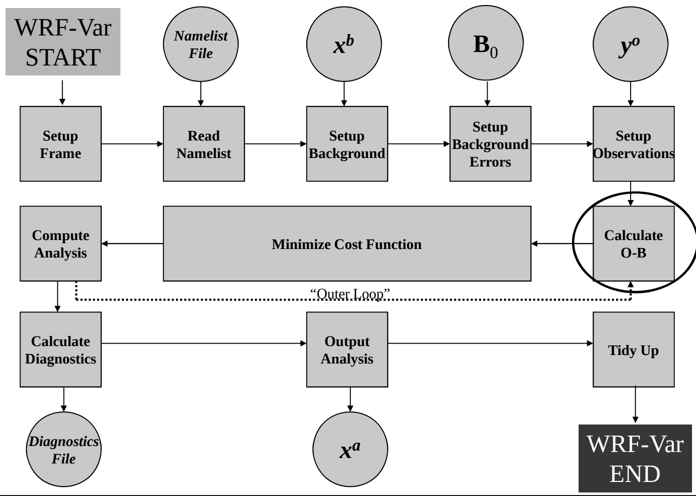
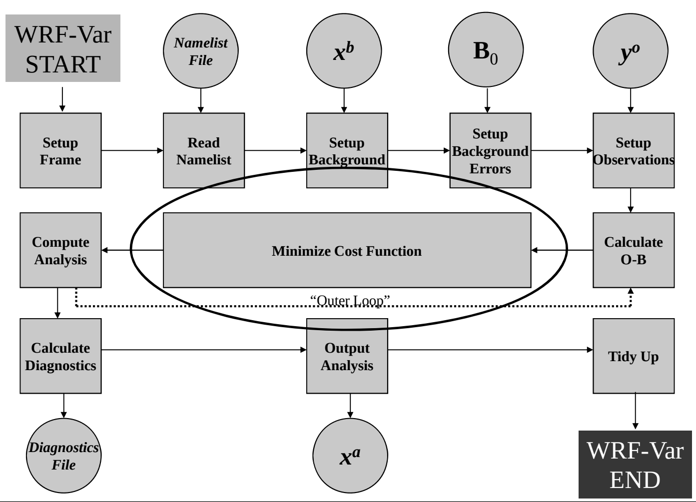
WRF-Var



Calculate Innovation Vector (O-B)

- Calculates "model equivalent" B of observation O through interpolation and change of variable.
- Computes observation minus first guess (O-B) value.
- Creates innovation vector FORTRAN 90 derived data type "iv" e.g. iv % metar(:), iv % qscat(:) % u, iv % sound(:) % u(:), etc ….

WRF-Var



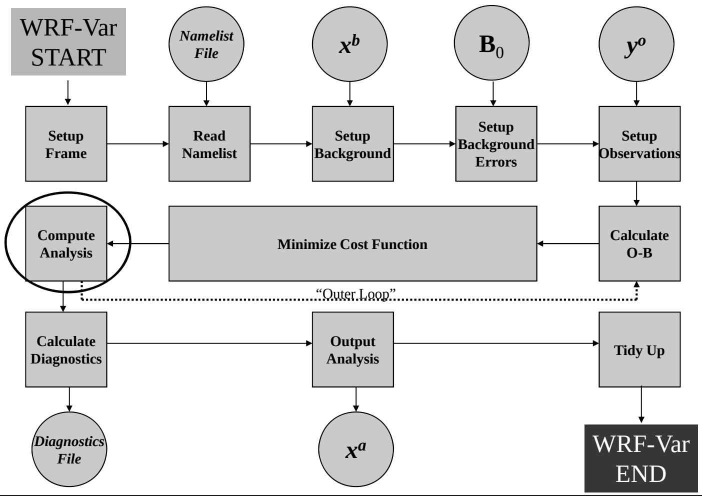
Minimize Cost Function

Use conjugate gradient method

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

Iterate (b) to (d)

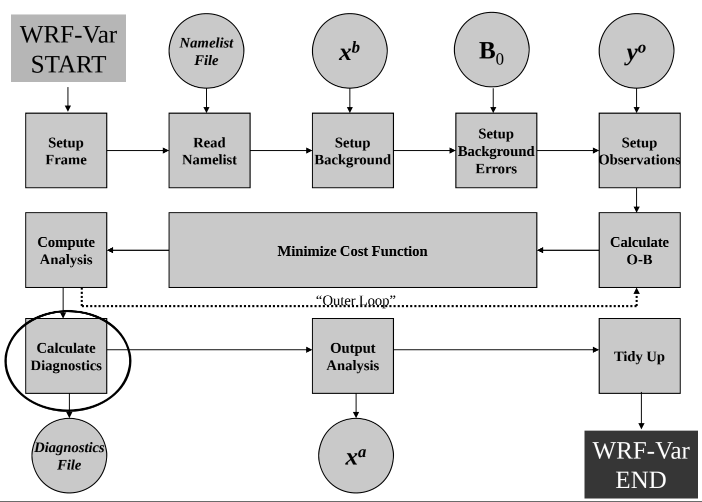
WRF-Var



Compute Analysis

- Once WRF-Var has found a converged control variable, convert control variable to model space analysis increments
- Calculate:
  analysis = first-guess + analysis increment
- Performs consistency checks, e.g., remove negative humidity etc.

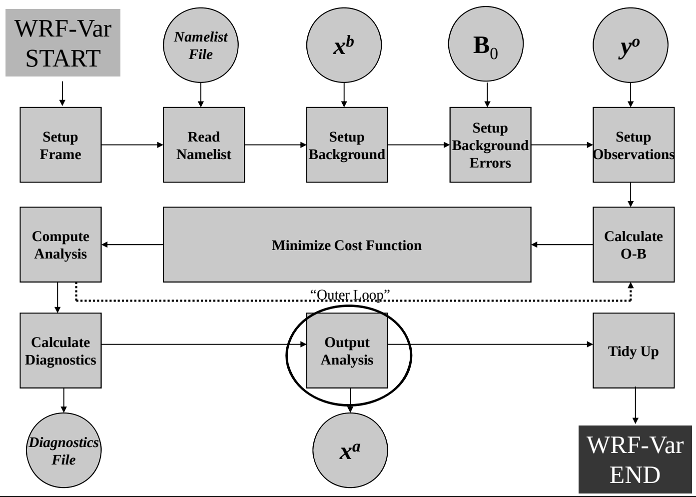
WRF-Var



Compute Diagnostics

- Compute O-B, O-A statistics for all observation types and variables.
- Compute A-B (analysis increment) statistics for all model variables and levels.
- Statistics include minimum, maximum (and their locations), mean and standard deviation.
- Compute "specialist diagnostics" for error tuning (fort.45, fort.46, fort.47, fort.50 etc.).

WRF-Var



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Output Analysis

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

  1 = WRF, etc.

- Also output analysis increments (for diagnostic purposes) in native model format. Switch off by setting WRITE_INCREMENTS = .FALSE. in namelist.input.

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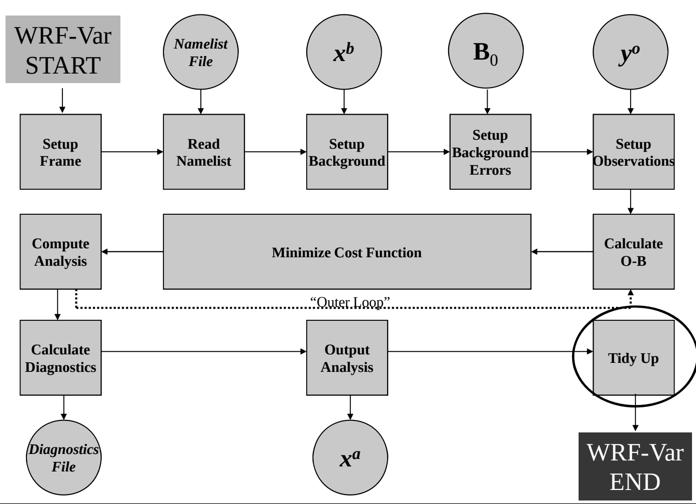
WRF-Var



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Tidy Up

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

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Procedure for Adding New Observations

- **Edit** da_define_structures.f90 **to add new data type.**
- **Make new observation sub-directory under "**var/da**".**
- **Develop desired programs like getting innovation vector, forward observation operator, tangent linear and its adjoint, gradient & cost function etc. in this new sub-directory.**
- **Input observation (update** da_obs**).**
- **Sometimes it might be needed to add certain grid arrays in** Registry.wrfvar**.**
- **Link into minimization package (**da_minimisation.f90**)**

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Learning to Use WRF-Var

- **Run through the Online WRF-Var Tutorial available at:**

  http://www.mmm.ucar.edu/wrf/users/docs/user_guide_V3/users_guide_chap6.htm

- **If still confused, ask questions via: wrfhelp@ucar.edu**

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Wrf-Var Setup, Run, and Diagnostics

WRF-Var Setup, Run and Diagnostics

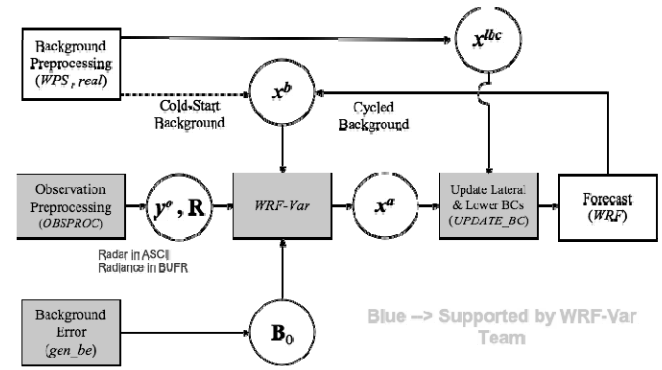
Hui Shao (hshao@ucar.edu)

Hui-Chuan Lin, Meral Demirtas, Yongrun Guo, Syed Rizvi,
Xin Zhang and Hans Huang

WRF-Var Tutorial, Feb 2-4, 2009

Review

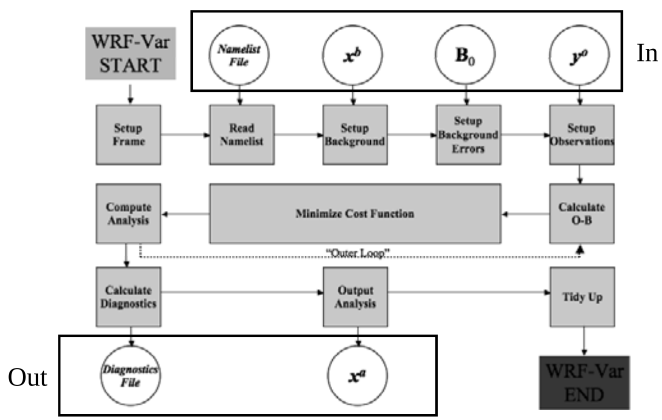
- **WRF-Var in the WRF Modeling System**



2

Review

- **WRF-Var Code Flow**



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Outline

- Steps to run WRF-Var code:
  - Before you run …
  - Working directory - input
  - Running WRF-Var
  - Working directory - output
- Steps to run UPDATE_BC
- WRF-Var diagnostics
  - Also check "**WRF-Var Tools and Verification Package**" talk.
- Basic runtime options (namelist)
  - Complementary to "**WRF-Var Namelists**" talk.

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Running WRF-Var

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Before You Run …

- Check WRF-Var executable has been created appropriately:
  - WRFDA/var/da/da_wrfvar.exe
- Get input files:
  - The following test data WRFV3-Var-testdata.tar.gz can be downloaded from http://www.mmm.ucar.edu/wrf/users/download/get_sources.htm.
  - Extract the test data into your local data directory, e.g., "*your_choice_of_dat_dir*".
  - Set up your environment variable $DAT_DIR:
    > Setenv DAT_DIR *your_choice_of_dat_dir*

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Before You Run …

- Check input files:
  - Background (x^b): $DAT_DIR/ob/2007010200/wrfinput_d01
    - NETCDF format.
    - For cold-start mode, x^b is generated by WRF *real*.
    - For cycling mode, x^b is generated by WRF from previous cycle (e.g., 6hr forecast).
  - Background Error Statistics: $DAT_DIR/be/be.dat
    - Generated by *gen_be*.
    - Please refer to "**WRF-Var Background Error Estimations**" talk.
  - Observations (y^o) : $DAT_DIR/ob/2007010200/obs_gts_2007-01-02+00:00:00.3DVAR (GTS data only)
    - ASCII format.
    - Generated by OBSPROC from ob.little_r included in the tar file of the test data.
    - Please refer to "**Radar Data**" and "**Satellite Data**" talks for assimilations of radar and radiance data.
- Prepare namelists for runtime options:
  - WRFDA/var/test/namelist.input (example)

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Working Directory - Input

- Create a working directory, for example, "*your_choice_of_ working_dir*".
- Go into the working directory:
  > cd *your_choice_of_working_dir*
- Prepare the input files for running WRF-Var:
  > ln -sf WRFDA/var/da/da_wrfvar.exe ./**da_wrfvar.exe**
  > ln -sf WRFDA/run/LANDUSE.TBL ./**LANDUSE.TBL**
  > ln -sf $DAT_DIR/rc/2007010200/wrfinput_d01 ./**fg**
  > ln -sf $DAT_DIR/be/be.dat ./**be.dat**
  > ln -sf $DAT_DIR/ob/obs_gts_2007-01-02_00:00:00.3DVAR ./**ob.ascii**
  > cp WRFDA/var/test/namelist.input ./**namelist.input**

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Running WRF-Var

> **da_wrfvar.exe** >&! wrfda.log (or your own log file name)

If running in distributed-memory mode, you need to set up the computer resources (e.g., processor numbers, memory, wallclock…) based on the platform you are using. The log file names would be rsl.out.0000, rsl.out.0001,…

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Working Directory - Output

In *your_choice_of_working_dir*, you should at least have the following files after running WRF-Var successfully:

```
-rw-r--r-- 1 username       1985 Jun 18 13:17 cost_fn (Cost function)
-rw-r--r-- 1 username       1745 Jun 18 13:17 grad_fn (Gradient of cost function)
-rw-r--r-- 1 username 9048641 Jun 18 13:17 gts_omb_oma (O, O-A information, etc)
-rw-r--r-- 1 username   276658 Jun 18 13:17 namelist.output (Complete namelist)
-rw-r--r-- 1 username     22730 Jun 18 13:17 statistics (Averaged O-B & O-A information)
-rw-r--r-- 1 username 3651560 Jun 18 13:17 wrfvar_output (Analysis x^a)
```

O: Observation
A: Analysis
B: Background (first-guess)

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Running UPDATE_BC

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Steps to Run UPDATE_BC

- Check UPDATE_BC executable has been created appropriately:
  - WRFDA/var/da/da_update_bc.exe

- Go into the working directory:
  > cd *your_choice_of_working_dir*

- Prepare the input files for running WRF-Var:
  > ln -sf WRFDA/var/da/da_update_bc.exe ./**da_update_bc.exe**
  > cp -p $DAT_DIR/rc/2007010200/wrfbdy_d01 ./**wrfbdy_d01**
  > cp WRFDA/var/test/param.in **./param.in** (or define your own file)

- Run UPDATE_BC:
  > da_update_bc.exe > &! da_update_bc.log

- Check output: wrfbdy_d01 (overwrites the original one!)

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WRF-Var Diagnostics

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ASCII output files in the WRF-Var working directory:

- wrfda.log or rsl.out.0000
- filtered_obs (analysis_type="QC-OBS")
- namelist.output
- check_max_iv
- cost_fn
- grad_fn
- gts_omb_oma
- statistics
- jo
- unpert_obs
- pert_obs (omb_add_noise=true)

wrfda.log

• Very important information about your WRF-Var run, including observation summary, values of cost function and its gradient, etc. If a WRF-Var run succeeded, the message

SUCCESS COMPLETE WRFVAR
**** WRF-Var completed successfully ****

would be written to the end of the log file.

filtered_obs

• Similar to ob.ascii (observation input file of WRF-Var) but with the observations filtered by WRF-Var using the following WRF-Var namelist option:

analysis_type = QC-OBS

namelist.output

- When WRF-Var is run, a namelist.output file will be produced with all values of namelist variables (default or/and from namelist.input).

namelist.input

```
&wrfvar1
write_increments=true,
var4d=false,
multi_inc=0,
global=false,
/
&wrfvar2
/
&wrfvar3
ob_format=2,
num_fgat_time=1,
/
&wrfvar4
/
```

namelist.output

```
&WRFVAR1
WRITE_INCREMENTS=T, WRFVAR_MEM_MODEL=0, VAR4D=F, MULTI_INC=0,
VAR4D_COUPLING=2, GLOBAL=F, PRINT_DETAI
L_AIREP=F, PRINT_DETAIL_RADAR=F, PRINT_DETAIL_RAD=F,
PRINT_DETAIL_XA=F, PRINT_DETAIL_XB=F, PRINT_DETAI
L_OBS=F, PRINT_DETAIL_F_OBS=F, PRINT_DETAIL_MAP=F,
PRINT_DETAIL_GRAD=F, PRINT_DETAIL_REGRESSION=F, PRI
NT_DETAIL_SPECTRAL=F, PRINT_DETAIL_TESTING=F,
PRINT_DETAIL_PARALLEL=F, PRINT_DETAIL_BE=F, PRINT_DETAIL_TIMING=F,
CHECK_MAX_IV_PRINT=T
 /
 &WRFVAR2
 ANALYSIS_ACCU=900, CALC_W_INCREMENT=F, DT_CLOUD_MODEL=F,
WRITE_QCW=F, WRITE_QRN=F, WRITE_QCI=F, WRITE_QSN=F, WRITE_QGR=F,
WRITE_FILTERED_OBS=F
 /
 &WRFVAR3
 FG_FORMAT=1, OB_FORMAT=2, NUM_FGAT_TIME=1
 /
 &WRFVAR4
 USE_SYNOPOBS=T, USE_SHIPSOBS=T, USE_METAROBS=T, USE_SOUNDOBS=T,
USE_MTGIRSOBS=T, USE_PILOTOBS=T,
```

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check_max_iv

• Contains information about observations that fail check_max_iv check.

```
For outer iteration     1, Total Rejections for Synop follows:

Number of failed u-wind observations:        25 on    230
Number of failed v-wind observations:        30 on    230
Number of failed pressure observations:       5 on    230
Number of failed temperature observations:    0 on    230
Number of failed mixing ratio observations:   1 on    230
Finally Total Synop rejections     61 on   1150

Err_max failed:ID=47843FM-12 SYNOP Ix=  204 Ixf= 30 Err_max ratio = 1.3 for V     inv, error: 0.708141E+01 0.110000E+01
Err_max < 0 ==>        0.0 -4444440.0        5.0  for V     OBS ID: 98752FM-12 SYNOP  LA/LON/ELV:      9.93    125.51     46.00
```

• Generated with the following namelist options:

&wrfvar1
CHECK_MAX_IV_PRINT=true (default)
&wrfvar5
CHECK_MAX_IV=true (default)

• Observations are rejected if the innovation (O-B) values are larger than certain maximum errors (max_error). Currently the max_error values are hard-wired in var/da/da_control/da_control.f90.

```
real, parameter :: max_error_t           = 5.0, &
                   max_error_uv          = 5.0, &
                   max_error_pw          = 5.0, &
                   max_error_ref         = 5.0, &
                   max_error_rh          = 5.0, &
                   max_error_q           = 5.0, &
                   max_error_p           = 5.0, &
                   max_error_tb          = 5.0, &
                   max_error_thickness   = 5.0, &
                   max_error_rv          = 5.0, &
                   max_error_rf          = 5.0, &
                   max_error_buv         = 500.0, &
                   max_error_bt          = 500.0, &
                   max_error_bq          = 500.0, &
                   max_error_slp         = 500.0
```

cost_fn and grad_fn

• Contain values of cost function and its gradient at each iteration.
E.g., calculate_cg_cost_fn=.false. (default):

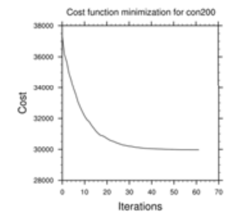
Outer Iter	EPS	Inner Iter	J	Jb	Jo	Jc	Je	Jp
1	0.100E-01	0	37293.267	0.000	37293.267	0.000	0.000	0.000
1	0.100E-01	61	29974.427	1093.616	28880.811	0.000	0.000	0.000

Outer Iter	EPS	Inner Iter	G	Gb	Go	Ge	Gp
1	0.100E-01	0	1619.534	0.000	1619.534	0.000	0.000
1	0.100E-01	61	12.931	46.768	48.511	0.000	0.000

b: background term
o: observation term
c: JcDFI term
e: alpha term
p: radiance variational bias correction term

• With calculate_cg_cost_fn=.true., the cost function and its gradient at each iteration can be written into **cost_fn** and **grad_fn**.

• NCL script example to plot these two files is var/graphics/ncl/plot_cost_grad_fn.ncl.



gts_omb_oma

• Contain complete point-by-point, detailed observation information.

