The Limb Adjustment of the TROPICS Microwave Sounder Constellation and MORE!!

Mitch Goldberg, CCNY

D.Li (CCNY), P. Heidary (CCNY),

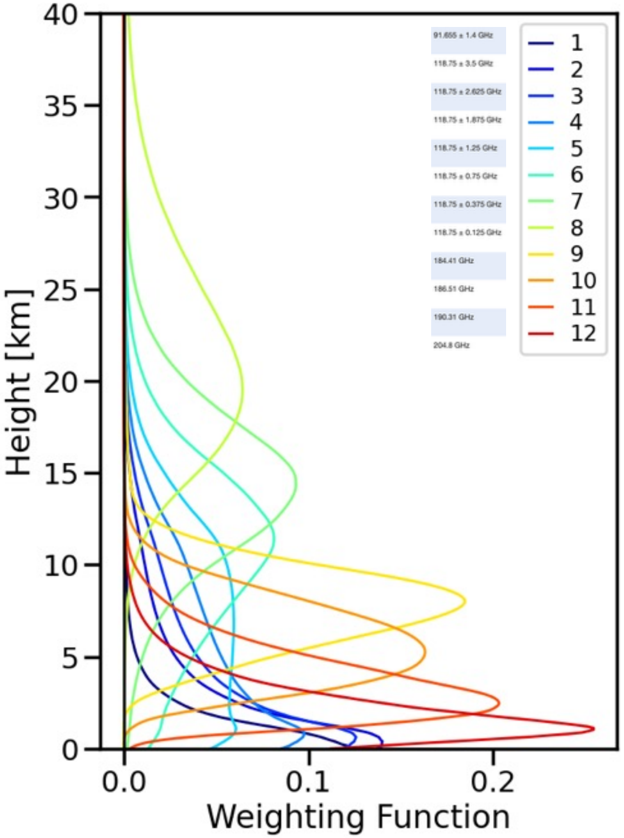
S. Kalluri (NESDIS), Lihang Zhou (NESDIS)

May 8, 2025

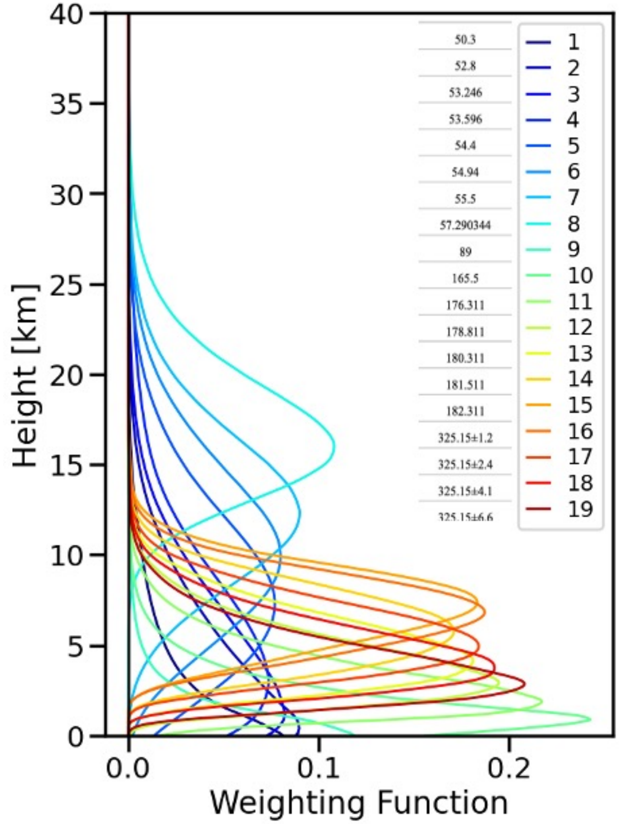
Many thanks to Joe Munchak (Tomorrow.IO) and Bill Blackwell (MIT/LL)

The MORE: Retrieval Comparisons between

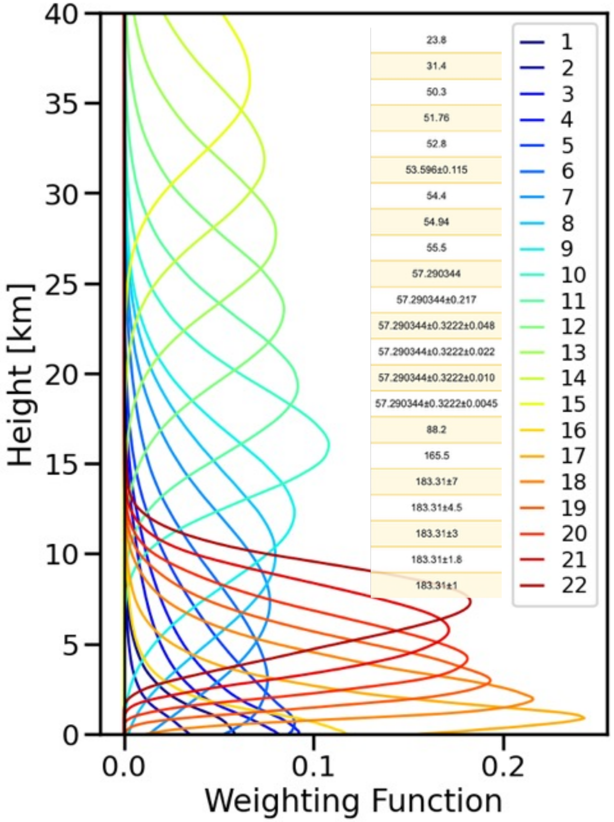
TMS



AWS



ATMS

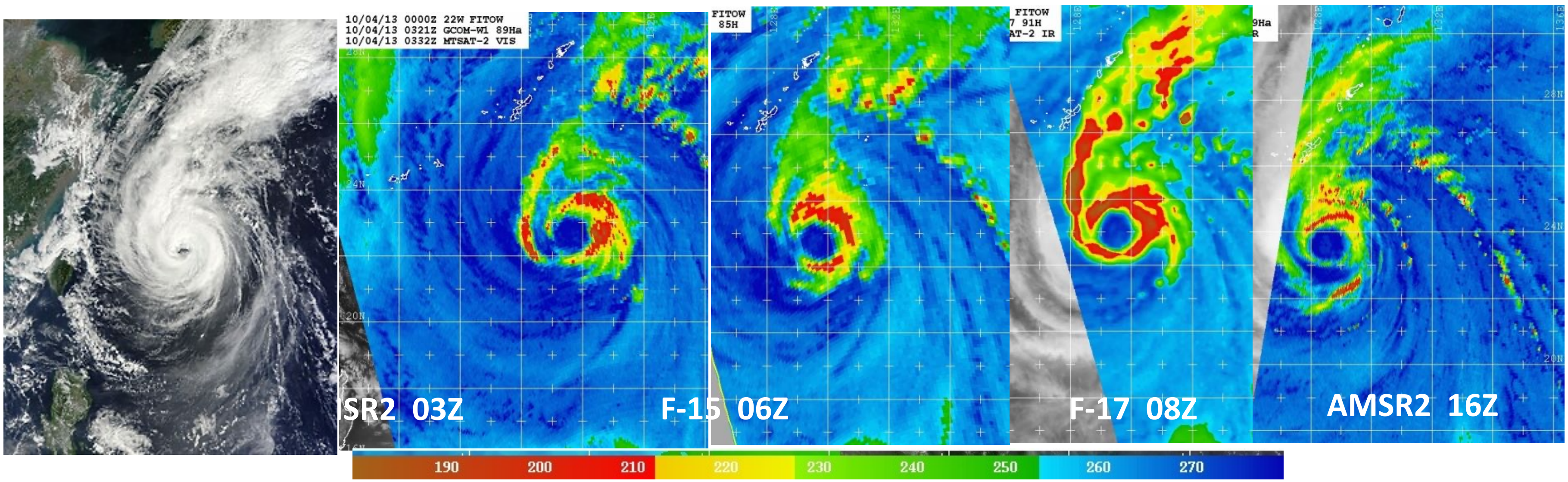


Figures >>Courtesy of Ben Johnson and Isaac Moradi

Motivation

- The proliferation of smallsat microwave constellation is now.
- How well do these constellations compare with ATMS?
- How many do we need for weather forecasting vs nowcasting?
- What noise performance is needed for weather forecasting (NWP)?
- For nowcasting applications, we need to limb adjust.
- For NWP, we need impact studies
- Can we compare different sensor performance using retrievals, if the retrieval methodology is identical?

Microwave imagery is widely used by forecasters



New GCOM AMSR2's large swath and excellent spatial resolution aids JTWC in monitoring Typhoon Fitow near Okinawa and Taiwan straits via 89 GHz brightness temperature imagery

1330 LTAN greatly augments existing constellation TEMPORAL sampling, but much more needed to have sampling similar to geostationary imagery

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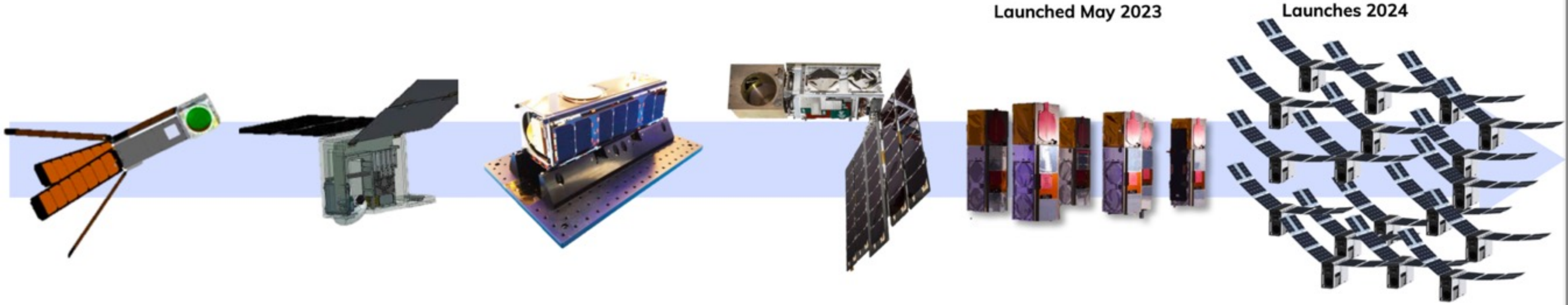
tomorrow.io

