Assimilation of Hyperspectral Infrared Shortwave CrIS Observations in the NOAA Global Data Assimilation System

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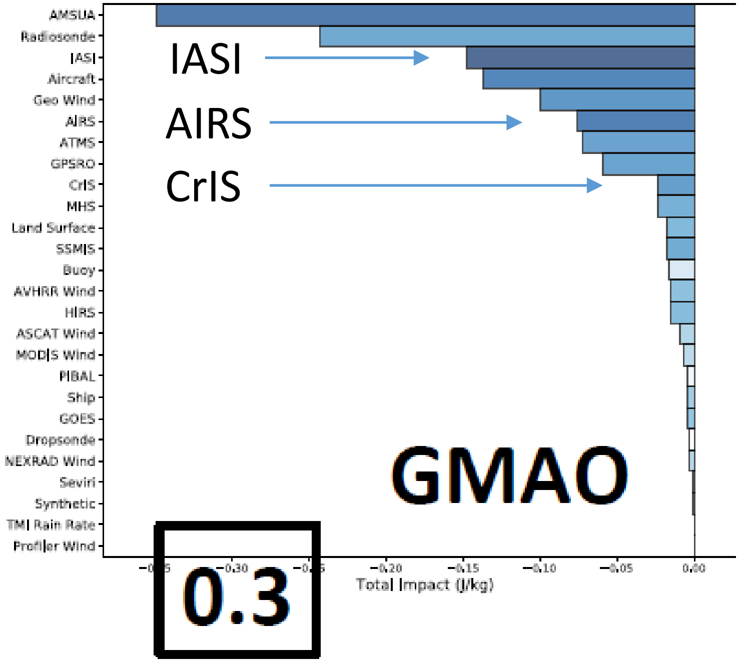
Objectives and Motivations

- **Hyperspectral Infrared:**
  - Cubesat technology supports an alternative/cost effective/agile constellation of shortwave/midwave IR (SWIR/MWIR) sensors to provide temperature and water vapor profile information to numerical weather prediction (NWP).
  - A SWIR constellation could compliment longwave (LWIR) sounders and add robustness to the global observation system
- **The Problem:**
  - SWIR data (e.g. 4 µm CO_2 band) is not operationally assimilated in NOAA NWP models (LWIR and few MWIR channels are assimilated)
- **The Question:**
  - *To help shape future satellite global observing system architecture, can a SWIR-only solution achieve or exceed positive impact provided by LWIR radiances in medium-range, global NWP?*
- **Goals and Operational Outcomes:**
  - Move towards the optimization of the NOAA GDAS for the assimilation of SWIR data (CrIS/IASI)
  - Improve radiance forward operator for SWIR (CRTM)
  - Assess whether the assimilation of SWIR can provide as much value as the assimilation of LWIR and advise on the potential use of future SWIR-only sensors

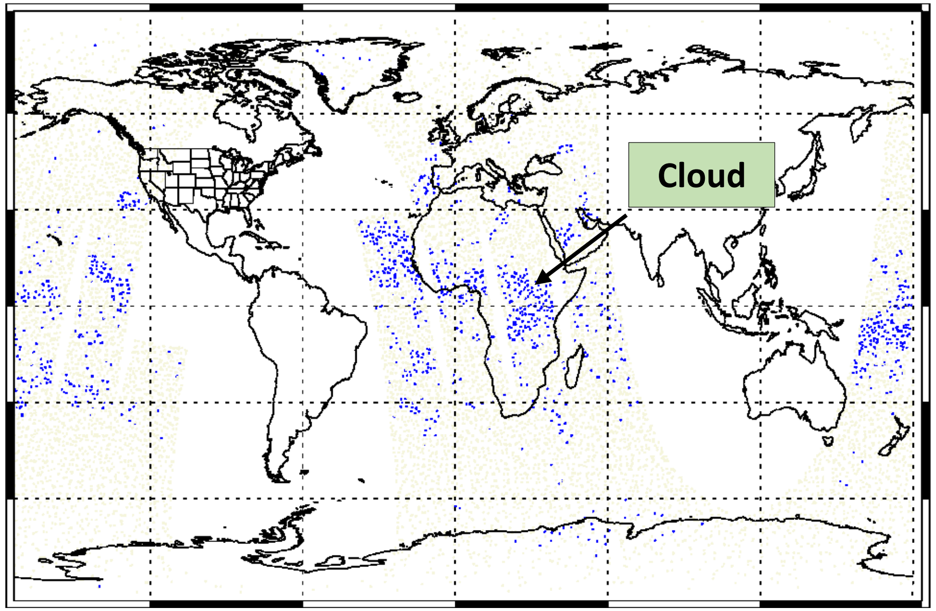


GMAO Ensemble Forecast Sensitivity to Observations Impact (EFSOI) showing reduction in 24-hour forecast errors per observation type. (Mahajan et al, 2017)

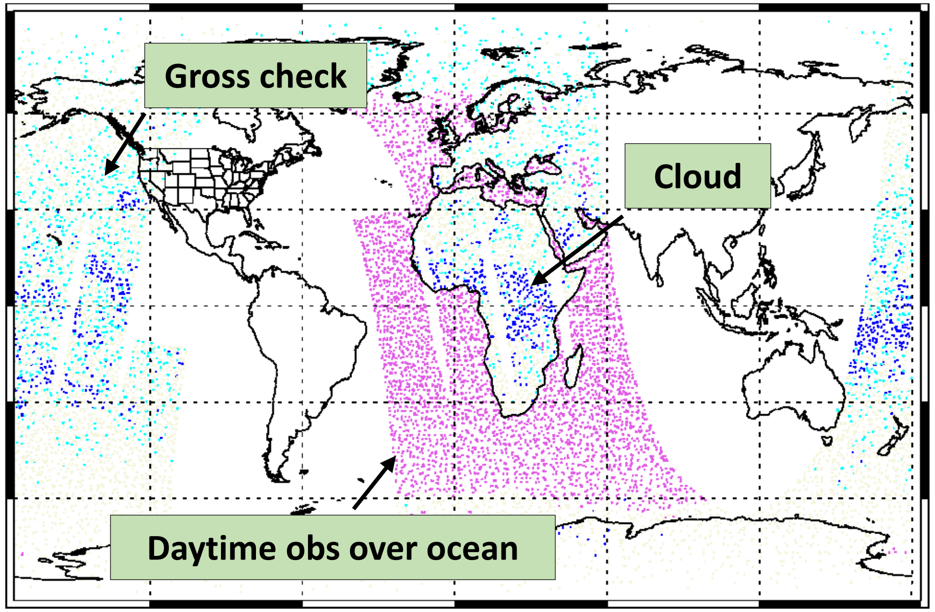
Current Status of SWIR in the NOAA GDAS

The NOAA FV3GFS/GDAS uses the Gridpoint Statistical Interpolation (GSI) data assimilation system with 4DEnVar

CrIS NPP 690 cm^{-1} QC Flags



CrIS NPP 2380 cm^{-1} QC Flags



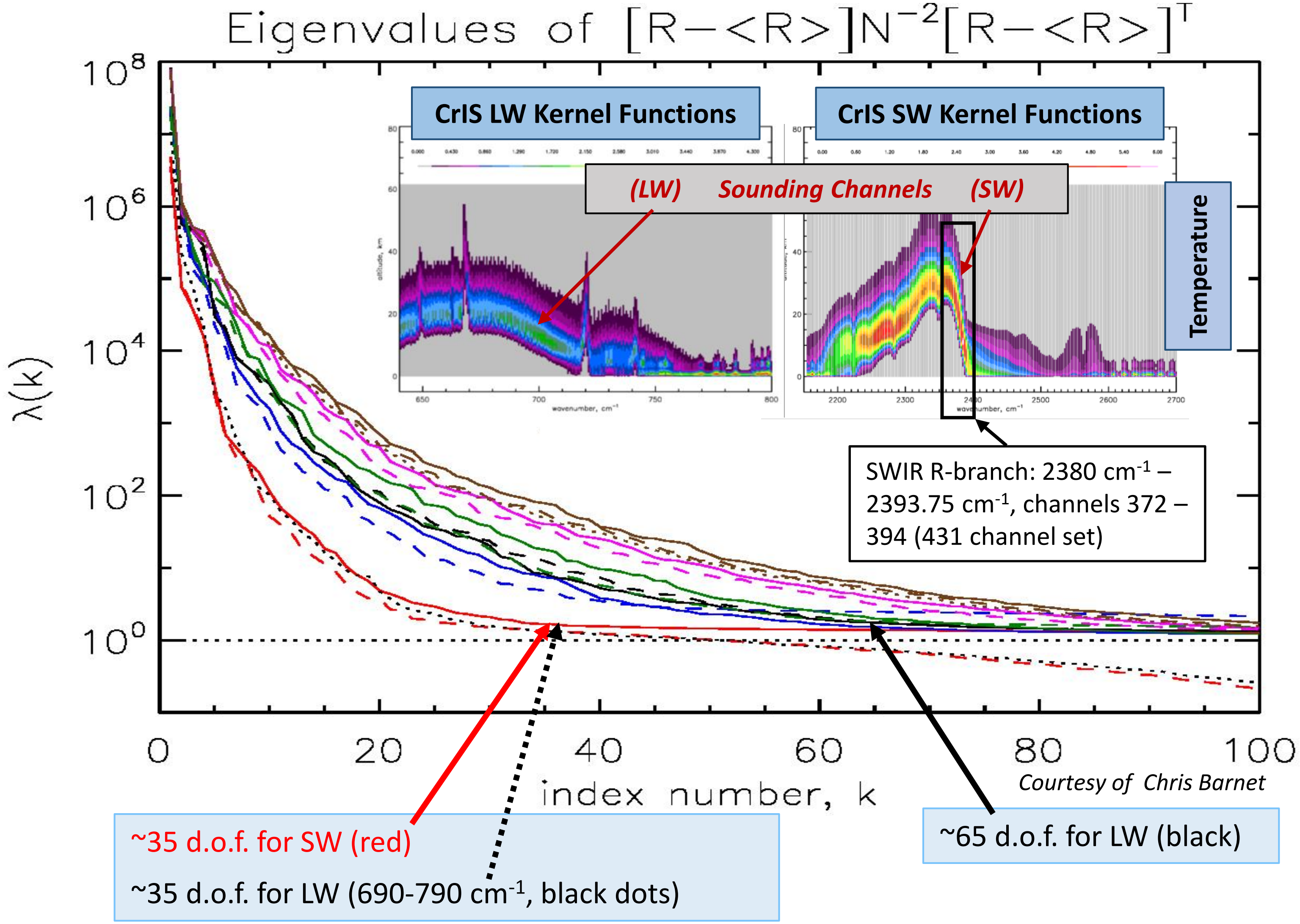
*Current GSI Quality Control flags for a Longwave IR channel (**left**) and Shortwave IR Channel (**right**)*