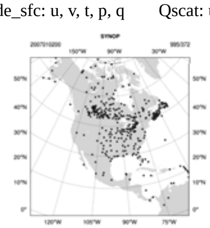
```
synop     995
    1
    1      176556    21.51  -104.90    89973.8836463       3.3147587       1.2193668       2       1.1000000       0.1849281      -1.5412909
  -1.4225501      2       1.1000000      -1.6862257     295.5511624       2.5999150       2       2.0000000       1.3689324    89973.8836463
 -273.5464584      2     100.0000000    -236.6028635       0.0134689       0.0048657       0       0.0036749       0.0050584
```

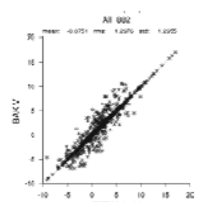
```
obs_type  number_of_obs
number_of_levels
level_index, station_id, lat, lon, pressure, (O, O-B, qcflag, Obs_err, O-A) for measured quantities for the obs_type
```

• Measured quantities for each observation type vary:

Synop: u, v, t, p, q	Polaramv: u, v	Airep: u, v, t	Profiler: u, v
Metar: u, v, t, p, q	Gpspw: tpw	Pilot: u, v	Buoy: u, v, t, p, q
Ship: u, v, t, p, q	Sound: u, v, t, q	Satem: thickness	Airsr: t, q
Geoamv: u, v	Sonde_sfc: u, v, t, p, q	Qscat: u, v	Gpsref: ref

• A NCL script example is var/graphics/ncl/plotobs.ncl.





statistics

• Contains domain-wise O-B and O-A information:

Diagnostics of OI for synop

var	u (m/s)	n	k	v (m/s)	n	k	t (K)	n	k	p (Pa)	n	k	q (kg/kg)	n	k
Number:	331			332			355			330			361		
Minimum(n,k):	-5.4017	363	0	-5.4086	878	0	-9.7206	592	0	-390.7893	931	0	-0.4461E-02	719	0
Maximum(n,k):	5.0466	886	0	5.2878	630	0	7.7302	421	0	471.9343	944	0	0.5408E-02	787	0
Average :	-0.8471			-0.1995			-1.1171			20.4177			-0.2525E-03		
RMSE :	2.3023			2.1150			3.1978			116.1518			0.8045E-03		

Diagnostics of AO for synop

var	u (m/s)	n	k	v (m/s)	n	k	t (K)	n	k	p (Pa)	n	k	q (kg/kg)	n	k
Number:	331			332			355			330			361		
Minimum(n,k):	-4.2496	172	0	-5.0463	683	0	-8.9005	583	0	-472.9290	931	0	-0.4152E-02	719	0
Maximum(n,k):	5.5540	886	0	5.7990	630	0	8.8192	421	0	392.4096	944	0	0.5058E-02	1	0
Average :	-0.0847			-0.0376			-0.4283			1.1709			0.1625E-04		
RMSE :	1.8650			1.8093			2.1990			101.3816			0.5958E-03		

Minimum of gridded analysis increments

Lvl	u	i	j	v	i	j	t	i	j	p	i	j	q	i	j
1	-1.8915	17	32	-1.9965	36	24	-5.2526	20	35	-314.7470	44	1	-0.1451E-02	18	32
2	-1.9476	16	32	-2.0070	36	24	-3.0142	21	36	-311.2885	44	1	-0.1438E-02	18	33

Maximum of gridded analysis increments

Lvl	u	i	j	v	i	j	t	i	j	p	i	j	q	i	j
1	1.3750	41	8	1.5739	28	12	3.2994	24	20	197.8351	28	2	0.1401E-02	39	8
2	1.4844	40	8	1.6180	28	13	1.7471	7	20	195.5165	28	2	0.1591E-02	39	8

Mean of gridded analysis increments

Lvl	u	v	t	p	q
1	-0.0327	0.0632	-0.1477	17.4414	-0.1047E-03
2	-0.0031	0.0736	0.0116	17.2543	-0.8066E-04

RMSE of gridded analysis increments

Lvl	u	v	t	p	q
1	0.7546	0.6040	1.3120	72.0441	0.4258E-03
2	0.7995	0.6483	0.9169	71.2614	0.4476E-03

jo

• Contains cost function for each observation type:

synop	obs,	Jo(actual)	=	1007	1709	475.29555	1.00000	448.89633	1.00000	214.58090	1.00000	169.59091	1.00000	39.54654	1.00000
metar	obs,	Jo(actual)	=	2551	4996	1142.22791	1.00000	1139.04835	1.00000	450.85222	1.00000	141.48881	1.00000	127.23786	1.00000
ships	obs,	Jo(actual)	=	270	739	295.61942	1.00000	328.81980	1.00000	38.63147	1.00000	76.05158	1.00000	10.88285	1.00000
geoamv	ob,	Jo(actual)	=	18216	35619	4375.80943	1.00000	4291.11244	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000	1.00000
gpspw	obs,	Jo(actual)	=	113	94	42.19891	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000	1.00000
sound	obs,	Jo(actual)	=	122	12507	1501.01081	1.00000	1417.89485	1.00000	2934.71994	1.00000	1412.34202	1.00000	0.00000	1.00000
sonde	obs,	Jo(actual)	=	122	12507	77.96908	1.00000	70.37029	1.00000	43.28542	1.00000	45.34806	1.00000	4.58217	1.00000
airep	obs,	Jo(actual)	=	1527	4506	699.19993	1.00000	655.45784	1.00000	776.57509	1.00000	0.00000	1.00000	0.00000	1.00000
pilot	obs,	Jo(actual)	=	112	5895	2582.21854	1.00000	2434.46137	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000	1.00000
satem	obs,	Jo(actual)	=	204	2079	108.15758	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000	1.00000
buoy	obs,	Jo(actual)	=	241	400	133.21166	1.00000	104.72975	1.00000	31.86149	1.00000	38.47701	1.00000	1.04651	1.00000

• Sum of individual Jo (numbers in red boxes) equals the printout value in WRF-Var log file, e.g., rsl.out.0000:

Final value of Jo = 28880.81069

• Numbers in blue boxes are observation error factors used in WRF-Var:

Tuned obs_error = obs_error * factor

Where obs_error values are assigned by OBSPROC and factor=1 by default (use_obs_errfac=false).

WRF-Var Running Options - Namelist

What is a Namelist?

- The Fortran namelist (namelist.input) file helps the user to configure a WRF-Var run without recompiling the code.
  - Specific Fortran 90 namelist format

```
&namelistname        - start
…
/                    - end
```

- Description of WRF-Var namelist variables are given in WRF User's Guide (Chapter 6).

WRF-Var Namelist

- Default values of the namelist variables are defined by WRF-Var Registry (registry.wrfvar).
- Define namelist.input with non-default and desired variable values before running WRF-Var.
- A WRF-Var namelist file includes two parts:

```
&wrfvar1
/
&wrfvar2
/
…
&wrfvar23
/
&time_control
/
&dfi_control
/
…
&namelist_quilt
/
```

WRF-Var namelist: Running options for WRF-Var code. (&wrfvar1 … &wrfvar23)

WRF namelist: WRF-Var needs certain information from this file including domain and time setting. Please make sure this part of the namelist file is consistent with the namelist used in your WRF *real* and WRF runs. (&time_control … &namelist_quilt)

Namelist - WRFVAR3

- Ob_format: The format of the conventional and satellite retrieval observation data going into WRF-Var.
  - 1 = BUFR (Please use this option with caution).
  - 2 = ASCII (ob.ascii): Default.
  - ✓ Both formats are supported by OBSPROC.

Namelist - WRFVAR4

- Use_obstype: Set to true to use particular observation types.
  - E.g, use_gpsrefobs=.true.: Assimilate GPS refractivity observations if any available in the data file.

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Namelist - WRFVAR5

- Check_max_iv: Option for WRF-Var internal QC procedure, which is basically a maximum observation error check based on the innovations (Obs-Background).
  - .true. : default
  - .false: Use this option only if the observation data have been cleaned before going into WRF-Var.

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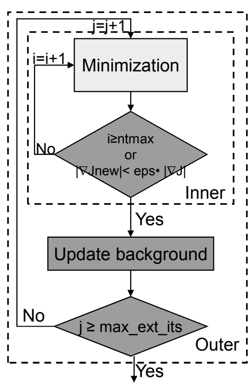
Namelist - WRFVAR6

The following namelist variables are for minimization options:

- Max_ext_its: Number of outer loops.
  - 1: Default. Only one outer loop.
  - Currently, maximum outer loop number is 10.
- Ntmax: Maximum number of iterations in an inner loop for the minimization in WRF-Var.
  - 200: Default. The minimization in the inner loop can not exceed 200.
- Eps: Value for minimization convergence criterion. It is an array with the dimension=max_ext_its.
  - 0.01(max_ext_its): The minimization is considered to converge when the norm of the cost function gradient is reduced at least 2 orders.



27

Namelist - WRFVAR9

The following namelist variables are for tracing:

Tracing gives additional diagnostics about program runs. It does not change results, but does slow the program down, so should be disabled in production environments.

- Trace_use: .true. (default). Use tracing function in WRF-Var if true.

In your test run, please make sure to set trace_use=.false.

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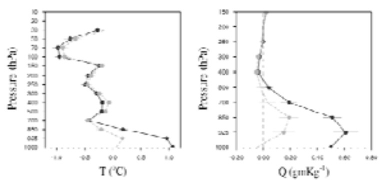
Namelist - WRFVAR11

- Sfc_assi_options:
  - 1 (default): The surface observations will be assimilated based on the lowest model level first guess.
  - 2: The surface observations will be assimilated based on surface similarity theory in PBL. Innovations are computed based on 10-m wind and 2-m temperature & moisture.

✓Please use this option with caution, since the results could be very sensitive.



Namelist - WRFVAR11

- Calculate_cg_cost_fn:
  - .false. : Only the initial and final cost functions are computed and output.
  - .true. : The cost functions are computed and output (cost_fn) at every iteration for diagnostic purpose.

✓ The conjugate gradient algorithm for the minimization does not require the computation of cost function at every iteration.

✓ The cost function gradient values will be output (grad_fn) at every iteration as well if this option is set true.

Outer Iter	EPS	Inner Iter	J	Jb	Jo	Jc	Je	Jp
1	0.100E-01	0	11251.182	0.000	11251.182	0.000	0.000	0.000
1	0.100E-01	19	8634.570	885.427	7749.143	0.000	0.000	0.000

Outer Iter	EPS	Inner Iter	J	Jb	Jo	Jc	Je	Jp
1	0.100E-01	0	11251.182	0.000	11251.182	0.000	0.000	0.000
1	0.100E-01	1	10384.156	41.768	10342.388	0.000	0.000	0.000
1	0.100E-01	2	9633.557	184.109	9449.448	0.000	0.000	0.000
1	0.100E-01	3	9245.700	327.121	8918.579	0.000	0.000	0.000
1	0.100E-01	4	9014.861	453.787	8561.075	0.000	0.000	0.000
1	0.100E-01	5	8872.989	559.714	8313.275	0.000	0.000	0.000
1	0.100E-01	6	8777.974	652.105	8125.869	0.000	0.000	0.000
1	0.100E-01	7	8720.998	721.735	7999.263	0.000	0.000	0.000
1	0.100E-01	8	8689.342	768.464	7920.878	0.000	0.000	0.000
1	0.100E-01	9	8665.605	810.136	7855.469	0.000	0.000	0.000
1	0.100E-01	10	8654.051	833.590	7820.461	0.000	0.000	0.000
1	0.100E-01	11	8646.376	851.091	7795.285	0.000	0.000	0.000
1	0.100E-01	12	8641.869	862.515	7779.355	0.000	0.000	0.000
1	0.100E-01	13	8638.219	872.853	7765.365	0.000	0.000	0.000
1	0.100E-01	14	8636.669	877.707	7758.962	0.000	0.000	0.000
1	0.100E-01	15	8635.794	880.667	7755.127	0.000	0.000	0.000
1	0.100E-01	16	8635.176	882.929	7752.247	0.000	0.000	0.000
1	0.100E-01	17	8634.861	884.169	7750.693	0.000	0.000	0.000
1	0.100E-01	18	8634.686	884.909	7749.777	0.000	0.000	0.000
1	0.100E-01	19	8634.570	885.427	7749.143	0.000	0.000	0.000

Namelist - WRFVAR17

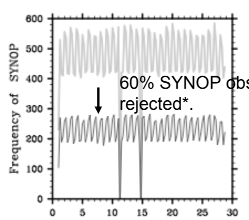
- Analysis_type: Indicate job type of WRF-Var.
  - 3D-VAR (default): Run 3D-Var data assimilation.
  - VERIFY: Run WRF-Var verification mode (then Check_max_iv=.false. and ntmax=0 by default).
    - ✓ Please refer to "**WRF-Var Tools and Verification package**" talk.
  - QC-OBS: Run 3D-Var data assimilation and produce filtered_obs.
    - ✓ By combining with Check_max_iv=.true. and ntmax=0, you can produce a WRF-Var filtered (QCed) observation data set (filtered_obs) without running the data assimilation.

➢ 1st screen/QC procedure performed by observation preprocessor (OBSPROC).

➢ 2nd screen/QC procedure performed in WRF-Var.

➢ Main impact of 2nd screen/QC is on surface observations*.

➢ Rejection rates will reduce with higher resolution, higher-order interpolation.



* Surface observation rejection here is mostly due to surface elevation check with sfc_assim_options=1. Such a rejection may be bypassed by using sfc_assim_options=2.

Namelist - WRFVAR17

- Analysis_date: Specify the analysis time. It should be consistent with the first guess time.

WRF-Var Background Error Estimation

WRF-Var
Background Error Estimation

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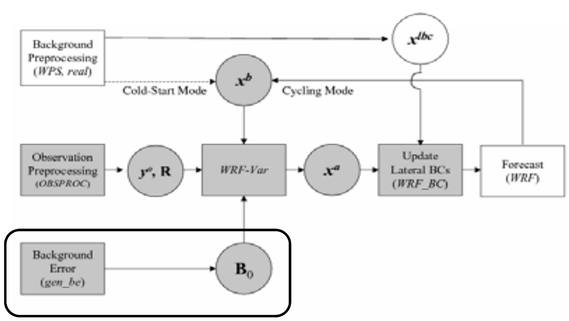
Talk overview:

- What is Background Error (BE) ?
- Role of BE in WRF-Var
- Various components of BE
- Impact of BE on minimization and forecasts
- How to compute (“gen_be” utility)?
- Single Observation Test
- Introduction to Practice Session-3

Where BE fits in WRF-modelling System



What is BE?

- It is the covariance of forecast-truth in analysis control variable space

  BE = $<(x-x^t), (x-x^t)^T>$

- Since truth is not known, it needs to be estimated

- Common methods to estimate BE
  - Innovation Based approach (Hollingsworth & Lonnberg,1986)
  - NMC Method: $(x-x^t) \approx (x^{t1} - x^{t2})$
    (Forecast differences valid for same time
  - Ensemble Method: $(x-x^t) \approx (x^{ens} - <x^{ens}>)$
    (Ensemble - Ensemble mean)
  - Flow dependent (adaptive approach)

Role of BE in WRF-Var cost Function:

- Basic WRF-Var cost function (J):

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

x	- Analysis control variable
x^b	- Background (FG)
B	- Background Error covariance
H	- Forward Observation Operator (Possibly non-linear)
y^o	- Observations
R	- Observation error covariance

Role of BE:

- BE is used for preconditioning the analysis equation

$$x^a = x^b + BH^T(HBH^T + R)^{-1}[y^o - H(x^b)]$$

- It is represented with a suitable choice of U as follows
  $B = U U^T$ with $U = U_p U_v U_h$

  U_h Horizontal Transform
  U_v Vertical Transform
  U_p Physical Transform

- Horizontal transformation (U_h) is via
  Regional ----- Recursive filters
  Global ----- Power spectrum
- Vertical transformation (U_v) is via EOF's
- Physical transformation (U_p) depends upon the choice of the analysis control variable

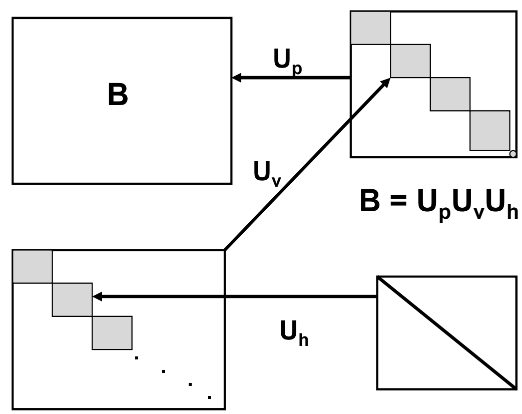
How BE is represented?

- In true sense, size of B is typically of the order of $10^7 \times 10^7$
- Size of B is reduced by designing the analysis control variables in such a way that cross covariance between these variables are minimum
- Currently the analysis control variables for WRF-Var are the amplitudes of EOF's of

  stream function (ψ)
  Unbalanced part of velocity potential (χ_u)
  Unbalanced part of temperature (T_u)
  Relative Humidity (q)
  Unbalanced part of surface pressure (p_{s_u})

- With this choice of analysis control variables off-diagonal elements of BE is very small and thus its size typically reduces to the order of 10^7

How BE is represented *Contd.*



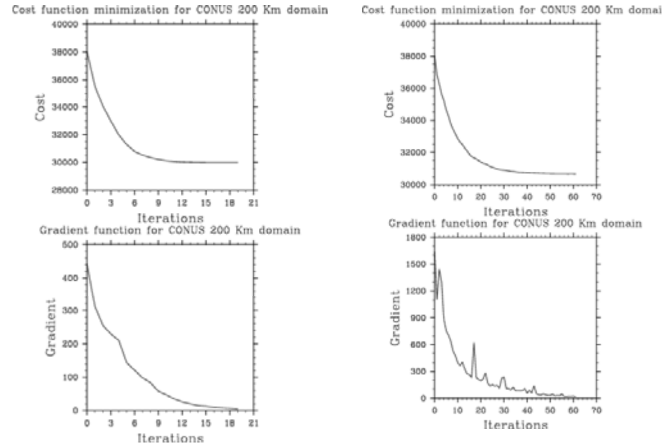
$$B = U_p U_v U_h U_h^T U_v^T U_p^T$$

Components of BE

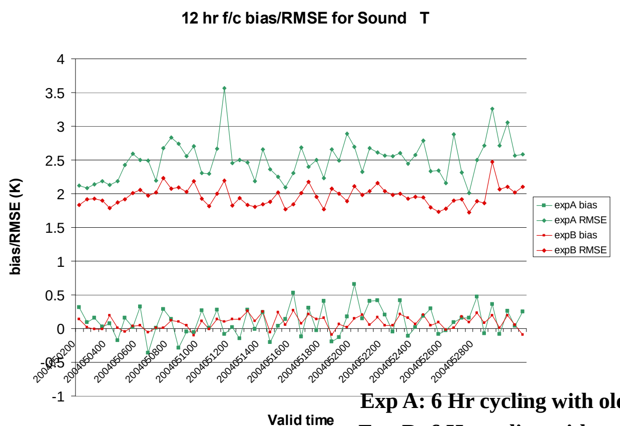
Corresponding to each control variable, following are the main components of BE

- Regression Coefficient for balanced part of Velocity potential, Temperature and Surface pressure
- Eigen vectors and Eigen values
- Scalelength for regional and power spectrum for global option

Impact of BE on Minimization

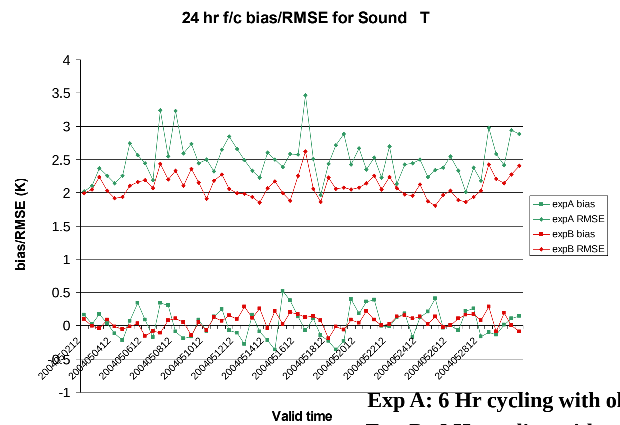


Impact of BE on Temperature forecast



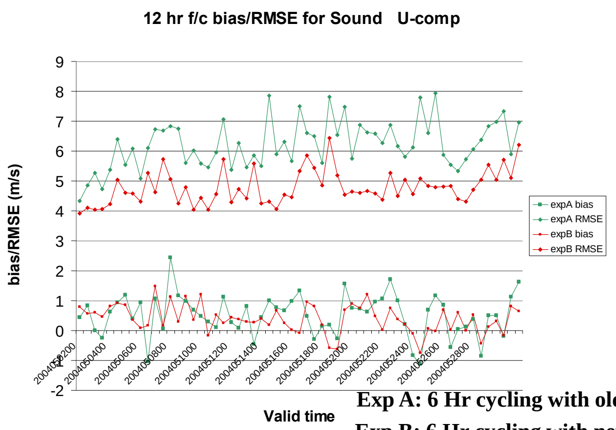
Exp A: 6 Hr cycling with old BE
Exp B: 6 Hr cycling with new BE

