# On Expanding the Use of CrIS Observations in NOAA's Global Systems: What Has Been, and Still Needs to Be, Done


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# Background and Motivations

## The Cross-Track Infrared Sounder (CrIS):

- A Fourier Transform Spectrometer with 2211 channels in 3 bands:
  - CrIS longwave (LW): 650 – 1095 $cm^{-1}$, 713 channels
  - CrIS midwave (MW): 1210 – 1750 $cm^{-1}$, 865 channels
  - CrIS shortwave (SW): 2155 – 2550 $cm^{-1}$, 633 channels
- Currently flying on three polar-orbiting satellites (Suomi-NPP, NOAA-20, and the recently launched JPSS-2 / NOAA-21)
  - Also planned to fly on the JPSS-3 (no earlier than 2028 launch) and JPSS-4 (no earlier than 2032 launch)
  - **The CrIS instrument should be providing us with global hyperspectral IR data until at least 2039**: almost two more decades with CrIS!
- NOAA uses a subset of 431 CrIS channels in operational data assimilation for NWP:
  - **263 CrIS LW** channels, **103 CrIS MW** channels, and **65 CrIS SW** channels are available; **92 LW** channels, **8 MW** channels, and **0 SW** channels are operationally assimilated from NOAA-20 CrIS
    - Only 92 LW channels are operationally assimilated from S-NPP CrIS due to the failure of the LW band on one side of S-NPP CrIS and the failure of the MW band on the other side


**Rendering of the JPSS satellite constellation – NESDIS JPSS Program Office** (https://www.nesdis.noaa.gov/about/our-offices/joint-polar-satellite-system-jpss-program-office)

## Motivating Questions:

- **Can the CrIS SW band be used for assimilation in global NWP?**
  - The use of the CrIS SW band is a good proxy for testing the potential impacts of sensors with ***similar spectral resolution and instrument error*** on future smallsats (e.g. CIRAS)
- **Can NOAA get greater benefit from using the CrIS sensor?**
  - Will using more channels from the different CrIS bands provide a positive impact on global forecasts?
    - This is currently also (I think!) being investigated at other NWP centers, e.g. ECMWF, GMAO
  - What can be done to improve the assimilation of CrIS in NOAA's global NWP system?

# Objectives and Approach

## Objectives:

- Investigate of the use of the CrIS SW band and the expanded use of the CrIS MW band in NOAA's Global Data Assimilation System (GDAS):
  - Assimilate CrIS SW channels in the absence of CrIS LW to determine whether the SW band is practical to use in global NWP
  - Assimilate more CrIS MW channels in conjunction with the other CrIS bands to assess the impacts of adding more CrIS channels to the data assimilation system
- Make some determinations of what can still be done in the GDAS to further improve the assimilation of CrIS data

## Approach:

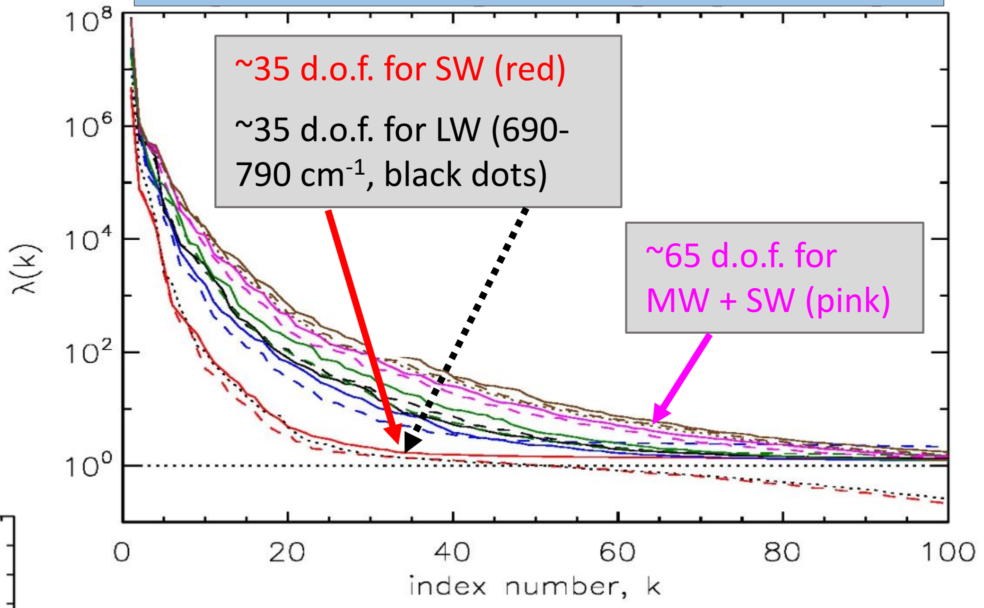
- Assess the current treatment of CrIS observations in the NOAA GDAS
- Select channels from CrIS SW and CrIS MW for use in global OSEs
- Implement appropriate enhancements to the Gridpoint Statistical Interpolation system (GSI) for the effective assimilation of new CrIS data in the GDAS
  - Enhancements to quality control (QC) and observation errors required for the use of CrIS SW data; specification of new observation errors required for the use of new CrIS MW data
- Performance and evaluation of OSEs to assess impacts of the assimilation of previously unused CrIS data on the GDAS analysis and the Global Forecast System (GFS) forecast
  - Assessment of innovations – observation minus background (OmB) and observation minus analysis (OmA) – from CrIS and other sensors
  - Forecast verification against ECMWF analyses and the operational GDAS
  - Iterate on QC, observation errors, etc. based on findings from OSEs; propose additional areas of further study after evaluating the impacts of initial GDAS enhancements