Recent Progress in CubeSat Microwave Sounding

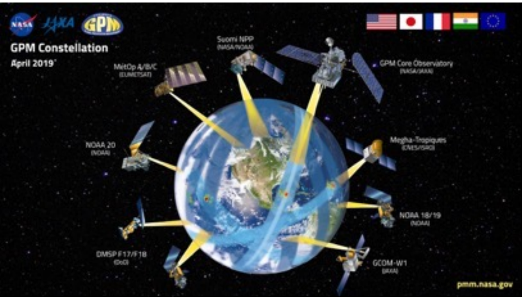
First CubeSat MW sounder demonstration	First "long-life" (3 years) CubeSat MW sounder	First commercial CubeSat MW sounder demonstration	First CubeSat MW sounder to provide a global image	First CubeSat MW sounder constellation demonstration	First commercial CubeSat MW sounder constellation
MicroMAS-2a Deployed Jan 2018	**TEMPEST-D** Deployed May 2018	**OMS GEMS-1** Deployed July 2019	**TROPICS Pathfinder** Deployed June 2021	**TROPICS Constellation** Launched May 2023	**Tomorrow.io Constellation** Launches 2024



T + H_20	H_2O only	T only	T + H_20 + 205 GHz	T + H_20 + 205 GHz High Revisit	T + H_20 + 205 GHz Breakthrough Revisit

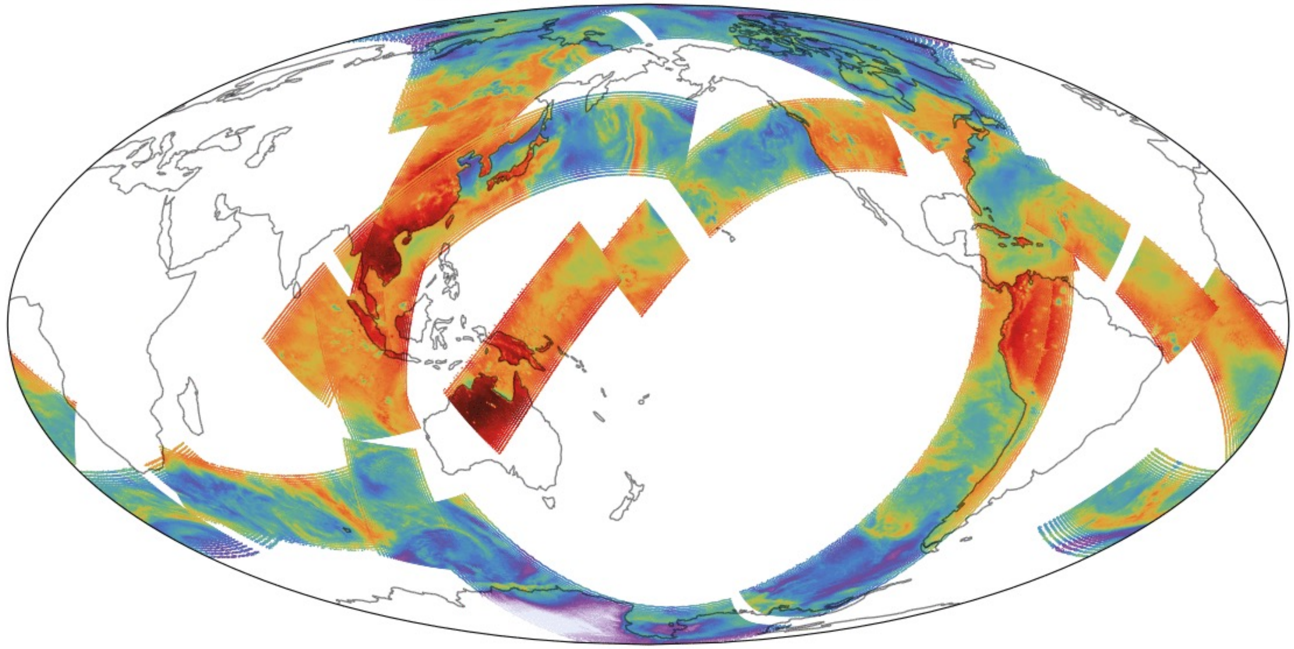
& AWS/PFM (Smallsat)

Courtesy of Bill Blackwell, MIT-LL

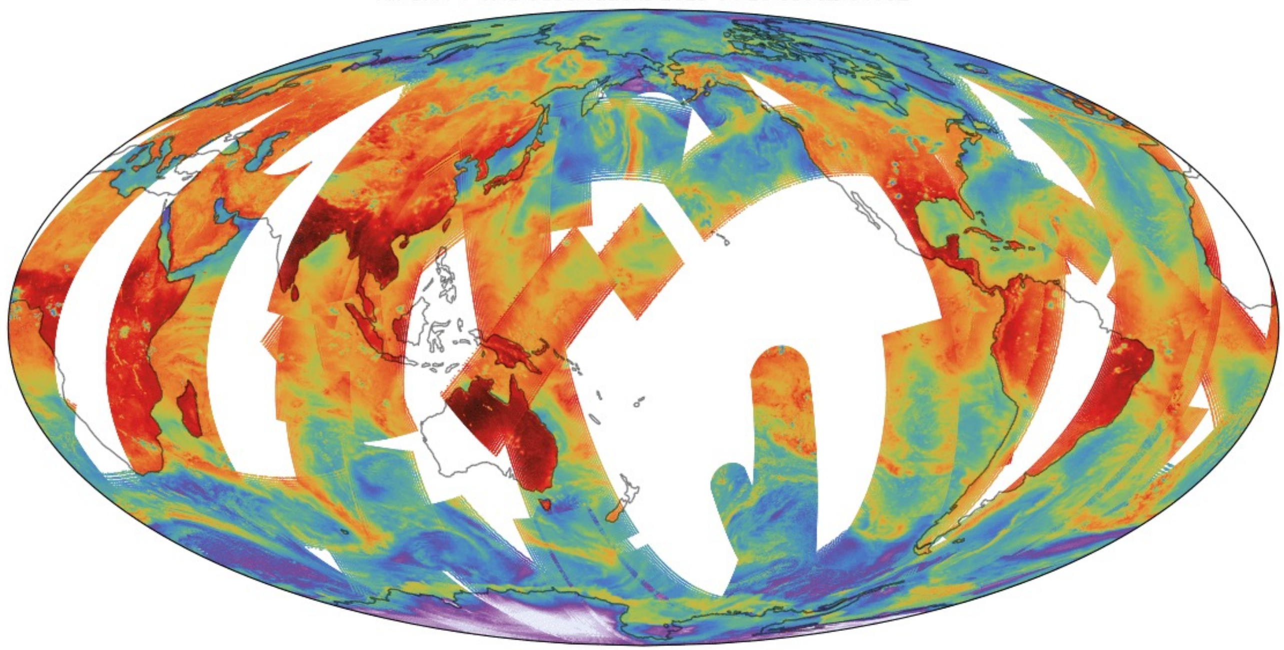


From Joe Munchak
4/23/2025

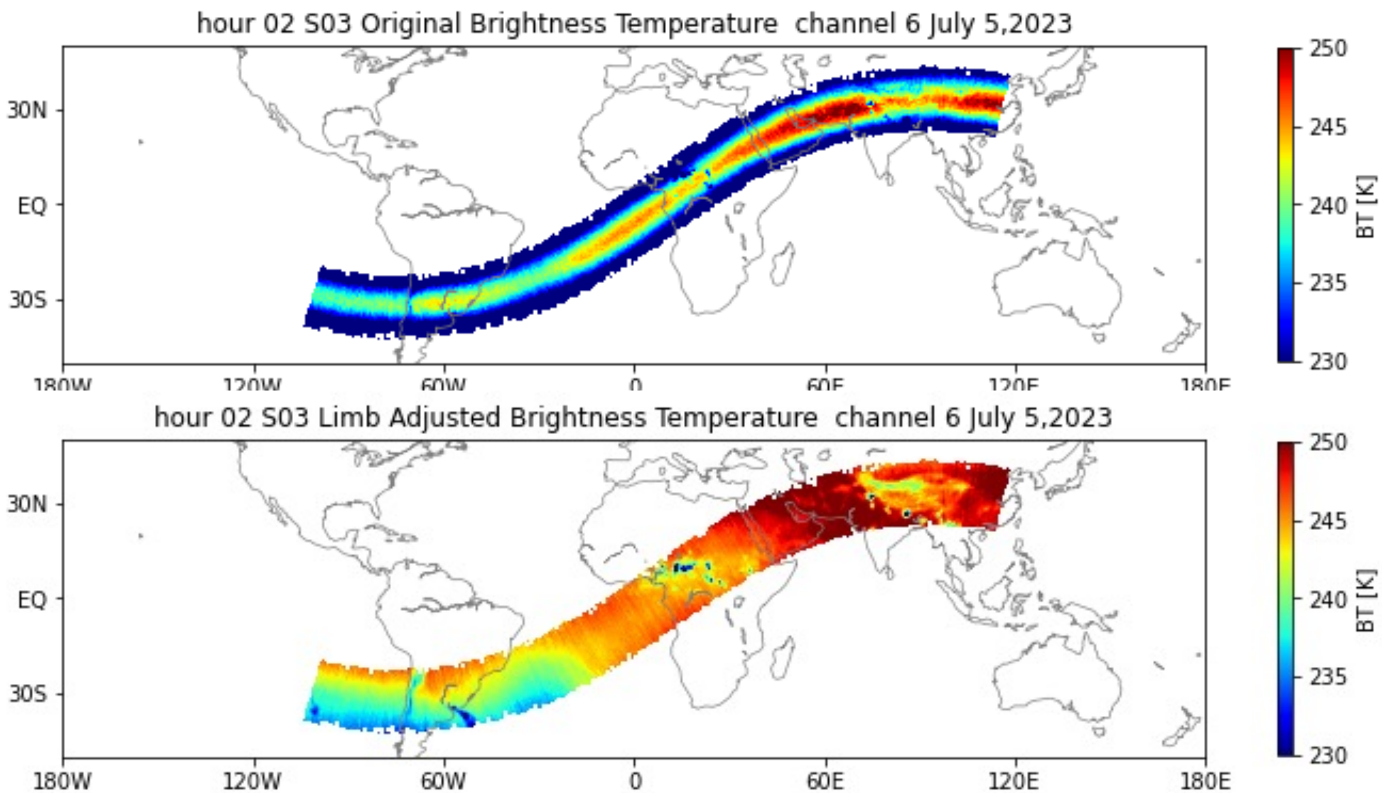
All TMS Observations 2025-04-23 0300Z-0400Z