Impact of BE on Temperature forecast



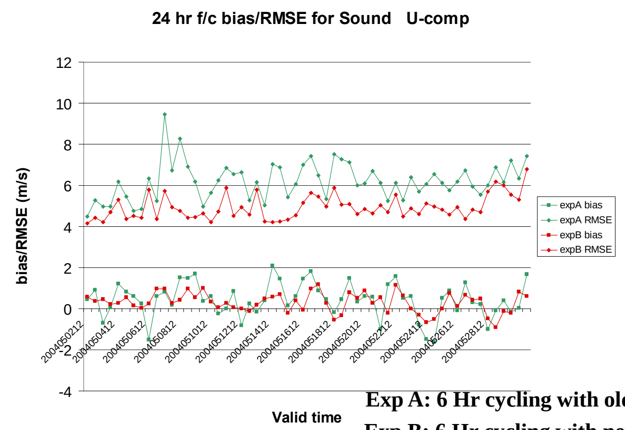
Exp A: 6 Hr cycling with old BE
Exp B: 6 Hr cycling with new BE

Impact of BE on Wind (U Comp.) forecast



Exp A: 6 Hr cycling with old BE
Exp B: 6 Hr cycling with new BE

Impact of BE on Wind (U Comp.) forecast



Exp A: 6 Hr cycling with old BE
Exp B: 6 Hr cycling with new BE

WRF-Var “gen_be” utility:

- **Computes various components of BE statistics**
- **Resides in WRFDA under “var” directory**
- **Designed both for NMC and Ensemble methods**
- **Consists of five stages**
- **Basic goal is to estimate the error covariance in Analysis Control Variable Space (Coefficients of the EOF’s for ψ, χ_u, T_u, q and p_{s_u}) from the Background Variable Space (U, V, T, q & P_s)**

“gen_be” - Stage0:

- **Computes (ψ , χ) from (u,v)**
- **Forms desired differences for the following fields**

ψ **- Stream Function**
χ **- Velocity potential**
T - Temperature
q - Relative Humidity
p_s **- Surface Pressure**

“gen_be” - Stage1:

- Reads “gen_be_stage1” namelist
- Fixes “bins” for computing BE statistics
- Computes “mean” of the differences formed in stage0
- Removes respective “mean” and forms perturbations for

Stream Function	(ψ')
Velocity potential	(χ')
Temperature	(T')
Relative Humidity	(q')
Surface Pressure	(p_s')

“gen_be” bins structure

- Currently “gen_be” utility has provisions of following seven (0-6) “bin_types”

0: No binning (each grid point is a bin)
1: mean in X-direction (Each latitude is a bin)
2: bins with binwidth_lat/binwidth_hgt
3: bins with binwidth_lat/nk
4: bins with binwidth_lat/nk (binwidth_lat (integer) is defined in terms of latitudinal grid points)
5: bins with all horizontal points (nk bins)
6: Average over all points (only 1 bin)

nk - Number of vertical levels

Default option is “bin_type=5”

“gen_be” - Stage2 & 2a:

- Reads “gen_be_stage2” namelist
- Reads field written in stage1 and computes covariance of the respective fields
- Computes regression coefficient & balanced part of χ, T & p_s

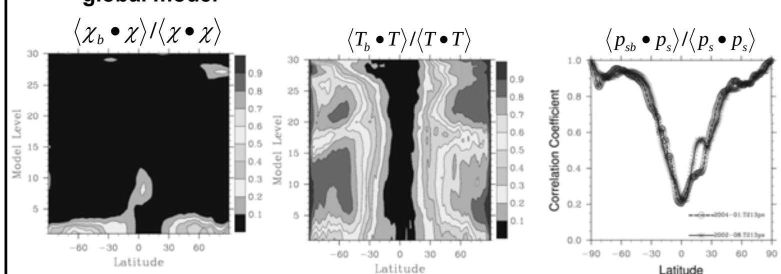
$$\chi_b = C\,\psi'$$
$$T_b(k) = \sum_l G(k,l)\,\psi'(l)$$
$$p_{s\_b} = \sum_l W(k)\,\psi'(k)$$

- Computes unbalanced part

$$\chi_u' = \chi' - \chi_b$$
$$T_u' = T' - T_b$$
$$p_{s\_u}' = p_s' - p_{s\_b}$$

WRF-Var Balance constraints

- WRF-Var imposes statistical balanced constraints between
  - Stream Function & Velocity potential
  - Stream Function & Temperature
  - Stream Function & Surface Pressure
- How good are these balanced constraints? Based on KMA global model



"gen_be" - Stage3:

- Reads "gen_be_stage3" namelist
- Removes mean for χ_u', T_u' & p_{s_u}'
- Computes eigenvector and eigen values for vertical error covariance matrix of ψ' , χ_u', T_u' & q
- Computes variance of p_{s_u}'
- Computes eigen decomposition of ψ' , χ_u', T_u' & q

"gen_be" - Stage4:

- Reads "gen_be_stage4" namelist
- For each variable & each eigen mode, for regional option computes "lengthscale (s)"

$$B(r) = B(0)\exp\{-r^2/8s^2\}$$

$$y(r) = 2\sqrt{2}[\ln(B(0)/B(r)]^{1/2} = r/s$$

- For global option, computes "power spectrum (D_n)"

$$D_n = \sum_{m=-n}^{n}\left(F_n^m\right)^2 = \left(F_n^0\right)^2 + 2\sum_{m=1}^{n}\left[\left(\mathrm{Re}(F_n^m)\right)^2 + \left(\mathrm{Im}(F_n^m)\right)^2\right]$$

Single observation test

- Through single observation, one can understand
  - structure of BE
  - It identifies the "shortfalls" of BE
  - It gives a broad guidelines for tuning BE

Basic concept:

Analysis equation: $x^a = x^b + BH^T(HBH^T + R)^{-1}[y^o - H(x^b)]$

Set single observation (U,V,T etc.) as follows:

$[y^o - H(x^b)] = 1.0$; $R = I$

Thus,

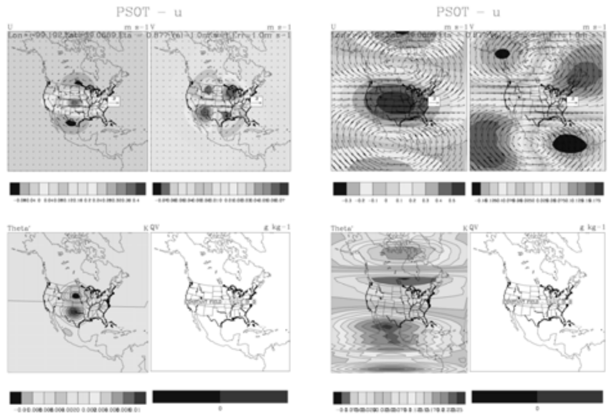
$x^a - x^b = B$ * constant delta vector

How to activate Single obs test (PSOT)?

"single obs utility" or "psot" may be activated by setting the following namelist parameters

num_pseudo = 1
pseudo_var =" Variable name" like "U", "T", "P", etc.
pseudo_x = "X-coordinate of the observation"
pseudo_y = "Y-coordinate of the observation"
pseudo_z = "Z-coordinate of the observation"
pseudo_val = "Observation value", departure from FG"
pseudo_err = "Observation error"

Single Obs (U) test with different BE



How to perform tuning of BE?

- Horizontal component of BE can be tuned with following namelist parameters

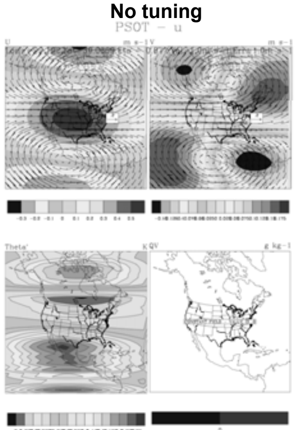
  LEN_SCALING1 - 5 (Length scaling parameters)
  VAR_SCALING1 - 5 (Variance scaling parameters)

- Vertical component of BE can be tuned with following namelist parameter

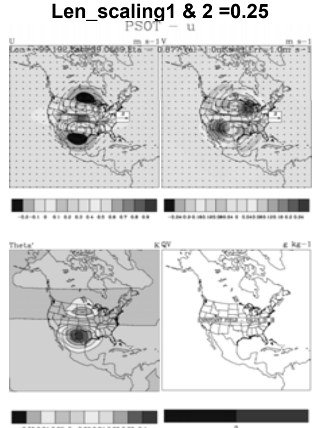
  MAX_VERT_VAR1 - 5 (Vertical variance parameters)

Results with BE Tuning

No tuning



Len_scaling1 & 2 =0.25



Practice Session 3

- Compilation of “gen_be” utility
- Generation of BE statistics
- Familiarization with various graphical utilities to display “gen_be” diagnostics
- Running single observation tests to understand the structure of BE
- BE error tuning

Generation of BE

- "gen_be_wrapper.ksh" script for generating BE for "CONUS" at 200 Km domain with:

  Grid Size : 45 x 45 x 28
  BE Method : NMC Method
  Data Input : January, 2007 forecasts, both from 00 & 12 UTC IC

Basic environment variables that needs to be set are:

- Gen_be executables location (WRFVAR_DIR)
- Forecast input data (FC_DIR)
- Run directory (BE_DIR)
- Data Range (START_DATE, END_DATE)

"gen_be" wrapper script basically executes "var/scripts/gen_be/gen_be.ksh" script

Gen_be diagnostics

- "gen_be" creates various diagnostic files which may be used to display various components of BE statistics.
- Important files are:

  Eigen vectors: fort.174, fort.178, fort.182, fort.186
  Eigen values: fort.175, fort.179, fort.183, fort.187
  scalelength: fort.194, fort.179, fort.183, fort.187
  Correlation between χ_u & χ_b (chi_u.chi.dat)
  Correlation between T_u & T_b (T_u.T.dat)
  Correlation between p_{s_u} & (ps_u.ps.dat)

Important Strings that needs to be defined in the wrapper script "var/script/gen_be/gen_be_plot_wrapper.ksh"

BE_DIR --- gen_be Run directory

How to run Single Observation Test ?

- Familiarization with single observation "wrapper" script ("da_run_suite_wrapper_con200.ksh") to run Single Observation test
- Key parameters are

  Type of observation (pseudo_var)
  Obs co-ordinates (pseudo_x, pseudo_y & pseudo_z)
  Observation value (pseudo_val)
  Observation error (pseudo_err)

- Display analysis increments to understand BE structure

BE tuning

- Understand the role of BE-tuning parameters through namelist options

  LEN_SCALING1 - 5 (Length scaling parameters)
  VAR_SCALING1 - 5 (Variance scaling parameters)
  MAX_VERT_VAR1 - 5 (Vertical variance parameters)

Note: If BE is available for the same domain configuration, it's tuning is not required

Radar Data

Doppler Radar Data Assimilation with WRF-Var

Qingnong Xiao, NCAR/MMM
Email: hsiao@ucar.edu

Outline:

- Introduction
  - Background and motivation
  - WRF-Var
- Methodology
  - Radial velocity
  - Reflectivity
- Procedure
  - Data preprocessing
  - Setup of namelist and scripts
- Summary

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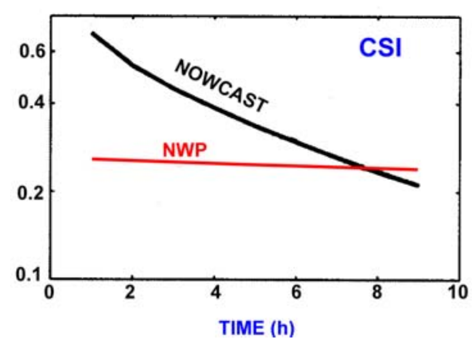
Operational NWP: poor short-term QPF skill

- Current operational NWP can not beat extrapolation-based radar nowcast technique for the first few forecast hours.

- One of the main reasons is that NWP is not initialized by high-resolution observations, such as radar.

0.1 mm hourly precipitation skill scores for Nowcast and NWP averaged over a 21 day period

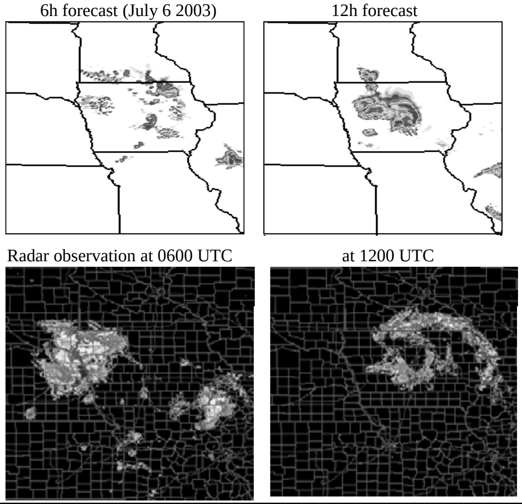


From Lin et al. (2005)

Example of model spin-up from BAMEX

Without high-resolution initialization:

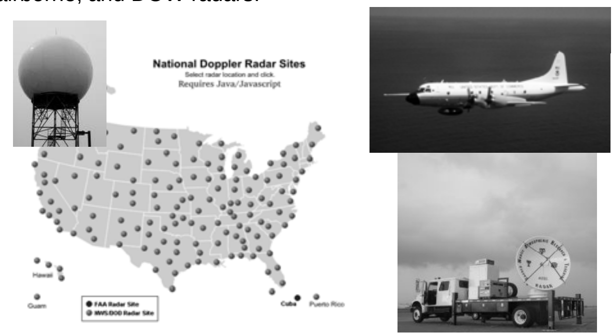
- A model can takes a number of hours to spin up.
- Convections with weak synoptic-scale forcing can be missed.



Graphic source: http://www.joss.ucar.edu

Opportunities

- There are wealth of Doppler radar observations from ground-based, airborne, and DOW radars.



- Assimilation of Doppler radar data should improve the small-scale structures in the initial conditions, reduce the model spin-up time, and enhance the short-time NWP skills.

Doppler radar observations

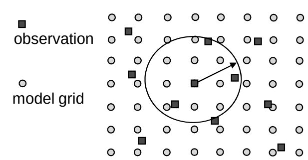
- The level II data are radial velocity and reflectivity
- High spatial (~1 km) and temporal (5-10 minutes) resolution, but coverage is limited to regions with hydrometeors
- Huge amount of data (in a storm mode, the estimate number of data is ~3 million/ 5minute from one radar

Doppler radar observations

Conventional Observation:

Resolution ~ a few 100 km -- much poorer than model resolutions.

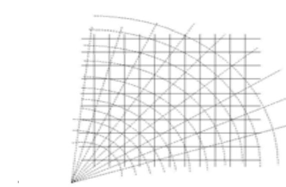
The observed is usually model variables.



Radar observation:

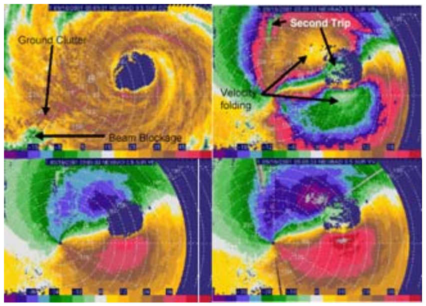
Resolution ~ a few km -- equivalent to model resolutions.

Radial velocity and reflectivity data are not model variables.

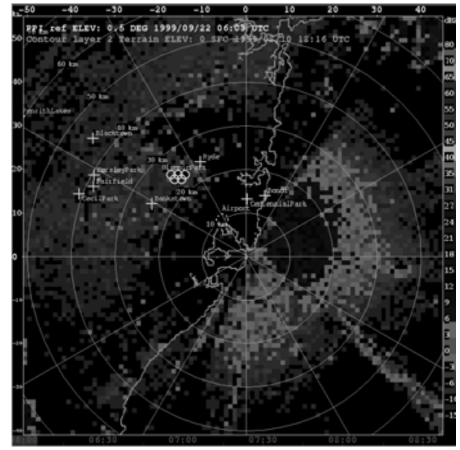


Doppler radar observations

- Data quality control is a major issue for radar data assimilation
  - Dealiasing
  - Removal of clutters, second-trip echo and other noises

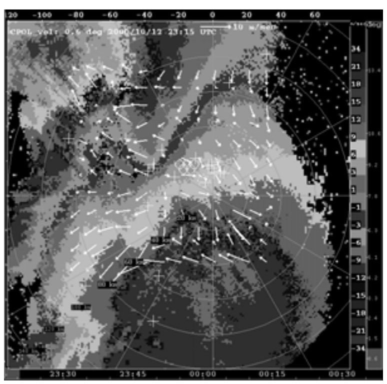


Doppler radar observations

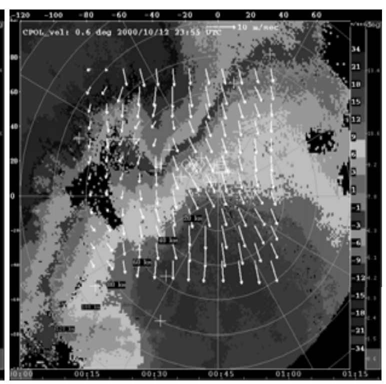


Sea clutter: Radar echo has vertical gradient near the surface.

Doppler radar observations

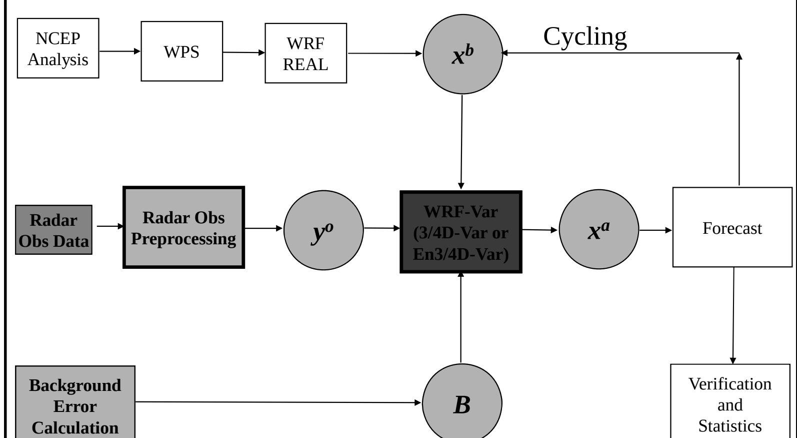


Aliased velocities



De-aliased velocities

WRF-Var Flow Chart



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Challenges for radar DA with 3D-Var

- Cost function

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

- To assimilate data, we need to construct observation operators.
- The possibly simplest operators for radial velocity and reflectivity:
  - Radial velocity:

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

$$v_T = 5.40a\cdot q_r^{0.125}, \quad a=(p_0/\overline{p})^{0.4}$$

  - Reflectivity:

$$dbZ = 43.1 + 17.5\log(\rho q_r)$$

Challenges for radar DA with 3D-Var

- The WRF 3D-Var cost function minimization is performed in the control variable space via preconditioning.

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

- The preconditioning control variables are **v** : (ψ', χ_u', T'_u, p'_{su}, and r'_s).
- The analysis increments **X**' are obtained through a series of transform: **X**'=$\boldsymbol{U}\mathbf{v}=\boldsymbol{U}_p\boldsymbol{U}_v\boldsymbol{U}_h\mathbf{v}$.

Challenges for radar DA with 3D-Var

- The relation between control variable space and model space is through "physical transform in WRF 3D-Var system, $\boldsymbol{U}_p$, and its adjoint $\boldsymbol{U}_p^T$.
  - $\boldsymbol{U}_p$: Convert control variables (ψ', χ_u', T'_u , p'_{su}, and r'_s) to model variables (u', v', T', p', q')

WRF 3D-Var

- Control variables (ψ', χ_u', T'_u, p'_{su}, r'_s)
  <=> model variables (u', v', T', p', q')

Doppler radar data assimilation

Radial velocity data

3D-Var needs vertical velocity increments (w')
to have a full assimilation of radial velocity data.

Reflectivity data

3D-Var needs at least rainwater increments (q_r').
It is better to have increments of all other
hydrometeor variables as well in 3D-Var analysis.

Challenges for radar DA with 3D-Var

- There is an inconsistency between what the WRF 3D-Var increments have and what the Radar data assimilation needs.
- To overcome the problem, we need either to introduce new control variables (e.g. w', q_r', etc.), or to construct new "physical transforms $\boldsymbol{U}_p$ and its adjoint $\boldsymbol{U}_p^T$" in WRF 3D-Var system".

Challenges for radar DA with 3D-Var

- If new control variables are introduced, then it is required to modify the whole system. In addition, the background error statistics for the new control variables (e.g. w' and q_r') are very difficult.
- We selected to construct new "physical transform" to enable WRF 3D-Var assimilate Doppler radar data.

W Increments in WRF 3D-Var

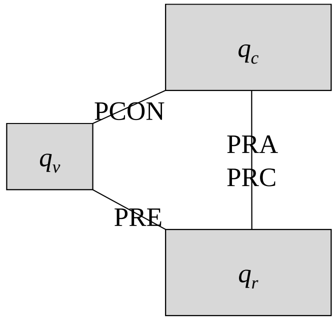
- Richardson's Equation ($\psi', \chi_u', T'_u, p'_{su} \rightarrow u', v', T', p' \rightarrow w'$)

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

  - Richardson's equation is a higher-order approximation of the continuity equation than the incompressible continuity equation or anelastic continuity equation.
  - It can build an efficient linkage between dynamic and thermodynamic fields because the thermodynamic equation is directly involved.
  - Its computation is affordable, just a little more than the anelastic continuity equation.

Hydrometeor increments in WRF 3D-Var

A warm rain process is currently built in WRF 3D-Var to bridge water hydrometeors and other variables.



