Interaction of Bending Angle Assimilation from GNSS Sensors in the U.S. Navy's Assimilation System

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Navy's Data Assimilation Tools

NCODA

NRL Coupled Ocean Data Assimilation System
Multivariate Analysis of ocean u,v,T,s,ice,SSH,SWH.
Global, Regional, Local Ocean Data Assimilation.

NAVDAS

NRL Atmospheric Variational Data Assimilation System
3D Variational Analysis, Observation Space.
Global, Regional, or Local Application.

NAVDAS-AR

NAVDAS Accelerated Representer
4D Variational Analysis, Weak Constraint, Model Space.
Global or Regional Application. High Altitude DA.

ADJOINTS

NAVDAS(–AR) Adjoints of 3D & 4D Data Assimilation Systems
NOGAPS TLM; Moist Adjoint
COAMPS® TLM; Moist Adjoint, ***including explicit moist physics***

NAVOBS

NAVDAS-Adjoint OBservation Monitoring System (web-based)
Real-time monitoring of all data assimilated.
Identification of observation quality problems.
Real-time data selection and data targeting.

EnKF

Ensemble Kalman Filter Algorithm
Testing for COAMPS® using real observations.
EnKF/4DVAR Hybrid for the NAVDAS-AR framework.

NRL/FNMOC Global Analysis System

NAVDAS-AR – NRL Atmospheric **V**ariational **D**ata **A**ssimilation **S**ystem-**A**ccelerated **R**epresenter

NRL Scientists developed and transitioned to FNMOC the first operational global 4D-Var in the United States: 23 September 2009

- Full 4D-Var algorithm solved in observation space using representer approach
- Weak constraint formulation allows inclusion of model error
- **T319L42, model top at 0.04 hPa (~70 km)**
- More effective use of asynoptic and single-level data
- **More computationally efficient than NAVDAS (3D-Var) for large # of obs**
  - NAVDAS assimilated ~500K observations in each cycle
  - NAVDAS-AR assimilates 2.0 M observations per cycle
- **Adjoint developed for observation impact with real-time web monitoring capability, computed 4x/day**

Brief Timeline of NAVDAS-AR (4D-Var)

- NAVDAS-AR *(strong constraint, CRTM)* Sep2009
- New Satellite Data sources added or improved with NAVDAS-AR
  - ✓ IASI, AIRS assimilation added, *refined and skill improved*; NOAA-19 AMSU-A
  - ✓ DMSP F16, F17, F18 UPP operational; *Assimilating radiances, surface winds, TPW, ice*
  - ✓ ASCAT, WindSAT *(winds and TPW)*
- T319L42 NOGAPS *(increased horizontal & vertical resolution)* May2010
- Subsequent sensors added to NAVDAS-AR
  - ✓ GPS RO bending angle Sep2010
    - COSMIC, GRAS, GRACE-A, Terra SAR-X, SAC-C, C/NOFS
  - ✓ RARS ATOVS retransmission data Sep2010
  - ✓ Combined LEO/GEO atmospheric motion vectors (AMV) Nov2010
  - ✓ Hourly geostationary winds (AMV) from MTSAT, Meteosat and GOES-W Dec2010
  - ✓ MHS and SSMIS 183 GHz channel assimilation Jan2011
- Sensors and enhancements to be added to NAVGEM
  - Variational bias correction
  - SBU/V and OMPS ozone
  - HIRS and Geostationary Clear-Sky Radiance
  - Aerosols, clouds, land surface

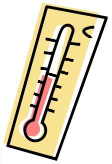
Data Assimilation provides initial conditions to the NWP forecast model

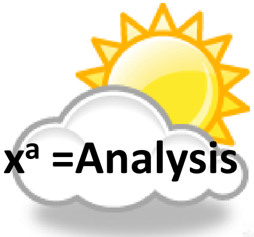
Length of model state vector: $10^7 - 10^8$ **Number of obs: 10^6**

Error assumptions

P^f - model state; R - observation

y = Observations





x^a =Analysis

$$\mathbf{x}^a = \mathbf{x}^f + \mathbf{P}^f\mathbf{H}^T\left(\mathbf{H}\mathbf{P}^f\mathbf{H}^T + \mathbf{R}\right)^{-1}\underbrace{\left(\mathbf{y} - \mathcal{H}\left(\mathbf{x}^f\right)\right)}_{\text{Innovation}}$$

x^f = Model forecast "background"

$H(x^f)$ - nonlinear mapping from state into ob space

$\mathbf{H}^T$ - linearized operator

Combine a relatively accurate "first guess" model **forecast** with a variety of **observations**, and produce an **analysis** that observes the mass/wind balances found in nature.

NOGAPS/NAVDAS-AR Operational System Observational Data Types Assimilated

Conventional Data Types

- Radiosondes and Pibals
- Dropsondes
- Driftsonde (Concordiasi)
- Land and Ship Surface Obs
- Aircraft Obs
    - AIREPS
    - AMDAR
    - MDCRS
- Synthetic Obs
    - TC Bogus

Satellite Data Types

- Surface Winds
    - Scatterometer, ASCAT and ERS-2
    - SSMI/SSMIS
    - WindSat
- Feature Tracked Winds
    - Geostationary (6 satellites)
    - Polar Orbiters (AVHRR and MODIS)
    - Combined polar/geo winds (CIMSS)
- Total Water Vapor
    - SSMI/SSMIS TVAP
    - WindSat TVAP
- GPS Bending Angle
- IR Sounding Radiances
    - IASI and AIRS
- MW Sounding Radiances
    - 6 AMSU-A (Ch 4-14)
    - 3 SSMIS (Ch 2-7, 22-24)
    - 3 SSMIS/3 MHS 183 GHz

FNMOC OPS Upgrades
Sep 15, 2010

- Addition of GPS bending angle assimilation
    - no bias correction, very low error 8km – 30km
    - EUMETSAT GRAS-SAF Software Deliverable ROPP* version 4
        - *Radio Occultation Processing Package
    - COSMIC FM1-6; GRAS MetOp-A; GRACE-A; Terra SAR-X, SAC-C, and C/NOFS CORISS
- Additional IR/MW radiance for stratospheric channels:
    - 4 -- AMSU-A: ch 11-14
    - 3 -- SSMIS: ch 22-24
    - 10 -- IASI: 122, 128, 135, 141, 148, 154, 161, 173, 185, 187
- Assimilate 24 IASI stratospheric channels over land/sea-ice
    - prior use of hyperspectral was over open ocean only
- Perform consistent antenna pattern correction for all AMSU-A
    - AVHRR and ATOVS Preprocessing Package (AAPP)
- Supplement real-time AMSU-A data feed with RARS
    - adds 10-15% more data to real-time OPS run

