



WRFDA Overview

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NCAR/MMM

WRFDA is a Data Assimilation system built within the WRF software framework, used for application in both research and operational environments....

Outline

- What is data assimilation
 - Scalar case
 - Two state variables case
 - General case
- Introduction to WRF Data Assimilation

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- What is data assimilation
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- Introduction to WRF Data Assimilation

What is data assimilation?

- A **statistical** method to obtain the **best** estimate of **state variables**
- In the atmospheric sciences, DA involves combining **model forecast (prior)** and **observations**, along with their respective errors characterization, to produce an ***analysis (Posterior)*** that can initialize a numerical weather prediction model (i.e., WRF)

Scalar Case

- State variable to estimate “ x ”, e.g., consider today’s temperature in Boulder at 12 UTC.
- Now we have a “background” (or “prior”) information x_b of x , which is from a 6-h GFS or WRF forecast initiated from 06 UTC today.
- We also have an **observation** y of x at a surface station in Boulder
- What is the best estimate (**analysis**) x_a of x ?

Scalar Case

- We can simply average them: $x_a = \frac{1}{2}(x_b + y)$
 - This means we trust equally the background and observation.
- But if their accuracy is different and we have some estimation of their errors
 - e.g., for background, we have statistics (e.g., mean and variance) of $x_b - y$ from the past
 - For observation, we have instrument error information from manufacturer

Scalar Case

- Then we can do a weighted mean: $x_a = ax_b + by$ in a least square sense, i.e.,

- Minimize $J(x) = \frac{1}{2} \frac{(x-x_b)^2}{\sigma_b^2} + \frac{1}{2} \frac{(x-y)^2}{\sigma_o^2}$

- Requires $\frac{dJ(x)}{dx} = \frac{(x-x_b)}{\sigma_b^2} + \frac{(x-y)}{\sigma_o^2} = 0$

- Then we can easily get

$$x_a = \frac{\sigma_o^2}{\sigma_b^2 + \sigma_o^2} x_b + \frac{\sigma_b^2}{\sigma_b^2 + \sigma_o^2} y$$

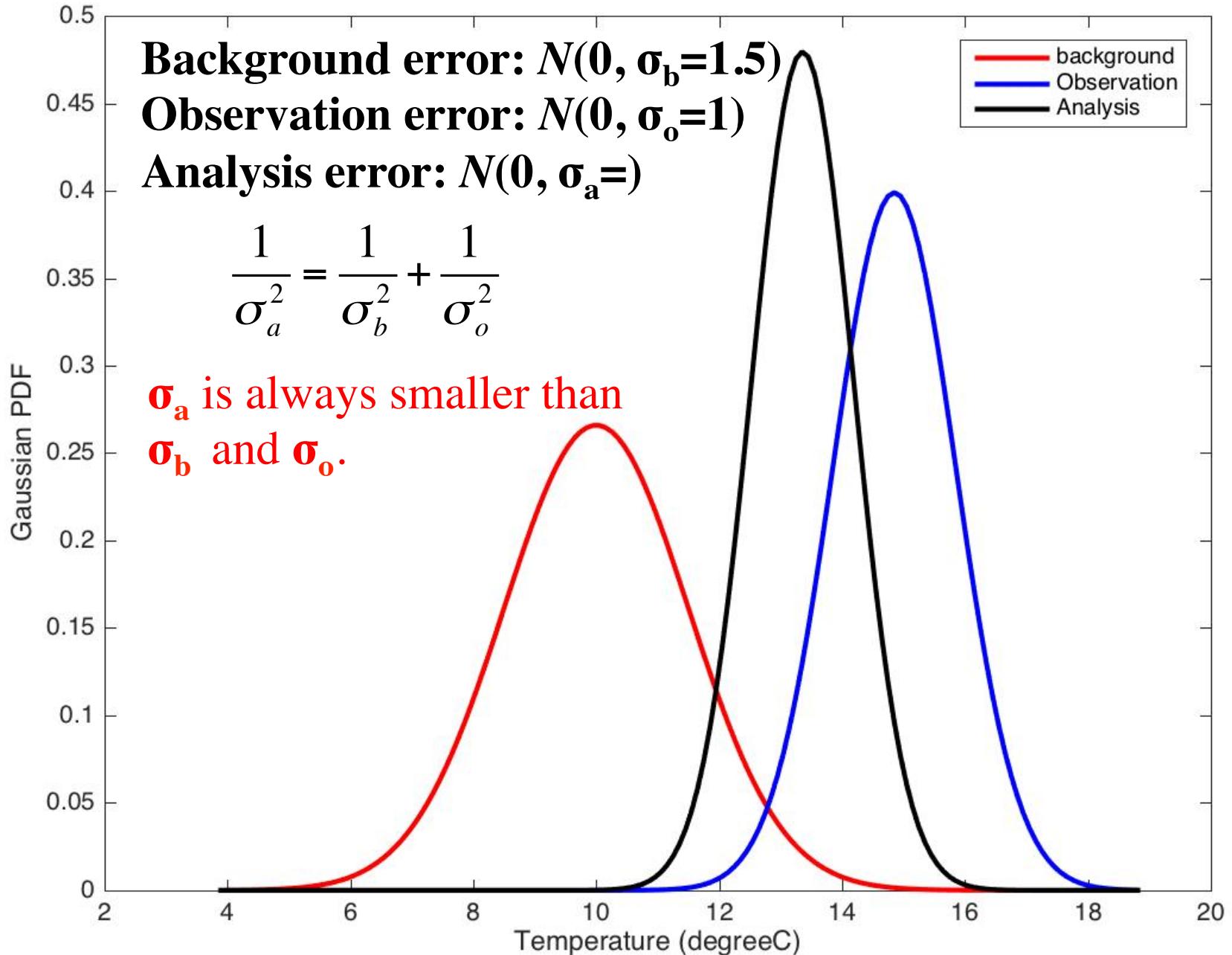
- We can also write in the form of analysis increment

$$x_a - x_b = \frac{\sigma_b^2}{\sigma_b^2 + \sigma_o^2} (y - x_b)$$

Scalar Case

- Minimize $J(x) = \frac{1}{2} \frac{(x-x_b)^2}{\sigma_b^2} + \frac{1}{2} \frac{(x-y)^2}{\sigma_o^2}$
- Is actually equivalent to maximize a Gaussian PDF

$$ce^{-J(x)}$$



Two state variables case

- Consider two state variables to estimate: Boulder and Denver's temperatures x_1 and x_2 at 12 UTC today.
- Background from 6-h forecast: x_1^b and x_2^b
 - and their error covariance with correlation c

$$\mathbf{B} = \begin{bmatrix} \sigma_1^2 & c\sigma_1\sigma_2 \\ c\sigma_1\sigma_2 & \sigma_2^2 \end{bmatrix}$$

- We only have an observation y_1 at a Boulder station and its error variance σ_o^2

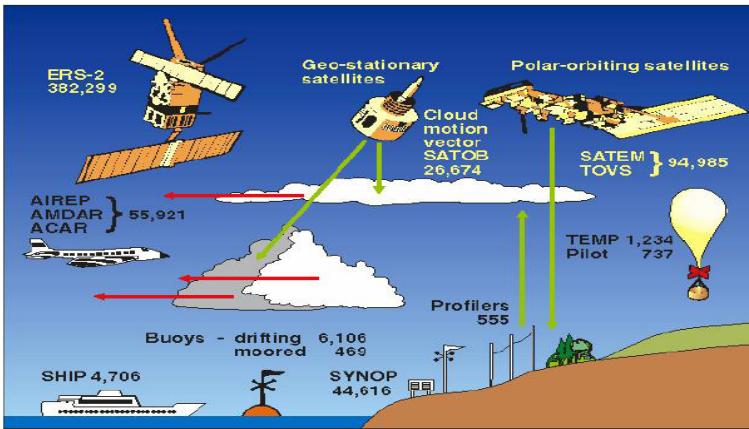
Analysis increment for two variables

$$x_1^a - x_1^b = \frac{\sigma_1^2}{\sigma_1^2 + \sigma_o^2} (y_1 - x_1^b)$$

$$x_2^a - x_2^b = \frac{c\sigma_1\sigma_2}{\sigma_1^2 + \sigma_o^2} (y_1 - x_1^b)$$

Unobserved variable x_2 gets updated through the error correlation c in the background error covariance.

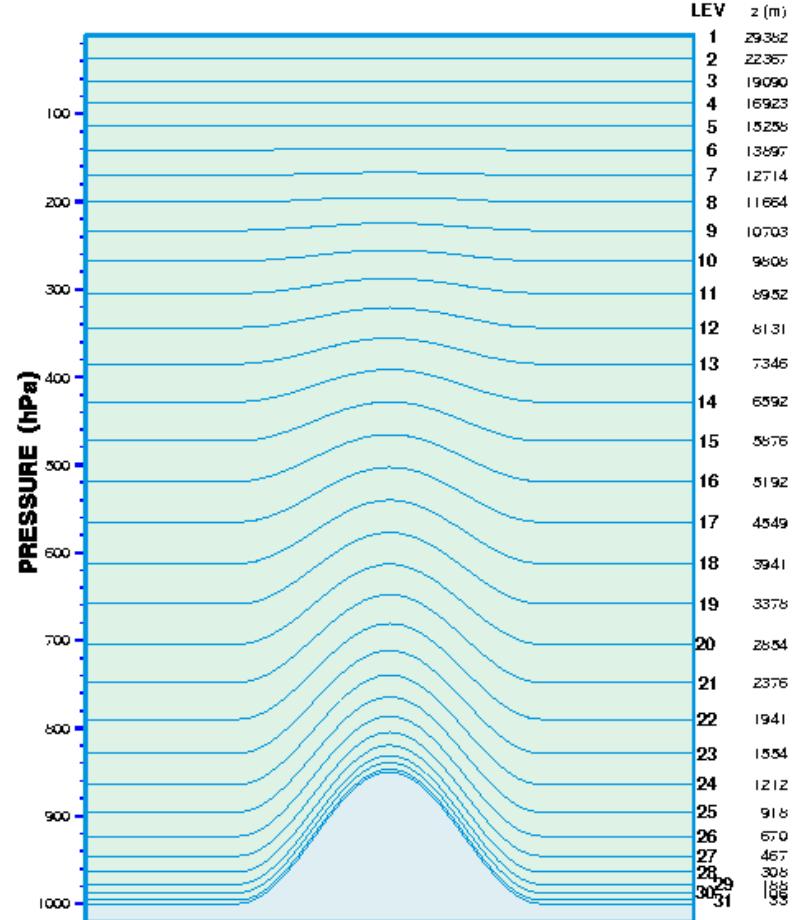
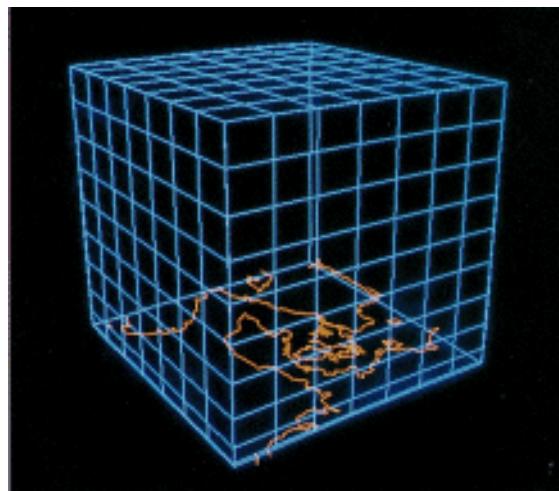
This correlation can be correlation between two locations (spatial), two variables (multivariate), or two times (temporal).



General Case

Observations
 y^0 , $\sim 10^5$ - 10^6

Model state
 x , $\sim 10^7$



Vertical resolution of the DMI-HIRLAM system

General Case: vector and matrix notation

state vector

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix}$$

observation vector

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}$$

background error covariance

$$\mathbf{B} = \begin{bmatrix} \sigma_1^2 & c_{12}\sigma_1\sigma_2 & \dots & \dots \\ c_{12}\sigma_1\sigma_2 & \sigma_2^2 & \dots & \dots \\ \dots & \dots & \ddots & \dots \\ \dots & \dots & \dots & \sigma_m^2 \end{bmatrix}$$

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

\mathbf{H} maps x to y space, e. g., interpolation.

