Data Assimilation and the use of Satellite Observations in the NOAA/NCEP GFS Global Model

Presented by

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Overview of Talk

- Introduction
- Radiative Transfer Upgrades
- Bias Correction Upgrades
- SSMI/S
- 3DVar → EnKF 3DVar Hybrid → 4DEnsVar
- Conclusion

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Summary of Radiance Data Assimilated in NCEP global model

- GOES-15 Sounder
- SEVIRI (Meteosat-10)
- AMSU-A (N-15, N-18, N-19, Aqua, MetOp-A,MetOp-B)
- MHS (N-18, N-19, MetOp-A, MetOp-B)
- HIRS (Metop-A)
- ATMS (SNPP)
- CrIS (SNPP)
- AIRS (Aqua)
- IASI (MetOp-A, MetOp-B)
- SSMIS (F17, F18)

Green was added in August 2013 Upgrade

Blue is part of next upgrade (aim is August 2014)

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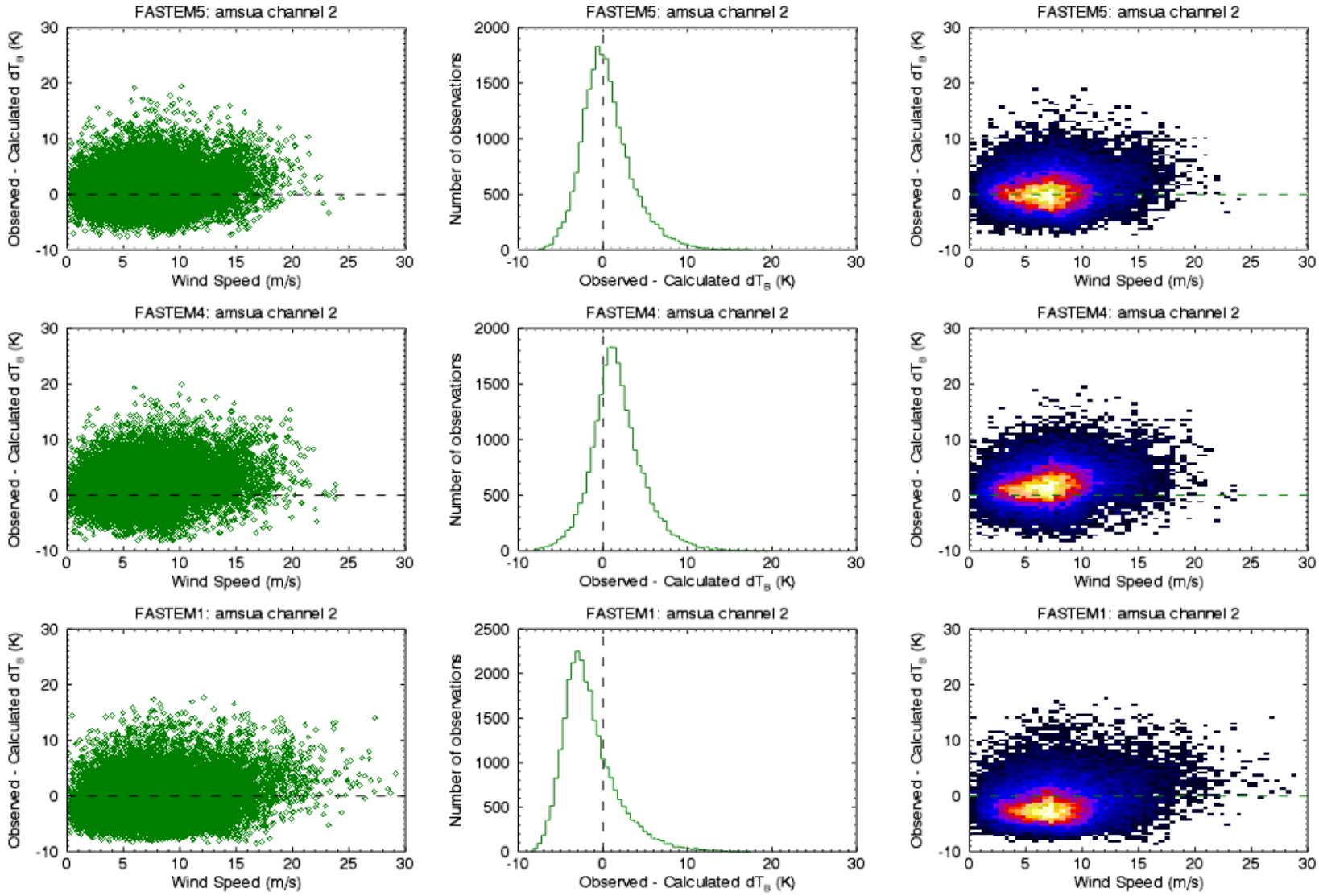
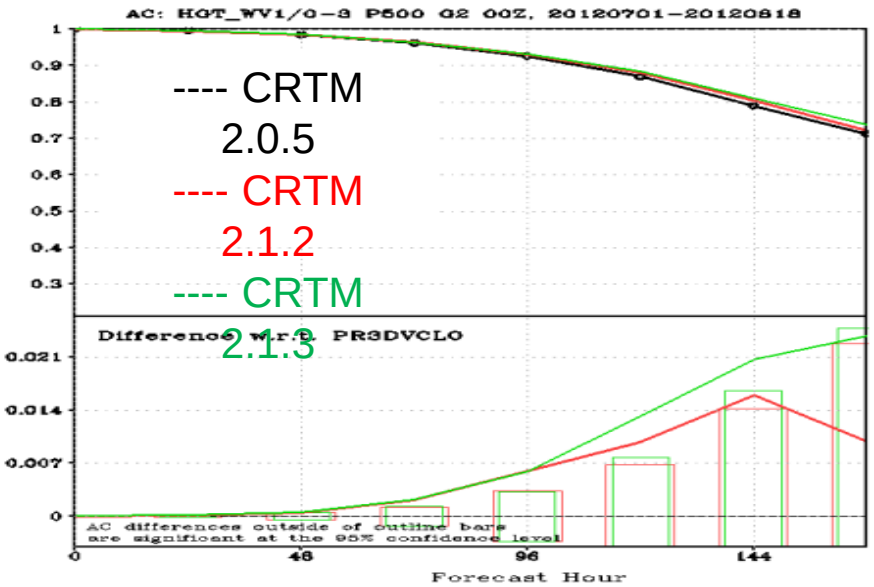
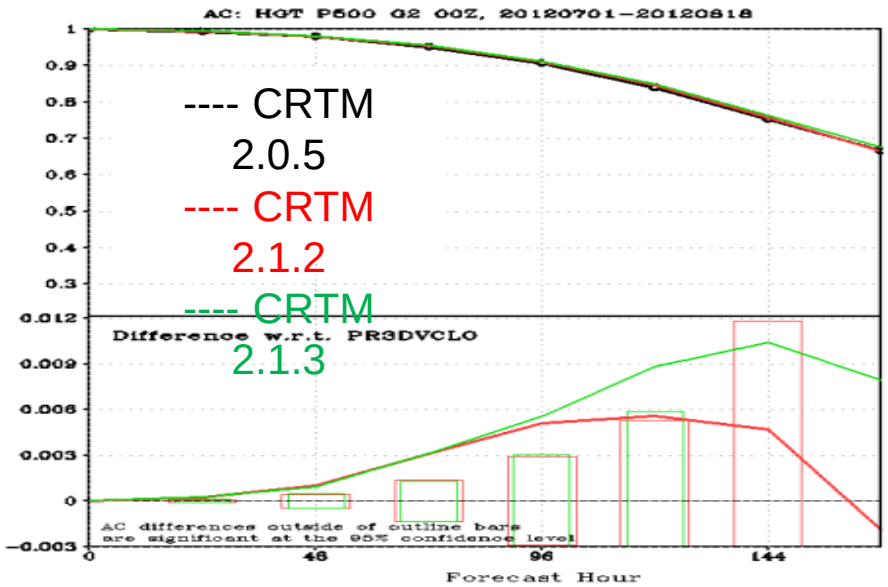
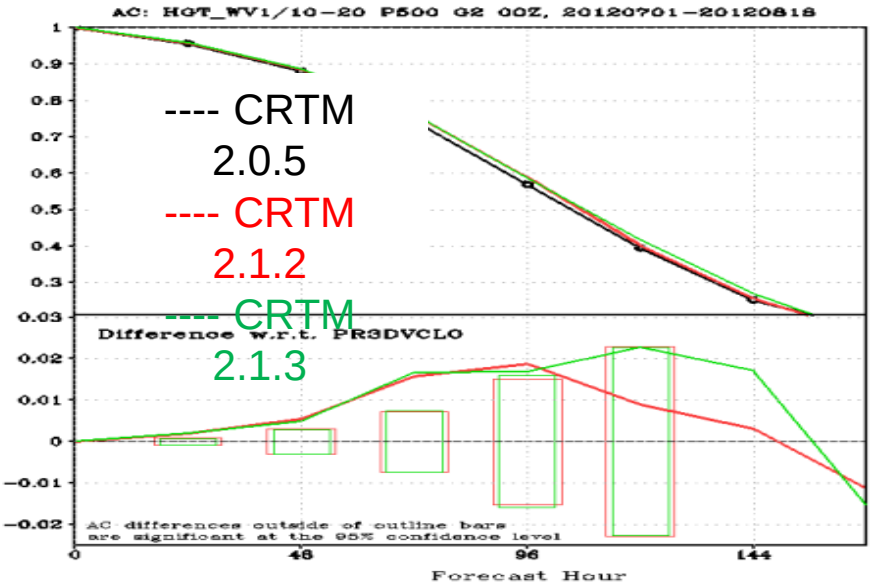
FASTEM-5