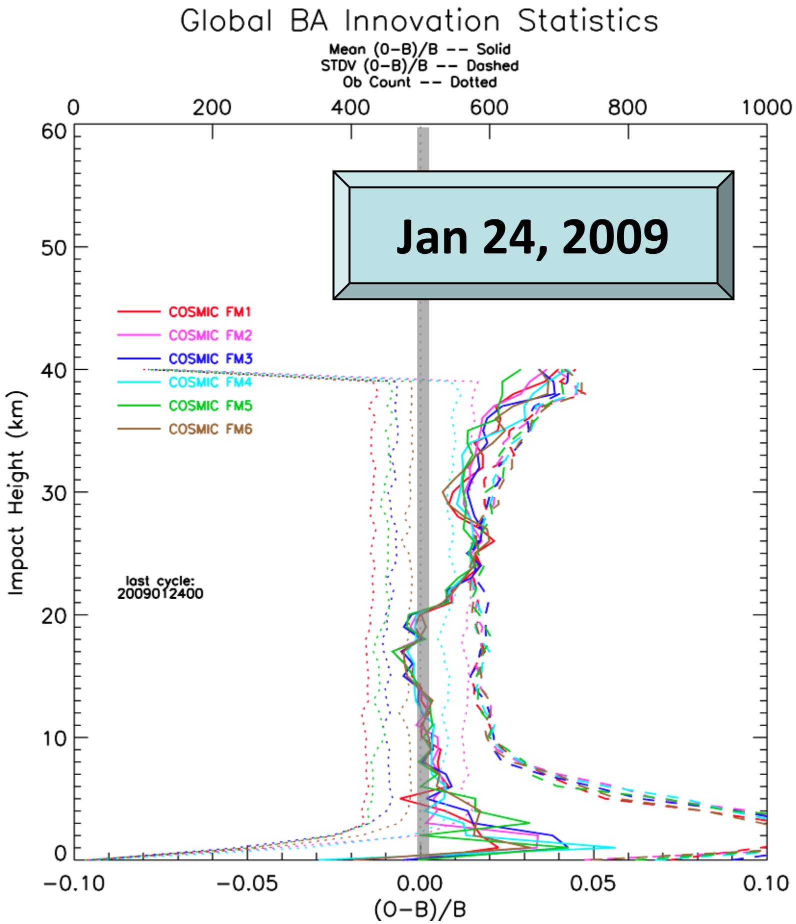
GPS Bending Angle Monitoring

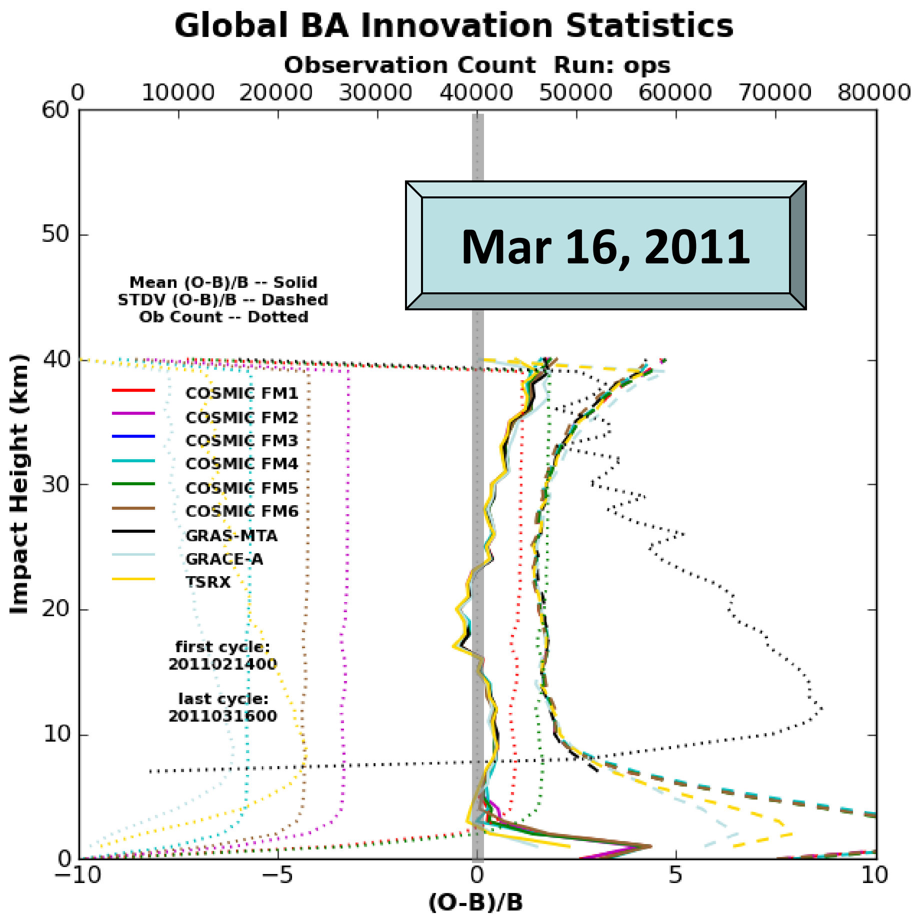
global innovation statistics

Bending Angle innovation normalized by the background bending angle

Before GPS assimilation

After GPS assimilation



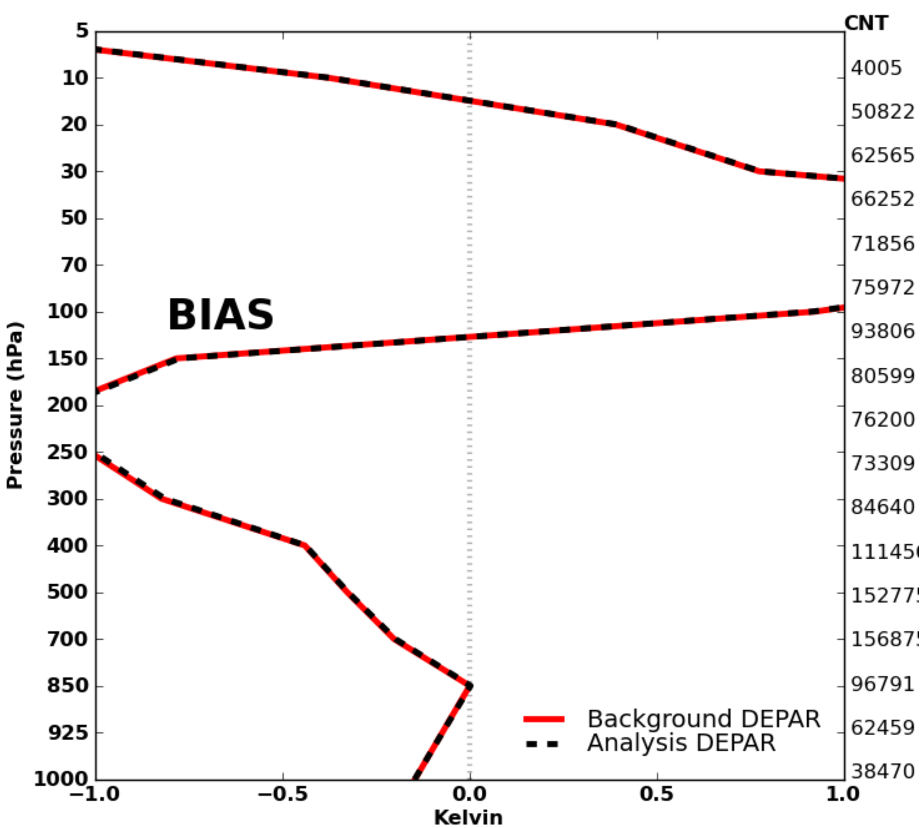


GPS Bending Angle: Raob Impact

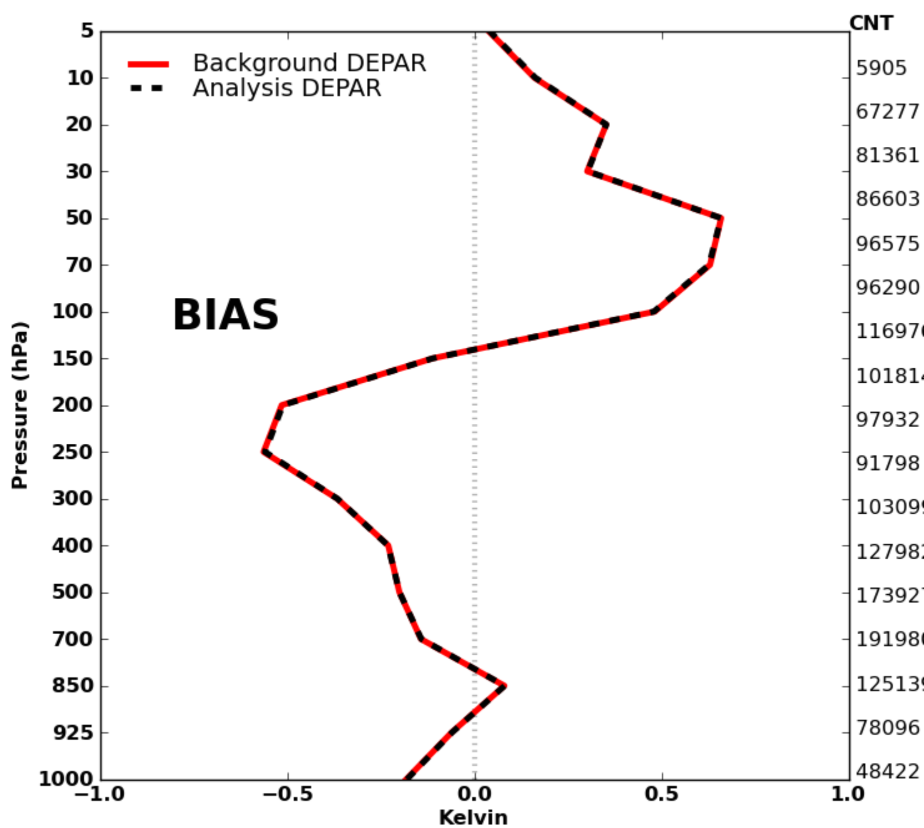
30-day global innovation statistics

Aug15-Sep15, 2010	Sep15-Oct15, 2010
Before GPS assimilation	**After GPS assimilation**