Terminology in DA: **observation operator**

Minimize $J(x)$ is equivalent to maximize a multi-dimensional Gaussian PDF

$$\text{Constant} * e^{-J(x)}$$

Observation error covariance

$$\mathbf{R} = \begin{bmatrix} \sigma_{o1}^2 & 0 & \dots & 0 \\ 0 & \sigma_{o2}^2 & \dots & 0 \\ \vdots & \dots & \ddots & \vdots \\ 0 & \dots & \dots & \sigma_{on}^2 \end{bmatrix}$$

General Case: analytical solution

Again, minimize J requires its gradient (a vector) with respect to x equal to zero:

$$\nabla J_x(x) = \mathbf{B}^{-1}(x - x_b) - \mathbf{H}^T \mathbf{R}^{-1}[\mathbf{y} - \mathbf{H}x] = 0$$

This leads to analytical solution for the analysis increment:

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

$\mathbf{H} \mathbf{B} \mathbf{H}^T$: projection of background error covariance
in observation space

$\mathbf{B} \mathbf{H}^T$: projection of background error covariance
in background-observation space

Precision of Analysis

$$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \mathbf{H}^T \mathbf{R}^{-1} \mathbf{H} = (\mathbf{I} - \mathbf{K}\mathbf{H})\mathbf{B}$$

Generalization of scalar case $\frac{1}{\sigma_a^2} = \frac{1}{\sigma_b^2} + \frac{1}{\sigma_o^2}$

With

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

called Kalman gain matrix

Analysis increment with a single humidity observation

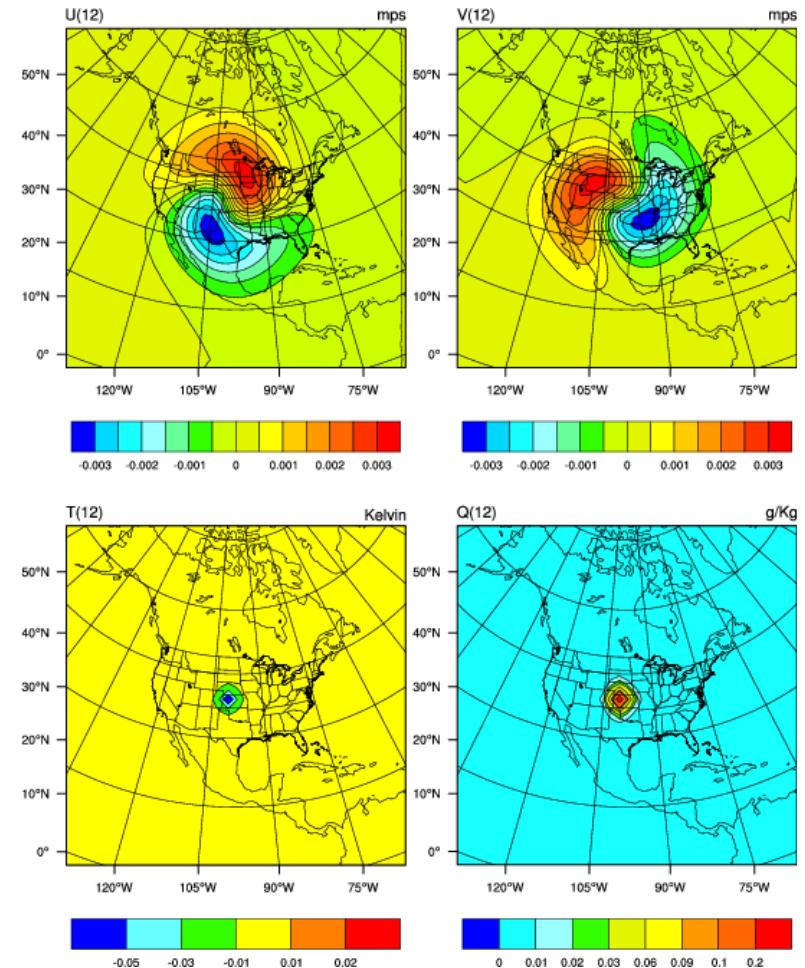
$$x^a - x^b = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R})^{-1}[y - \mathbf{H}x^b]$$

$$x_l^a - x_l^b = \frac{c_{lk}\sigma_l\sigma_k}{\sigma_k^2 + \sigma_{ok}^2}(y_k - x_k^b)$$

It is generalization of previous two variables case:

$$x_1^a - x_1^b = \frac{\sigma_1^2}{\sigma_1^2 + \sigma_o^2}(y_1 - x_1^b)$$

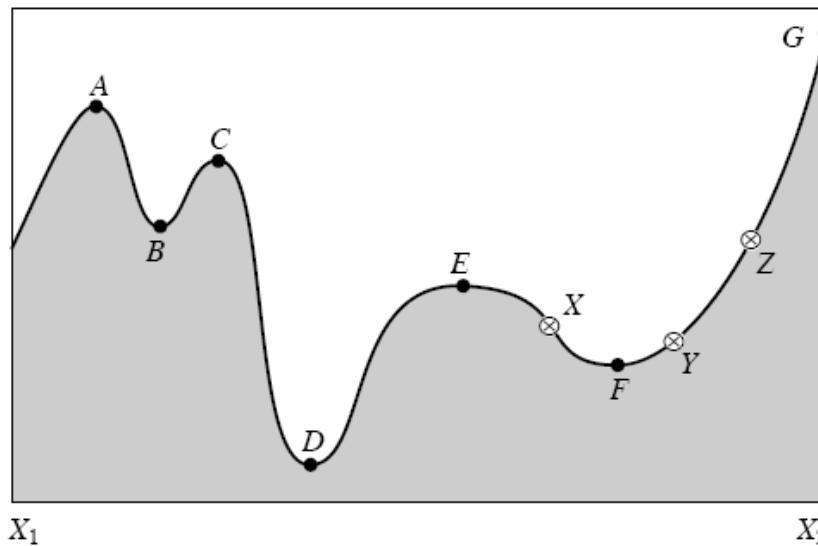
$$x_2^a - x_2^b = \frac{c\sigma_1\sigma_2}{\sigma_1^2 + \sigma_o^2}(y_1 - x_1^b)$$



cv_options=6 in WRFDA

Other Remarks

- Observation operator can be non-linear and thus analysis error PDF is not necessarily Gaussian
- $J(x)$ can have multiple local minima. Final solution of least square depends on starting point of iteration, e.g., choose the background x_b as the first guess.



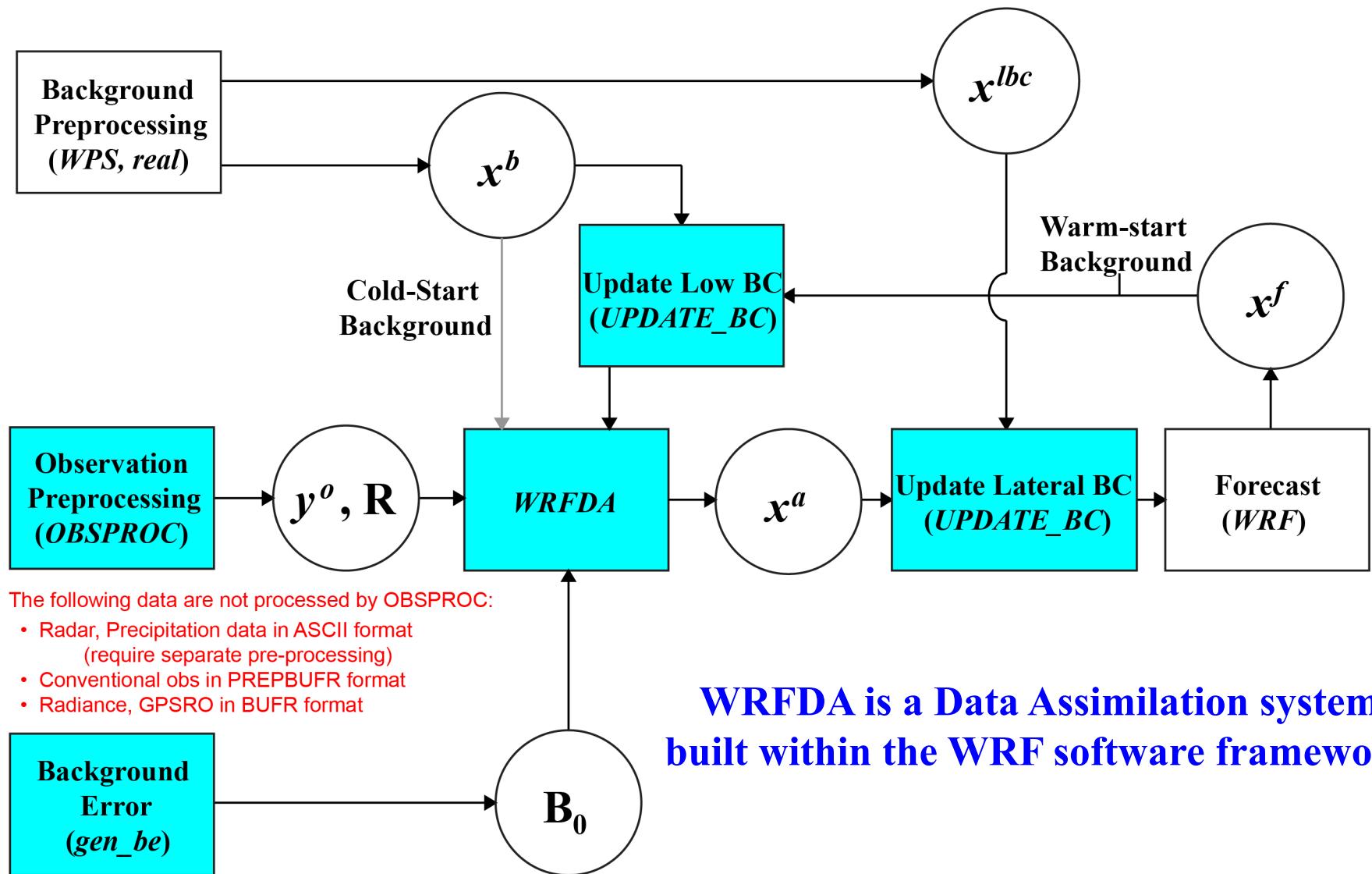
Other Remarks

- **B** matrix is of very large dimension, explicit inverse of **B** is impossible, substantial efforts in data assimilation were given to the estimation and modeling of **B**.
- **B** shall be spatially-varied and time-evolving according to weather regime.
- Analysis can be sub-optimal if using inaccurate estimate of **B** and **R**.
- Could use non-Gaussian PDF
 - Thus not a least square cost function
 - Difficult (usually slow) to solve; could transform into Gaussian problem via variable transform

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WRFDA in the WRF Modeling System



What WRFDA can do?

- Provide Initial conditions for the WRF model forecast
- Verification and validation via difference b.w. obs and model
- Observing system design, monitoring and assessment
- Reanalysis
- Better understanding:
 - Data assimilation methods
 - Model errors
 - Data errors
 - ...