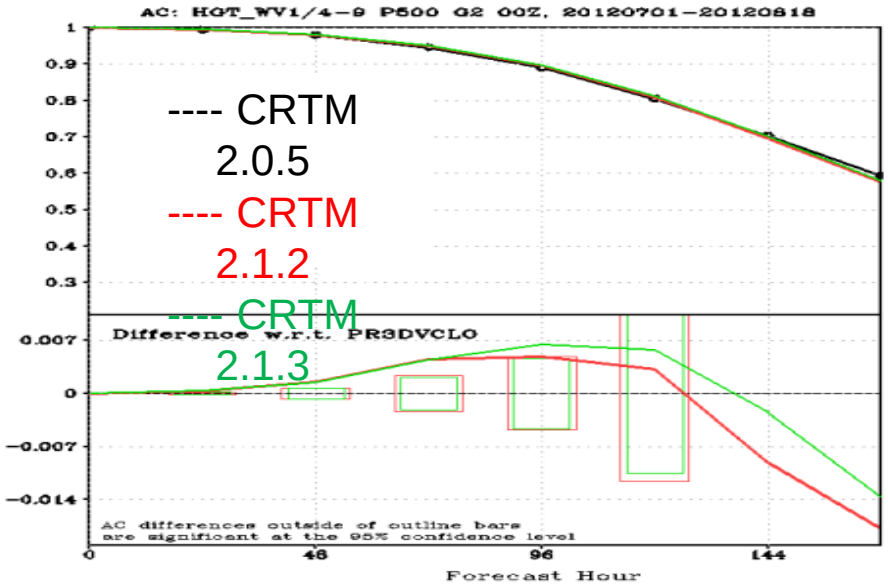

FASTEM5: amsua channel 2
Observed - Calculated dT_B (K)
Wind Speed (m/s)
Number of observations
Observed - Calculated dT_B (K)
FASTEM4: amsua channel 2
FASTEM1: amsua channel 2

Bug Fix Forecast Impact









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Original radiance bias correction scheme

A two-step procedure
- **Air-mass dependent in GSI**
- **Separate scan-angle dependent**

$$\boxed{\tilde{h} = h(x) + b^{air}(x,\beta) + b^{angle},}$$

where $b^{air}(x,\beta) = \sum_{i=1}^{N} \beta_i \left[\alpha_i p_i(x)\right]$

$h(x)$ is radiative transfer model

p_i is predictor term with predictor coeff. β_i

α_i is pre-specified parameter

The control variables x and β are estimated by minimizing (Derber et al., 1991, Derber and Wu, 1998)

$$J(x,\beta) = \frac{1}{2}(x - x_b)^T B_x^{-1}(x - x_b) + \frac{1}{2}(\beta - \beta_b)^T B_\beta^{-1}(\beta - \beta_b)$$

$$+ \frac{1}{2}\left[y - \tilde{h}(x,\beta)\right]^T R^{-1}\left[y - \tilde{h}(x,\beta)\right]$$

What we expect to achieve with the enhanced radiance bias correction scheme

- **Combine the scan angle and air-mass bias components inside the GSI** variational framework.
  - Eliminate the duplications and potential risk of opposite drifting between the two components
- **Remove the pre-specified parameter for each predictor**, so avoid the trial-and-error procedure for any new bias predictors
- Apply a new pre-conditioning to the predictor coefficients taking into account of observation contribution, **speeding up the convergence**

Original scheme: a two-step procedure

- b^{angle} is computed outside GSI, a running average of OMF
- The predictors of air-mass are computed inside the GSI

Enhanced scheme: a one-step procedure

$$b^{angle} = \sum_{k=1}^{K} \beta_{N+k} \phi^{k}$$

- Variational angle bias correction, b^{angle} is computed inside the GSI along with other predictor terms
- satang file no longer needed
- Special attention to the initialization of bias coefficients: using quality-controlled data from previous run; or mode of all data

Change of the Preconditioning

Current preconditioner **Modified preconditioner**

$$\mathbf{B} = \begin{bmatrix} \mathbf{B}_{\mathbf{x}} & 0 \\ 0 & \mathbf{B}_{\boldsymbol{\beta}} \end{bmatrix} \longrightarrow \mathbf{B} = \begin{bmatrix} \gamma\mathbf{B}_{\mathbf{x}} & 0 \\ 0 & \mathbf{M}_{\boldsymbol{\beta}} \end{bmatrix}$$