raob temperature bias global innovation



raob temperature bias global innovation

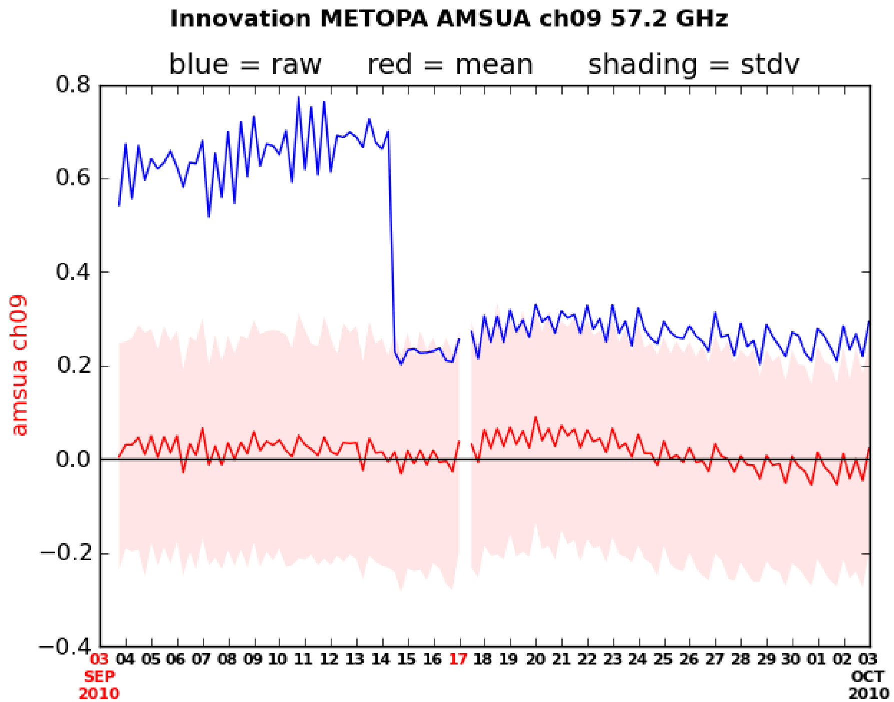


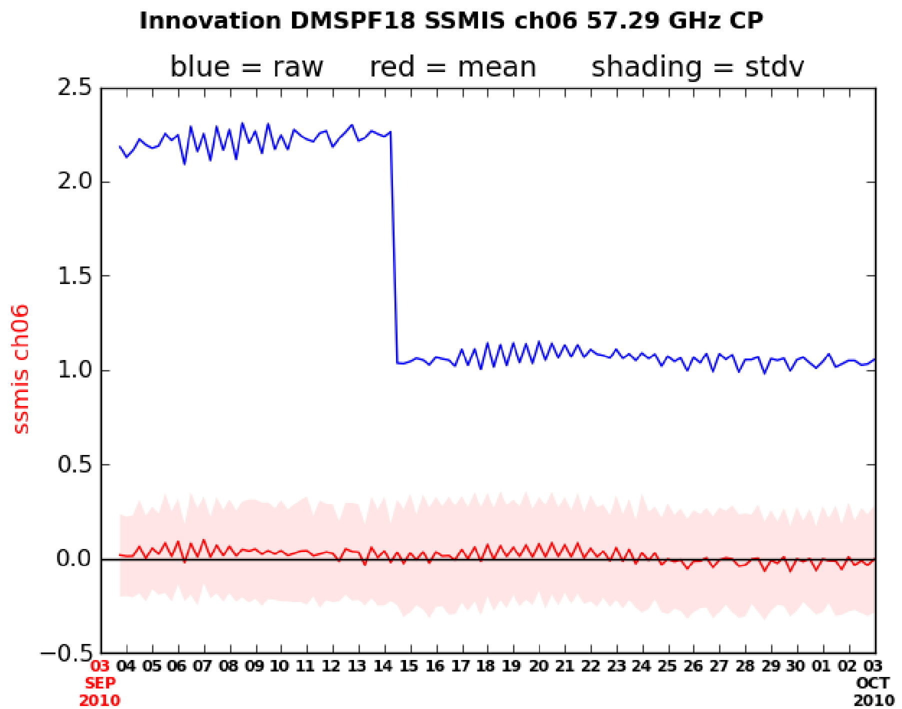
GPS Bending Angle Impacts
MW sounder radiance

The assimilation of GPS reduced a stratospheric bias which dramatically **improved the raw departures** (observed – simulated) **shown in blue**

Due to the stratospheric improvement these channels were added to the operational assimilation system:

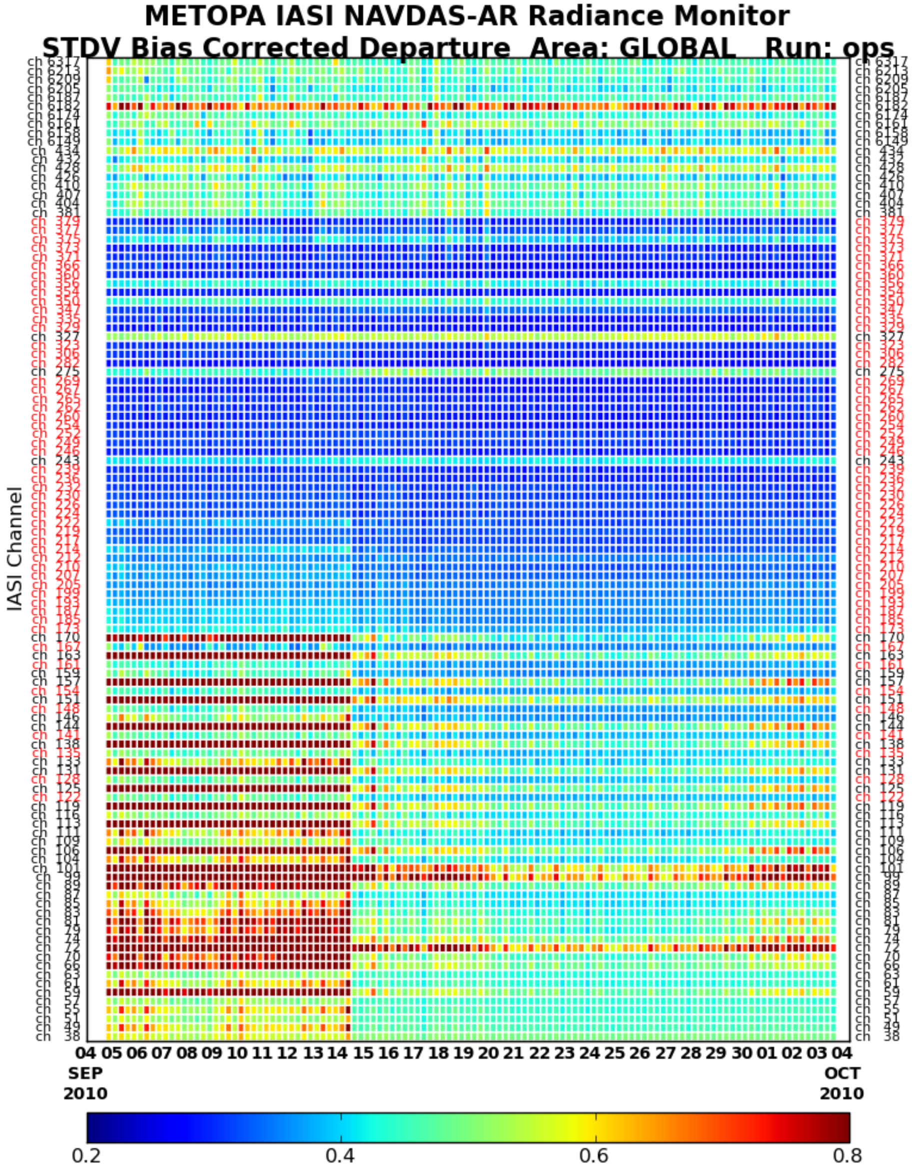
AMSU-A: ch 11-14 (5x: NOAA-15, -16, -18, -19 and MetOp-A)
SSMIS: ch 22-24 (3x: DMSP F16, F17 and F18)