# Motivation for Using CrIS MW and SW

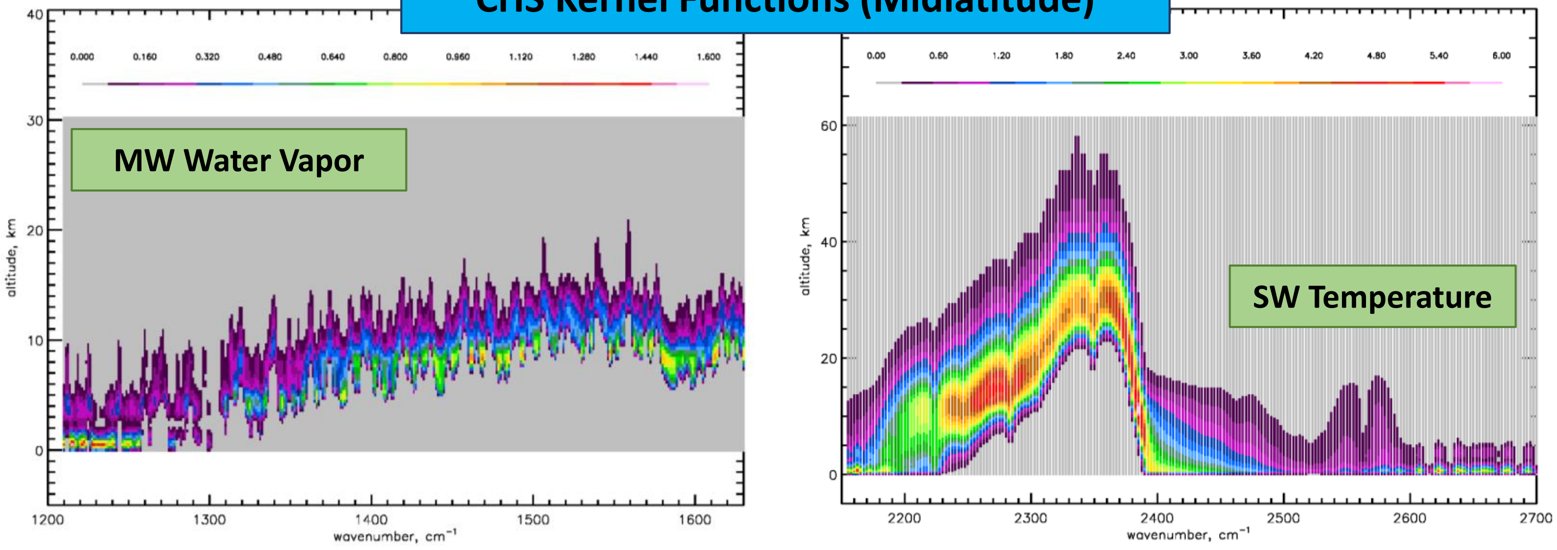
## CrIS MW and SW bands have potential for NWP:

- Empirical Orthogonal Function (EOF) analysis shows that the **CrIS SW band provides a similar amount of unique information** as the portion of the CrIS LW band (690 – 790 cm$^{-1}$) most heavily used in data assimilation at NOAA
  - The combination of CrIS LW (690 – 790 cm$^{-1}$) and CrIS MW bands (not shown) provides a similar amount of unique information as the combination of the CrIS MW and SW bands
  - The most information is found when all three bands are examined together

**EOF Analysis for CrIS Bands**




**CrIS Kernel Functions (Midlatitude)**



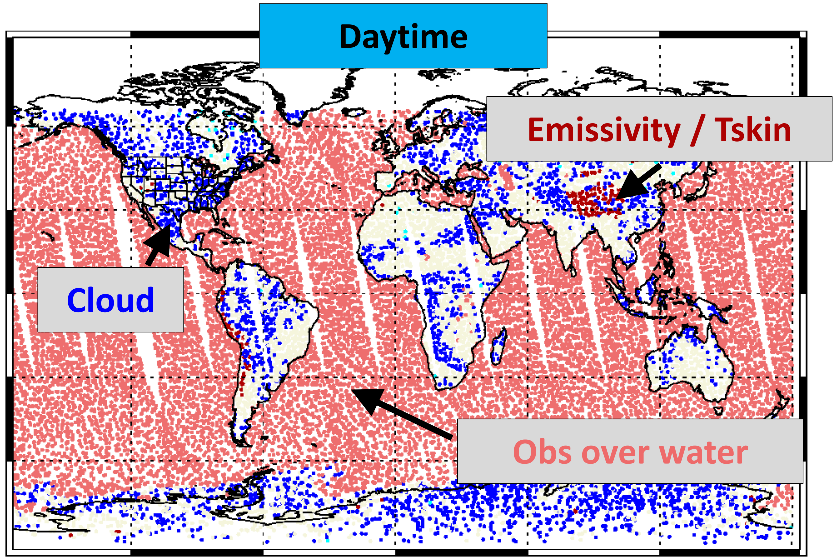

**CrIS MW water vapor and SW temperature sounding channels are largely free from trace gas interference** (SW sounding channels have minimal water vapor interference)

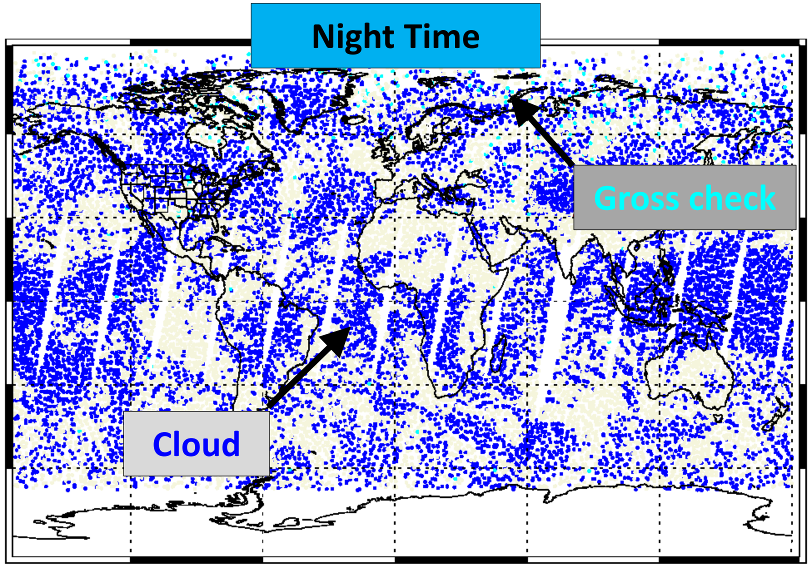
## CrIS MW and SW bands have good sounding capabilities:

- The SW R-branch has high sensitivity to atmospheric temperature
- CrIS MW channels (including those not in NOAA's 431 channel subset) have sensitivity to water vapor throughout much of the troposphere

# Assimilation of CrIS in the GDAS: Current Status

**NOAA-20 CrIS 2386.88 cm$^{-1}$ QC Flags**




**Operational assimilation of CrIS at NOAA relies on CrIS LW channels:**

- **431 of 2211** CrIS channels are ingested into the GDAS, **100 of 431** available CrIS channels are actively assimilated, **92 of 100** actively assimilated CrIS channels are in the LW band
- CrIS is assimilated only in clear-sky conditions: cloud detection for QC of CrIS observations is determined by CrIS LW channels
  - This works for CrIS MW channels, but may not be appropriate for CrIS SW channels
- **Failure of the CrIS LW band prevents the assimilation of all CrIS observations**