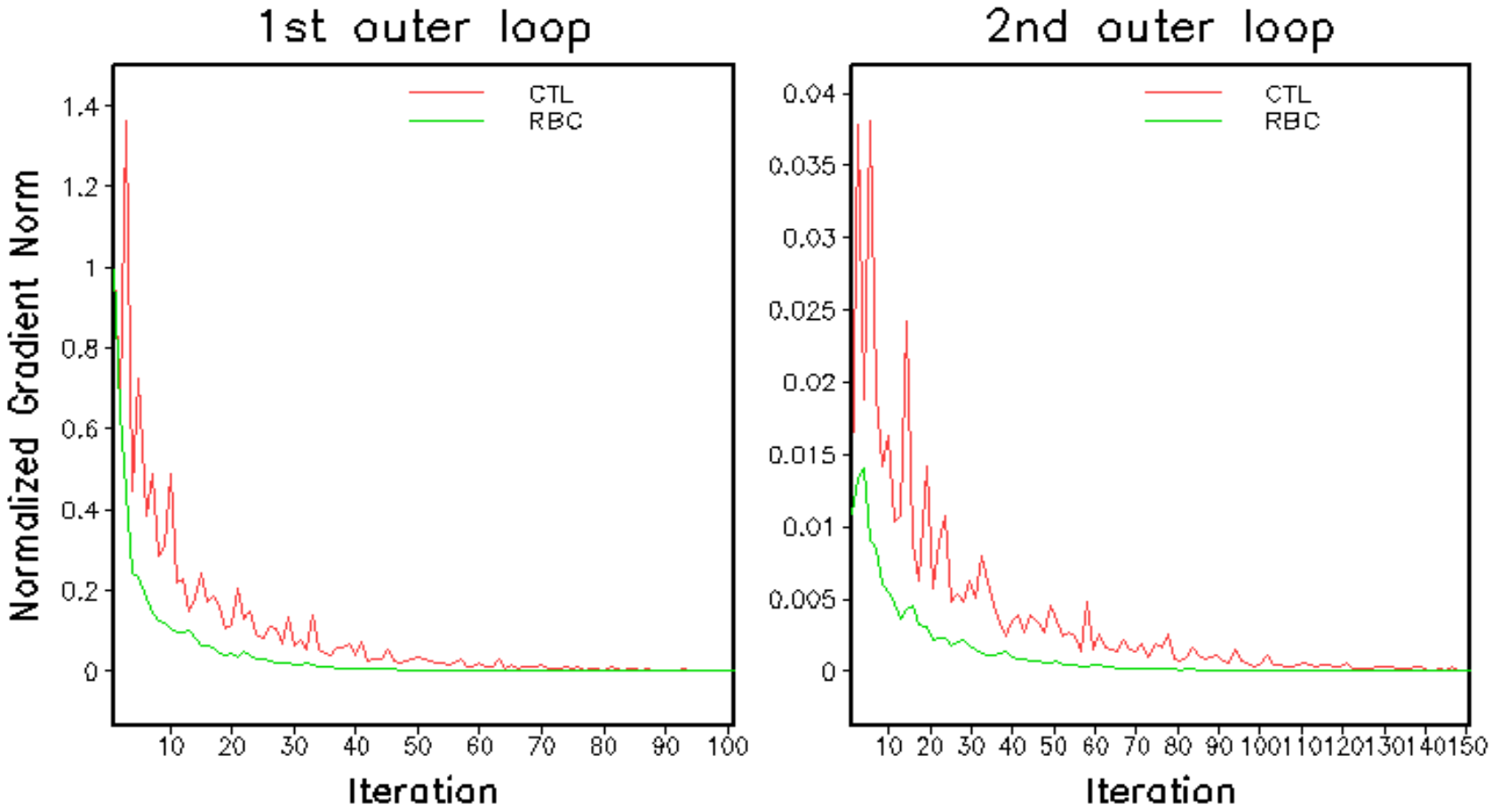
- Hessian w.r.t. predictor coeff. of the cost function

$$\left.\frac{\partial^2 J}{\partial \boldsymbol{\beta}^2}\right|_{\boldsymbol{\beta}=\boldsymbol{\beta}_a} = \mathbf{B}_{\boldsymbol{\beta}}^{-1} + \mathbf{H}_{\boldsymbol{\beta}}^{\mathrm{T}}\mathbf{R}^{-1}\mathbf{H}_{\boldsymbol{\beta}}, \quad \mathbf{H}_{\boldsymbol{\beta}} = \left.\frac{\partial \tilde{h}}{\partial \boldsymbol{\beta}}\right|_{\boldsymbol{\beta}=\boldsymbol{\beta}_a}$$

Modified block-diagonal preconditioning $\mathbf{M}_{\boldsymbol{\beta}}$ is set to be the inverse of $\dfrac{\partial^2 J}{\partial \boldsymbol{\beta}^2}$ (Dee 2004)

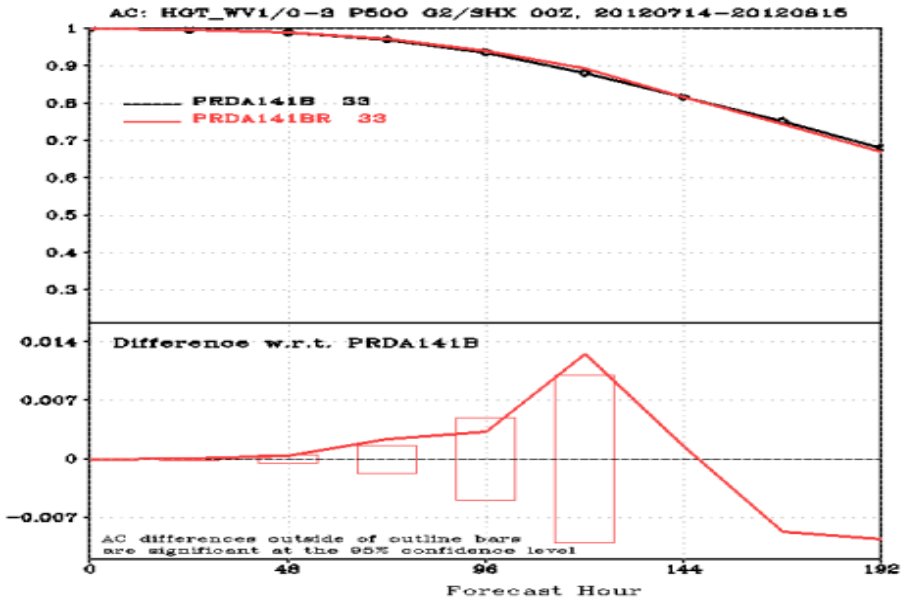
For simplicity, only diagonal elements of $\mathbf{M}_{\boldsymbol{\beta}}$ are considered at each analysis cycle