DA algorithms currently available in WRFDA

- 3DVAR and FGAT
 - Different options for choice of control variables (e.g., Psi/Chi or U/V) and background error covariance modeling (e.g., vertical EOF or vertical recursive filter)
- 4DVAR
 - TL/Adjoint (i.e., WRFPlus code) of WRF up-to-date with WRF
 - Allow LBC control variable and Jc-DFI
- Hybrid-3DEnVar
 - Can run in dual-resolution mode
 - Can ingest ensemble from global or regional sources
- ETKF: for generating ensemble analysis

WRFDA Observations

- **In-Situ:**
 - SYNOP
 - METAR
 - SHIP
 - BUOY
 - TEMP
 - PIBAL
 - AIREP, AIREP humidity
 - TAMDAR
- **Bogus:**
 - TC bogus
 - Global bogus
- **Radiances:**

| | |
|----------------|--|
| - HIRS | NOAA-16, NOAA-17, NOAA-18, NOAA-19, METOP-A |
| - AMSU-A | NOAA-15, NOAA-16, NOAA-18, NOAA-19, EOS-Aqua, METOP-A, METOP-B |
| - AMSU-B | NOAA-15, NOAA-16, NOAA-17 |
| - MHS | NOAA-18, NOAA-19, METOP-A, METOP-B |
| - AIRS | EOS-Aqua |
| - SSMIS | DMSP-16, DMSP-17, DMSP-18 |
| - IASI | METOP-A, METOP-B |
| - ATMS | Suomi-NPP |
| - MWTS | FY-3 |
| - MWHS | FY-3 |
| - SEVIRI | METEOSAT |
| - AMSR2 | GCOM-W1 (new in V3.8) |
- **Remotely sensed retrievals:**
 - Atmospheric Motion Vectors (geo/polar)
 - SATEM thickness
 - Ground-based GPS **TPW or ZTD**
 - SSM/I oceanic surface wind speed and TPW
 - Scatterometer oceanic surface winds
 - Wind Profiler
 - **Radar data (reflectivity/retrieved rainwater, and radial-wind)**
 - Satellite temperature/humidity/thickness profiles
 - GPS refractivity (e.g. COSMIC)
 - **Stage IV precipitation/rain rate data (4D-Var only)**

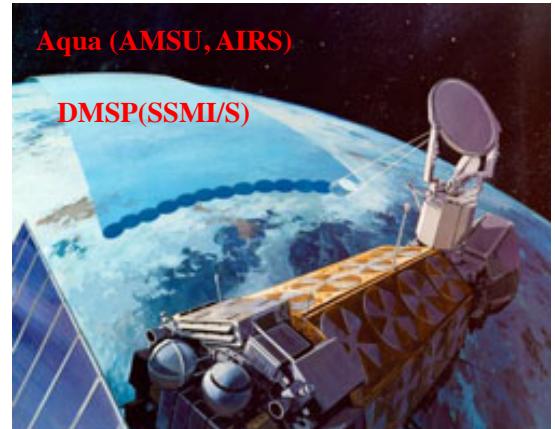
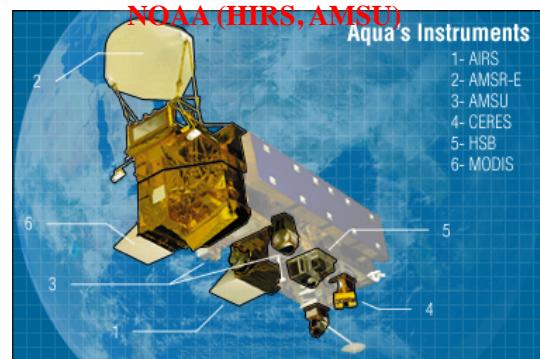
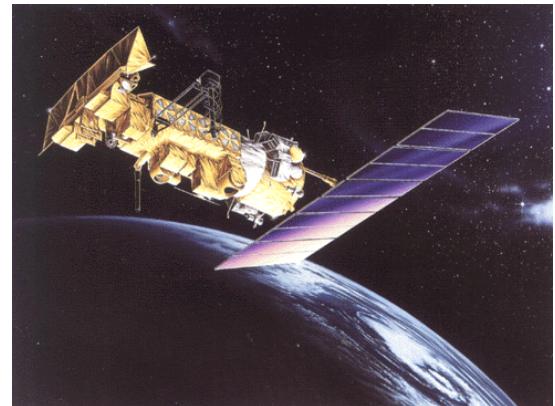
WRFDA is flexible to allow assimilation of different formats of observations:

- **Little_r (ascii), HDF, Binary**
- **NOAA MADIS (netcdf),**
- **NCEP PrepBufr,**
- **NCEP radiance bufr**

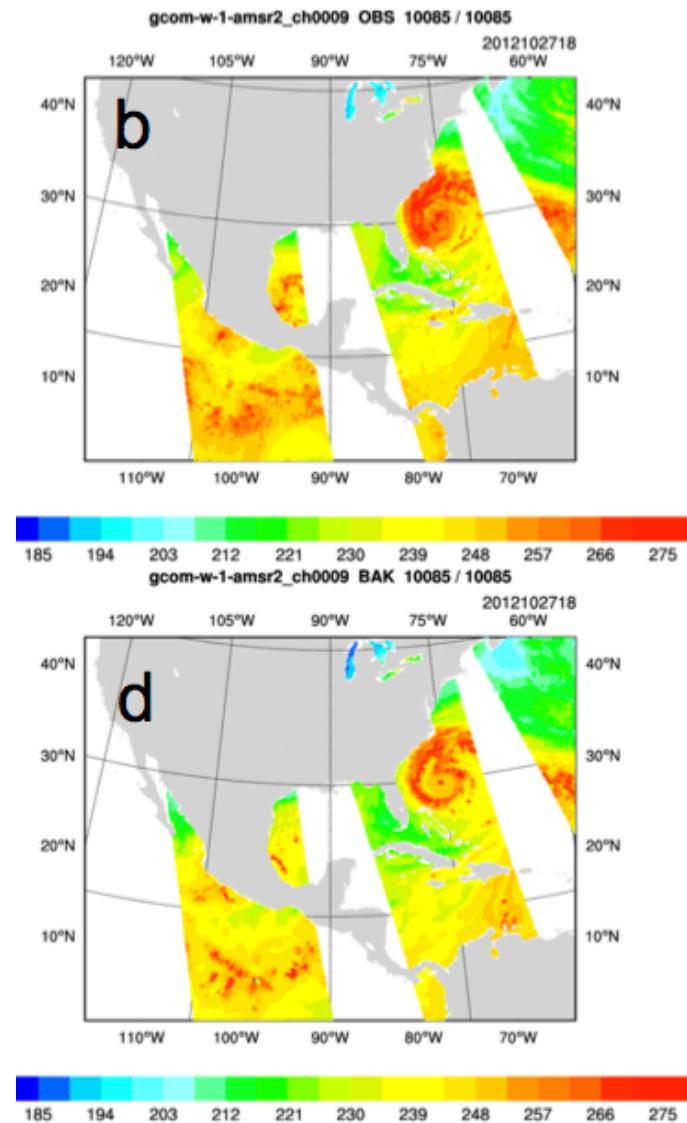
WRFDA

Radiance Assimilation

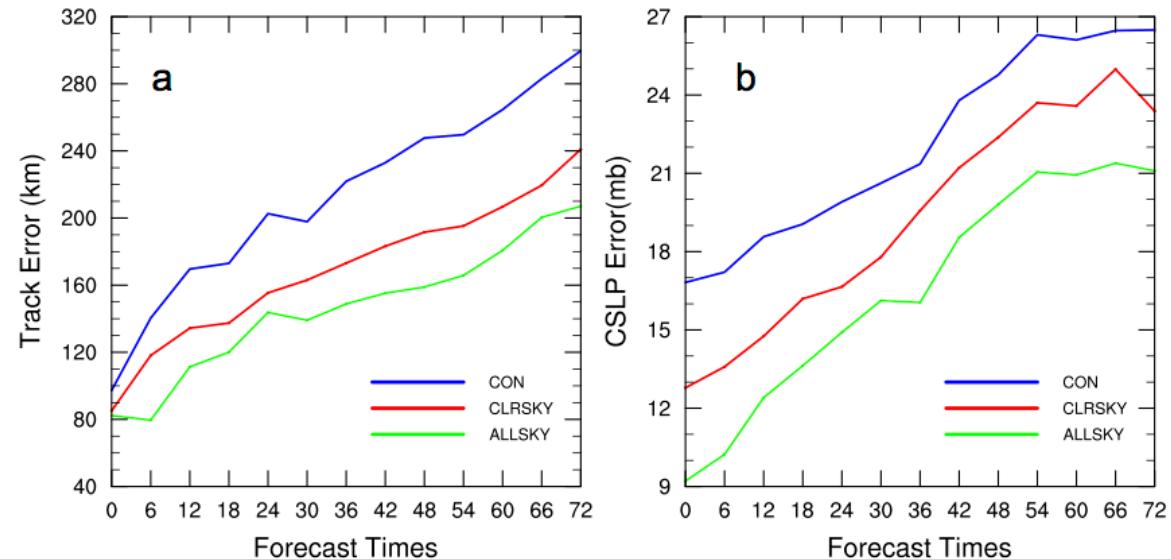
- Two RTM interfaces
 - RTTOV or CRTM
- Variational Bias Correction
- Modular code design to ease adding new satellite sensors
- Capability for cloudy radiance DA

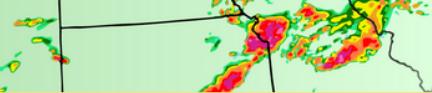


New: all-sky radiance DA: AMSR2



| Channel | Frequency (GHz) | Polarization | Footprint (along scan* along track) |
|---------|-----------------|--------------|-------------------------------------|
| 1,2 | 6.925 | V,H | 35*61 km |
| 3,4 | 7.3 | V,H | 35*61 km |
| 5,6 | 10.65 | V,H | 24*41 km |
| 7,8 | 18.7 | V,H | 13*22 km |
| 9,10 | 23.8 | V,H | 15*26 km |
| 11,12 | 36.5 | V,H | 7*12 km |
| 13,14 | 89.0 | V,H | 3*5 km |





WRFDA: Beta releases

WRFDA is undergoing continuous development as more capabilities are added, both by NCAR scientists and community contributors. On this page you can find pre-release versions of new capabilities. As these capabilities are new and not fully tested, we appreciate any feedback you can offer us: contact us through [wrfhelp](#) or the [WRFDA webmaster](#).

Below is a list of the current beta releases we have available.

AMSR2 CLOUDY RADIANCE ASSIMILATION

Typically, with radiance assimilation in WRFDA, pixels which are determined to have clouds in them are rejected. However, we have developed the ability to assimilate cloud-affected radiance observations with the JAXA GCOM-W1 AMSR2 instrument. This capability is described in [this PDF guide](#), and in the following publication:

Chun Yang, Zhiqian Liu, Jamie Bresch, Syed R. H. Rizvi, Xiang-Yu Huang and Jinzhong Min, 2016: [AMSR2 all-sky radiance assimilation and its impact on the analysis and forecast of Hurricane Sandy with a limited-area data assimilation system](#). *Tellus A*, **68**, 30917, doi:10.3402/tellusa.v68.30917.