GSI ingests the CrIS FSR 431 channel subset:

- 92 LWIR channels assimilated (642 – 1095 cm^{-1}), 8 MWIR (1227 – 1425 cm^{-1})
- **SWIR channels are monitored only**, with strict QC
- Similar status for IASI and AIRS (using channel subsets)

Outlook on SWIR Assimilation

SWIR channels show similar information content as LWIR temperature (CO_2) channels



Data assimilation system enhancements needed for SWIR:

- **Cloud detection scheme**
  - SWIR channels in place of LWIR
- **New SWIR observation errors**
  - From fixed 1 K to scene-dependent
- **Quality control modifications based on the above**
- **Activate 52 SWIR channels (2380 – 2507 cm^{-1})**
  - Disable 92 LWIR channels to isolate SWIR impact
- **Forward operator, Community Radiative Transfer Model (CRTM)**
  - Modeling of BRDF
  - NLTE correction

SWIR-based Cloud Detection for Clear-Sky Radiances

- Cloud detection for IR in the GSI is based on Eyre and Menzel (1989)
- The scheme seeks to find cloud top pressure (p) and cloud fraction (N) that minimize

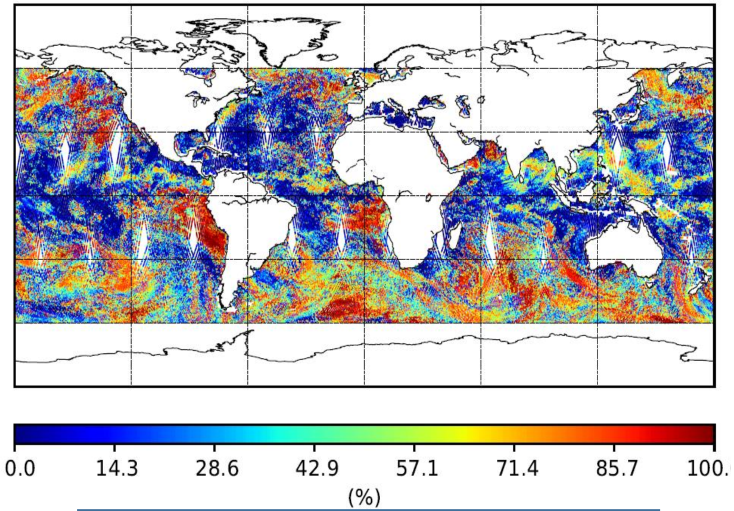
$$\sum_j \delta_j^2 = \sum_j \left[\left(R_j^m - R_j^{clr} \right) - N \left(R_j^{cld}(p) - R_j^{clr} \right) \right]^2$$

$$\delta_j = R_j^m - R_j$$

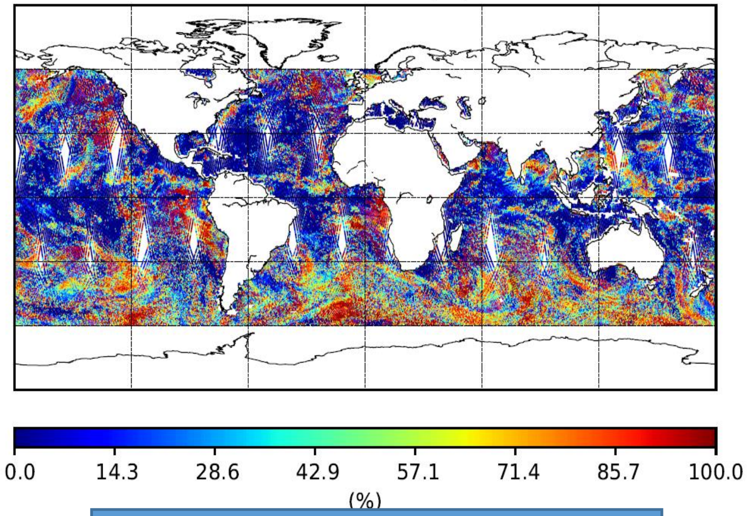
Where R_j^m is the measured radiance for channel j, and R_j^{clr} and R_j^{cld} are simulated clear and cloudy radiances

SWIR-based cloud detection allows more SWIR observations to pass cloud check – likely due to increased vertical resolution and increased sensitivity to cloud as a result of the non-linearity of the Planck Function in SWIR