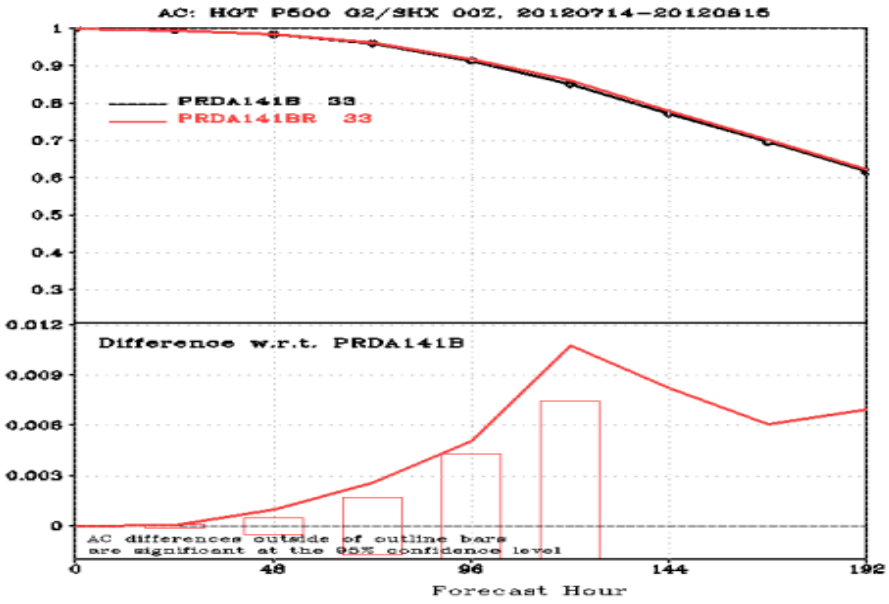
Convergence comparison

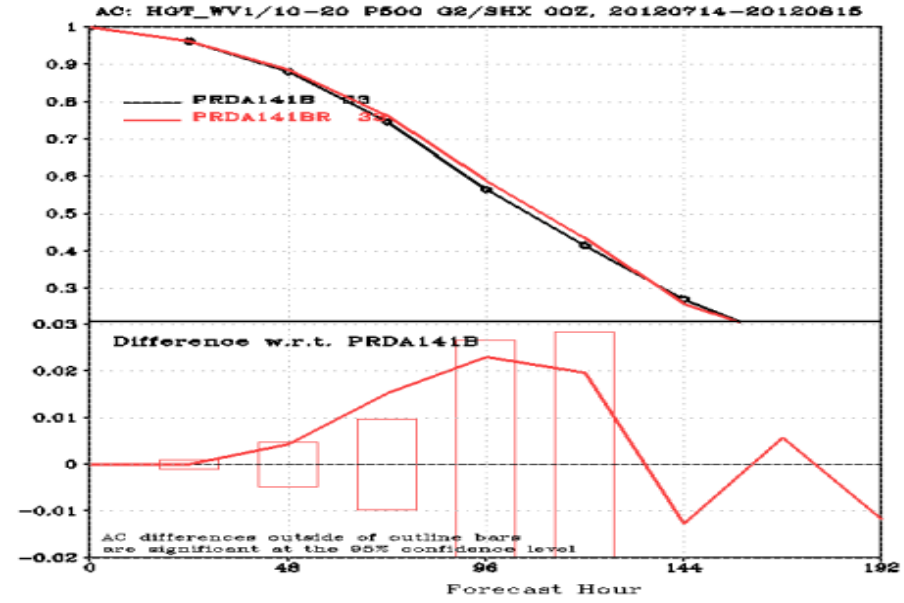


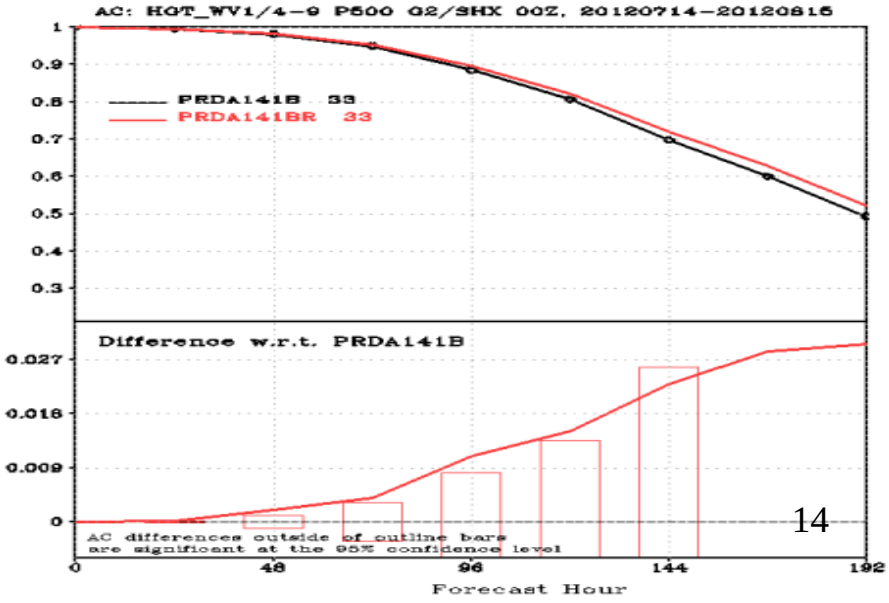
00Z July 15, 2012

HGT 500hpa SH Anomaly Correlation









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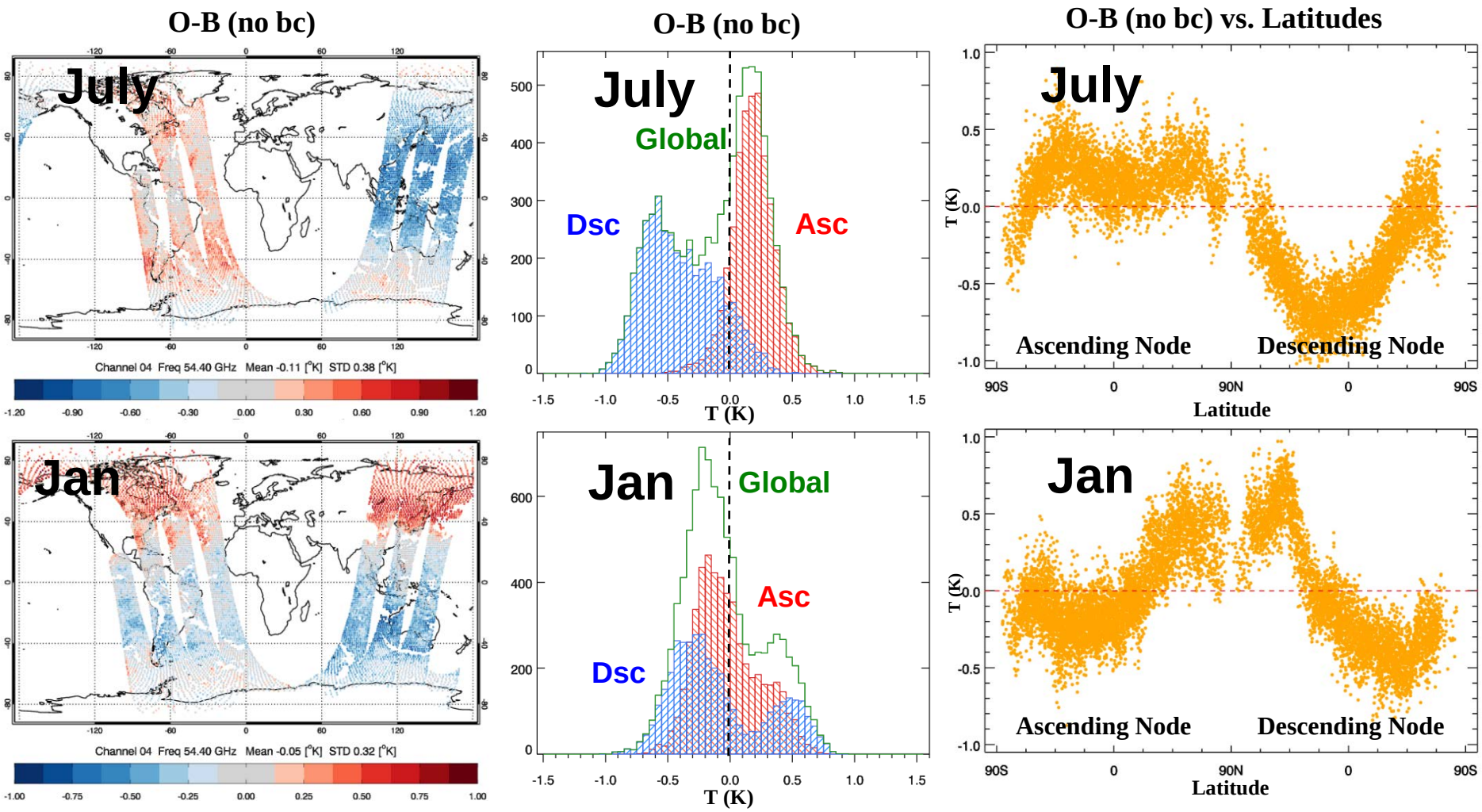
SSMIS F18 Bias Characteristics



- Ascending and descending biases are significant (summer season is worse)
- Ascending pass is warmer than the descending pass
- Latitudinal biases are significant; locations of max/min biases change with season

Variational Bias Correction Scheme

- **Variational bias correction provides an automatic inter-calibration of the observing system in the context of the forecast model, producing bias corrections that improve the consistency of the information entering the analysis**
- **For instruments other than SSMIS the bias correction is calculated using five air-mass predictors and four scan angle predictors**
- **For SSMIS a variety of different additional predictors were tried based on experience at the Met Office, NRL and ECMWF**
- **The Met Office scheme was found to give the best results**

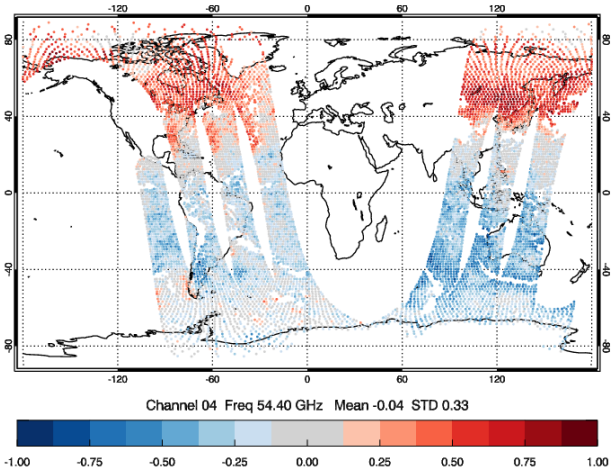
Bias correction predictors used are:

Air-mass					SSMIS specific		Scan angle (θ)			
const offset	zenith angle	cloud liquid water	lapse rate	lapse rate square	$node^{*} \times \cos(lat)$	$\sin(lat)$	θ^4	θ^3	θ^2	θ

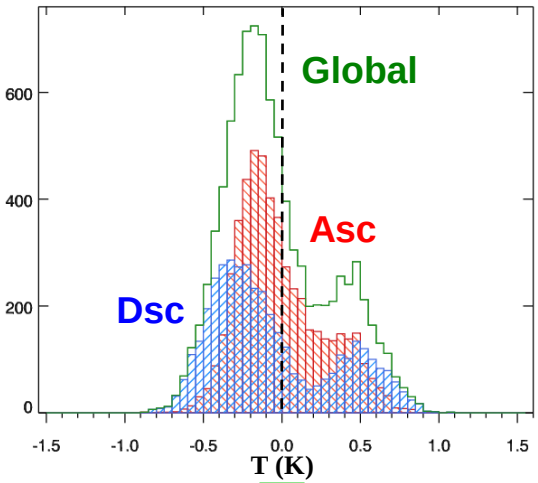
*node is +1 if ascending, -1 if descending

Application of NWP Bias Correction for SSMIS F18

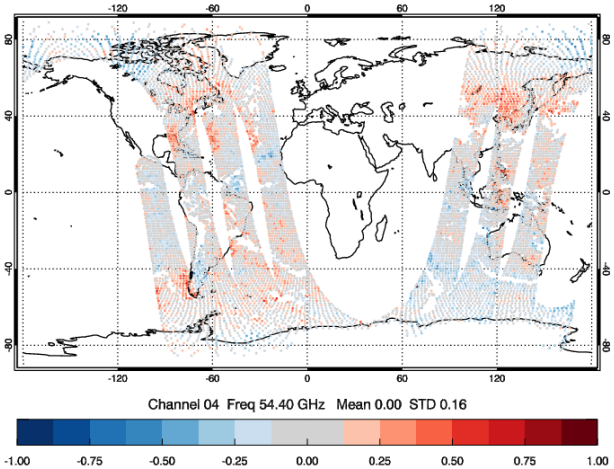
O-B Before Bias Correction



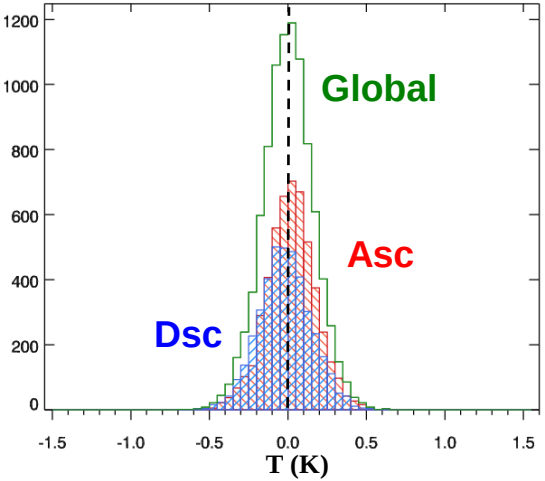
O-B Before Bias Correction



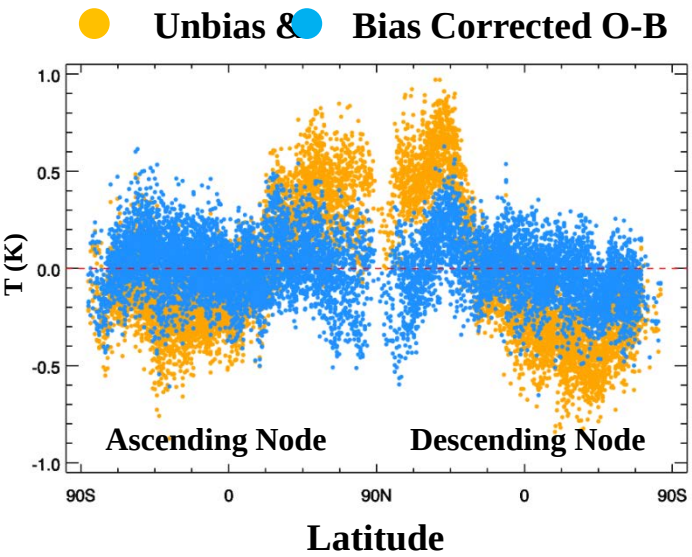
O-B After Bias Correction



O-B After Bias Correction

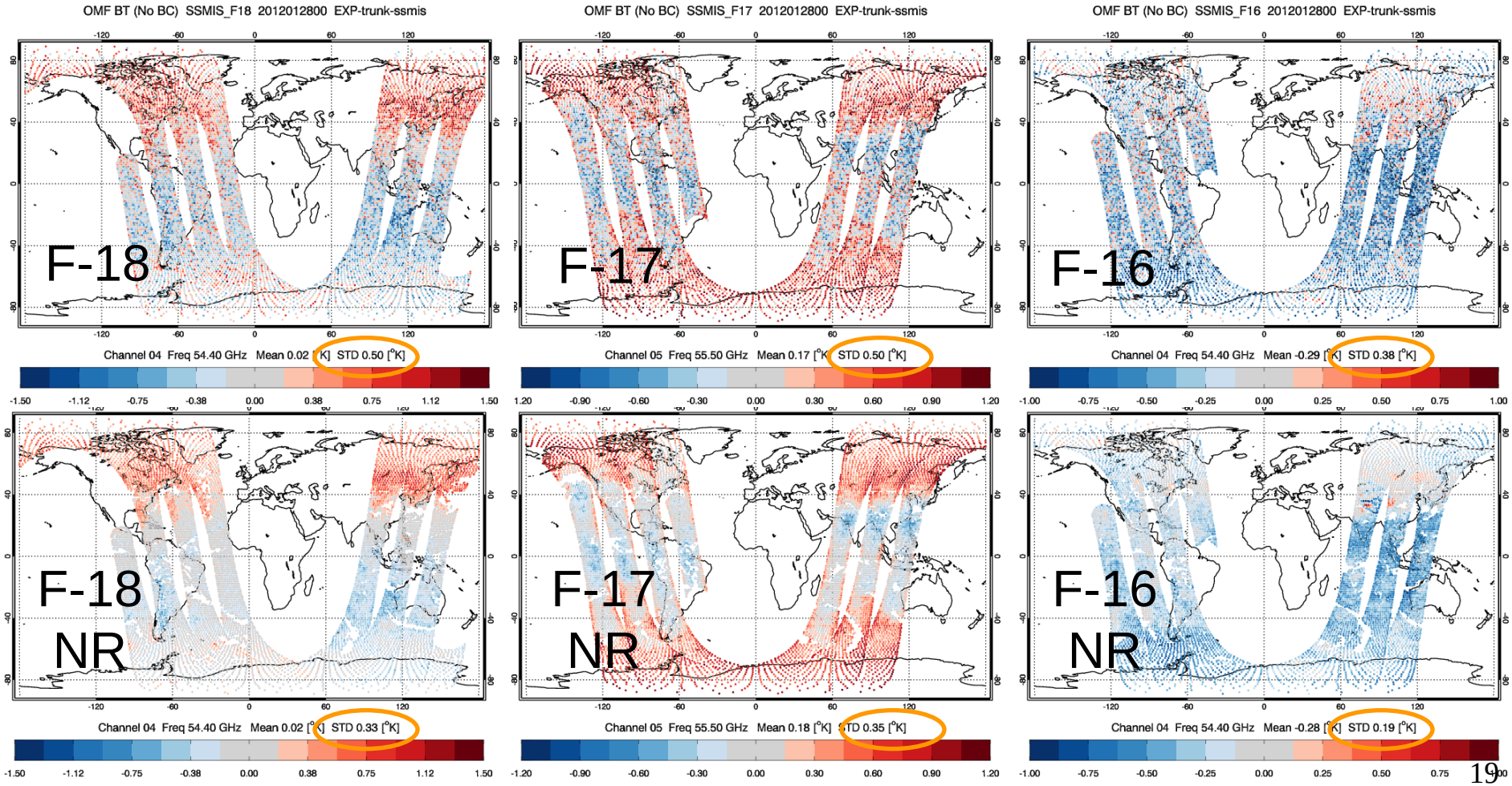


Using Met Office SSMIS Bias Correction Predictors



Application of NWP Noise Reduction for SSMIS

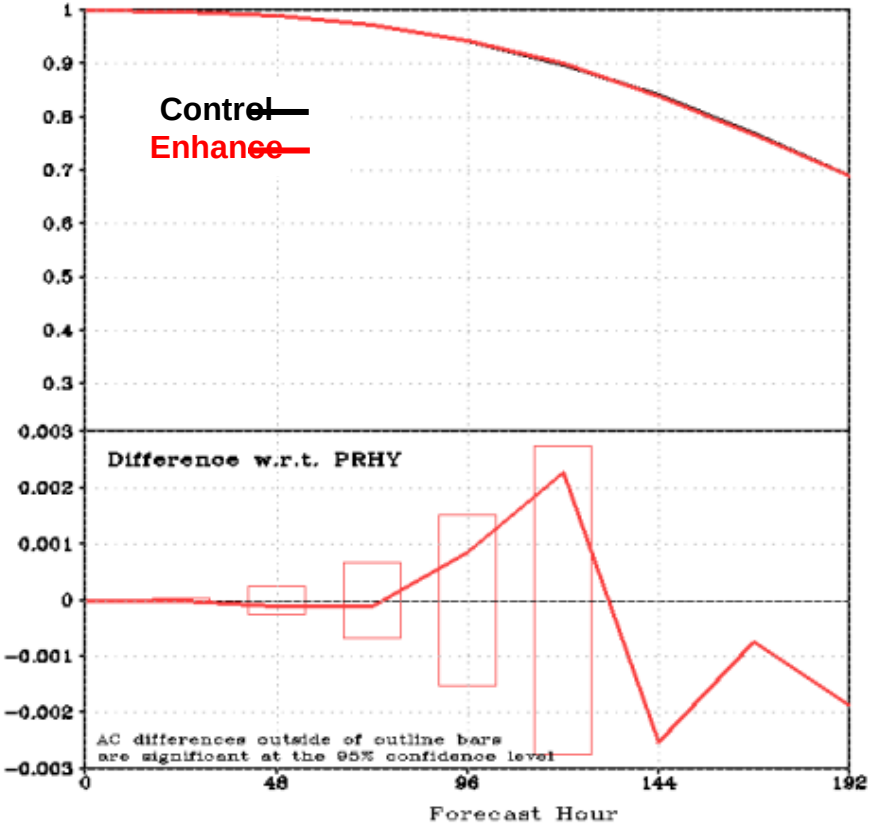