Download pre-release code

To download beta release code:

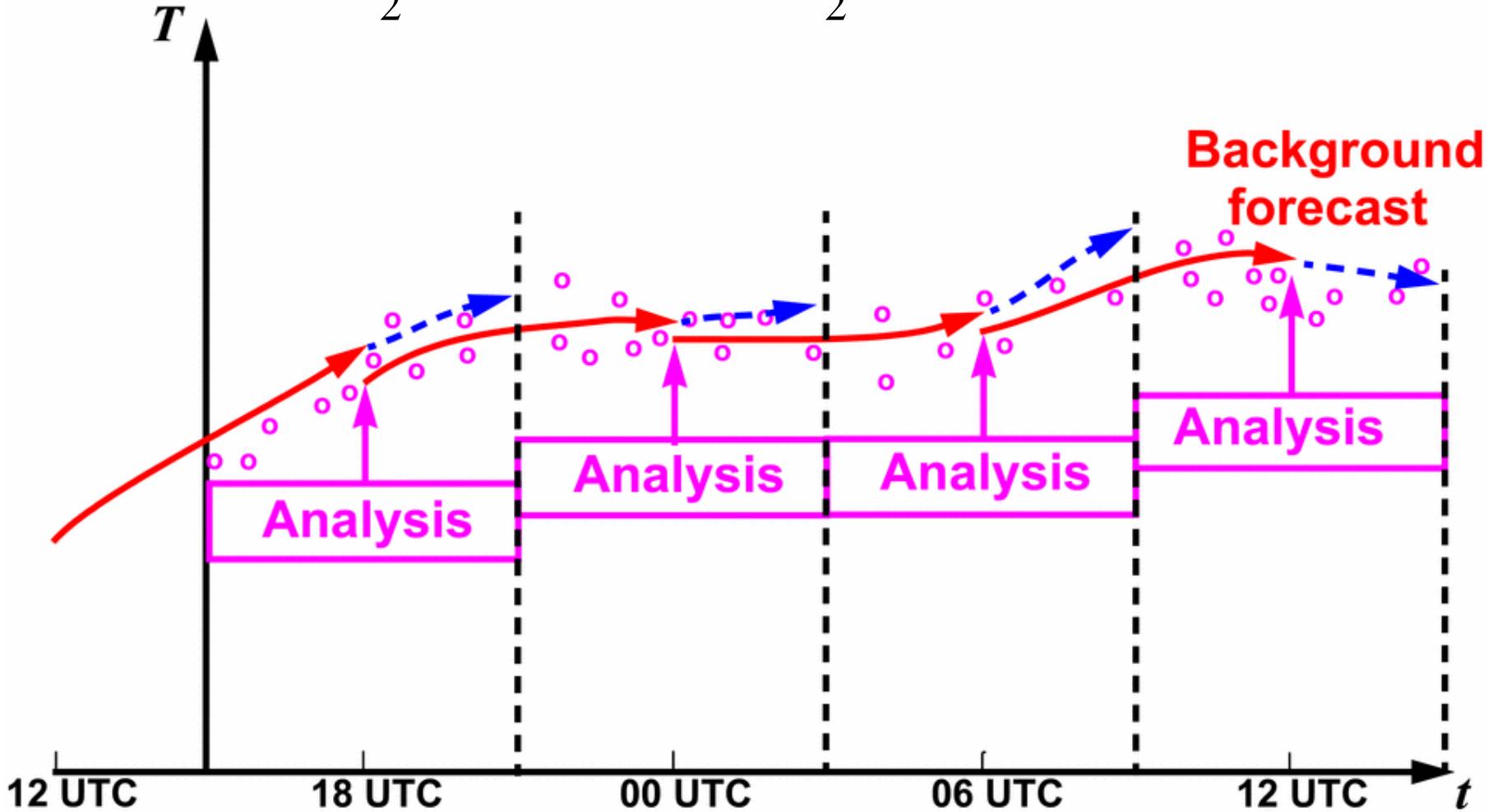
Fill out the registration form by clicking '**New Users**' below, or select '**Returning Users**' if you have already registered to download WRF or WRFDA in the past. You will be redirected to a page where you can download a tar file with the code you are interested in.

[New Users](#)

[Returning Users](#)

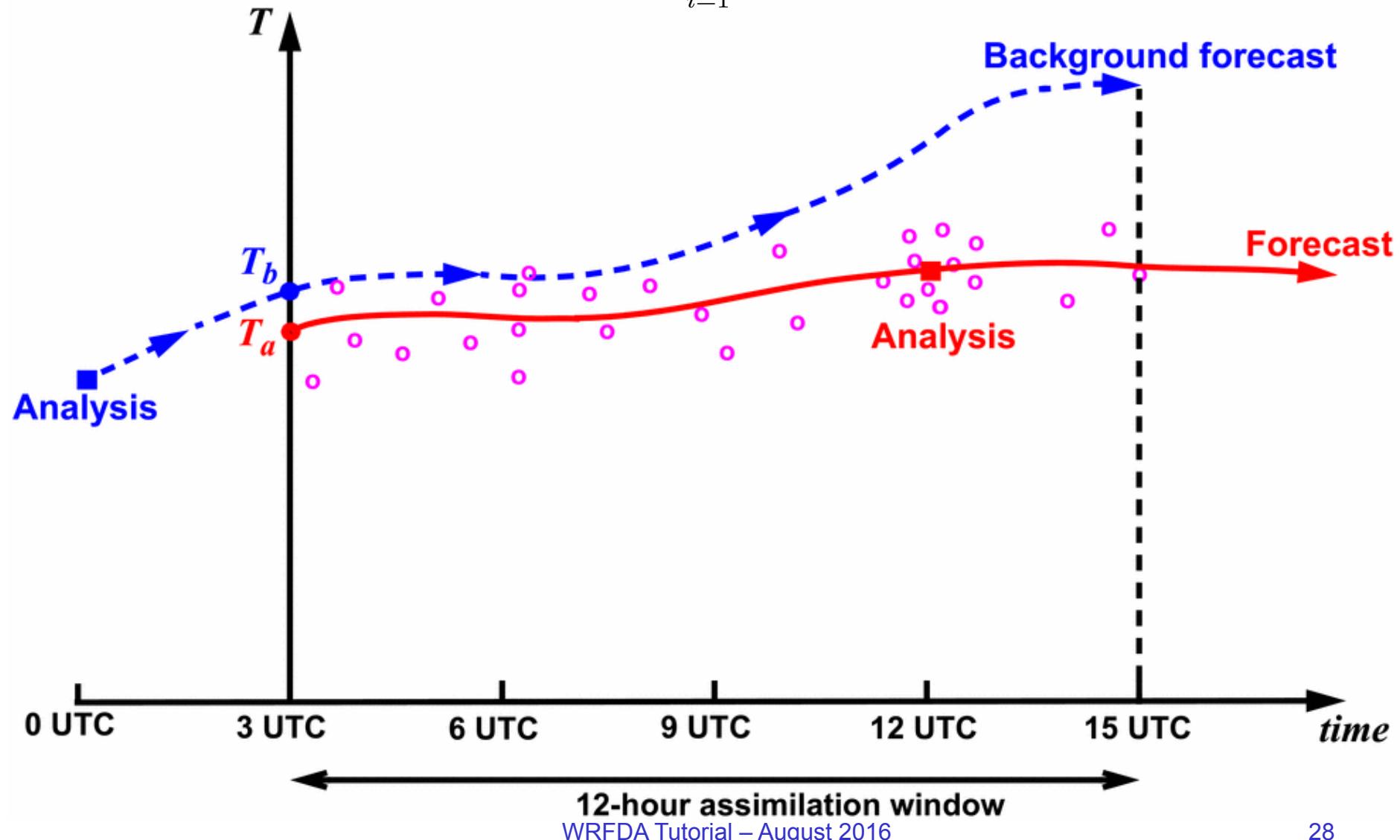
3DVAR (Barker et al. 2004)

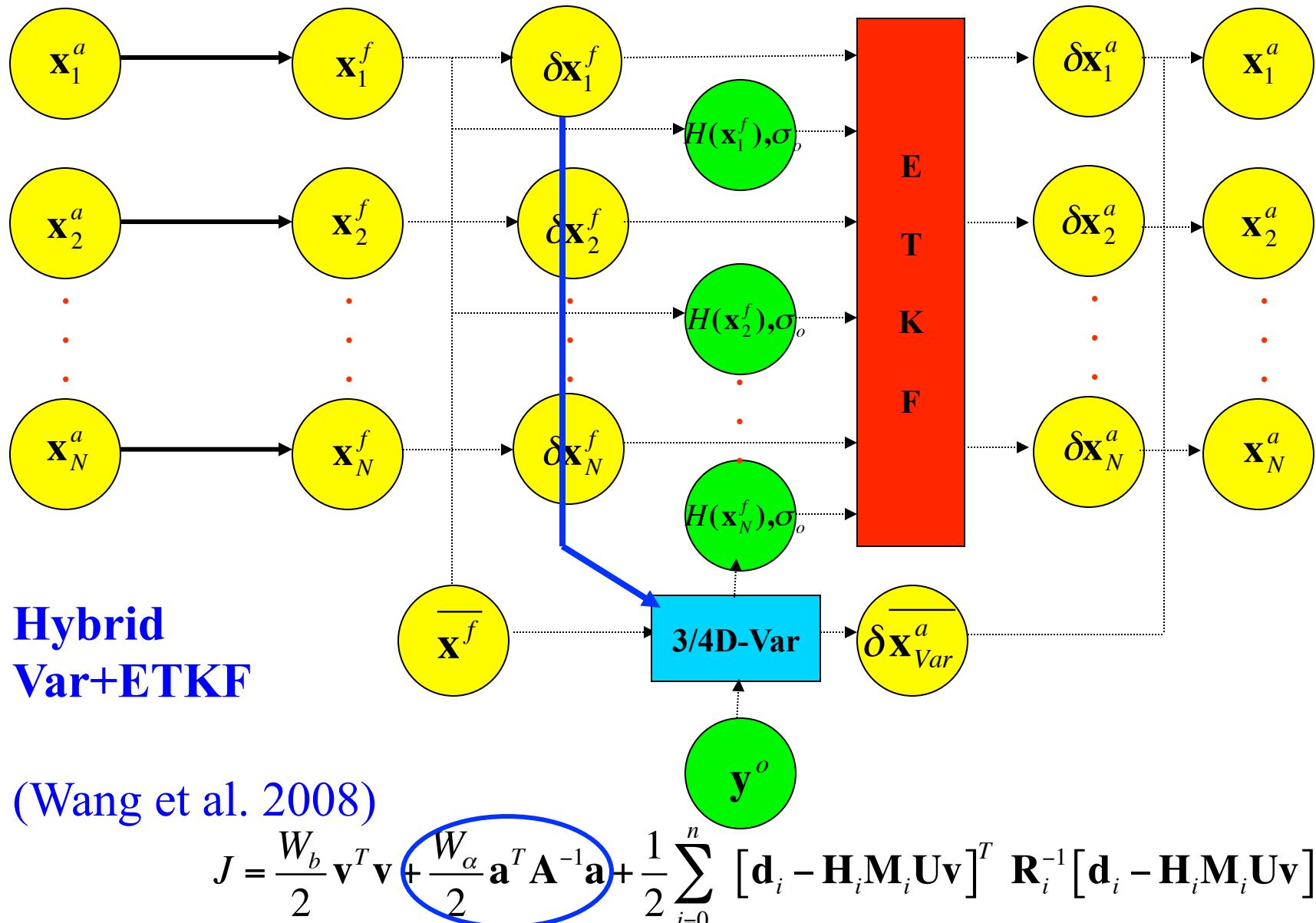
$$J(x) = \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}[H(x) - y]^T R^{-1}[H(x) - y]$$