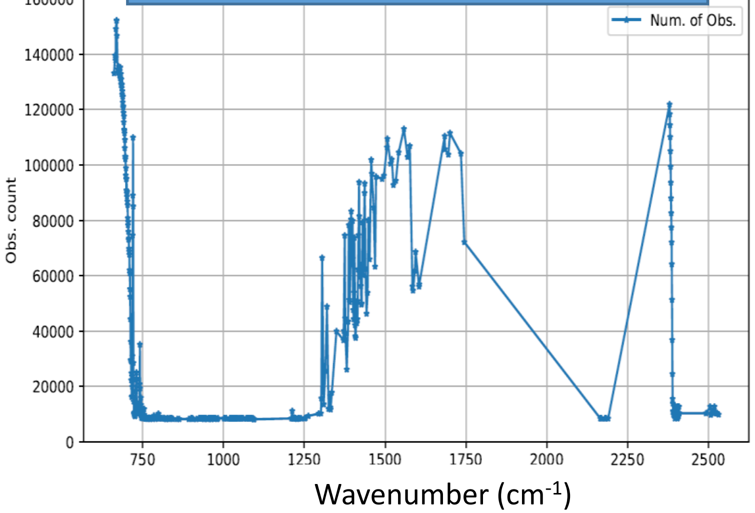
Cloud Fraction using LWIR



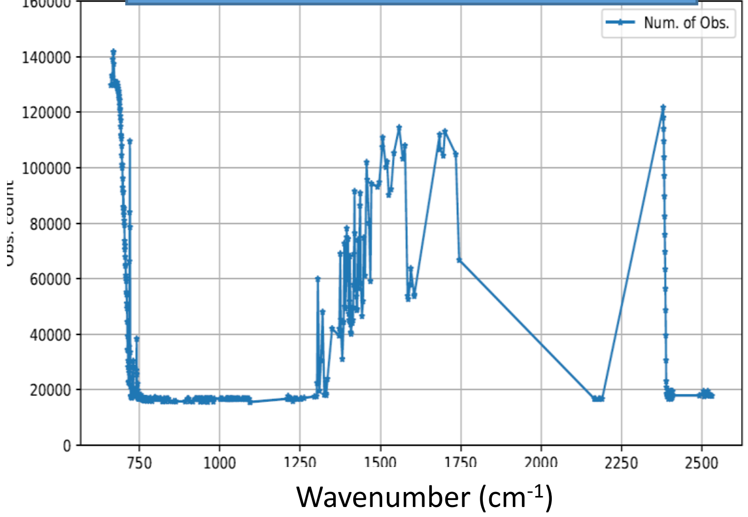
Cloud Fraction using SWIR



Number of Observations

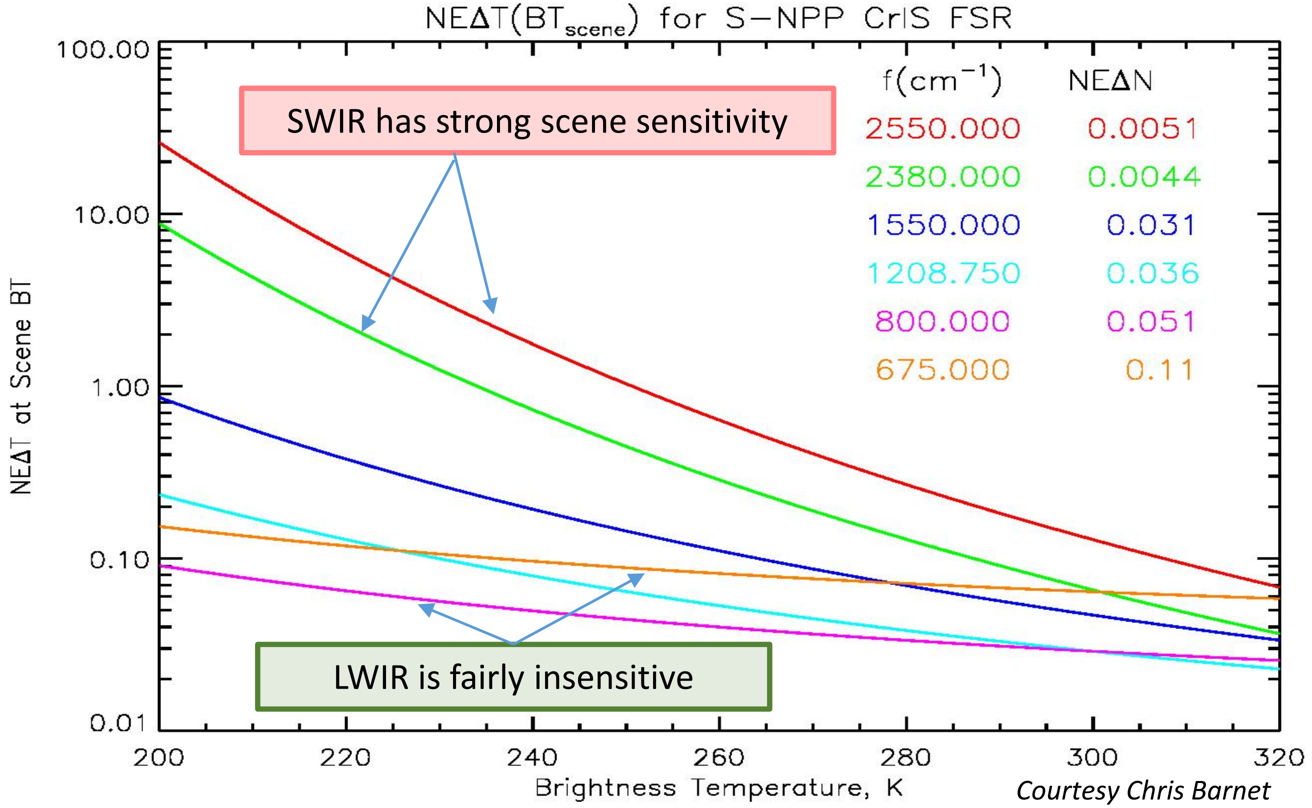


Number of Observations



Scene-Dependent Observation Error Specification

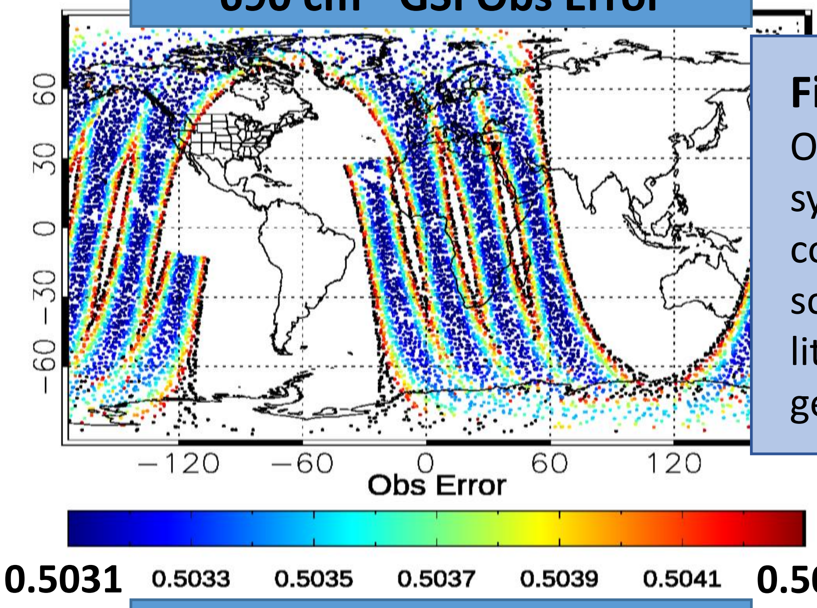
Non-linearity in the Planck function → Noise dependence on scene temperature



Observation error for higher peaking (i.e. colder, noisier) SWIR channels scaled from error at reference scene brightness temperature using derivative of Planck function, $B(T_b)$:

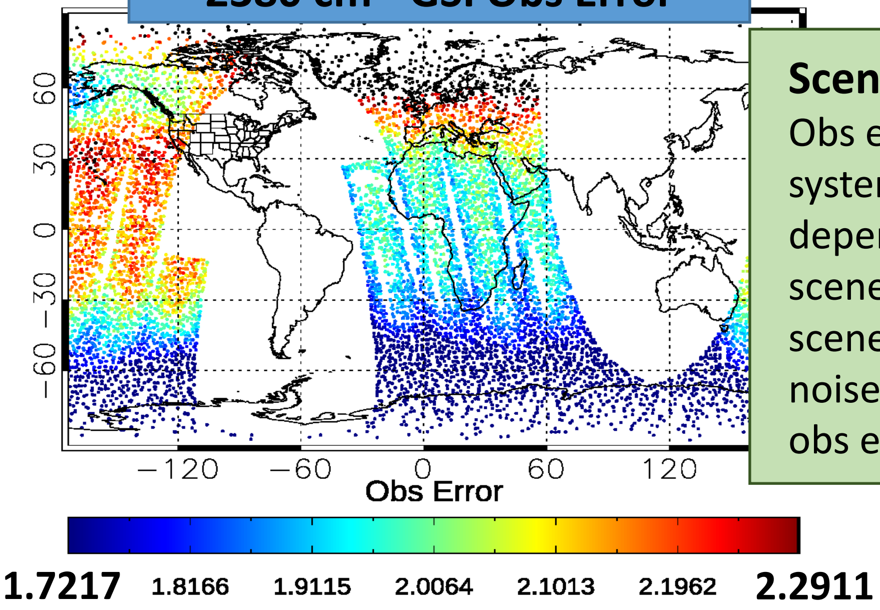
$$\Delta T_b = \frac{\Delta R}{dB(T_b)/dT_b}$$

690 cm^{-1} GSI Obs Error



Fixed Err: Obs errors in DA system are near constant for all scenes (vary little due to scan geometry, etc)

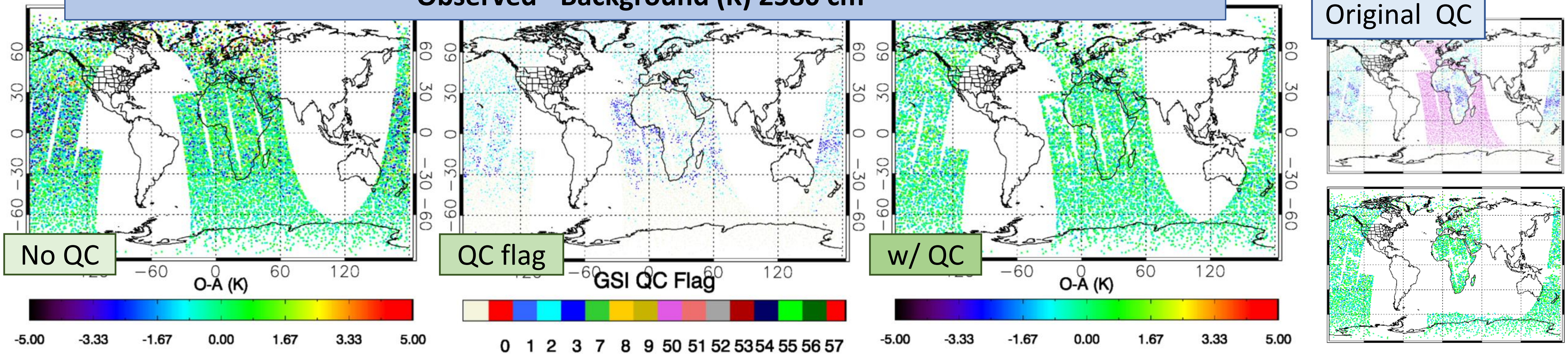
2380 cm^{-1} GSI Obs Error



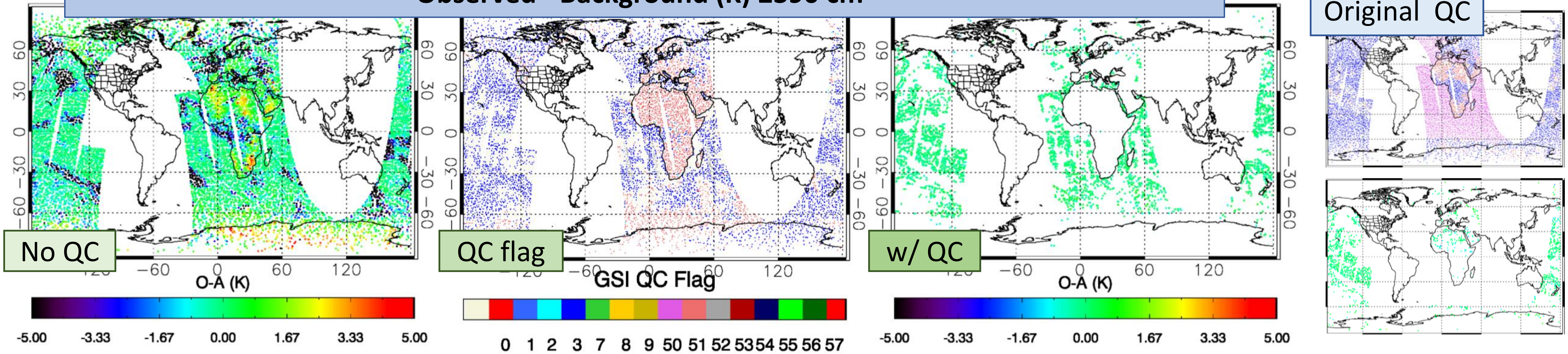
Scene-Dep Err: Obs errors in DA system vary depending on scene TB (colder scene → higher noise → higher obs error)