PCON: condensation/evaporation;
PRA: accretion; PRC: conversion;
PRE: evaporation/deposition

Observation operators

- Radial velocity

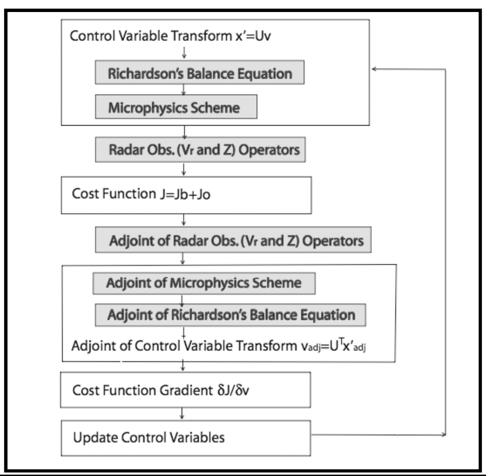
$$v_r = u\frac{x-x_i}{r_i} + v\frac{y-y_i}{r_i} + (w-v_T)\frac{z-z_i}{r_i}$$

$$v_T = 5.40a \cdot q_r^{0.125}, \qquad a = (p_0/\overline{p})^{0.4}$$

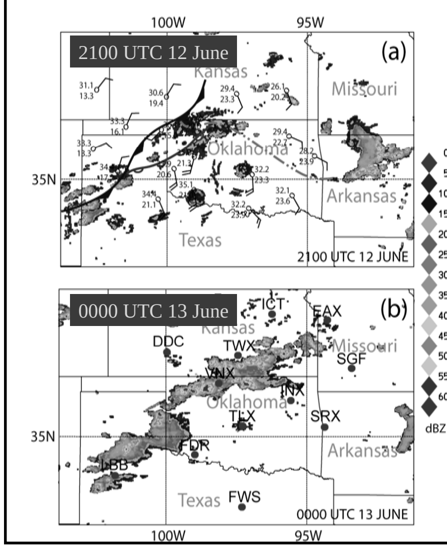
- Reflectivity

$$dbZ = 43.1 + 17.5\log(\rho q_r)$$

Flow Chart of Radar Data Assimilation in WRF 3D-Var



QPF of an IHOP_2002 Squall Line Case



Xiao and Sun (2007), *Mon. Wea. Rev.*, **135**, 3381-3404.

Surface analysis and Composite radar reflectivity observations at (a) 2100 UTC 12 and (b) 0000 UTC 13 June 2002.

The cold front (blue line), dry line (brown line), and outflow boundary (pink line) at 2100 UTC 12 June are depicted in (a). The 12 red dots in (b) indicate 12 WSR-88D radar stations with their station name above the red dot. The data from the 12 WSR-88D radars are used for the Doppler radar data assimilation experiments.

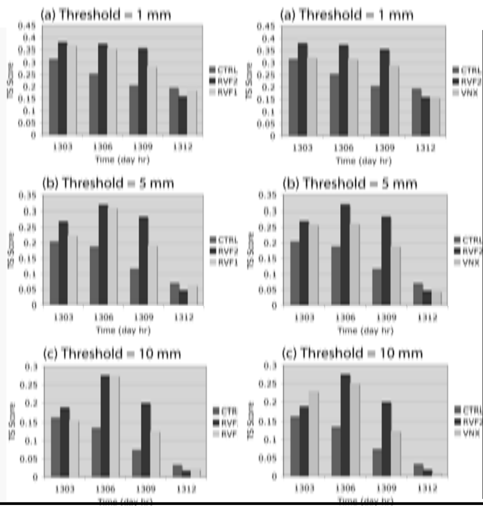
QPF of an IHOP_2002 Squall Line Case

Left panel

Red: CTRL

Blue: Cycling

Cyan: No cycling



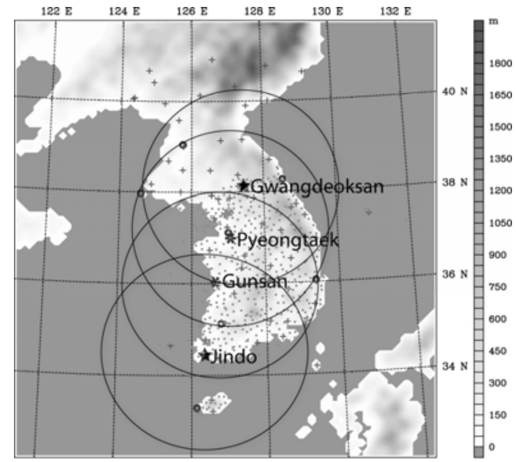
Right panel

Red: CTRL

Blue: 12 radars

Grey: Single radar

KMA radars used in 3D-Var analysis



Doppler radar data from 4 radar sites were included in assimilation In 2006

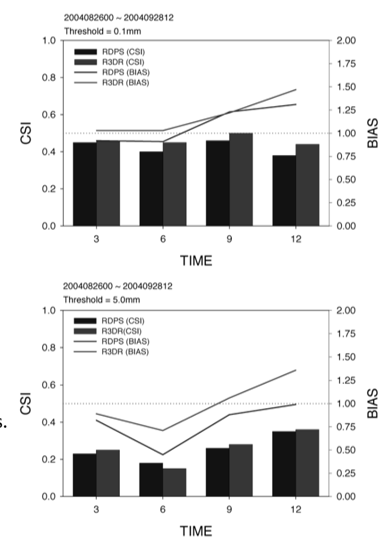
One-month Verification in KMA

- Period: 2004. 8. 26. 00UTC ~ 2004. 9. 28. 12UTC (3hr-accumulated rainfall)
- Operation without radar data/experiment with radar data (blue/red)

➢ 0.1mm threshold (top) : CSI is increased, but BIAS is also increased at the 12 hour forecasts.

➢ 5.0 mm threshold (bottom) : CSI is increased except for the 6 hour forecast, BIAS is increased at the 12 hour forecasts.

➢ Xiao et al. (2008), *Bull. Amer. Met. Soc*. **89**, 39-43.



Outline:

- Introduction
  - Background and motivation
  - WRF-Var
- Methodology
  - Radial velocity
  - Reflectivity
- Procedure
  - Data preprocessing
  - Setup of namelist and scripts
- Summary

Doppler radar data preprocessing

- Preprocessing Doppler radar data is an important procedure before assimilation.
- It usually contains the following:
  - Quality control
    - To deal with clutter, AP, folded velocity, bird contamination, …
  - Mapping
    - Interpolation, smoothing, super-observation, data filling, …
  - Error statistics
    - Variance and covariance

Doppler radar data preprocessing

- NCAR software:
  - SPRINT: Sorted Position Radar INTerpolation
  - CEDRIC: Custom Editing and Display of Reduced Information in Cartesian-space
  - SPRINT and CEDRIC are released in NCAR/MMM website http://www.mmm.ucar.edu/pdas/pdas.html
- NCAR software:
  - ANT: Auto-Nowcasting System
  - VDRAS: Variational Doppler Radar Analysis System
  - ANT and VDRAS are not released to the public
- There is no standard and automatic software to perform radar data preprocessing.

Radar data preprocessing

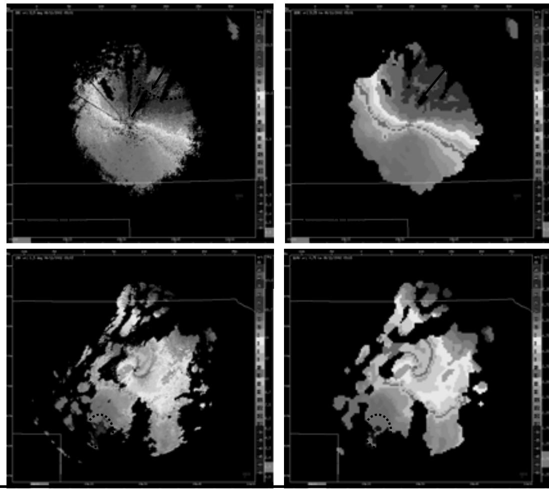
- An example: VDRAS preprocessor
- Input: griddid data at elevation angles
- Eliminate ground-clutter contamination
  - ✓ $v_r < 0.1\ ms^{-1}$
- Remove noises
  - ✓ Remove data with high local variance of v_r and reflectivity
    - > 60 m^2s^{-2} / 150 dbZ^2 (empirical values) in 3×3 grid points
  - ✓ Filter out isolated and questionable velocities
    - 3×3 filter (Bargen and Brown 1980)
      - If more than 3 of its 8 neighboring are missing, it is assigned a missing value

Radar data preprocessing

- Dealias
  - ✓ 1st step: Compare with a reference wind from model run (automatic)
  - ✓ 2nd step: Compare with local average wind (automatic)
  - ✓ 3rd step: Examine velocity at each elevation angle (manual)
- Fill missing data
  - ✓ 9×9 grid points, more than 20 grid points in at least 2 quadrates
- Interpolate data to the same resolution as model runs (3 km)
  - ✓ Bi-linear interpolation to 3×3 km on elevation angles
- Final output
  - ✓ Radial velocity, reflectivity and their errors
    - Error: standard deviation from values at 3×3 grid points
    - Min/Max radial velocity error is 1.0/10.0 ms^{-1}

Radar data preprocessing

20020611 09UTC



Radial velocity de-aliasing

Data format

TOTAL RADAR (14X, I3) – FMT = (A14,I3)

#--

Head record for specific Radar information (site, lat0, lon0, elv, date, # of data locations, max_levs)

– FMT = (A5,2X,A12,2(F8.3,2X),F8.1,2X,A19,2I6)

#--

Head record for the specific location (FM-128 RADAR, date, lat, lon, elv, levs)

-- FMT=(A12,3X,A19,2X,2(F12.3,2X),F8.1,2X,I6)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

………………………………………………………………………………………

– FMT=(3X,F12.1,2(F12.3,I4,F12.3,2X))

Head record for specific Radar information (site, lat0, lon0, elv, date, # of data locations, max_levs)

#--

Head record for the specific location (FM-128 RADAR, date, lat, lon, elv, levs)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

………………………………………………………………………………………

Data format

```
TOTAL RADAR =   2
#--------------------------------------------------------------------------#

RADAR      JINDO 126.328   34.471    499.0  2002-08-31_00:00:00  5706    9
#--------------------------------------------------------------------------#
FM-128 RADAR   2002-08-31_00:00:00       34.314      124.003     499.0      2
       3803.5          7.918    1          0.500          17.704    1           1.125
       7480.6 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
FM-128 RADAR   2002-08-31_00:00:00       34.360      124.002     499.0      2
       3795.2          7.125    1          0.500          18.214    1           1.160
       7467.1 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
FM-128 RADAR   2002-08-31_00:00:00       34.405      124.000     499.0      2
       3790.2          6.714    1          0.598          14.864    0           0.707
       7459.0 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
FM-128 RADAR   2002-08-31_00:00:00       35.275      123.974     499.0      2
       4325.9          4.118    0          0.500          16.650    0           3.959
       8315.9 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
..............................................................................................
```



```
RADAR      JINDO 126.328   34.471    499.0  2002-08-31_00:00:00  5706    9
#--------------------------------------------------------------------------#
FM-128 RADAR   2002-08-31_00:00:00       34.314      124.003     499.0      2
       3803.5          7.918    1          0.500          17.704    1           1.125
       7480.6 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
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       7467.1 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
FM-128 RADAR   2002-08-31_00:00:00       34.405      124.000     499.0      2
       3790.2          6.714    1          0.598          14.864    0           0.707
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       4325.9          4.118    0          0.500          16.650    0           3.959
       8315.9 -888888.000 -88 -888888.000   -888888.000 -88 -888888.000
..............................................................................................
```


Namelist

- In the namelist.input, the following additions should be made for radar data assimilation:

  &wrfvar2
  CALC_W_INCREMENT = T (to have w increments)

  &wrfvar4
  USE_RADAROBS = T (to assimilate radar data)
  USE_RADAR_RV = T (to assimilate radial velocity)
  USE_RADAR_RF = T (to assimilate reflectivity)

Linking the radar observation file

- In the run working directory, please link the radar observation file.

ln -sf /ptmp/hsiao/tutorial08/ob.radar ./test/ob.radar

  – This is the only additional dataset you should include for radar data assimilation. Other input files for WRF-Var are the same as conventional data assimilation.

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Summary

- The WRF 3D-Var with Doppler radar data assimilation showed positive impact, and was implemented in KMA operational numerical weather prediction in Korea. However, we found several issues to work on in order to improve the capability of the system:

  ▪ Latent heat release with reflectivity assimilation - Reflectivity assimilation not only changes hydrometeors, but it also has direct impact on vertical velocity and temperature by including latent heat release in 3D-Var constraint.

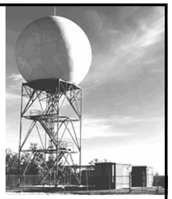
  ▪ More sophisticated microphysics - The tangent linear and adjoint of WSM6 microphysics are coded. We will implement them in WRF 3D-Var to have analysis of ice-phase hydrometeors with assimilation of reflectivity data. The TGL and ADJ codes will also be used in WRF 4D-Var.

  ▪ Implementation of digital filtering with rapid update cycling of radar data in WRF 3D-Var. WRF 3D-Var analysis can still have spin-up problem. DFI can alleviate the problem.

Summary

- Doppler radar data assimilation using WRF 4D-Var
  - WRF 3D-Var Doppler radar data assimilation shows promises. However, studies using WRF 4D-Var for radar data assimilation should be our major focus in the next several years.
  - There are several scientific studies and technical developments for WRF 4D-Var Doppler radar data assimilation.
    - Incremental or non-incremental approach?
    - Control variables change?
    - Coding the tangent linear and adjoint of sophisticated microphysics schemes and included in WRF 4D-Var.
- Doppler radar data assimilation using WRF En4D-Var
  - It uses flow-dependent background error covariance matrix constructed by ensemble forecasts and performs 4D-Var optimization.
  - It avoids the tangent linear and adjoint so that it can be easily implemented.

Thanks for your attention



Some references with Doppler radar data assimilation:

- Xiao, Q., Eunha Lim, D.-J. Won, J. Sun, W.-C. Lee, M.-S. Lee, W.-J. Lee, J. Cho, Y.-H. Kuo, D. Barker, D.-K. Lee, and H.-S. Lee, 2008: Doppler radar data assimilation in KMA's operational forecasting. *Bull. Amer. Meteor. Soc.*, **89**, 39-43.
- Xiao, Q., and J. Sun, 2007: Multiple radar data assimilation and short-range quantitative precipitation forecasting of a squall line observed during IHOP_2002. *Mon. Wea. Rev.*, **135**, 3381-3404.
- Xiao, Q., Y.-H. Kuo, J. Sun, Wen-Chau Lee, D. M. Barker, and Eunha Lim, 2007: An approach of radar reflectivity data assimilation and its assessment with the inland QPF of Typhoon Rusa (2002) at landfall. *J. Appl. Meteor. Climat.*, **46**, 14-22.
- Xiao, Q., Y.-H. Kuo, J. Sun, Wen-Chau Lee, Eunha Lim,Y.-R. Guo , and D. M. Barker, 2005: Assimilation of Doppler radar observations with a regional 3D-Var system: Impact of Doppler velocities on forecasts of a heavy rainfall case. *J. Appl. Meteor,* **44**, 768-788.

Hybrid Data Assimilation System: Integrating 3D-Var with Ensemble (ETKF)

Hybrid Data Assimilation System: Integrating 3D-VAR with Ensembles (ETKF)

Meral Demirtas

WRF-Var Tutorial Presentation

NCAR, Boulder, Colorado

Acknowledgements with my special thanks:

Dale Barker, Xuguang Wang, Chris Snyder, Josh Hacker, and Yongsheng Chen

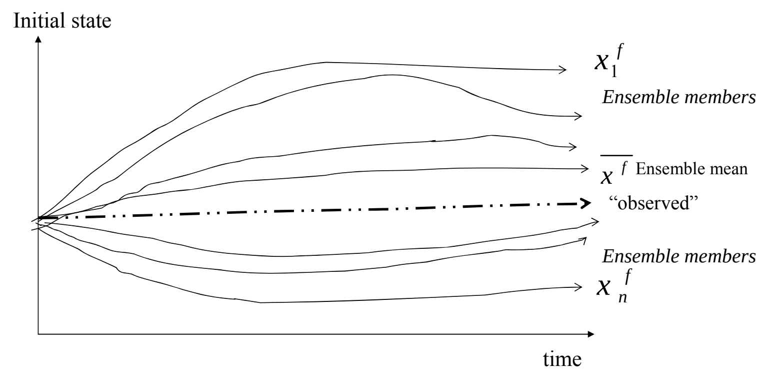
What is on the menu?

- Basic ingredients of a hybrid DA system
- Ensemble Transform Kalman Filter (ETKF)
- Hybrid system: Integrating ETKF into the 3D-VAR system
- Hybrid-ETKF implementation at Data Assimilation Testbed Center (DATC)
- Some examples from the latest NCAR applications
- the menu for the hybrid practice session

Basic ingredients of a hybrid system

1. WRF-Ensembles
2. Updating ensembles: Ensemble Transform Kalman Filter (ETKF)
3. Data assimilation system: 3D-VAR
4. Hybrid: Integrating ETKF into 3D-VAR system

Ensembles to address uncertainties in initial state



Ensembles in Formulas

Assume the following ensembles:

$$X^f = (x_1^f, x_2^f, x_3^f, ...x_N^f)$$

Ensemble mean: $\overline{x}^f = \frac{1}{N}\sum_{i=1}^{N} X_n^f$

Ensemble perturbations: $\delta X_n^f = x_n^f - \overline{x^f}$

Ensemble perturbations in vector form:

$$\delta X^f = (\delta x_1^f, \delta x_2^f, \delta x_3^f, ..., \delta_N^f)$$

Updating ensemble-based analyses

There are several approaches for ensemble-based data assimilation, we shall cover only Ensemble Transform Kalman Filter (ETKF) in this presentation. (For more details on DA ensemble techniques, I'd recommend Chris Snyder's talk at 9:10 on 4th Feb. 2009.)

ETKF technique produces ensemble members by re-scaling innovations with a transformation matrix. (Wang and Bishop 2003, Wang et. al. 2004, 2007.)

$$x^a = x^f T$$

T*ransformation matrix*
(solved by Kalman Filter Theory)

How does ETKF inflates ensemble analysis?

An adaptive scalar inflation factor has been introduced by Wang and Bishop 2003, $\prod$, :

$$\tilde{d}_i^T \tilde{d}_i = trace(\tilde{H}\alpha_i P_i^e \tilde{H}^T + \mathrm{I})$$

$$\tilde{d} = \left[y^o - \overline{H(x^f)}\right] / \sigma_o$$

$$\alpha_i = (\tilde{d}_i^T \tilde{d}_i - N) / (\sum_{i=1}^{k-1} \lambda_i)$$

$$\tilde{H} = H / \sigma_o$$

λ are the eigenvalues of $1/(N_k - 1)\tilde{H}P_i^e\tilde{H}$

$$\Pi_i = \sqrt{\alpha_1 \alpha_2 ... \alpha_i} \qquad x_i = x_i^f T_i \Pi_i$$

Pros and Cons of ETKF Technique

- Desirable aspects:
  - ETKF is fast (computations are done in model ensemble perturbation subspace).
  - It is suitable for generating ensemble initial conditions.
  - It updates initial condition perturbations.

- Less desirable aspects:
  - ETKF does not localize, therefore it does not represent sampling error efficiently. It may need very high inflation factors.

Hybrid: 3D-VAR and Ensembles Integrated

- Flow-dependent covariance through ensembles.
- Coupling wind, temperature and moisture fields.
- Hybrid can be more robust for small size ensembles and/or model errors (Wang et al. 2007, 2008a).
- It can be adapted to an existing 3D-VAR system.
- It is less expensive compared to other ensemble filters.

Advantages of a Hybrid System

- Background errors are flow-dependent:
  - 3D-Var: uses static background error covariances
  - Ensemble DA: computes flow-dependent covariances
  - Hybrid: flow-dependent information from ensemble perturbation fed into the WRF-Var system.

  Flow-dependent ensemble covariance has the largest impact over and downstream of where observation is sparse (Wang et al. 2008b).

The theory behind hybrid DA….

Ensemble covariance is implemented into the 3DVAR cost function via control variables:

$$J(x_1',\alpha) = \beta_1 \frac{1}{2} x_1'^T B^{-1} x_1' + \beta_2 \frac{1}{2} \alpha^T C^{-1} \alpha + \frac{1}{2}(y^{o'} - Hx')^T R^{-1} (y^{o'} - Hx')$$

$$x' = x_1' + \sum_{k=1}^{K} (\alpha_k \circ x_k^e)$$

(Wang et. al. 2007, 2008a)

C: correlation matrix for ensemble covariance localization

x_1' 3D-VAR increment

x' Total increment including hybrid

α Extended control variable

β_1 Weighting coefficient for static 3D-VAR covariance

β_2 Weighting coefficient for ensemble covariance

The theory part continued….