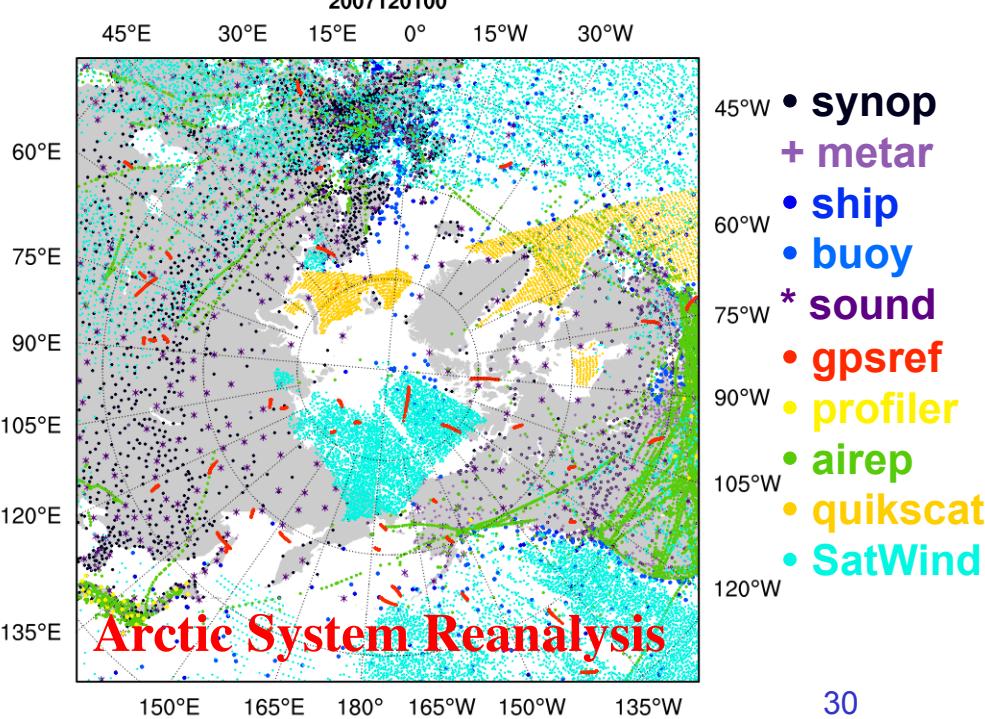
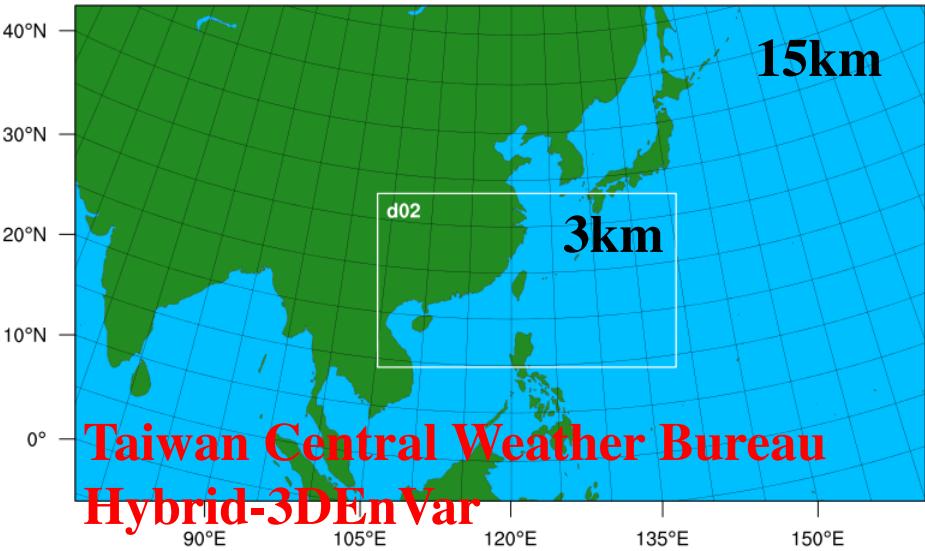
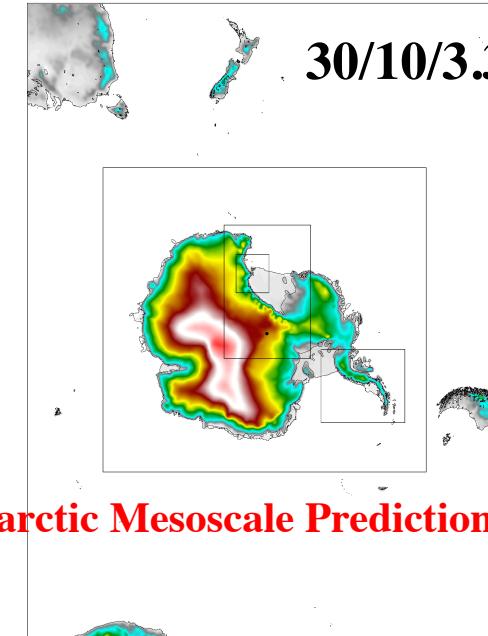
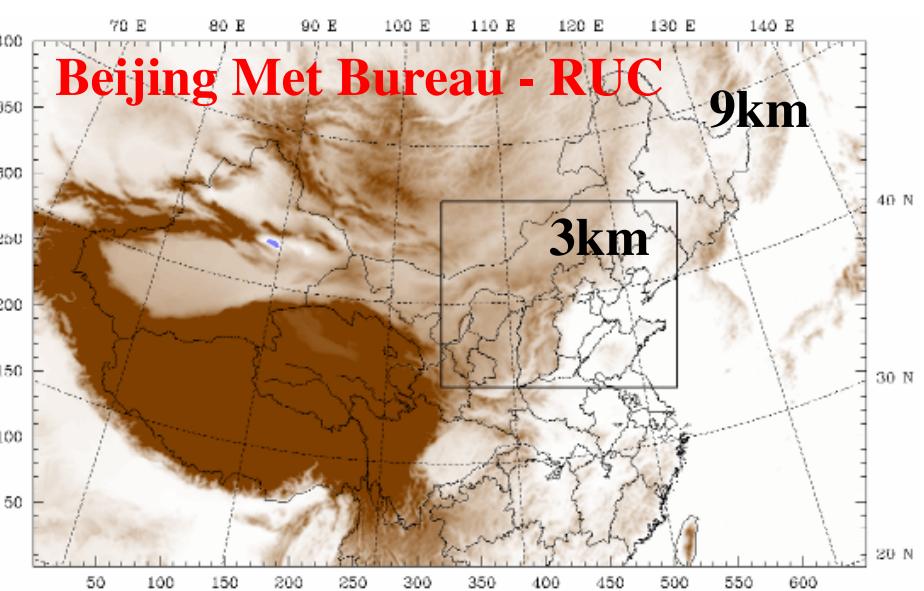


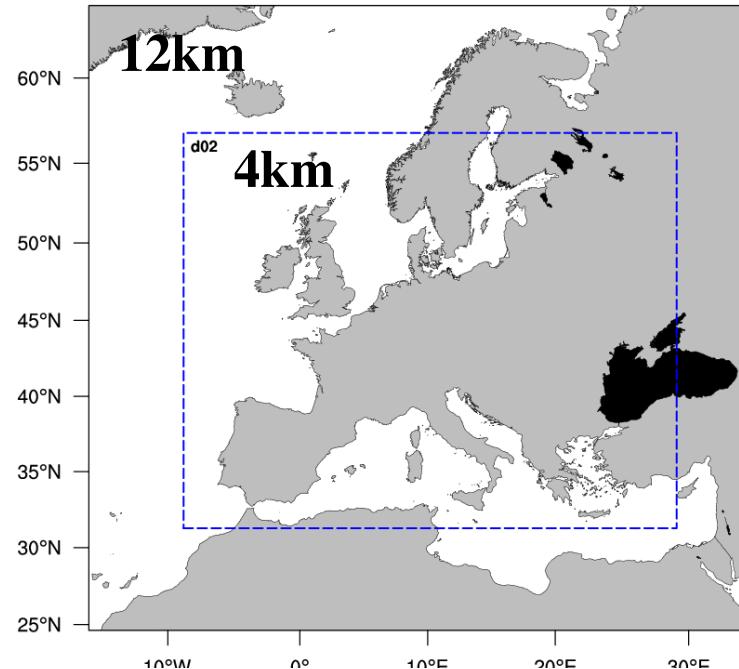
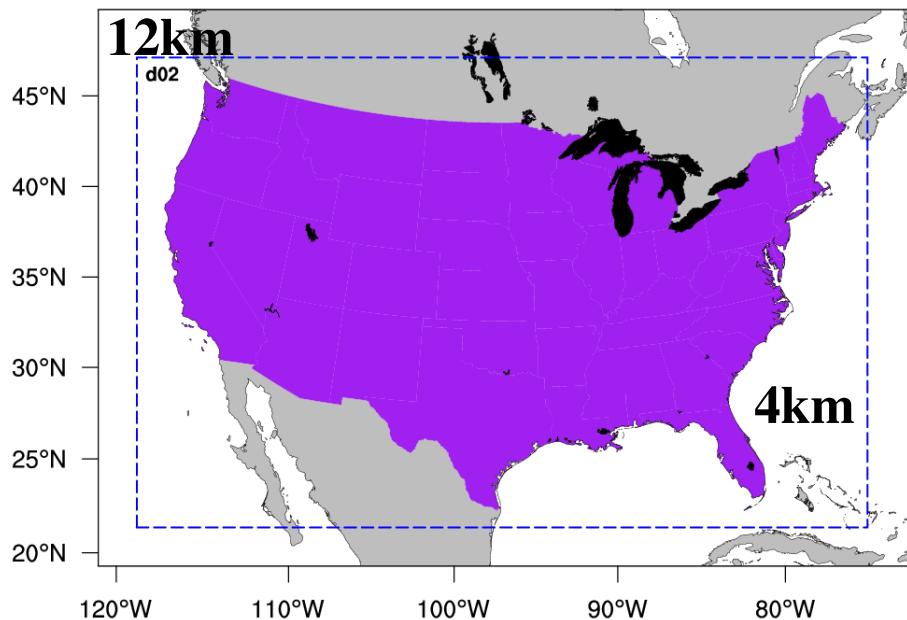
4DVAR (Huang et al. 2009)

$$J(\mathbf{x}_0) = \frac{1}{2}(\mathbf{x}_0 - \mathbf{x}_0^b)^T \mathbf{B}^{-1} (\mathbf{x}_0 - \mathbf{x}_0^b) + \frac{1}{2} \sum_{i=1}^N [\mathbf{H}_i(M_i(\mathbf{x}_0)) - \mathbf{y}_i]^T \mathbf{R}_i^{-1} [\mathbf{H}_i(M_i(\mathbf{x}_0)) - \mathbf{y}_i]$$

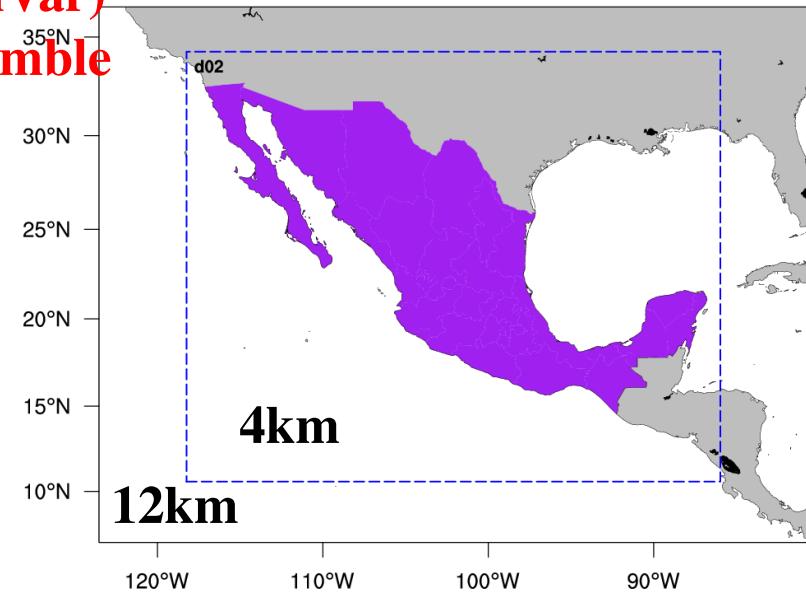
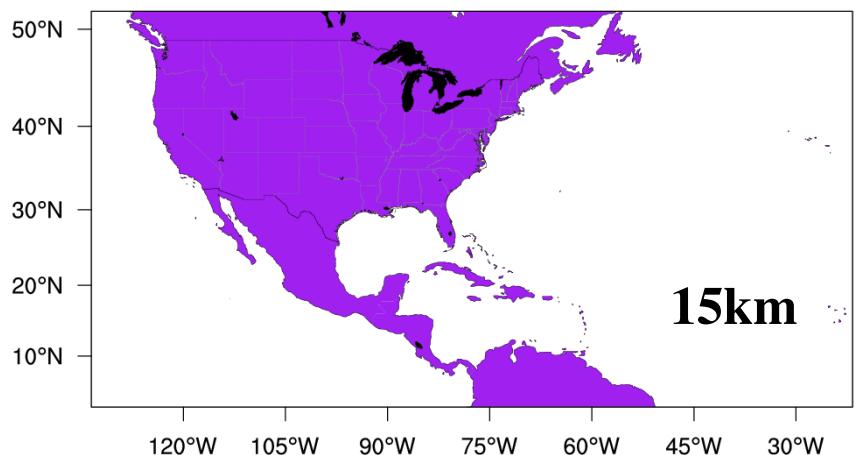








