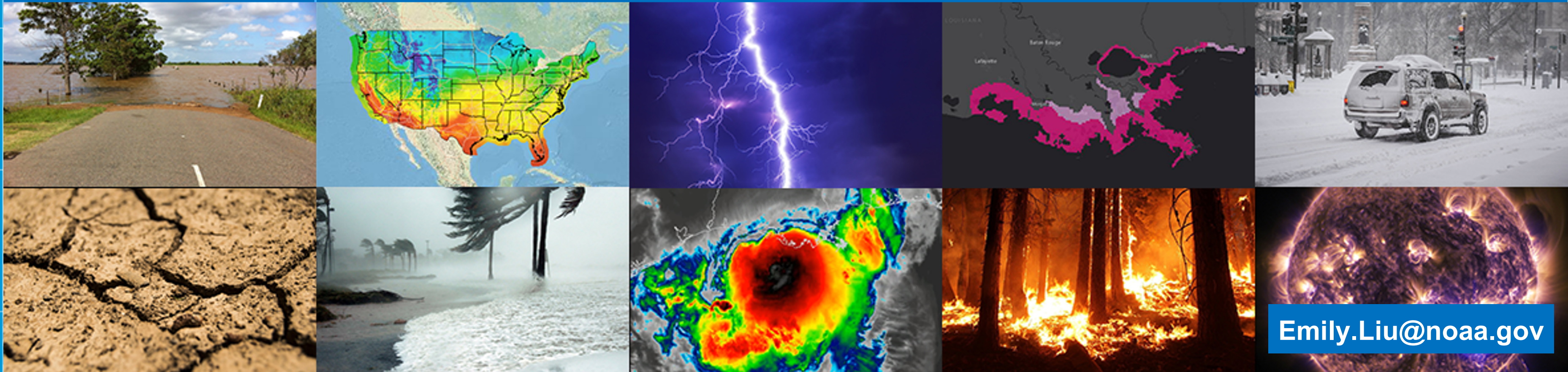
NATIONAL
WEATHER
SERVICE

The Use of Microwave Sounder Data in NCEP Global Forecast System - Current Status and Outlook

NOAA Microwave Sounder Workshop
Wednesday, July 28, 2021

Emily, Huichun Liu[1], James Jung[2], Rahul Mahajan[1], Daryl Kleist[1]

[1]NOAA/NWS/NCEP/EMC *[2]CIMSS@UW-Madison*



Emily.Liu@noaa.gov

Outline

- MW Sounder Data Assimilated in NCEP Global Forecast System
- Impact of Observations in GFS
- Outlook of Using MW Sonder Data in GFS

Outline

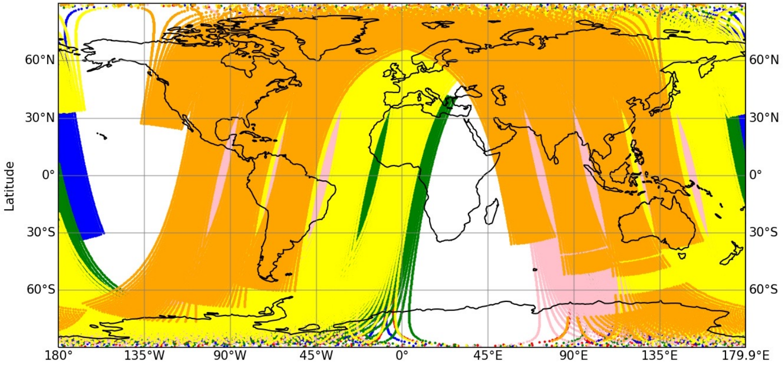
- **MW Sounder Data Assimilated in NCEP Global Forecast System**
- Impact of Observations in GFS
- Outlook of Using MW Sonder Data in GFS

MW Sounder Radiances used in GFS

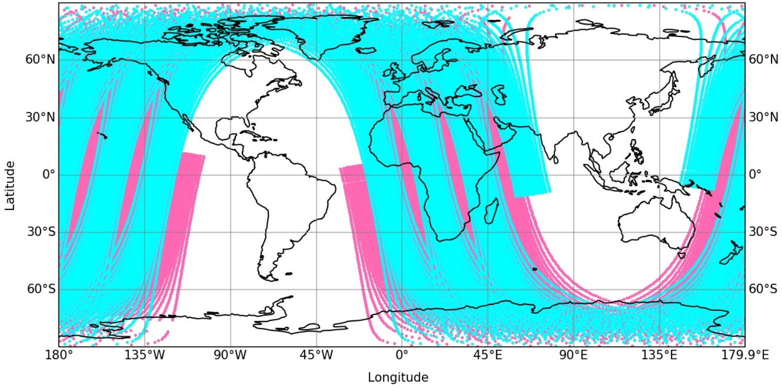
Sensor	Platform	Orbit	Channels
AMSU-A	● NOAA-15	AM; Drifting	1-5,6,7-10,11,12-13,14,15
	● NOAA-18	PM; Drifting	1-4,5,6-7,8-9,10-15
	● NOAA-19	PM; Drifting	1-6,7-8,9-15
	● MetOp-A	Mid AM	1-6,7-8,9-15
	● MetOp-B	Mid AM	1-7,8-14,15
	● MetOp-C	Mid AM	1-15

Sensor	Platform	Orbit	Channels
ATMS	● S-NPP	PM	1-16,17-22
	● NOAA-20	PM	1-16,17-22

GSI observation data: AMSU-A



GSI observation data: ATMS

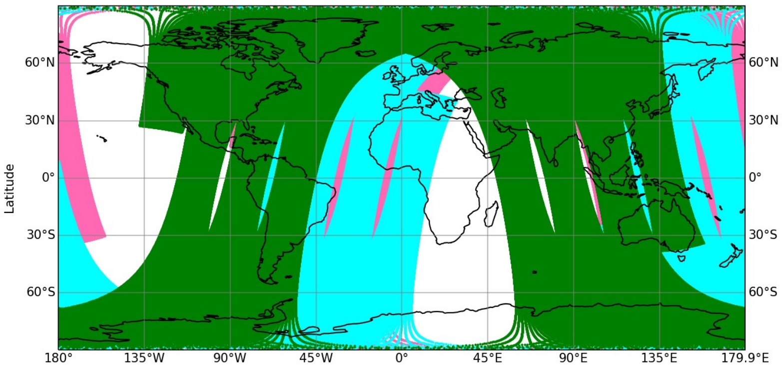


MW Sounder Radiances used in GFS

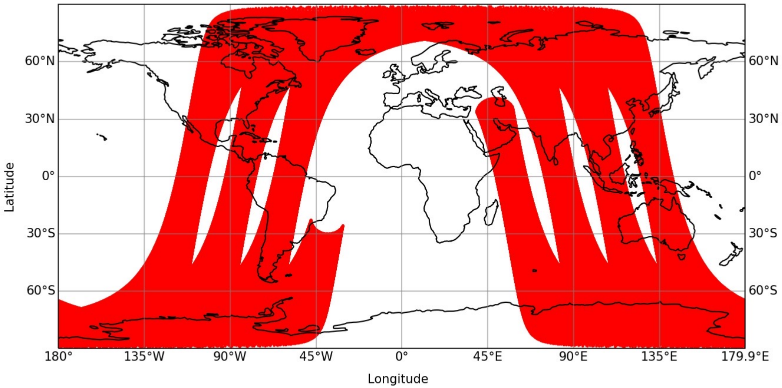
Sensor	Platform	Orbit	Channels
MHS	NOAA-18	PM; Drifting	1,2,3,4,5
	● NOAA-19	PM; Drifting	1,2,3,4,5
	MetOp-A	Mid AM	1,2,3,4,5
	● MetOp-B	Mid AM	1,2,3,4,5
	● MetOp-C	Mid AM	1,2,3,4,5

