On the treatment of random and systematic errors in satellite data assimilation for NWP

CVarBC
(Constrained Variational Bias Correction)

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[1]JCSDA, [2]NWPC/CMA, [3]ECMWF

ECMWF/EUMETSAT NWP SAF Workshop
November 2-5, 2020

Outline

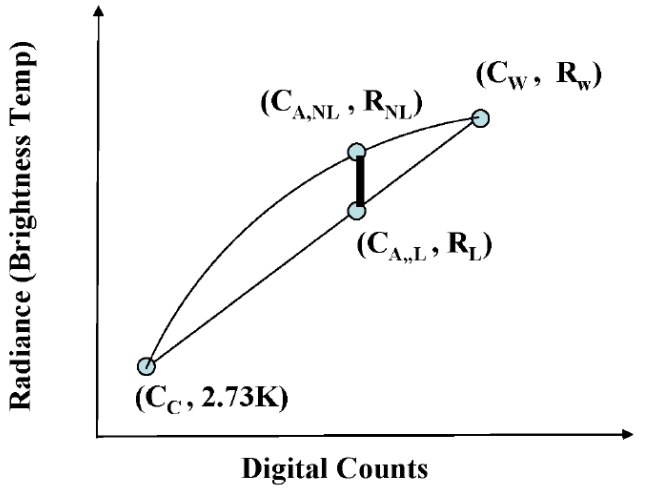
- **Background**
  - The bias correction is an ill-posed problem
  - PRIORI information for observation bias
- **Methodology**
  - **Use of priori information as constraint**
  - Constrained BC(**CBC**) and Constrained VarBC (**CVarBC**)
- **CBC in GRAPES (2014) and CVarBC in ECMWF IFS (2016,2018)**
  - Window channel and Upper sounding channels
  - Stratospheric Temperature sounding AMSUA Ch14
- **Summary and Discussions**
  - Using Priori: Radiance Uncertainty (RU)
  - Optimal estimate of parameters in CVarBC

Motivation

$$\delta J = \left\langle \frac{\partial J}{\partial \mathbf{y}}, \mathbf{y} - \mathbf{H}\mathbf{x}_b - \mathbf{b} \right\rangle$$

FSO: Forecast sensitivity to observation
Over or under bias correction could lead to negative impact

- **Interaction between Bias Correction and Quality Control**
  - **Window channel**: cloud contamination
  - Bias estimation for **Non-Gaussian** observations(IR: cold tail; MW: warm tail)
- **How to separate observation bias and model bias from O-B?**
  - Temperature sounding channels in **stratosphere**
  - **Trace gas** sounding channels, e.g. IASI Ozone channels
  - **Humidity** sounding channels
  - Developing NWP systems
- **What did we know about Observation Bias?**
  - **Radiometric Uncertainty** Estimation
  - Systematic differences from **GSICS**
  - **RT** model uncertainty
- **Using the PRIORI information to constrain BC**

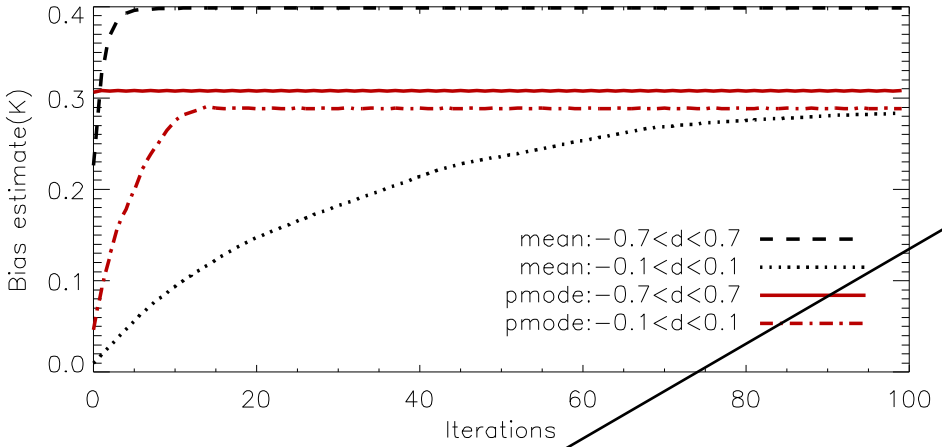


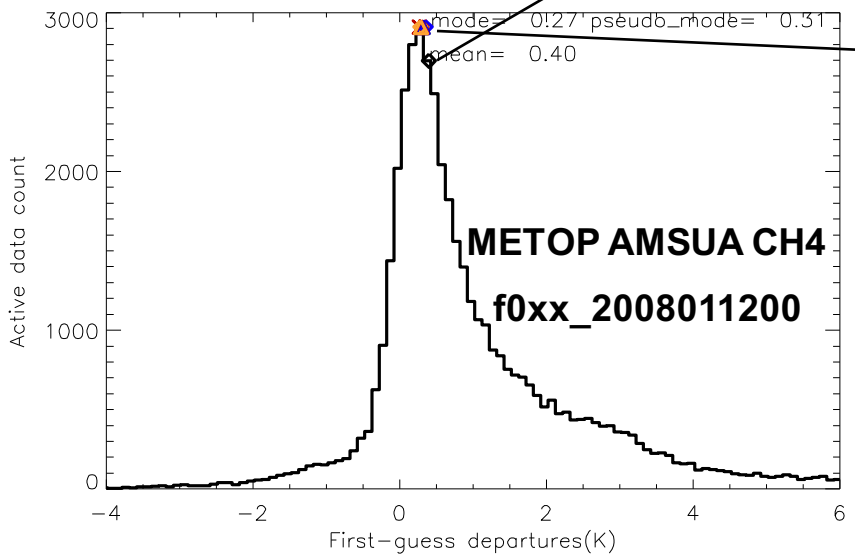
$$R_A = R_C + S(C_A - C_C) + \mu S^2 (C_A - C_C)(C_A - C_W)$$

BC and QC interaction

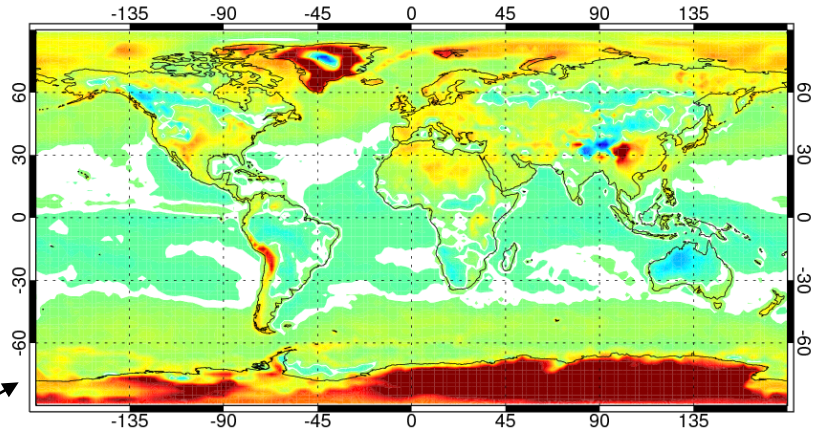
Mean: If bias is estimated by <O-B>, It will strongly depend on the QC,

0.7 → b=0.4; 0.1 → b=0.28

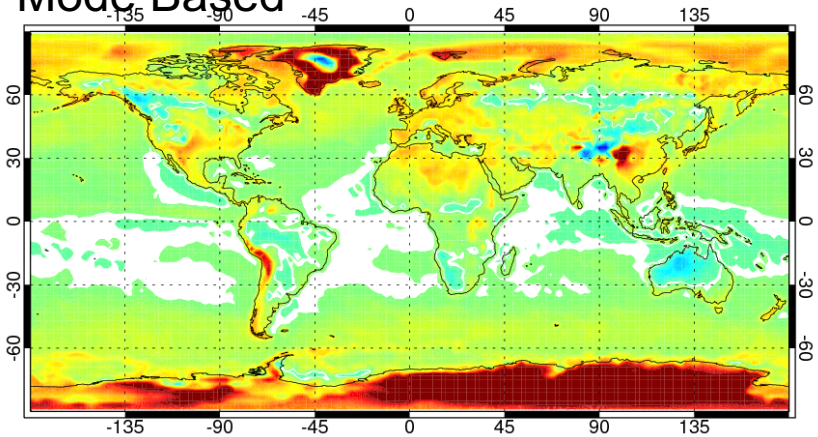




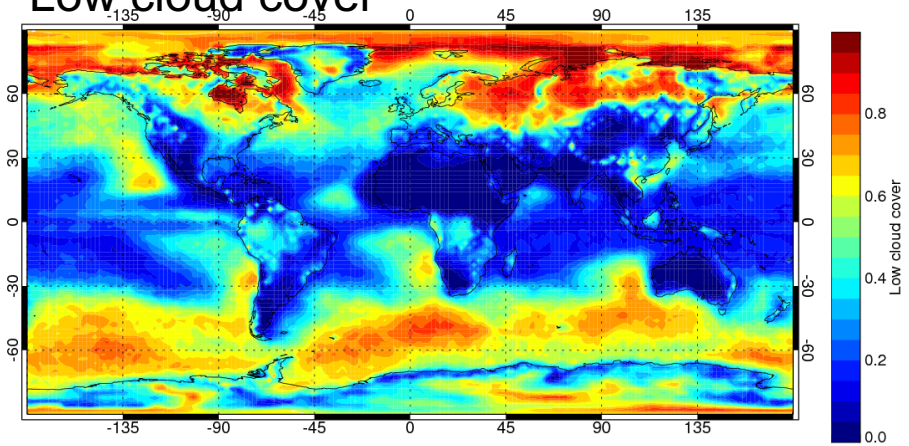
Mean Based **2007D08JF,ECMWF,IFS**



Mode Based

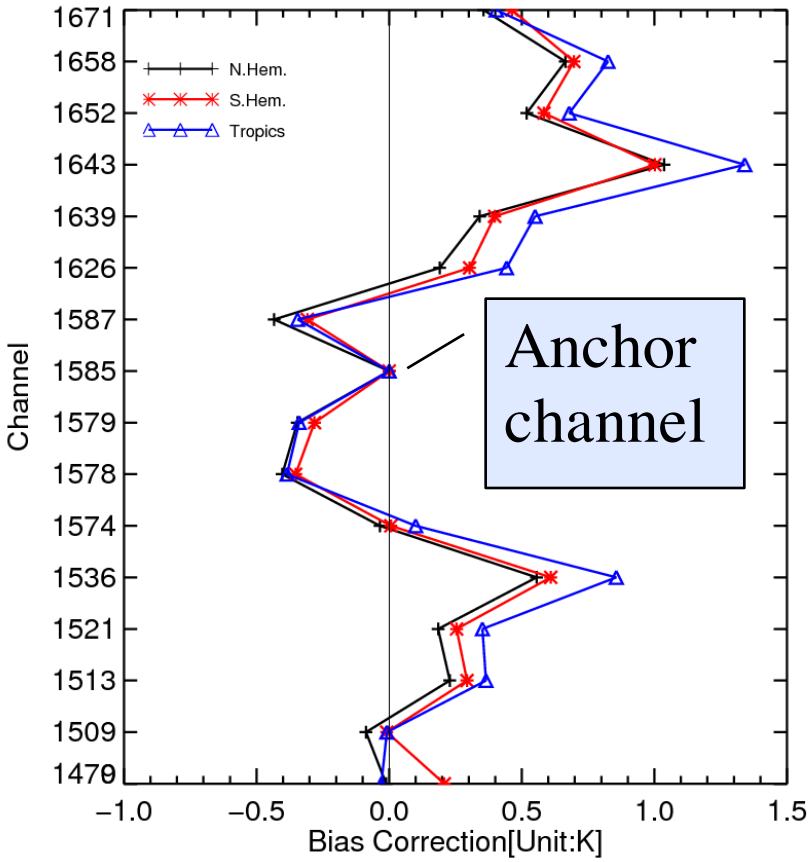


Low cloud cover



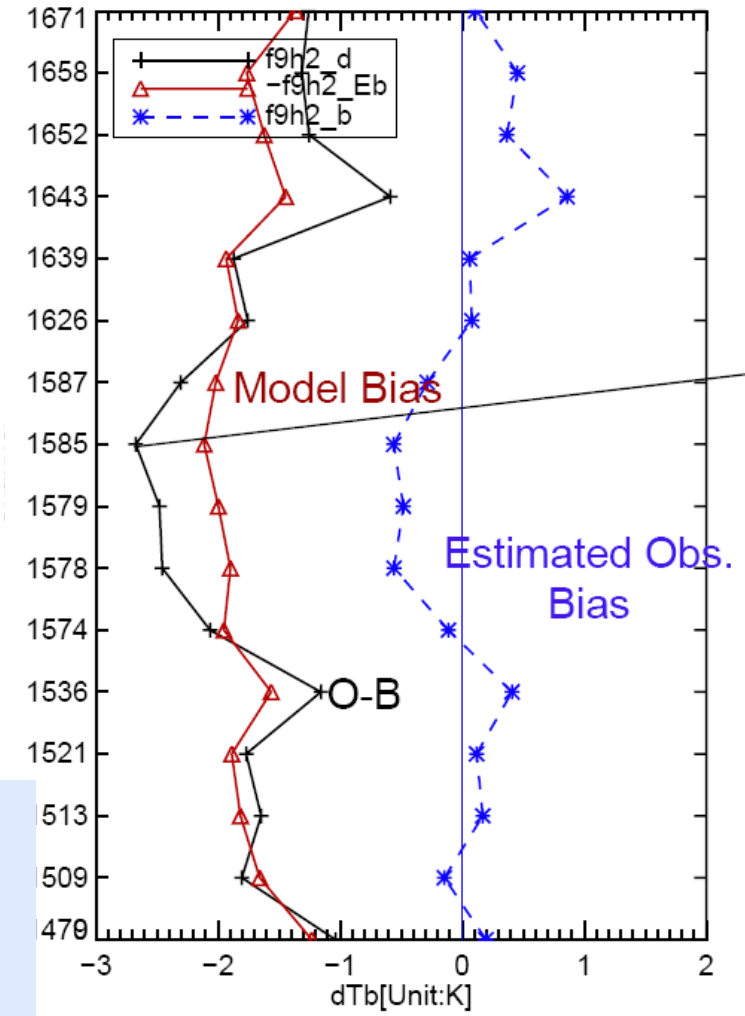
Han and McNally 2008; Li ,McNally and Geer,2010

“Anchor channel” method for IASI ozone channels

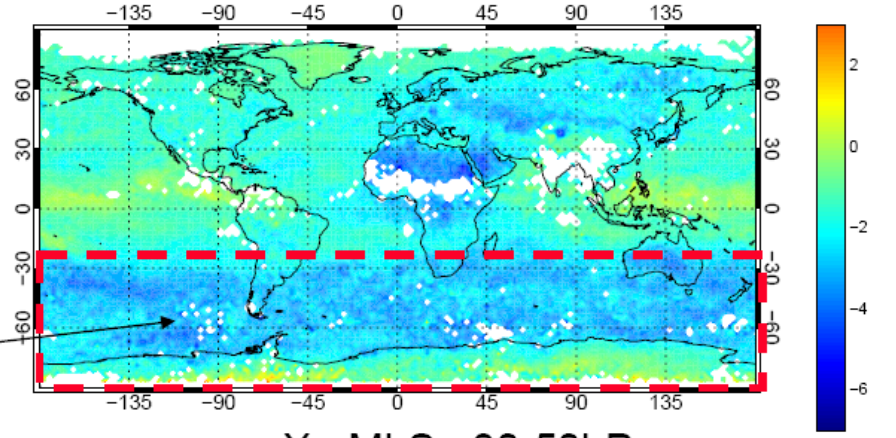


MLS→ Model Bias and Obs. Bias

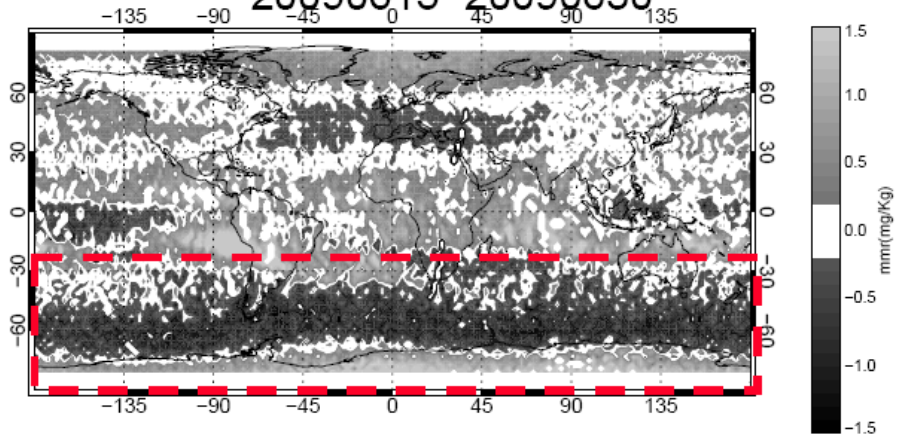
d=Yo-Hx=(Yt+b)-H(Xt+Eb)
<d>=<b>-H(Eb)
<b>=<d>+ H(Eb)