**The GDAS has not been optimized to assimilate CrIS MW or SW observations:**

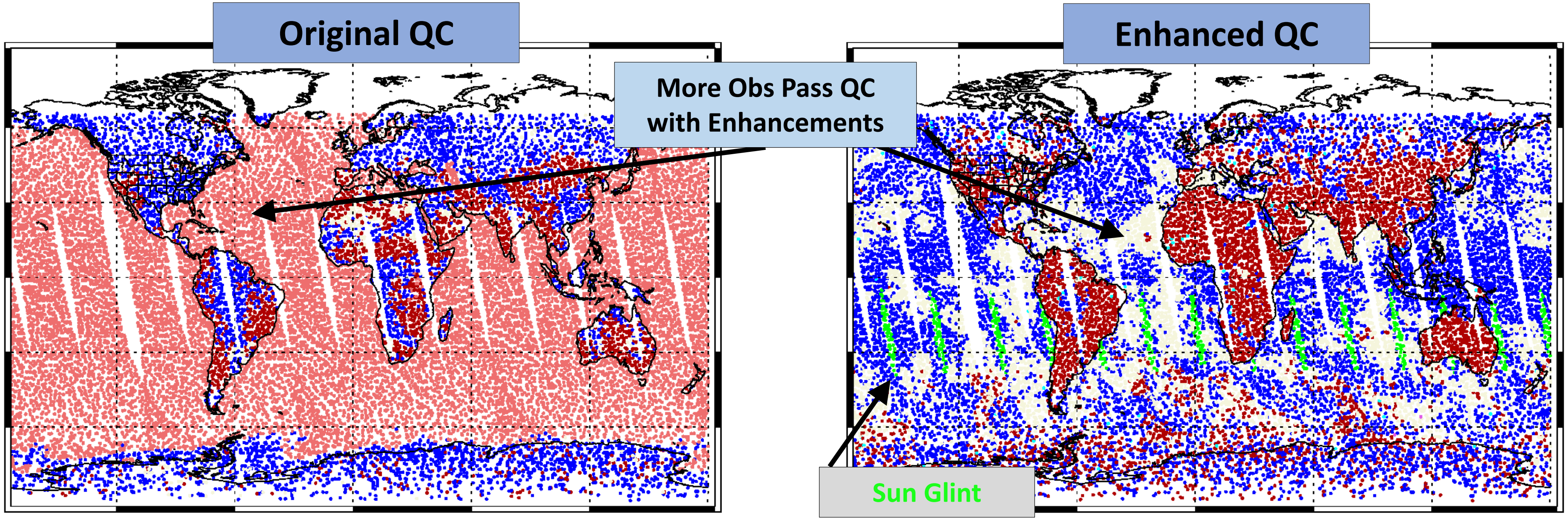
- 8 CrIS MW and 0 CrIS SW channels are operationally assimilated
- QC for CrIS SW observations is very strict:
  - Daytime observations over water are flagged and de-weighted (if they were to be assimilated), or removed completely (for wavenumbers over 2400 cm$^{-1}$)
  - Cloud QC determined by LW channels may remove too many SW observations
- Observation errors have not been optimized for all CrIS SW and most CrIS MW channels
  - Values set to a default 1 K; only the 8 actively assimilated CrIS MW channels are part of the operational observation error covariance matrix

# Enhancements to the GDAS for CrIS

## QC enhancements implemented for CrIS SW:

- **Sun glint check** applied to low-peaking CrIS SW channels replaces QC for observations taken over water in daytime
- **Cloud detection for CrIS SW observations performed using CrIS SW channels**
  - Allows more CrIS SW observations to pass QC, without degrading innovation statistics
  - Capability implemented to allow for concurrent use of SW channels for CrIS SW observations and LW channels for CrIS LW observations in cloud QC

**NOAA-20 CrIS 2390.00 cm$^{-1}$ QC Flags**

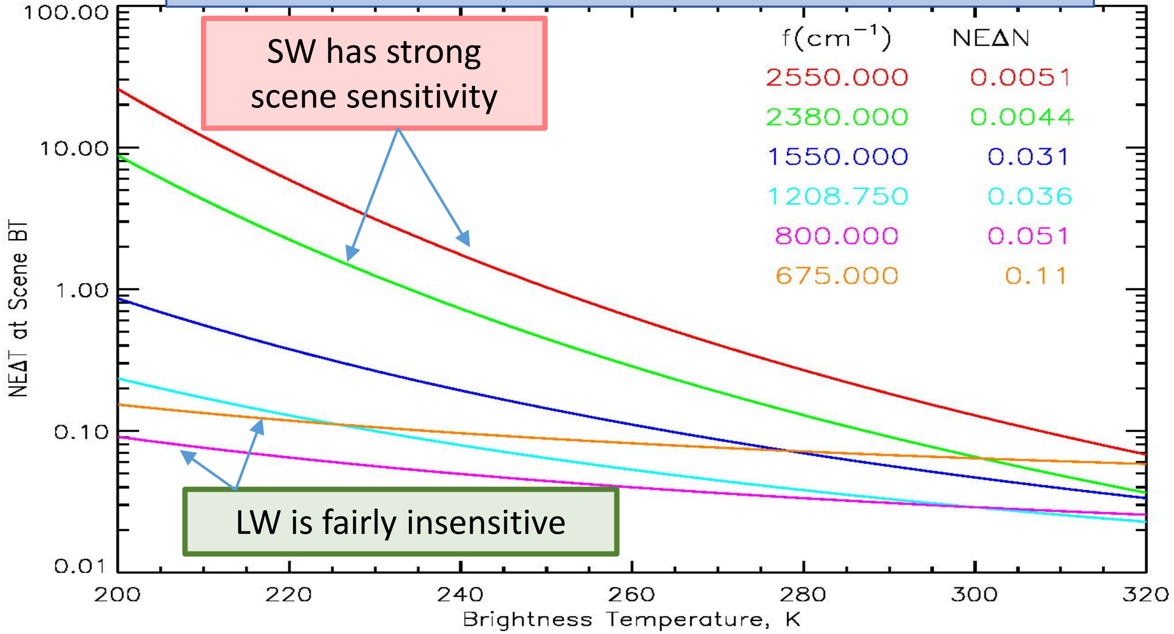


# Enhancements to the GDAS for CrIS

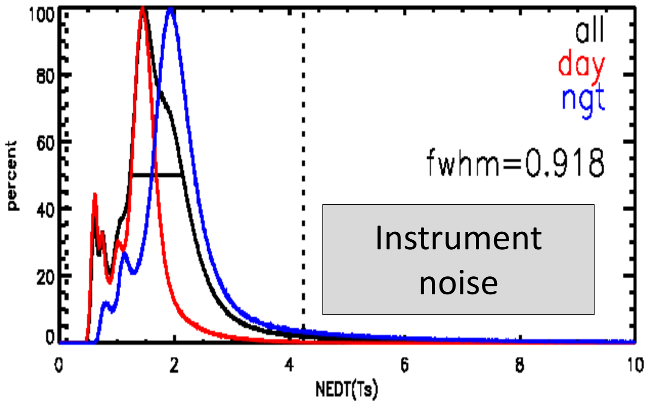
**Modifications to observation errors:**