Sensor	Platform	Orbit	Channels
DMSP-F17	● SSMIS	Early AM	1,2-4,5-7,8-23,24

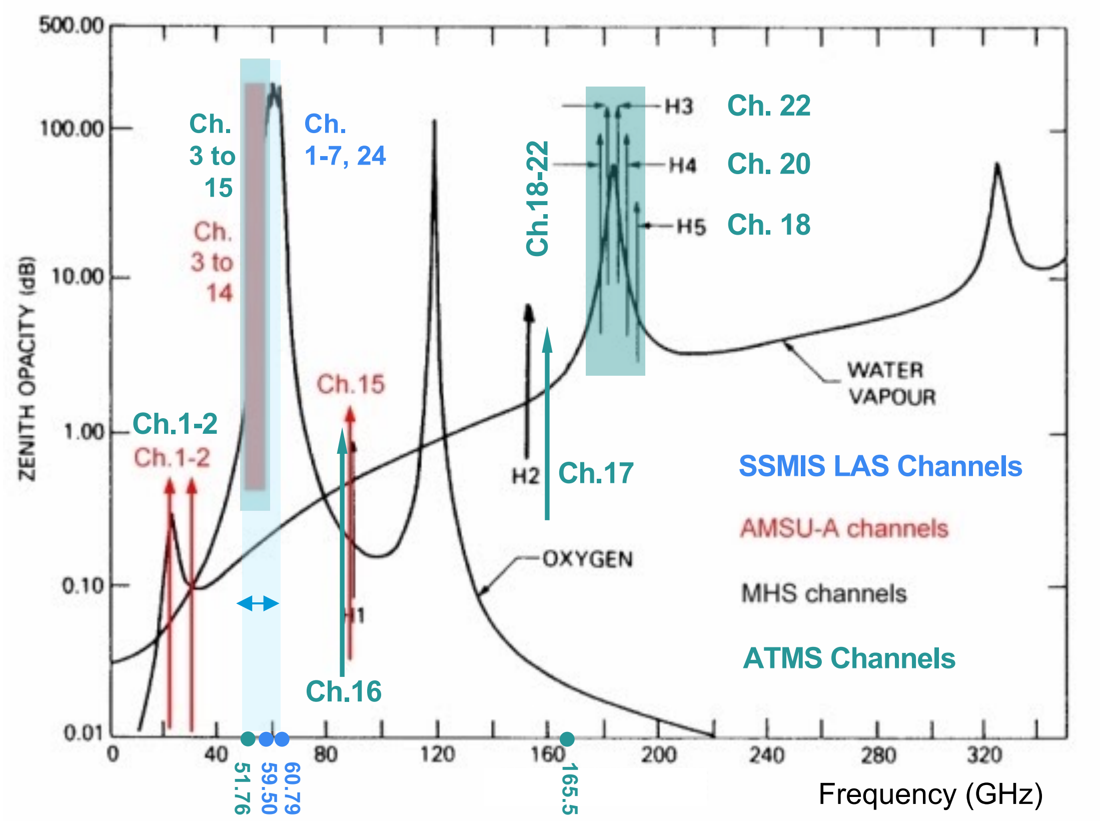
GSI observation data: MHS



GSI observation data: SSMIS



MW Sounder Data Spectral Range in GFS



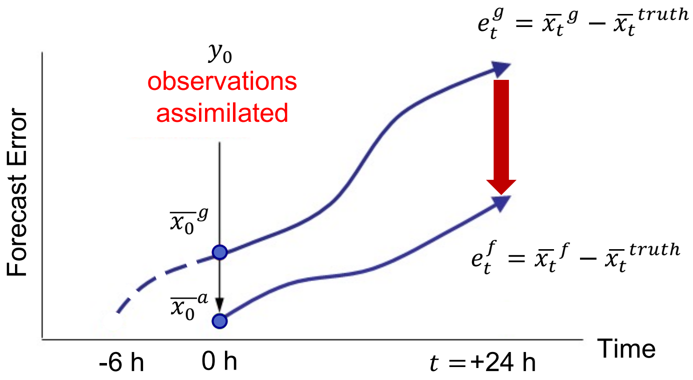
Outline

- MW Sounder Data Assimilated in NCEP Global Forecast System
- Impact of Observations in GFS
- Outlook of Using MW Sonder Data in GFS

Impact of Observation in GFS --- Evaluation Metrics

- Ensemble Forecast Sensitivity to Observation Impact (EFSOI)
- Observing System Experiments
  - Addition of MW Sounders to Baseline
  - Addition of SNPP and NOAA-20 to Baseline

Ensemble Forecast Sensitivity to Observation Impact



The forecast error difference $e_t^f - e_t^g$ is due entirely to the assimilation of observation at 00 hour

The impact of l th observation on the forecast at j th grid point

$$(\Delta e_t)_{j,i} \approx \frac{1}{2(k-1)} (\delta \boldsymbol{y}_o^T)_i \left[\rho_j \, \boldsymbol{R}^{-1} (\boldsymbol{H}\boldsymbol{X}_o^a) \left(\left(\boldsymbol{X}_t^f \right)^T \right)_j C_{jj} \left(\boldsymbol{e}_t^f + \boldsymbol{e}_t^g \right)_j \right]_i$$

$$\boldsymbol{e}_t^f - \boldsymbol{e}_t^g \equiv \overline{\boldsymbol{x}_t}^f - \overline{\boldsymbol{x}_t}^g$$

$$\approx \boldsymbol{M} \left(\overline{\boldsymbol{x}_o}^a - \overline{\boldsymbol{x}_o}^g \right) = \boldsymbol{M}\,\boldsymbol{K}\,\delta \boldsymbol{y}_o = \boldsymbol{M}\,\boldsymbol{K} \left(\boldsymbol{y}_o - h(\overline{\boldsymbol{x}_o}^g) \right)$$

$$where\ \boldsymbol{K} = Kalman\ gain\ matrix = P^a \boldsymbol{H}^T\ \boldsymbol{R}^{-1} = \boldsymbol{X}_o^a\ (\boldsymbol{X}_o^a)^T\ \boldsymbol{H}^T\ \boldsymbol{R}^{-1}$$

Define e as a quadratic energy-weighted (C) forecast error

The **forecast error reduction** at time t can be expressed as:

$$\Delta \boldsymbol{e}_t \equiv \frac{1}{2} \left(\boldsymbol{e}_t^f \right)^T C\, \boldsymbol{e}_t^f - \frac{1}{2} \left(\boldsymbol{e}_t^g \right)^T C\, \boldsymbol{e}_t^g \equiv \frac{1}{2} \left(\boldsymbol{e}_t^f - \boldsymbol{e}_t^g \right)^T C \left(\boldsymbol{e}_t^f + \boldsymbol{e}_t^g \right)$$

$$\approx \frac{1}{2}\, \delta \boldsymbol{y}_o^T\ \boldsymbol{K}^T\ \boldsymbol{M}^T C \left(\boldsymbol{e}_t^f + \boldsymbol{e}_t^g \right)$$ (Adjoint of analysis and forecast model)

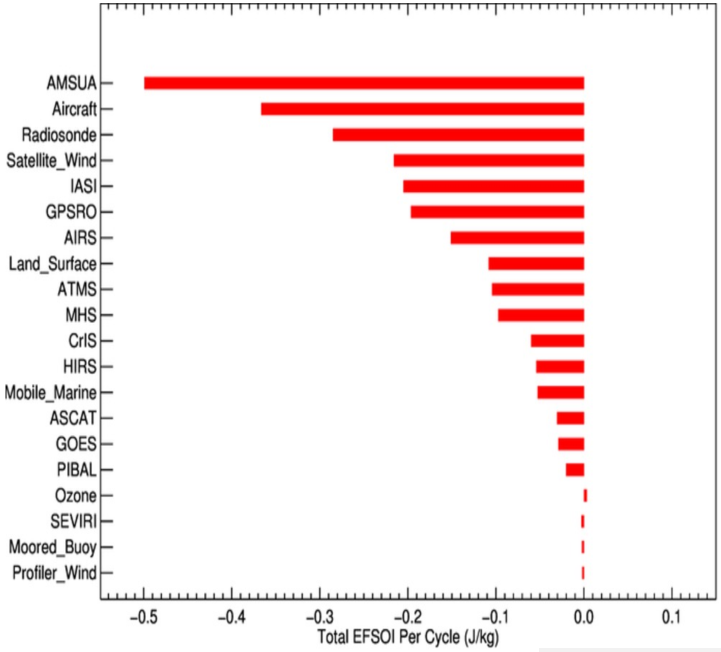
$$\approx \frac{1}{2(k-1)} \left[\ \boldsymbol{M}\boldsymbol{X}_o^a\ (\boldsymbol{H}\boldsymbol{X}_o^a)^T\ \boldsymbol{R}^{-1}\ \delta \boldsymbol{y}_o\ \right]^T C \left(\boldsymbol{e}_t^f + \boldsymbol{e}_t^g \right)$$

$$\approx \frac{1}{2(k-1)}\, \delta \boldsymbol{y}_o^T\ \boldsymbol{R}^{-1}\ (\boldsymbol{H}\boldsymbol{X}_o^a) \left(\boldsymbol{X}_t^f \right)^T C \left(\boldsymbol{e}_t^f + \boldsymbol{e}_t^g \right)$$