<O-B>,CH1585
20090615~20090630



<Xa-MLS>,30-50hPa
20090615~20090630

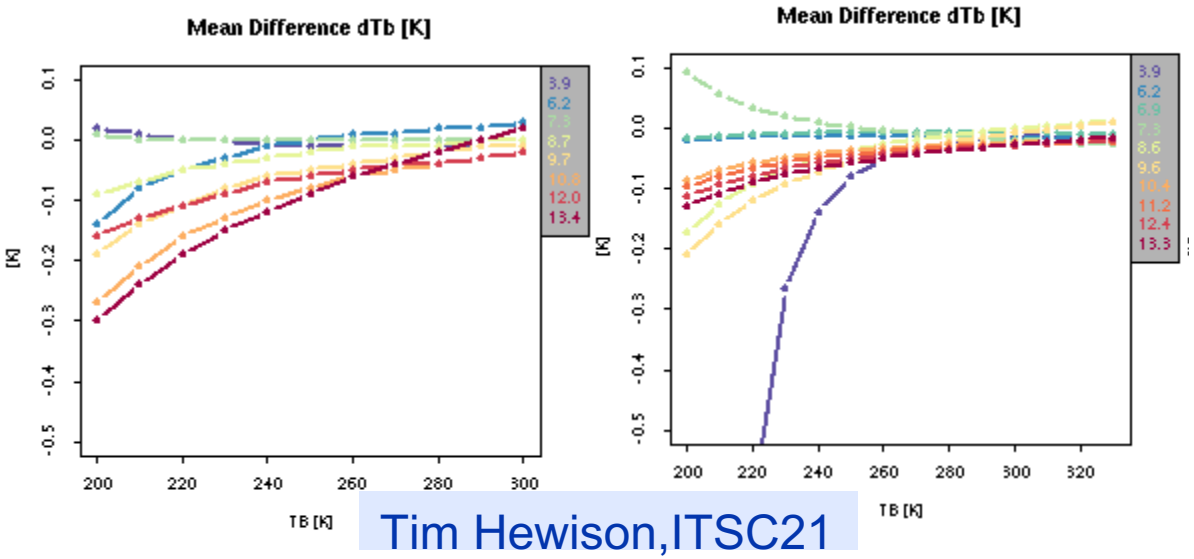


Han W. and McNally AP. 2010: The 4D-Var assimilation of ozone-sensitive infrared radiances measured by IASI. *Q. J. R. Meteorol. Soc.* 136: 2025–2037. DOI:10.1002/qj.708

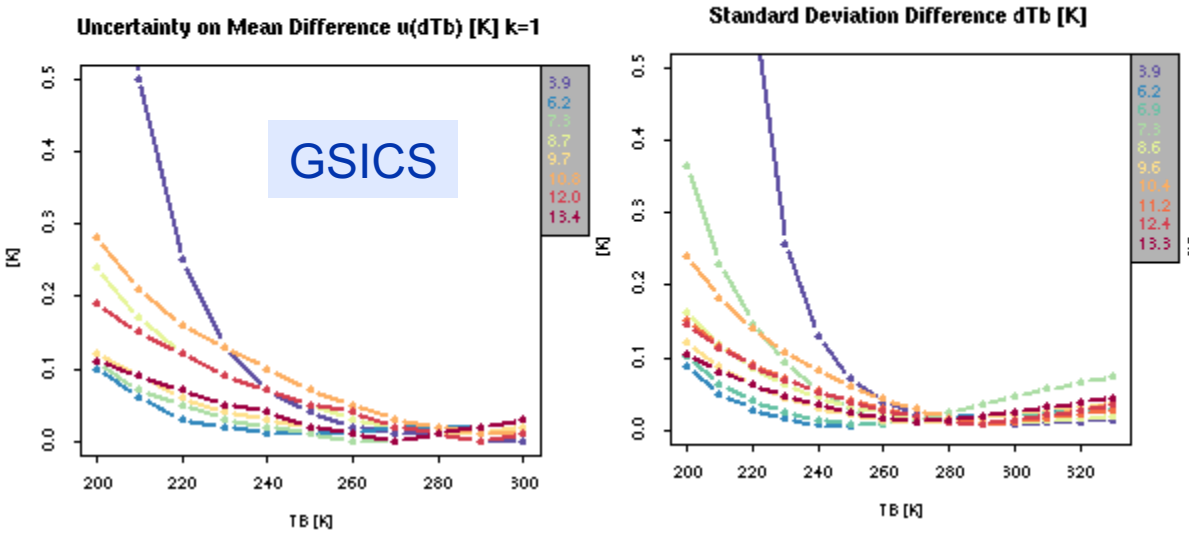
Radiometric Uncertainty

Meteosat-10/SEVIRI IR
2013-03-01/2017-03-01

Himawari-8/AHI IR
2015-07-01/2017-06-30

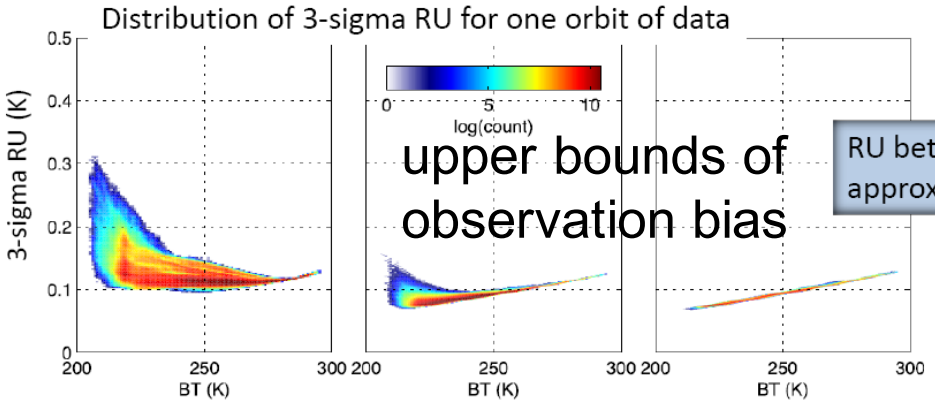


Tim Hewison,ITSC21



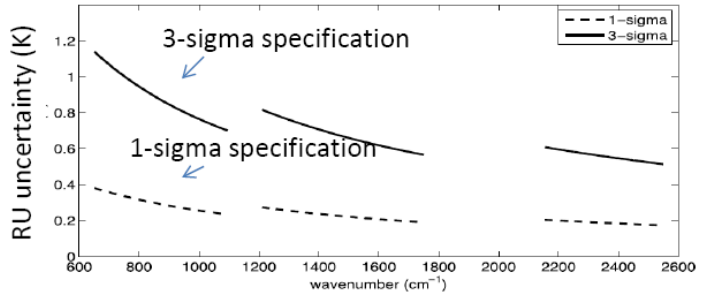
GSICS

Radiometric Uncertainty (RU)



upper bounds of observation bias

RU better than spec by approximately a factor 4

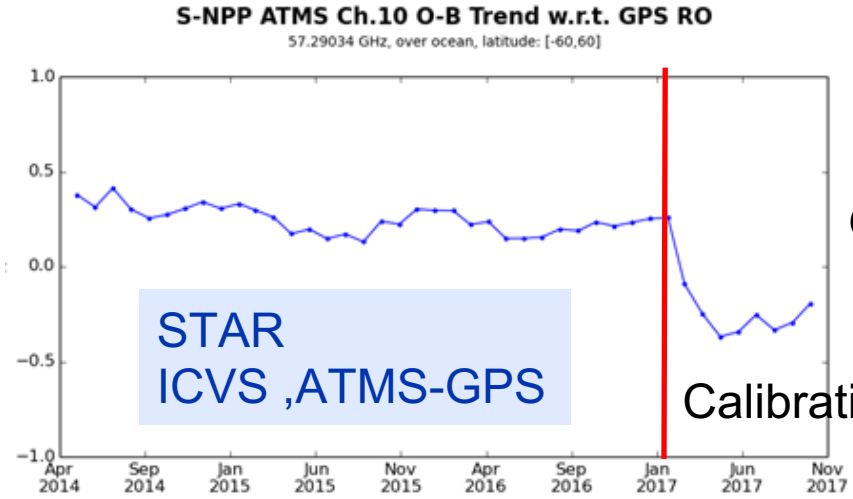


Tobin et al ,2013

Uncertainty specification
@287K blackbody

Tobin et al. 2013, JGR

15



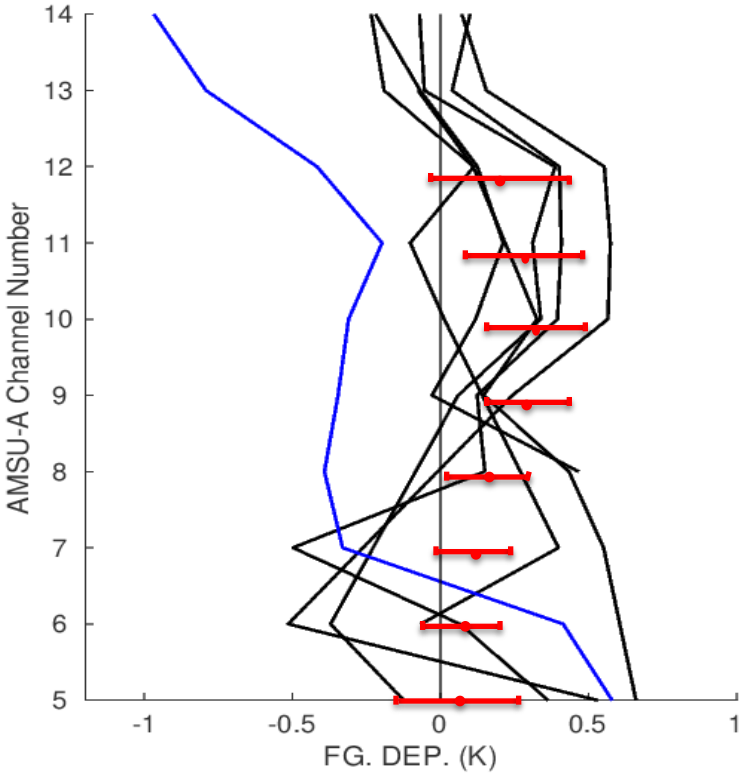
GPS RO as refrence

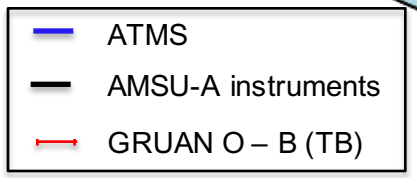
STAR
ICVS ,ATMS-GPS

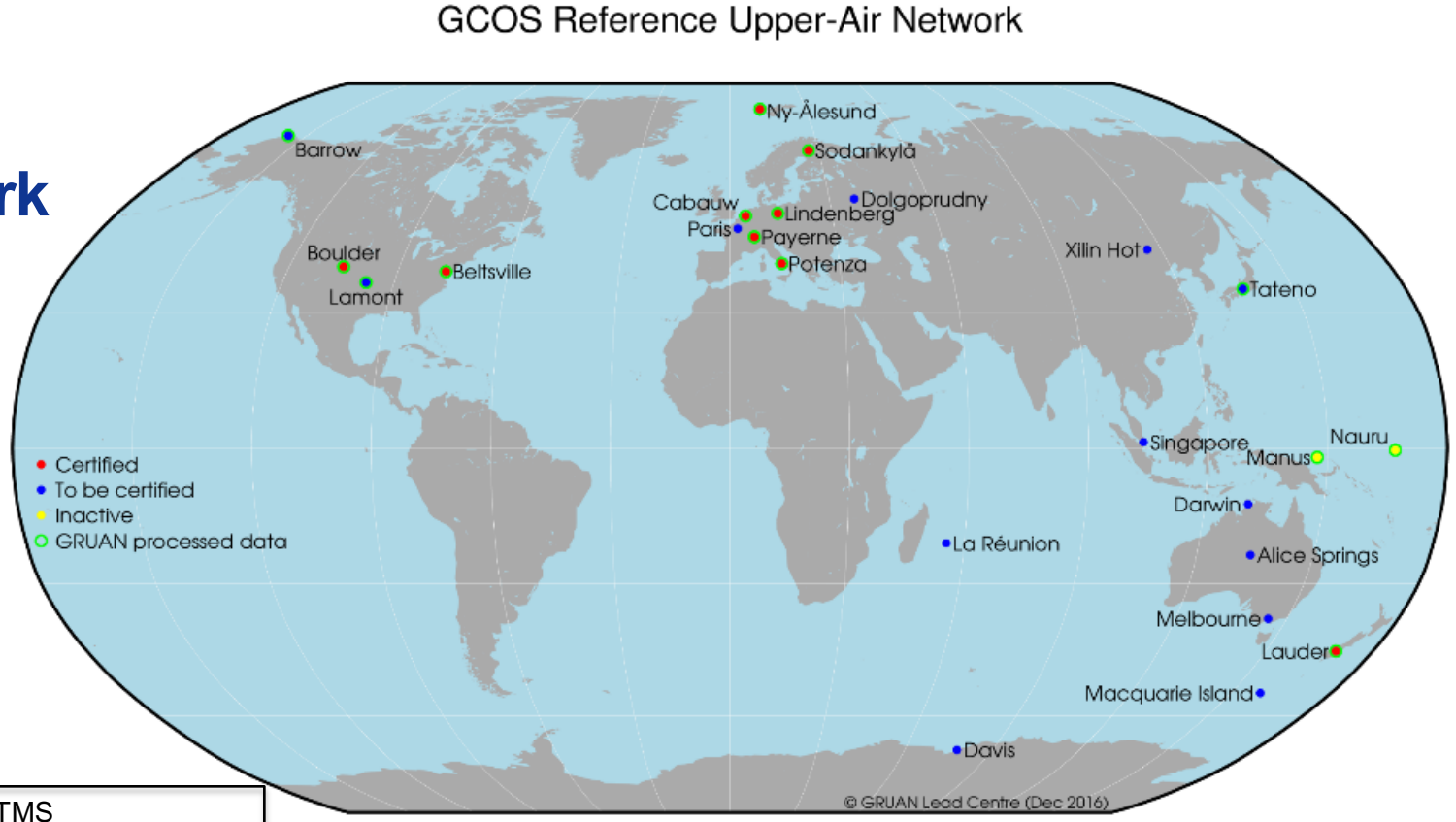
Calibration update

Uncertainty estimation of Satellite observations:

GCOS reference Upper-air Network







GAIA-CLIM project(ECMWF,UKMO)

Comparison of IASI radiances with NWP models from four operational centres

Fiona Hilton[1], Andrew Collard[2], Lars Fiedler[3],Lydie Lavanant[4]

[1]Met Office [2]ECMWF [3]EUMETSAT [4]Météo-France/CMS

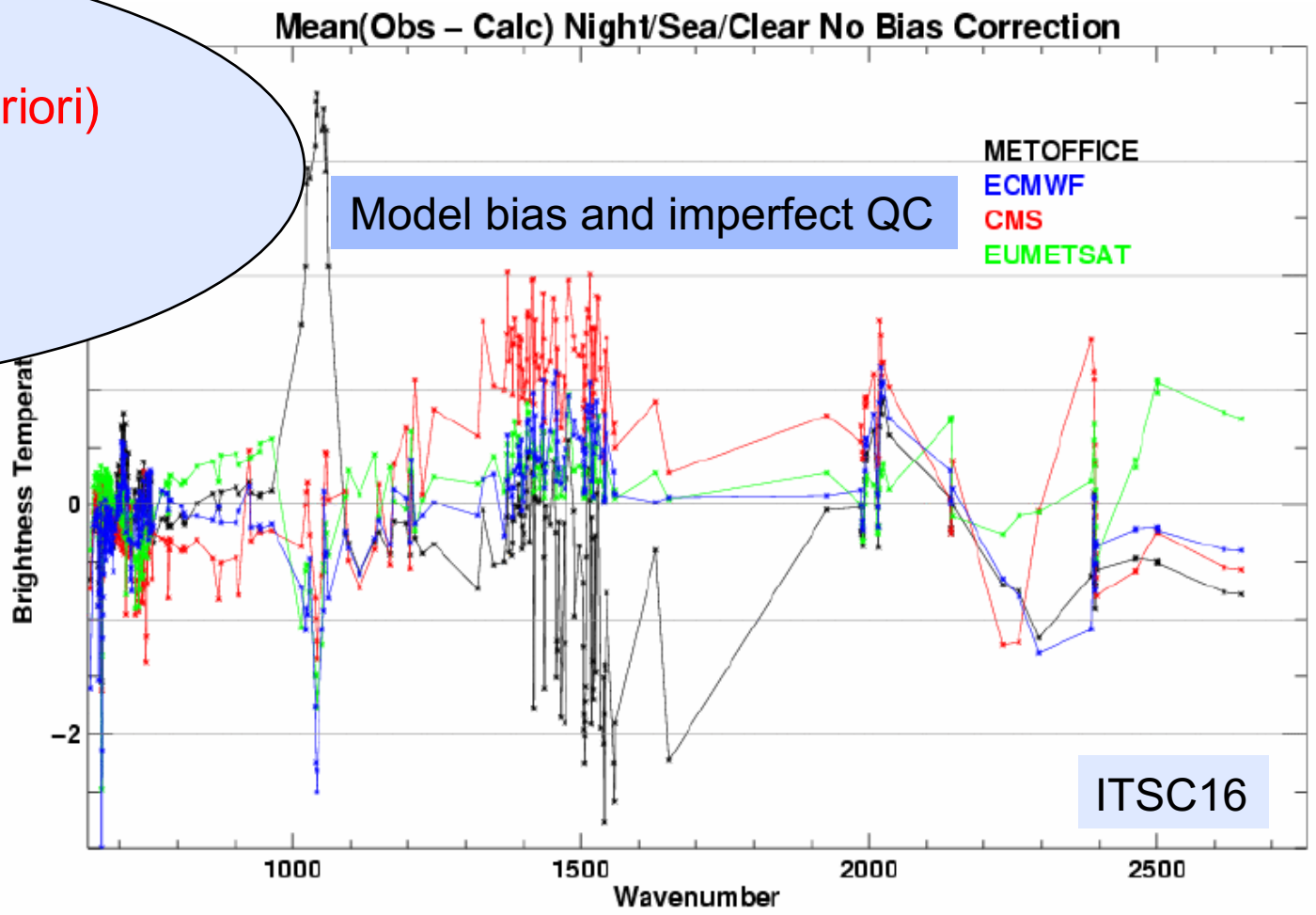
Constrained Bias Correction

How to use the
UNCERTAINTY INFORMATION(Priori)
From GSICS、calibration and RT model in
BIAS CORRECTION?