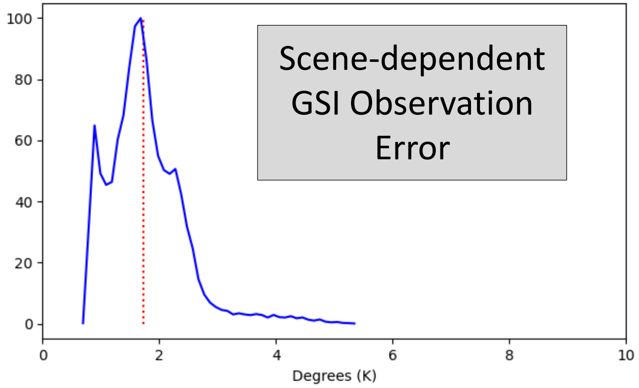
- New initial observation errors based off of OmBs specified for all CrIS SW channels in the 431 channel subset (correlated observation errors not used for SW)
- A **scene-dependent observation error** implemented for cold, high-peaking SW channels
  - Used for CrIS SW channels with wavenumbers less than 2386 $cm^{-1}$
  - Necessary due to the non-linearity of the Planck Function: higher noise for SW wavenumbers in cold scenes and at high altitudes (e.g. the upper troposphere)
  - **Allows for higher weighting of observations when noise is low**, rather than de-weighting entire channels
- New initial observation errors based off of OmBs specified for select CrIS MW channels from NOAA-20 CrIS:
  - New CrIS MW not present in the current observation error covariance matrix; correlated observation errors not used for these channels

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




**NOAA-20 CrIS: 2380.00 $cm^{-1}$**



# CrIS Observing System Experiments

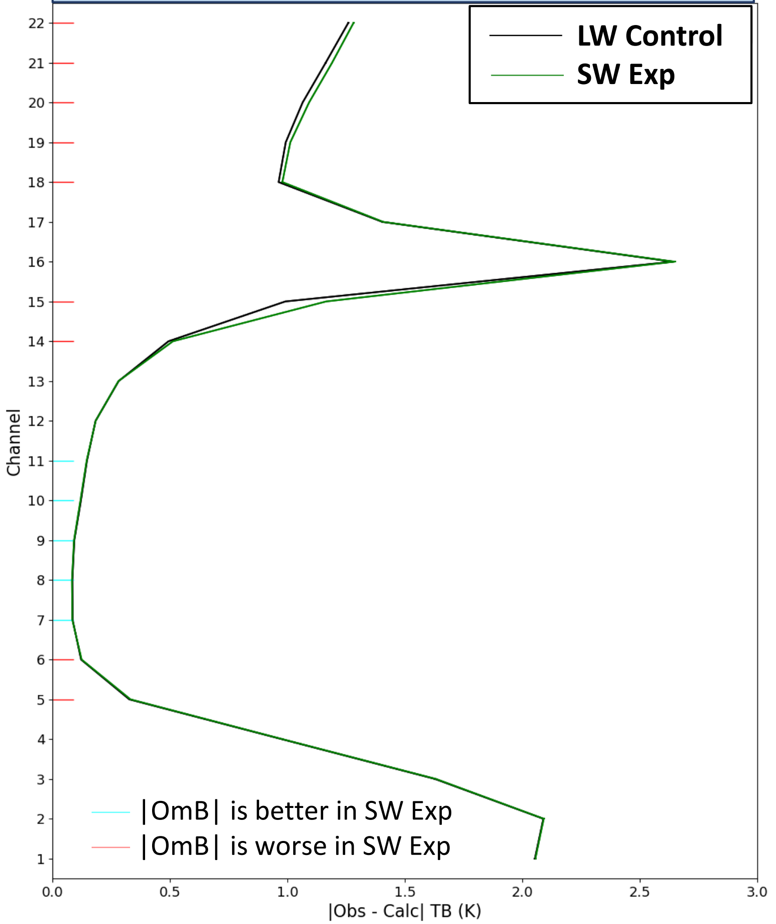
| Observation | No IR Exp | LW Control | LWMW Exp | SW Exp |
|---|---|---|---|---|
| Conventional | | | | |
| Sat-winds | | | | |
| IASI | | | | |
| AIRS | | | | |
| CrIS LW | | | | |
| CrIS MW | | | | |
| CrIS SW | | | | |
| ATMS | | | | |
| AMSU/MHS | | | | |
| GPSRO | | | | |

- Model: FV3GFS 4DEnVar, 80 ensemble members, C384/C192 resolution (~25 km GDAS/GFS, ~50 km ensemble), 127 vertical layers
- Experiment time period: 2018-12-01 to 2019-02-01
- Observations to be assimilated as in table to the left; expanded CrIS MW channel selection for N20 assimilated in LWMW experiment (using CrIS 2211 data)
  - No changes to operational CrIS LW channel selection
  - Operationally assimilated CrIS MW channels used in LW Control, LWMW Exp, and SW Exp
  - Expanded CrIS MW channel selection (22 new channels from the full 2211 channel set) used for NOAA-20 CrIS in the LWMW Exp
  - 52 CrIS SW channels assimilated in the SW Exp
- Operational correlated observation errors used for operationally assimilated channels (except in the SW Exp); errors uncorrelated for CrIS SW and new CrIS MW channels
  - Scene-dependent error used for some CrIS SW channels
- QC Enhancements for CrIS SW used in SW Exp
- No changes to VarBC for bias correction or thinning for observation selection