GPS Bending Angle Impacts

IR sounder radiance



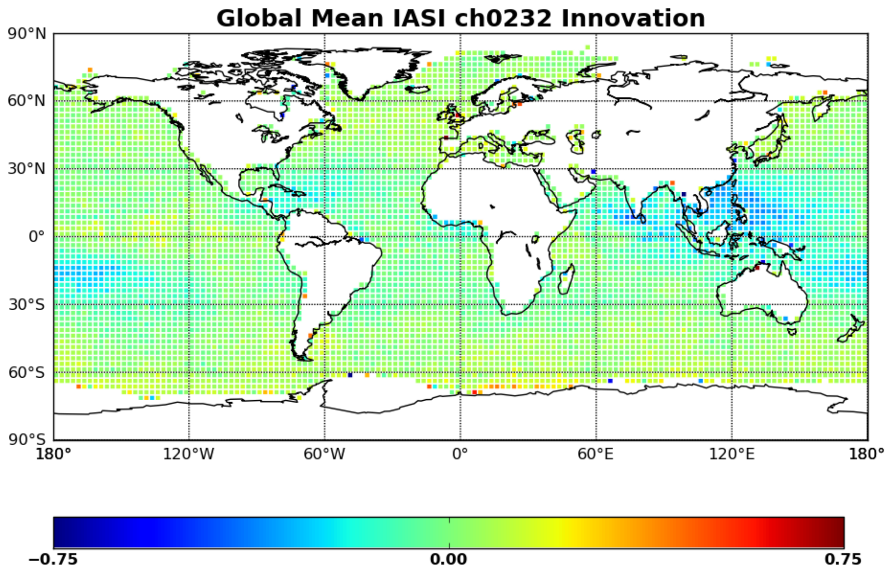
Similarly the improved stratosphere due to GPS impacted the standard deviation **(STDV) of the bias corrected departures** (observed – simulated) for IASI ***shown on left***

As a result additional channels were added for both the IASI and AIRS hyperspectral IR sounders:

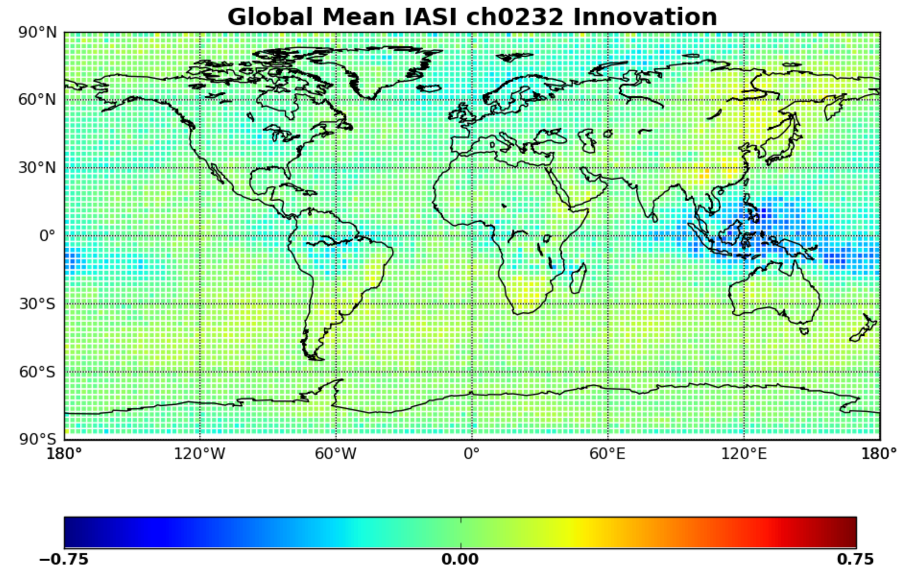
- 10 additional for IASI
- 31 additional for AIRS

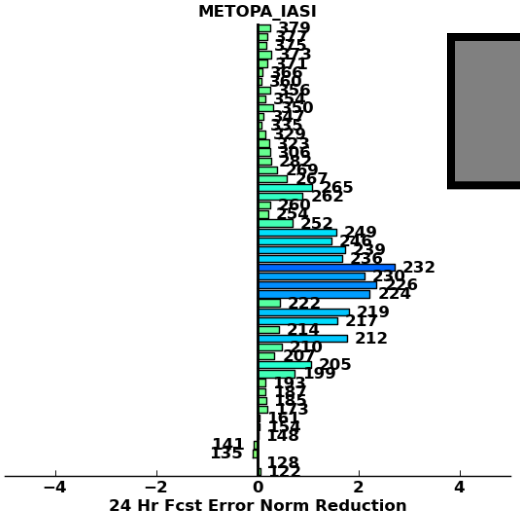
Impact on IASI Assimilation

May 2010



Jan 2011





add data over land and sea ice
mean innovation remains stable

IASI ch 232 has largest impact on 24-hr fcst error

Bias Correction Experiment

- Satellite radiances are bias corrected while radiosondes and GPS bending angle are not

- Start two experiments: **ZZtop** & **varBC** (01Oct – 01Dec, 2011)
  - Identical initial conditions
  - Spin-up (zero bias correction at the beginning)
    - Variational bias correction typically longer spin-up times
  - Both bias correction schemes contain
    - Offset
    - Scan position predictor
    - Two airmass predictors 850-300 hPa, 200-50hPa

ZZtop - Offline Bias Correction: Harris and Kelly (2001) style using statistics from creation of past analysis

varBC - Variational Bias Correction: New corrections are part of 4D-Var minimization. This allows for dynamic fitting between all observation types (i.e. **raob and GPS can correct radiances directly**)

Bias Correction Experiment

Data Stoplight Chart

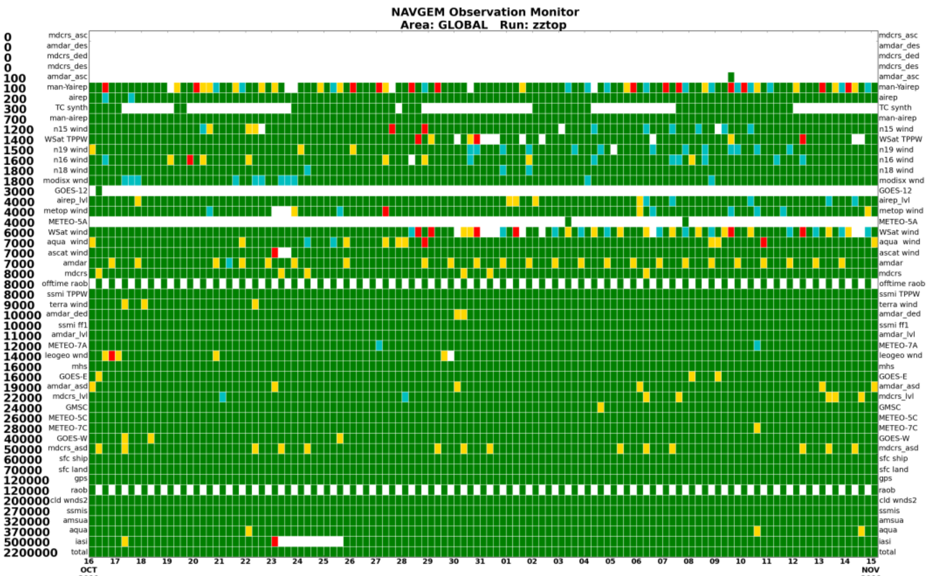
- Gross check to ensure all data types were used consistently between experiments