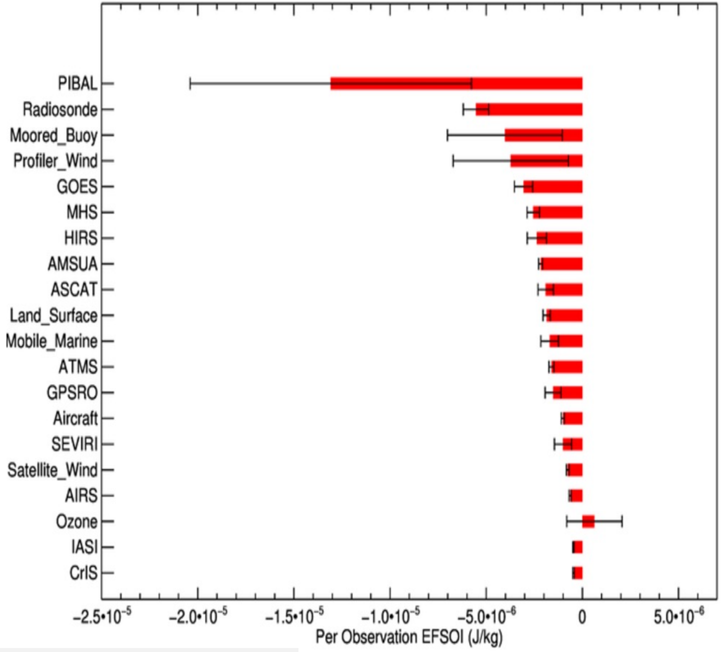
Assess observation impact without using adjoint models

EFSIO

Total Impact



Impact Per Observation



$\Delta \boldsymbol{e}_t < 0$ Observation is beneficial

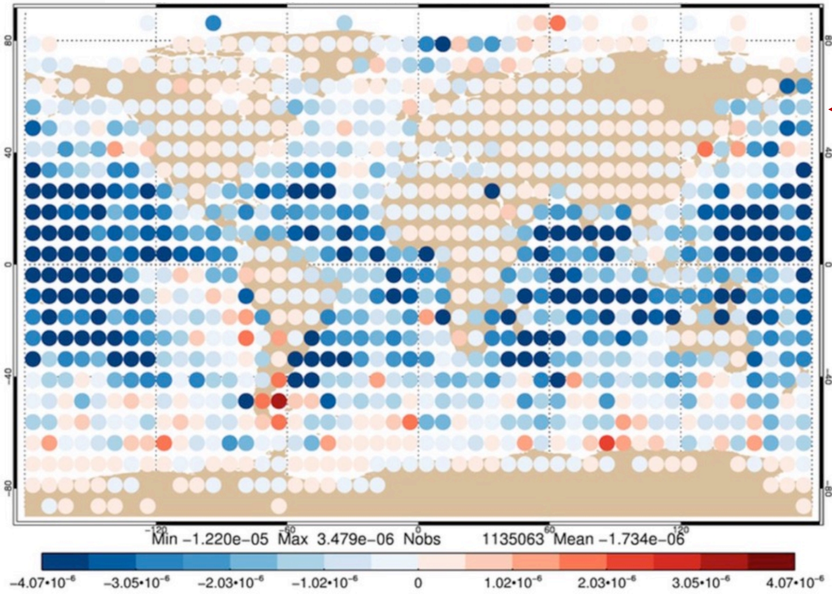
$\Delta \boldsymbol{e}_t > 0$ Observation is detrimental

EFSIO

$\Delta \boldsymbol{e}_t < 0$ Observation is beneficial

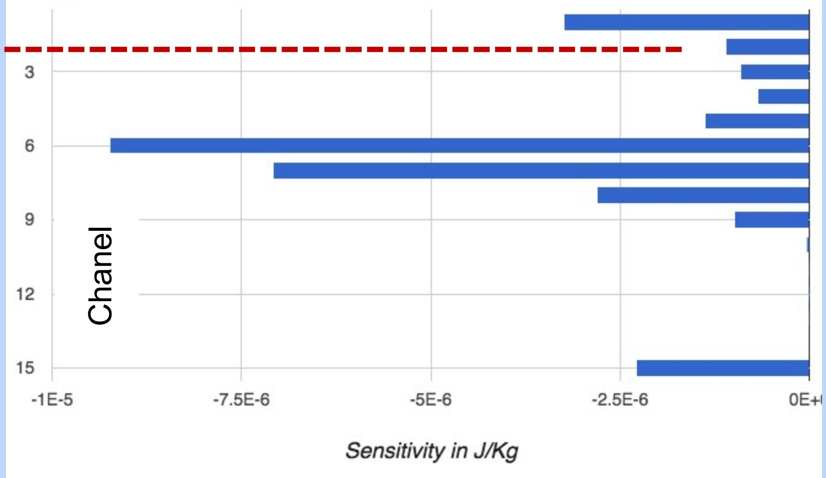
$\Delta \boldsymbol{e}_t > 0$ Observation is detrimental

AMSU-A Channel 2 (7.5° x 7.5°)