All GPM + TMS Observations 2025-04-23 0300Z-0400Z



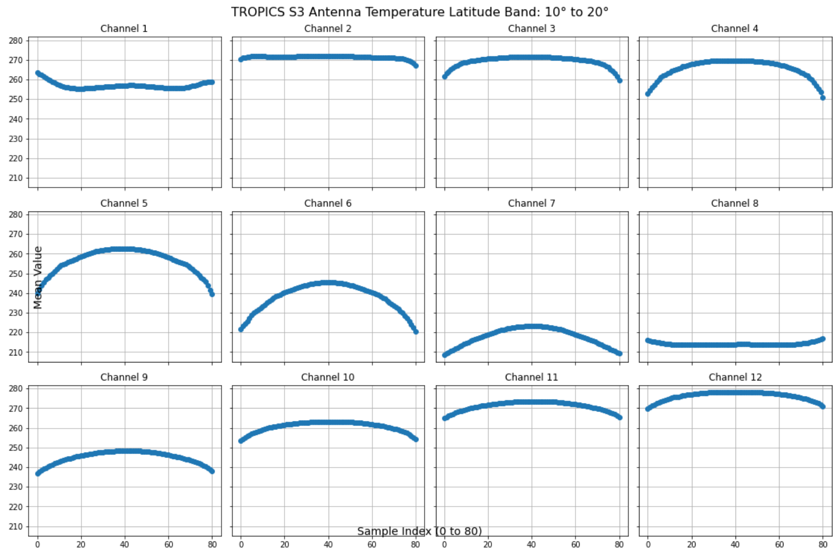
TROPICS S3



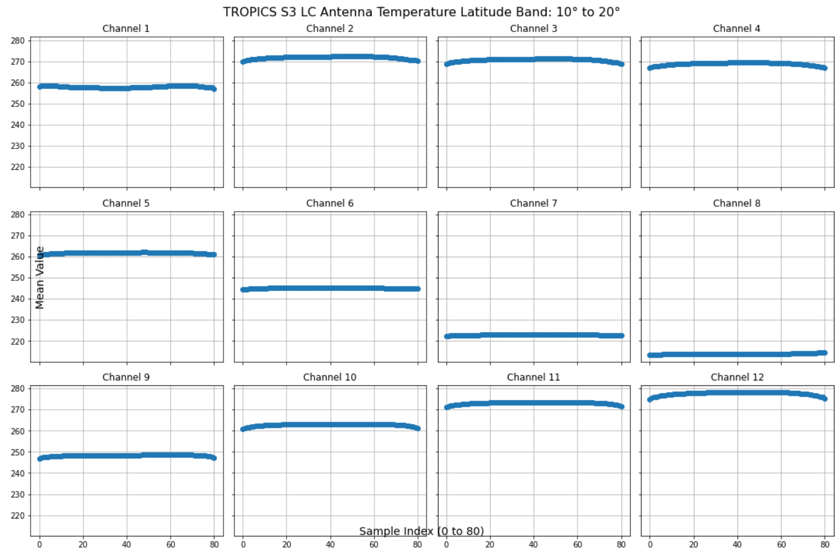
TROPICS Limb Adjustment is based on Goldberg, M.D., D.S. Crosby, and L. Zhou, 2001: The limb adjustment of AMSU-A observations: methodology and validation , Journal Appl. Meteor, 40, 70-83. https://journals.ametsoc.org/view/journals/apme/40/1/1520-0450_2001_040_0070_tlaoaa_2.0.co_2.xml

TROPICS S3

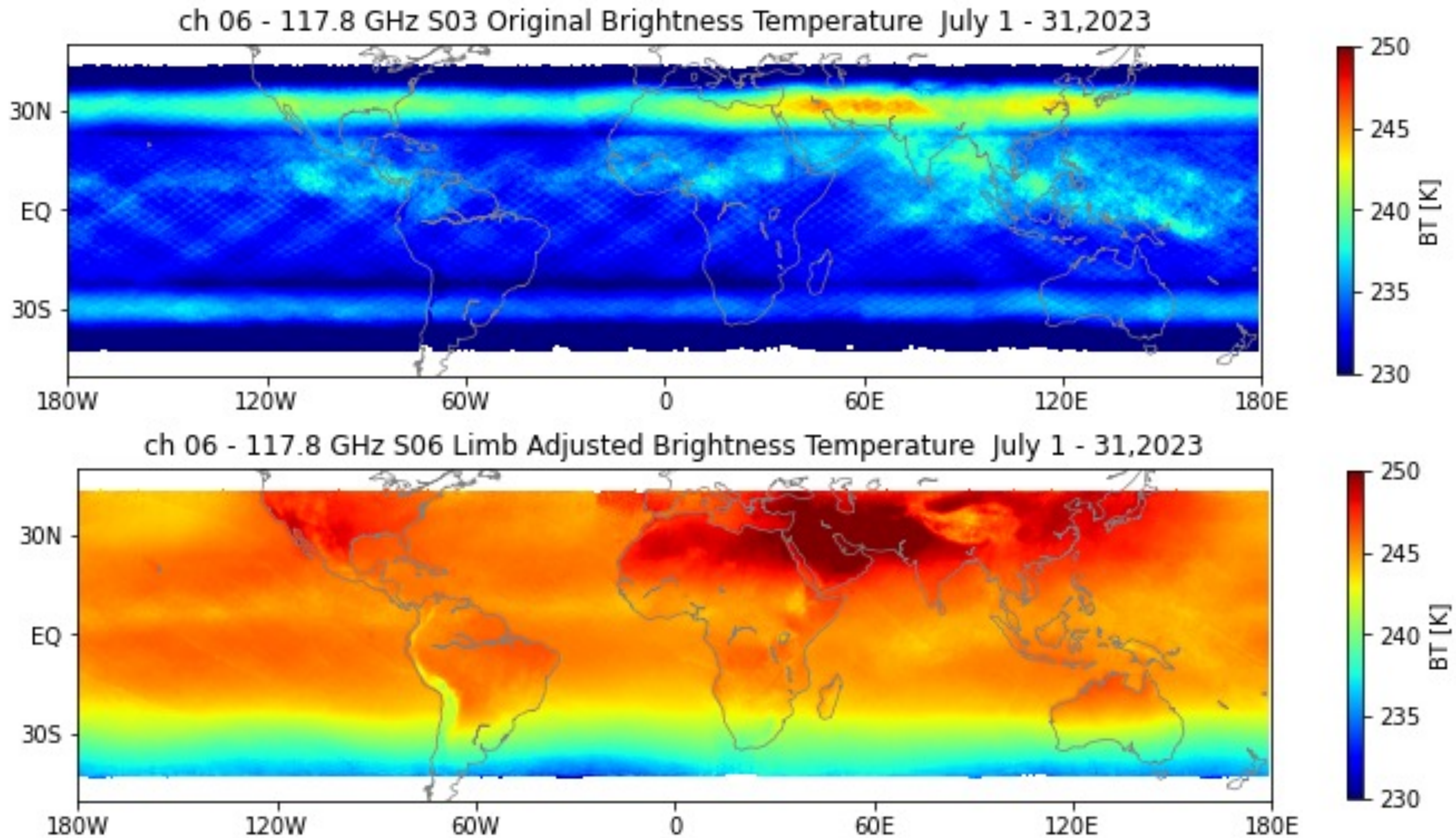
Original Brightness Temperature



Limb Adjusted Brightness Temperature

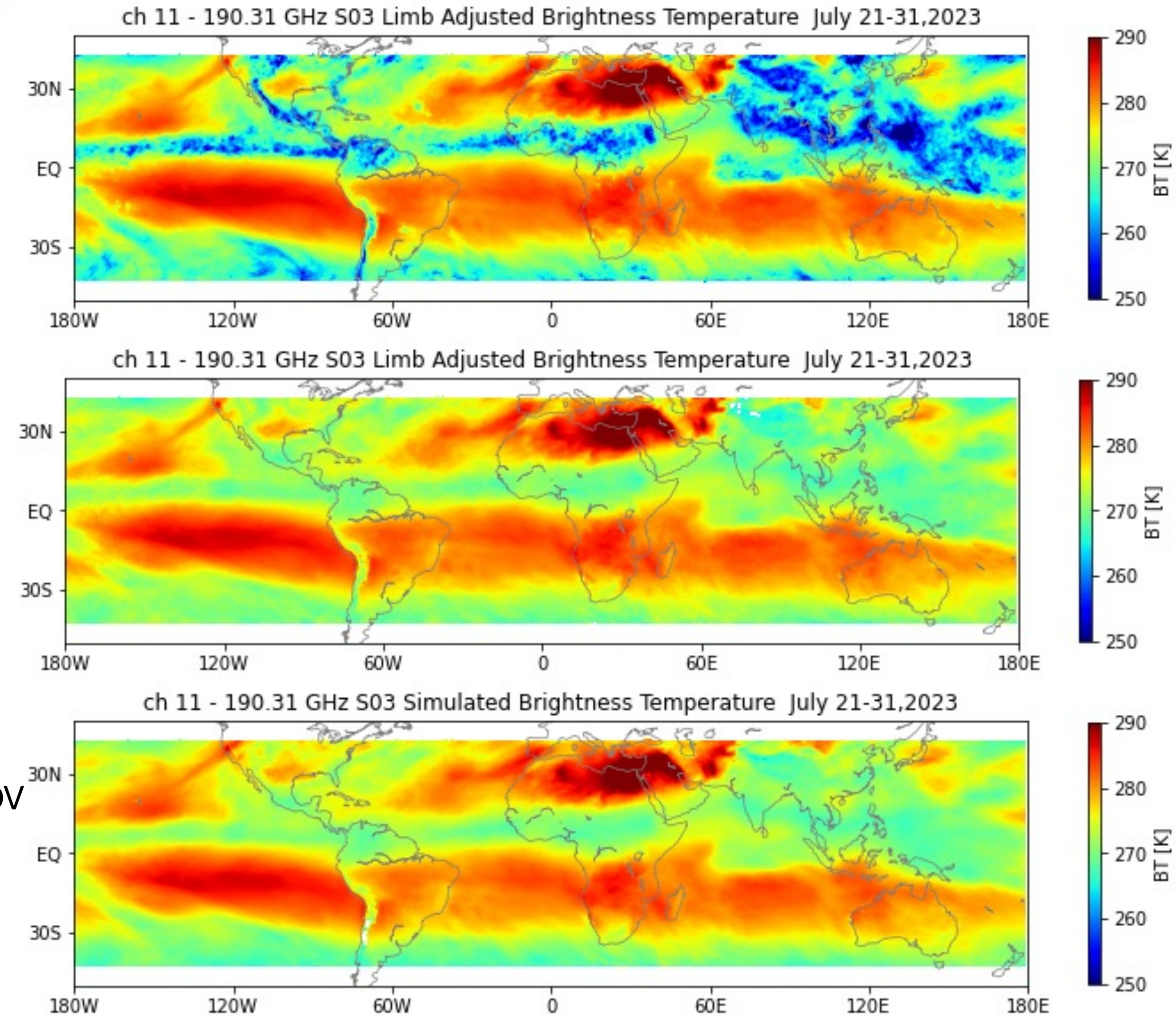


TROPICS S3



ch 06 - 117.8 GHz S03 Original Brightness Temperature July 1 - 31,2023
30N
EQ
30S
180W
120W
60W
0
60E
120E
180E
250
245
240
235
230
BT [K]
ch 06 - 117.8 GHz S06 Limb Adjusted Brightness Temperature July 1 - 31,2023
30N
EQ
30S
180W
120W
60W
0
60E
120E
180E
250
245
240
235
230
BT [K]