- By design SSMIS oversamples the brightness temperature field at relatively high noise
- Must apply spatial averaging before assimilating the data to reduce the noise
- A spatial averaging scheme was implemented inside of analysis(GSI) for SSMIS



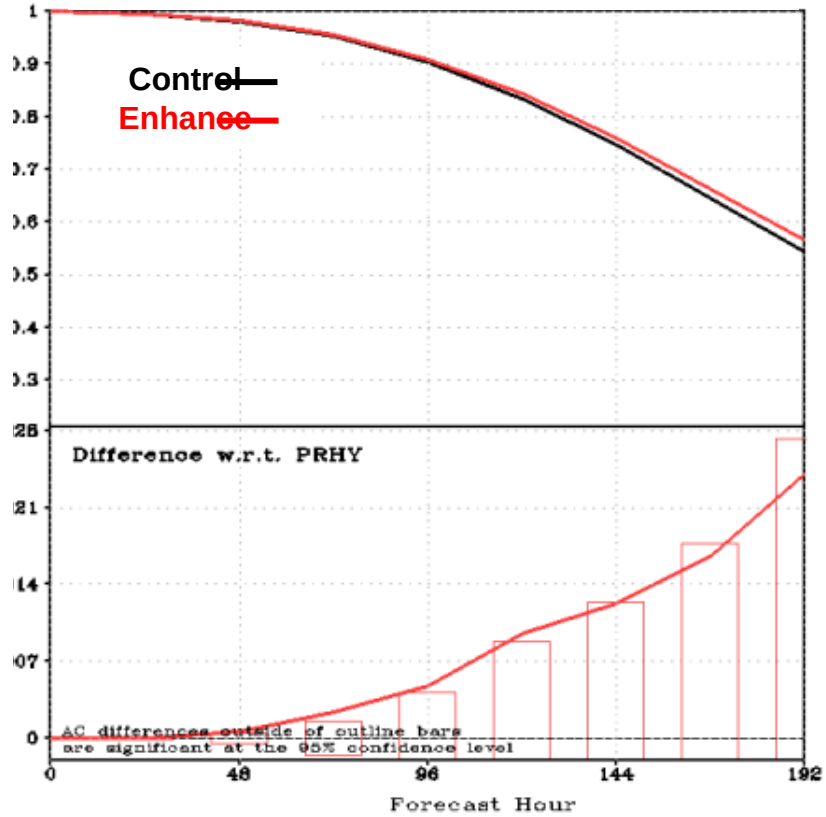
Impact of Assimilating SSMIS into Current Operational System (1)

15 Jan to 30 Mar 2012 (00Z cycles only)

Northern Hemisphere 500 hPa Geopotential Height Anomaly Correlation



Southern Hemisphere 500 hPa Geopotential Height Anomaly Correlation



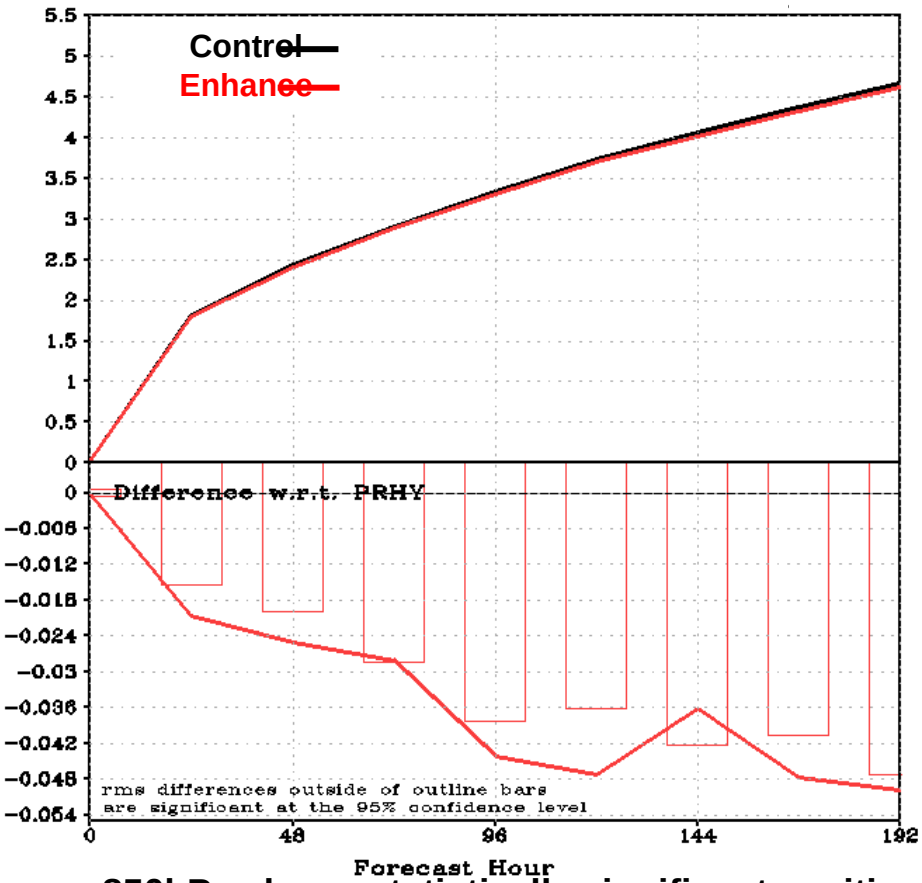
- Impact is not significant in northern hemisphere
- Marginally significant positive impact in southern hemisphere