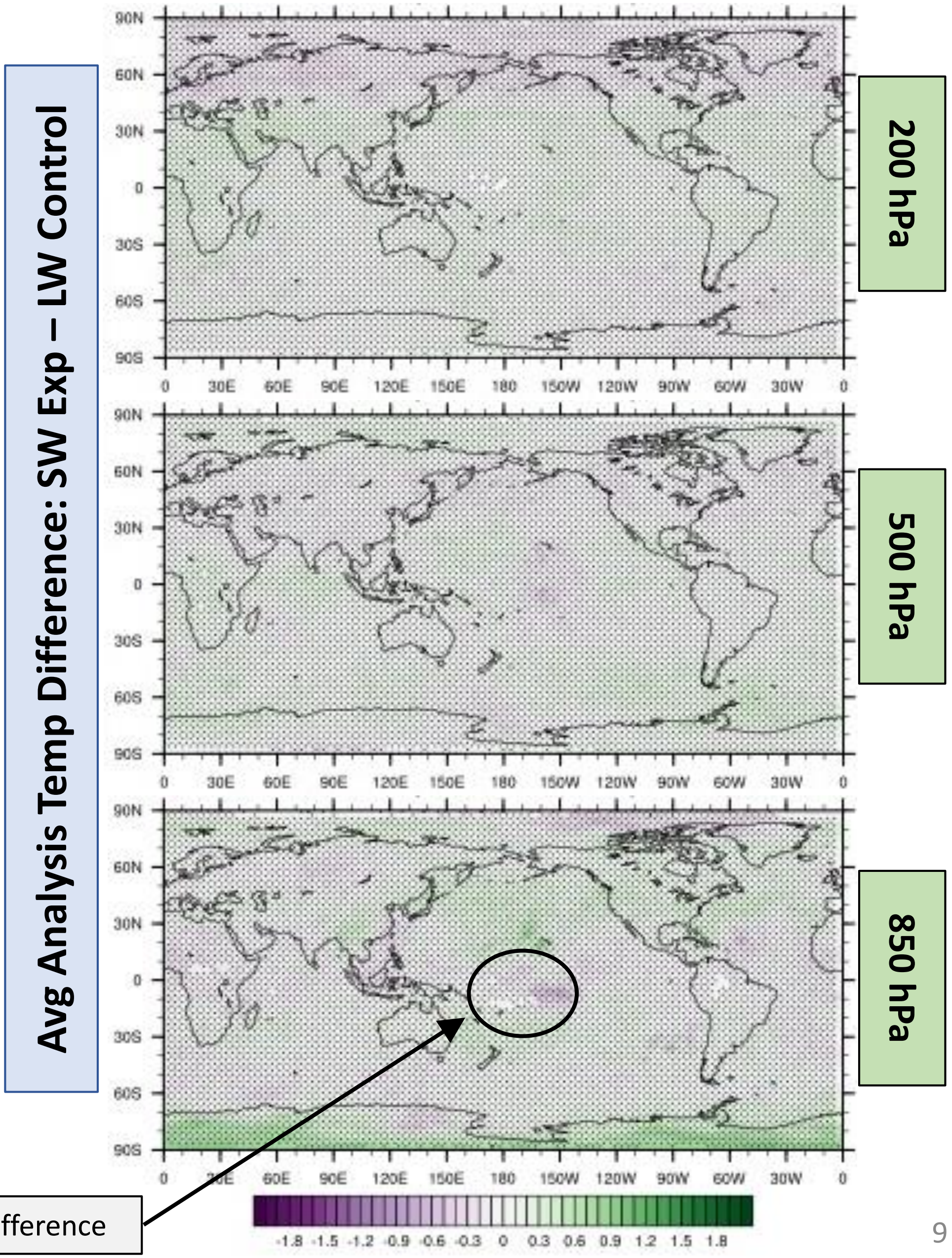
# SW Analysis Impacts

## Question: Can CrIS SW be used for assimilation in global NWP?

**Avg N-20 ATMS |OmB|:**
**20181215 - 20181231**




- Temperature analysis fields look realistic after assimilating CrIS SW temperature sounding channels; **analysis differences between the LW Control and SW Exp are often not statistically significant**
- Differences in mean |OmB| values for N-20 ATMS are not significant between the LW Control and SW Exp for several ATMS channels
    - Differences are small, but some significant differences (both better and worse) are seen; degradation especially seen for 183 GHz ATMS channels – Assimilated CrIS SW channels have little water vapor sensitivity; operationally assimilated CrIS LW channels have some water vapor sensitivity

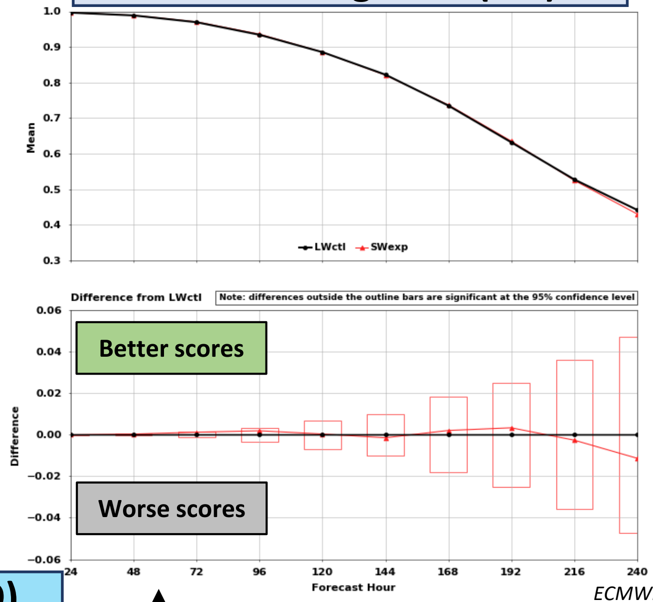


# SW Forecast Impacts

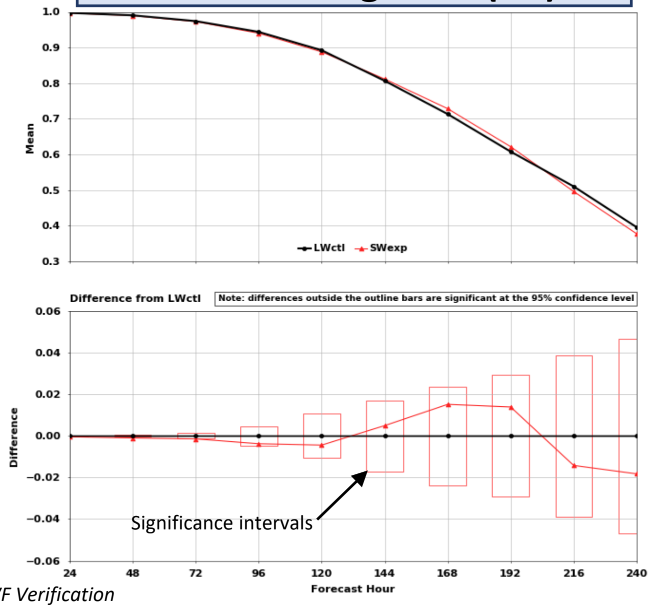
## Question: Can CrIS SW be used for assimilation in global NWP?