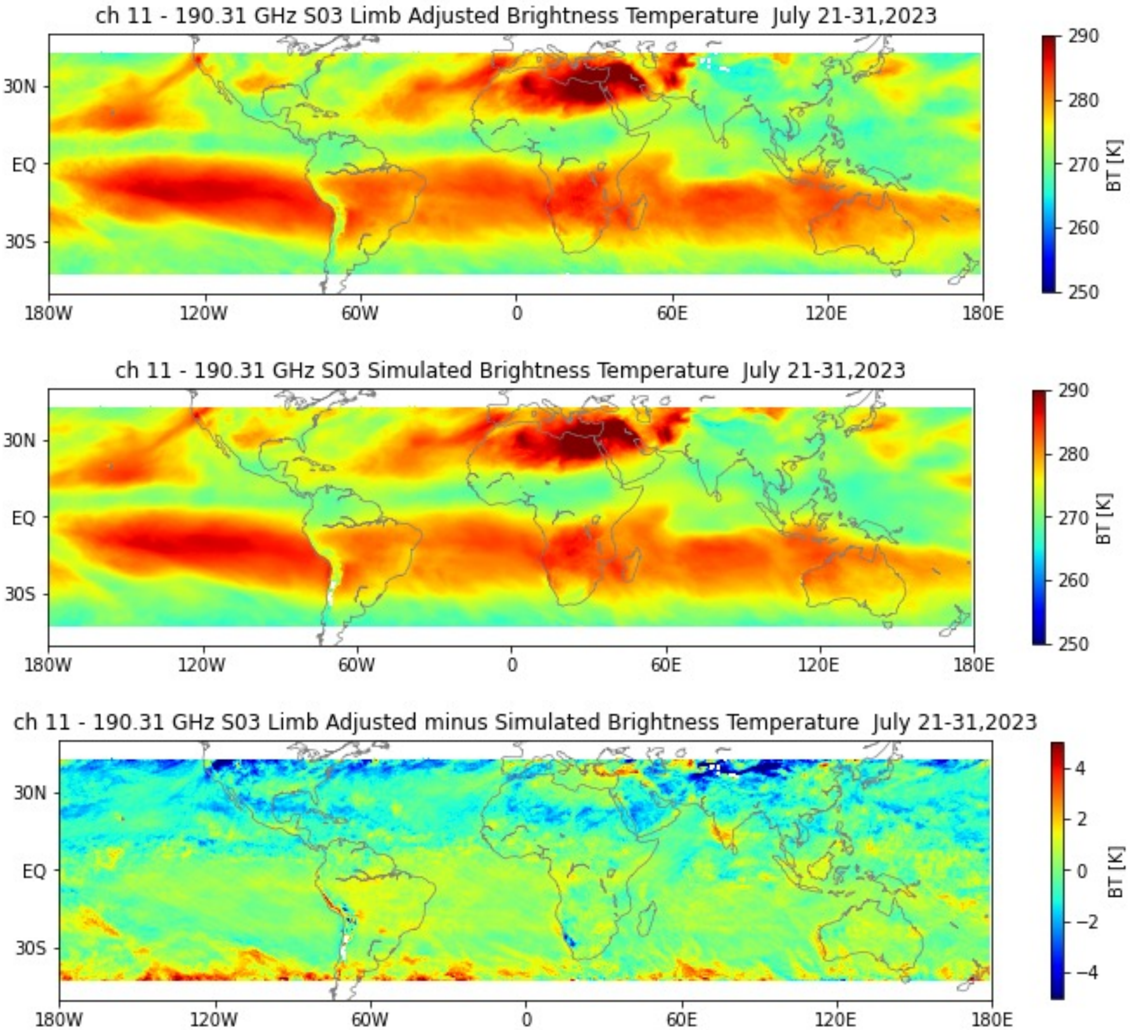
TROPICS S3



Simple precipitation removal: only keep $btemp_{(channel\ 11)} > 263$ K

Simulated using RTTOV
And ECMWF ERA5

TROPICS S3


ch 11 - 190.31 GHz S03 Limb Adjusted Brightness Temperature July 21-31,2023
ch 11 - 190.31 GHz S03 Simulated Brightness Temperature July 21-31,2023
ch 11 - 190.31 GHz S03 Limb Adjusted minus Simulated Brightness Temperature July 21-31,2023
30N
EQ
30S
180W
120W
60W
0
60E
120E
180E
BT [K]
290
280
270
260
250
4
2
0
−2
−4

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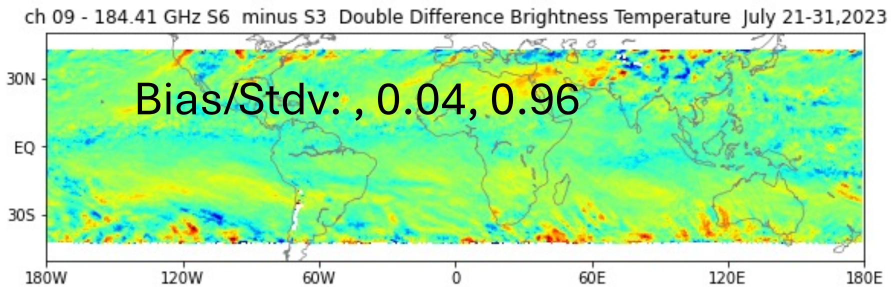
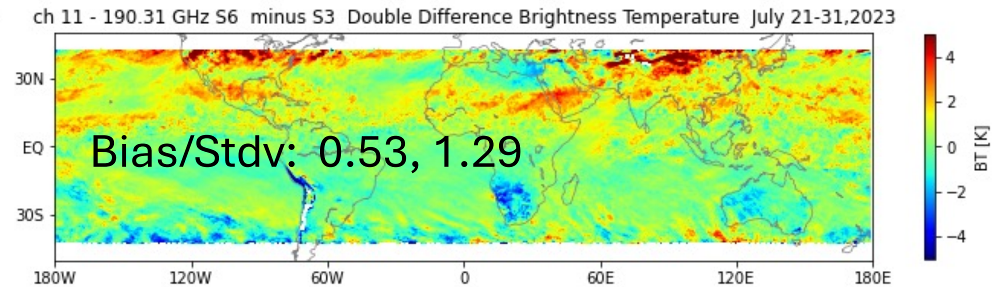
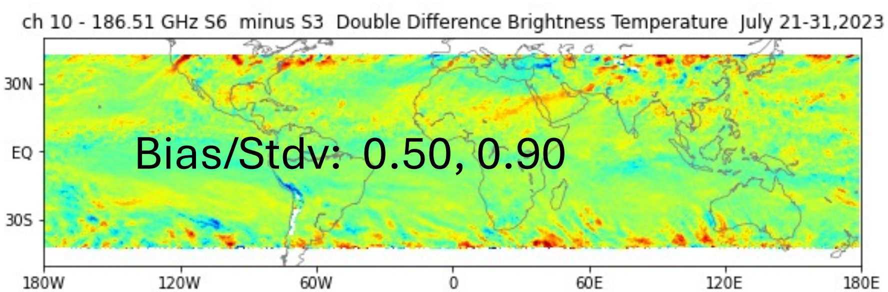
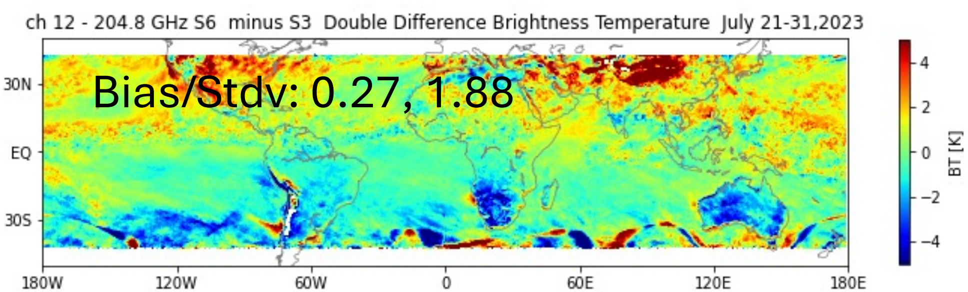
TROPICS S6 minus S3 – Double Difference