Conserving total variance requires: $\frac{1}{\beta_1} + \frac{1}{\beta_2} = 1$

Ensemble covariance localization is done through recursive filters. Since extended control variables are constrained by horizontal correlation matrix, C, only horizontal localization is utilized.
Preconditioning designed as:

$x_1' = U_1 v_1$ $\quad U_1 \approx B^{1/2}$

$\alpha = U_2 v_2$ $\quad U_2 \approx C^{1/2}$

(Wang et. al. 2007, 2008a)

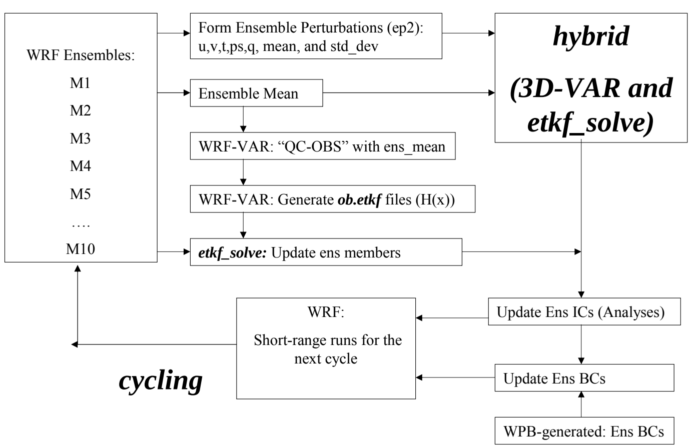
Some Hybrid Namelist Parameters

- alpha_corr_scale=1500km (Default)
- je_factor (β_1)= 2.0
- jb_factor (β_2)= je_factor/(je_factor -1)
- alphacv_method =2 (ensemble perturbations on model space)
- ensdim_alpha= Ensemble size
- alpha_std_dev=1.0

Some Recent Work

- NCAR:
  - DATC applications (Meral Demirtas)
  - JME applications (Josh Hacker)
- The UK Met Office:
  - Global 4D-Var/Localized-ETKF (Dale Barker)
  - Adaptive localization within hybrid (with BOM, NRL)

WRF-VAR-ETKF Hybrid DA System Implementation at Data Assimilation Testbed Center (DATC)

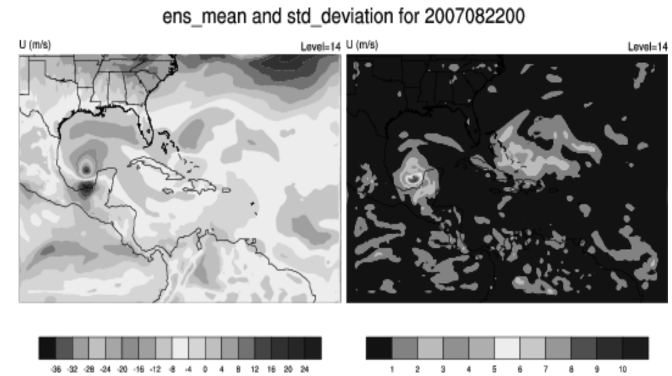


DATC's t8_45km Domain Application

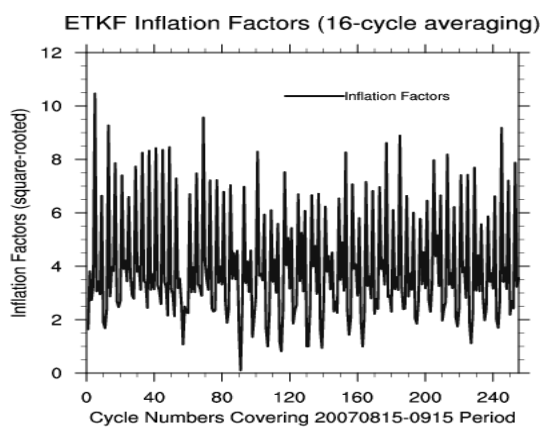
Ensemble size: 10
Test Period: 20070815-20070915
Cycle frequency: 3 hours
Ensemble analysis: ETKF technique
WRF-VAR technique: hybrid
WRF: Short-range (3hrs) runs for the next cycle
Observations: GTS
Initial and boundary conditions: GFS
Horizontal resolution: 45km
Number of vertical levels: 57

Preliminary results from DATC applications (snapshots)
Note that the work is still in progress…..

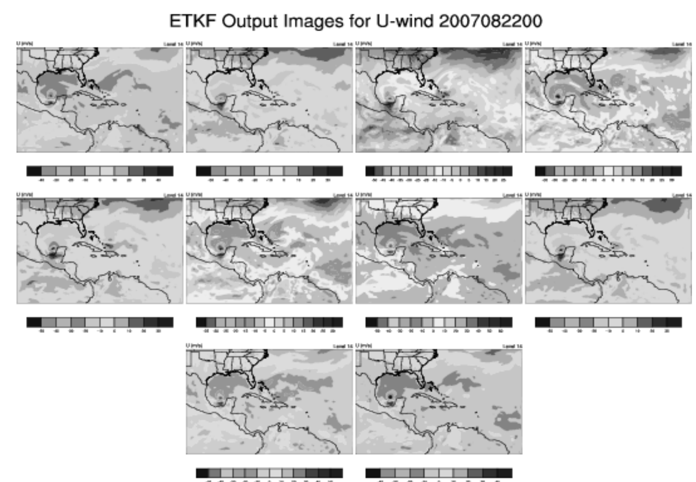
Ensemble Mean and Std. Deviation (spread)



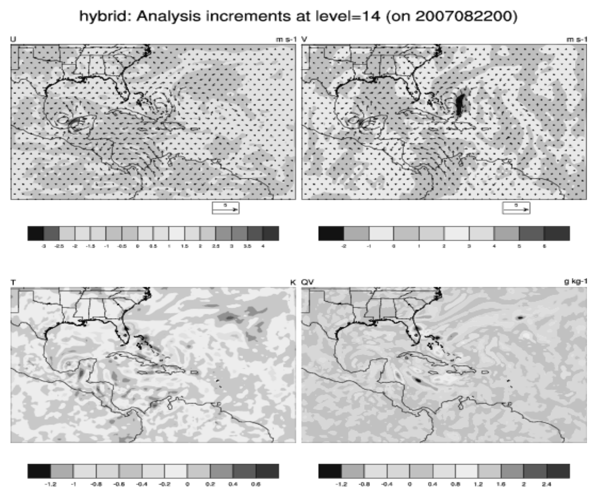
Inflation Factors (from 3-hourly cycling)



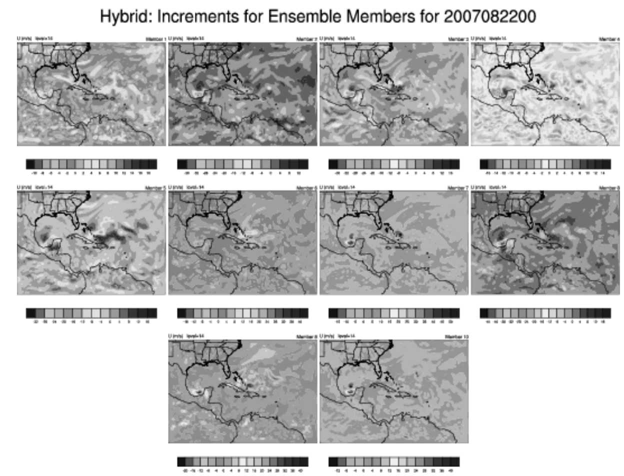
Stable, no-smoothing has been applied yet.

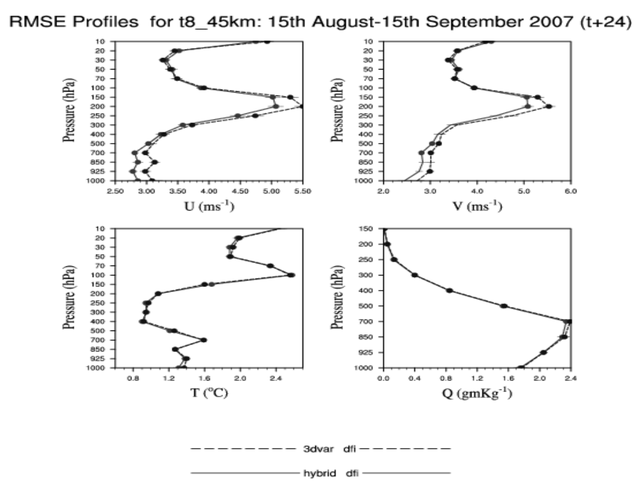


A snapshot of 10 ensemble members after ETKF procedure.



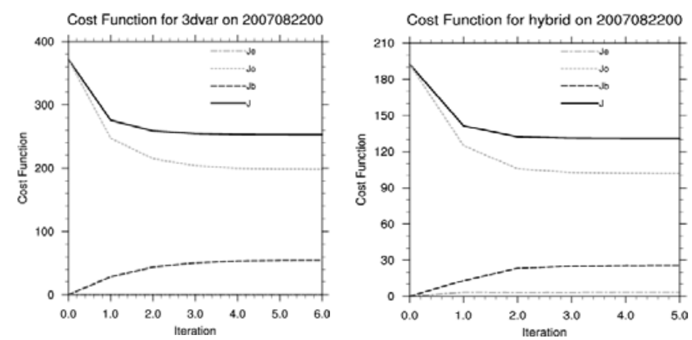
Flow-dependent increments from the hybrid system





Hybrid gives low RMSE scores for wind compared to 3D-Var.

Cost function: 3DVAR and Hybrid



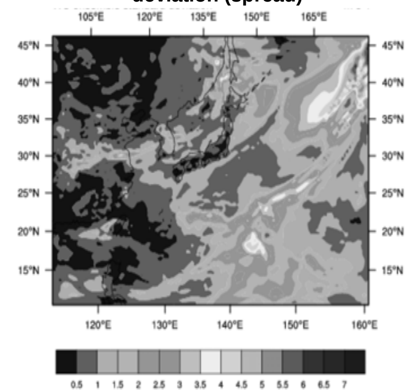
Cost function is smaller in hybrid.

Preliminary results from JME applications (snapshots)
Note that the work is still in progress…..

Joint Mesoscale Ensemble (JME) Applications

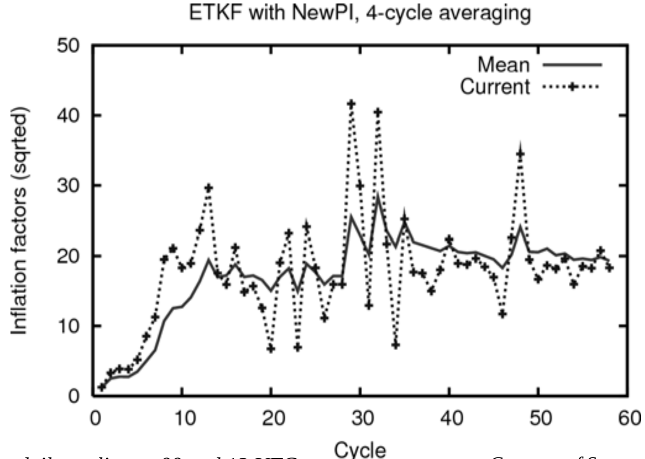
- 10 to 20 WRF physics configurations
- Capability for WRF-Var to update mean and/or individual members
- Capability for ETKF perturbations
- Lateral boundary conditions from global ensemble (GFS)
- Research on multi-parameter and stochastic approaches
- WRF-Var used to compute innovations for verification

10-m wind speed ensemble standard deviation (spread)



Courtesy of Josh Hacker

Inflation Factors Generated by JME



Twice daily cycling at 00 and 12 UTC

Courtesy of Soyoung Ha

What is on the menu for practice session

- **Computation:**
  - Computing ensemble mean.
  - Extracting ensemble perturbations (EP).
  - Running WRF-VAR for “hybrid”.
  - Displaying results for: ens_mean, std_dev, ensemble perturbations, hybrid increments, cost function and, etc.
  - If time permits, tailor your own test by changing hybrid settings; testing different values of “je_factor” and “alpha_corr_scale” parameters.
- **Scripts to use:**
  - A wrapper to make above listed runs.
  - Some NCL scripts to display results.

Brief information for the chosen case

Ensemble size: 10

Domain info:

- time_step=240,
- e_we=122,
- e_sn=110,
- e_vert=42,
- dx=45000,
- dy=45000,

Input data provided (courtesy of JME Group):

- WRF ensemble forecasts valid at 2006102800
- Observation data (ob.ascii) for 2006102800
- 3D-VAR “be.dat” file

Referred references

Wang, X., and C. H. Bishop, 2003: A comparison of breeding and ensemble transform Kalman filter ensemble forecast schemes. *J. Atmos. Sci.*, **60**, 1140-1158.

Wang, X., T. M. Hamill, J. S. Whitaker and C. H. Bishop, 2007: A comparison of hybrid ensemble transform Kalmanfilter-OI and ensemble square-root filter analysis schemes. *Mon. Wea. Rev.*, **135**, 1055-1076.

Wang, X., D. Barker, C. Snyder, T. M. Hamill, 2008a: A hybrid ETKF-3DVAR data assimilation scheme for the WRF model. Part I: observing system simulation experiment. *Mon. Wea. Rev.*, in press.

Wang, X., D. Barker, C. Snyder, T. M. Hamill, 2008b: A hybrid ETKF-3DVAR data assimilation scheme for the WRF model. Part II: real observation experiments. *Mon. Wea. Rev.*, in press.

WRF-Var Tools and Verification Package

WRF-Var
Analysis/Forecast Verification

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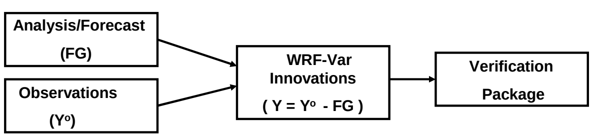
rizvi@ucar.edu

How to Verify Analysis/Forecast?

- **Two ways:**
  - **- Against Observations**
  - **- Against any analysis available in grid space (Control Analysis)**
- **Verification scores:**
  - **- Root Mean Square Error (RMSE)**
  - **- Mean bias (BIAS)**
  - **- Absolute Mean bias (ABIAS)**

Observation based Verification



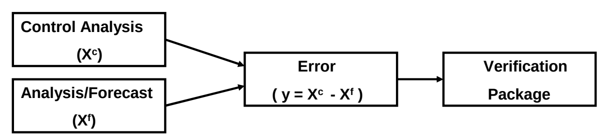
Verification code is under

var/da/da_verif_obs

compile all_wrfvar creates the desired executable

da_verif_obs.exe

Analysis based Verification



Code resides under “var/da/da_verif_anal” directory

“compile all_wrfvar” creates the desired executable

(da_verif_anal.exe)

Advantages

- Consistent with WRF-Var QC
- Consistent with WRF model topography
- It makes use of built-in WRF-Var observation operators
- In principle, verification is possible against any
  - Observation type individually or collectively
  - Verification analysis may be from any independent source or produced by any experiment
- It has its own built-in graphics (NCL) package

How to run verification against observation?

It works in two steps

- **Step 1: Execute "var/script/da_run_suite_verif_obs.ksh"**
  It will create all the desired input files (gts_omb_oma") for verification
- **Step 2: Execute "var/script/da_verif_obs_plot.ksh"**
  It will generate the desired graphics
- **These scripts are executed (in the same order) via a suitable wrapper script, which needs to be written depending on the requirements**

Wrapper for da_run_suite_verif_obs

Important variables needs to be declared for this wrapper script:

INITIAL_DATE	: Vrification starting date (yyyymmddhh)
FINAL_DATE	: Verification ending date (yyyymmddhh)
CYCLE_PERIOD	: Date advance increment in hour
EXP_DIR	: Experiment directory name (full path)
FILTERED_OBS_DIR	: Directory where filtered_obs, against which verification will be done
VERIFICATION_FILE_STRING	: It is either "wrfout" or "wrf_3dvar_input", depending on which files are saved while running WRF-forecasts in FC_DIR
VERIFY_HOUR	: 0 for analysis & 12, 24, etc. corresponding to the desired forecast hour verification

Wrapper for da_verif_obs_plot

Important variables:

WRFVAR_DIR : Main WRFDA directory (full path)
REG_DIR : Directory holding sub-directories for each experiment generated in Step 1
For example: "gts_omb_oma" file corresponding to experiment "verify_12" (directory for 12 hr forecast verification) for "2005081700" should be in $REG_DIR/verify_12/2005081700/wrfvar

RUN_DIR	: Full path of the directory where plots will be generated
NUM_EXPT	: Total number of experiments (Currently maximum 10)
EXP_NAMES	: Experiment directory names as they exist in REG_DIR (blank separated)
EXP_LEGENDS	: Legend strings for each experiments respectively (comma separated)
START_DATE	: Starting date ("YYYYMMDDHH") for verification
END_DATE	: Ending date ("YYYYMMDDHH") for verification
INTERVAL	: Time interval (in hours) for incrementing date/time.
NUM_OBS_TYPE	: Number of observation types for verification
OBS_TYPES	: Verification observation types like, "synop", "buoy", "sound" etc.
PLOT_WKS	: Name of workstation for plots like "X11", "pdf" etc.
DESIRED_LEVELS	: Pressure levels (in hPa) for plotting diagnostics
DESIRED_SCORES	: Diagnostics like "RMSE", "BIAS" or "ABIAS"
EXP_LINES_COLORS	: Color sequence for various experiments.
VERIFY_DATE_RANGE	: String to specify title for X-axis

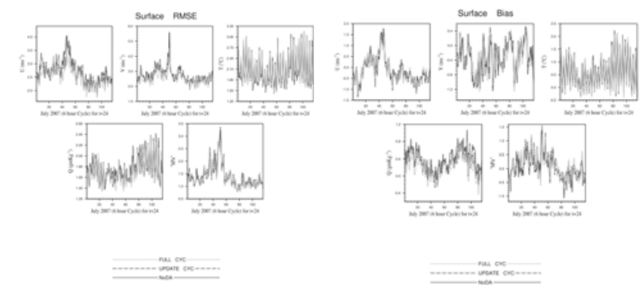
Verif_obs_plot output

In RUN_DIR, following graphics will be generated for each of the desired scores (RMSE, BIAS, ABIAS)

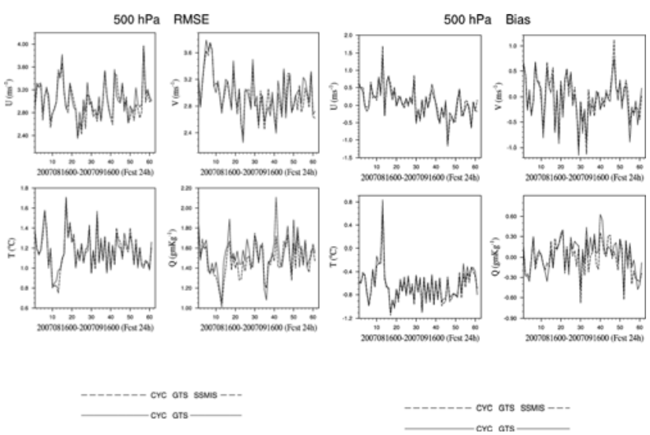
- **Time series for surface and all the desired upper air levels**
- **Vertical profiles**
- **Time Average for surface and all the upper air levels (Histograms)**

```
-rw-r--r--   1 rizvi   ncar      597691 Oct 13 12:49 Time_Series_SFC_RMSE.pdf
-rw-r--r--   1 rizvi   ncar      291856 Oct 13 12:49 Time_Series_SFC_BIAS.pdf
-rw-r--r--   1 rizvi   ncar      319570 Oct 13 12:49 Time_Series_SFC_ABIAS.pdf
-rw-r--r--   1 rizvi   ncar     1571714 Oct 13 12:49 Time_Series_UPA_RMSE.pdf
-rw-r--r--   1 rizvi   ncar      753440 Oct 13 12:49 Time_Series_UPA_BIAS.pdf
-rw-r--r--   1 rizvi   ncar      769452 Oct 13 12:49 Time_Series_UPA_ABIAS.pdf
-rw-r--r--   1 rizvi   ncar      463151 Oct 13 12:49 Profile_RMSE.pdf
-rw-r--r--   1 rizvi   ncar      467553 Oct 13 12:49 Profile_BIAS.pdf
-rw-r--r--   1 rizvi   ncar    12769280 Oct 13 14:54 Profile_ABIAS.pdf
-rw-r--r--   1 rizvi   ncar      129469 Oct 13 12:49 Time_Average_SFC_RMSE.pdf
-rw-r--r--   1 rizvi   ncar      136679 Oct 13 12:49 Time_Average_SFC_BIAS.pdf
-rw-r--r--   1 rizvi   ncar      142219 Oct 13 12:49 Time_Average_SFC_ABIAS.pdf
-rw-r--r--   1 rizvi   ncar      352928 Oct 13 12:49 Time_Average_UPA_RMSE.pdf
-rw-r--r--   1 rizvi   ncar      402740 Oct 13 12:49 Time_Average_UPA_BIAS.pdf
-rw-r--r--   1 rizvi   ncar      365264 Oct 13 12:49 Time_Average_UPA_ABIAS.pdf
```

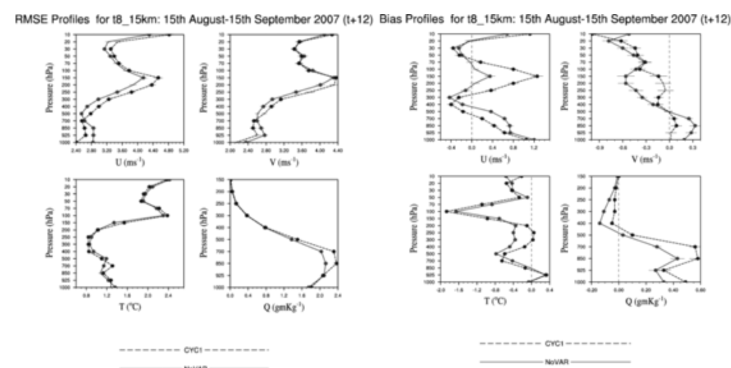

Verif_obs_plot -- Surface Time Series



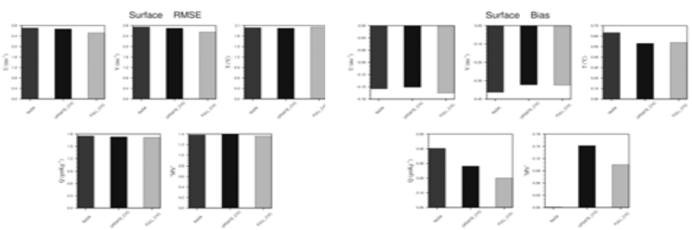
Verif_obs_plot -- Upper air Time Series



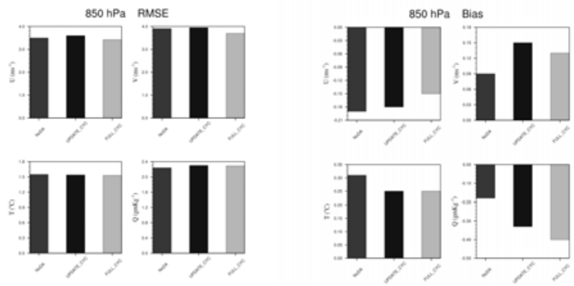
Verif_obs_plot -- Profile



Verif_obs_plot -- Surface Time Average



Verif_obs_plot -- Upper air Time Average



How to run verification against Analysis?