24-hr Forecast Error Reduction

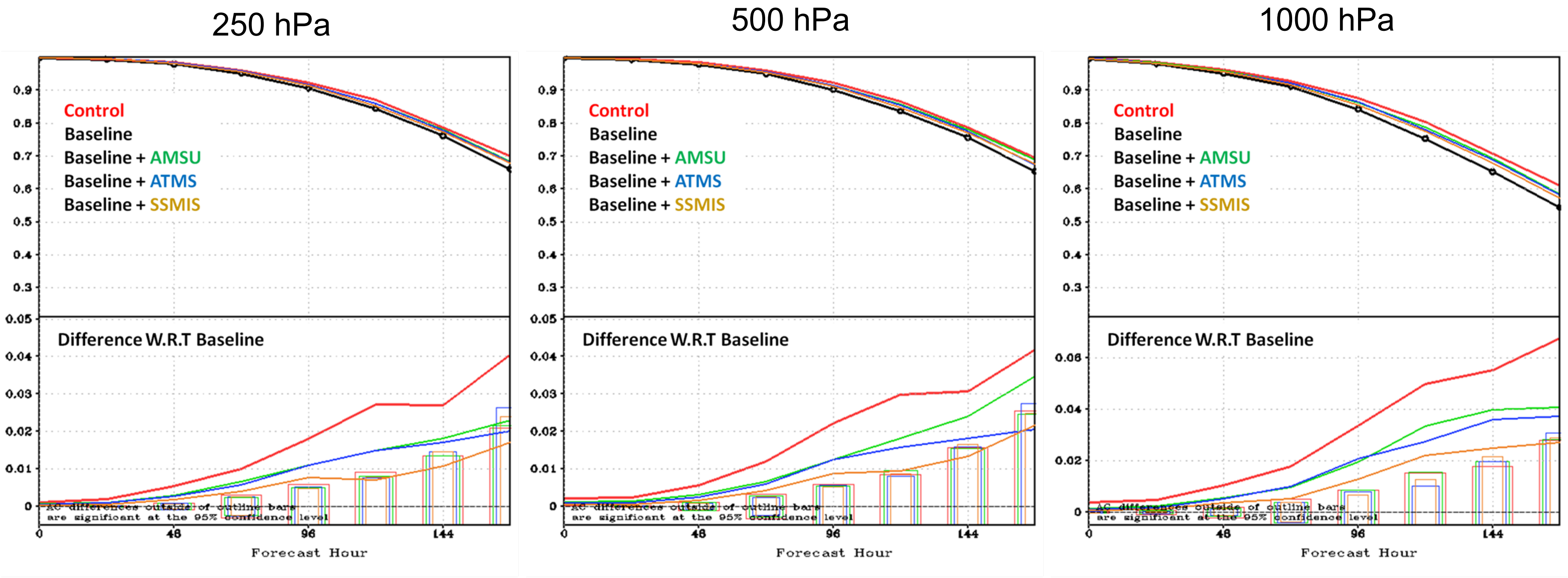
due to AMSU-A MetOp-B



Addition of MW Sounders to Baseline Experiments

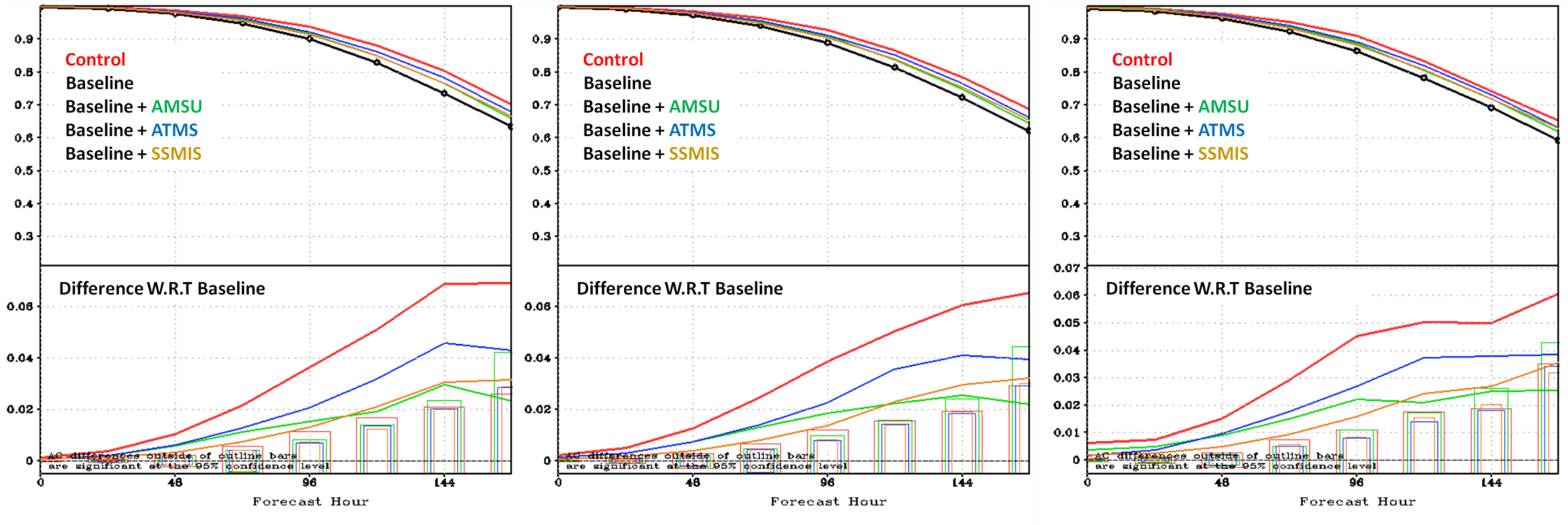
- Hybrid 4D Ensemble-Variational Assimilation System
- Reduce resolution:
  - Forecast & Analysis: C384 (~25 km) L64
  - Ensemble: C192 (~50 km) L64
- Period: Winter (January) and Summer (August)
- Baseline: non-restricted conventional data and GPSRO
- Control: all non-restricted operational satellite and conventional data
- Experiments add single instruments
  - ATMS
  - AMSUA + MHS
  - SSMIS

Northern Hemisphere AC Scores



Summer Season (August)

Southern Hemisphere AC Scores



250 hPa

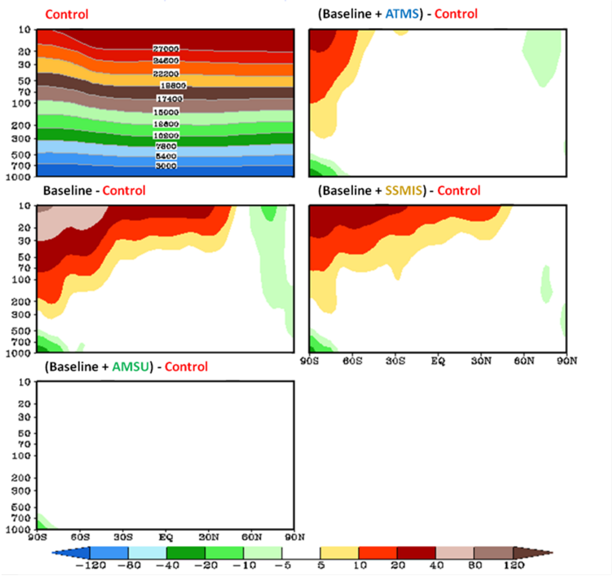
500 hPa

1000 hPa

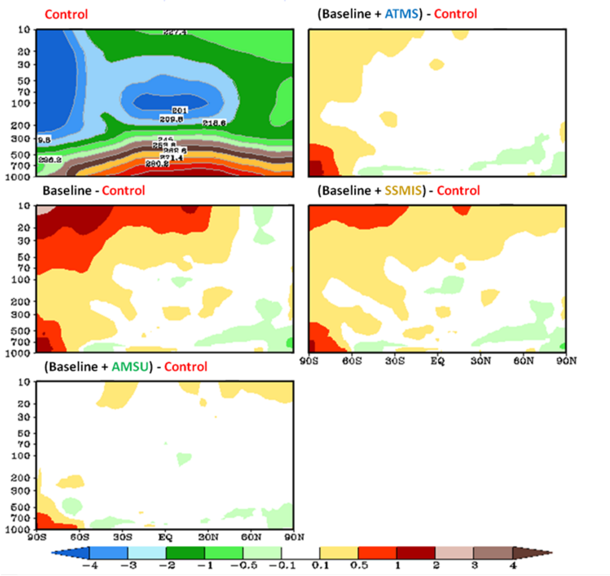
Summer Season (August)