- Overall, **forecasts from an OSE assimilating the CrIS SW band don't differ greatly** from forecasts from an OSE assimilating the CrIS LW band
- An encouraging result considering the assimilation of SW observations was not thought to be feasible until relatively recent advances in radiative transfer!

**500 hPa Height AC (NH)**




**500 hPa Height AC (SH)**

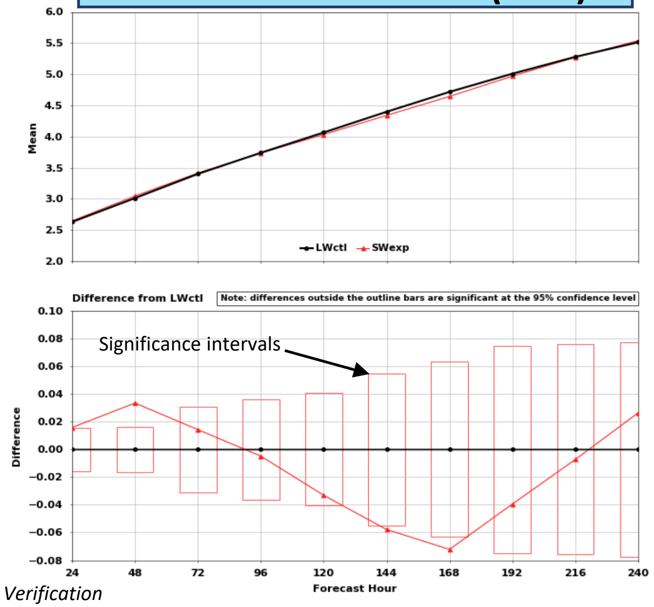



*ECMWF Verification*

**500 hPa Heights:** Some improvement in 500 hPa Southern Hemisphere heights in mid-long range forecast hours when CrIS SW observations are assimilated. *Differences are not significant between LW Control and SW Exp forecasts*.

**200 hPa Wind RMSE (TRO)**


**850 hPa Wind RMSE (TRO)**

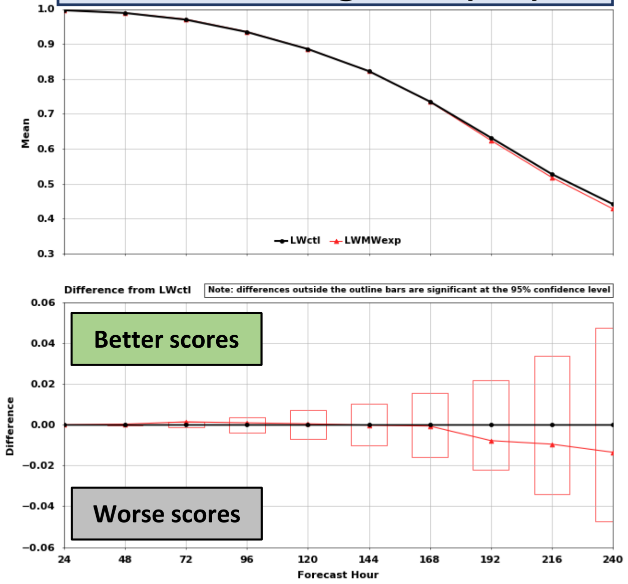



*ECMWF Verification*

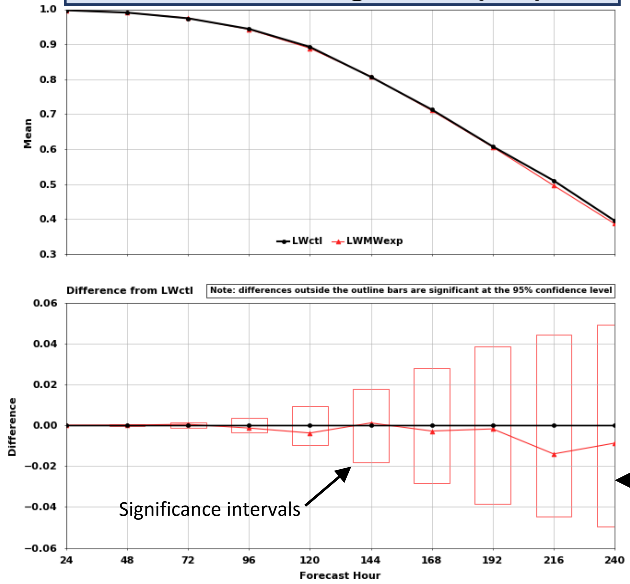
**Tropical Winds:** Assimilating CrIS SW channels doesn't yield improved performance for 200 hPa tropical winds, but differences are not significant when compared to the LW Control. There is some significant improvement in 850 hPa tropical wind forecasts at later forecast hours in the SW Exp, following significant degradation in the 2 day forecast.

# LWMW Analysis/Forecast Impacts

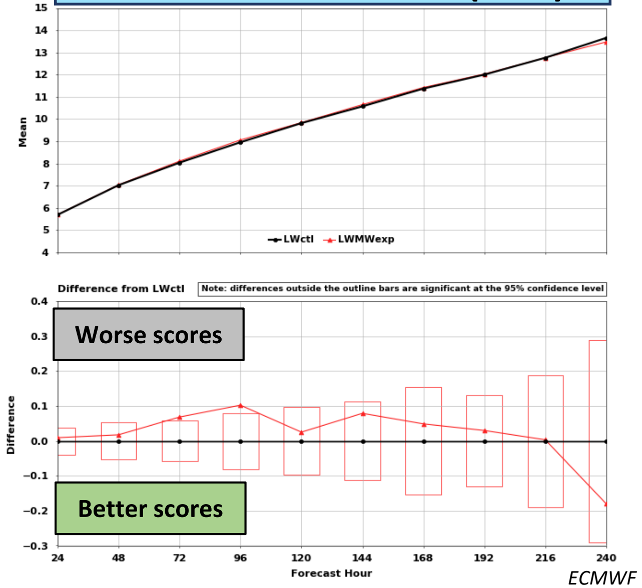
## 500 hPa Height AC (NH)