UNCERTAINTY

BIAS CORRECTION

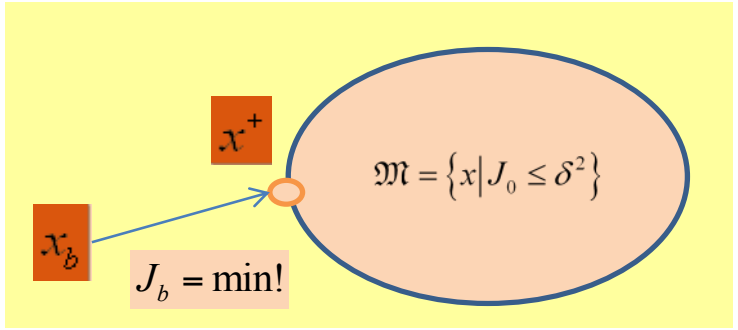
Connect the two GROUP



Methodology: Constrained Variational Bias Correction (CvarBC)

$$2J(\mathbf{x},\boldsymbol{\beta}) = (\mathbf{x}_b-\mathbf{x})^T\mathbf{B}_x^{-1}(\mathbf{x}_b-\mathbf{x}) + (\boldsymbol{\beta}-\boldsymbol{\beta}_b)^T\mathbf{B}_\beta^{-1}(\boldsymbol{\beta}-\boldsymbol{\beta}_b) + [\mathbf{y}-H(\mathbf{x})-h(\mathbf{x},\boldsymbol{\beta})]^T\mathbf{R}^{-1}[\mathbf{y}-H(\mathbf{x})-h(\mathbf{x},\boldsymbol{\beta})]$$

$$\|\mathbf{b}\| \le \|\mathbf{e}\|_{calibration} + \|\mathbf{e}\|_{RT\,model} + \|\mathbf{e}\|_{other}$$



$$J_b = \min_{x \in m} \qquad m = \{x | J_0 \le \delta\}$$

$$||h(x,\beta) - b_0|| \le \delta^2$$

Constrain the total size of bias correction to each channel (Weak Constraint)

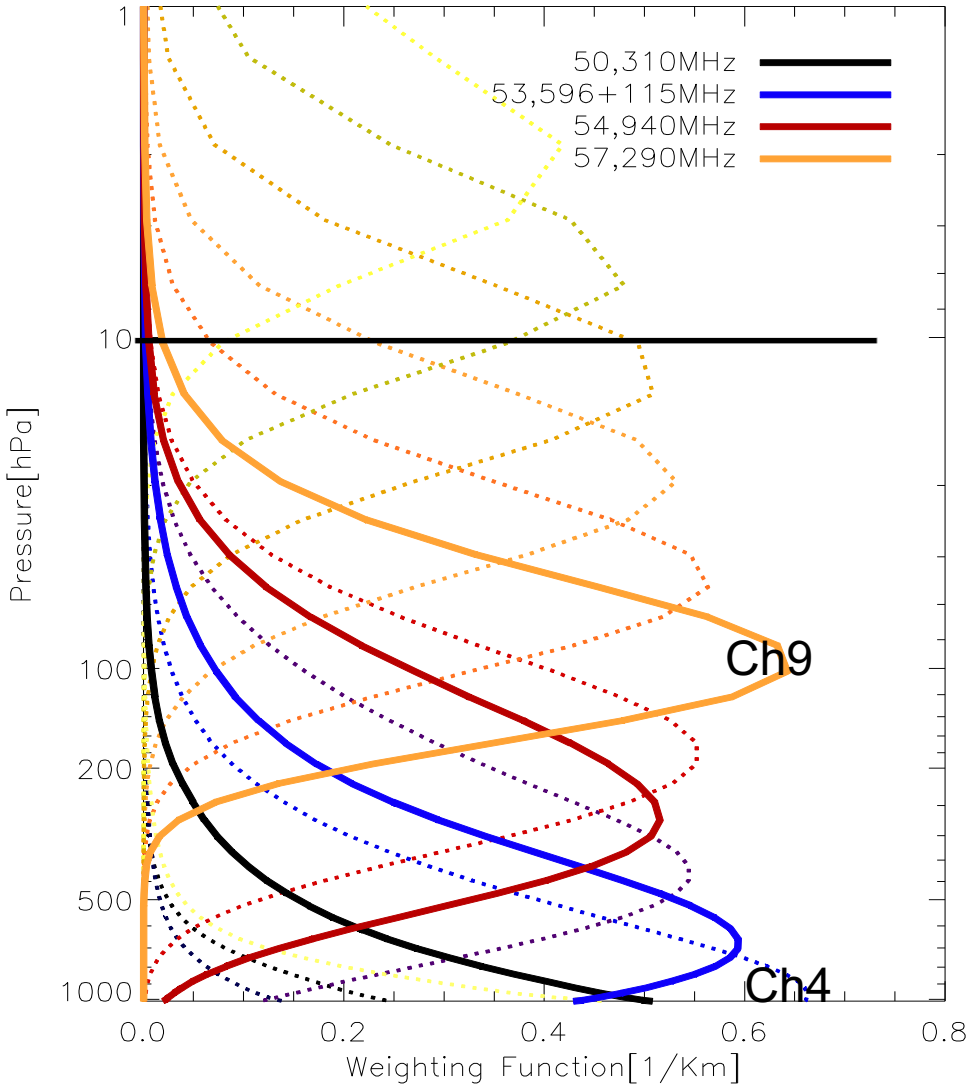
$$2J(\mathbf{x},\boldsymbol{\beta}) = (\mathbf{x}_b-\mathbf{x})^T\mathbf{B}_x^{-1}(\mathbf{x}_b-\mathbf{x}) + (\boldsymbol{\beta}-\boldsymbol{\beta}_b)^T\mathbf{B}_\beta^{-1}(\boldsymbol{\beta}-\boldsymbol{\beta}_b) + [\mathbf{y}-H(\mathbf{x})-h(\mathbf{x},\boldsymbol{\beta})]^T\mathbf{R}^{-1}[\mathbf{y}-H(\mathbf{x})-h(\mathbf{x},\boldsymbol{\beta})] + \alpha^2[h(\mathbf{x},\boldsymbol{\beta})-\mathbf{b}_0]^T\mathbf{R}_b^{-1}[h(\mathbf{x},\boldsymbol{\beta})-\mathbf{b}_0]$$

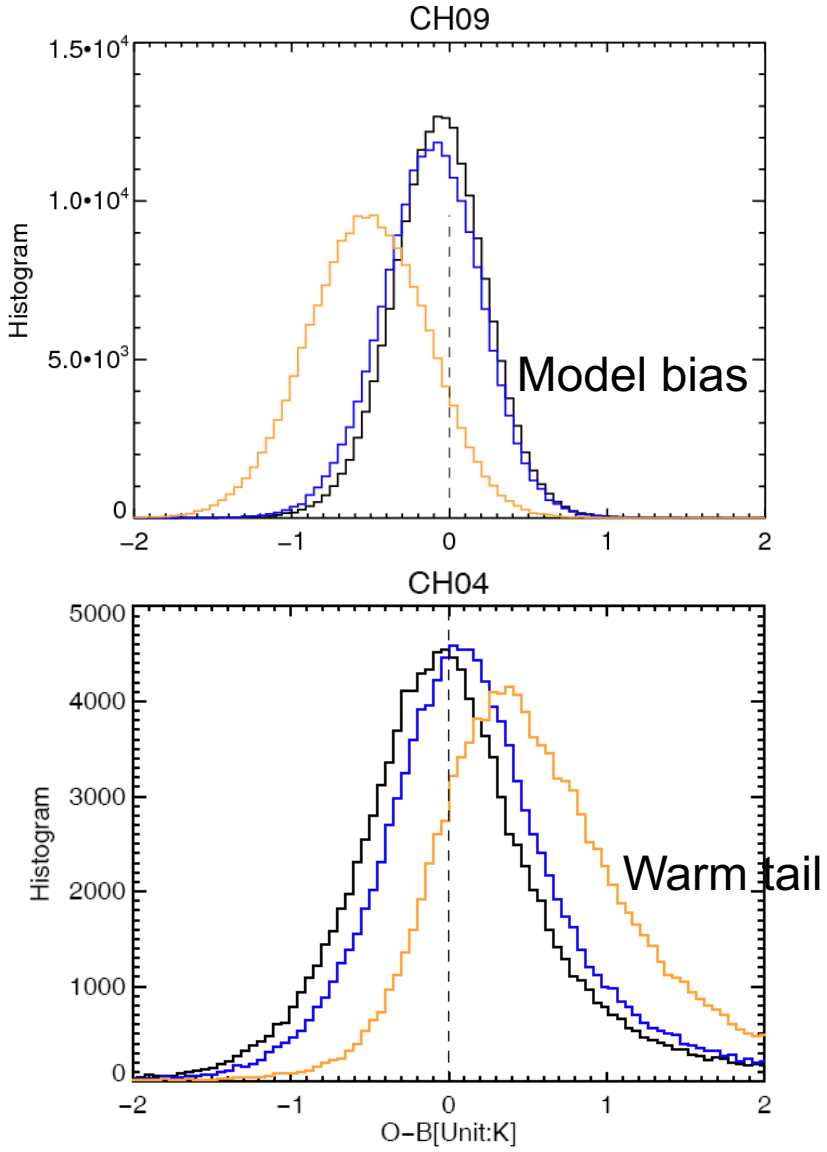
$$\mathbf{d} = \mathbf{y} - H(\mathbf{x})$$
$$\mathbf{P}\boldsymbol{\beta} = h(\mathbf{x},\boldsymbol{\beta})$$

$$\nabla_{\boldsymbol{\beta}} J(\mathbf{x},\boldsymbol{\beta}) = \mathbf{B}_\beta^{-1}(\boldsymbol{\beta}-\boldsymbol{\beta}_b) - \mathbf{P}^T\mathbf{R}^{-1}[\mathbf{d}-\mathbf{P}\boldsymbol{\beta}] + \alpha^2\mathbf{P}^T\mathbf{R}_b^{-1}[\mathbf{P}\boldsymbol{\beta}-\mathbf{b}_0]$$
$$= (\mathbf{B}_\beta^{-1} + \mathbf{P}^T\mathbf{R}^{-1}\mathbf{P} + \alpha^2\mathbf{P}^T\mathbf{R}_b^{-1}\mathbf{P})\boldsymbol{\beta} - (\mathbf{B}_\beta^{-1}\boldsymbol{\beta}_b + \mathbf{P}^T\mathbf{R}^{-1}\mathbf{d} + \alpha^2\mathbf{P}^T\mathbf{R}_b^{-1}\mathbf{b}_0)$$

Han,2014,ITSC19

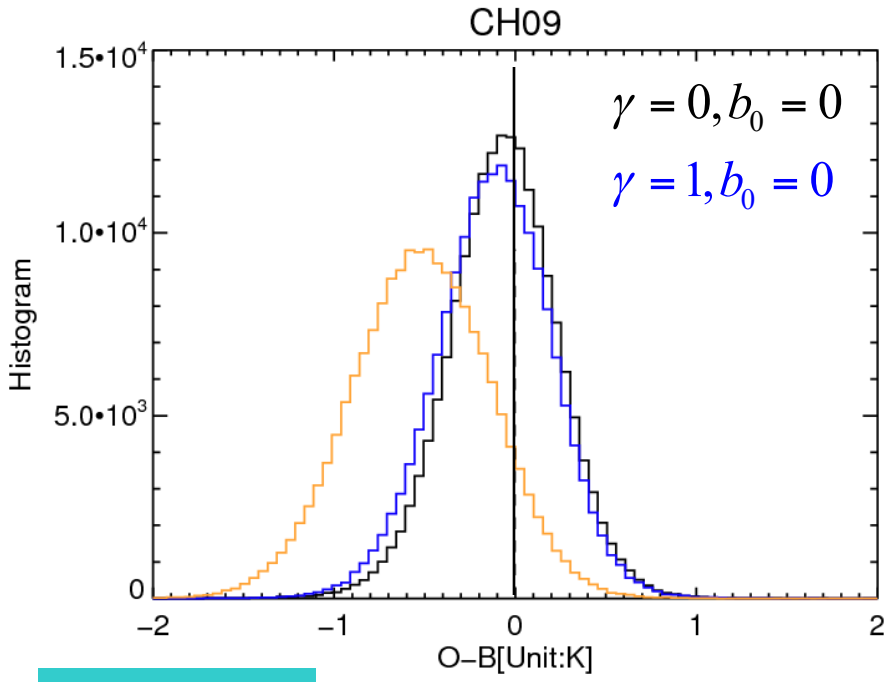
Experiments in GRAPES



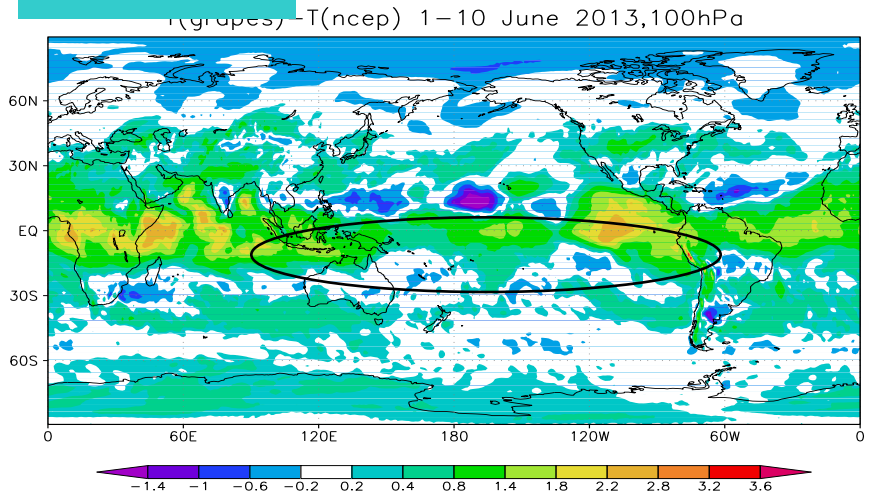


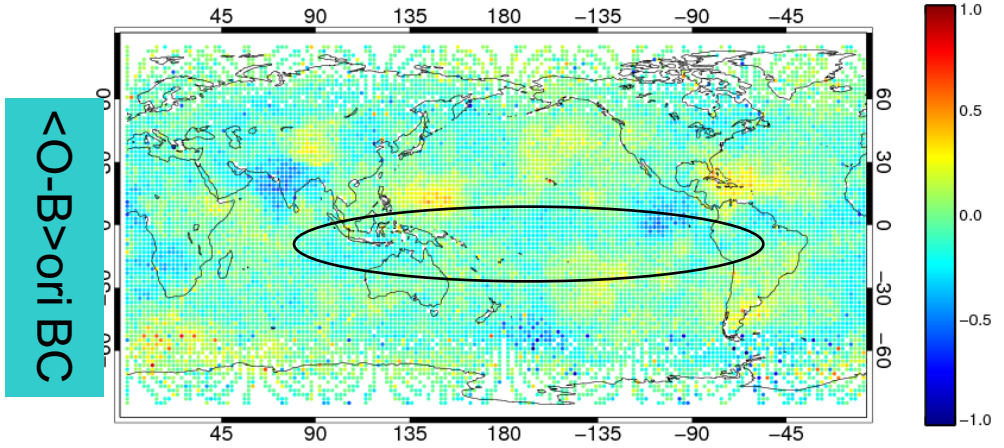
AMSUA CH9(Metop_A)