Monthly Mean Bias

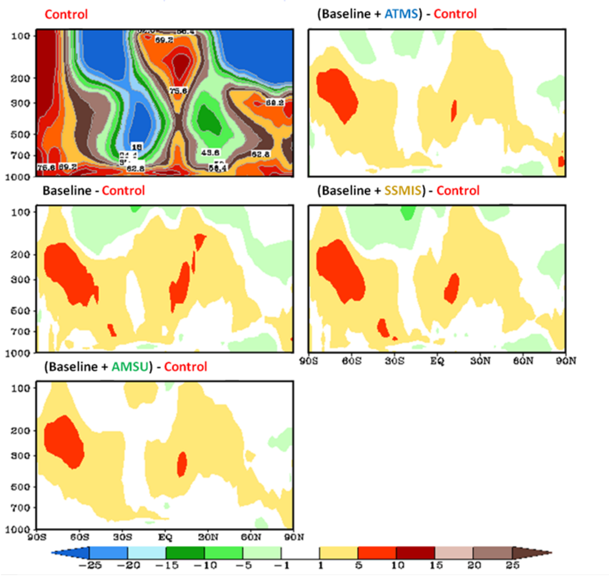
Geopotential Height



Temperature



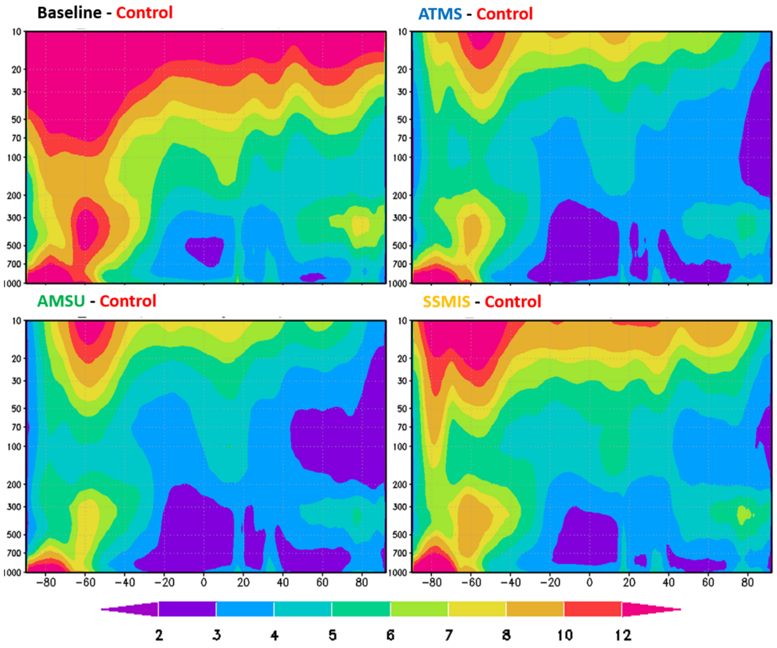
Relative Humidity



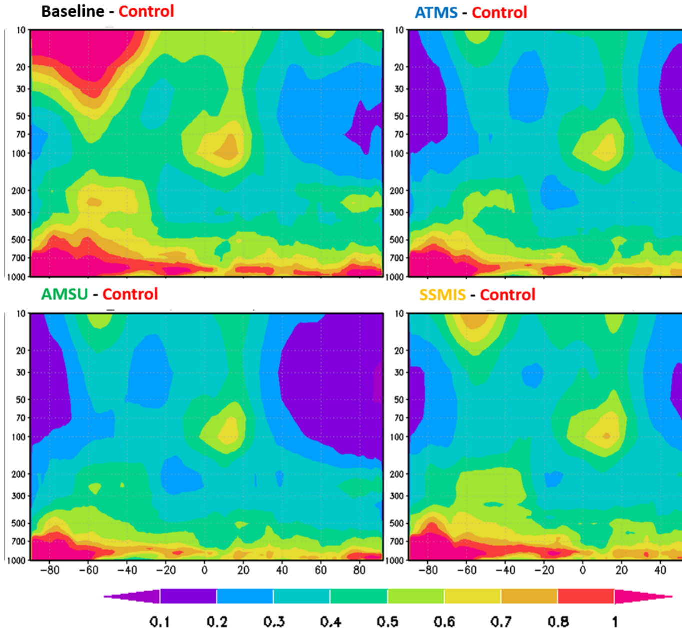
Summer Season (August)

Monthly Standard Deviation

Geopotential Height

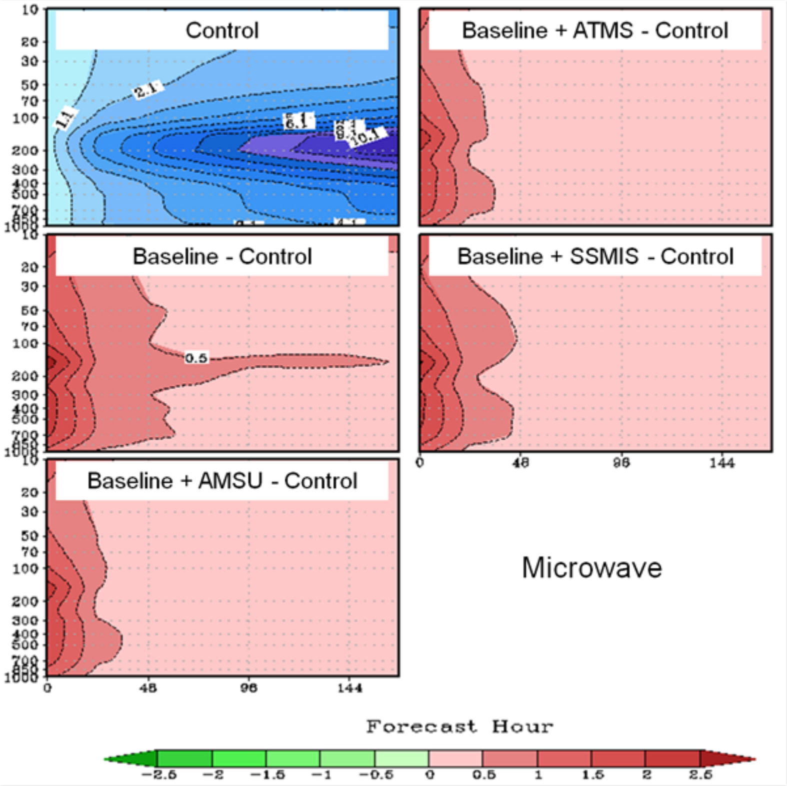


Temperature



Summer Season (August)

Monthly Tropical Vector Wind RMSE

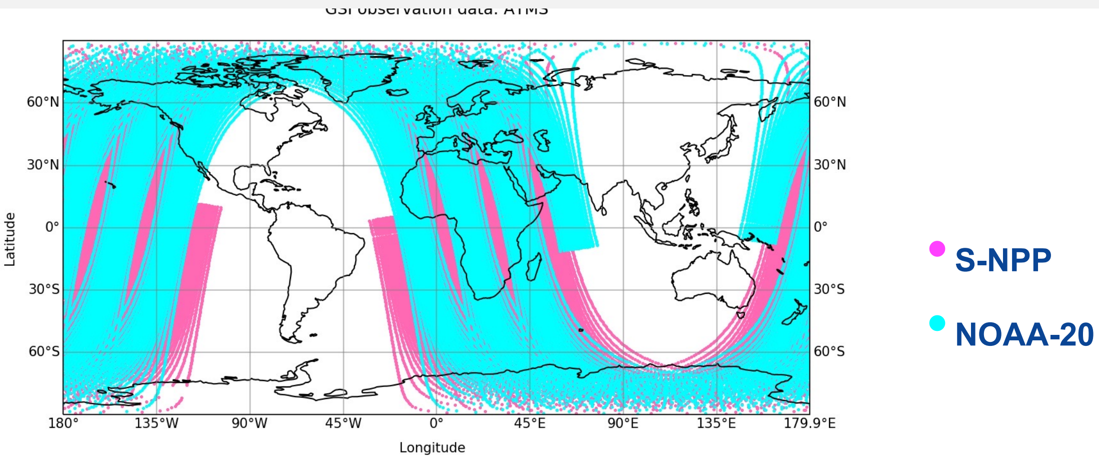


Summer Season (August)

Addition of S-NPP and NOAA-20 to Baseline Experiments

Objective

- S-NPP and NOAA-20 have ~50-minute orbit differential with a considerable data coverage overlap. Is there any value to Numerical Weather Prediction in having two polar orbiting satellites this close?
- Conduct data addition experiments to quantify analysis and forecast improvements from S-NPP and S-NPP + NOAA-20