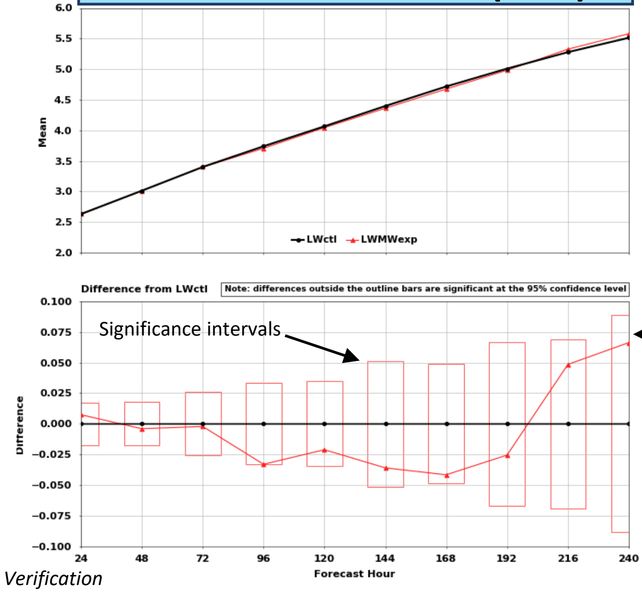

## 500 hPa Height AC (SH)




## 200 hPa Wind RMSE (TRO)




## 850 hPa Wind RMSE (TRO)




*ECMWF Verification*

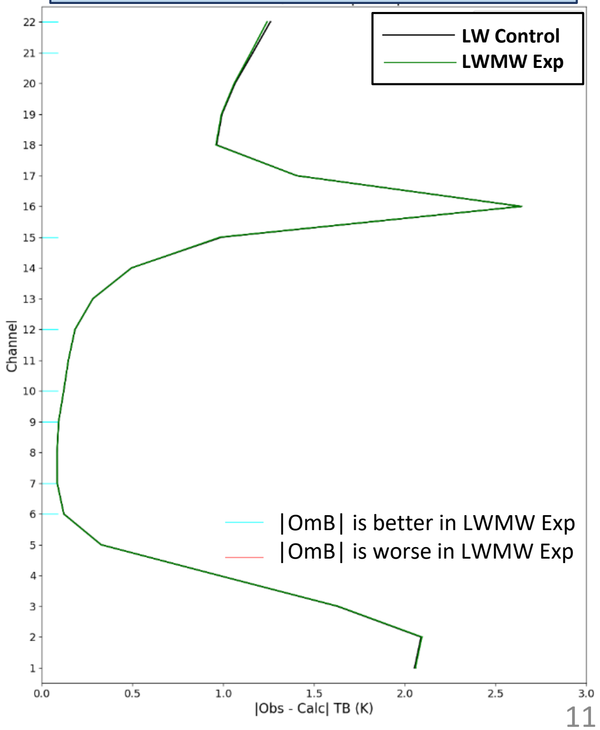
## Question: Will using more CrIS MW channels benefit forecast/analysis impacts?

- Assimilating additional CrIS MW channels improves OmBs for several NOAA-20 ATMS channels, but differences are small
- **Forecast impacts of assimilating more CrIS MW channels are largely neutral, though some improvement exists**

**500 hPa Heights:** *No significant difference* in AC scores when additional CrIS MW channels are assimilated.

**Tropical Winds:** Some degradation at 200 hPa for tropical winds in the mid-range forecast when assimilating additional CrIS MW channels; also some improvement at 850 hPa. Impact is otherwise neutral

**Avg N-20 ATMS |OmB|: 20181215 - 20181231**

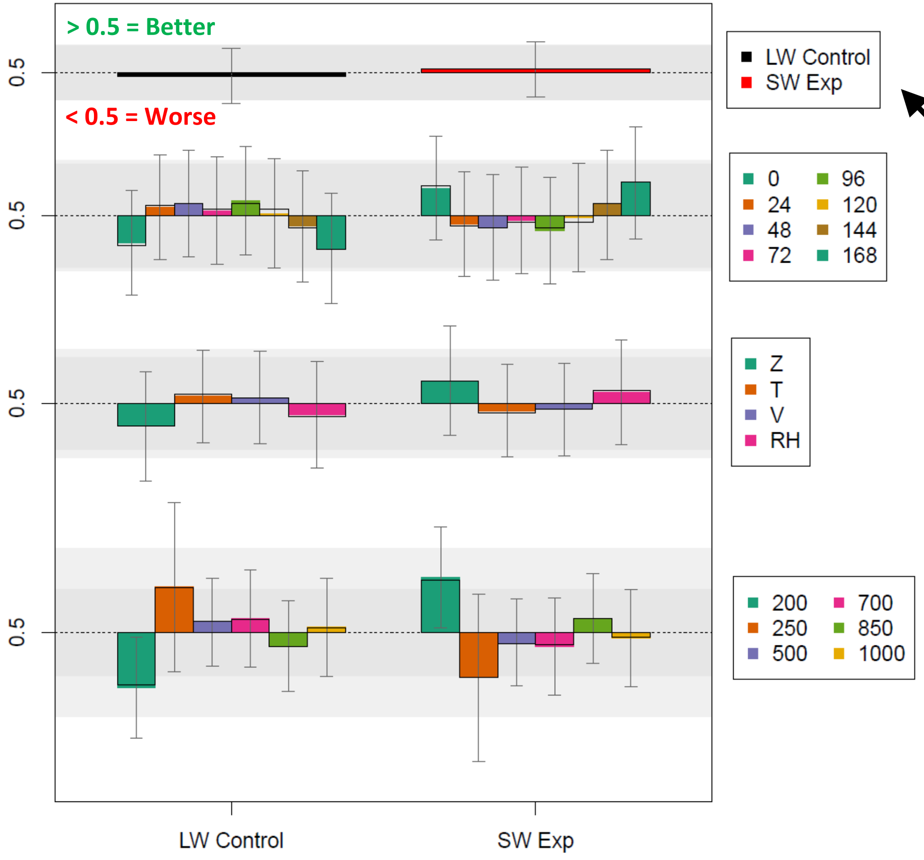


# A Summary of Impacts

## OSE Summary Assessment Metrics (SAMs):

- Overall assessment metric (combines AC, RMSE, and Bias scores; reference – Hoffman et al., 2018)
- Verification against ECMWF for the time period 20181208 – 20190131