Impact of New Quality Control

Observed - Background (K) 2380 cm^{-1}



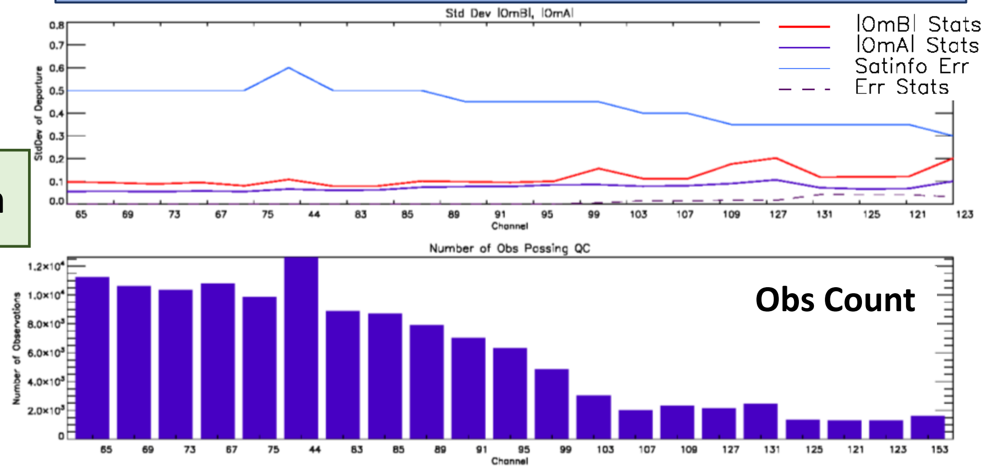
Observed - Background (K) 2390 cm^{-1}



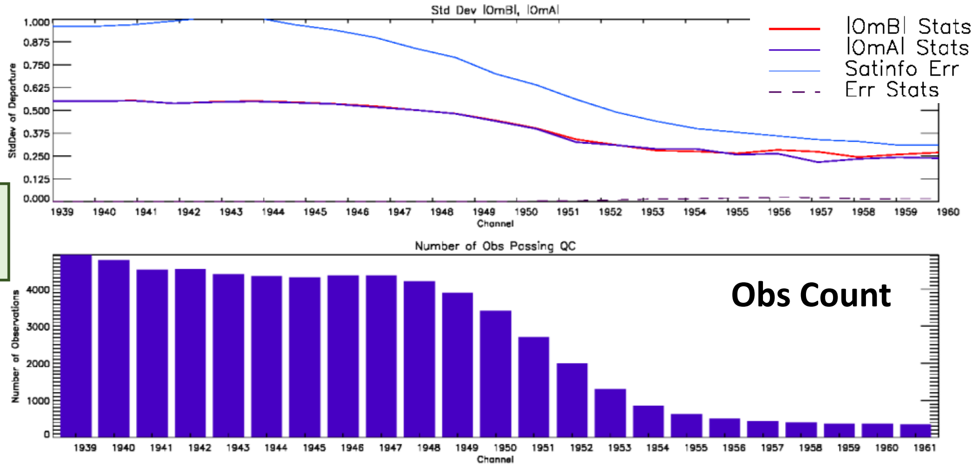
Observation Minus Background/Analysis

Abs. O-B/O-A with LWIR data assimilated (Control: no SWIR)

LW Region

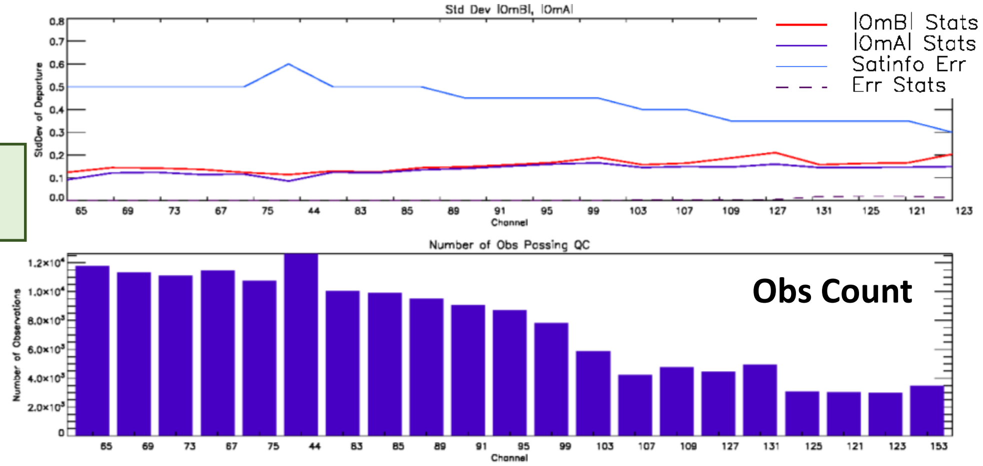


SW Region

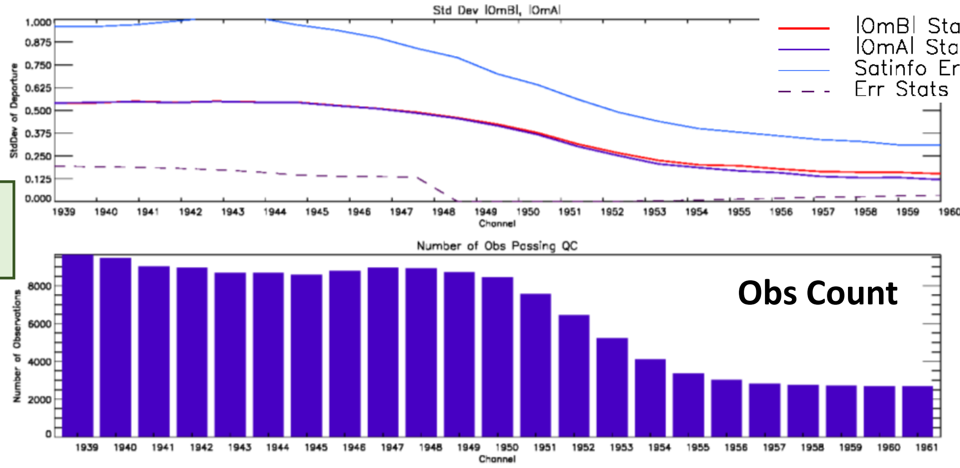


Abs. O-B/O-A with SWIR data assimilated (Exp: updated QC, no LWIR)

LW Region



SW Region



Improved SWIR QC shows increased number of observations assimilated (about double for SWIR), and reduced abs. O-B/O-A statistics

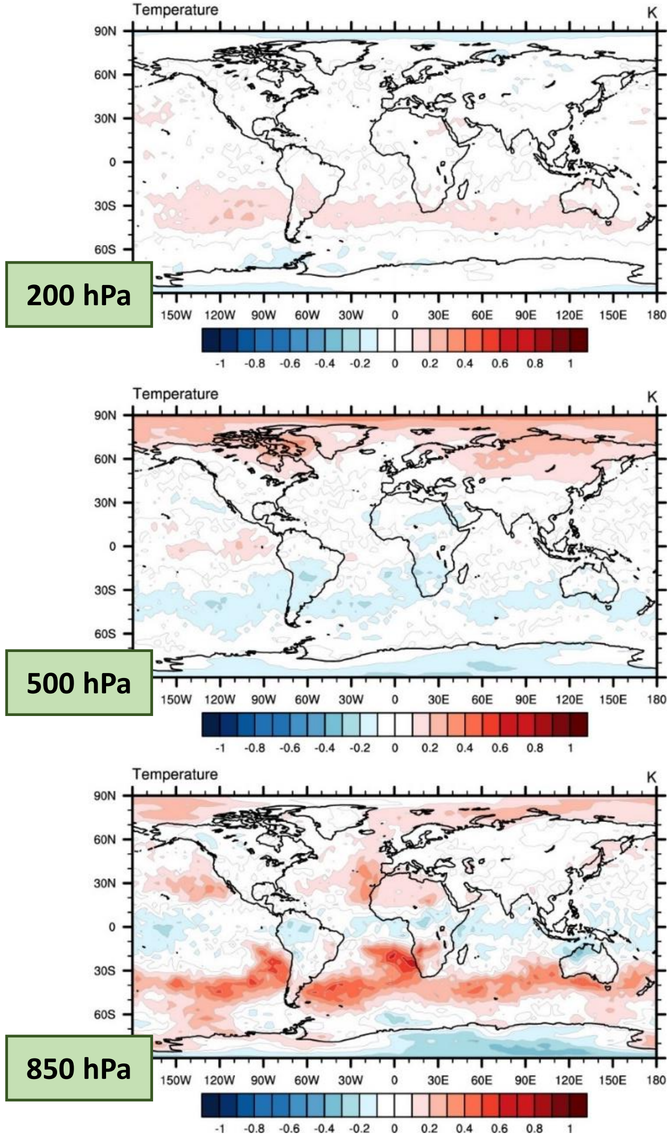
Observing System Experiment Setup

Observation	Baseline (Ops)	LWIR (Control)	SWIR (Exp)
Conventional			
Sat-winds			
IASI			
AIRS			
CrIS LWIR			
CrIS SWIR			
ATMS			
AMSU/MHS			
GPSRO			

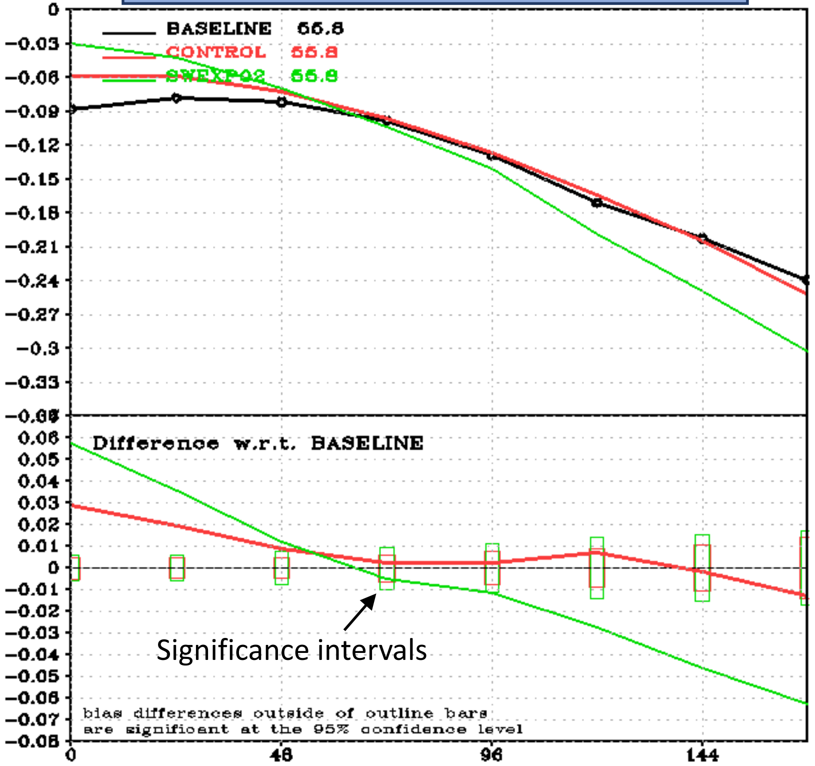
- FV3GFS 4DEnVar with 80 ensemble members at C384/C192 (~25 km GDAS/GFS, ~50 km ensemble)
- Experiments run 2018-12-01 to 2019-01-31
- Observations assimilated as in table to the left; AIRS/IASI turned off to enhance signal of CrIS LWIR and SWIR impact
- SWIR experiment uses updated SWIR quality control and observation errors
- Verified against ECMWF analysis
- Verification is using analyses/forecasts from 2018-12-07 to 2019-01-31

Temperature Analysis Differences/Forecast Impact (Preliminary)

Analysis Temp Diff: SWIR exp. – LWIR exp.