- Does not show fine-scale differences in data usage

ZZtop

Oct16-Nov15, 2011

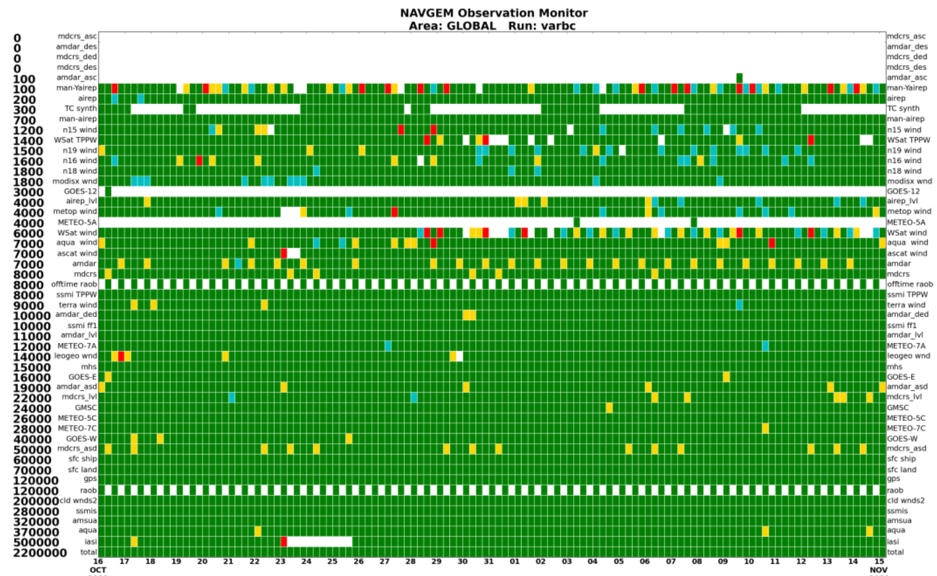
varBC



OB CNT

ob cnt < 3000: 0 - 12.5% | 12.5 - 25% | 25 - 175% | > 175%

ob cnt > 3000: 0 - 25% | 25 - 50% | 50 - 150% | > 150%



OB CNT

ob cnt < 3000: 0 - 12.5% | 12.5 - 25% | 25 - 175% | > 175%

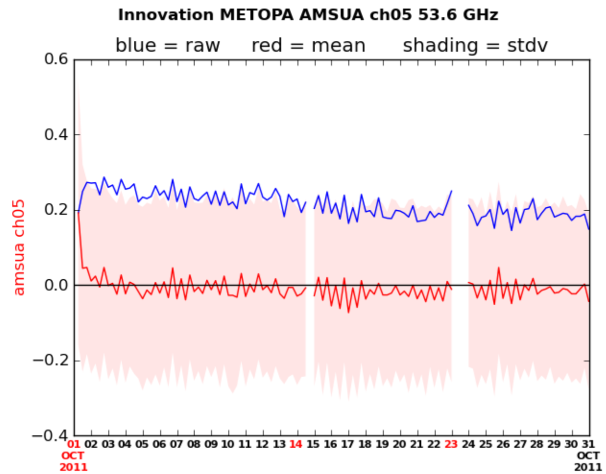
ob cnt > 3000: 0 - 25% | 25 - 50% | 50 - 150% | > 150%

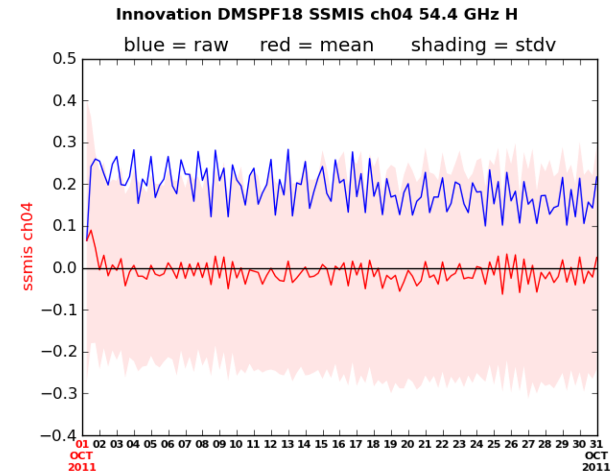
Bias Correction Experiment

AMSU-A bias spin up

- Conventional wisdom always said: Variational bias correction (lower two figures) can take up to a month to converge on a bias correction

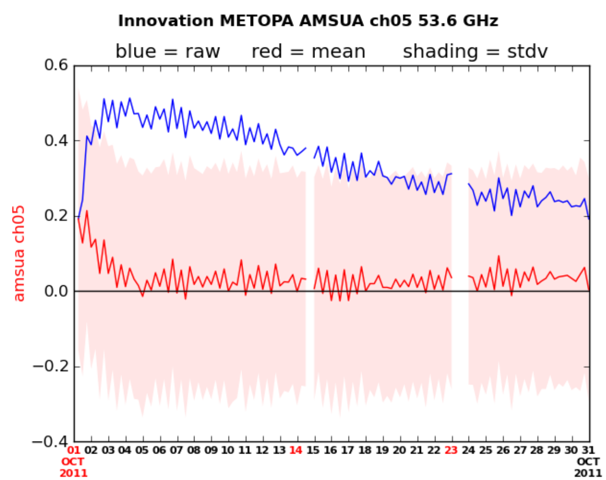
ZZtop

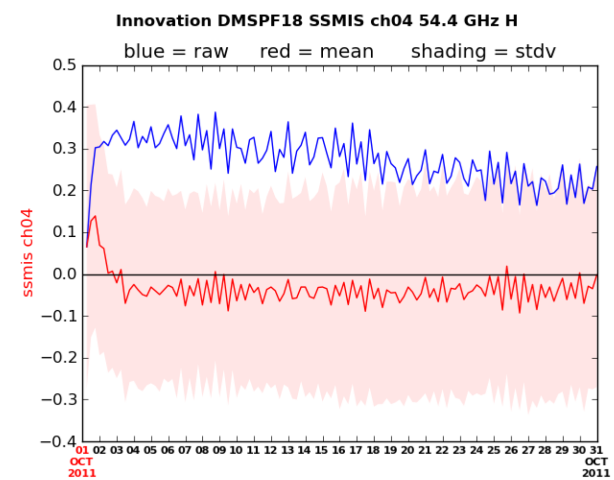




Oct01-Oct31, 2011

varBC





Bias Correction Experiment

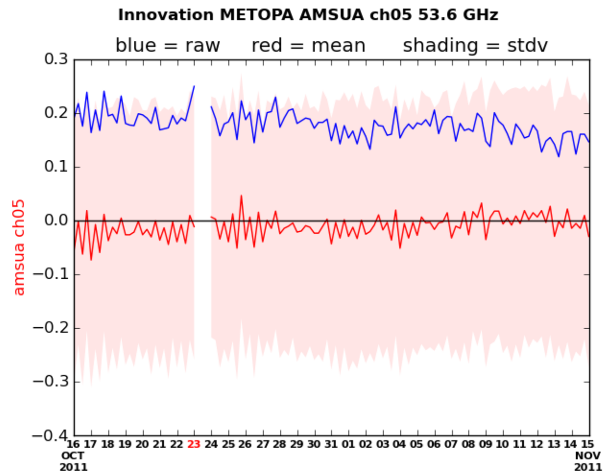
AMSU-A bias spin up

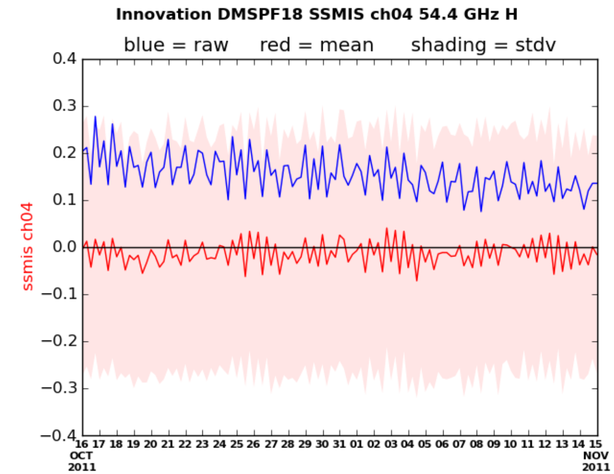
- Looks like both methods are still converging after 45 days!