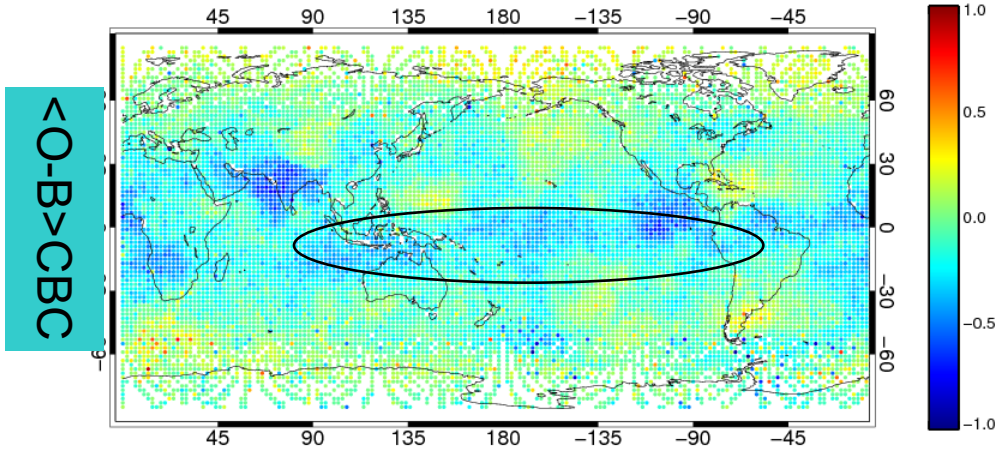
1-10 June 2013

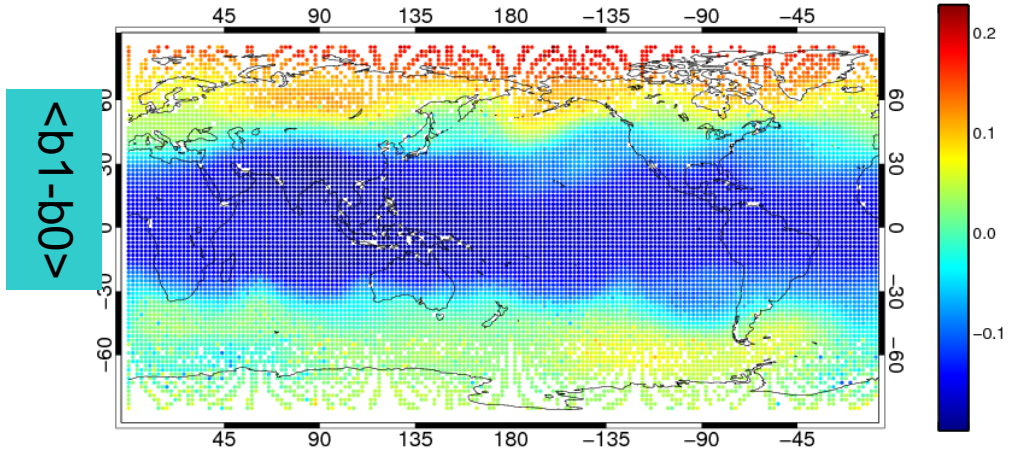


Model Bias

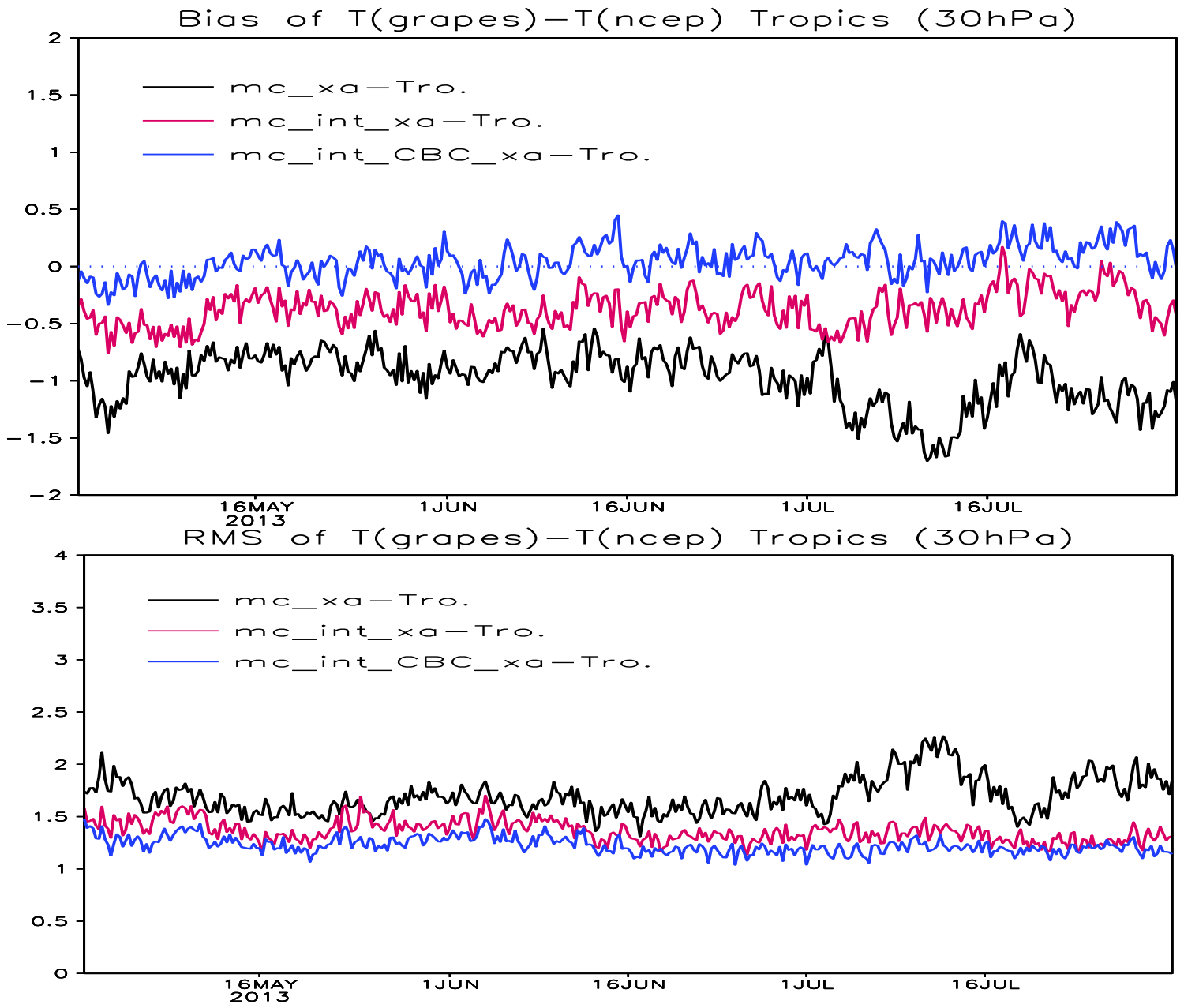








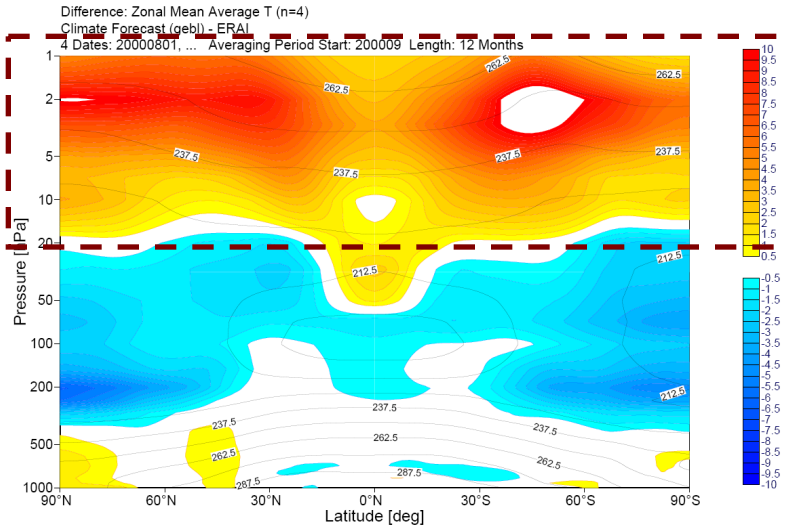
Two months cycle experiments in GRAPES global May-June 2013



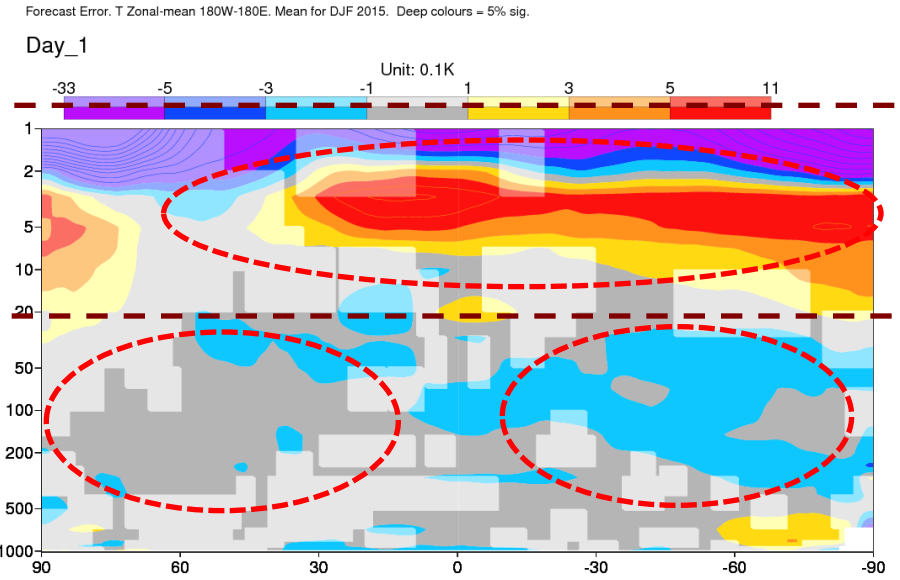
CVarBC for AMSU-A Ch14 in ECMWF IFS: Background

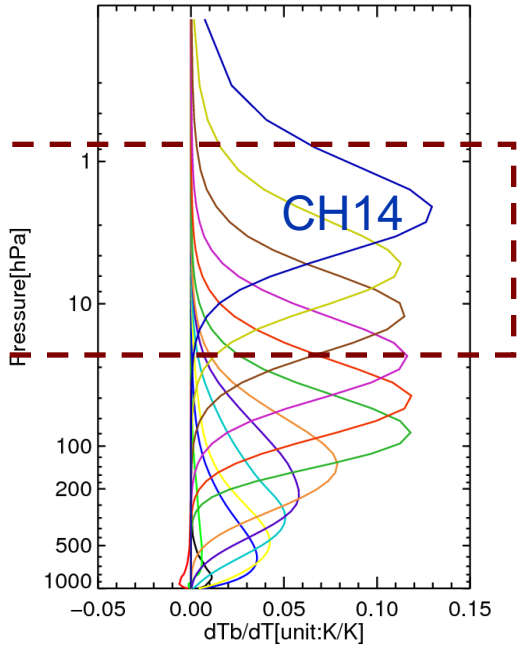
There are systematic errors in model background,
IF there are not enough unbiased observations to constrain the analysis.

CY42R1: **Climate Run** Tbias
2000-2001



CY42R1: **24h Forecast** T bias
2014D15JF



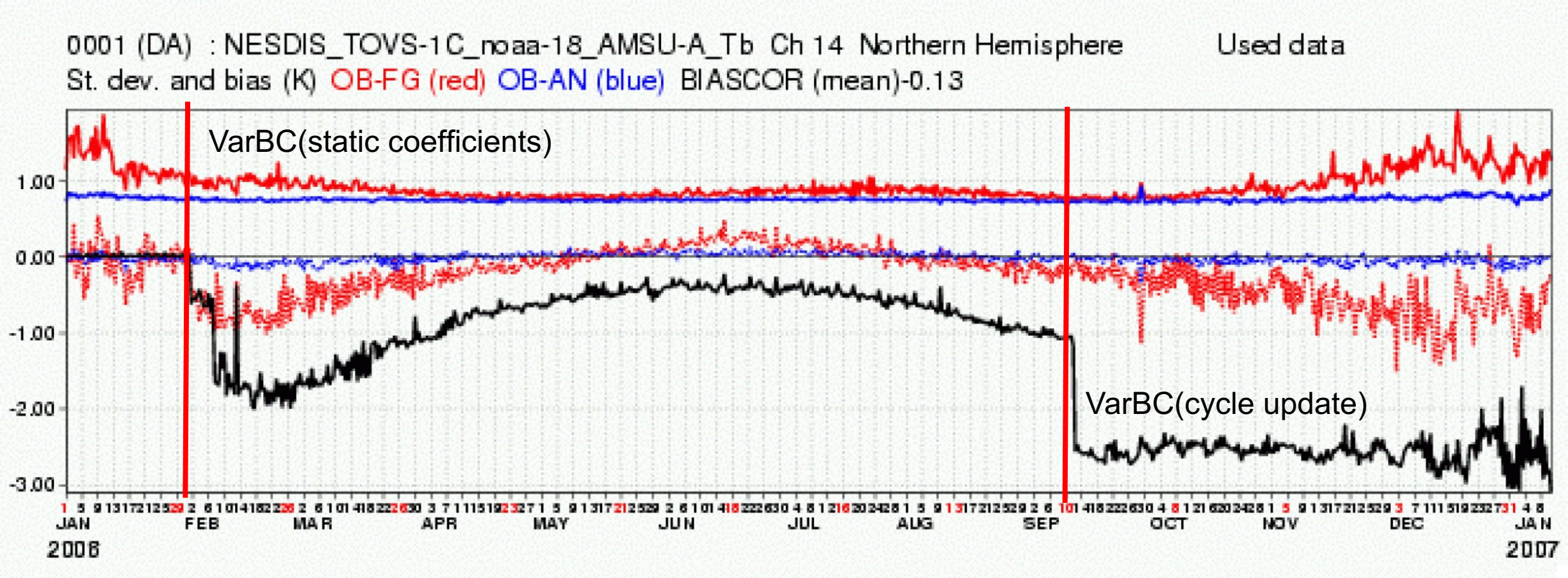


Sonde as anchor in N.H.

Constrained VarBC in IFS

CVarBC for AMSU-A Ch14 in ECMWF IFS : Background

Anchor channel

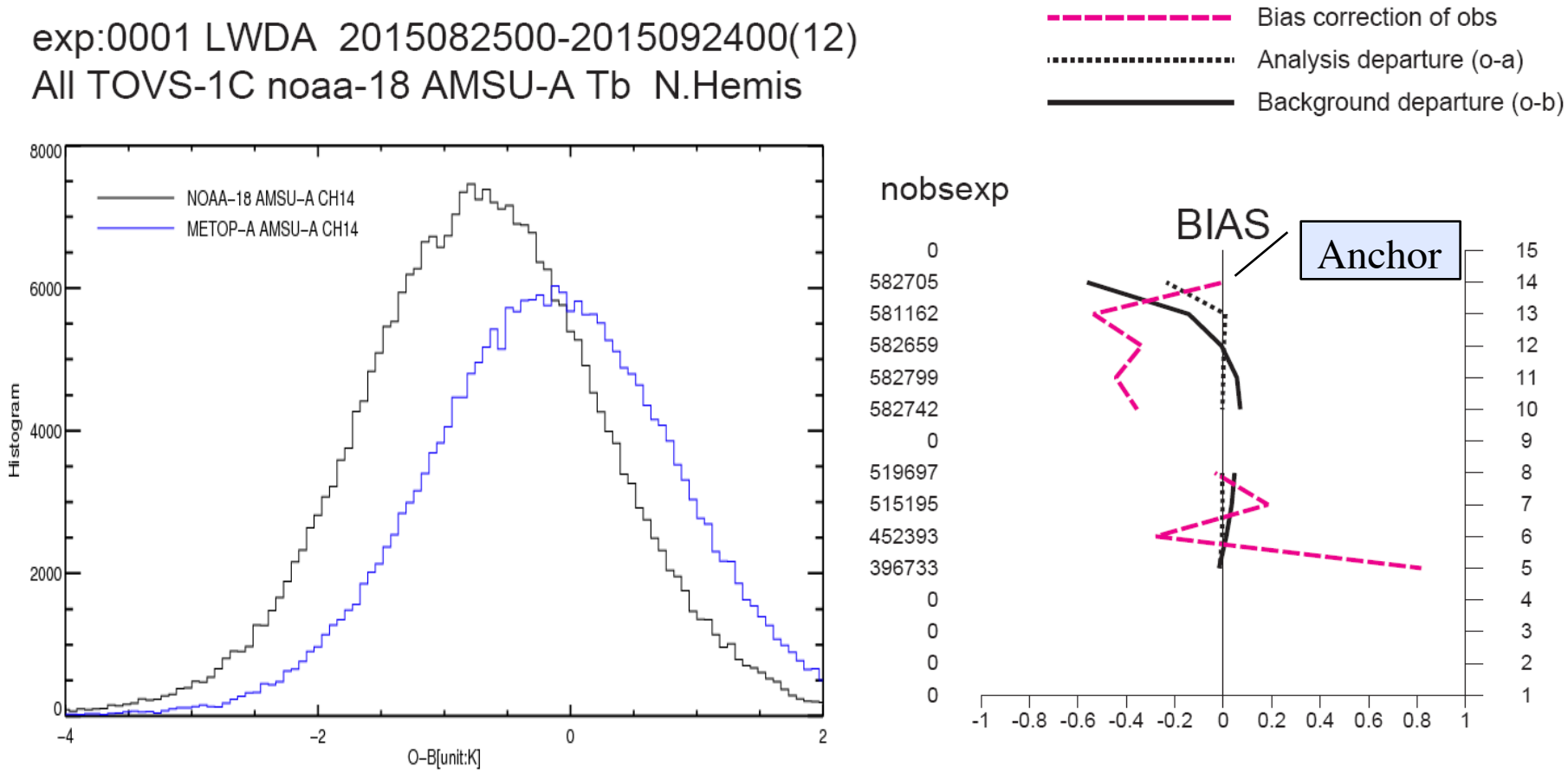


McNally, A.P. (2007), The assimilation of uncorrected AMSU-A channel 14 to anchor the VarBC system in the stratosphere. Research Department Memorandum, ECMWF, R43.8/AM/0715.

CVarBC for AMSU-A Ch14 in ECMWF IFS : Background

There are two issues need to be revisited:

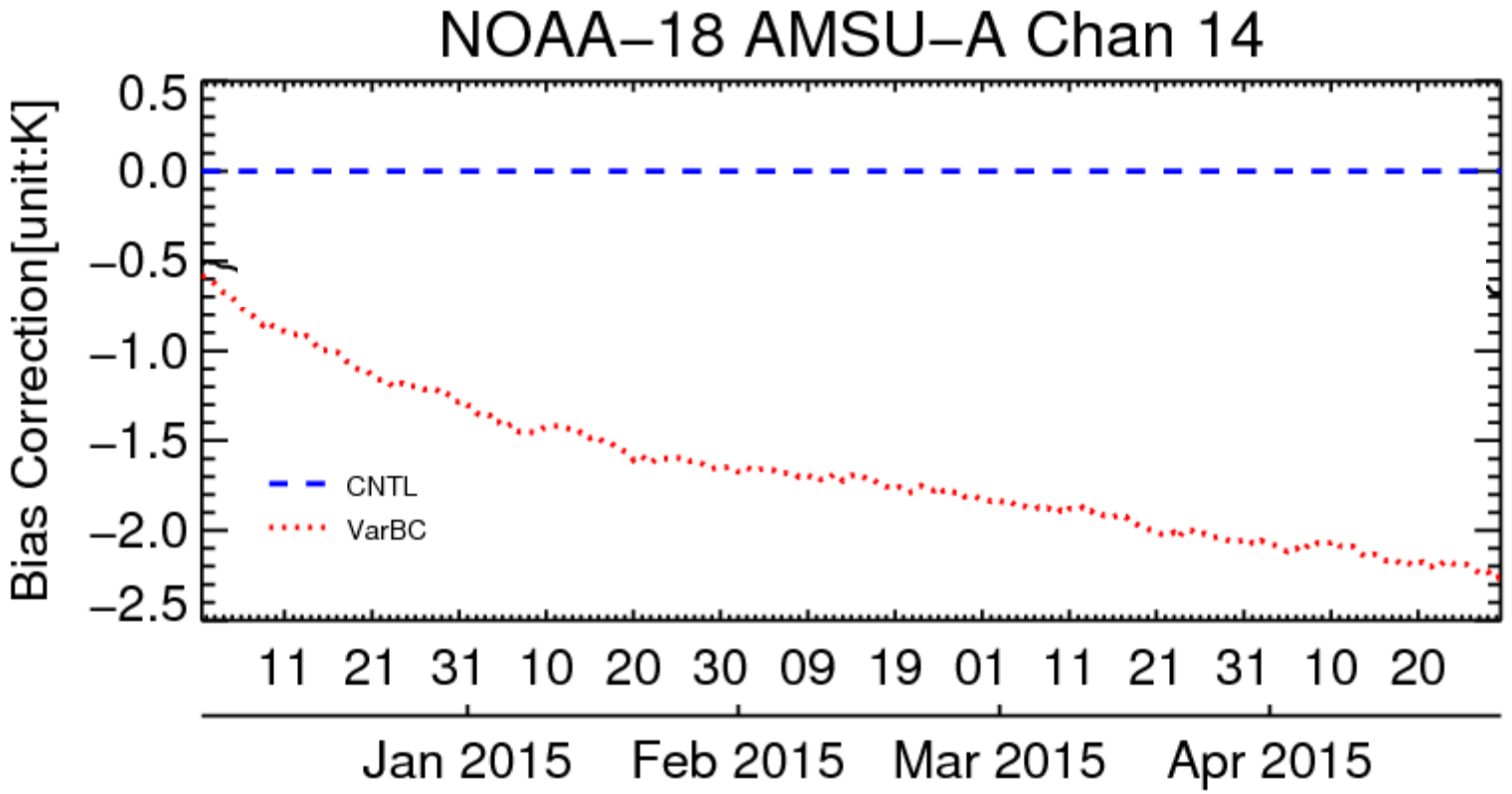
1)Inter-satellite biases; 2)Scan biases.