- **Each experiment forecasts needs to be arranged in separate directories with date-wise sub-directories**
- **By executing “var/script/da_verif_anal_plot.ksh” via a suitable wrapper script will generate the desired graphics in RUN_DIR**

Wrapper for da_verif_anal_plot

Important variables:

WRFVAR_DIR	**: Main WRFDA directory (full path)**
REG_DIR	**: Directory holding forecast sub-directories for each experiment**
RUN_DIR	**: Directory where plots will be generated**
NUM_EXPT	**: Total number of experiments (Currently maximum 10)**
EXP_DIR	**: Experiment directory names as they exist in REG_DIR (blank separated)**
EXP_NAMES	**: Experiment names as they exist in REG_DIR (blank separated)**
EXP_LEGENDS	**: Legend string for each experiments (comma separated)**
DESIRED_LEVELS	**: Legend string for each experiments (comma separated)**
DESIRED_SCORES	**: Diagnostics like "RMSE", "BIAS" or "ABIAS"**
START_DATE	**: Starting date ("YYYYMMDDHH") for verification**
END_DATE	**: Ending date ("YYYYMMDDHH") for verification**
INTERVAL	**: Time interval (in hours) for incrementing date/time**
VERIFY_HOUR	**: Verification hour**
CONTROL_EXP_DIR	**: Directory name for verifying analysis**

VERIFY_ITS_OWN_ANALYSIS	**: Set “true” or “false” if each experiment is going to be verified against its own analysis or against a fixed analysis in “CONTROL_EXP_DIR”**
VERIFICATION_FILE_STRING	**: It should be “wrfout” or “wrfinput” depending on what is available**
VERIFY_DATE_RANGE	**: String to specify X-axis title**
PLOT_WKS	**: Name of workstation for plots like "X11", "pdf" etc.**

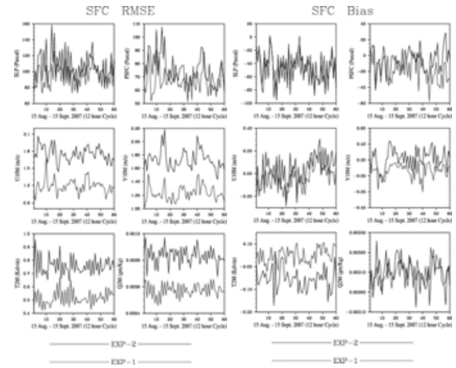
Verif_anal_plot output

In RUN_DIR, following graphics will be generated for each of the the desired scores (RMSE, BIAS, ABIAS)

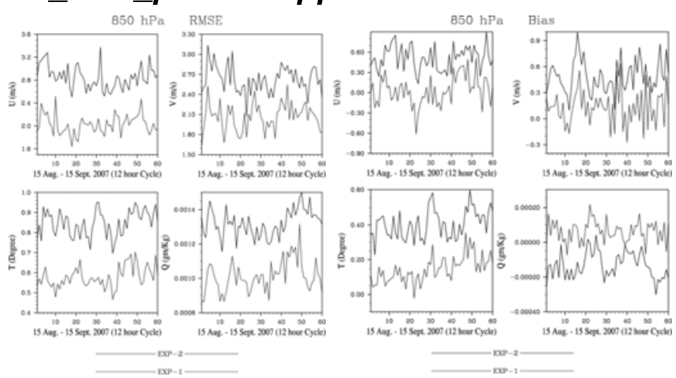
- **Time series for surface fields (U10, V10, T2, Q2 & Psfc)**
- **Time series for upper air fields (U, V, T & Q) for the desired levels**
- **Upper air profiles for U, V, T & Q**
- **Time average for surface and upper air fields for the desired levels (Histogram)**

```
-rw-r--r--   1 rizvi   ncar      235624 Dec 31 15:14 Time_Series_UPA_RMSE-850-hr24.pdf
-rw-r--r--   1 rizvi   ncar      237504 Dec 31 15:14 Time_Series_UPA_BIAS-850-hr24.pdf
-rw-r--r--   1 rizvi   ncar      183367 Dec 31 15:14 Time_Series_UPA_RMSE-200-hr24.pdf
-rw-r--r--   1 rizvi   ncar      173293 Dec 31 15:14 Time_Series_UPA_BIAS-200-hr24.pdf
-rw-r--r--   1 rizvi   ncar      322432 Dec 31 15:14 Time_Series_SFC_RMSE-hr24.pdf
-rw-r--r--   1 rizvi   ncar      325796 Dec 31 15:14 Time_Series_SFC_BIAS-hr24.pdf
-rw-r--r--   1 rizvi   ncar      100323 Dec 31 15:14 Time_Average_UPA_RMSE-850-hr24.pdf
-rw-r--r--   1 rizvi   ncar      112711 Dec 31 15:14 Time_Average_UPA_BIAS-850-hr24.pdf
-rw-r--r--   1 rizvi   ncar       71525 Dec 31 15:14 Time_Average_UPA_RMSE-200-hr24.pdf
-rw-r--r--   1 rizvi   ncar       81035 Dec 31 15:14 Time_Average_UPA_BIAS-200-hr24.pdf
-rw-r--r--   1 rizvi   ncar      163671 Dec 31 15:14 Time_Average_SFC_RMSE-hr24.pdf
-rw-r--r--   1 rizvi   ncar      182593 Dec 31 15:14 Time_Average_SFC_BIAS-hr24.pdf
-rw-r--r--   1 rizvi   ncar      237409 Dec 31 15:14 Profile_RMSE-hr24.pdf
-rw-r--r--   1 rizvi   ncar      238775 Dec 31 15:14 Profile_BIAS-hr24.pdf
```

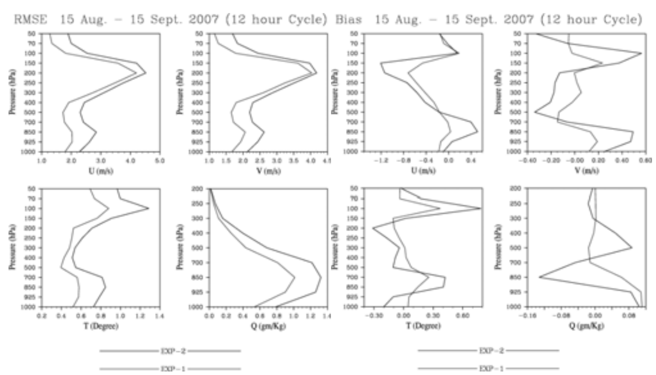

Verif_anal_plot -- Surface Time Series



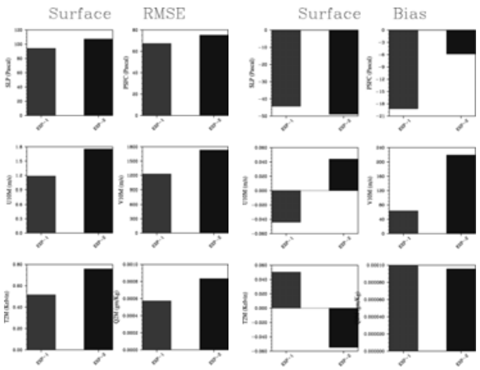
Verif_anal_plot -- Upper air Time Series



Verif_anal_plot -- Profile

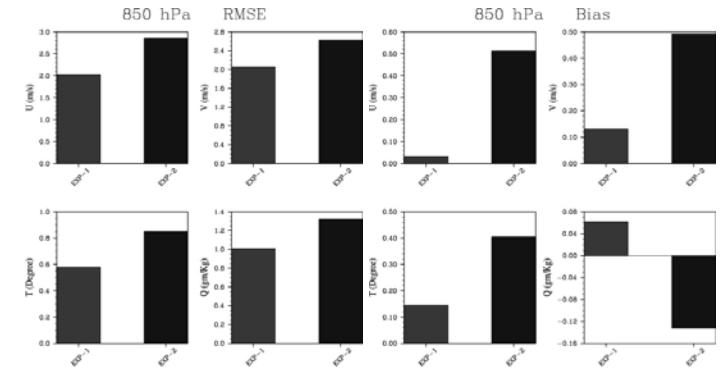


Verif_anal_plot -- Surface Time Average



WRF-Var Tutorial Syed RH Rizvi

Verif_anal_plot -- Upper air Time Average



WRF-Var Tutorial Syed RH Rizvi

Satellite Data

Satellite Data Assimilation in WRF-Var

Tom Auligné, Hui-Chuan Lin, Zhiquan Liu,
Hans Huang, Syed Rizvi, Hui Shao, Meral Demirtas, Xin Zhang

National Center for Atmospheric Research

Work supported by AFWA, NASA, NSF, KMA

Collaborations... but no support :-(

Outline

- Basic concepts of satellite data assimilation
- Satellite DA in WRF-Var + impact studies
- Practical issues: current status on satellite work
- Conclusions

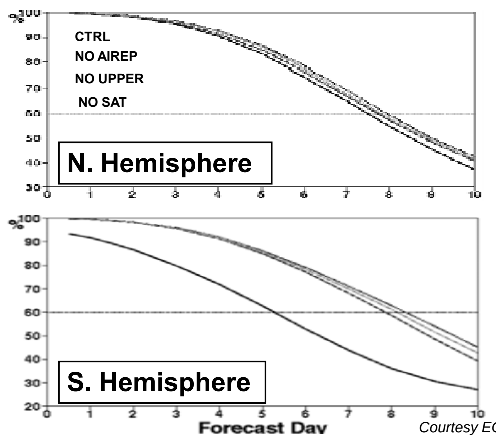
Basic Concepts

Why should I care about satellites?

Basic Concepts: Satellite Impact

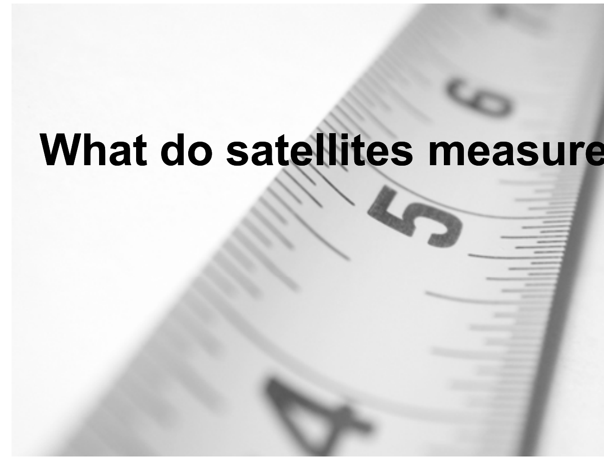
Satellites = main source of information within observing network for NWP

4-month Observing System Experiments (OSEs)



Courtesy ECMWF

Basic Concepts



What do satellites measure?

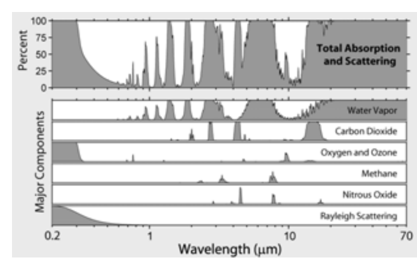
Basic Concepts: Satellites measure…

- ♠ Temperature / Humidity / Ozone profiles 
- ♥ Surface Temperature / Emissivity / Albedo 
- ♦ Wind 
- ♣ Radiance / Radio Signal 

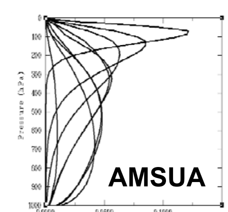
Basic Concepts: Radiative Transfer

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz}\right] dz \quad + \text{ Surface } + \text{ Cloud/rain}$$

- $L(\nu)$: TOA radiance at frequency □
- $B(\nu, T(z))$: Planck function
- $\frac{d\tau(\nu)}{dz}$: Atmospheric absorption
- Surface: Emission/reflection
- Cloud/rain: Diffusion/scattering



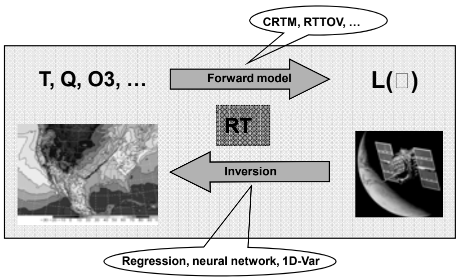
- Temperature information derived from well-mixed absorbents (CO_2, …)
- Channels sensitive to Humidity, Ozone, …
- Surface channels: "window" parts of spectrum



Basic Concepts: Radiative Transfer

$$L(\nu) = \int_0^\infty B(\nu, T(z)) \left[\frac{d\tau(\nu)}{dz} \right] dz + \text{Surface} + \text{Cloud/rain}$$

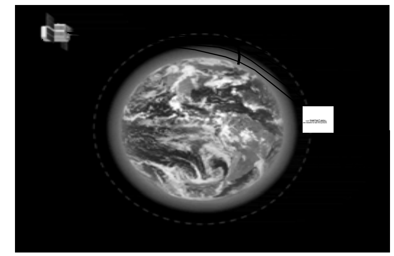
TOA radiance at frequency — Planck function — Atmospheric absorption — Emission/reflection — Diffusion/scattering



Basic Concepts: GPS Radio Occultation

The ray path of a transmitted radio signal during an occultation is bent due to the atmospheric refraction related to the atmospheric state (T, p and q) in neutral atmosphere.

Constellation Observing System for Meteorology, Ionosphere & Climate (COSMIC)



Features of measurements
- high vertical resolution
- all-weather
- unbiased
- coarse horizontal resolution
- multi-path problem in lower levels

Outline

Basic concepts of satellite data assimilation

Satellite DA in WRF-Var + impact studies

Practical issues: current status on satellite work

Conclusions

Satellite DA: WRF-Var capabilities

- **Retrievals (T / Q profiles)**
  - SATEM (from AMSU)
  - AIRS retrievals (NASA version 5)
- **GPS Radio Occultation**
  - Retrieved refractivity from COSMIC
- **Winds**
  - Retrieved winds: polar MODIS, SATOB
  - Active sensors: Quikscat
- **Radiances** (BUFR format from NCEP/NRL/AFWA/NESDIS)
  - **HIRS** from NOAA16, 17, 18
  - **AMSU-A** from NOAA15, 16, 18, EOS-Aqua, METOP-2
  - **AMSU-B** from NOAA15, 16, 17
  - **MHS** from NOAA18, METOP-2
  - **AIRS** from EOS-Aqua
  - **SSMIS** from DMSP16

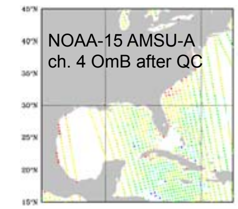
Satellite DA: WRF-Var capabilities

- **Radiative Transfer Model**
  CRTM (**C**ommunity **R**adiative **T**ransfer **M**odel)
  JCSDA (Joint Center for Satellite Data Assimilation)
  ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/
  Latest released version: CRTM REL-1.2_beta, September 2008
  Version used in WRF-Var: CRTM REL-1.1
  Documentation still under development

  RTTOV (**R**adiative **T**ransfer for **TOVS**)
  EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites)
  http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/index.html
  Latest released version: RTTOV_9_2, July 2008
  Version used in WRF-Var: RTTOV_8_7 (with a small bug fix)

- **Radiance monitoring tools**

Case Study: Hurricane Katrina

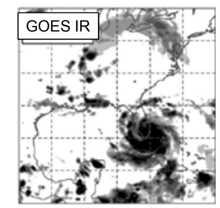


12km51L, model top 10mb

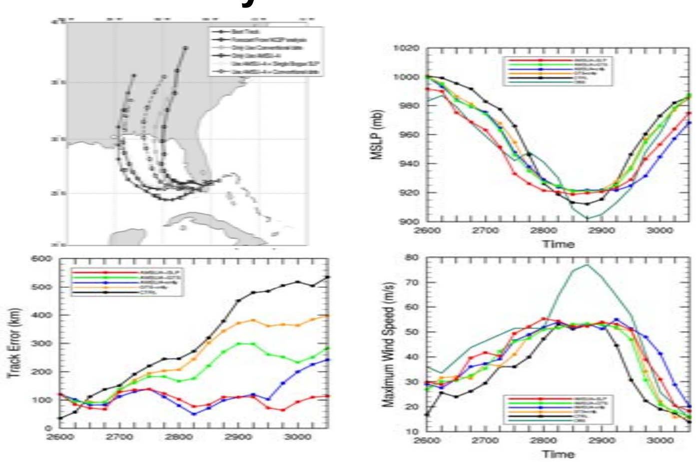
RTTOV Radiative Transfer Model

AMSU-A assimilated
Ch. 1~4 over sea
Ch. 5~10 both over sea and land

Pixels over precipitating area rejected

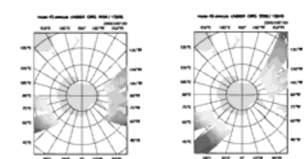


Case Study: Hurricane Katrina

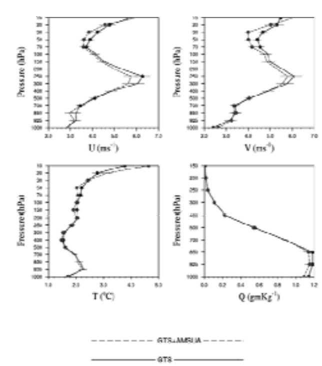


Impact study: Antarctic Region

- 60km horizontal resolution
- 57 vertical levels, model top = 10mb
- Full cycling expt for 14 days
  (1 ~ 14 October 2006)
- NOAA 15/16/18 AMSUA ch. 4~9



RMSE: 36h forecast *vs.* Radiosondes



Outline

Basic concepts of satellite data assimilation

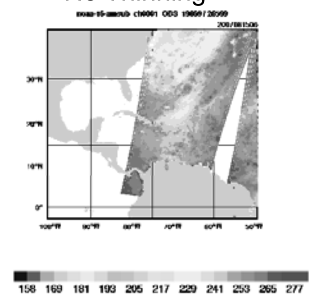
Satellite DA in WRF-Var + impact studies

Practical issues: current status on satellite work

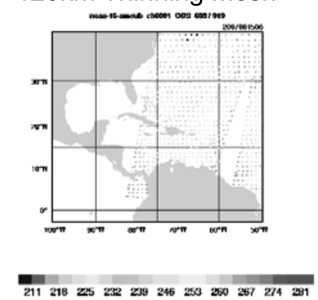
Conclusions

Practical issues: Thinning

No Thinning

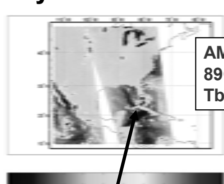


120km Thinning Mesh



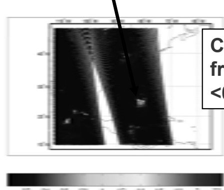
Practical issues: Quality Control

- **Specific QC for each sensor**
  AMSU-A, AMSU-B, MHS, SSMIS, AIRS
- **Pixel-level QC**
  - Reject **limb** observations
  - Reject pixels over **land** and **sea-ice**
  - **Cloud/Precipitation** detection
  - **Synergy** with imager (AIRS/VIS-NIR)
- **Channel-level QC**
  - **Gross check** (innovations <15 K)
  - **First-guess check** (innovations < $3\sigma_o$).
- **Observation error tuning**
  - Error factor tuned from objective method
    (Desrozier and Ivanov, 2001)



AMSU-B
89GHz-150GHz
Tb < 3K

Katrina Location (2005/08/26/06Z)



CLWP(mm)
from Guess
<0.2mm

Practical issues: Bias Correction

Modeling of errors in satellite radiances:

$$y = H(x_t) + B(\beta) + \varepsilon$$

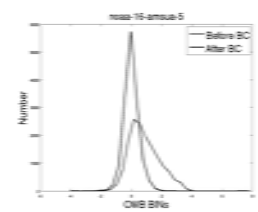
$$\begin{cases} \langle \varepsilon \rangle = 0 \\ B(\beta) = \sum_{i=1}^{N} \beta_i p_i \end{cases}$$

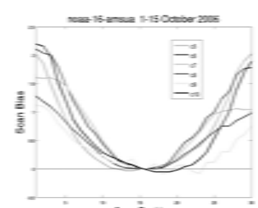
Parameters

Predictors:
- Offset
- 1000-300mb thickness
- 200-50mb thickness
- Surface skin temperature
- Total column water vapor
- Scan

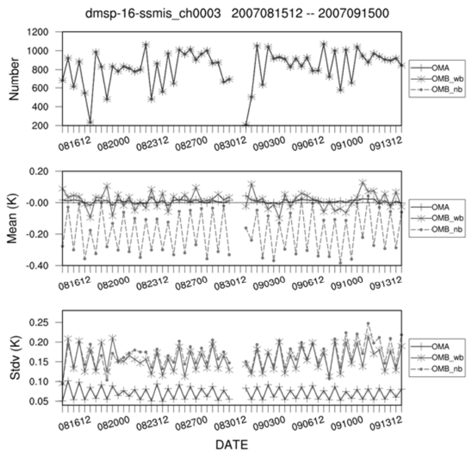
"Offline" bias correction

"Variational" bias correction





Practical issues: Bias Correction

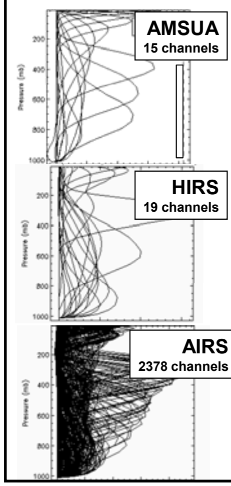


------ Observation minus Background BEFORE bias correction

------ Observation minus Background AFTER bias correction

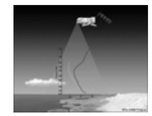
------ Observation minus Analysis

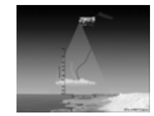
Practical issues: AIRS Cloud Detection

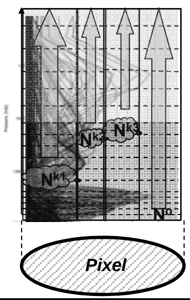


From « hole hunting » (identifying clear pixels)…

… to identifying clear channels (insensitive to the cloud).