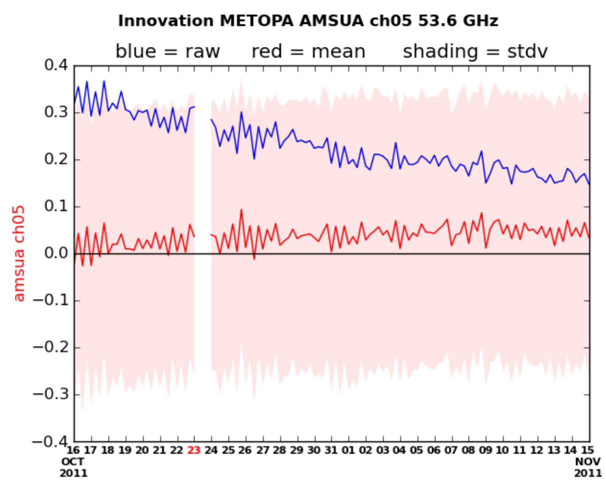
ZZtop

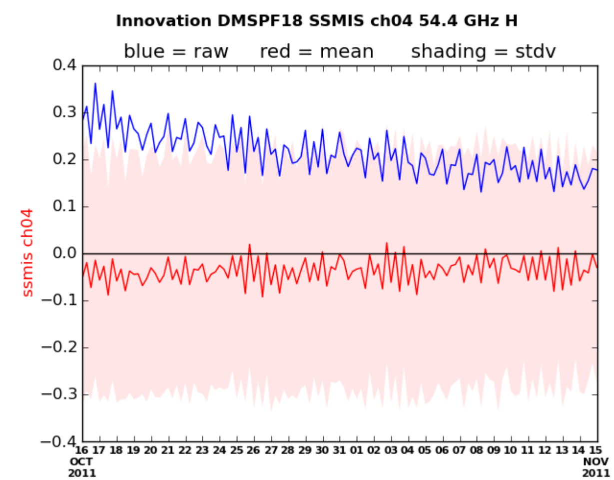
Oct16-Nov15, 2011

varBC









Bias Correction Experiment

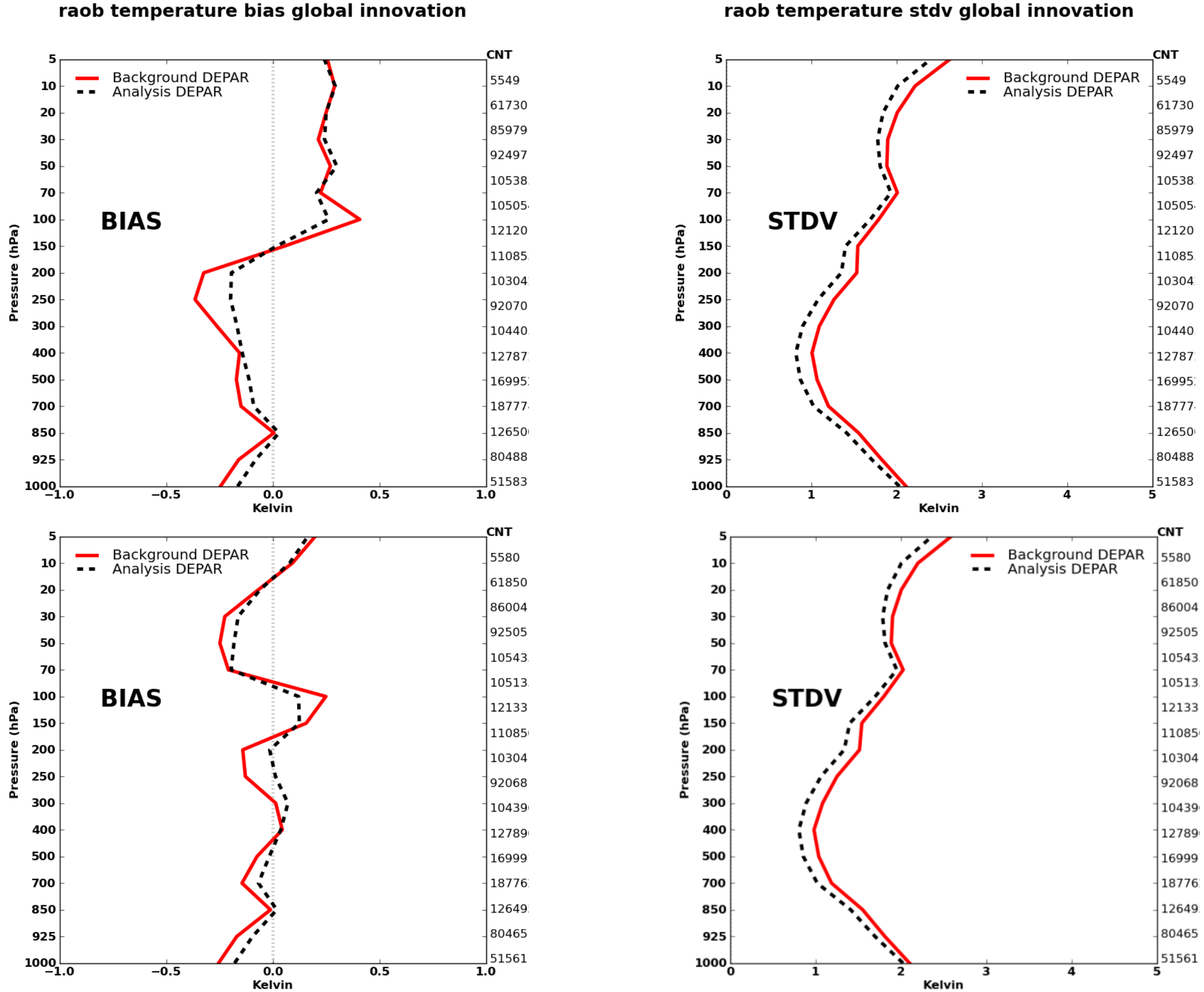
Raob Temperature

- Variational bias correction overall better fit, particularly in the stratosphere
- ZZtop analysis fit clearly better in mid- to upper-troposhere (*weakly influenced by GPS*)