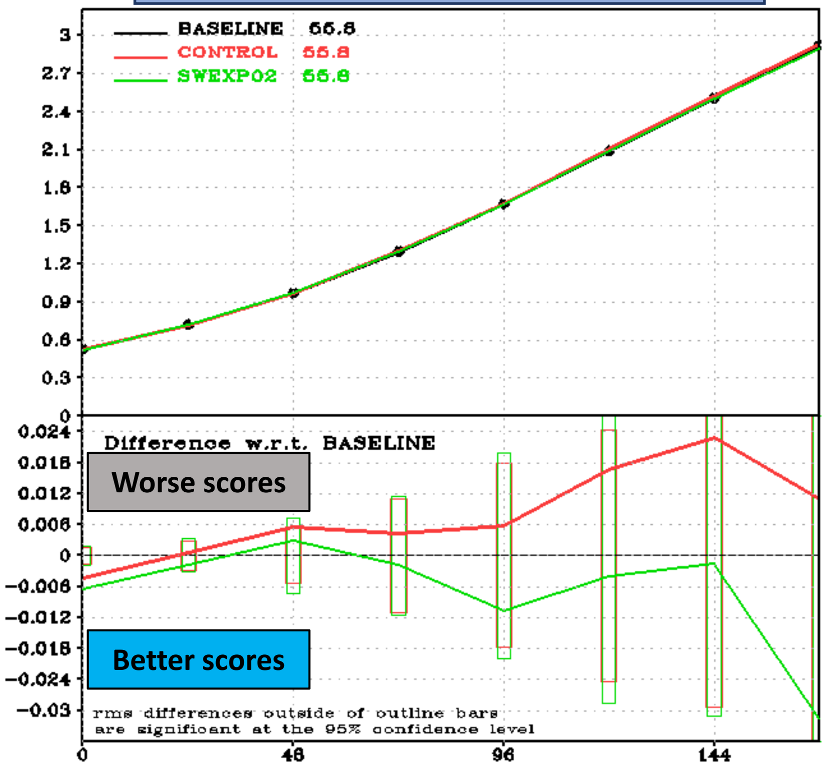


200 hPa Temperature Bias (GL)



Forecast Hour

200 hPa Temperature RMSE (GL)



Forecast Hour

Verified against ECMWF

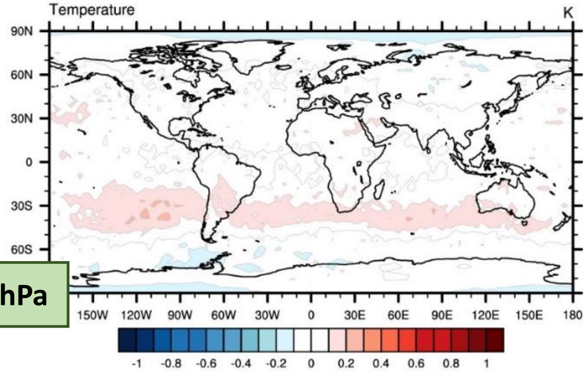
Small global 200 hPa temperature analysis differences:

- SWIR degrades 200 hPa bias over the control in the temperature forecast
- SWIR improves RMSE of the temperature forecast, but not significantly

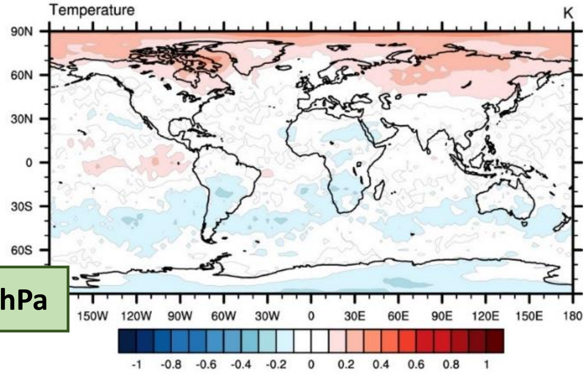
Temperature Analysis Differences/Forecast Impact (Preliminary)

Analysis Temp Diff: SWIR exp. – LWIR exp.

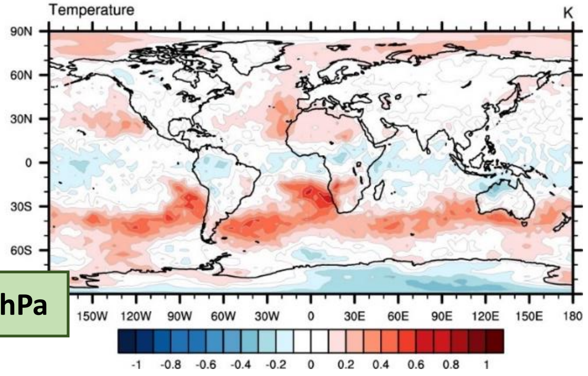
200 hPa



500 hPa



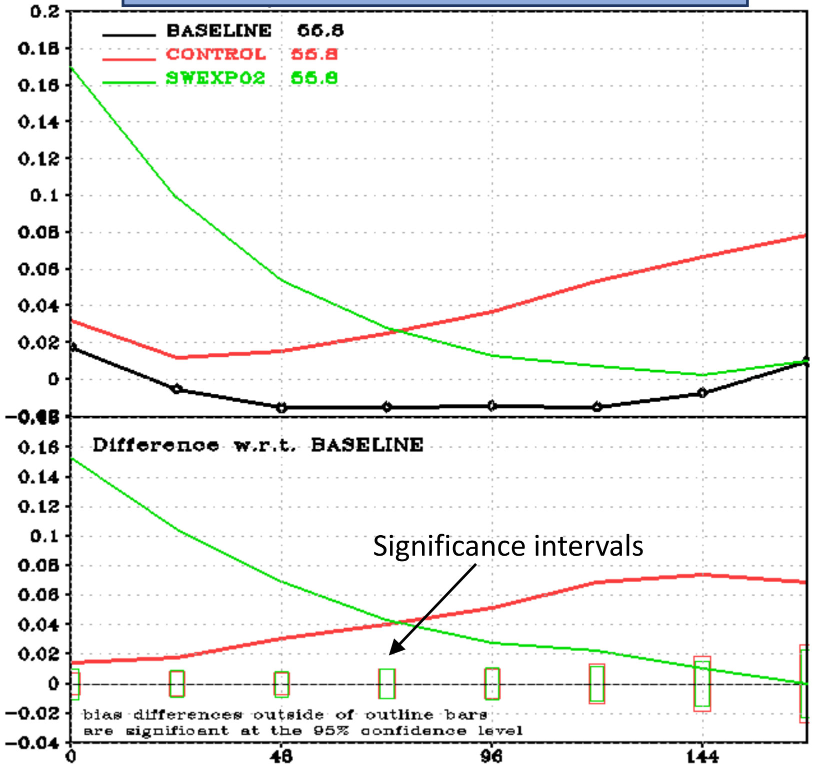
850 hPa



850 hPa temperature analysis differences in the Southern Hemisphere:

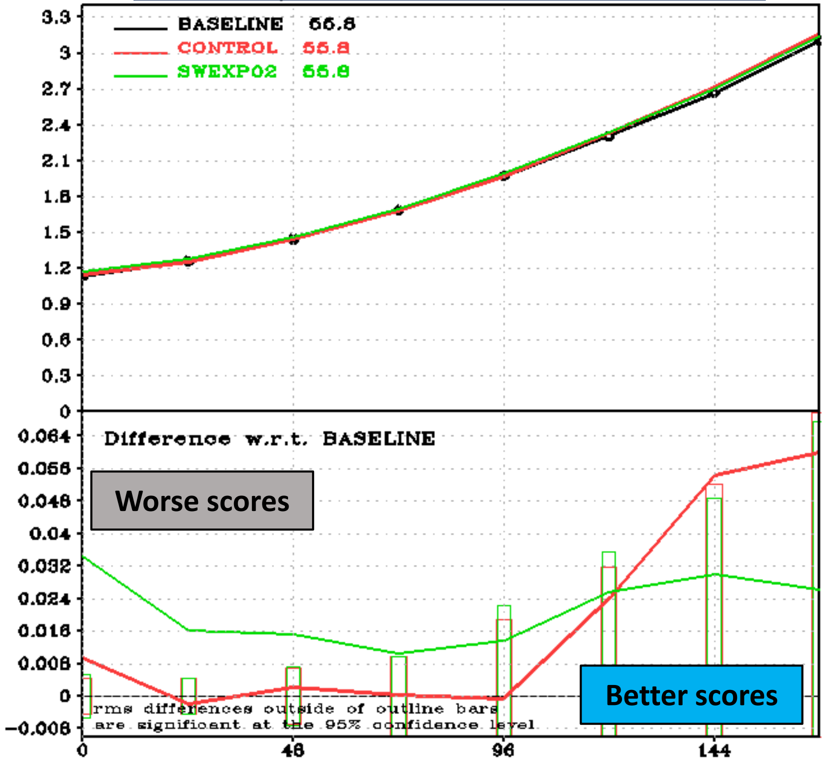
- SWIR improves bias over the control in the 850 hPa Southern Hemisphere temperature mid-range forecast; bias degraded in short term
- Degraded (with respect to the control) Southern Hemisphere temperature RMSE with SWIR at earlier forecast times

850 hPa Temperature Bias (SH)



Forecast Hour

850 hPa Temperature RMSE (SH)