Constrained VarBC in IFS

Drift to model bias without anchor

Bias correction of AMSU-A Ch14 in IFS CY41R2:
1) Free VarBC will drift gradually;
2) It will also affect the bias correction of Ch13 and Ch12;



Constrained VarBC in IFS

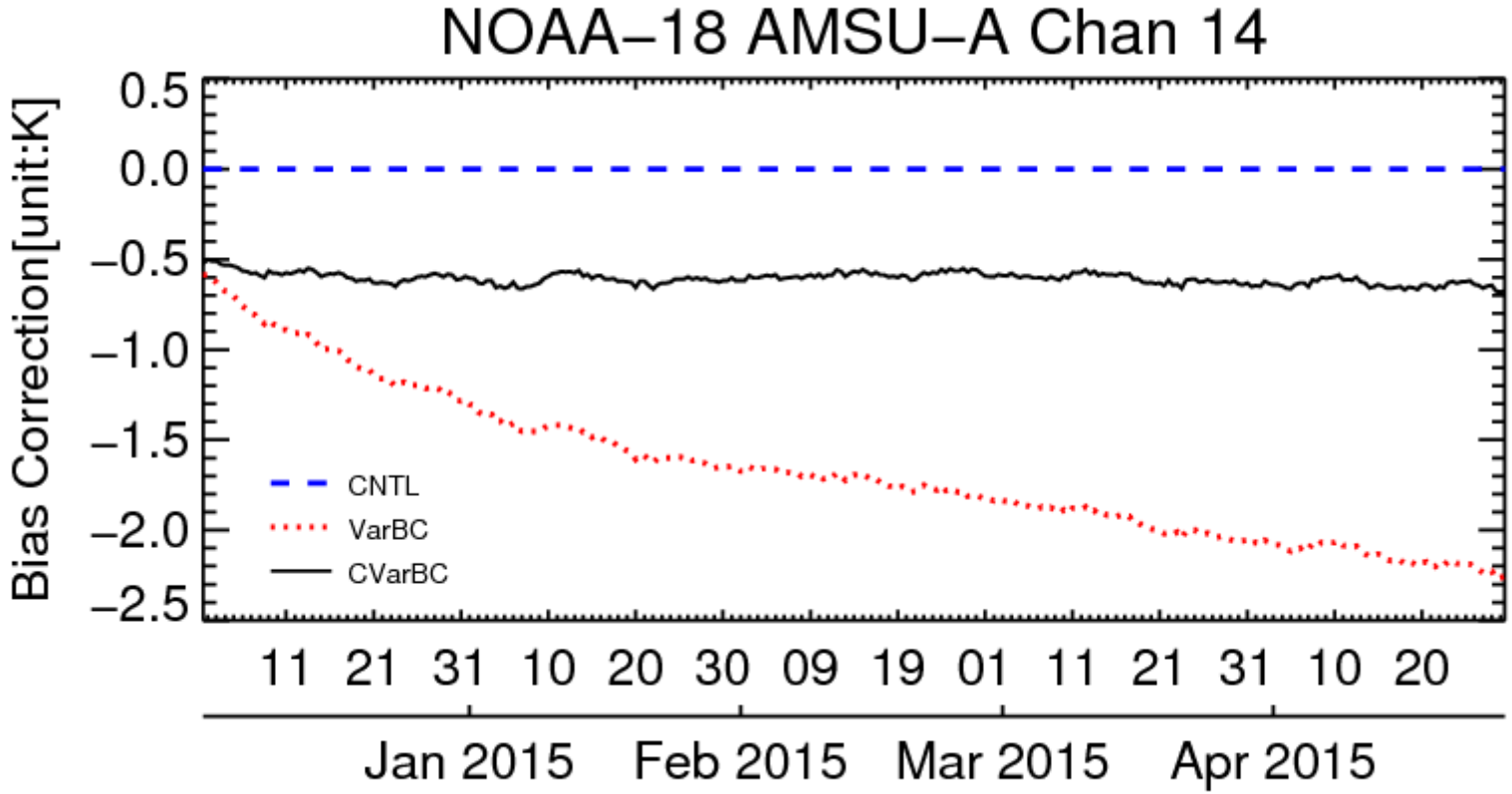
Implementation of Constrained VarBC in IFS and CY41R2 experiments

$$\alpha^2[h(\mathbf{x},\boldsymbol{\beta})-\mathbf{b}_0]^T\mathbf{R}_b^{-1}[h(\mathbf{x},\boldsymbol{\beta})-\mathbf{b}_0]$$

CVarBC

AMSU-A	alpha	Bias0	B(bias0)*
Channel 14	0.3	0	1.4
Channel 13	0.0	0	0.85
Channel 12	0.0	0	0.5