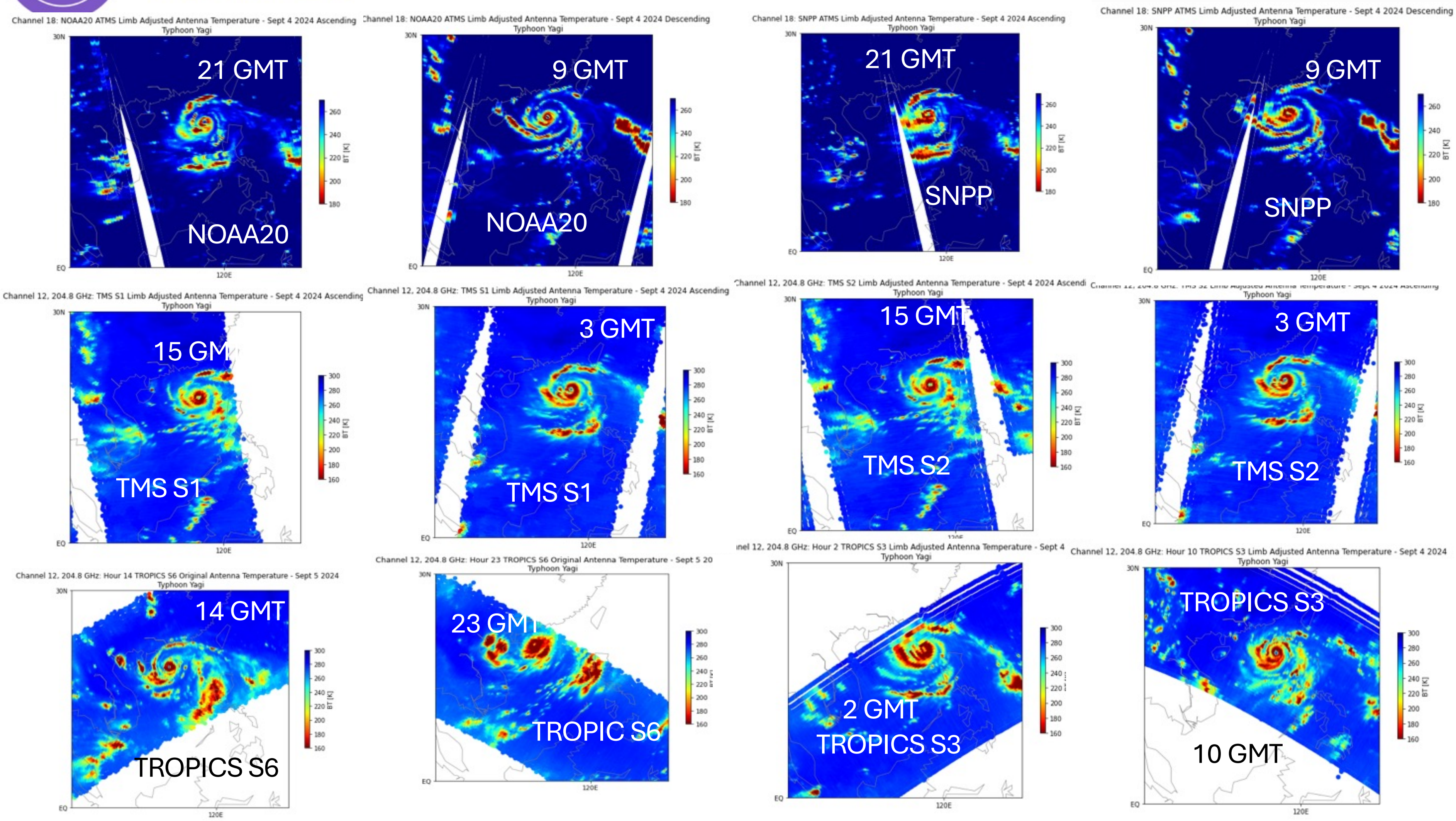


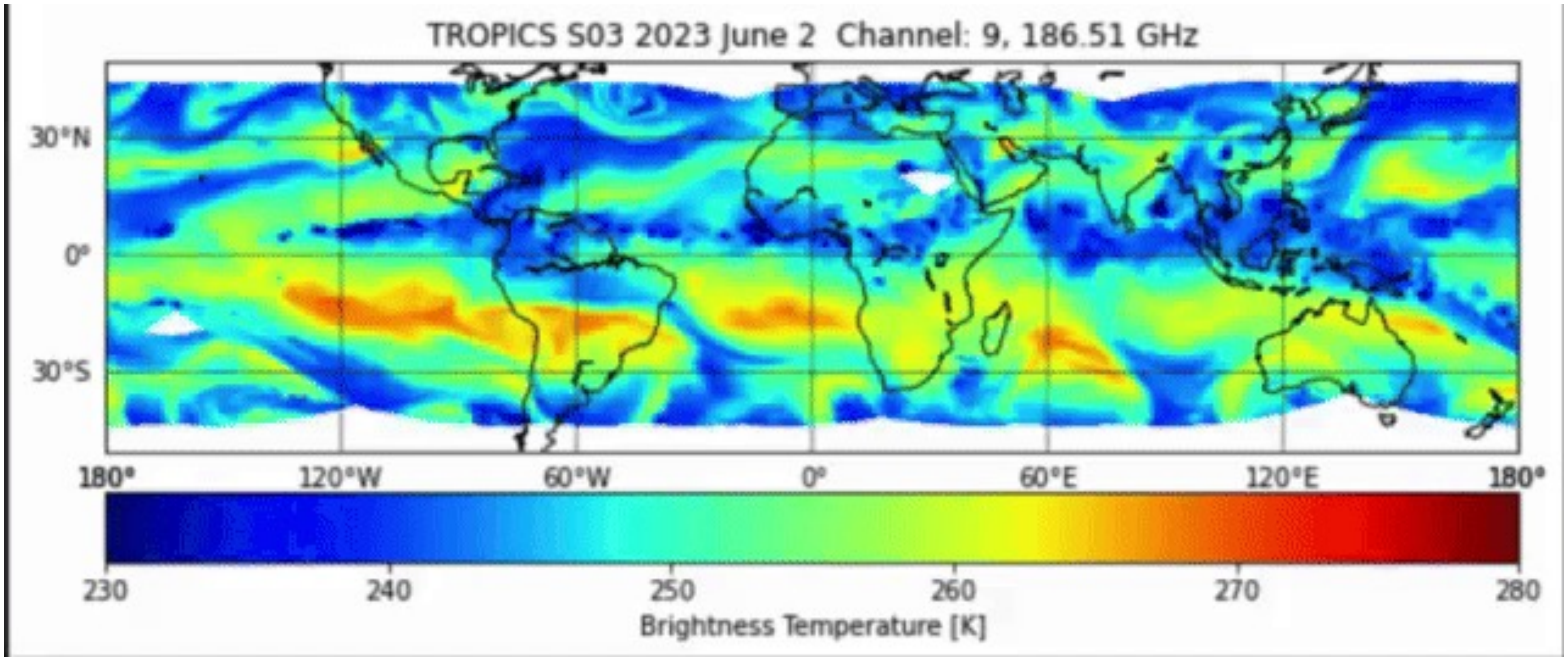






Typhoon Yagi- September 4, 2025





With a large constellation, imagine every 30 minutes instead of these daily animations

Sensor comparisons

- For this experiment – we compare ATMS, TMS, AWS/PFM
- Compare weighting functions and instrumental noise
- Developed an independent method to estimate instrumental noise
- For all sensors we use the same time period. We use 3/21 to 3/30/2025
- We use the data collection period to generate limb adjustments, similar to the methodology first developed by Goldberg et al.(2000) for AMSU and updated by Zhang et al (2017) for ATMS.
  - https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017JD026820
- Note AWS has 145 fovs per scanline. We skipped every other one (72), we ran one experiment averaging a 3x3 center for each primary 72 fov to reduce noise and assess the impact
- Retrievals are based on polynomial regression.

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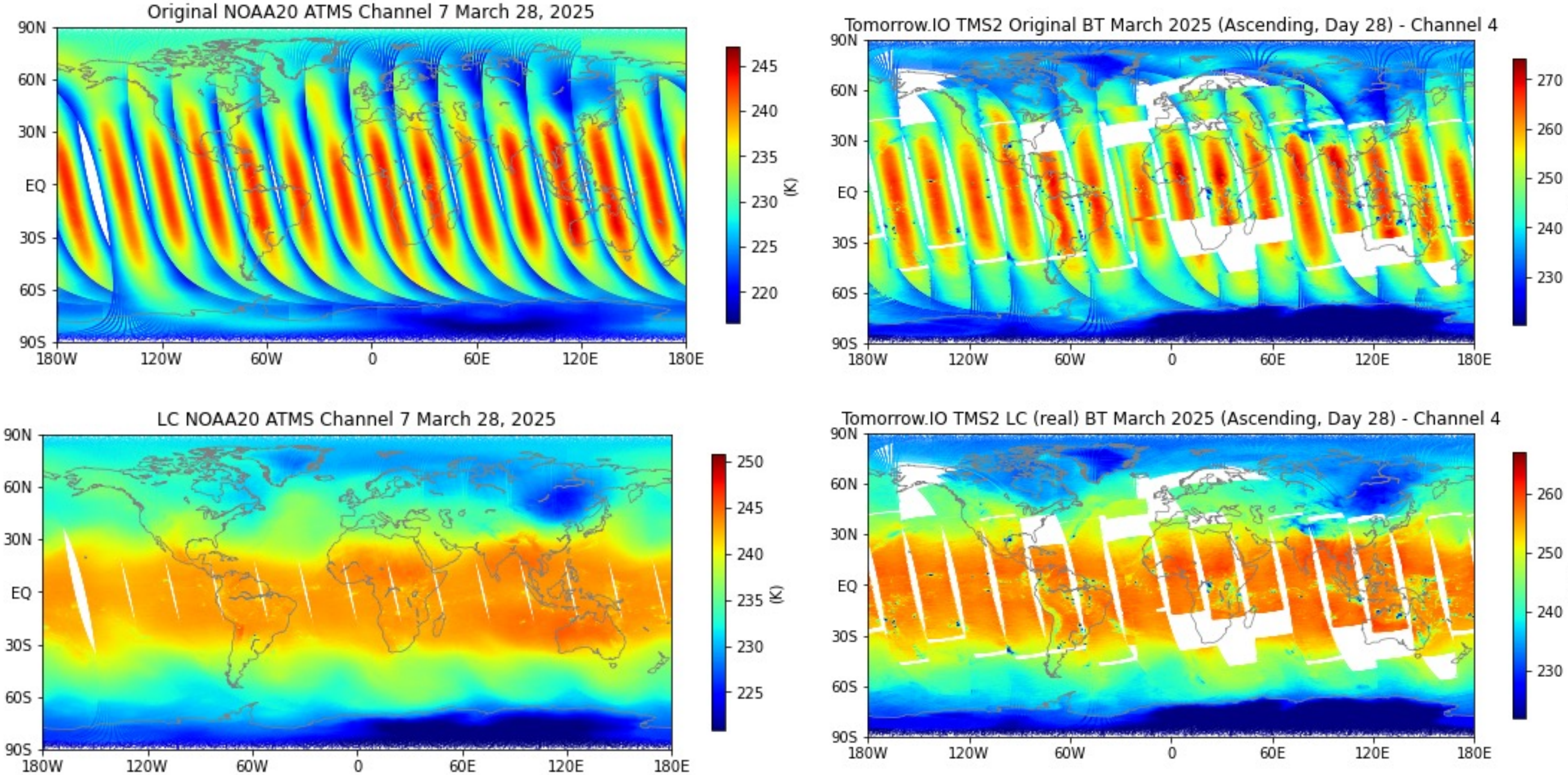
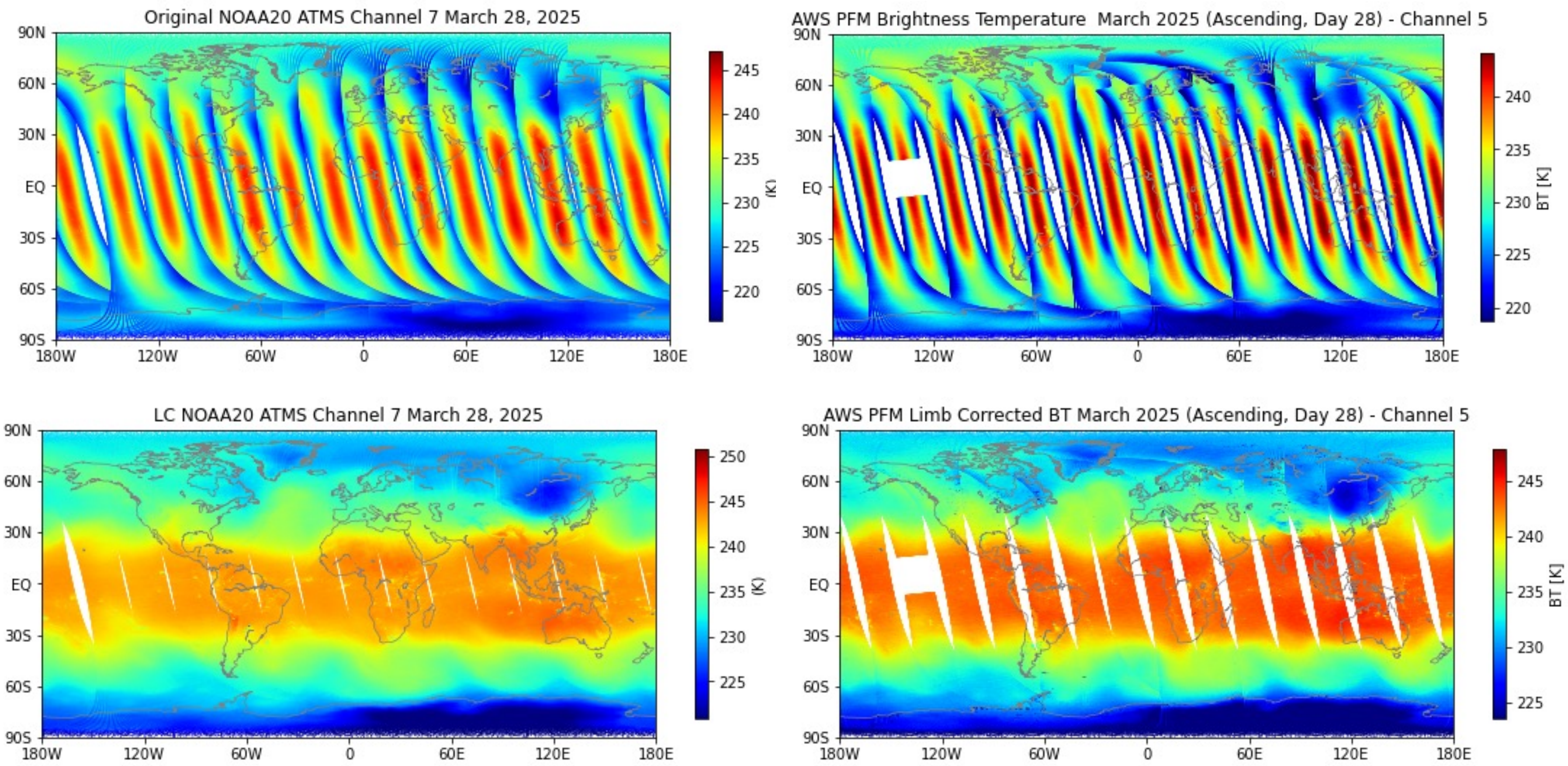
Example of ATMS\TMS Limb Adjustment – Temperature Channel