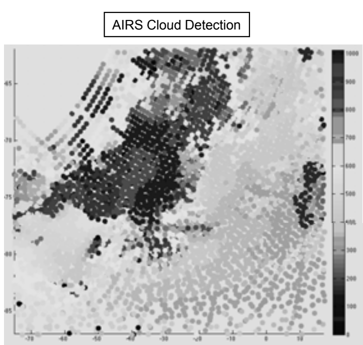


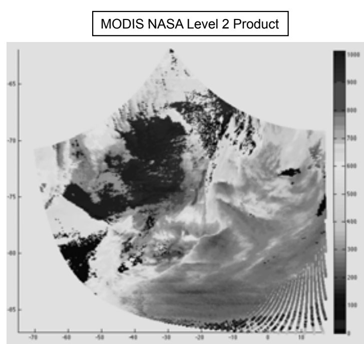




Cloud fractions N^k are ajusted **variationally** to fit observations.

Practical issues: AIRS Cloud Detection





Cloud Top Pressure (hPa)

Outline

Basic concepts of satellite data assimilation

Satellite DA in WRF-Var + impact studies

Practical issues: current status on satellite work

Conclusions

Conclusions

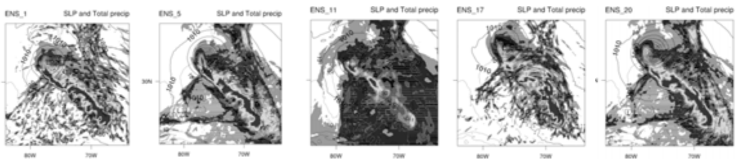
- **Satellite data are important**
  - Major source of information within observations for global NWP
  - Positive impact on Limited Area Models
- **Satellite assimilation is not trivial**
  - Very easy to degrade the analysis!
  - Each sensor requires a lot of attention (observation operator, bias correction, QC, observation error, cloud/rain detection, …)
- **It's only the beginning…**
  - New generation of satellite instruments
  - Future developments will increase satellite impact
    - Better representation of surface emissivity over land
    - Use of cloudy/rainy radiances
    - ……………………………………………………

Conclusions: Steps for Collaboration

- **Get familiar with WRF-Var code**
  - Run test cases
  - Run your Control expt, assimilating conventional data
- **Plan your satellite experiments**
  - Sensors of interest for your application
  - Ways to get data and corresponding format
  - Potential code developments
- **Contact NCAR/MMM developers**
  - Zhiquan Liu: liuz@ucar.edu
  - Tom Auligné: auligne@ucar.edu
  - Hans Huang: huangx@ucar.edu

Ensemble

Ensemble Kalman Filters for WRF-ARW



Chris Snyder
MMM and IMAGe
National Center for Atmospheric Research

Preliminaries

Notation:

- **x** = model's state w.r.t. some discrete basis, e.g. grid-pt values
- **y** = **Hx** + ε = vector of observations with random error ε
- Superscript *f* denotes forecast quantities, superscript *a* analysis, e.g. $\mathbf{x}^f$
- $\mathbf{P}^f$ = Cov($\mathbf{x}^f$) = forecast covariance matrix … a.k.a. **B** in Var

The Kalman Filter (KF)

Assume

- $\mathbf{x}^t \sim N(\bar{\mathbf{x}}^f, \mathbf{P}^f)$; Gaussian forecast errors
- $\epsilon \sim N(\mathbf{0}, \mathbf{R})$; Gaussian observation errors

KF analysis implements Bayes rule for Gaussians

- analysis equations:

$$\bar{\mathbf{x}}^a = \bar{\mathbf{x}}^f + \mathbf{K}(\mathbf{y} - \mathbf{H}\bar{\mathbf{x}}^f) \quad ; \quad \mathbf{P}^a = (\mathbf{I} - \mathbf{KH})\mathbf{P}^f,$$

- Kalman gain

$$\mathbf{K} = \mathbf{P}^f\mathbf{H}^T(\mathbf{H}\mathbf{P}^f\mathbf{H}^T + \mathbf{R})^{-1}$$

Computationally difficult unless problem is small

- $\mathbf{P}^f$, $\mathbf{P}^a$ are $N_x \times N_x$, w/ $N_x = \dim \mathbf{x}$

Ensemble Kalman Filter (EnKF)

EnKF analysis step

- As in KF analysis step, but uses sample (ensemble) estimates for covariances
- e.g. one element of $\mathbf{P}^f\mathbf{H}^T$ is

$$\mathrm{Cov}(x^f, y^f) = N_e^{-1}\sum(x_i^f - \mathrm{mean}(x))(y_i^f - \mathrm{mean}(y^f))$$

  where $y^f = \mathbf{H}\mathbf{x}^f$ is the forecast, or prior, observation.
- Output of EnKF analysis step is ensemble of analyses

EnKF forecast step

- Each member integrated forward with full nonlinear model
- Monte-Carlo generalization of KF forecast step

Relation of Var and KF

Analysis equations

- Variational: compute $\mathbf{x}^a$ as minimizer of

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x}^f)(\mathbf{P}^f)^{-1}(\mathbf{x} - \mathbf{x}^f)^T + (\mathbf{y}^o - \mathbf{Hx})\mathbf{R}^{-1}(\mathbf{y}^o - \mathbf{Hx})^T$$

- Kalman filter,

$$\mathbf{x}^a = \mathbf{x}^f + \mathbf{K}(\mathbf{y}^o - \mathbf{Hx}^f), \quad \mathbf{K} = \mathbf{P}^f\mathbf{H}^T(\mathbf{HP}^f\mathbf{H}^T + \mathbf{R})^{-1}$$

These are equivalent

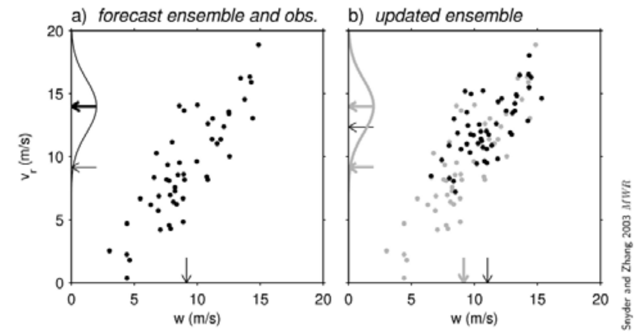
… as long as $\mathbf{P}^f$ and **R** are the same in both systems

EnKF Analysis/Update

Example: update w given v_r observation

- calculate $v_r^f = \mathbf{Hx}^f$ for each member and $d = \mathrm{Var}(v_r^f) + \mathbf{R}$
- update w via

$$w^a = w^f + (\mathrm{Cov}(w^f, v_r^f)/d)(v_r^o - v_r^f + \epsilon), \quad \epsilon \sim N(0, \mathbf{R})$$



Flavors of EnKF

ETKF

- $\mathbf{P}^f$ is sample covariance from ensemble
- Analysis increments lie in ensemble subspace
- Computationally cheap--reduces to N_x x N_x matrices
- Useful for EF but not for DA: In Var "hybrid" system, ETKF updates ensemble deviations but **not** ensemble mean

"Localized" EnKF

- Cov(y,x) assumed to decrease to zero at sufficient distances
- Reduces computations and allows increments outside ensemble subspace
- $\exists$ approximate equivalence with α-CV option in Var--different way of solving same equations
- Numerous variants; DART provides several with interfaces for WRF

Data Assimilation Research Testbed (DART)

DART is general software for ensemble filtering:

- Assimilation scheme(s) are independent of model
- Interfaces exist for numerous models: WRF (including global and single column), CAM (spectral and FV), MOM, ROSE, others
- See http://www.image.ucar.edu/DAReS/DART/

Parallelization

- Forecasts parallelized at script level as separate jobs; also across processors, if allowed by OS
- Analysis has generic parallelization, independent of model and grid structure

WRF/DART

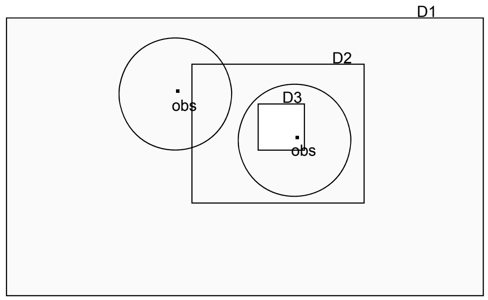
Consists of:
- Interfaces between WRF and DART (e.g. translate state vector, compute distances, …)
- Observation operators
- Scripts to generate IC ensemble, generate LBC ensemble, advance WRF

Easy to add fields to state vector (e.g. tracers, chem species)
- Plan to add namelist control of fields in state vector

A few external users (5-10) so far

Nested Grids in WRF/DART

Perform analysis across multiple nests simultaneously
- Innovations calculated w.r.t. finest availble grid
- All grid points within localization radius updated



Var/DART

DART algorithm
- First, calculate "observation priors:" $\mathbf{H}(\mathbf{x}^f)$ for each member
- Then solve analysis equations

Possible to use Var for $\mathbf{H}(\mathbf{x}^f)$, DART for rest of analysis
- Same interface as between Var and ETKF: $\mathbf{H}(\mathbf{x}^f)$ are written by Var to gts_omb_oma files, then read by DART
- Allows EnKF within existing WRF/Var framework, and use of Var observation operators with DART
- Under development

Some Applications

Radar assimilation for convective scales
- Altug Aksoy (NOAA/HRD) and David Dowell (NCAR)

Assimilation of surface observations
- Dowell
- Also have single-column version of WRF/DART from Josh Hacker (NCAR)

Tropical cyclones
- Ryan Torn (SUNY-Albany), Yongsheng Chen (York), Hui Liu (NCAR)

GPS occultation observations
- Liu

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http://www.mmm.ucar.edu/people/snyder/papers/

WRF 4D-Var

WRF 4D-Var System
(Will be released soon)

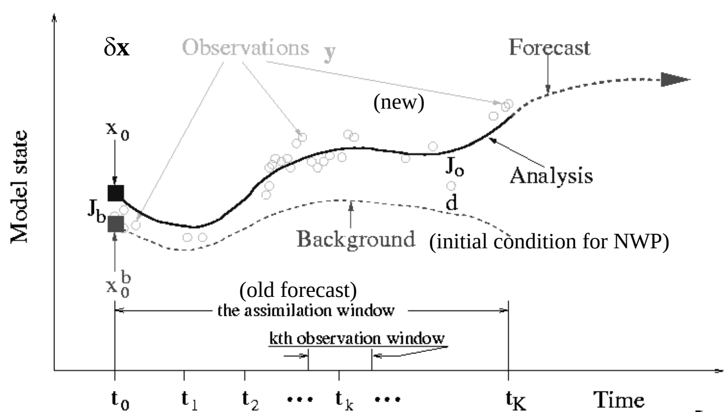
Xin Zhang, Xiang-Yu Huang
Qingnong Xiao, Zaizhong Ma, John Michalakes, Tom Henderson and Wei Huang

MMM Division
National Center for Atmospheric Research
Boulder, Colorado, USA

Contents

- Current status of WRF 4D-Var
- Scientific Performance of WRF 4D-Var
- Software Engineering Performance of WRF 4D-Var
- On-going Works

4D Variational Data Assimilation



Current Status of WRF 4D-Var

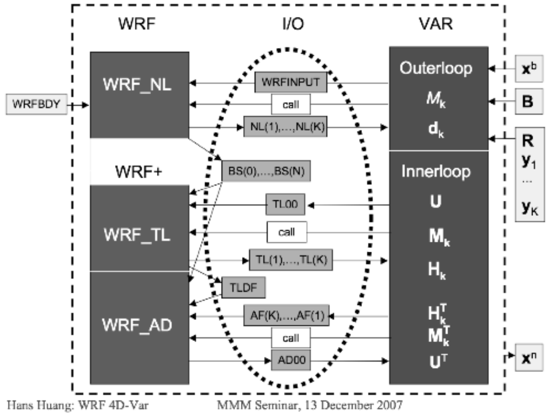
Black – WRF-3DVar [$\mathbf{B}$, $\mathbf{R}$, $\mathbf{U}=\mathbf{B}^{1/2}$, $\mathbf{v}^n=\mathbf{U}^{-1}(\mathbf{x}^n-\mathbf{x}^{n-1})$]
Green – modification required
Blue – existing (for 4DVar)--WRF
Red – new development

$$J'_{\mathbf{v}n} = \mathbf{v}^n + \sum_{i=1}^{n-1} \mathbf{v}^i + \mathbf{U}^T\mathbf{S}_{V\text{-}W}{}^T \sum_{k=1}^{K} \mathbf{M}_k{}^T\mathbf{S}_{W\text{-}V}{}^T\mathbf{H}_k{}^T\mathbf{R}^{-1}[\mathbf{H}_k\mathbf{S}_{W\text{-}V}\mathbf{M}_k\mathbf{S}_{V\text{-}W}\mathbf{U}^{-1}\mathbf{v}^n + H_k(M_k(\mathbf{x}^{n-1})) - \mathbf{y}_k]$$

WRF AD WRF TL ARW WRF

(Huang, et.al. 2006: Preliminary results of WRF 4D-Var. WRF users' workshop, Boulder, Colorado.)

Basic system: 3 exes, disk I/O, parallel, full dyn, simple phys, JcDF



Scientific Performance of WRF 4D-Var

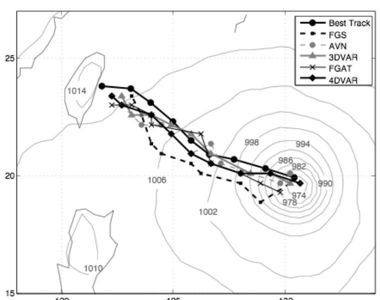
Typhoon Haitang experiments:

5 experiments, every 6 h, 00Z 16 July - 00 Z 18 July, 2005.
Typhoon Haitang hit Taiwan 00Z 18 July 2005

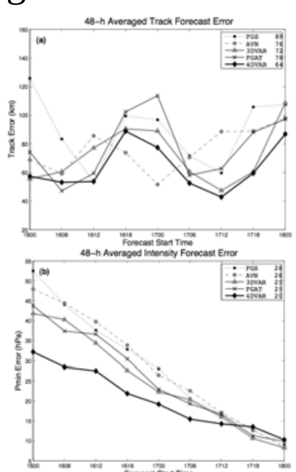
1. FGS – forecast from the background [The background fields are 6-h WRF forecasts from NCEP GFS analysis.]
2. AVN – forecast from the NCEP GFS analysis
3. 3DVAR – forecast from WRF 3D-Var
4. FGAT – first guess at appropriate time (A option of WRF-3DVAR)
5. 4DVAR – forecast from WRF 4D-Var

Domain size: 91x73x17
Resolution: 45 km
Time Window: 6 Hours,
Observations: GTS conventional observations, bogus data from CWB

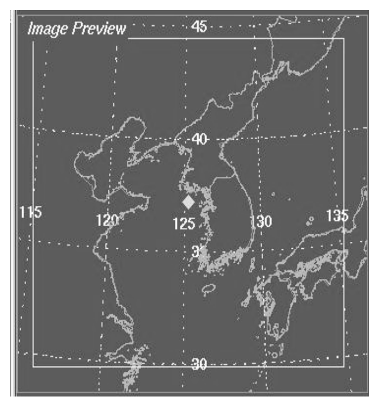
Typhoon Haitang Verification



48-h forecast typhoon tracks from FGS, AVN, 3DVAR, FGAT, 4DVAR, together with the observed best track. Forecasts are all started from 0000 UTC 16 July 2005.

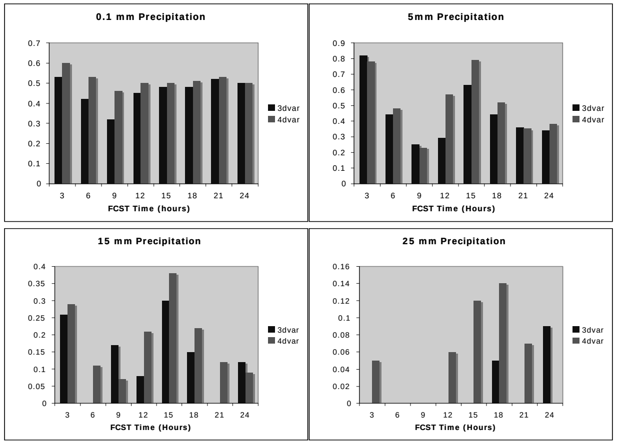


KMA Heavy Rain Case



- **Period**: 12 UTC 4 May - 00 UTC 9 May, 2006
- **Grid** : (60,54,31)
- **Resolution** : 30km
- **Domain size**: the same as the operational 10km do-main.
- **Assimilation window**: 6 hours
- Warm started cycling run

Precipitation Verification



The first radar data assimilation experiment using WRF 4D-Var (OSSE)

Yong-Run Guo

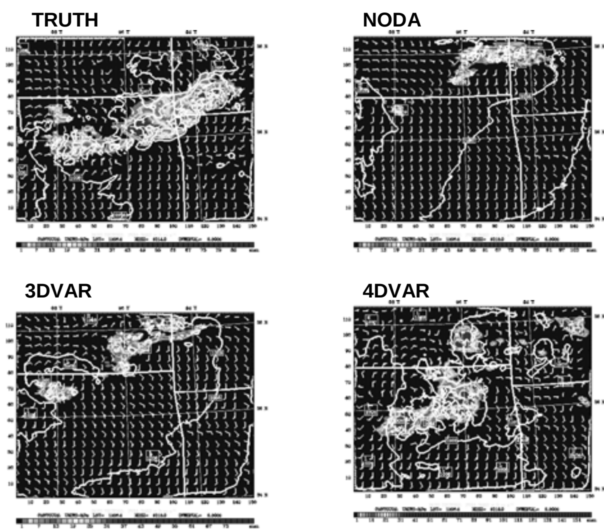
TRUTH ----- Initial condition from TRUTH (13-h forecast initialized at 2002061212Z from AWIPS 3-h analysis) run cutted by ndown**,** boundary condition from NCEP GFS data.

NODA ----- Both initial condition and boundary condition from NCEP GFS data.

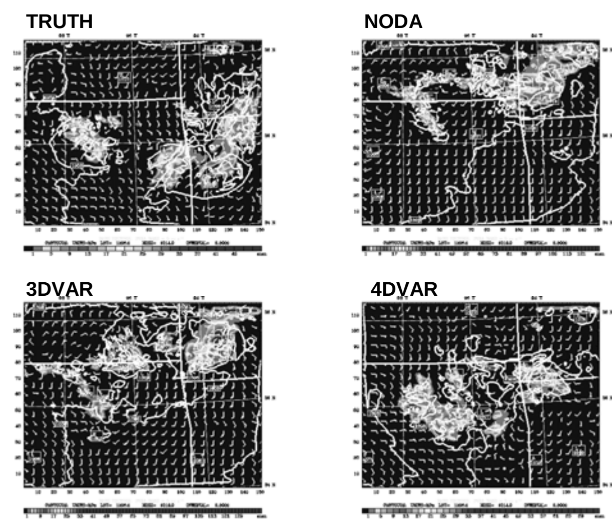
3DVAR ----- 3DVAR analysis at 2002061301Z used as the initial condition, and boundary condition from NCEP GFS. Only Radar radial velocity at 2002061301Z assimilated (total # of data points = 65,195).