ZZtop

Oct16-Nov15, 2011

varBC



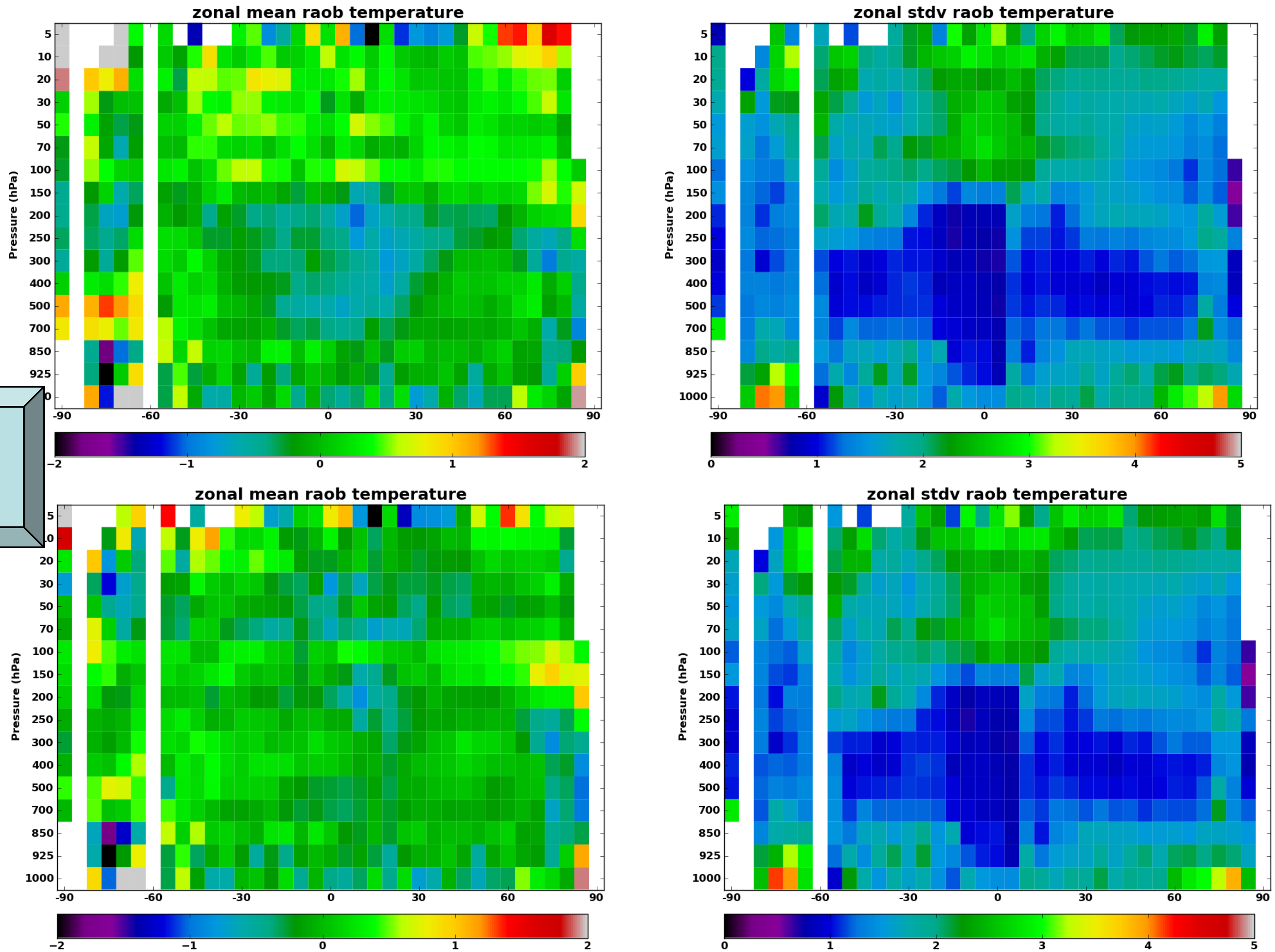
Bias Correction Experiment

Raob Temperature

ZZtop

Oct16-Nov15, 2011

varBC



Bias Correction Experiment

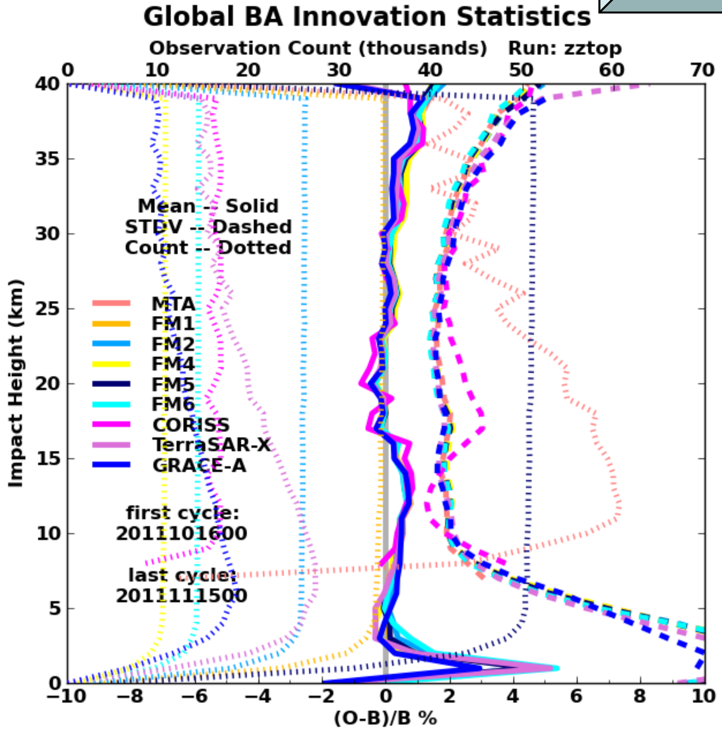
GPS innovation statistics

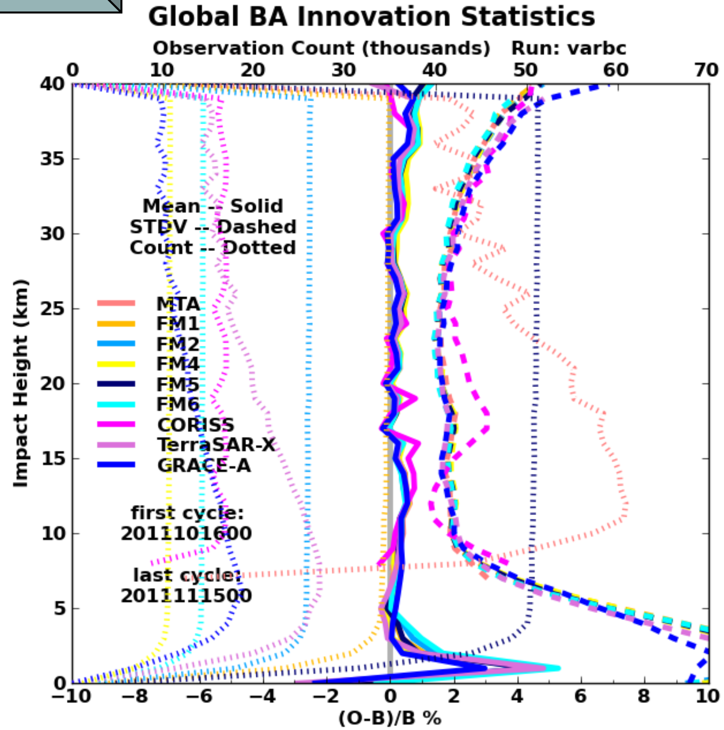
- Variational bias correction does fit GPS sensors more closely
- Issues with NWP model have been corrected; resulting in a better depiction of the stratosphere in general