Example of ATMS/AWS Limb Adjustment - Temperature Channel



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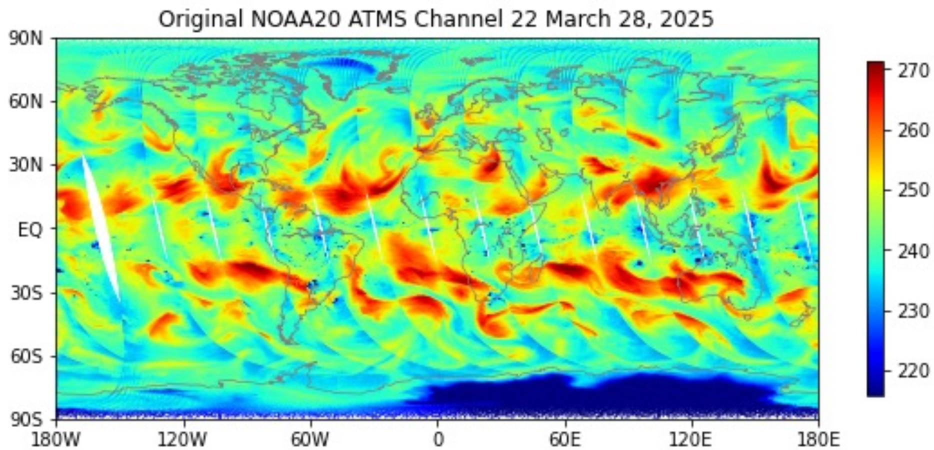
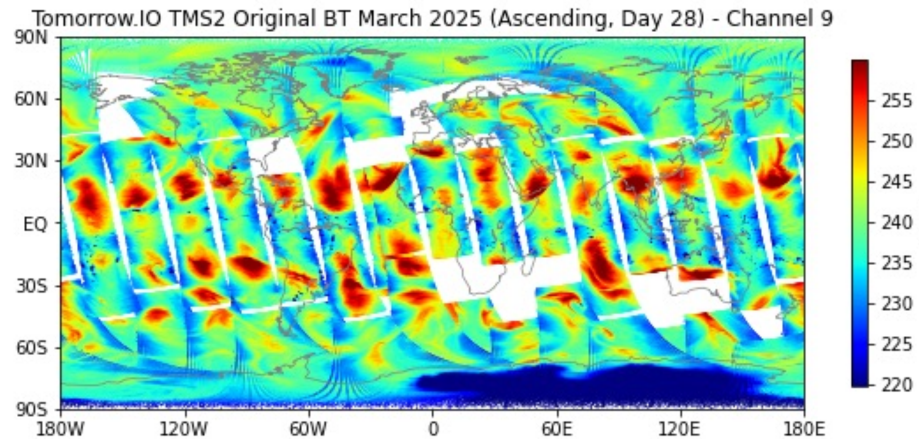
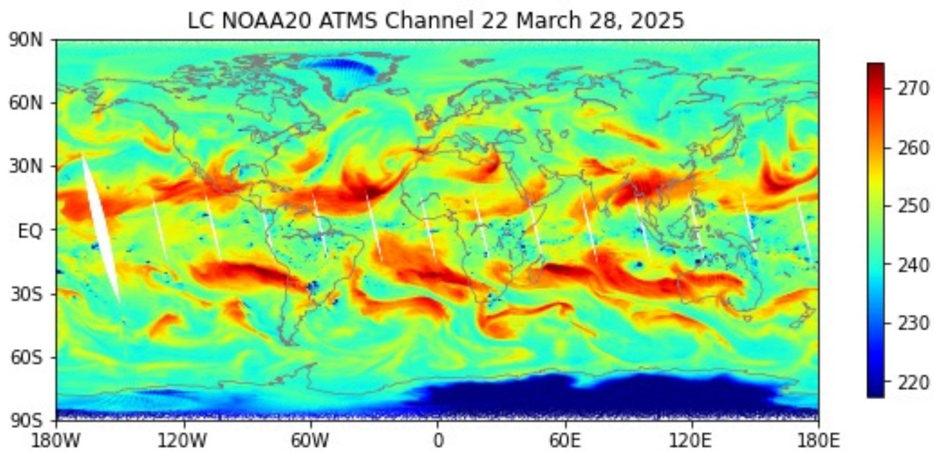
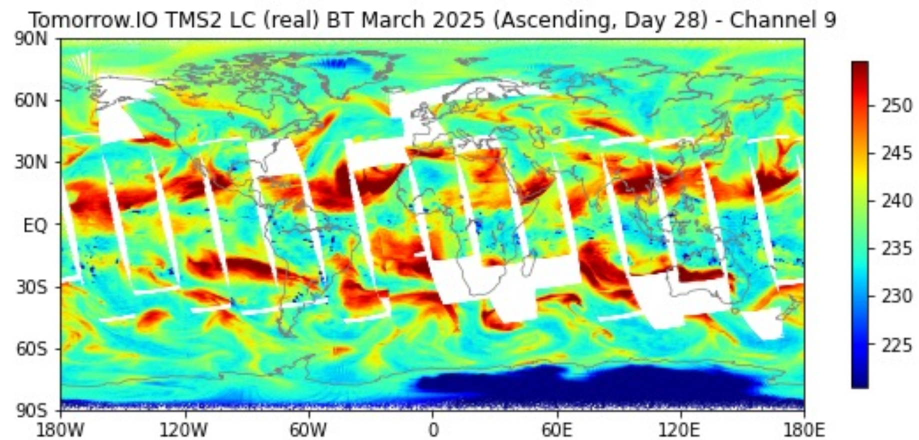
Example of ATMS\TMS Limb Adjustment – Water Vapor Channel