4DVAR ----- 4DVAR analysis at 2002061301Z used as initial condition, and boundary condition from NCEP GFS. The radar radial velocity at 4 times: 200206130100, 05, 10, and 15, are assimilated (total # of data points = 262,445).

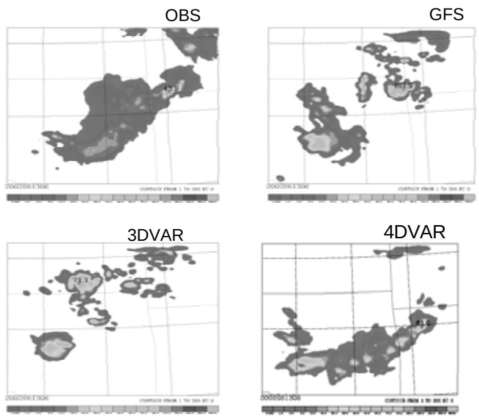
Hourly precipitation ending at 03-h forecast



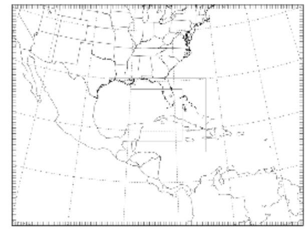
Hourly precipitation ending at 06-h forecast



Real data experiments



IKE----Domain Configuration (From Fuqing Zhang, real time setup)



Period: 2008091000-2008091500

IC is from 6h forecast.

Votex following moving nest domains:

D1: 160x121x35, 40.5 km

D2: 160x121x35, 13.5 km (moving domain from beginning, interpolated from mother domain)

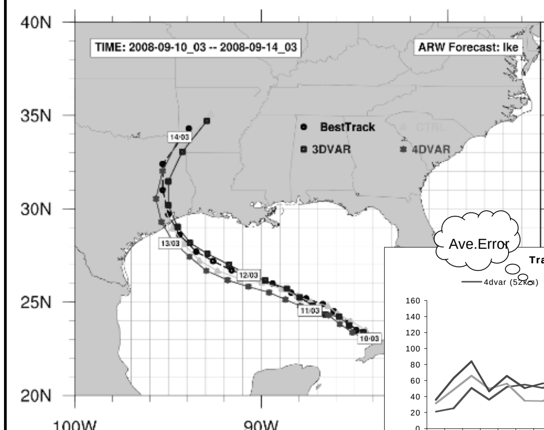
D3: 253x253x35, 4.5 km (moving domain from beginning, interpolated from mother domain)

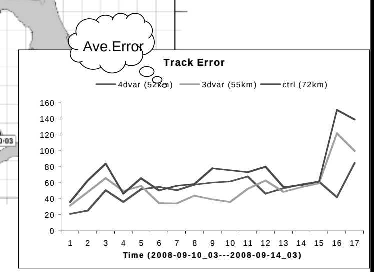
```
&physics
mp_physics             = 6,  6,  6,  6,
ra_lw_physics          = 1,  1,  1,  1,
ra_sw_physics          = 1,  1,  1,  1,
radt                   = 30, 30, 30, 30,
sf_sfclay_physics      = 1,  1,  1,  1,
sf_surface_physics     = 1,  1,  1,  1,
bl_pbl_physics         = 1,  1,  1,  1,
bldt                   = 0,  0,  0,  0,
cu_physics             = 3,  0,  0,  0,
cudt                   = 5,  5,  5,  5,
isfflx                 = 1,
ifsnow                 = 0,
icloud                 = 1,
surface_input_source   = 1,
num_soil_layers        = 5,
maxiens                = 1,
maxens                 = 3,
maxens2                = 3,
maxens3                = 16,
ensdim                 = 144,
/
```


Conventional Obs.

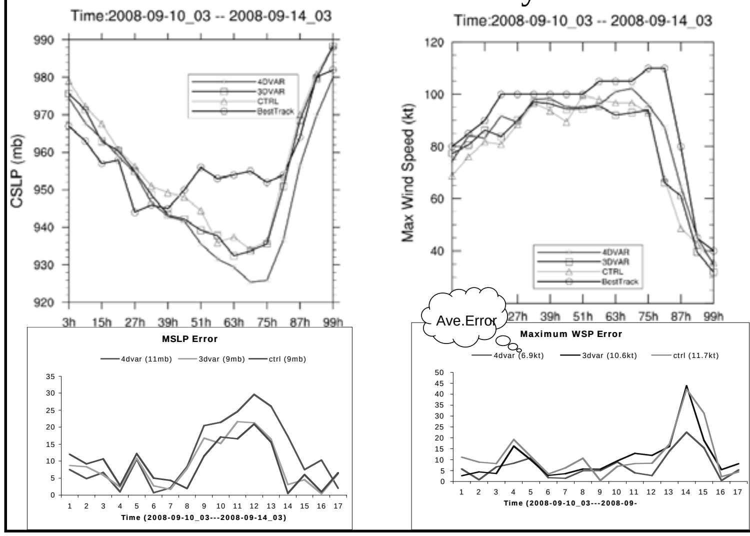
Time	1	2	3	4	5	6	7
Sound	62						
Synop	126						214
Pilot	60						
Satem	62	25					
Geoamv				4175	2168	1452	
Airep	488	16	5			23	81
Gpspw	203	404	200			196	193
Gpsrf		2				2	4
Ships	97	115				106	
Metar	903	643					1178
Qscat							
Profiler	54	6760					
Buoy	642	1277	141		19	1126	634
Sond_sfc	62						

Hurricane Track





Hurricane Intensity

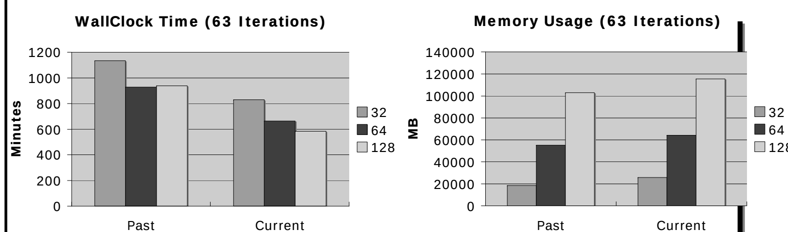


- For general cases, the performance of WRF 4D-Var is comparable with WRF 3D-Var.
- For some fast developing, fine scale cases such as squall line, tropical cyclone, heavy rainfall case , WRF 4D-Var does a much better job than 3D-Var.

Software Engineering Performance of WRF 4D-Var

- Ability to assimilation all kinds of observation as 3D-Var (include Radiance and Radar).
- Both serial and parallel runs are supported.
- Tested Platforms: IBM with XLF, Linux with PGI & G95, Mac G5 with G95 & XLF.
- Flexible assimilation time window (for example, 15 minutes ~ 6 hours)

Computational Efficiency of IKE case on NCAR Bluefire



Past: Before optimization

Current: Eliminate the disk IO for basic states

Timing of a Radar Assimilation Case on IBM blueice

Domain size:151x118x31

Resolution:4km

Time-step: 25s

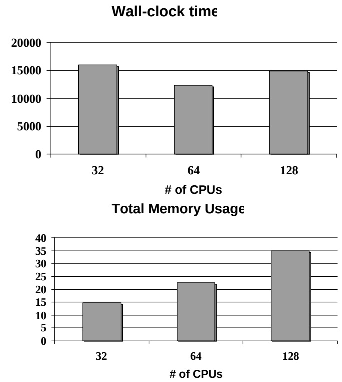
Time window:15m

# of iterations: 60

Obs.: OSSE radar wind

# of obs.: 262517

Obs Freq: 5m



(P5.6 ASSIMILATION OF DOPPLER RADAR DATA WITH WRF 4DVAR FOR A CONVECT IVE CASE. Yong-Run Guo et al. 9th Annual WRF Users' Workshop)

On-going Works

- Remove Disk IO which is used as communication among WRF 4D-Var components, ESMF is a candidate.(~50% wall-clock time reduction, improve parallel scalability)
- Improve the portability.
- Prepare the WRF 4D-Var release with WRF 3.1 in Spring.

WRF-Var Namelists

WRF-Var Namelist

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Hui-Chuan Lin and Hans Huang

WRF-Var Tutorial, Feb 2-4, 2009

- This talk is complementary to the "WRF-Var Setup, Run and Diagnostics" talk.

Namelist - WRFVAR1

- Write_increments
  - .false. : Default
  - .true. : Output analysis increment file "analysis_increments" (analysis-background). The file is a binary file, generated every time you run WRF-Var by using a FORTRAN code given in *WRFVAR/da/da_setup_structures/da_write_increments.inc*.

```
-rw-r--r--    1 huishao  ncar   43271476 Jul  7 16:27 analysis_increments
lrwxrwxrwx    1 huishao  ncar         32 Jul  7 16:27 be.dat -> /ptmp/huishao/tutorial/be/be.dat
-rw-r--r--    1 huishao  ncar       1600 Jul  7 16:27 check_max_iv
-rw-r--r--    1 huishao  ncar        313 Jul  7 16:27 cost_fn
```

✓ You could still produce your own analysis increment file by extracting first guess from analysis files (both in netcdf format). The advantage of using this "analysis_increment" is to avoid spurious increments (because it is generated directly from the code without including the first guess).

Namelist - WRFVAR1

- Print_detail_*
  - .false. : Default
  - .true. : Output extra diagnostics

Example: print_detail_grad=.true.

Iteration 0

```
jo_geoamv          0.118917669698E+03
jo%geoamv_u        0.371704152820E+02
jo%geoamv_v        0.817472544158E+02
jo%total           0.120493680229E+03
…
Calculate grad_v(jo) iter=     0
   cv_jb.cv_jb =     0.00000000000000E+00
   cv_je.cv_je =     0.00000000000000E+00
   xhat.xhat =     0.00000000000000E+00
   j_grad.j_grad =     0.93533513206338E+02
Calculate grad_v(j) iter=     0
   cv_jb.cv_jb =     0.00000000000000E+00
    cv_je.cv_je =     0.00000000000000E+00
   xhat_jb.xhat_jb =     0.00000000000000E+00
   xhat_je.xhat_je =     0.00000000000000E+00
   cv_xhat_jp.cv_xhat_jp = 0.00000000000000E+00
   j_grad.j_grad =     0.93533513206338E+02
```

Iteration 19

```
Inner iteration stopped after   19 iterations

   jo_geoamv          0.985110326458E+02
   jo%geoamv_u        0.292654551874E+02
   jo%geoamv_v        0.692455774585E+02
   jo%total           0.100697022398E+03
…
Calculate grad_v(jo) iter=    19
   cv_jb.cv_jb =     0.00000000000000E+00
   cv_je.cv_je =     0.00000000000000E+00
   xhat.xhat =     0.11886920460937E+02
   j_grad.j_grad =     0.12125274158977E+02
Calculate grad_v(j) iter=    19
   cv_jb.cv_jb =     0.00000000000000E+00
    cv_je.cv_je =     0.00000000000000E+00
   xhat_jb.xhat_jb =     0.11886920460937E+02
   xhat_je.xhat_je =     0.00000000000000E+00
   cv_xhat_jp.cv_xhat_jp = 0.00000000000000E+00
   j_grad.j_grad =     0.66566955863646E-02
```

Namelist - WRFVAR2

- Analysis_accu
  - 900 (Sec): Default.

  If |analysis time - first guess time| > Analysis_accu, WRF-Var will give a warning like "*Wrong xb time found???*".
- Write_filtered_obs
  - Not used.
  - Please refer to "analysis_type" for outputting filtered observation by WRF-Var (WRF-Var internal QC procedure).

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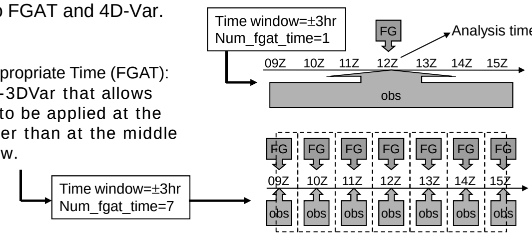
Namelist - WRFVAR3

- Fg_format: Format of the first guess of WRF-Var.
  - 1 = WRF-ARW: Default (recommended).
- Num_fgat_time: Number of data time windows (slots) used in WRF-Var.
  - 1 = 3DVAR: Default.
  - >1 apply to FGAT and 4D-Var.

✓ First-Guess at Appropriate Time (FGAT): An option in WRF-3DVar that allows the observations to be applied at the correct time, rather than at the middle of the time window.



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Namelist - WRFVAR4

- Use_obs_errfac: Option for using tuned observation error.
  - .false. : Default. At this moment, please use this option.
  - .true. : Use tuned observation error statistics (need to produce errfac.dat beforehand created by da_tune_obs_desrozier.f).

Namelist - WRFVAR5

- Put_rand_seed:
- Omb_set_rand:
- Omb_add_noise:

} For observation error tuning.

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Namelist - WRFVAR5 (Cont.)

- Obs_qc_pointer:
  - 0 : Default, Good data.
  - ✓ For ASCII observation files generated by OBSPROC, QC flag value ranges from -88 to 88 (please refer to the latest QC flags from OBSPROC).
    - qc = -88 : Missing data
    - qc = 0 : Good data
    - qc = -77 : Outside of horizontal domain
    - qc = -15 : Wind direction <0 or > 360 degrees
    - qc = -14 : Negative wind speed vector norm
    - qc = -13 : Null wind speed vector norm
    - qc = -12 : Spike in the wind profile
    - qc = -11 : Null temperature or dew point
    - qc = -10 : Superadiabatic temperature
    - qc = -9 : Spike in Temperature profile
    - qc = -8 : Height higher than model lid's height
    - qc = -5 : h,p or T from standard atmosphere
    - qc = -4 : h,p or T from background
    - qc = 1 : convective adjustement correction
    - qc = 2 : surface_correction
    - qc = 3 : Height recovery from hydrostaic + OBS
    - qc = 4 : Height recovery from reference + OBS
    - qc = 88 : Any other check
  - ✓ For PREBUFR observation files generated by OBSPROC, qc = 0 indicates the best quality (please refer to the latest QC flags from OBSPROC).

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Namelist - WRFVAR5 (Cont.)

- Max_obstype_input: Set to restrict the maximum number of observations used in each type.
  - The restriction is applied when the observations are read, and applies to the total number of observations across all processors before quality control.
  - E.g., max_sound_input=5000: the maximum number of radiosondes is 5000.

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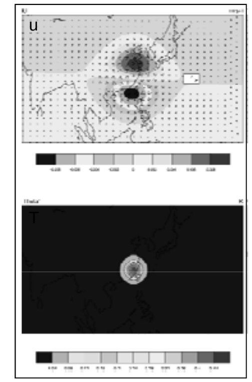
Namelist - WRFVAR7

- Rf_passes: number of passes of recursive filter used in WRF-Var to define the horizontal correlation shape of background errors.
- Var_scaling1(2,…5): The tuning factor of background error covariance for control variables.
  - ✓ Control variables:
    - — 1: stream function
    - — 2: unbalanced velocity potential
    - — 3: unbalanced temperature
    - — 4: Relative humidity
    - — 5: Unbalanced surface pressure
- Len_scaling1(2,…5): The tuning factor of scale-length for control variables.



An example of a pseudo single observation test (PSOT)

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Namelist - WRFVAR8

- Used for debugging purposes.

Namelist - WRFVAR9

- Stdout : 6 (default). Unit number for standard output.
- Stderr : 0 (default). Unit number for error output.
- Warnings_are_fatal: .false.(default). If true, warning messages that would normally allow the program to continue are treated as fatal errors.

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Namelist - WRFVAR9 (Cont.)

The following namelist variables are for tracing:

Tracing gives additional diagnostics about program runs. It does not change results, but does slow the program down, so should be disabled in production environments.

- Trace_use: .true. (default). Use tracing function in WRF-Var if true.
- Trace_unit : Unit number for tracing output.
  - Units 9 and 10 are reserved for reading and writing namelist.input and namelist.output.
- Trace_pe : 0 (default). Currently, statistics are always calculated for all processors, and output by processor 0.
- Trace_all_pes: .false. (default). Trace is output for all pes. As above, this does not change processor statistics.

Trace Output

* Calling Tree
* Local routine timings
* Overall routine timings
* Memory usage

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Namelist - WRFVAR9 (Cont.)

• Trace_repeat_head & trace_repeat_body: 10 (default). The number of times any trace statement will produce output for any particular routine.

✓This stops the trace output being overwhelmed when a routine is called multiple times. Once this limit is reached a 'going quiet' message is written to the trace file, and no more output is produced from the routine, though statistics are still gathered.

• Trace_max_depth: Define the deepest level to which tracing writes output.

- 30 : Default, which means effectively unlimited.

• Trace_memory: .true. (default). If true, calculate allocated memory using a mallinfo call.

✓On some platforms (Cray and Mac), mallinfo is not available and no memory monitoring can be done.

• Trace_csv: .true. (default). The tracing statistics are written to a xxxx.csv file in CSV format.

• Use_html: .true. (default). If true, the tracing and error reporting routines will use HTML tags.

Trace Output

* Calling Tree
* Local routine timings
* Overall routine timings
* Memory usage →

Maximum memory usage for routines

Routine	Max in any PE (kbytes)	Overall (kbytes)	Average per PE (kbytes)
da_transfer_xatoanalysis	508076	15803513	493859
da_transfer_xatowrf	508076	15803513	493859
da_write_increments	508076	15803513	493859
da_deallocate_observations	506698	15761784	492555
da_deallocate_y	506392	15756018	492375

Namelist - WRFVAR10

- Test_transforms:
  - .false. (default): Run data assimilation.
  - .true.: Perform adjoint check for the code debugging.

Namelist - WRFVAR11

- Cv_options_hum:
  - 1 (default): Please do not change.

- Check_rh:
  - 0 : No supersaturation check after minimization.
  - 1: With the supersaturation (rh> 100%) and minimum rh (rh<10%) check, and make the local adjustment of q.
  - 2 (default): With the supersaturation (rh> 95%) and minimum rh (rh<11%) check, and make the multi-level q adjustment under the constraint of integrated water vapor in column conserved.

Namelist - WRFVAR11 (Cont.)

- Set_omb_rand_fac
- Seed_array1
- Seed_array2

} For ensemble perturbation purposes.

The following namelist variables are related to Background Error (BE) computation and should be consistent to those in BE file (be.dat) computed from GEN_BE.

Namelist - WRFVAR11 (Cont.)

- Lat_stats_option: .False. (default). Only set true when be.dat is computed with i-dependence (approximately latitude-dependence) .

Namelist - WRFVAR13

- Vert_corr: 2 (default). Please do not change at this moment.
- Vert_evalue: 1 (default). Please do not change at this moment.
- Max_vert_var1(2,…5): Maximum truncation value (percentage) used in the vertical eigenvector decomposition in BE calculation.

Namelist - WRFVAR14

- Namelist options for radiance data assimilation (not supported).

Namelist - WRFVAR15

- **num_pseudo** = 0 (default). Set the number of pseudo observations. Currently only the value of 1 is allowed, i.e. num_pseudo = 1 --- the SINGLE-OBS test.
- **pseudo_x** = 1.0 (default). Set the x-position (J) of the OBS in units of grid-point.
- **pseudo_y** = 1.0 (default). Set the y-position (I) of the OBS in units of grid-point.
- **pseudo_z** = 1.0 (default). Set the z-position (ZK) of OBS with the vertical level index. In MM5, the top level has z=1, and bottom level, z=kx.
- **pseudo_val** = 1.0 (default). Set the innovation of the OBS variable: u/v at m/s, p at Pa, t at degree, and q at kg/kg.
- **pseudo_err** = 1.0 (default). Set the OBS error of the OBS variable.

Namelist - WRFVAR19

- **pseudo_var** = 't' (default)
  Set the name of the OBS variable:
  'u' = X-direction component of wind,
  'v' = Y-direction component of wind,
  't' = Temperature,
  'p' = Pressure,
  'q' = Specific humidity,
  'pw' = Total precipitable water,
  'ztd' = Zenith tropospheric delay,
  'ref' = Refractivity

The namelist variables here are for pseudo single-observation tests (PSOTs).

Please refer to “WRF-Var Background Error Estimation” talk.

Namelist - WRFVAR16

- For hybrid WRF-Var/Ensemble data assimilation namelist option (Please refer to “Hybrid Data Assimilation System” talk).

Namelist - WRFVAR21/22

- Time_window_min(max): Specify the lower (upper) time values of the assimilation time window.
  - These two values do not have any impact on the observation data (GTS) processed through OBSPROC, since OBSPROC already conducts time check and bundles the observation data within same time window into one file.
  - The radiance data do not go through OBSPROC currently and require the setting of these two variables.

Namelist - WRFVAR23

- Namelist variables related to the 4D-Var penalty term option, which controls the high-frequency gravity waves using a digital filter (Not supported).