ZZtop

Oct16-Nov15, 2011

varBC





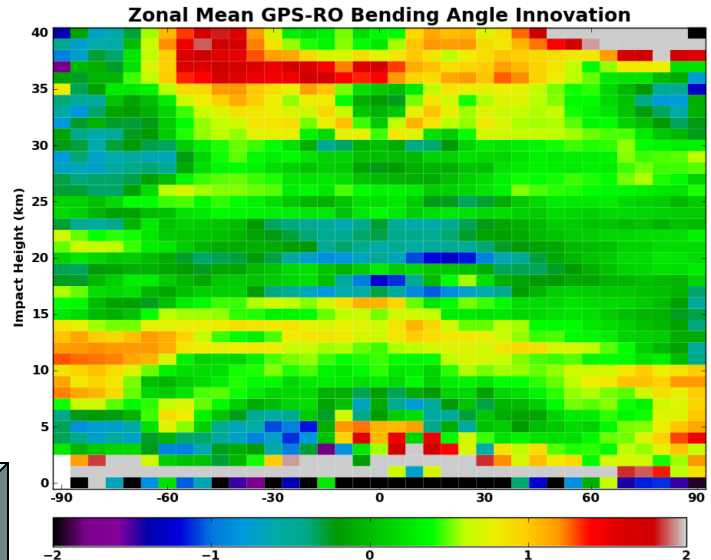
Bias Correction Experiment

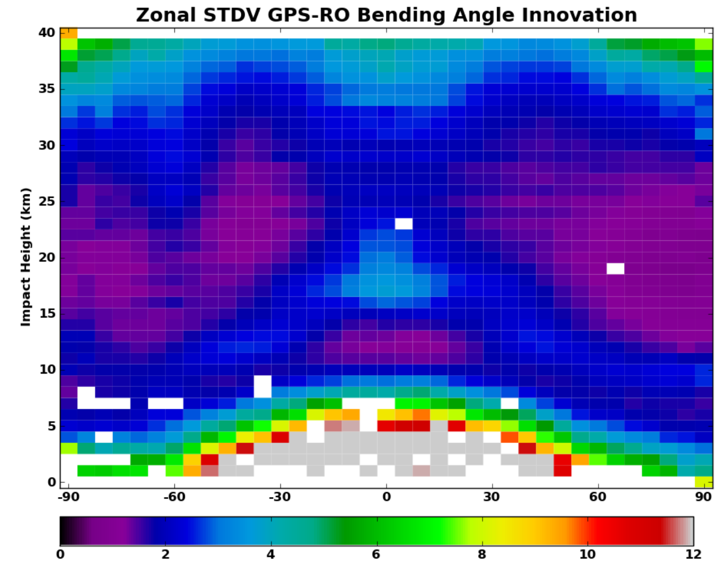
GPS innovation statistics

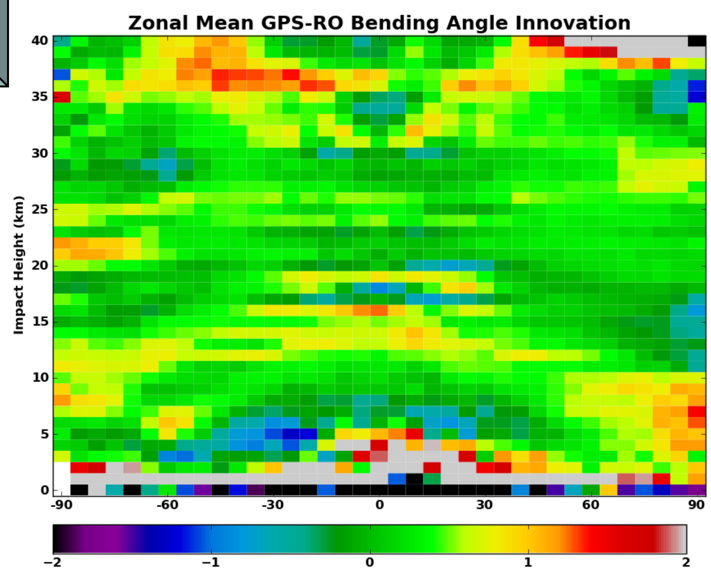
ZZtop

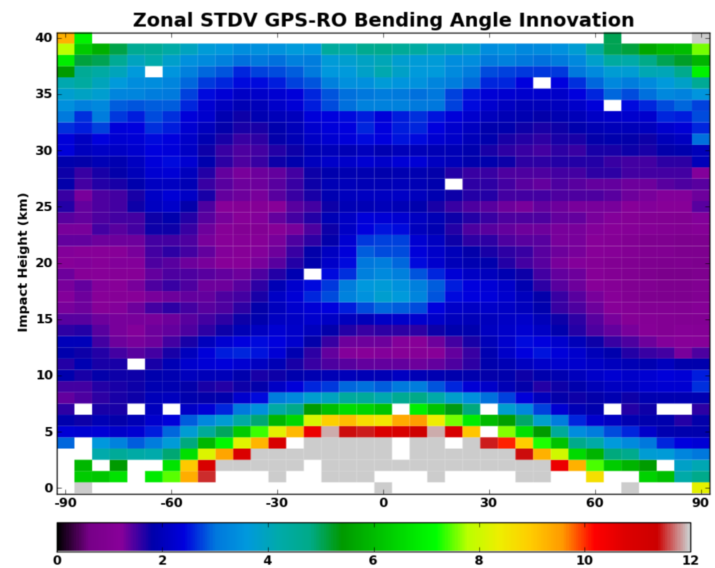
Oct16-Nov15, 2011

varBC



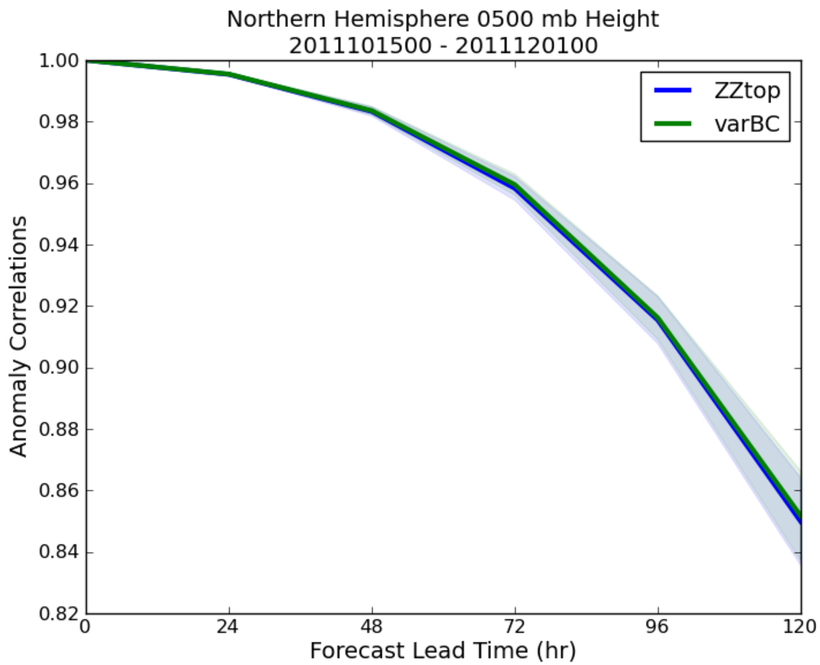


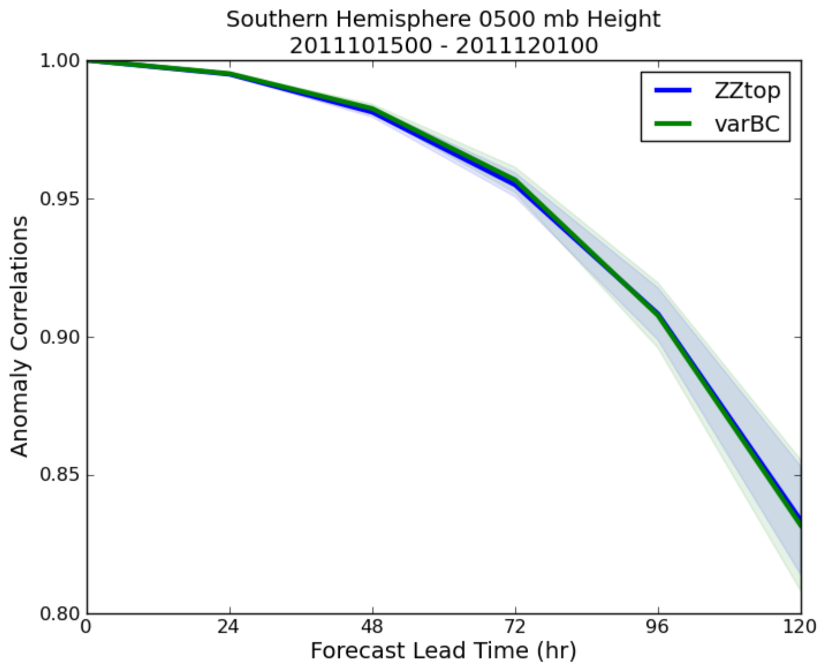




Bias Correction Experiment
Model impacts: height anomaly correlation

- If 500hPa anomaly correlations are degraded something is very wrong
- A strong impact on 500hPa AC is not expected

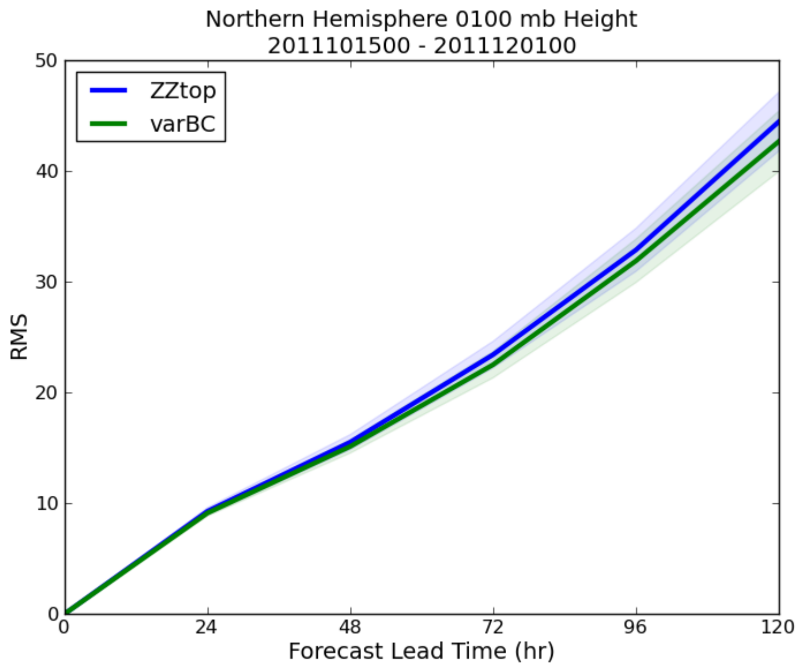


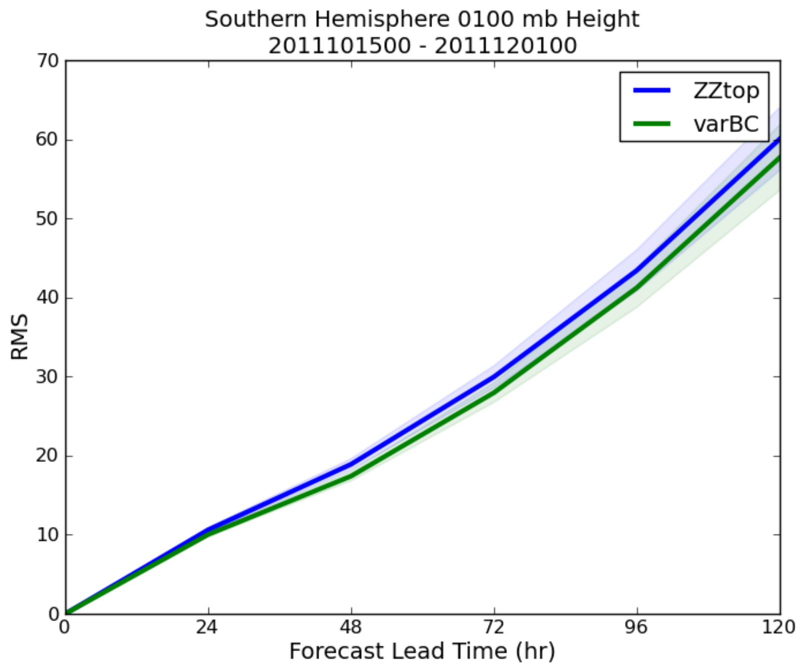


Bias Correction Experiment

Model impacts: height RMS errors

- 100hPa geopotential heights should be more directly impacted in this experiment
- Better fit to GPS and Radiosonde in the stratosphere translates to lower RMS at 100hPa





Conclusions & Future Work

• GPS bending angle observations have been operationally assimilated by NAVDAS-AR into NOGAPS since Sep2010

• GPS led to a dramatic improvement in fit to radiances and radiosondes in the stratosphere

  ✓ resulting changes to the NWP system have lowered the initial stratospheric bias in the model state

• Variational bias correction shows potential to further improve the analysis fit in the stratosphere

• Variational bias correction shows minimal impact on self-analysis anomaly correlations in the middle troposphere

• Near-term: tangent point drift added to current GPS assimilation
• Longer-term: 2D bending angle operator for GPS assimilation