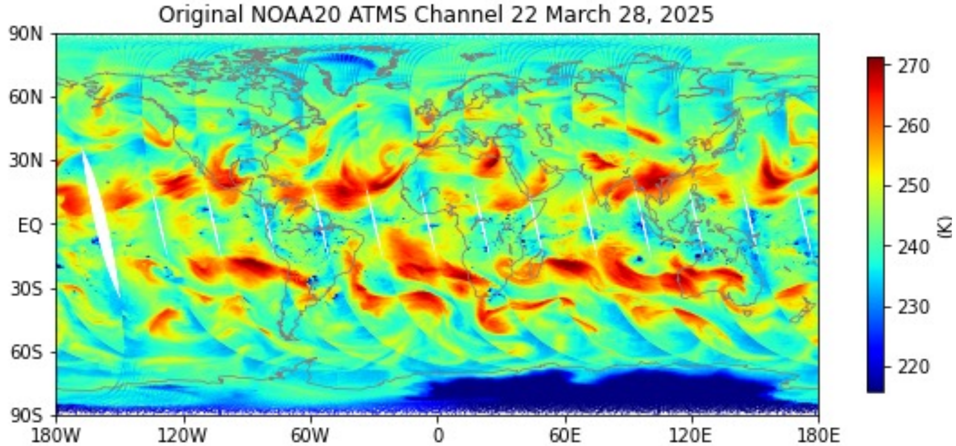


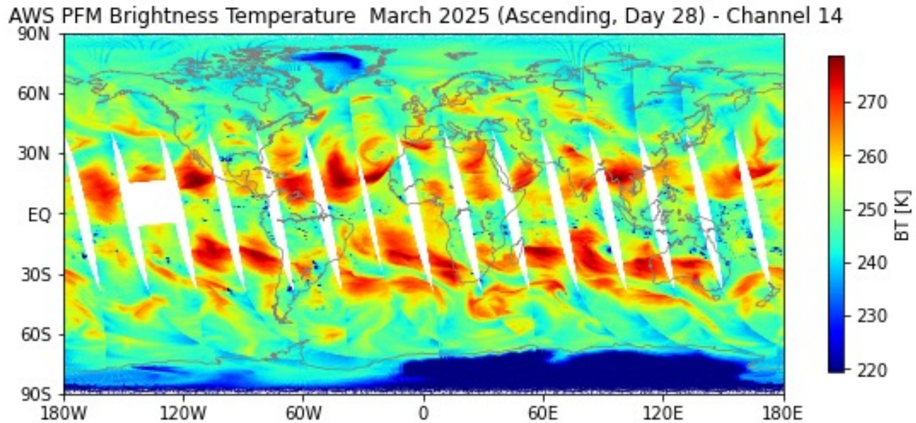


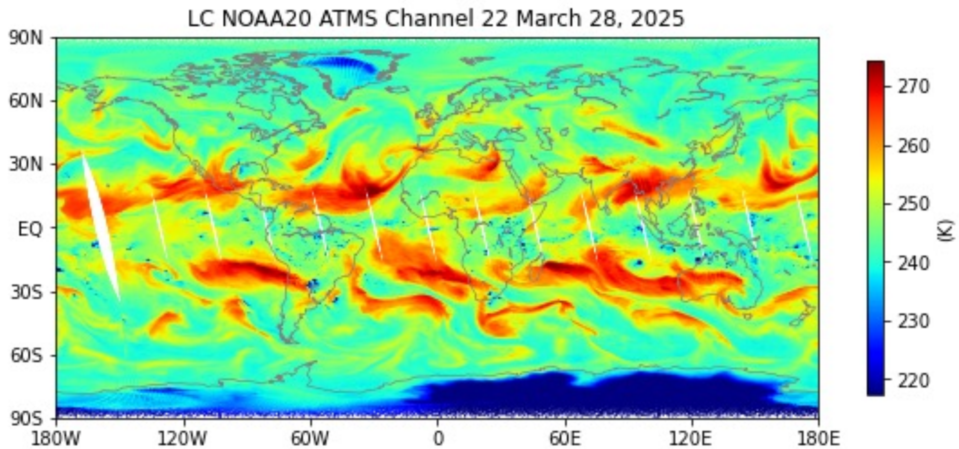


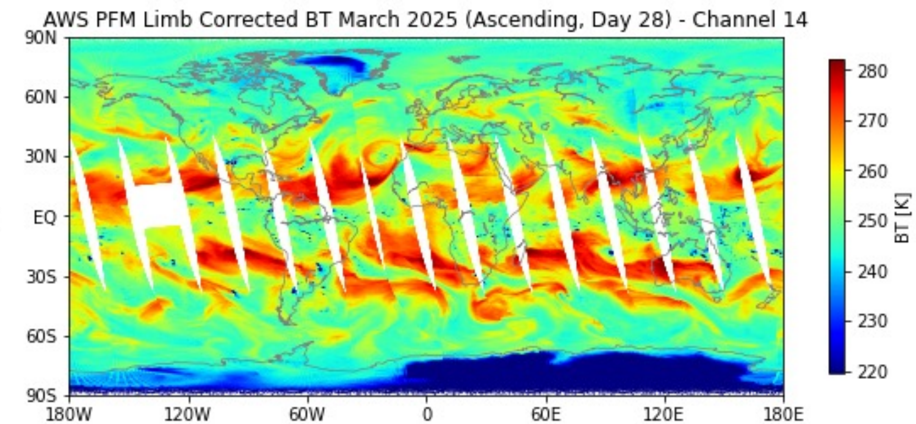


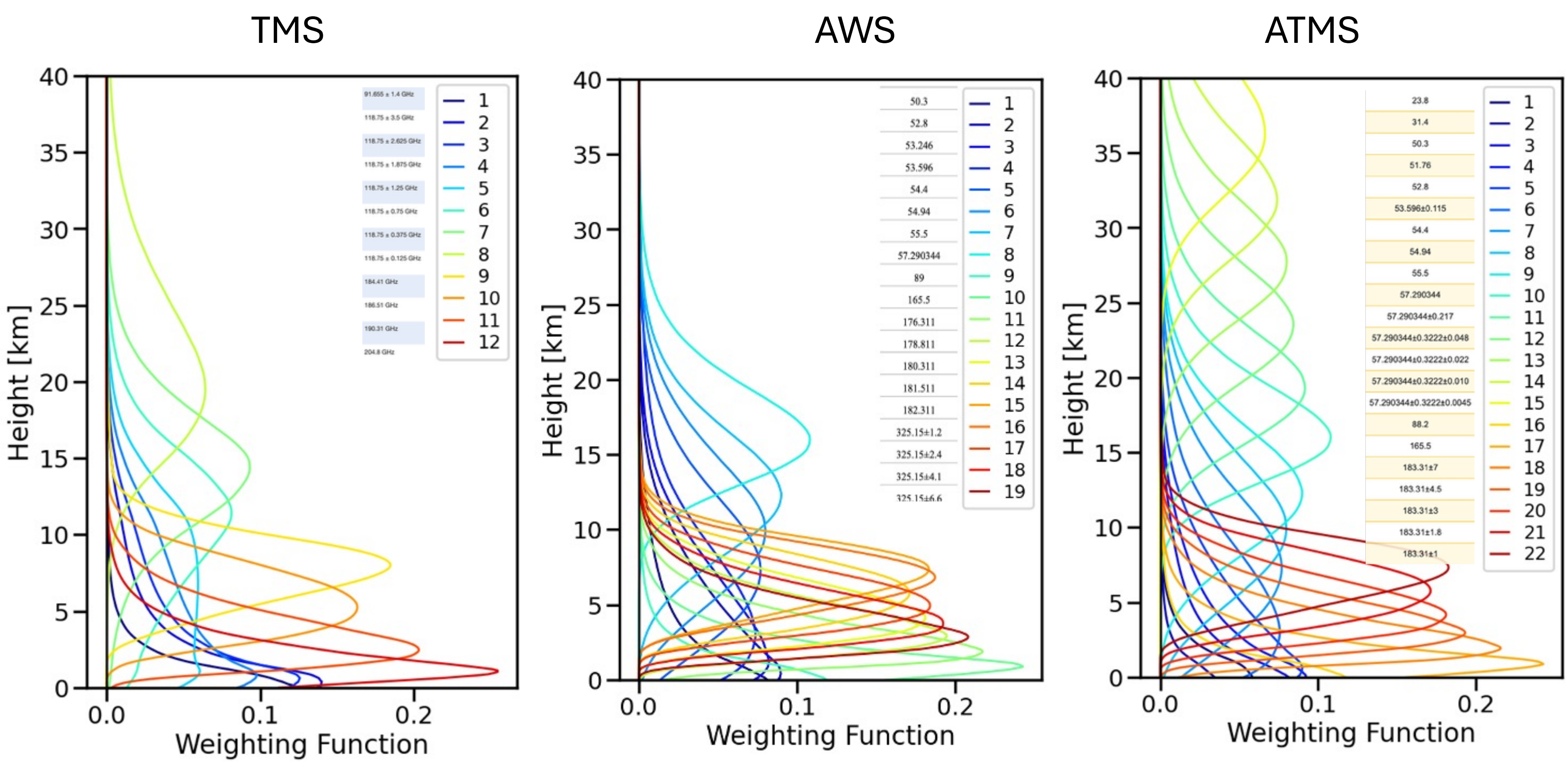
Example of ATMS\AWS Limb Adjustment – Water Vapor channel









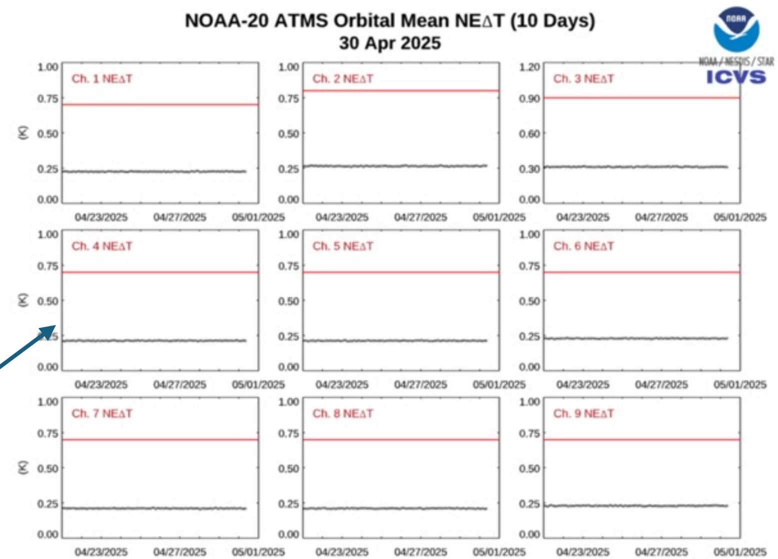


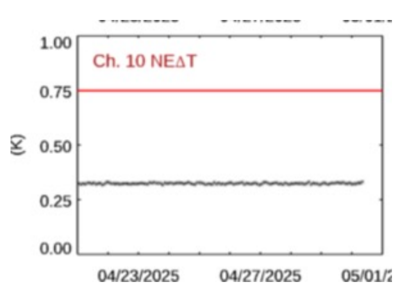
Courtesy of Ben Johnson and Isaac Moradi

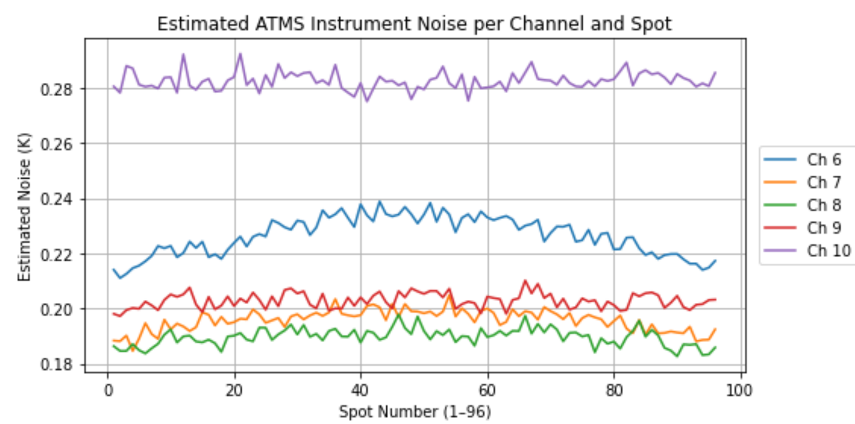
Noise estimation

- Independently estimated noise, by only selecting data over ocean, total column rain water (tcrw) =0 and total cloud cover < 0.2 and within latitude range of -30 to 30. And computing the square root of the sum of the squared differences between adjacent scanlines as a function of spot (fov) number and then divide by square root of 2.

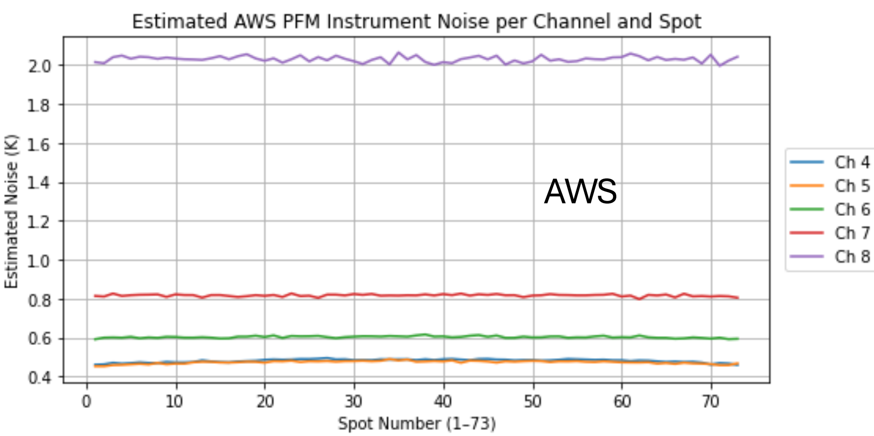
- Notice - ATMS noise is so much better than the specification.