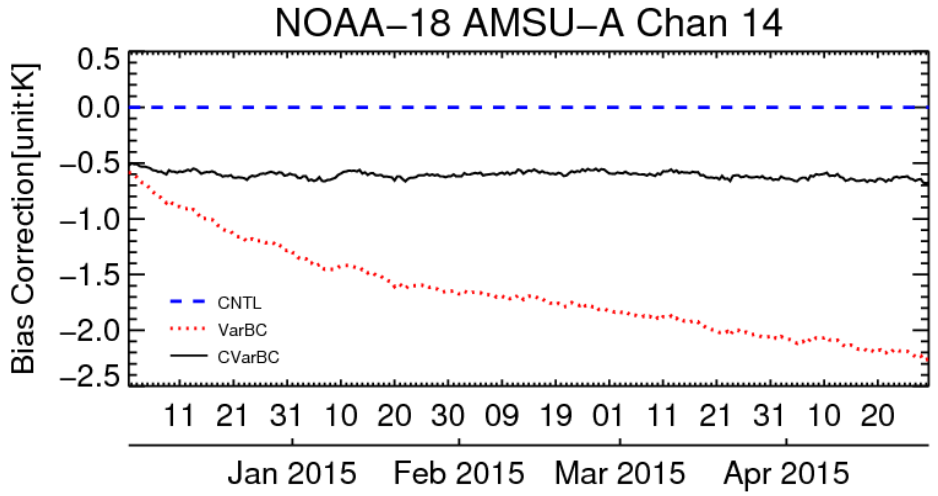
*Same as observation error

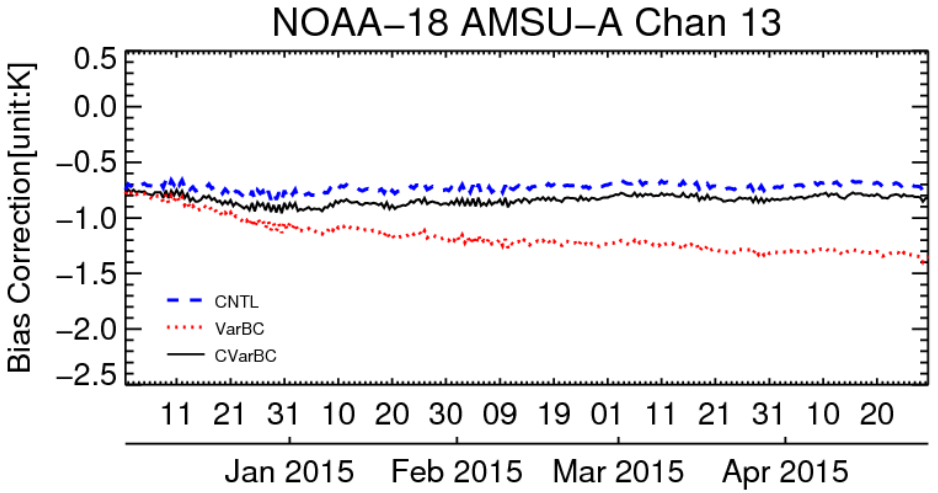


Constrained VarBC in IFS

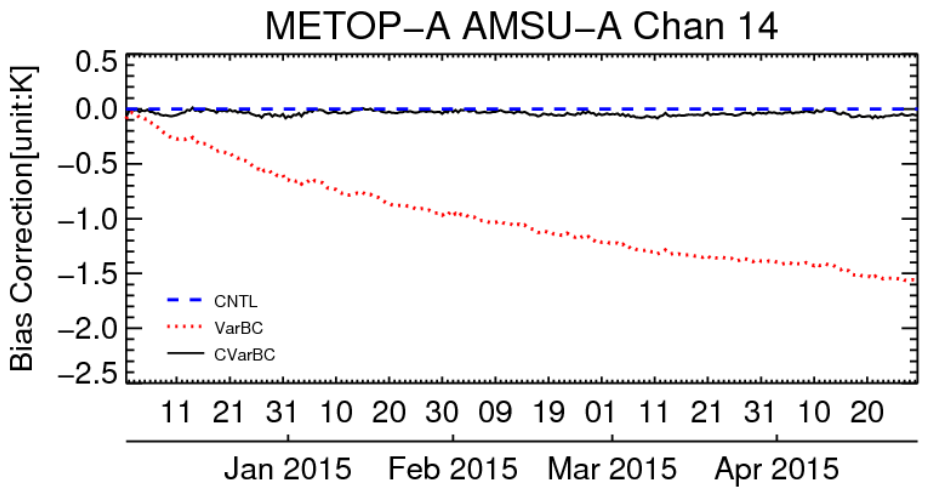
Temporal Evolution of bias correction

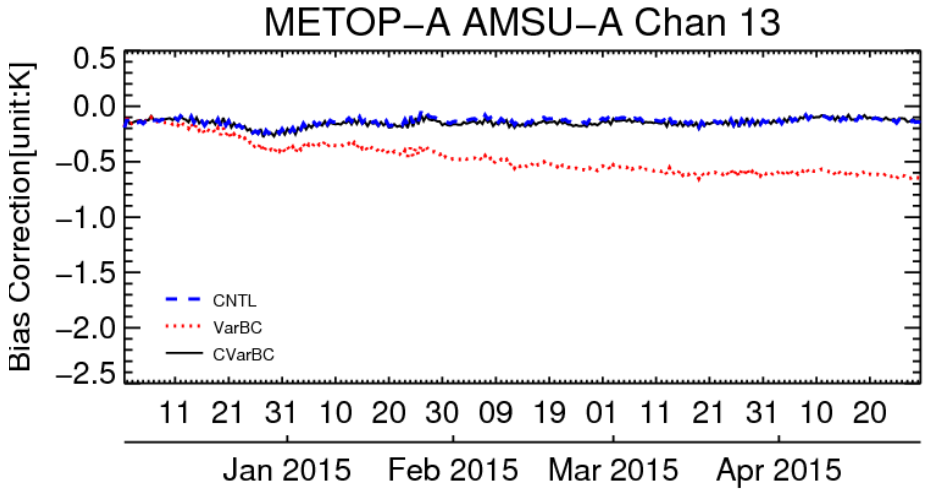
NOAA-18





METOP-A

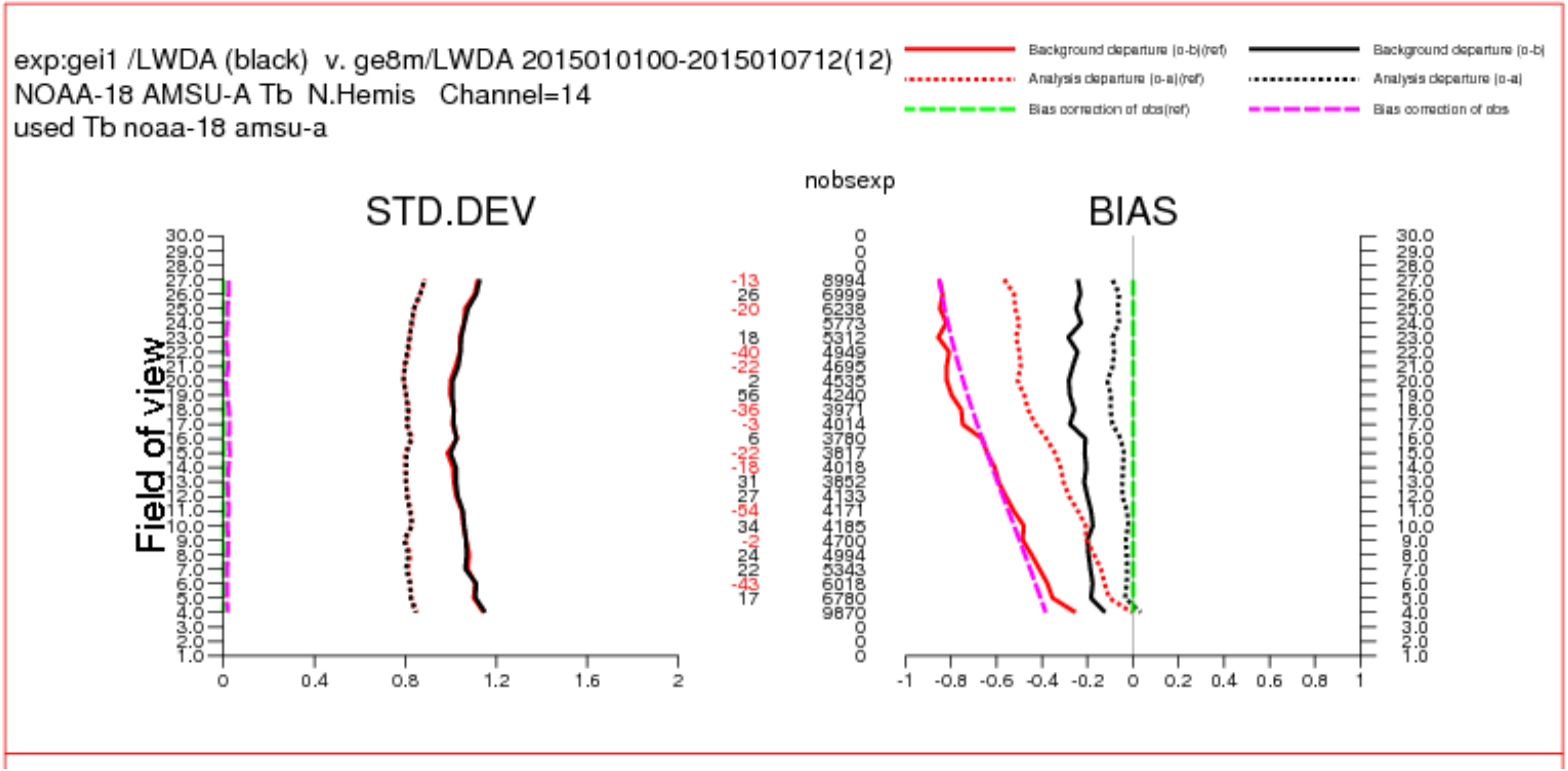




Constrained VarBC in IFS

Scan bias correction

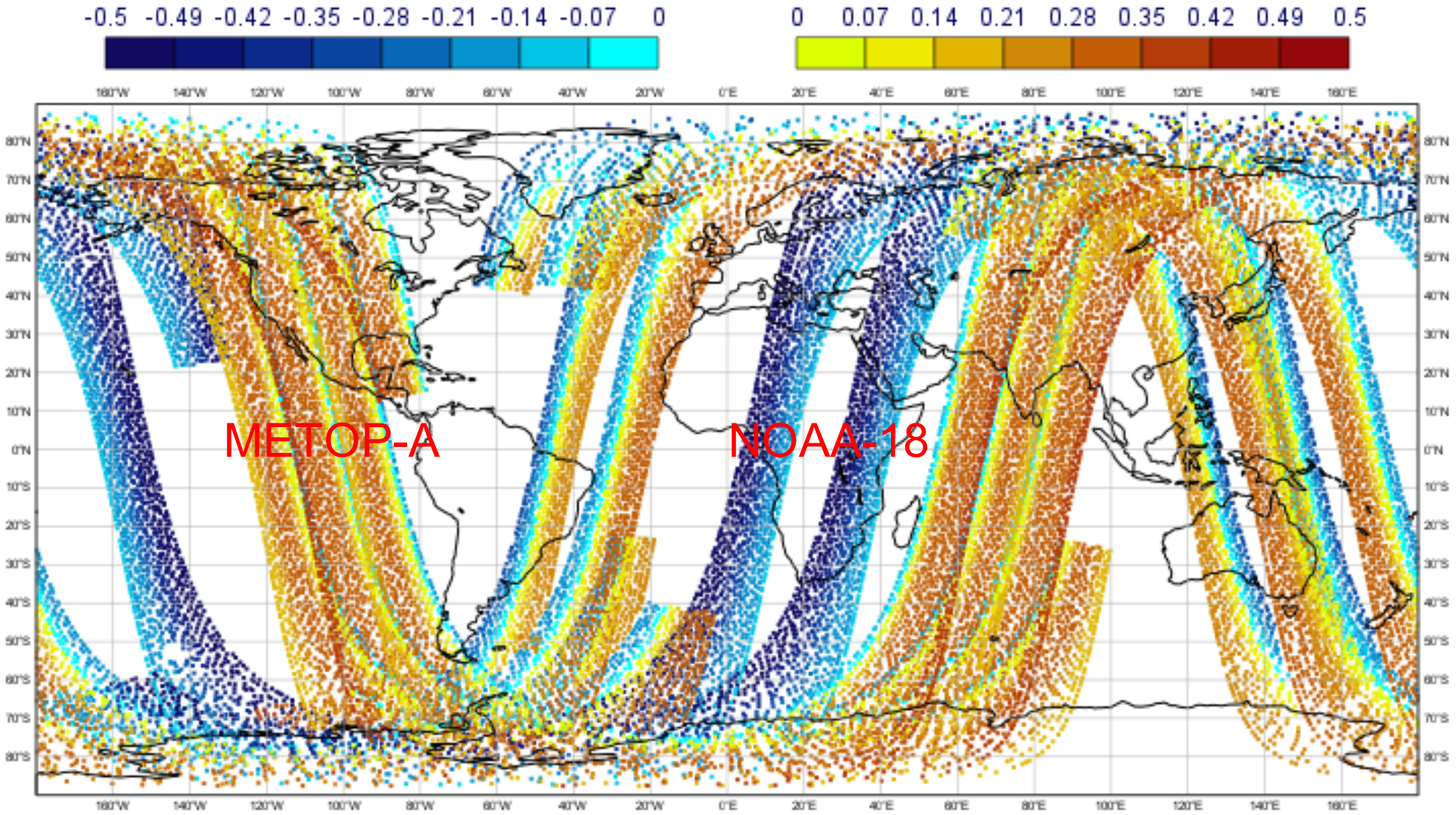
CNTL: anchor channel CVarBC



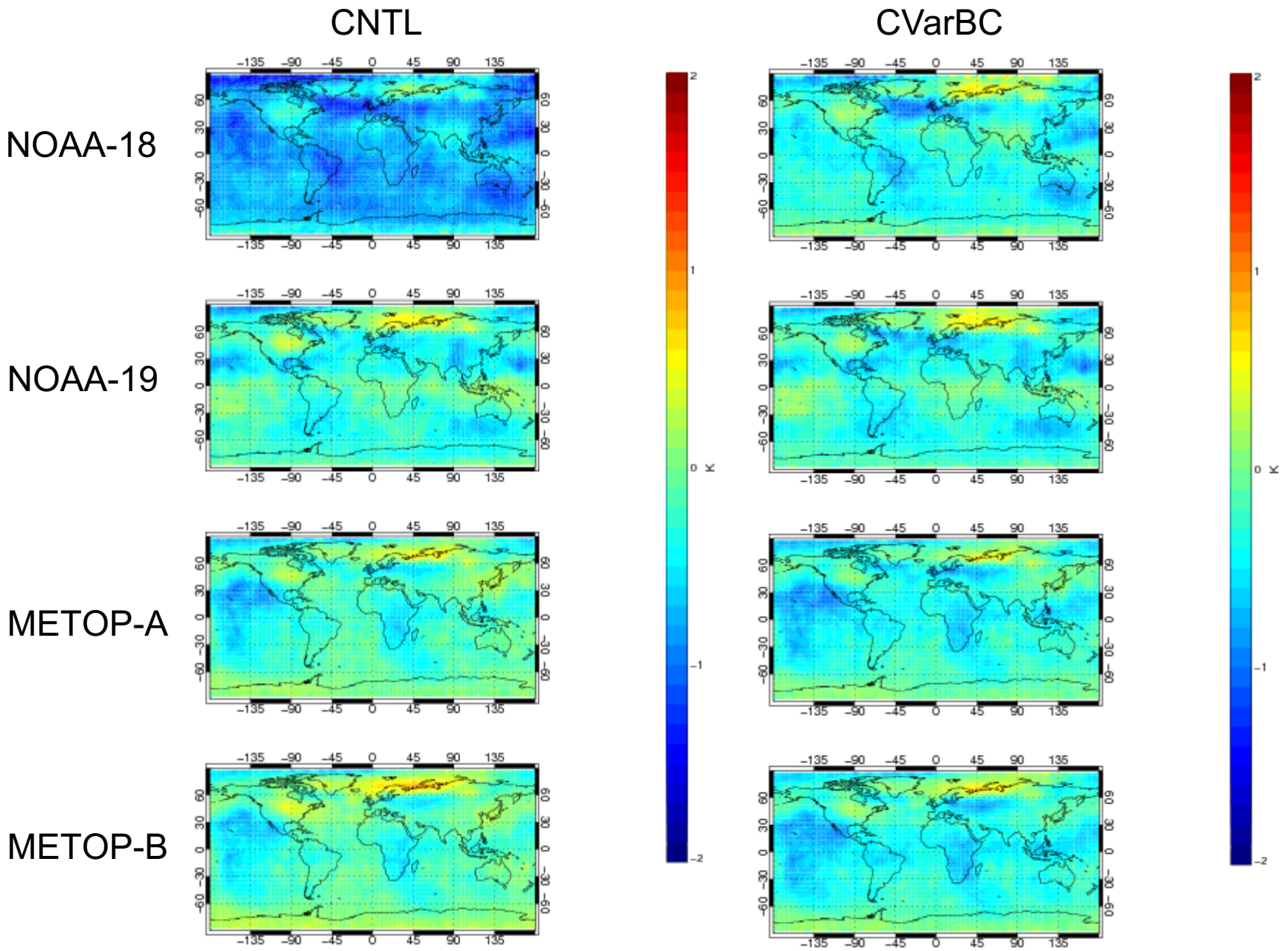
Constrained VarBC in IFS

CVarBC: AMSU-A 14 bias corrections

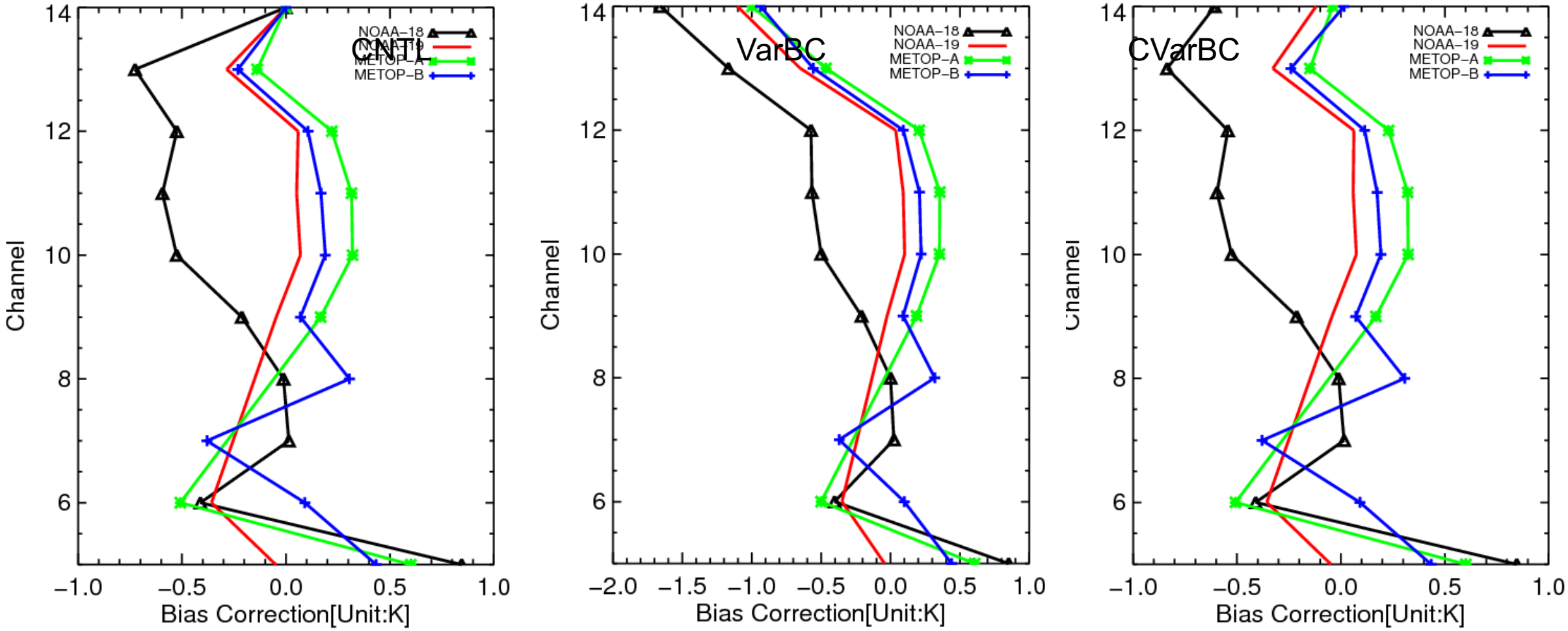
- Total size of bias correction
- Inter-satellite biases
- Scan biases



AMSU-A Ch14 <O-B>(2014-12-15~ 2014-12-31)



Mean Bias Correction in 2014D15JF

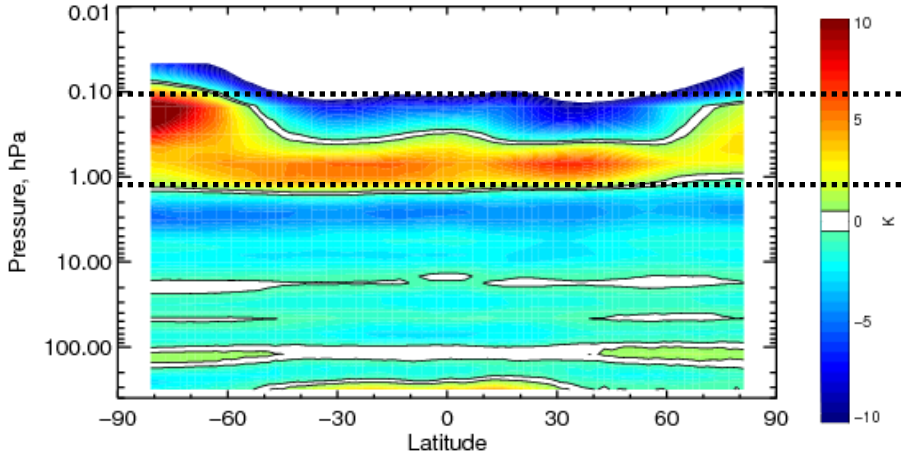


Constrained VarBC in IFS

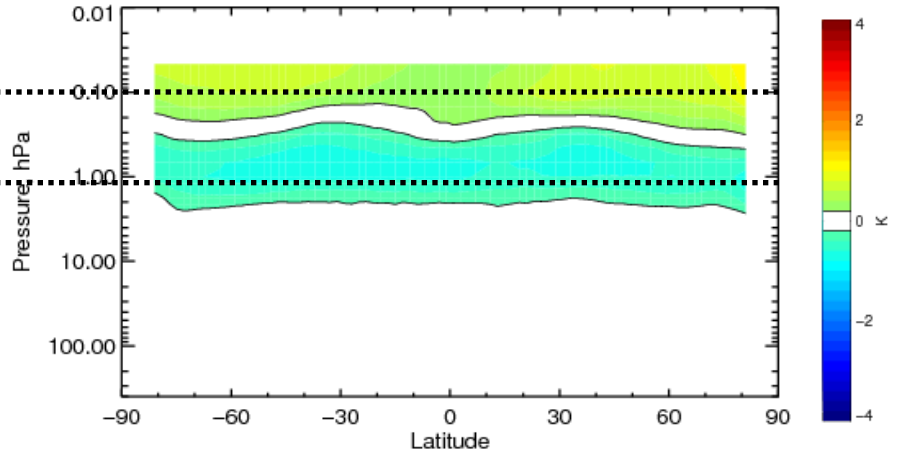
Thanks Rossana!