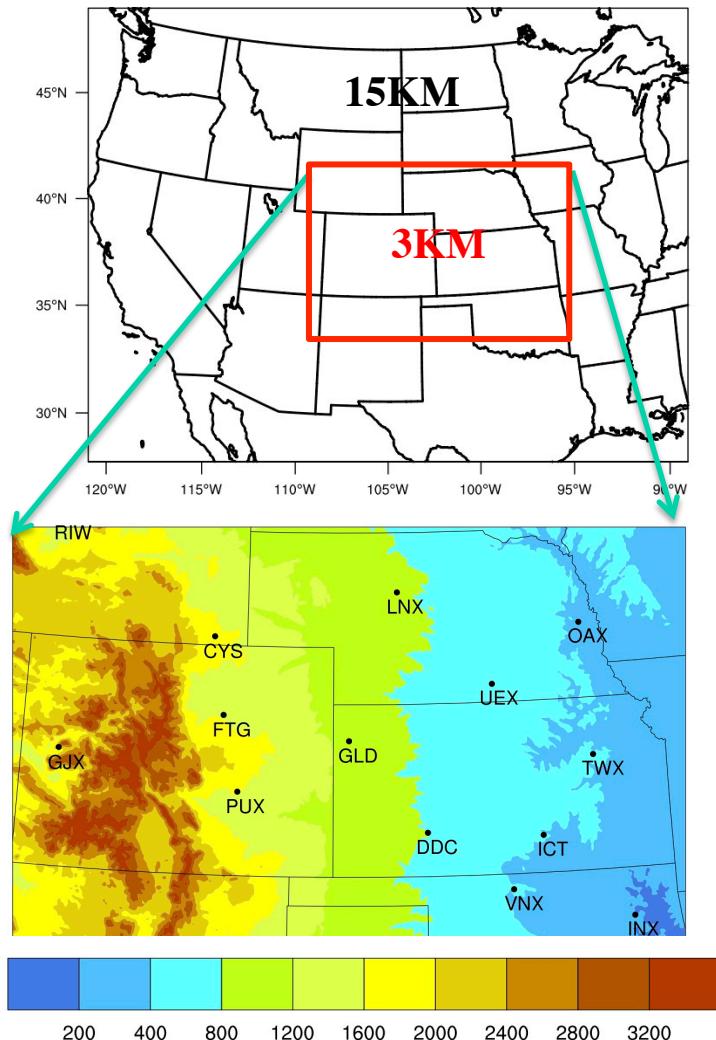
**Operational domains by PWS (hybrid-3DEnVar)
Ensemble covariances from global GFS ensemble**



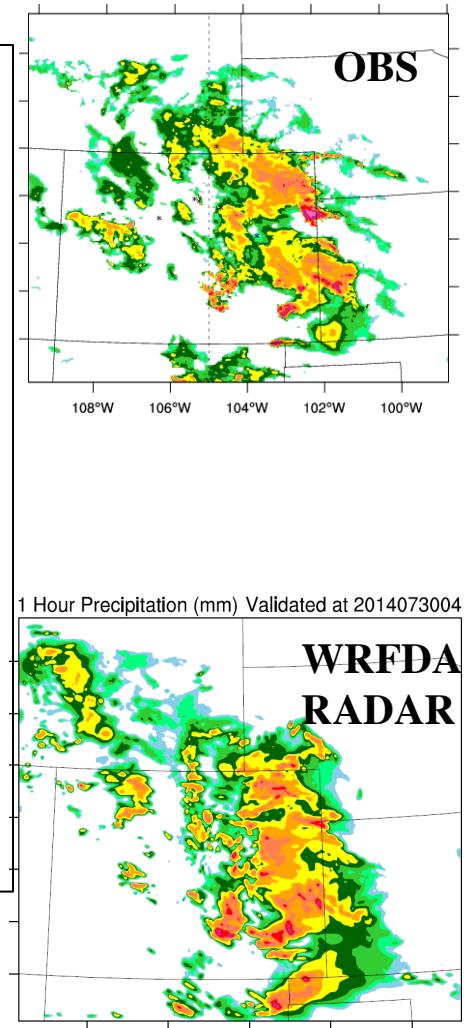
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Radar DA for hydrological application

STEP Hydromet Real Time Exp. during spring time



- The goal is to improve local-scale QPF in coupled hydromet system
- < 1 h rapid update
- Radar radial velocity and reflectivity assimilation
- High resolution vs. ensemble
- Impact of terrain
- Improved results in capturing localized storms



Real-Time WRF/WRFDA-hybrid analysis/forecast over CONUS

WRFDA USERS PAGE

The screenshot shows the WRFDA Users Page. At the top, there's a navigation bar with links: Home, System, User Support, Download, Publications & Documentation, Links, Internal, and WRFDA Testbeds (which is circled in red). Below the navigation bar, there's a search bar and a box containing the text "Have questions? Try our FAQ first!". The main content area has a heading "WRF Data Assimilation System Users Page". It includes a welcome message about the WRFDA system, a list of included components, and a note about future support. To the right, there's a "LATEST WRFDA RELEASE" section for Version 3.7.1 (released August 14, 2015), featuring a map of the Western US with temperature contours. A red arrow points from the "WRFDA Testbeds" link in the menu to this map. There are also sections for "UPCOMING EVENTS" (listing June 2016) and "WHAT'S NEW" (mentioning the 2016 WRF Workshop).

Home System User Support Download Publications & Documentation Links Internal **WRFDA Testbeds**

Search

Have questions? [Try our FAQ first!](#)

WRF Data Assimilation System Users Page

Welcome to the page for users of the Weather Research and Forecasting (WRF) model data assimilation system (WRFDA). The WRFDA system is in the public domain and is freely available for community use. It is designed to be a flexible, state-of-the-art atmospheric data assimilation system that is portable and efficient on available parallel computing platforms. WRFDA is suitable for use in a broad range of applications, across scales ranging from kilometers for regional and mesoscale modeling to thousands of kilometers for global scale modeling.

The Mesoscale and Microscale Meteorology (MMM) Laboratory of NCAR currently maintains and supports a subset of the overall WRF code (Version 3) that includes:

- WRF Software Framework (WSF)
- Advanced Research WRF (ARW) dynamic solver, including one-way, two-way nesting and moving nests, grid and observation nudging
- WRF Pre-Processing System (WPS)
- **WRF Data Assimilation System (WRFDA) (*found on this site*)**
- Numerous physics packages contributed by WRF partners and the research community

Other components of the WRF system will be supported for community use in the future, depending on interest and available resources.

LATEST WRFDA RELEASE

WRFDA Version 3.7.1
(Released August 14, 2015)

WRF / WRFDA REALTIME FORECAST

500 mb temperature (C) (T512), geopotential height, and winds (wts)

NCAR

Click here for latest 48-hr forecast

UPCOMING EVENTS

June, 2016

2016 WRF Workshop, NCAR Center Green Campus, Boulder, CO, USA.

WHAT'S NEW



Surface/Precip

Upper-Air

Severe

Obs. Diag.

Anl. State

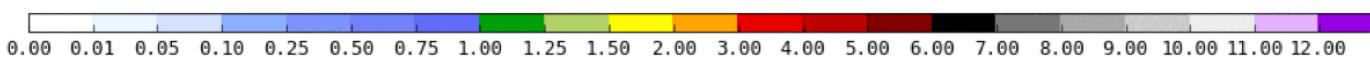
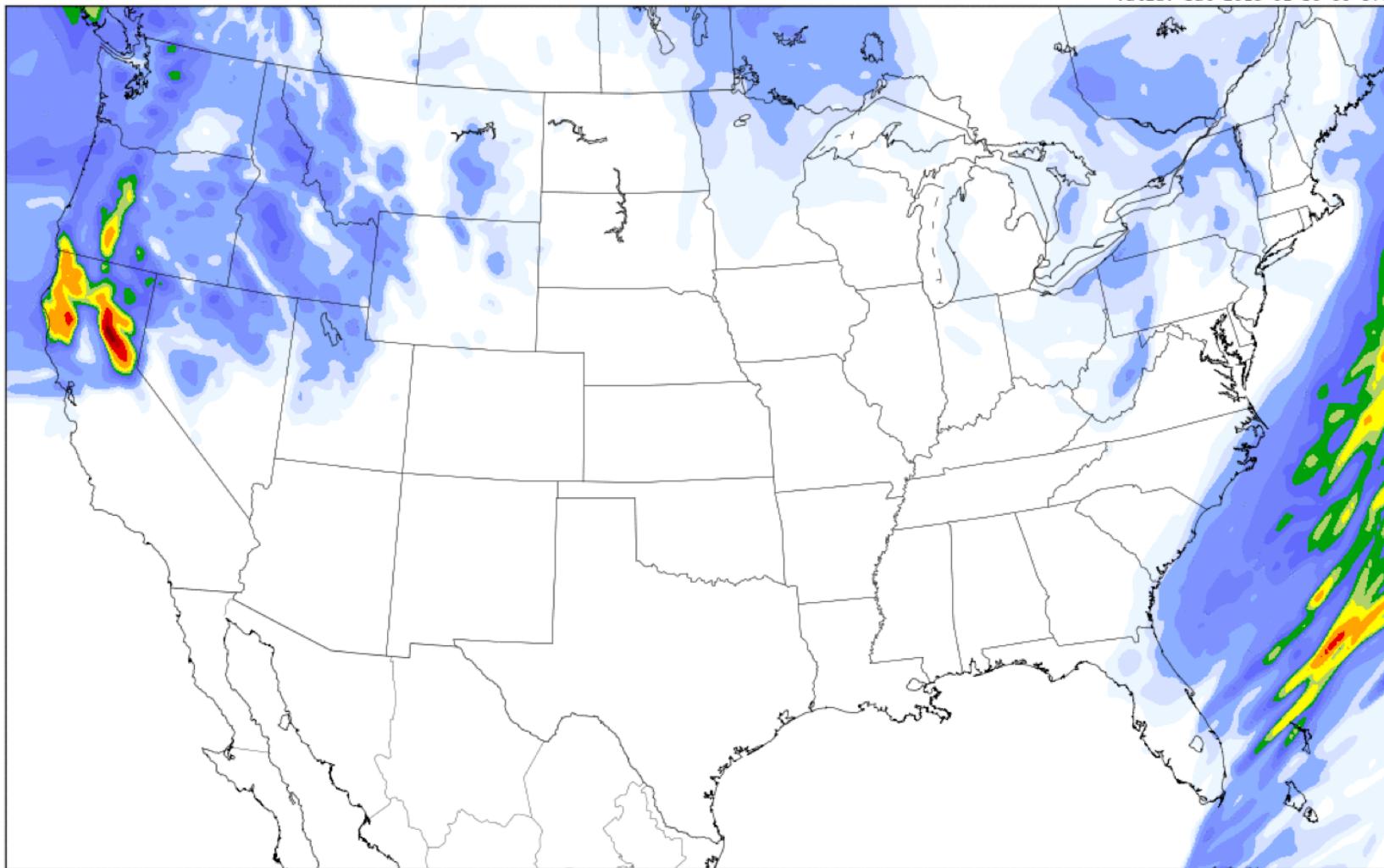
Increments