Addition of NPP and N20 to Baseline Experiments

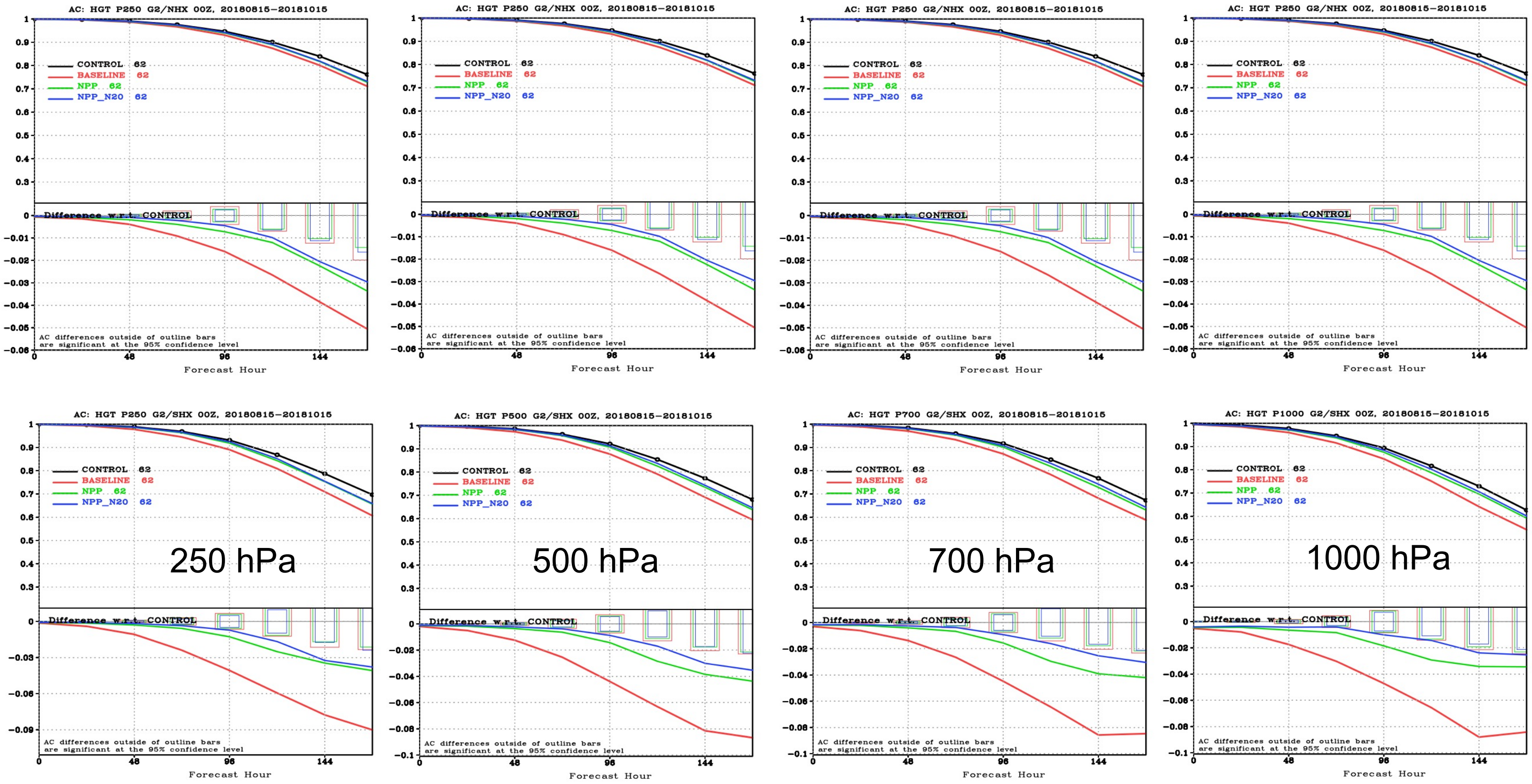
Configuration

- Hybrid 4D Ensemble-Variational Assimilation System
- Reduce resolution:
  - Forecast & Analysis: C384 (~25 km) L64
  - Ensemble: C192 (~50 km) L64
- Period: Two Month (August to October)
- Baseline: non-restricted conventional data and GPSRO
- Control: all non-restricted operational satellite and conventional data
- Experiments adding satellites:
  - S-NPP (CrIS + ATMS)
  - S-NPP + NOAA-20 (CrIS + ATMS)