Verification using MLS Temperature retrieval

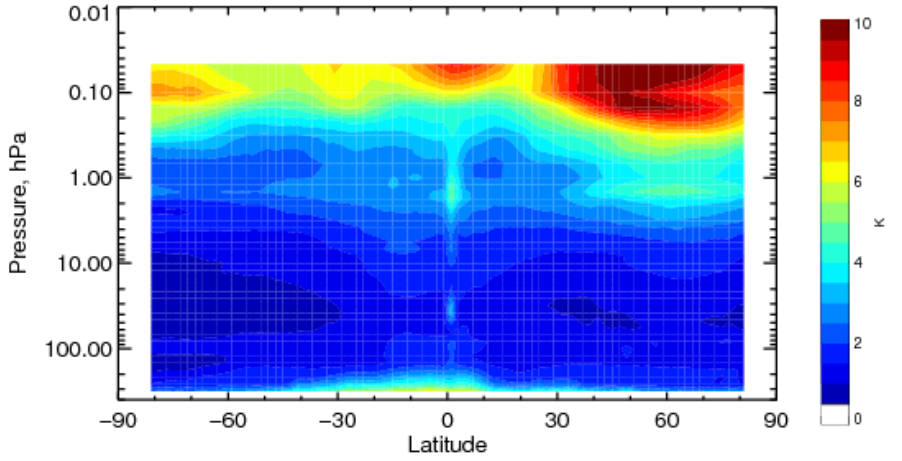
MEAN(MLS-CNTL),2014D15JF



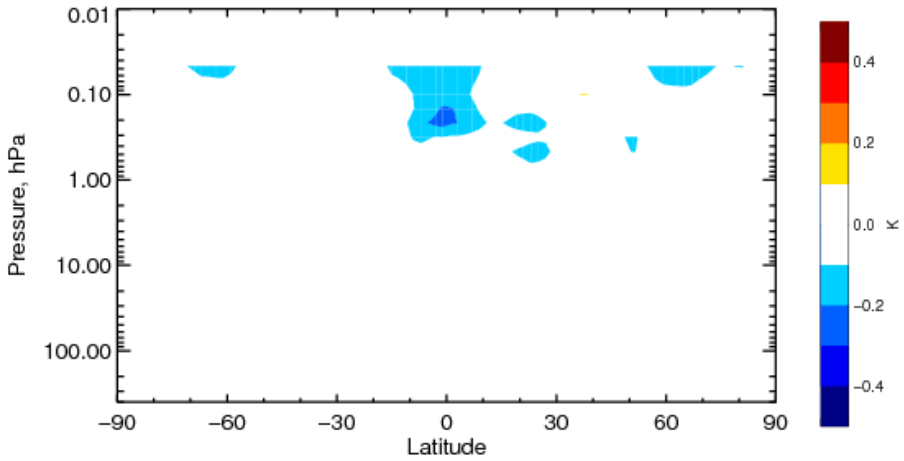
MEAN(CNTL-CVarBC), 2014D15JF



STD(MLS-CNTL),2014D15JF



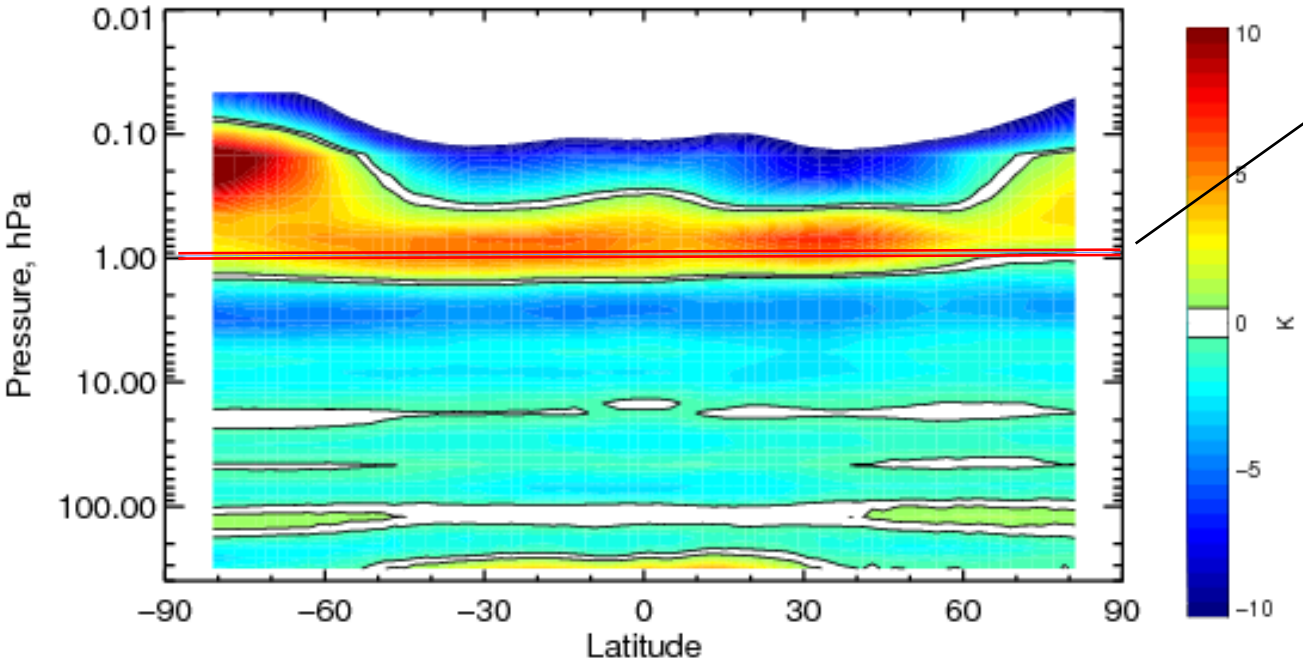
<STD_CVarBC-STD_CNTL>, 2014D15JF



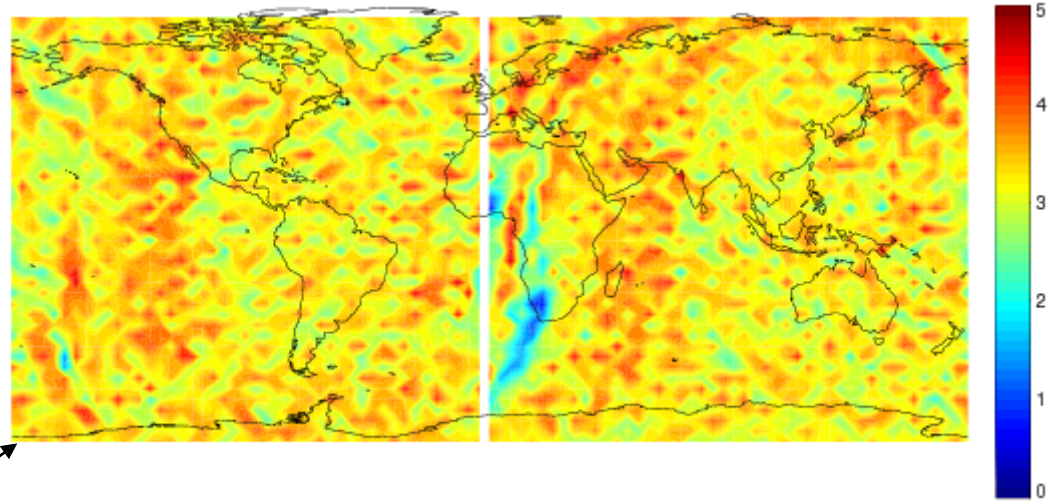
Temperature bias at 1hPa

Using MLS Temperature as reference

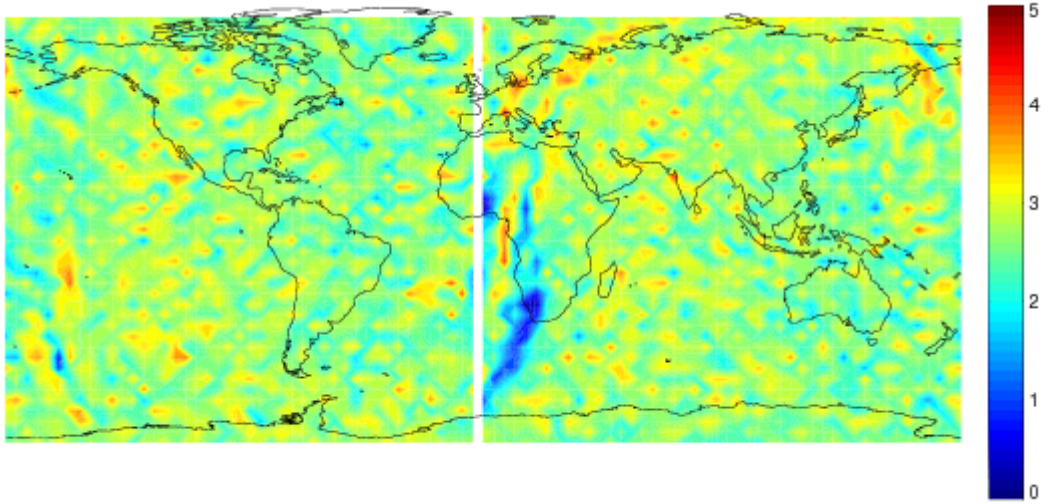
MEAN(MLS-CNTL),2014D15JF



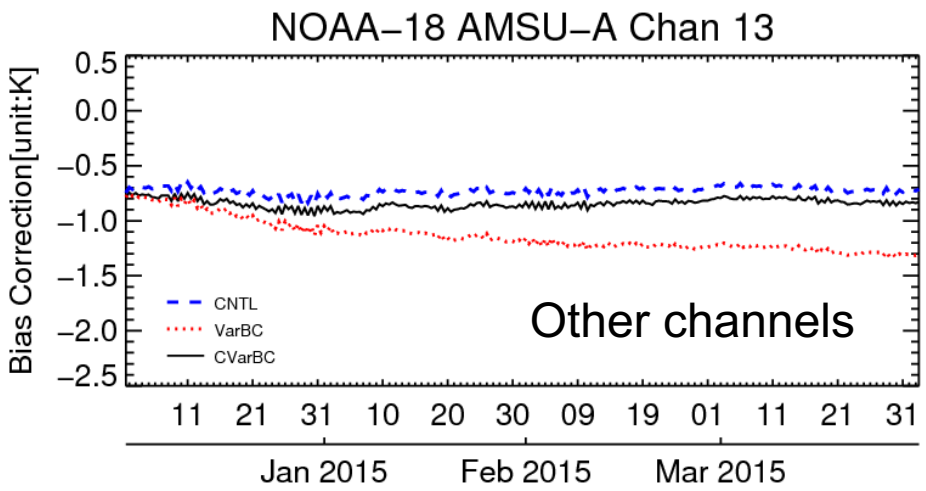
MEAN(MLS-CNTL),2014D15JF

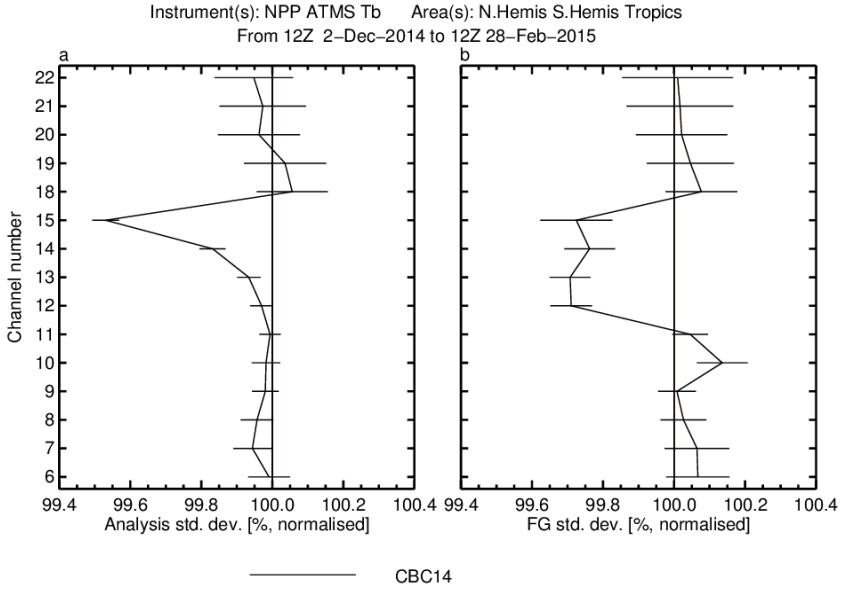


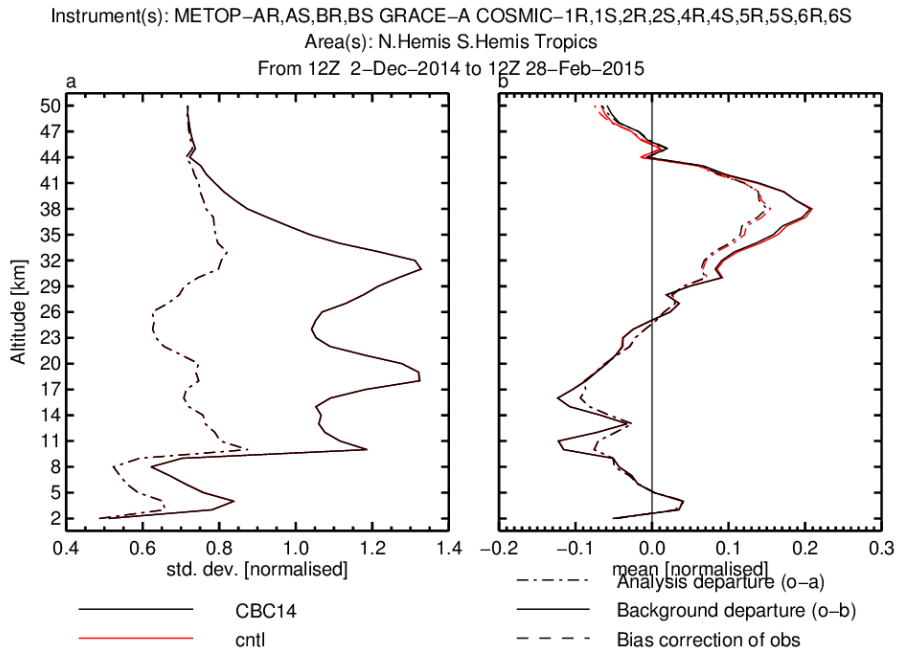
MEAN(MLS-CVarBC), 2014D15JF

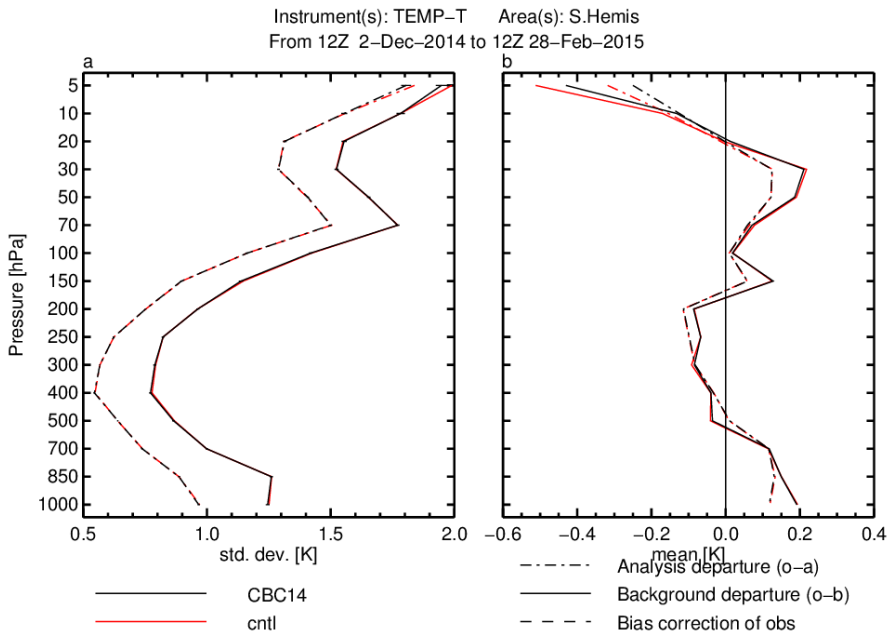


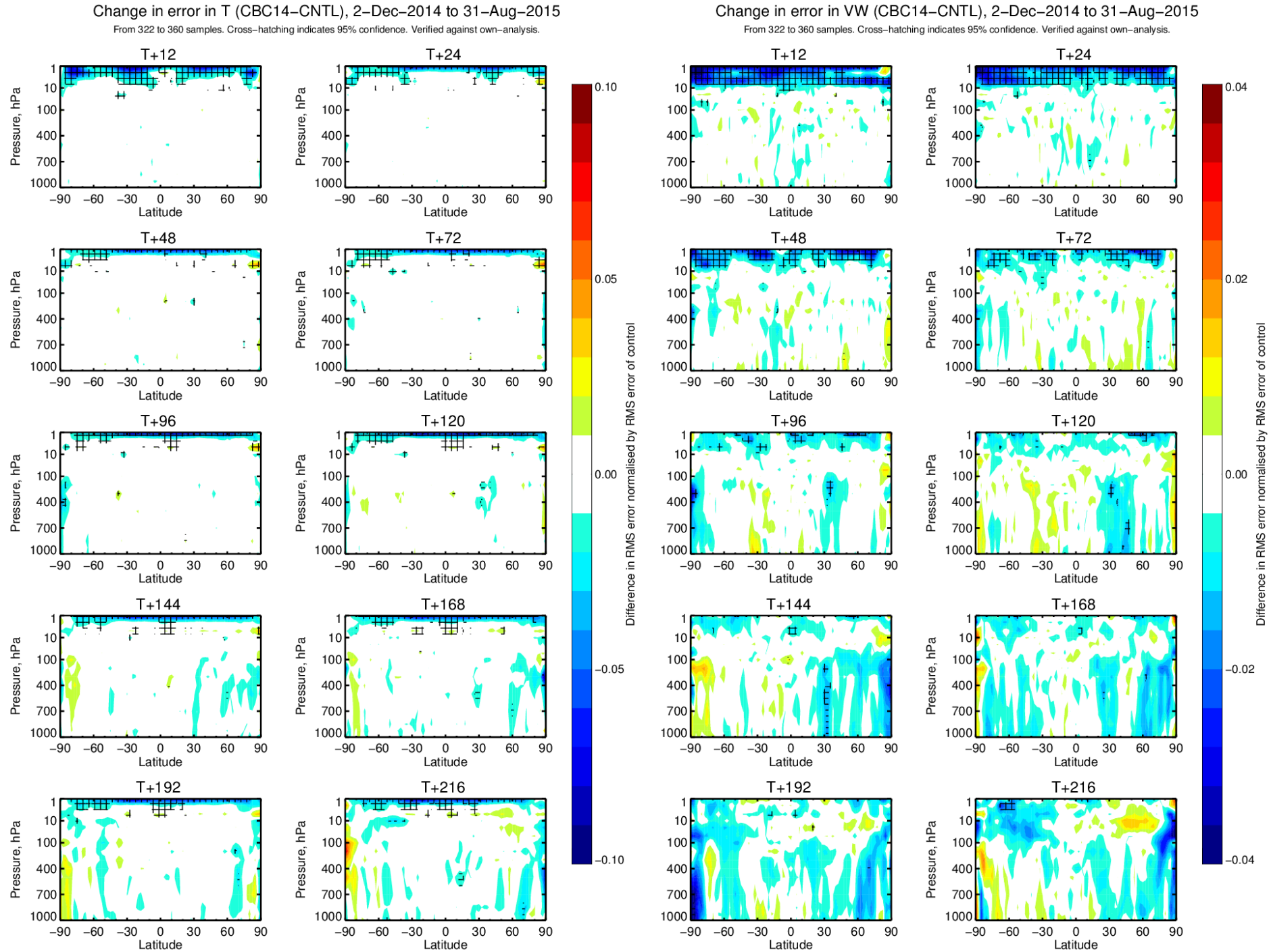
Impact on the fit of other observations



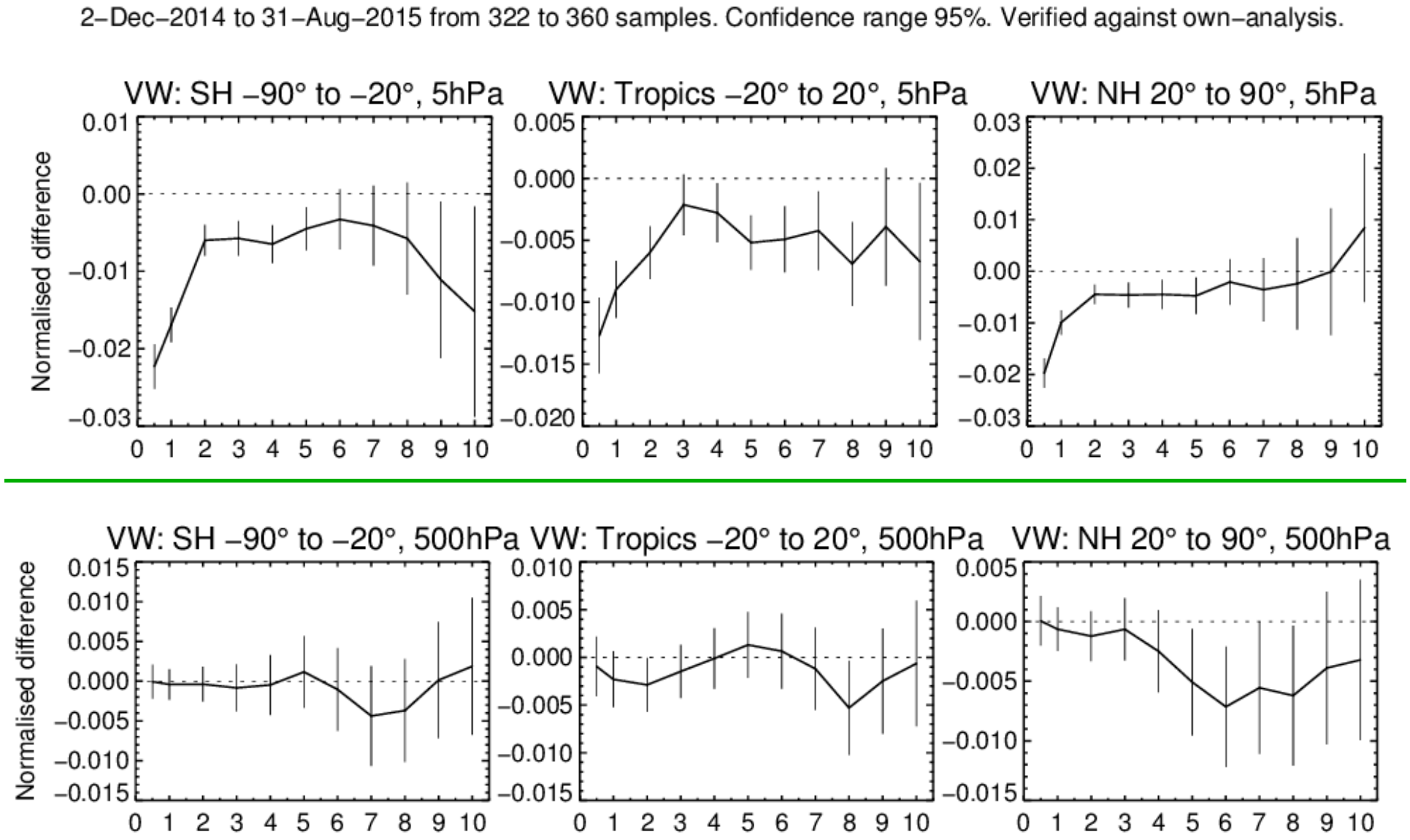







Change in error in T (CBC14−CNTL), 2−Dec−2014 to 31−Aug−2015
From 322 to 360 samples. Cross−hatching indicates 95% confidence. Verified against own−analysis.
Change in error in VW (CBC14−CNTL), 2−Dec−2014 to 31−Aug−2015
From 322 to 360 samples. Cross−hatching indicates 95% confidence. Verified against own−analysis.
T+12
T+24
T+48
T+72
T+96
T+120
T+144
T+168
T+192
T+216
Pressure, hPa
Latitude
Difference in RMS error normalised by RMS error of control
0.10
0.05
0.00
−0.05
−0.10
0.04
0.02
0.00
−0.02
−0.04

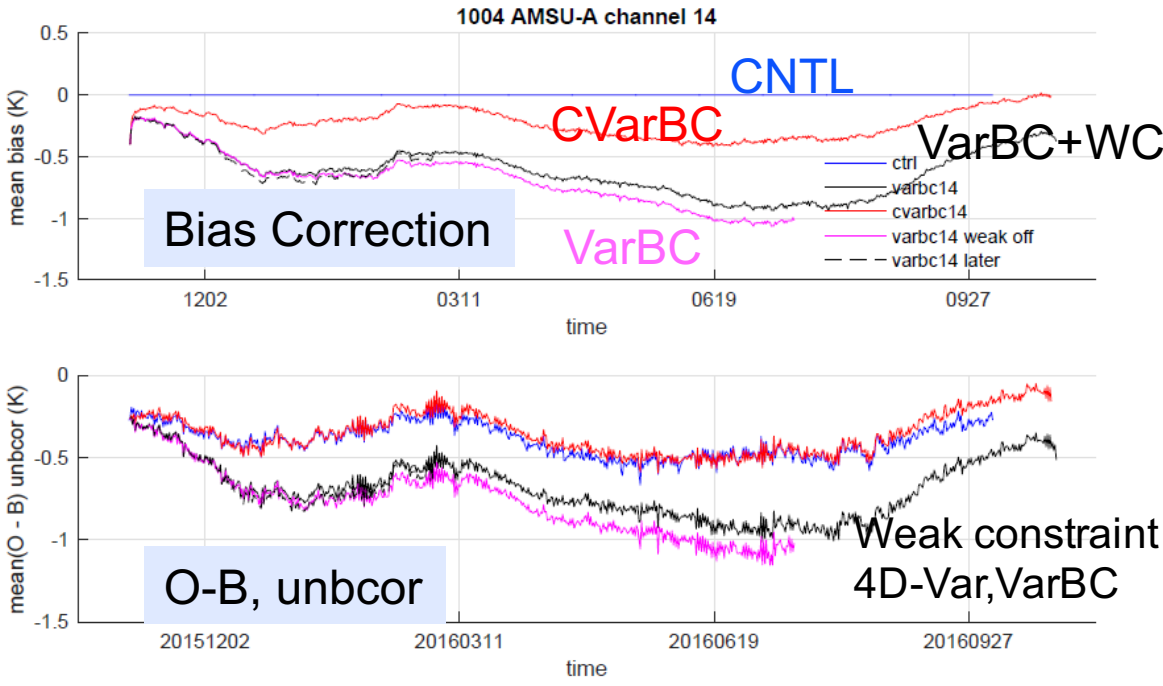
Impact of Constrained VarBC on AMSUA CH14 on Forecast (2014D15JF and 2015JJA)