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48

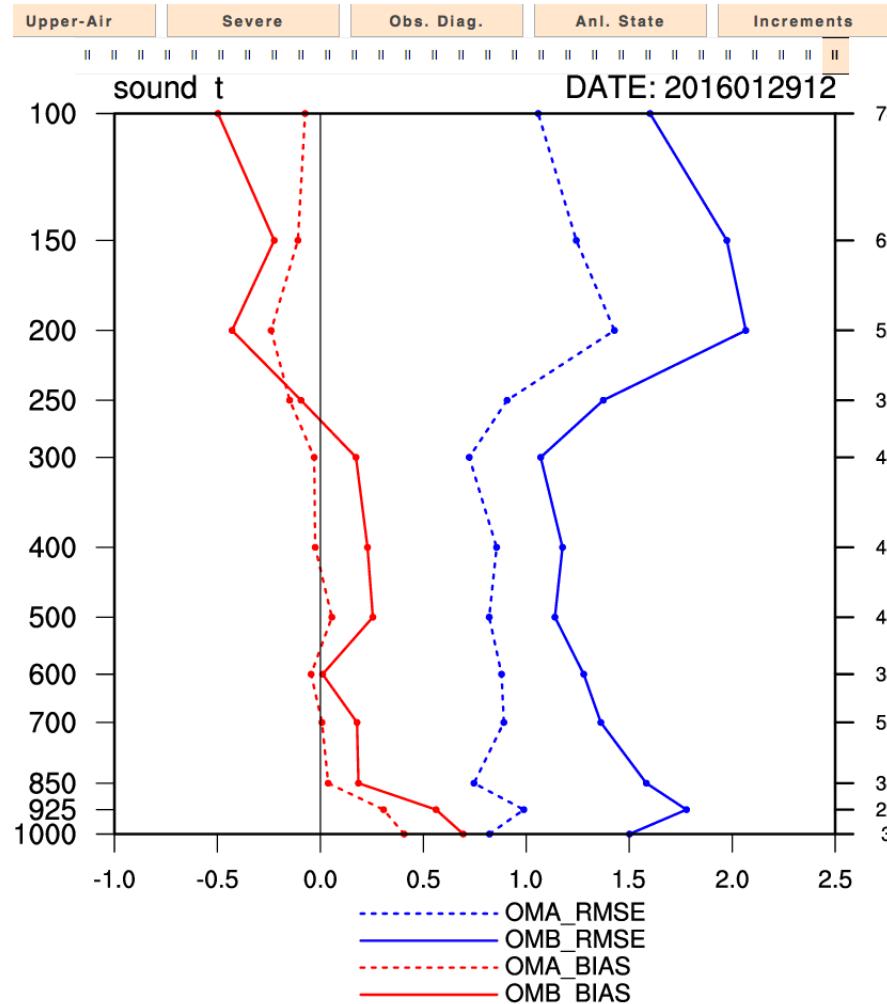
15-km ARW WRF 24-hr accumulated precipitation (in)

Init: Fri 2016-01-29 00 UTC

Valid: Sat 2016-01-30 00 UTC



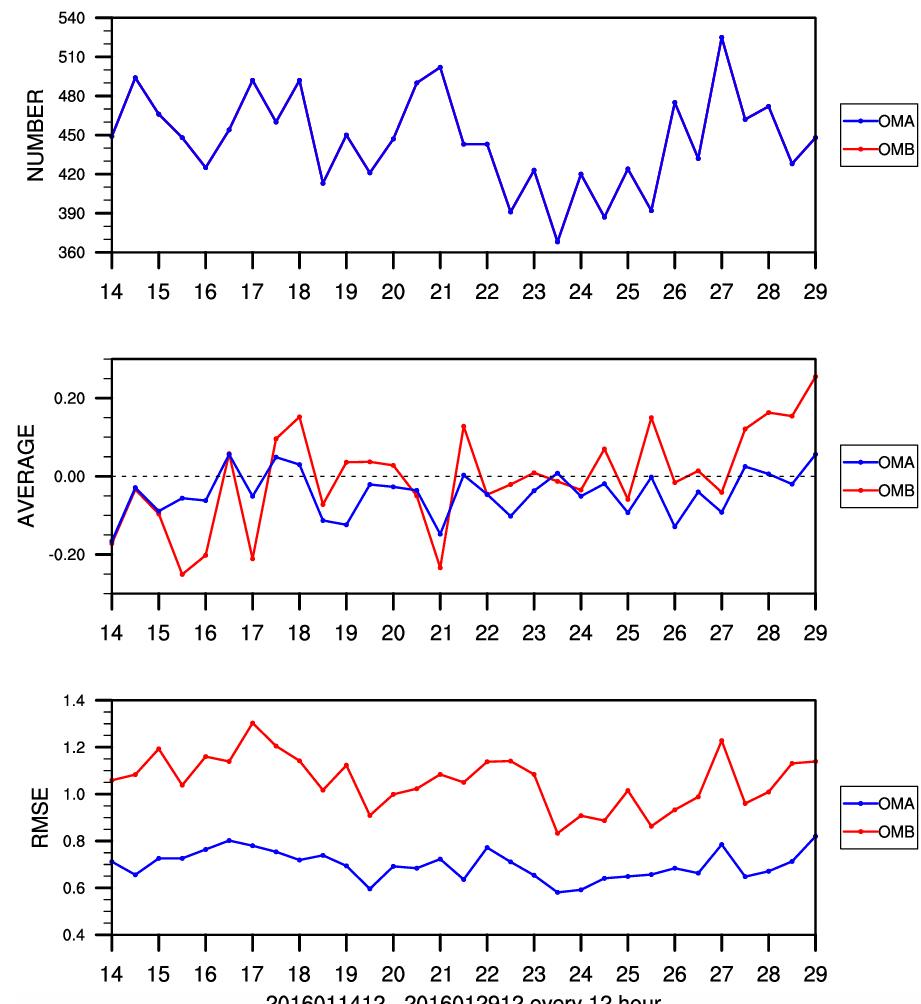
FDA Initialized: 12 UTC Fri 29 Jan 2016



/RFDA Initialized: 12 UTC Fri 29 Jan 2016

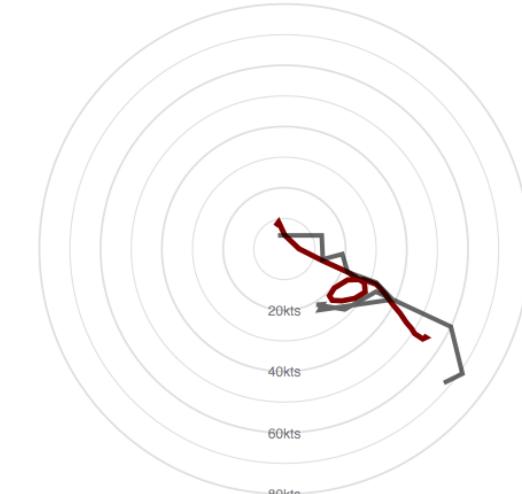
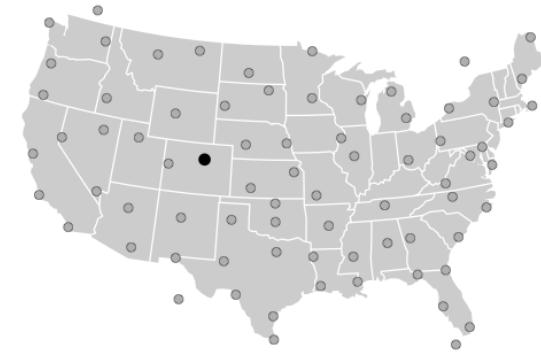
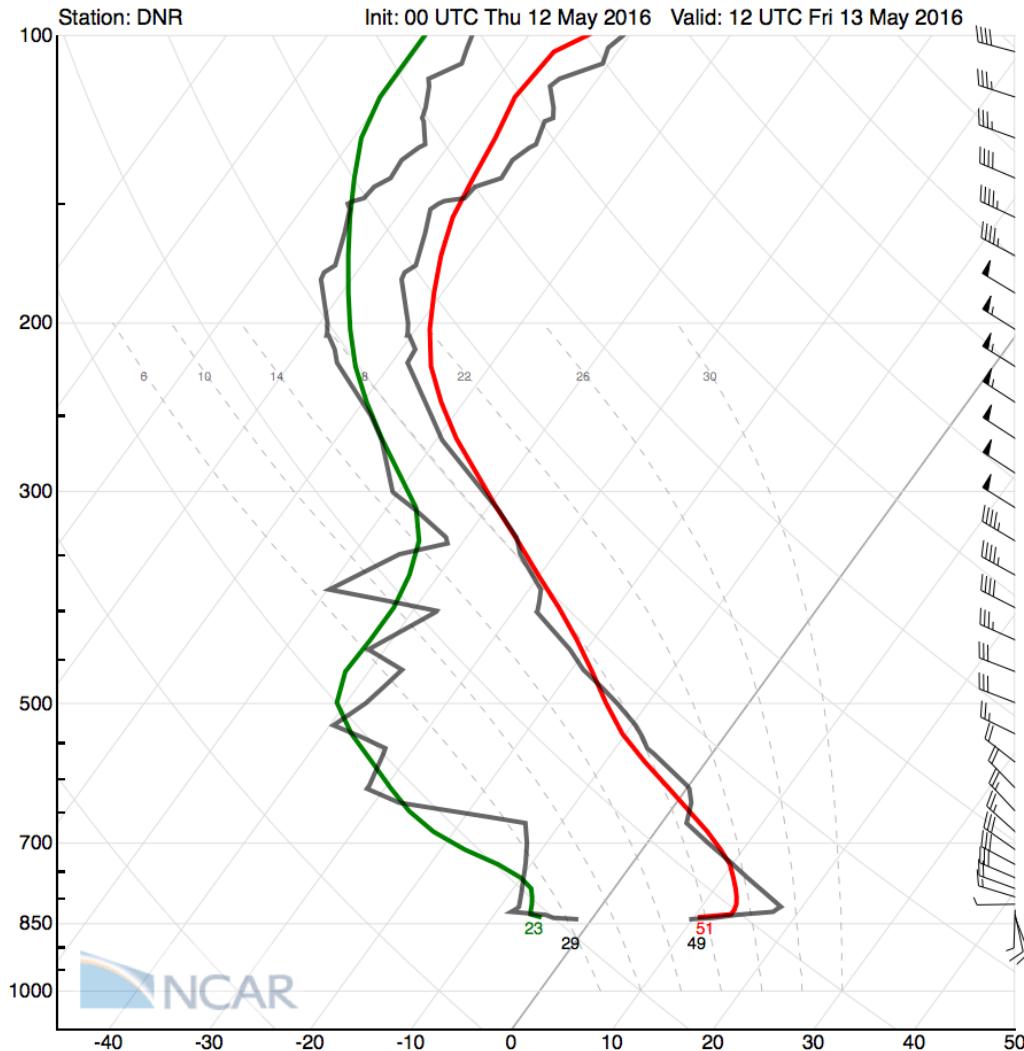
Upper-Air Severe Obs. Diag. Anl. State Increments

RT_WRFDA sound t 500hPa



Real-time WRF/WRFDA forecast

NCAR WRF/WRFDA Initialized: 00 UTC Thu 12 May 2016 



Overlay Observed Soundings (5) (Press "O" to turn on/off)

Ongoing work: Variational Bias Correction of Aircraft T

$$J(\mathbf{x}, \boldsymbol{\beta}) = (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}_x^{-1} (\mathbf{x} - \mathbf{x}_b) + (\boldsymbol{\beta} - \boldsymbol{\beta}_b)^T \mathbf{B}_{\boldsymbol{\beta}}^{-1} (\boldsymbol{\beta} - \boldsymbol{\beta}_b) + (\mathbf{y} - H[\mathbf{x}, \mathbf{y}, \boldsymbol{\beta}])^T \mathbf{R}^{-1} (\mathbf{y} - H[\mathbf{x}, \mathbf{y}, \boldsymbol{\beta}])$$

$$\cancel{H}(\mathbf{x}, \mathbf{y}, \boldsymbol{\beta}) = H(\mathbf{x}) - b(\mathbf{y}, \boldsymbol{\beta})$$

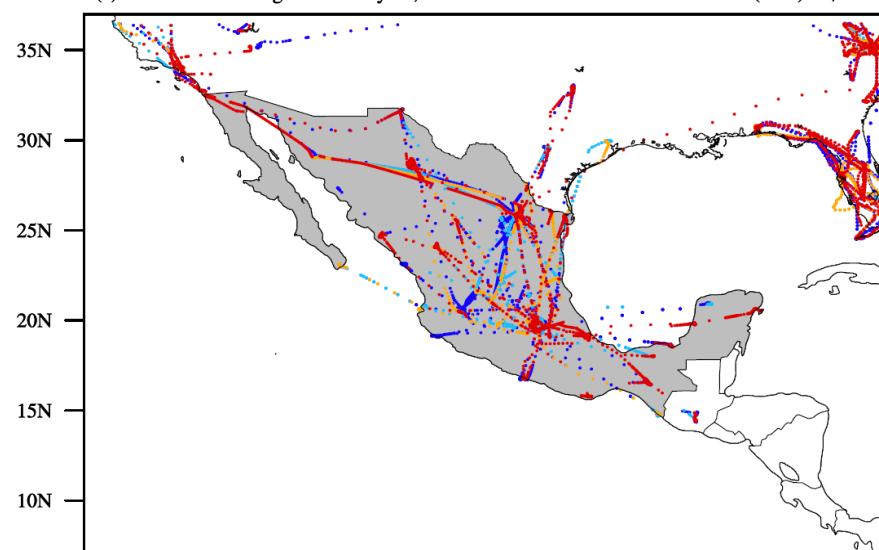
$$b(\mathbf{y}, \boldsymbol{\beta}) = \sum_{n=0}^N \beta_n p_n(\mathbf{y}) = \begin{cases} \beta_{0+} + \beta_{1+} w & \text{if } w > 0 \\ \beta_{0-} + \beta_{1-} w & \text{if } w < 0 \end{cases}$$

$w = \frac{dp}{dt}$, β is updated in cost function each cycle and written in parameter table.