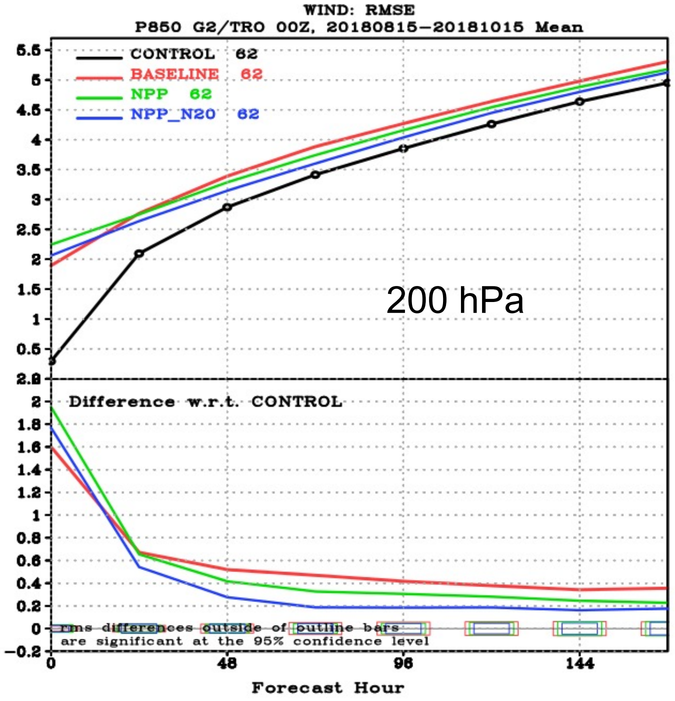
Anomaly Correlation Scores

NH

SH

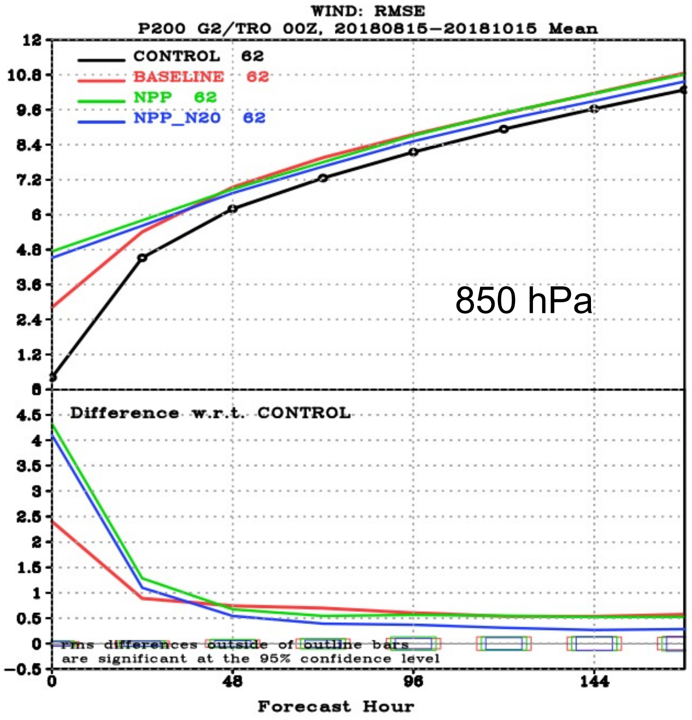


Tropical Winds RMSE



WIND: RMSE
P850 G2/TRO 00Z, 20180815–20181015 Mean

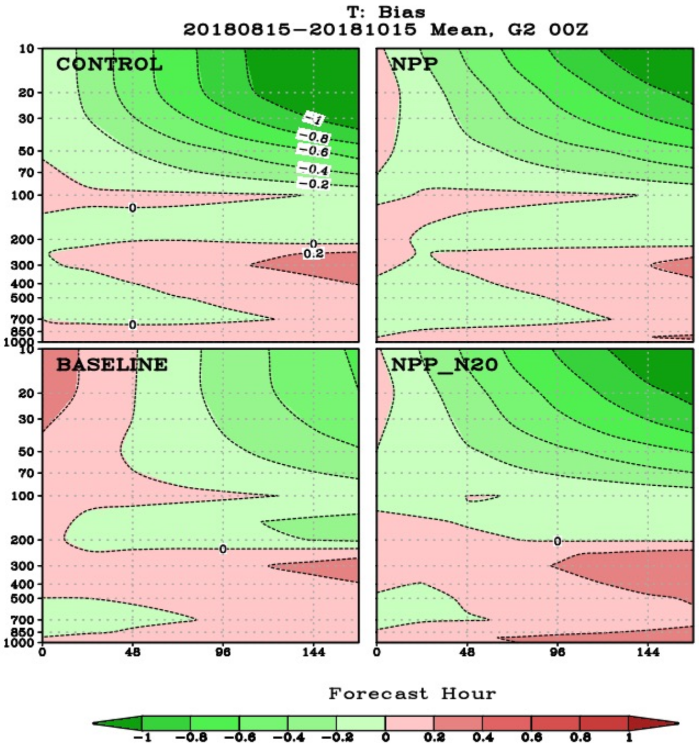
200 hPa

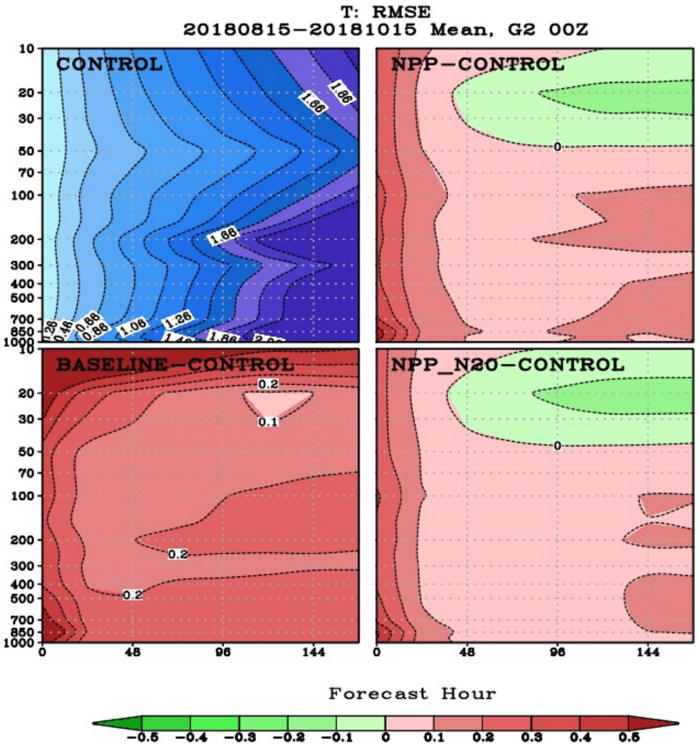


WIND: RMSE
P200 G2/TRO 00Z, 20180815–20181015 Mean

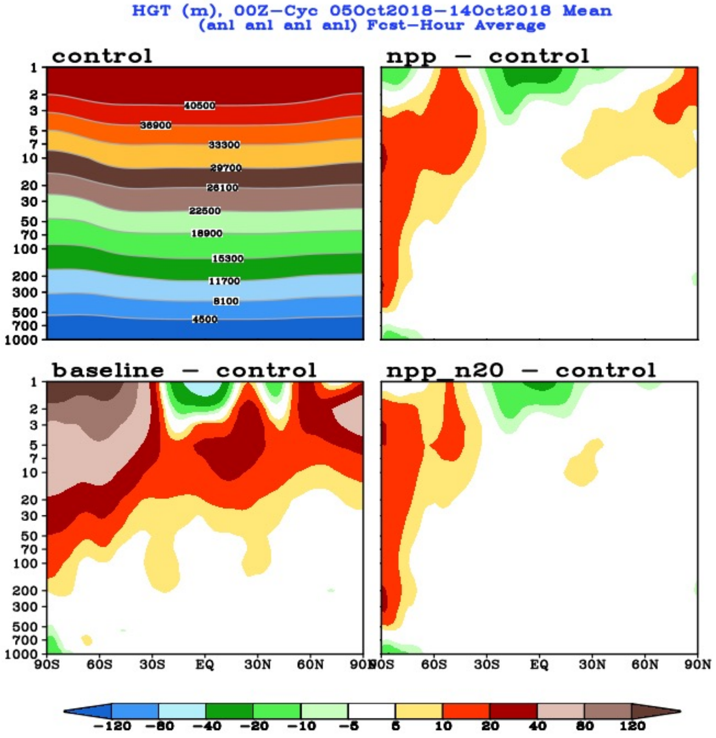
850 hPa

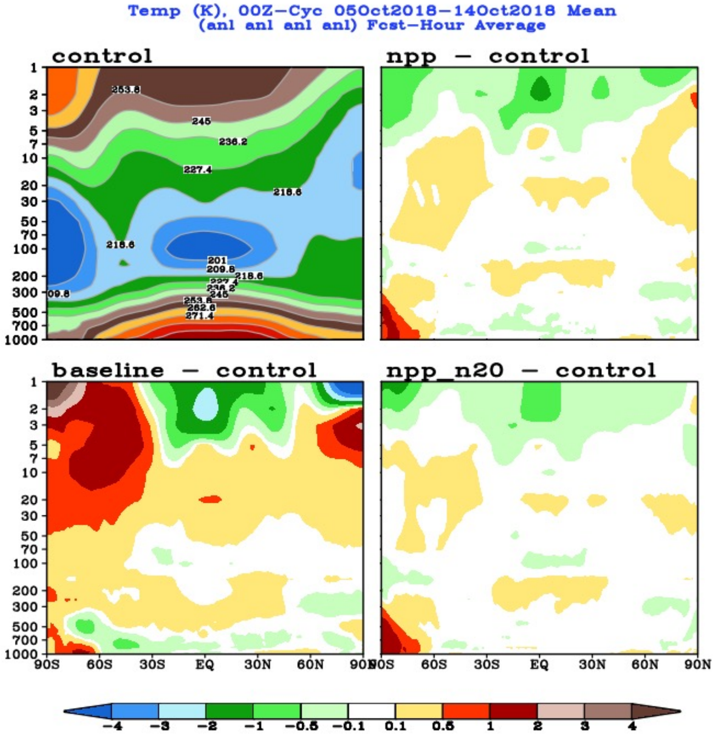
Global Temperature Bias and RMSE



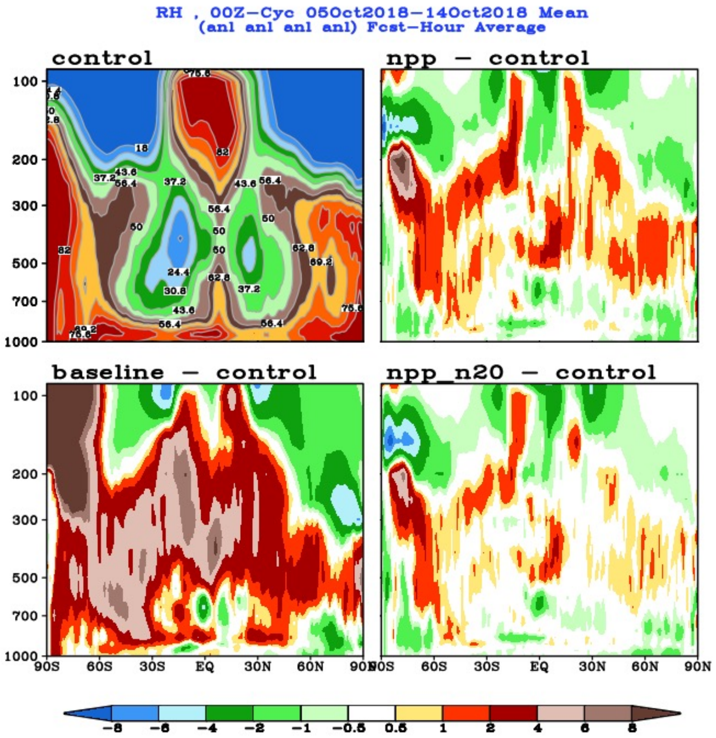


Analysis Differences: Heights and Temperature

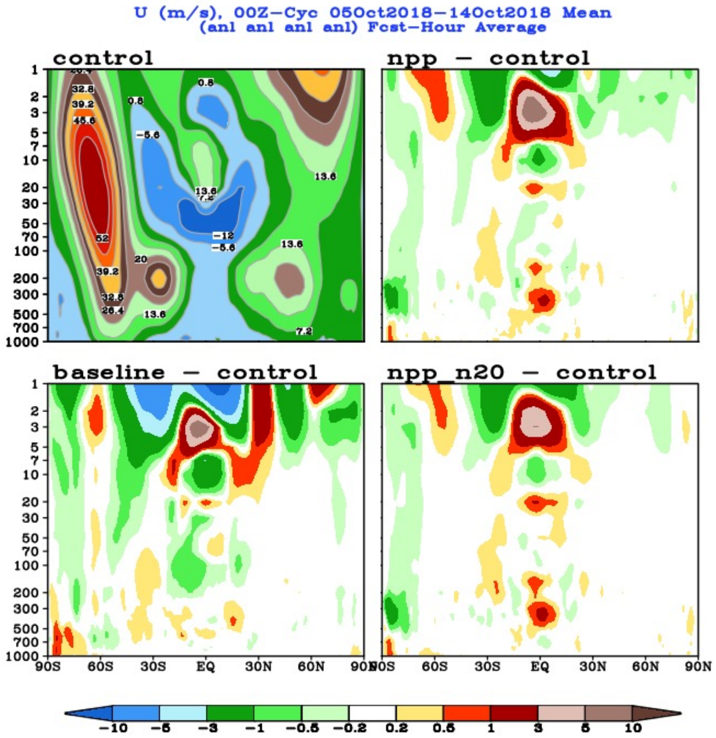

HGT (m), 00Z-Cyc 05Oct2018-14Oct2018 Mean
(anl anl anl anl) Fcst-Hour Average


Temp (K), 00Z-Cyc 05Oct2018-14Oct2018 Mean
(anl anl anl anl) Fcst-Hour Average

Analysis Differences: Relative Humidity and U Wind



RH , 00Z–Cyc 05Oct2018–14Oct2018 Mean
(anl anl anl anl) Fcst–Hour Average



U (m/s), 00Z–Cyc 05Oct2018–14Oct2018 Mean
(anl anl anl anl) Fcst–Hour Average

Outline

- MW Sounder Data Assimilated in NCEP Global Forecast System
- Impact of Observations in GFS
- **Outlook of Using MW Sonder Data in GFS**

Outlook of Using Sounder Data in GFS

Next Implementation

- Assimilate antenna-corrected AMSU-A, MHS, and ATMS brightness temperature (SDR)
- Precipitation-sensitive AMSU-A & ATMS radiances

NCEP EMC Data Assimilation 10-year Strategic Planning **(section related to the use of observations)**