One year experiments (2015-2016)

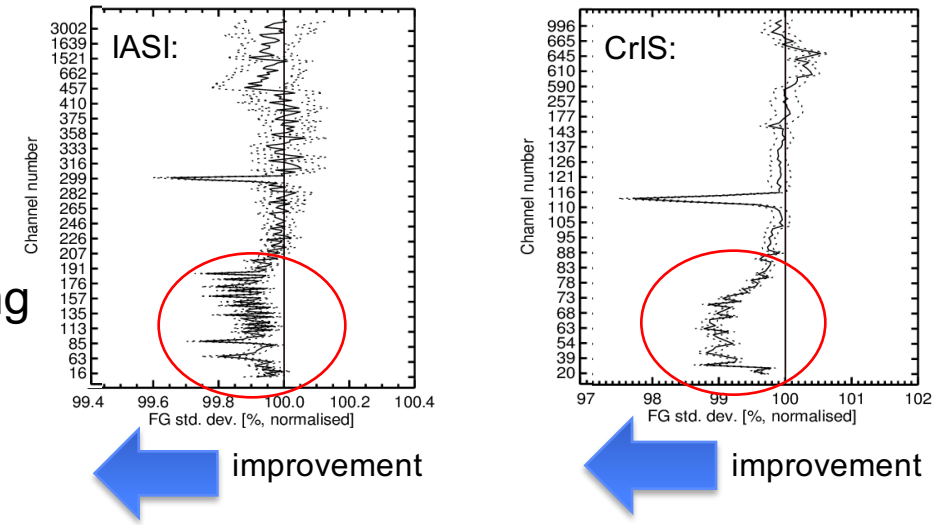
- Test the implementation for a long time series and with weak constraint 4D-Var

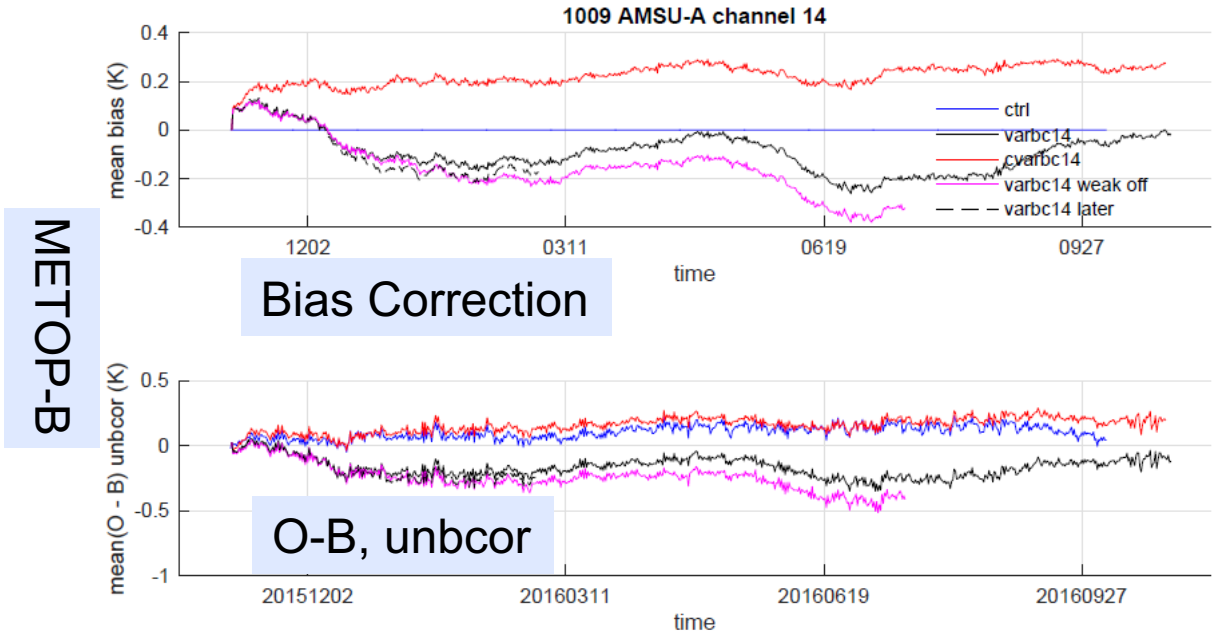
$$
\begin{aligned}
2J(\mathbf{x},\boldsymbol{\beta},\eta) \;=\; & (\mathbf{x}_b-\mathbf{x})^T\mathbf{B}_x^{-1}(\mathbf{x}_b-\mathbf{x}) \\
& + (\boldsymbol{\beta}-\boldsymbol{\beta}_b)^T\mathbf{B}_\beta^{-1}(\boldsymbol{\beta}-\boldsymbol{\beta}_b) \\
& + [\mathbf{y}-H(\mathbf{x})-h(\mathbf{x},\boldsymbol{\beta})]^T\mathbf{R}^{-1}[\mathbf{y}-H(\mathbf{x})-h(\mathbf{x},\boldsymbol{\beta})] \\
& + \alpha^2[h(\mathbf{x},\boldsymbol{\beta})-\mathbf{b}_0]^T\mathbf{R}_b^{-1}[h(\mathbf{x},\boldsymbol{\beta})-\mathbf{b}_0] + (\boldsymbol{\eta}-\boldsymbol{\eta}_b)^T\mathbf{Q}^{-1}(\boldsymbol{\eta}-\boldsymbol{\eta}_b)
\end{aligned}
$$



STDEV O – B:

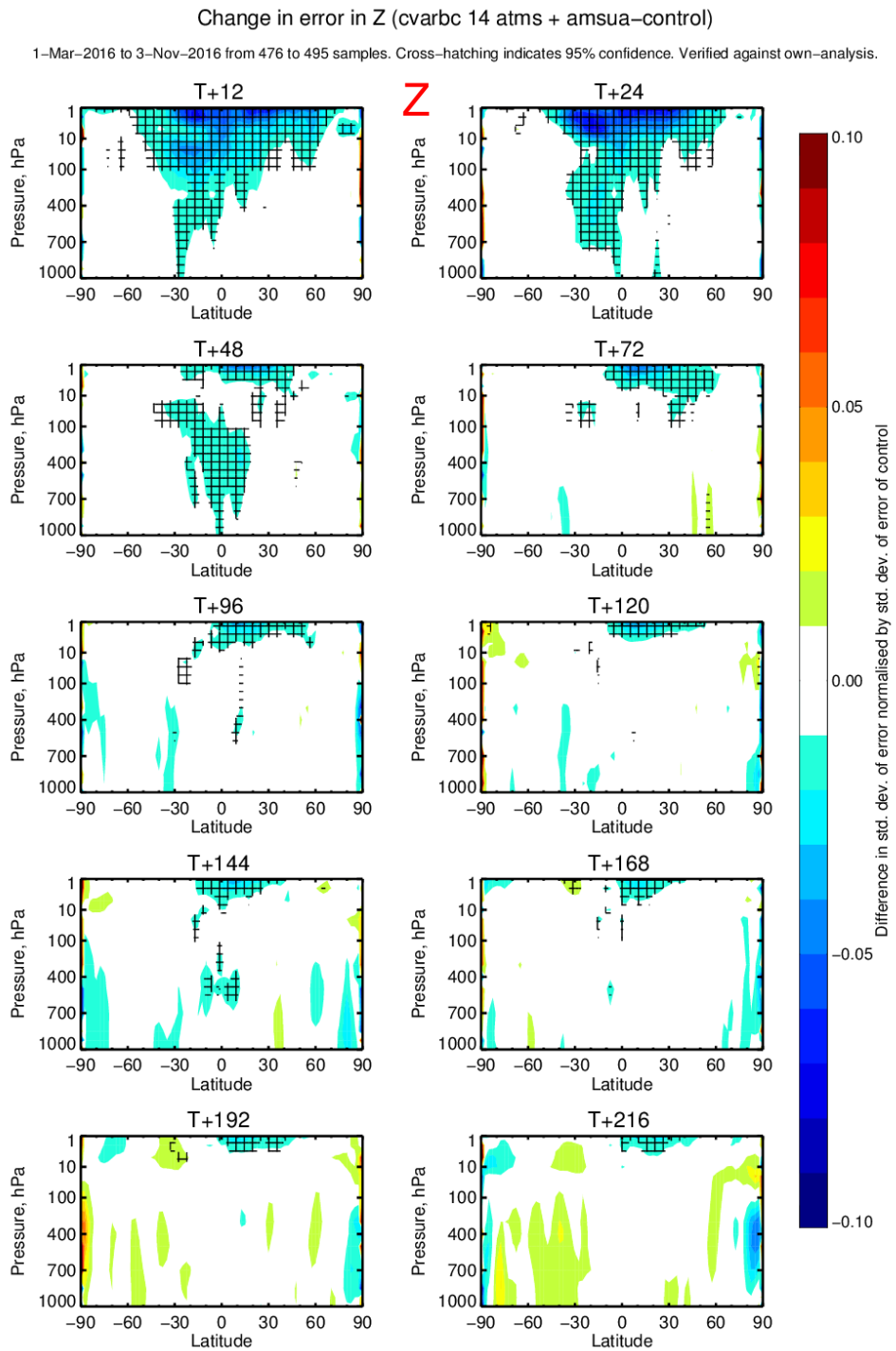
High peaking channels

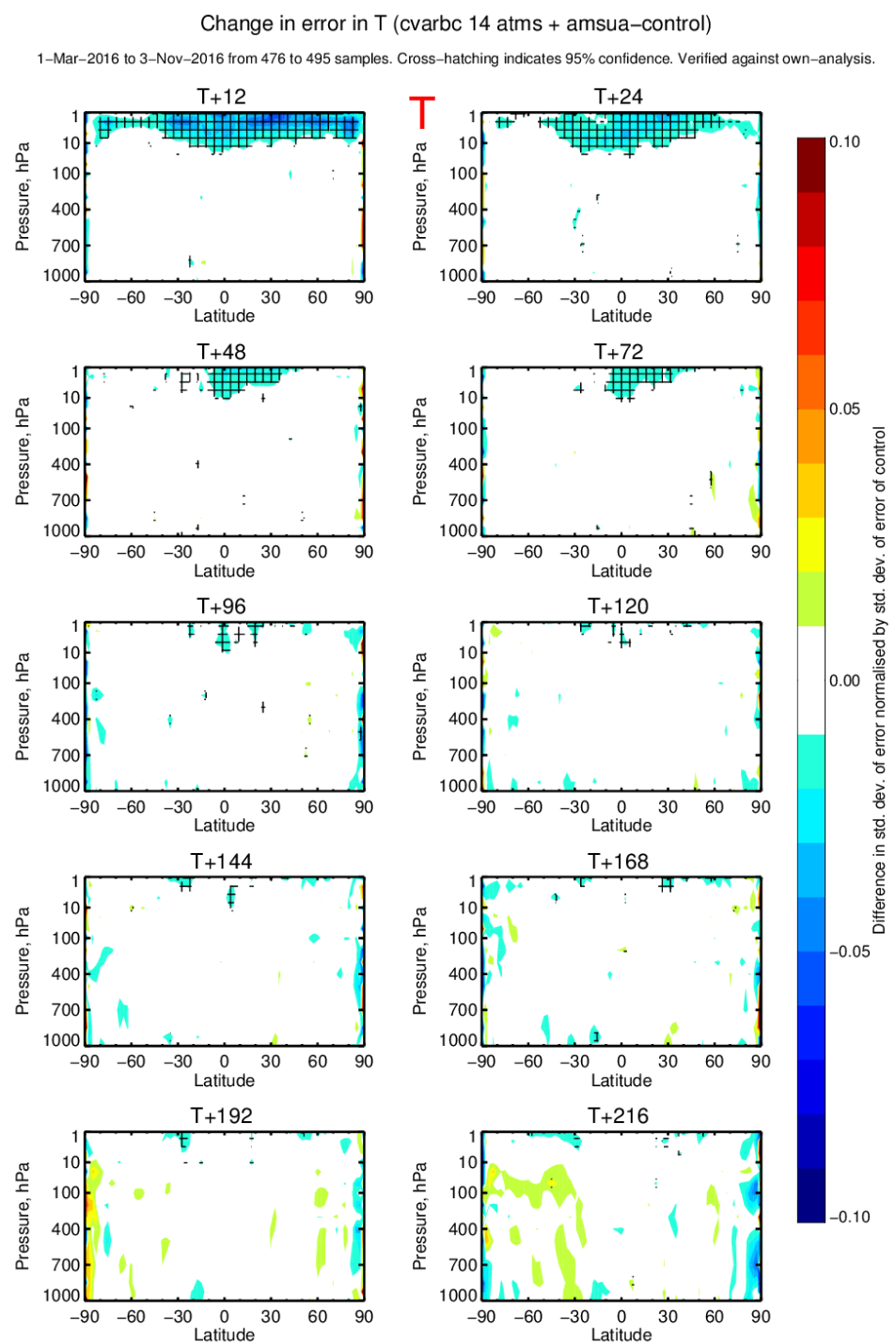




Heather Lawrence, 2017

CVarBC of AMSUA Ch14: Impact on forecasts



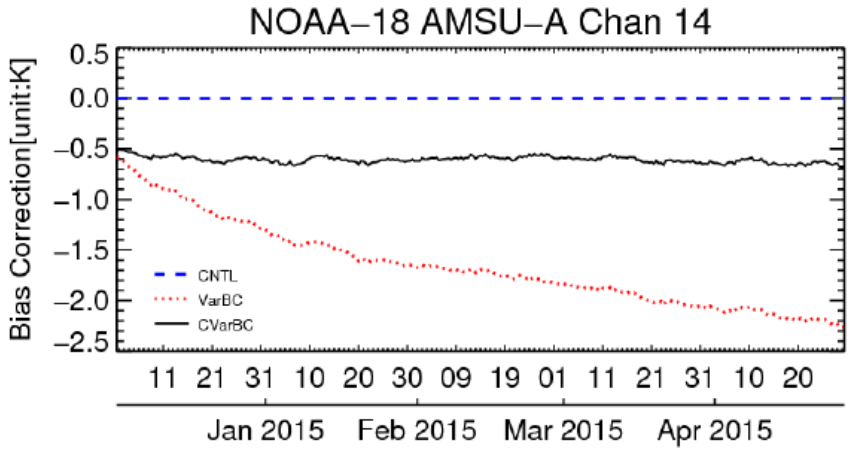


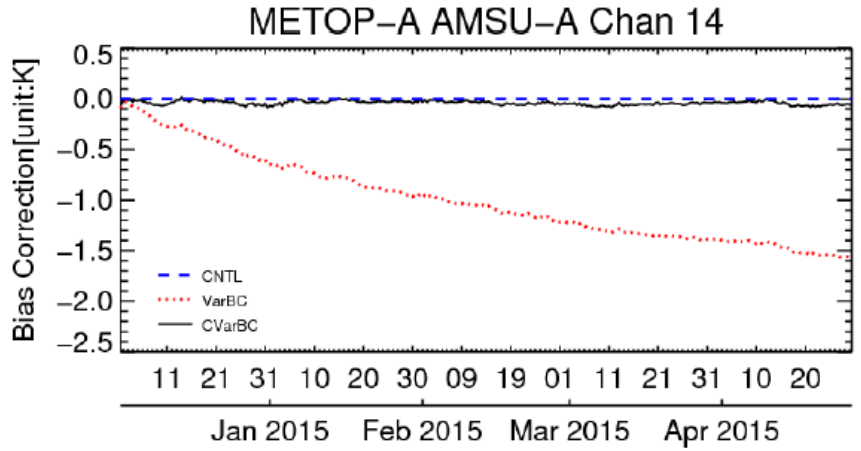
Heather Lawrence, 2017

CVarBC (since 5 June 2018, IFS CY45R1)

Constrained Variational Bias Correction
(Wei Han, SAF visiting scientist from CMA)

- Issue: Unrealistic drifts of VarBC in the presence of model bias (e.g., stratosphere; ozone)
- Previous solution: Use selected "anchor channels" with no bias correction (despite known biases)
- New CVarBC: Allow correction of bias, but penalise the size of the bias correction according to uncertainty in the bias.
- → Known bias pattern can be captured, such as different biases for different satellites, but unrealistic drifts are still avoided.
- **Used operationally since 5 June 2018 (cy 45R1)**





ECMWF Andy Brown,2018

https://confluence.ecmwf.int/display/FCST/Implementation+of+IFS+cycle+45r1

Summary and Discussions

- **Potential use of CVarBC**
  - **Reanalysis**
  - Window channels
  - Stratosphere amd mesosphere sounding
  - Humidity sounding
  - Chemistry DA

$$2J(\mathbf{x},\boldsymbol{\beta}) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}_x^{-1}(\mathbf{x}_b - \mathbf{x}) + (\boldsymbol{\beta} - \boldsymbol{\beta}_b)^T \mathbf{B}_\beta^{-1}(\boldsymbol{\beta} - \boldsymbol{\beta}_b) + [\mathbf{y} - H(\mathbf{x}) - h(\mathbf{x},\boldsymbol{\beta})]^T \mathbf{R}^{-1} [\mathbf{y} - H(\mathbf{x}) - h(\mathbf{x},\boldsymbol{\beta})] + \alpha^2 [h(\mathbf{x},\boldsymbol{\beta}) - \mathbf{b}_0]^T \mathbf{R}_b^{-1} [h(\mathbf{x},\boldsymbol{\beta}) - \mathbf{b}_0]$$

- **Priori information of observation Bias**
  - Systematic bias $\mathbf{b}_0$
  - **Uncertainty** $\mathbf{R}_b$
  - GSICS, GAIA-CLIM?

Quantitive use of RU and RT uncertainty:
DA+Calibration

- **How to determine the regularization parameter?** α
  - Posteriori estimation ?
  - Balance with anchor observations?
  - Deal with model bias?

Regularizaiton Parameter Estimation:
DA+Inverse Problem

Reference

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