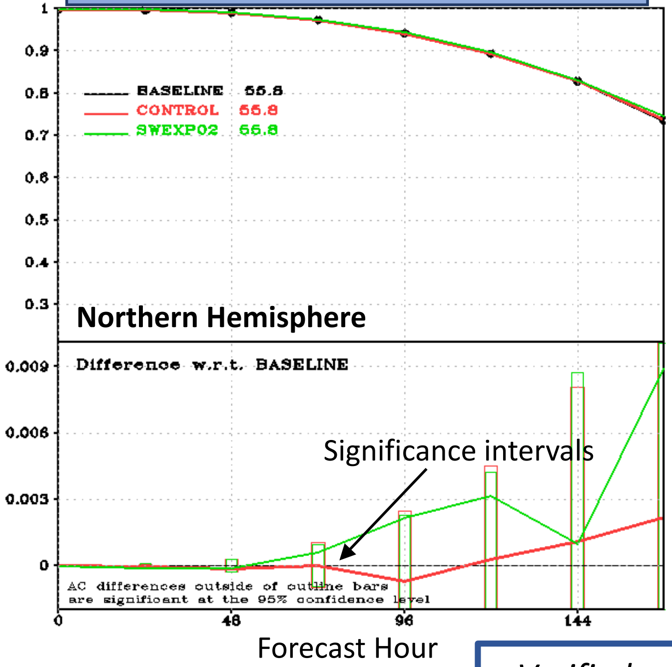


Forecast Hour

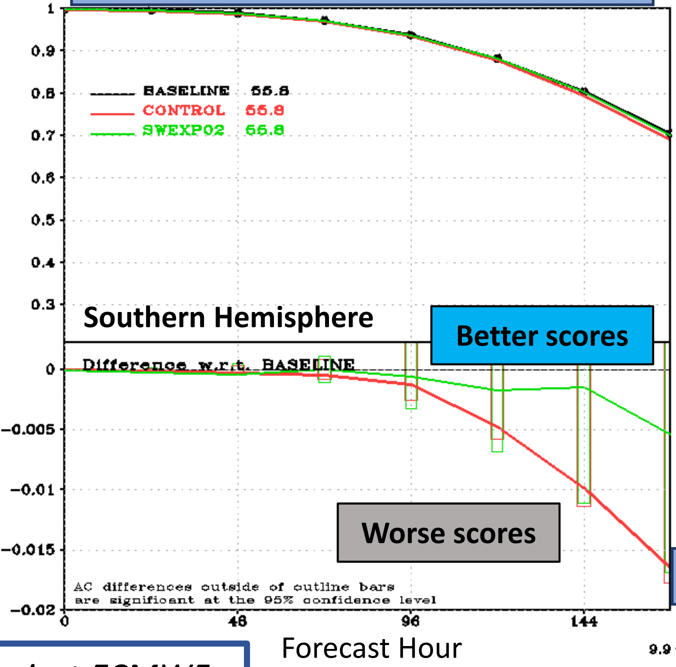
Verified against ECMWF

Forecast Impact on Heights and Winds (Preliminary)

500 hPa Height AC (NH)



500 hPa Height AC (SH)



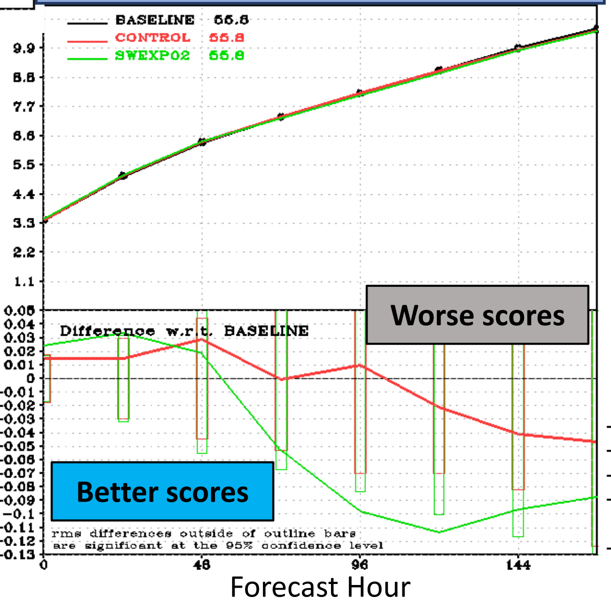
Verified against ECMWF

500 hPa geopotential height analysis differences:

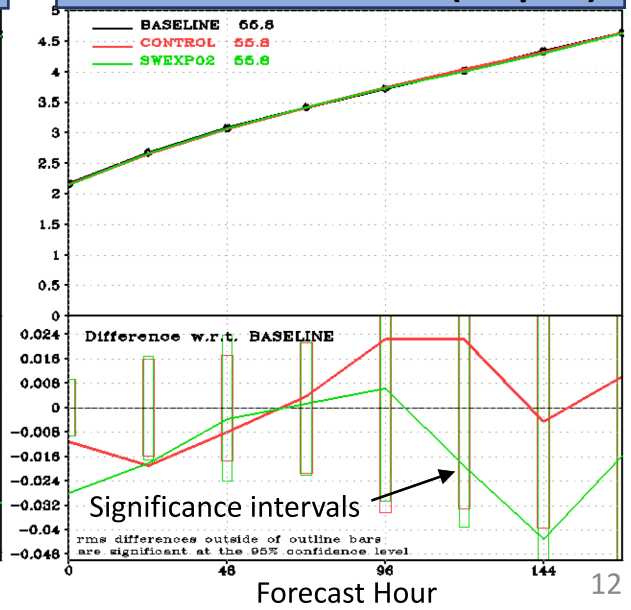
- SWIR 500 hPa height anomaly correlation in both the Northern and Southern Hemispheres at most forecast times is improved over the control; improvement is not statistically significant

Verified against ECMWF

200 hPa Wind RMSE (Tropics)



850 hPa Wind RMSE (Tropics)

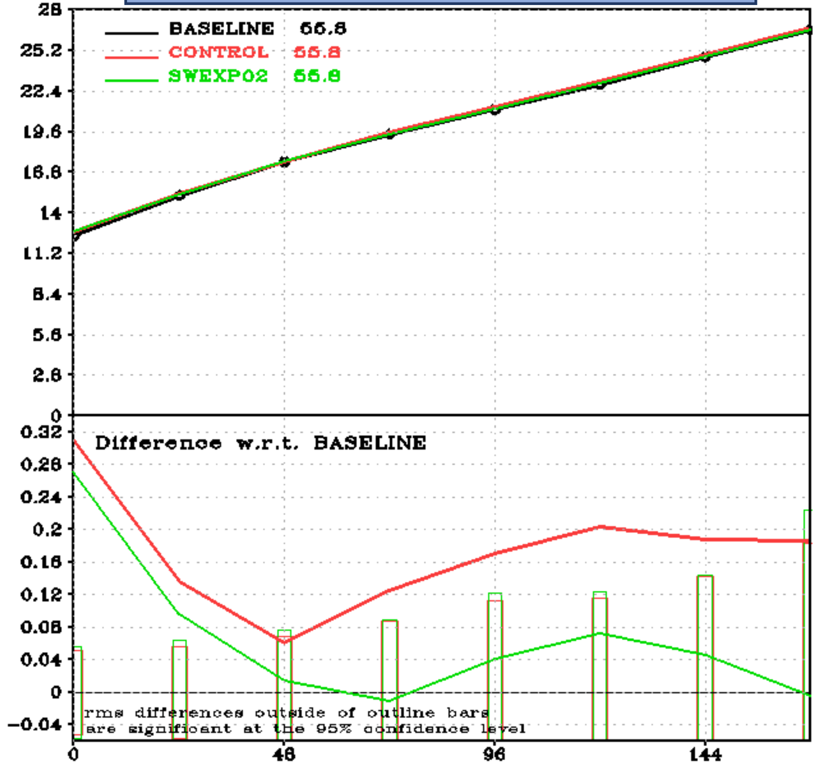


Tropical wind analysis differences:

- SWIR improves 200 hPa Tropical wind RMSE; improvements are significant at some forecast times
- SWIR generally improves 850 hPa Tropical wind RMSE, but not significantly

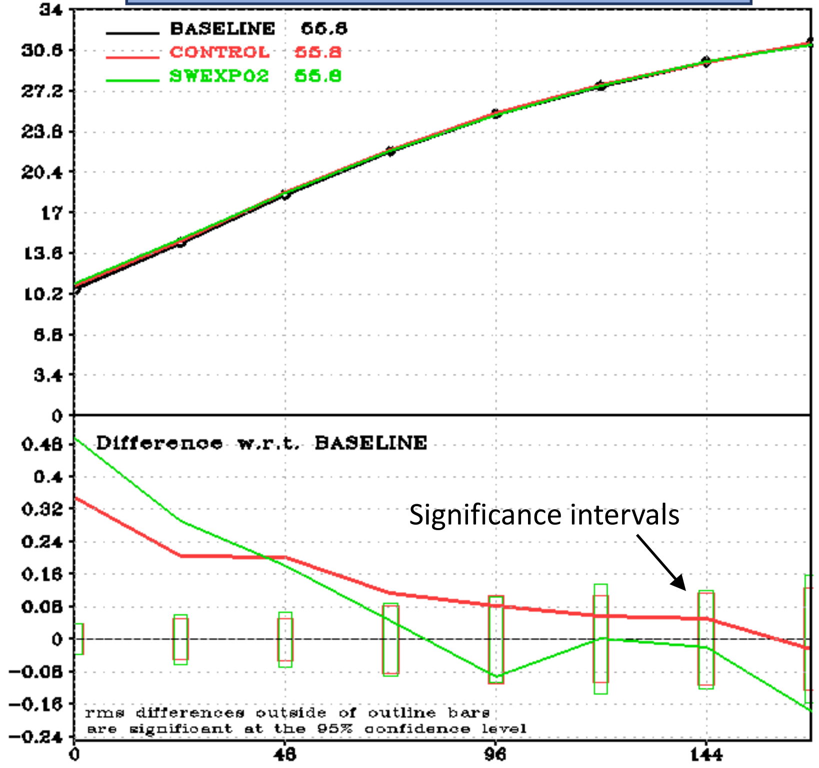
Forecast Impact on Global Relative Humidity (Preliminary)

200 hPa RH RMSE (GL)