- Sub-grid variability
  - Revisit the inclusion of sub-grid convective cloud and fraction in the observation operator for MW.
  - Explore the use of collocated cluster information from imager (IASI with AVHRR, ATMS with VIIRS…etc) for better handling the cloud sub-grid heterogeneity and overlap in a field of view.
- Second Generation of the EUMETSAT Polar System (EPS-SG)
  - Prepare for the assimilation of Microwave Sounder MWS (23-229 GHz)
- Exploration of new types of MW sounder data
  - SmallSats/CubeSats
    - Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D)
    - Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS)
  - Hyperspectral MW Sounder (~100 channels or more) --- better vertical resolution

NCEP GFS for Data Exploration

$$J(\boldsymbol{\delta x}_c, \boldsymbol{\alpha}) = \beta_c(\boldsymbol{\delta x_c})^T \boldsymbol{B}^{-1}(\delta \boldsymbol{x_c}) + \beta_e \frac{1}{2}\sum_{m=1}^{M} \boldsymbol{\alpha}_m^T \boldsymbol{L}^{-1} \boldsymbol{\alpha}_m + \boxed{\frac{1}{2}\sum_{k=1}^{K}(\boldsymbol{H}_k \boldsymbol{\delta x}_k - \boldsymbol{d}_k)^T \boldsymbol{R}_k^{-1}(\boldsymbol{H}_k \boldsymbol{\delta x}_k - \boldsymbol{d}_k)} + J_c$$

Adding time dimension in 4DEnVar

J_o term divided into observation bins as in 4DVar

4D increment is prescribed through llocal inear combinations of the 4D ensemble perturbations plus static contribution

$$\boldsymbol{\delta x}_k = \boldsymbol{\delta x}_c + \boxed{\sum_{m=1}^{M}\left(\boldsymbol{\alpha}_m \circ (\boldsymbol{\delta x}_{e,m})_k\right)}$$

Increment associated with
static background covariance
+
Increment associated with
flow-dependent ensemble covariance

Solution – the Minimizer

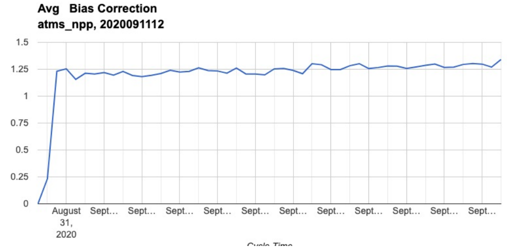
- J is a quadratic function. At minimum, $\nabla J = 0$
- Iterative minimization algorithm is used to solve $\nabla J = 0$ for δx_c and α
- Conjugate gradient method is used in NCEP hybrid analysis

- NCEP GFS is a 4D hybrid ensemble-variational system
- Cost function related to observation term is divided into observation bins as in 4DVar
- Background error covariances consistent static part and flow-dependent part from ensemble
- Beneficial in extracting information from the observations

NCEP GFS for Data Exploration

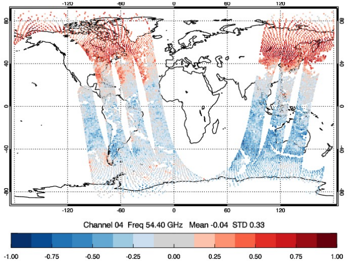
Variational Bias Correction

- Satellite radiance biases can be much larger than signal – essential to bias correct the data before assimilation
- GSI uses variational bias correction – the bias estimate is adaptive and consistent with all component in the analysis
- Built-in bias initialization step for new radiance type
- Automatically detect any new/missing/recovery of radiance data
- Adaptive background error variance for bias coefficient – quickly capture any changes in the data and data assimilation system
- New passive channel bias correction capability – an efficient way to obtain the bias of any new satellite data that are not assimilated by monitored for preparation for future use (facilitate R2O process)

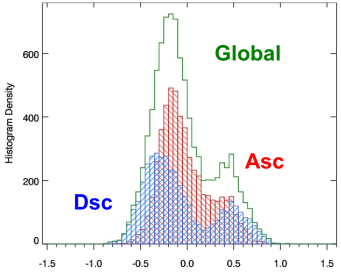


ATMS
Channel 01

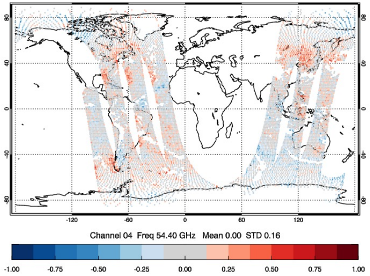
O-B before Bias Correction



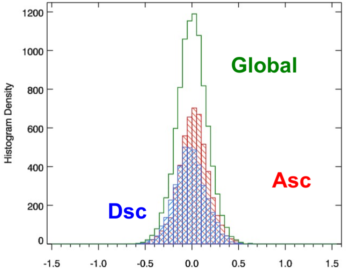
O-B before Bias Correction



O-B after Bias Correction



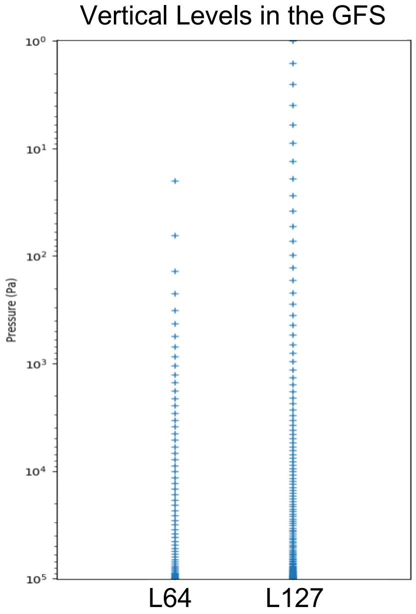
O-B after Bias Correction

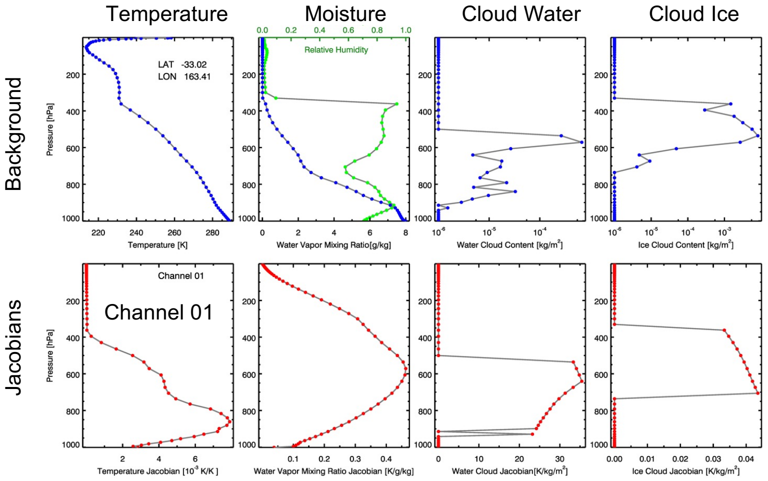


SSMIS F18

NCEP GFS for Data Exploration

- Operational GFS has extended model layers from 64 to 127, raising model top from 55 km to 80 km
- Much finer resolution in the troposphere
- Higher vertical resolution in background error


Vertical Levels in the GFS



- **AMSU-A** sees deep into the clouds, giving information on temperature, moisture and cloud structure. Much less sensitive to ice clouds than water clouds
- Broad Jacobians mean good background error info is necessary to project increments in the right place in the vertical
- **Hyperspectral MW instrument** with finer Jacobians can potentially provide useful information in the cloudy/precipitation region

~ The End ~
Thank You

Appendix

J	Penalty = fit to bkg J_b + fit to ensemble J_e + fit to obs J_o + Constraints J_c	L	Correlation matrix for ensemble covariance localization (effectively the localization of ensemble perturbations)
$\beta_c \ \ \beta_e$	Weighting factor for statistic and ensemble bkg error covariances ($\beta_s + \beta_e = 1$)	B	Static bkg error covariance (time invariant)
δx_c	Increment from variational analysis	d_k	Observation innovation $(y_{o,k} - h(x_k) - Bias)$
$(\delta x_{e,m})_k$	The m-th ensemble perturbations at time k	$y_{o,k}$	Observation at time k
δx_k	Hybrid increment at time k	h	Forward observation operator
α_m	Extended control variable: weight to each ensemble member (varies in space which determines the ensemble covariance localization scale)	H	Linearized observation operator $H = \left(\frac{\partial h}{\partial x}\right)$
R_k	Observation error covariance	K, M	*K* number of time bins, *M* number of ensemble members