Impact of Assimilating SSMIS into Current Operational System (2)

Tropical (20°N-20°S) 0 to 5 Day Wind Forecast RMS Errors

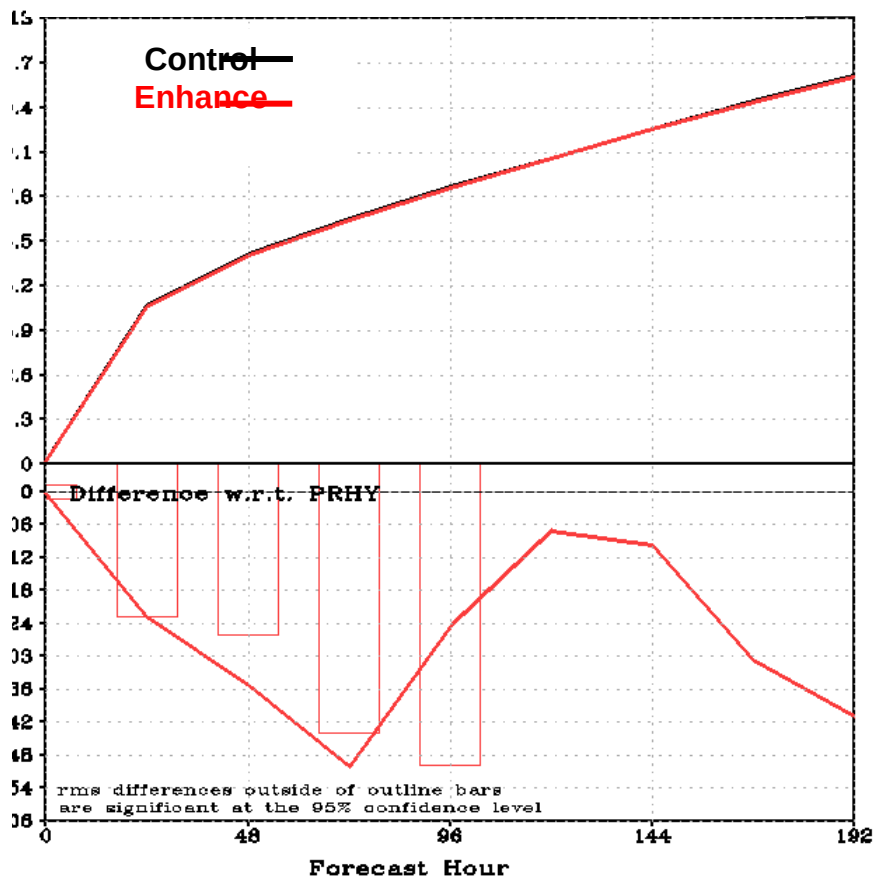
15 Jan to 30 Mar 2012 (00Z cycles only)

850hPa



- **850hPa shows statistically significant positive impact in medium range**

200hPa



- **Some small but significant positive impact in short range for 200hPa winds**

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GSI Hybrid [3D] EnVar

(ignoring preconditioning for simplicity)

- Incorporate ensemble perturbations ***directly*** into variational cost function through extended control variable
  - Lorenc (2003), Buehner (2005), Wang et. al. (2007), etc.

$$J\left(\mathbf{x}_{\mathrm{f}}',\boldsymbol{\alpha}\right)=\boxed{\beta_{\mathrm{f}}\frac{1}{2}\left(\mathbf{x}_{\mathrm{f}}'\right)^{\mathrm{T}}\mathbf{B}_{\mathrm{f}}^{-1}\left(\mathbf{x}_{\mathrm{f}}'\right)}+\boxed{\beta_{\mathrm{e}}\frac{1}{2}\sum_{n=1}^{N}\left(\boldsymbol{\alpha}^{n}\right)^{\mathrm{T}}\mathbf{L}^{-1}\left(\boldsymbol{\alpha}^{n}\right)}+\frac{1}{2}\left(\mathbf{H}\mathbf{x}_{\mathrm{t}}'-\mathbf{y}'\right)^{\mathrm{T}}\mathbf{R}^{-1}\left(\mathbf{H}\mathbf{x}_{\mathrm{t}}'-\mathbf{y}'\right)$$

$$\mathbf{x}_{\mathrm{t}}'=\mathbf{x}_{\mathrm{f}}'+\mathbf{T}\sum_{n=1}^{N}\left(\boldsymbol{\alpha}^{n}\circ\mathbf{x}_{\mathrm{e}}{}^{n}\right)$$

β_{f} & β_{e}: weighting coefficients for fixed and ensemble covariance respectively

$\mathbf{x}_{\mathrm{t}}'$: (total increment) sum of increment from fixed/static **B** ($\mathbf{x}_{\mathrm{f}}'$) and ensemble **B**

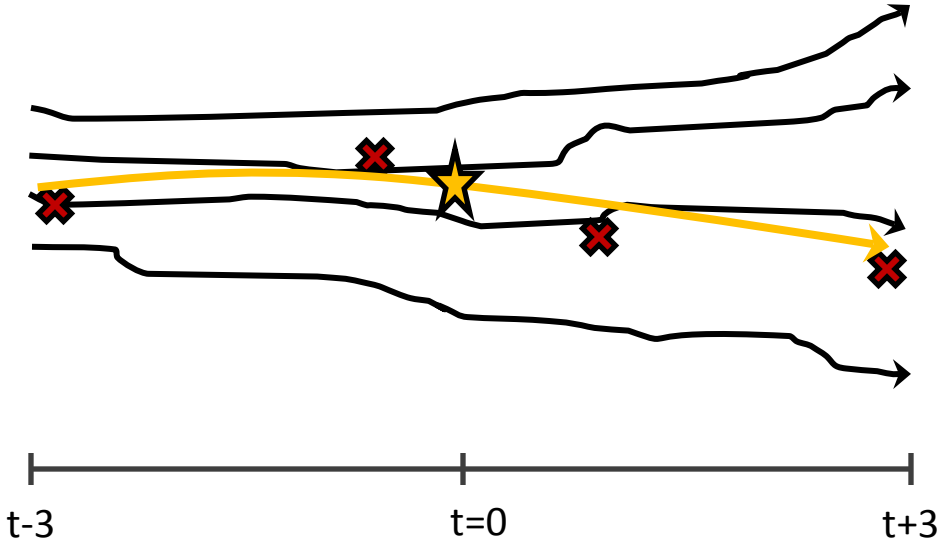
$\boldsymbol{\alpha}_k$: extended control variable; χ_e^{n} :ensemble perturbations

- analogous to the weights in the LETKF formulation

L: correlation matrix [effectively the localization of ensemble perturbations]

T: operator mapping from ensemble grid to analysis grid

4D Data Assimilation



Observations are not necessarily taken at the analysis time, so what can we do?