**LW Control vs SW Exp**



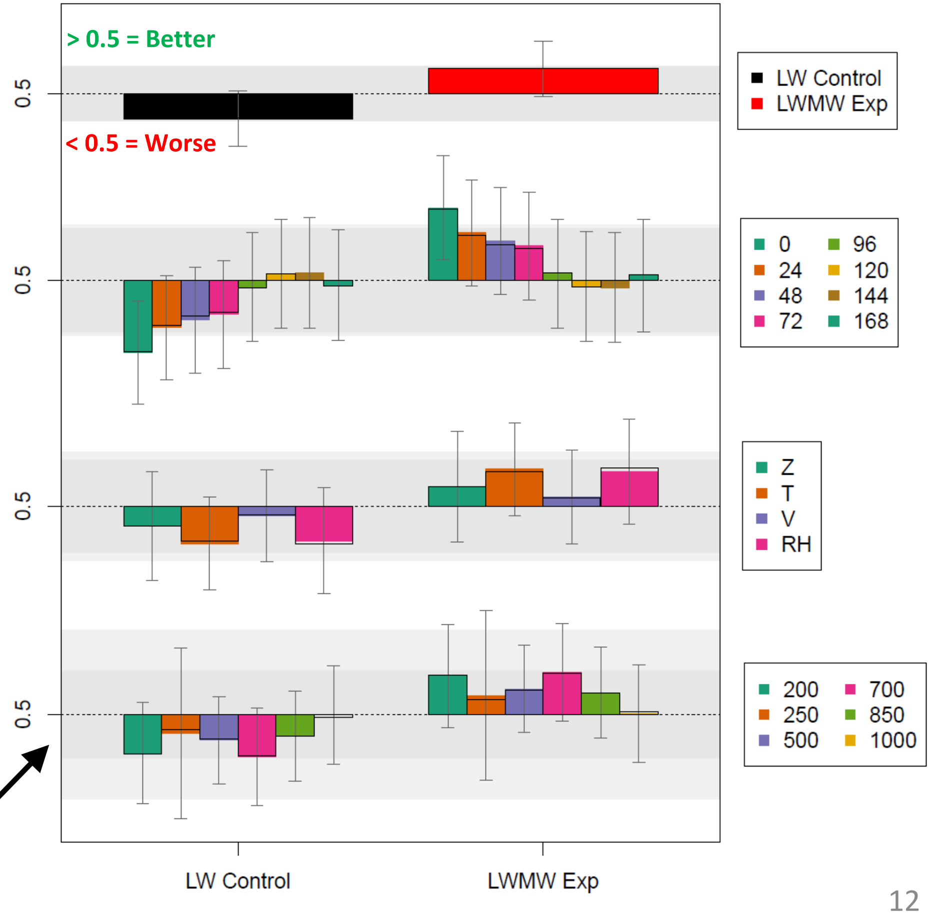

**SW Exp:**

- *Overall performance is largely not significantly different than the LW Control*
- Some improvement seen at later forecast hours and upper levels
- Widespread negative impacts not seen in the SW Exp

**LWMW Exp:**

- *Generally performs similarly or better than the LW Control*
- Best performance in the Northern Hemisphere (not shown), and for temp and RH (understandable; new MW channels add water vapor, and by extension temperature, information)

**LW Control vs LWMW Exp**



# Conclusions and Recommendations for Future Work

## Summing up:

- **CrIS SW channels can be effectively assimilated** in NOAA's global system with overall neutral impacts
  - **Suggests instruments with SW channels that have the spectral resolution of CrIS *and* similar/lower instrument noise are viable for use in global NWP**
- Assimilating additional **CrIS MW channels can benefit the FV3GFS forecast**
  - These channels can be added with minimal changes to the assimilation system

## Recommendations:

- **Assimilating CrIS SW channels and additional CrIS MW channels is a realistic prospect**, but more can be done to improve the assimilation of observations from CrIS:
  - **Scene-dependent observation errors** could be used for more SW channels and some MW channels, and **correlated observation errors** for these new channels should be explored; research should also look into how **correlated AND scene-dependent errors** can be implemented concurrently (this is necessary, especially for CrIS SW channels)
  - **Cloud detection could be improved**; the existing cloud detection scheme for hyperspectral IR sensors in the GSI was not crafted for CrIS
  - **Bias correction could be investigated**; cursory evaluation found cloud signals in the bias of some CrIS channels
  - **Use of additional CrIS channels** such as those sensitive to $N_2O$ and CrIS SW channels capable of providing information above the tropopause should be considered
  - **CrIS LW assimilation could be optimized**; OSE results in some cases found degradation in the LW Control when compared against the NoIR Exp

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# Questions?

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## Publications:

Barnet, C. D., N. Smith, K. Ide, K. Garrett, and E. Jones, 2023: Evaluating the Value of CrIS Shortwave-Infrared Channels in Atmospheric-Sounding Retrievals. *Remote Sens.*, **15**(3), 547, https://doi.org/10.3390/rs15030547.

Manuscript(s?) on CrIS SW in the GDAS in progress.

# Backup

# Newly Assimilated CrIS Channels

## New CrIS MW Channels

| Channel No | Wave No |
|---|---|
| 1498 | 1700.00 |
| 1273 | 1559.38 |
| 1552 | 1733.75 |
| 1475 | 1685.62 |
| 1298 | 1575.00 |
| 1267 | 1555.62 |
| 1556 | 1736.25 |
| 1570 | 1745.00 |
| 1074 | 1435.00 |
| 1014 | 1397.50 |
| 1127 | 1468.12 |
| 1053 | 1421.88 |
| 1346 | 1605.00 |
| 1020 | 1401.25 |
| 1060 | 1426.25 |
| 1030 | 1407.50 |
| 993 | 1384.38 |

## CrIS SW Channels

| Channel No | Wave No | Channel No | Wave No | Channel No | Wave No |
|---|---|---|---|---|---|
| 1939 | 2380.00 | 1960 | 2393.13 | 1981 | 2406.25 |
| 1940 | 2380.63 | 1961 | 2393.75 | 1982 | 2406.88 |
| 1941 | 2381.25 | 1962 | 2394.38 | 1983 | 2407.50 |
| 1942 | 2381.88 | 1963 | 2395.00 | 1984 | 2408.13 |
| 1943 | 2382.50 | 1964 | 2395.63 | 1985 | 2408.75 |
| 1944 | 2383.13 | 1965 | 2396.25 | 1986 | 2409.38 |
| 1945 | 2383.75 | 1966 | 2396.88 | 1987 | 2410.00 |
| 1946 | 2384.38 | 1967 | 2397.50 | 2119 | 2492.50 |
| 1947 | 2385.00 | 1968 | 2398.13 | 2140 | 2505.63 |
| 1948 | 2385.63 | 1969 | 2398.75 | 2143 | 2507.50 |
| 1949 | 2386.25 | 1970 | 2399.38 | | |
| 1950 | 2386.88 | 1971 | 2400.00 | | |
| 1951 | 2387.50 | 1972 | 2400.63 | | |
| 1952 | 2388.13 | 1973 | 2401.25 | | |
| 1953 | 2388.75 | 1974 | 2401.88 | | |
| 1954 | 2389.38 | 1975 | 2402.50 | | |
| 1955 | 2390.00 | 1976 | 2403.13 | | |
| 1956 | 2390.63 | 1977 | 2403.75 | | |
| 1957 | 2391.25 | 1978 | 2404.38 | | |
| 1958 | 2391.88 | 1979 | 2405.00 | | |
| 1959 | 2392.50 | 1980 | 2405.63 | | |