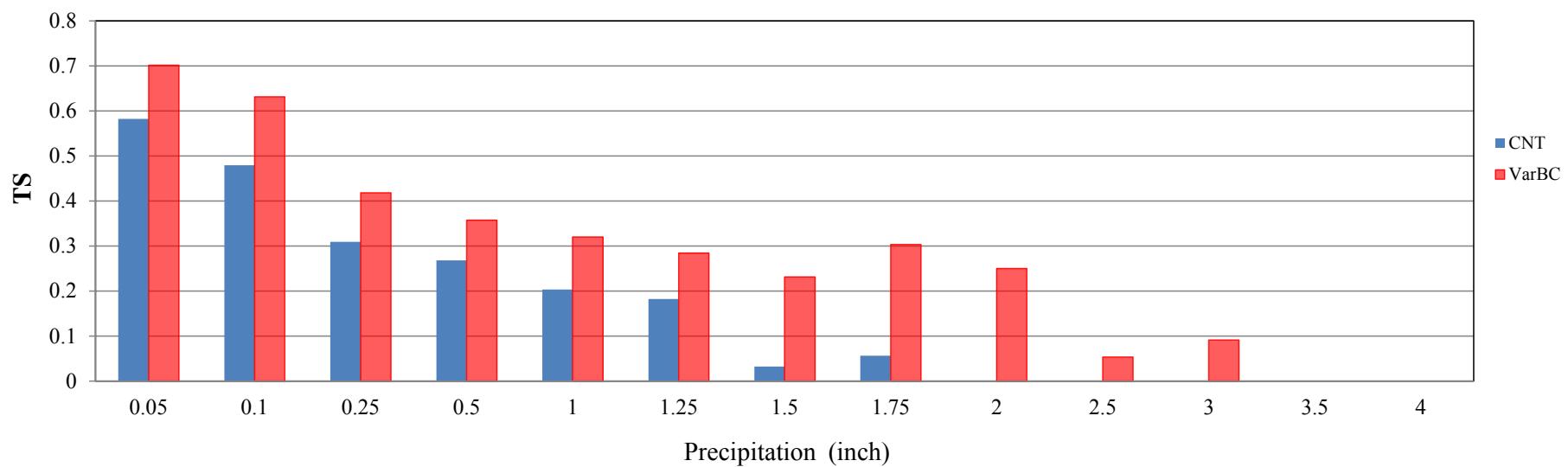
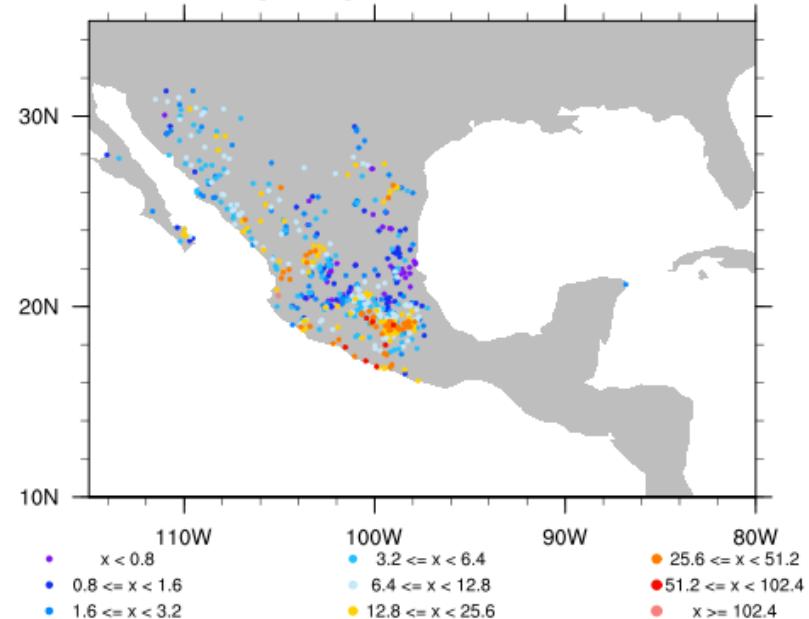
Impact of Aircraft T VarBC on rainfall forecast

(a) TAMDAR coverage on January 15, 2016

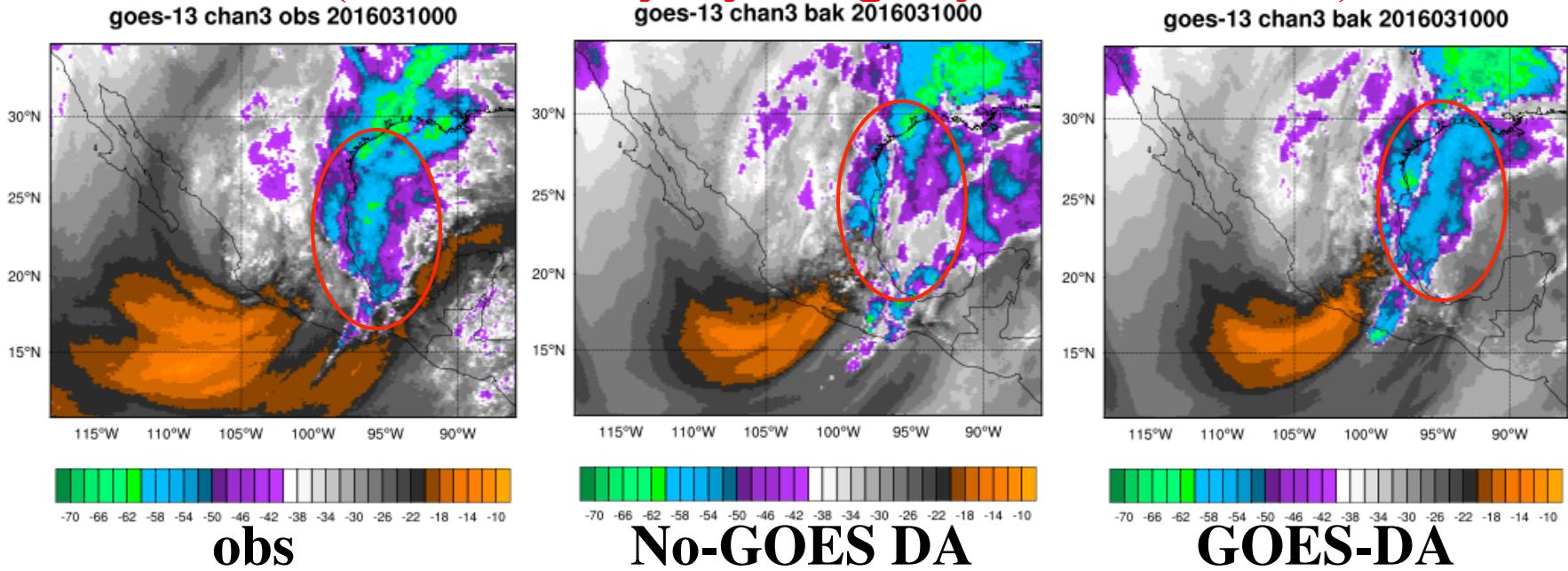
| Time Window (hour): -3/+3 |



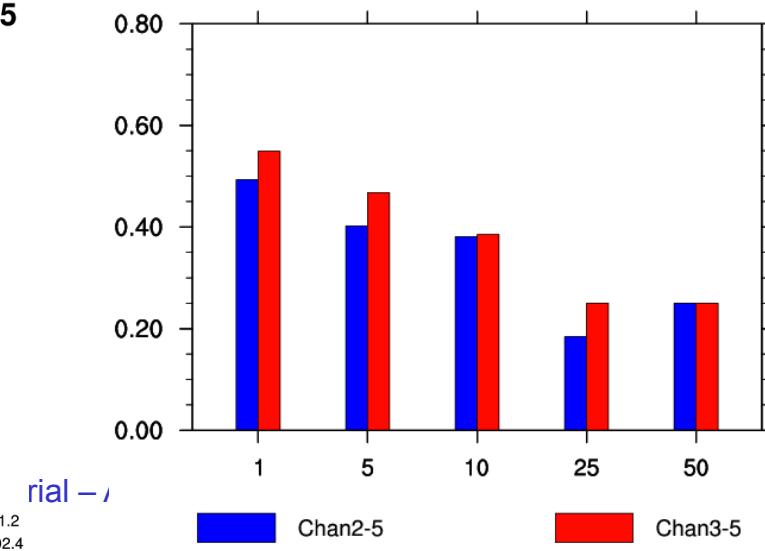
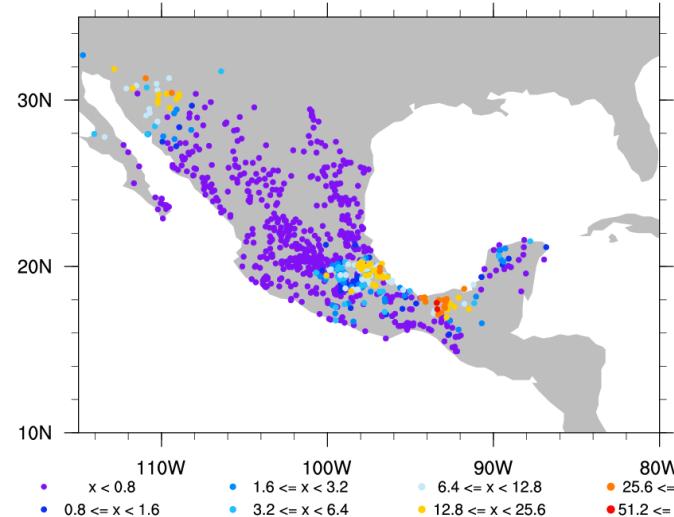
Mexico station precipitation data 2016.03.08-03.09



GEOS imager radiance DA at convection-permitting scale (4km, hourly-cycling, hybrid-3DVAR)



Mexico station precipitation data 2016.01.04-01.05



Other ongoing work

- Implemented Hybrid-4DEnVAR
 - Improving computing efficiency
- Continue developing Multi-Resolution Incremental 4DVAR (MRI-4DVAR)
- Continue developing cloudy radiance/product DA
- Improving surface data assimilation
- Improving radar DA
 - Adding divergence constraint
 - Assimilation of non-rain data
- WRFPlus-Chem & WRFDA-Chem
 - CU Boulder.

Last Remarks

- We welcome contributions from external users/developers.
 - Contact wrfhelp@ucar.edu or directly email to me liuz@ucar.edu for contributing back your code
- We maintain a WRFDA-related publications list, please inform us your papers to be included
 - <http://www2.mmm.ucar.edu/wrf/users/wrfda/publications.html>