Hybrid 4D-Ensemble-Var [H-4DENSV]

If we explicitly take account of the time component of the ensembles we have Hybrid 4D Ensemble Var (the extra k indices indicate time sub-windows)

$$J\left(\mathbf{x}'_{\mathrm{f}},\boldsymbol{\alpha}\right)=\beta_{\mathrm{f}}\frac{1}{2}\left(\mathbf{x}'_{\mathrm{f}}\right)^{\mathrm{T}}\mathbf{B}_{\mathrm{f}}^{-1}\left(\mathbf{x}'_{\mathrm{f}}\right)+\beta_{\mathrm{e}}\frac{1}{2}\sum_{n=1}^{N}\left(\boldsymbol{\alpha}^{n}\right)^{\mathrm{T}}\mathbf{L}^{-1}\left(\boldsymbol{\alpha}^{n}\right)+\frac{1}{2}\sum_{k=1}^{K}\left(\mathbf{H}_{k}\mathbf{x}'_{k}-\mathbf{d}_{k}\right)^{\mathrm{T}}\mathbf{R}_{k}^{-1}\left(\mathbf{H}_{k}\mathbf{x}'_{k}-\mathbf{d}_{k}\right)$$

Where the 4D increment is prescribed exclusively through linear combinations of the 4D ensemble perturbations plus static contribution

$$\mathbf{x}'_{k}=\mathbf{x}'_{\mathrm{f}}+\mathbf{T}\sum_{n=1}^{N}\left(\boldsymbol{\alpha}^{n}\circ\left(\mathbf{x}_{\mathrm{e}}\right)_{k}^{n}\right)$$

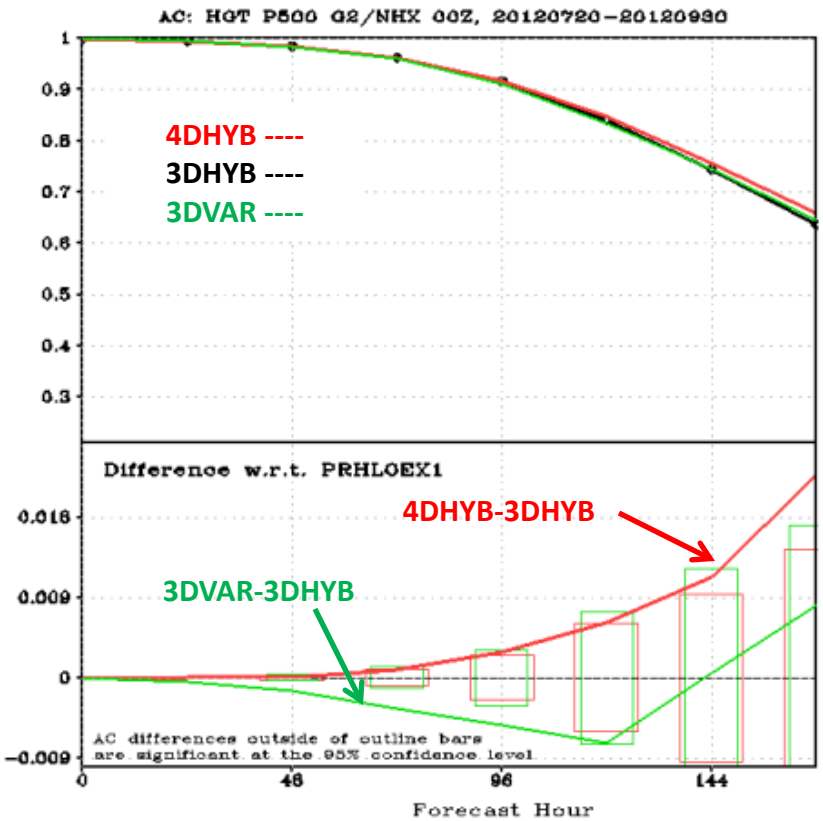
Here, the static contribution is considered time-invariant (i.e. from 3DVAR-FGAT). Weighting parameters exist just as in the other hybrid variants. Again, **no TLM or ADJ**!

4D EnVar: Way Forward

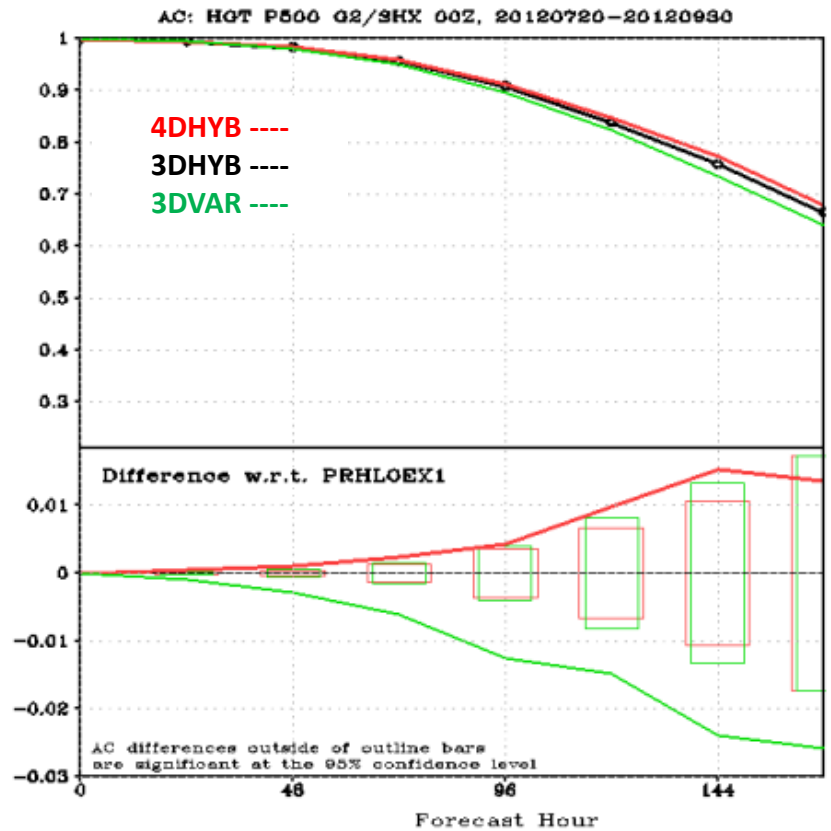
- Natural extension to operational EnVar
  - Uses variational approach in combination with already available 4D ensemble perturbations (covariance estimates)
- No need for development of maintenance of TLM and ADJ models
  - Makes use of 4D ensemble to perform 4D analysis
  - Very attractive, modular, usable across a wide variety of applications and models
- Highly scalable
  - And can be improved even further
  - Aligns with technological/computing advances
- Computationally inexpensive relative to 4DVAR (with TL/AD)
  - Estimates of improved efficiency by 10x or more, e.g. at Env. Canada (6x faster than 4DVAR on half as many cpus)
- Compromises to gain best aspects of (4D) variational and ensemble DA algorithms
- Other centers pursuing similar path forward for deterministic NWP
  - Canada (replace 4DVAR), UMKO? (ensemble of 4D Ensemble Var)

500 hPa Die Off Curves

Northern Hemisphere



Southern Hemisphere



Move from 3D Hybrid (current operations) to Hybrid 4D-EnVar yields improvement that is about 75% in amplitude in comparison from going to 3D Hybrid from 3DVAR.

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Other on-going and future projects

- Cloudy radiance assimilation:
  - Mutli-pronged attack on the problem for both infrared and microwave observations.
- GOES-R readiness:
  - Preparing to switch to new processing for GOES AMVs in preparation for GOES-R
  - Developed clear-sky radiance generation capability in preparation for GOES-R radiances.
  - Starting work on assimilating cloudy GOES-R radiances using SEVIRI as a proxy
  - Improved sea-surface temperature analysis will aid assimilation of geo radiances through better simulation of the diurnal cycle.