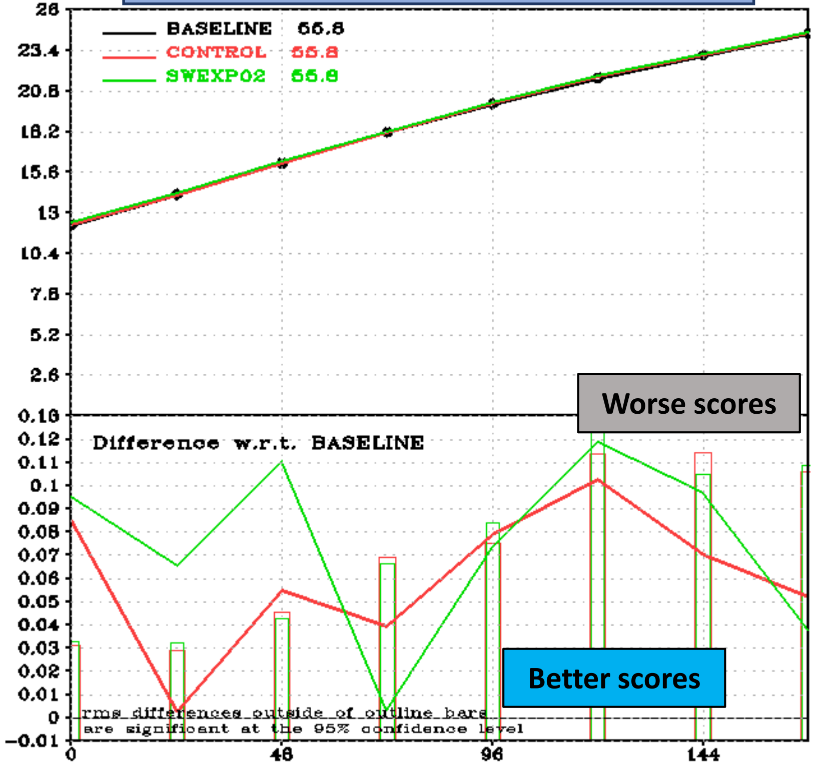
Forecast Hour

500 hPa RH RMSE (GL)



Forecast Hour

850 RH RMSE (GL)



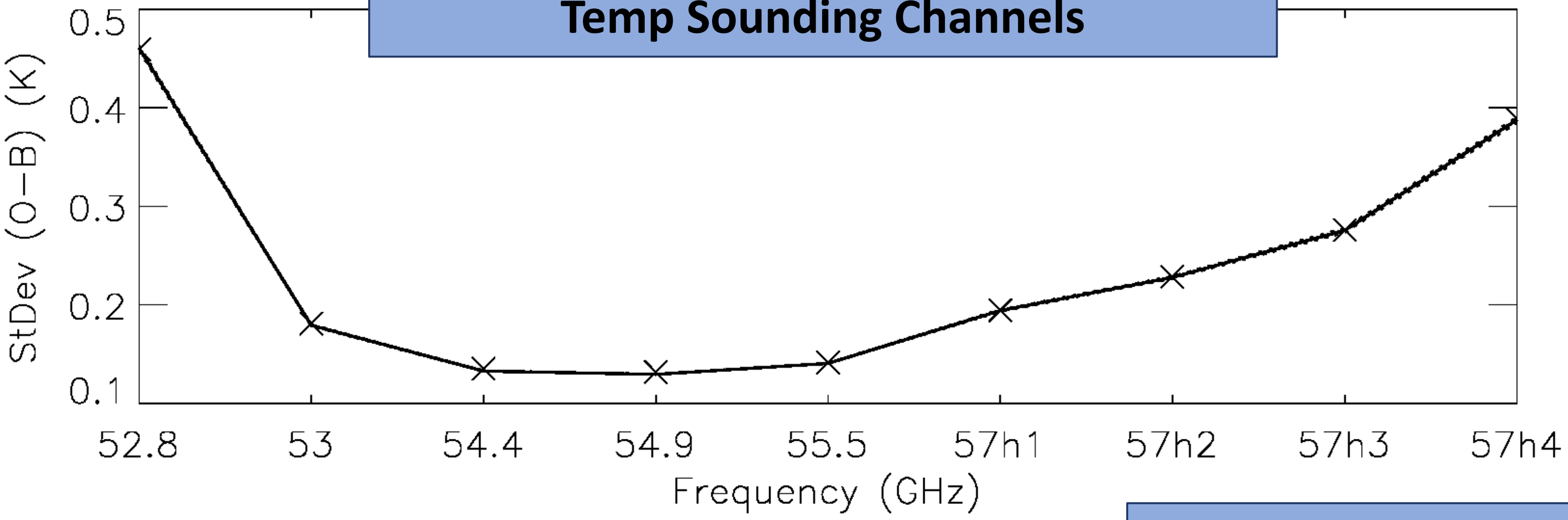
Forecast Hour

Verified against ECMWF

Global relative humidity analysis differences:

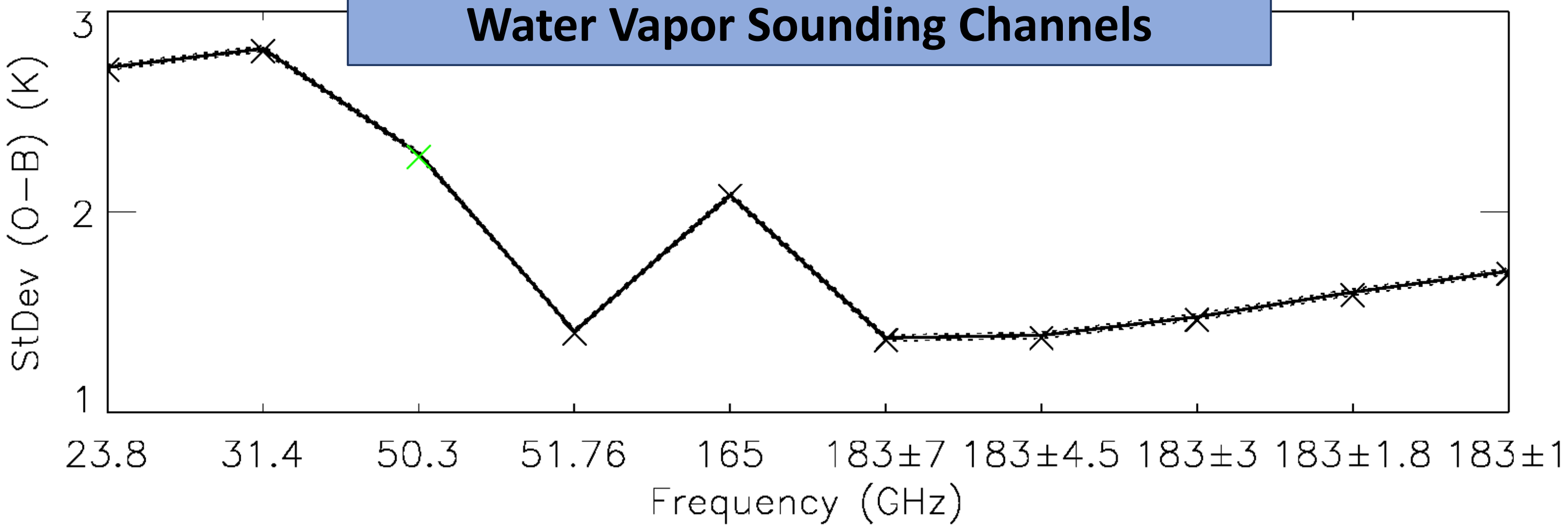
- SWIR degrades RH RMSE performance over the control at 500 and 850 hPa in the short-term (e.g. 24-48 hours)
- SWIR improves RH RMSE scores at 200 and 500 hPa over the control at most forecast times

Background Fit to ATMS Sounding Channels



Using SWIR doesn't degrade the background fit to ATMS:

- Temperature sounding channel O-B differences minimal (~ 10^{-3} K)
- Low frequency / water vapor sounding channel O-B differences minimal (~ 10^{-2} K)



- × SWIR exp ATMS O-B Neutral
- × SWIR exp ATMS O-B Improved
- × SWIR exp ATMS O-B Degraded

Conclusions and Future Work

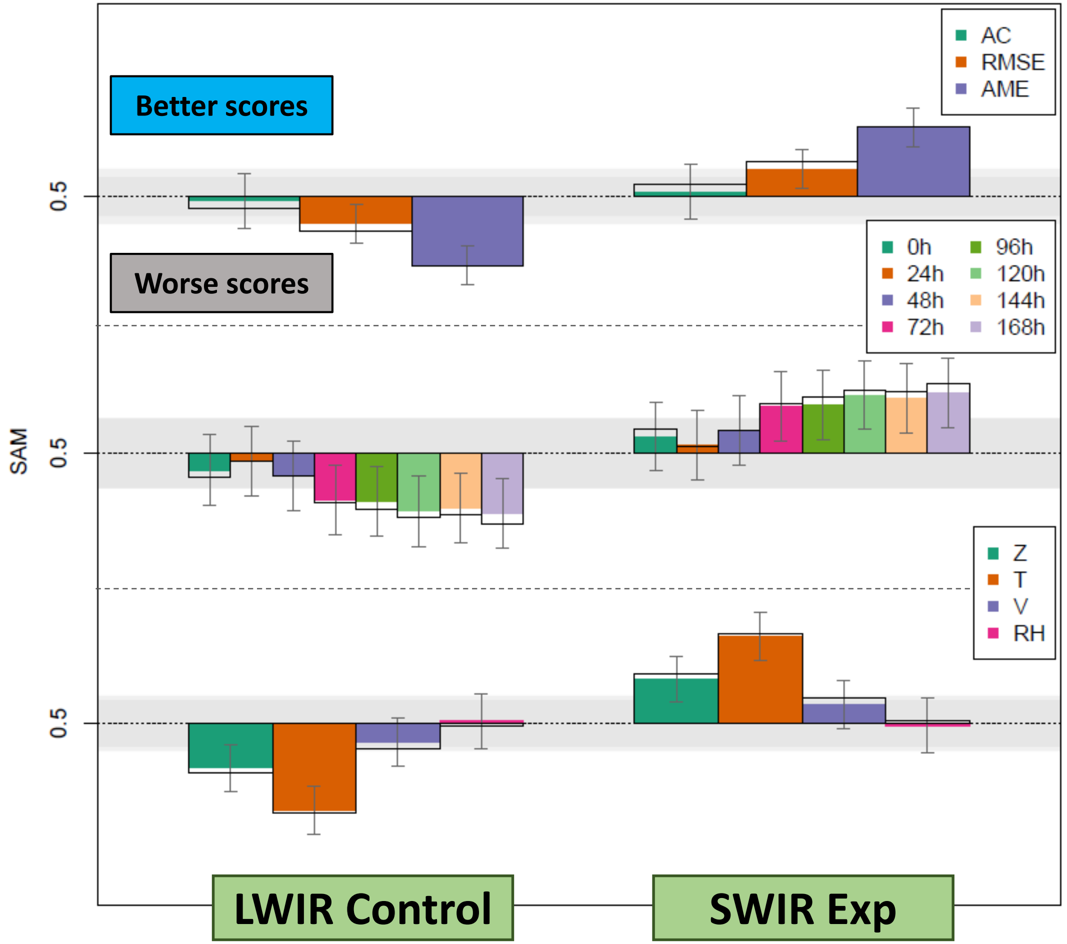
Summing up:

- QC and obs error enhancements improve SWIR assimilation and increase number of SWIR observations used
- Preliminary results from initial experiments demonstrate that SWIR has potential to maintain skill of LWIR for parameters at several levels, forecast lead times, etc.

Next steps:

- Evaluate more forecast/analysis metrics, including cumulative metrics/statistics
- Further improve NLTE to allow for the assimilation of the full 2211 CrIS channel set
- Run an experiment assimilating both LWIR and SWIR to test their skill together

Summary Assessment Metric (SAM): LWIR Control + SWIR Exp, verif. ECMWF



The SAM overall skill score (Hoffman et al., 2018) suggests assimilating SWIR has a generally favorable impact on forecast skill

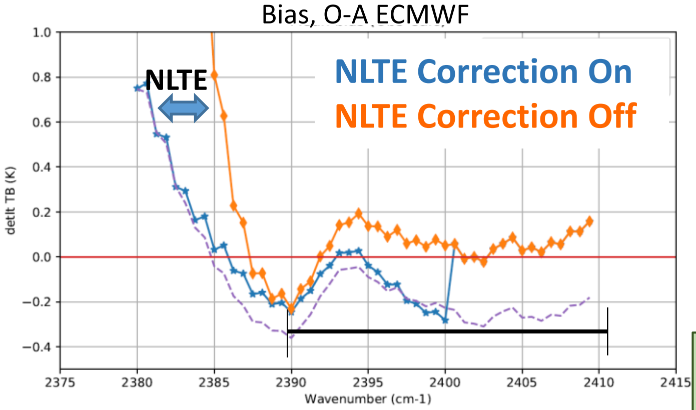
Acknowledgement: This project is funded by the NESDIS/OPPA Technology Maturation Program

Questions?

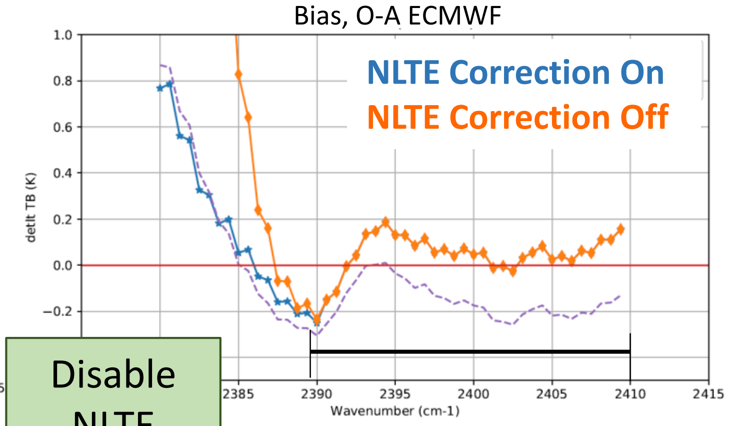
Backup Slides

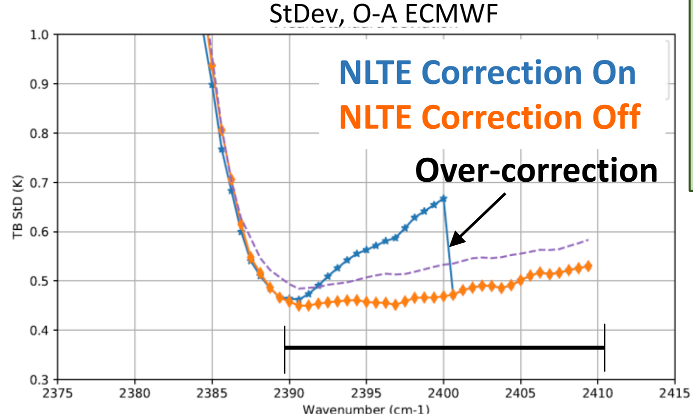
Forward Operator Enhancements

NLTE Correction Before Fix

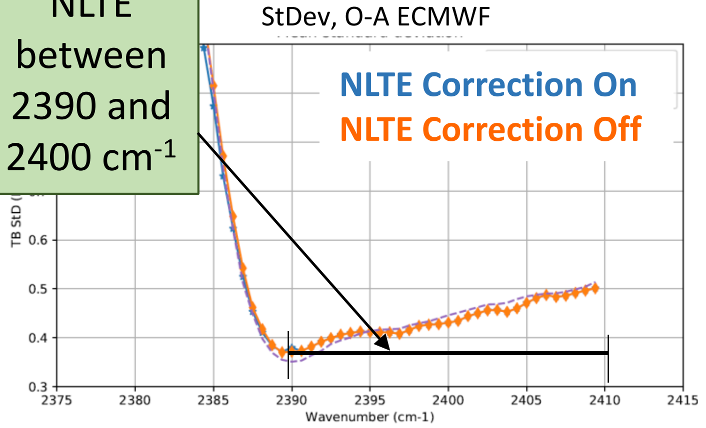


NLTE Correction After Fix





Disable NLTE between 2390 and 2400 cm^{-1}



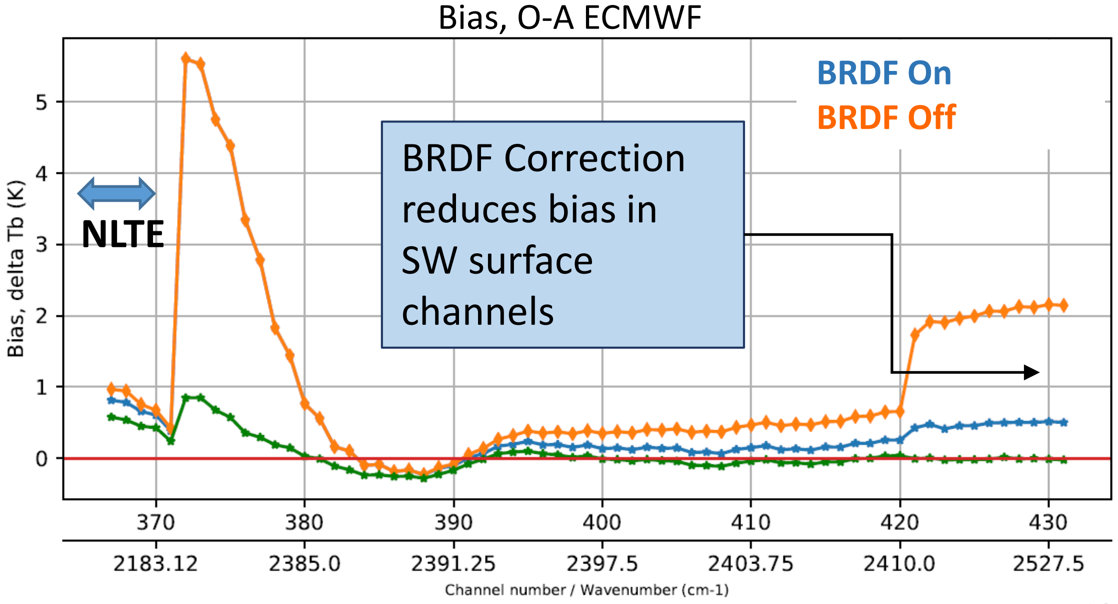
Non-Local Thermodynamic Equilibrium (NLTE):

- NLTE impacts few channels in the CrIS 431 channel subset
- Pre-modification, the NLTE correction in CRTM was negatively affecting channels not impacted by NLTE

Bidirectional Reflectance Distribution Function (BRDF):

- BRDF performs well in the CRTM for most SWIR surface channels, except when impacted by sun glint
- Results suggest that it's advantageous to keep QC in place for sun glint for SWIR surface channels over ocean

CRTM BRDF Evaluation



LWIR / SWIR Channel Equivalence

LWIR			SWIR		
Channel	431-subset channel	Wave No.	Channel	431-subset channel	Wave No.
65	30	690.00	1939	372	2380.00
69	34	692.50	1940	373	2380.62
73	38	695.00	1941	374	2381.25
67	32	691.25	1942	375	2381.88
75	40	696.25	1943	376	2382.50
44	12	676.50	1944	377	2383.12
83	48	701.25	1945	378	2383.75
85	50	702.50	1946	379	2384.38
89	54	705.00	1947	380	2385.00
91	56	706.25	1948	381	2385.62
95	60	708.75	1949	382	2386.25
99	64	711.25	1950	383	2386.88
103	68	713.50	1951	384	2387.50
107	72	716.25	1952	385	2388.12
109	74	717.50	1953	386	2388.75
127	92	728.75	1954	387	2389.38
131	96	731.25	1955	388	2390.00
125	90	727.50	1956	389	2390.62
121	86	725.00	1957	390	2391.25
123	88	726.25	1958	391	2391.88
153	118	745.00	1959	392	2392.50
			1960	393	2393.12
			1961	394	2393.75

SWIR R-branch