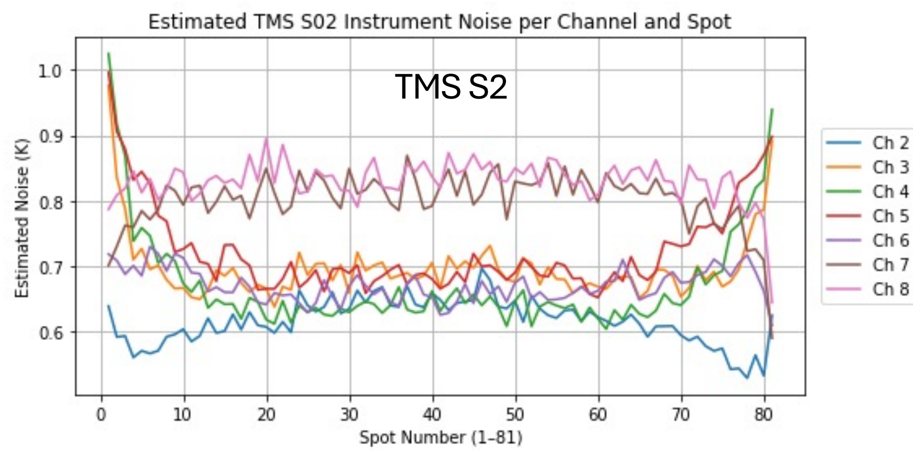




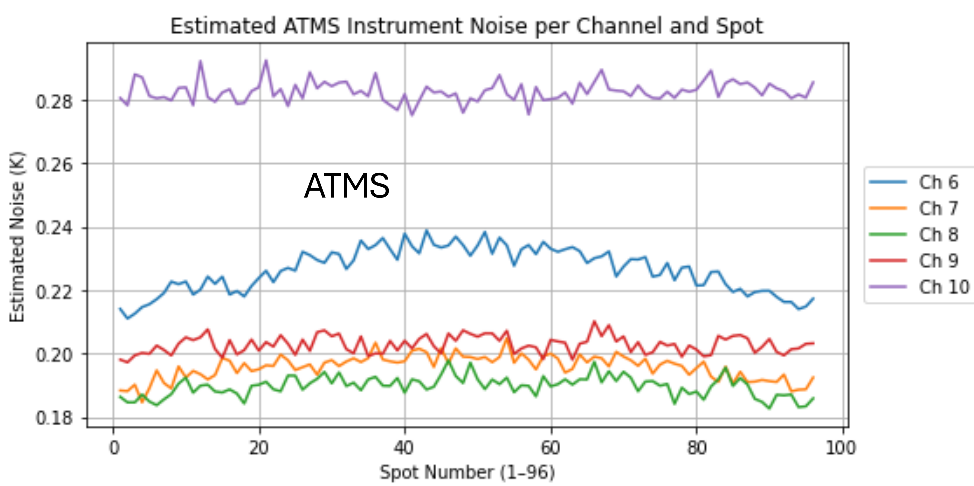


Temperature channels





The AWS channels similar to ATMS channels have higher noise



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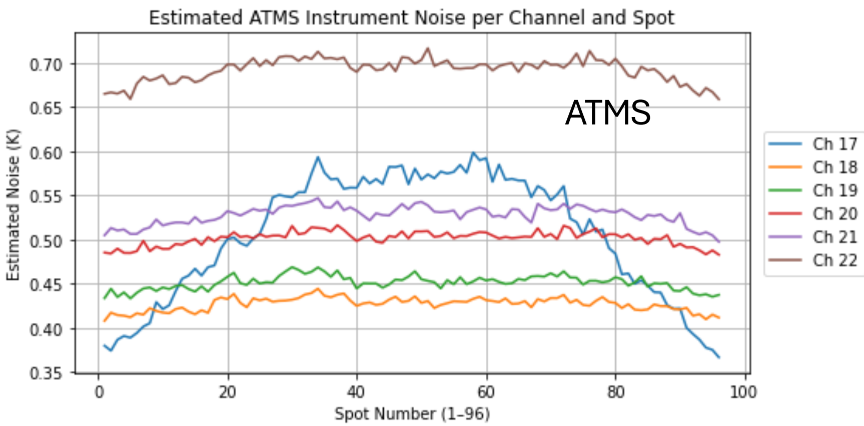
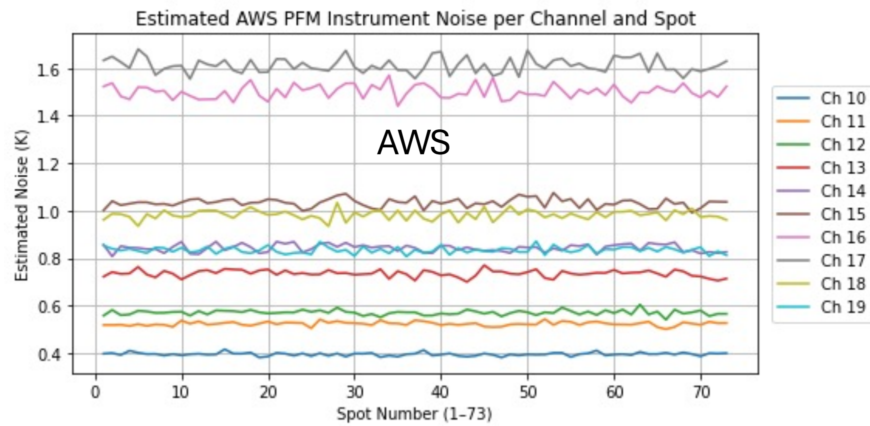
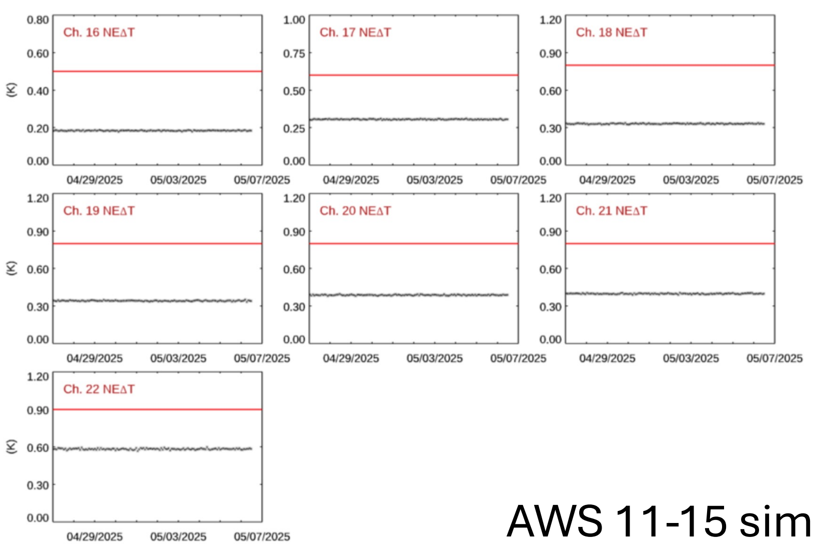
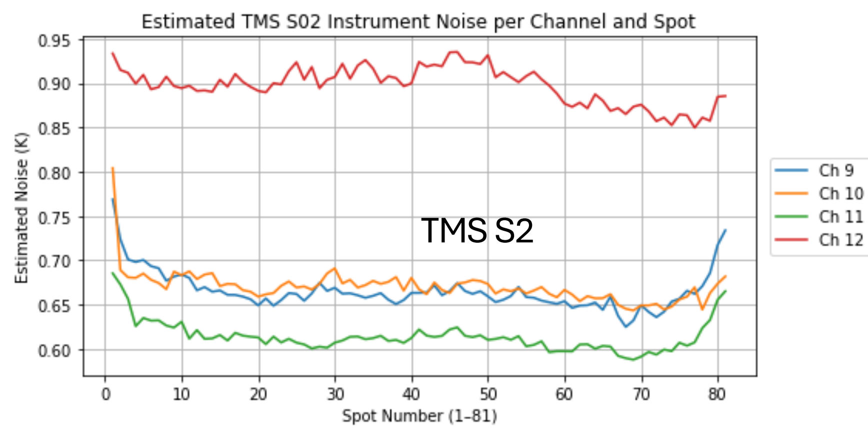
Water Vapor Channels





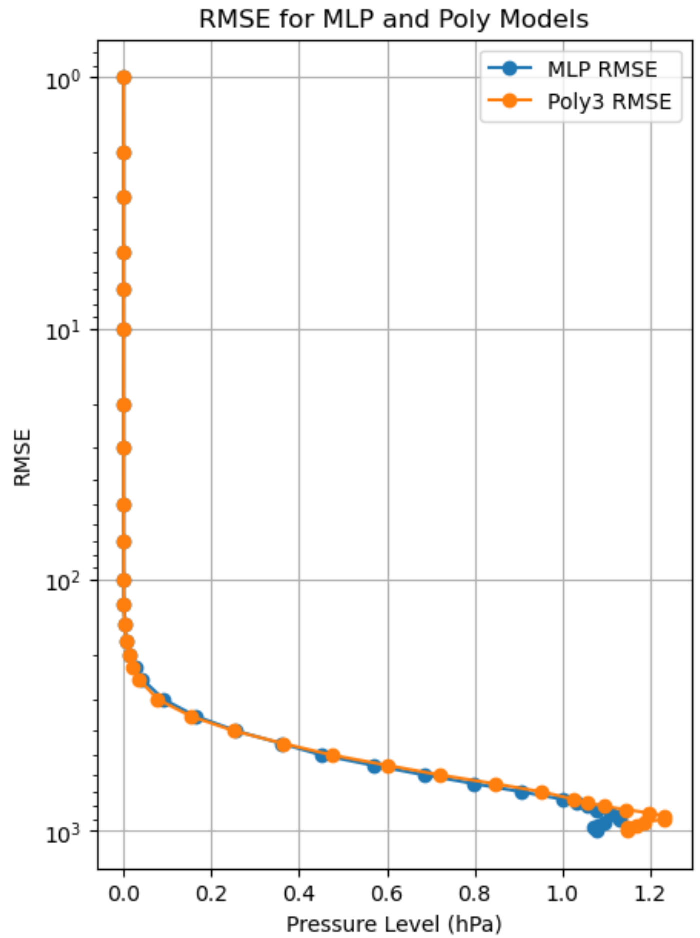




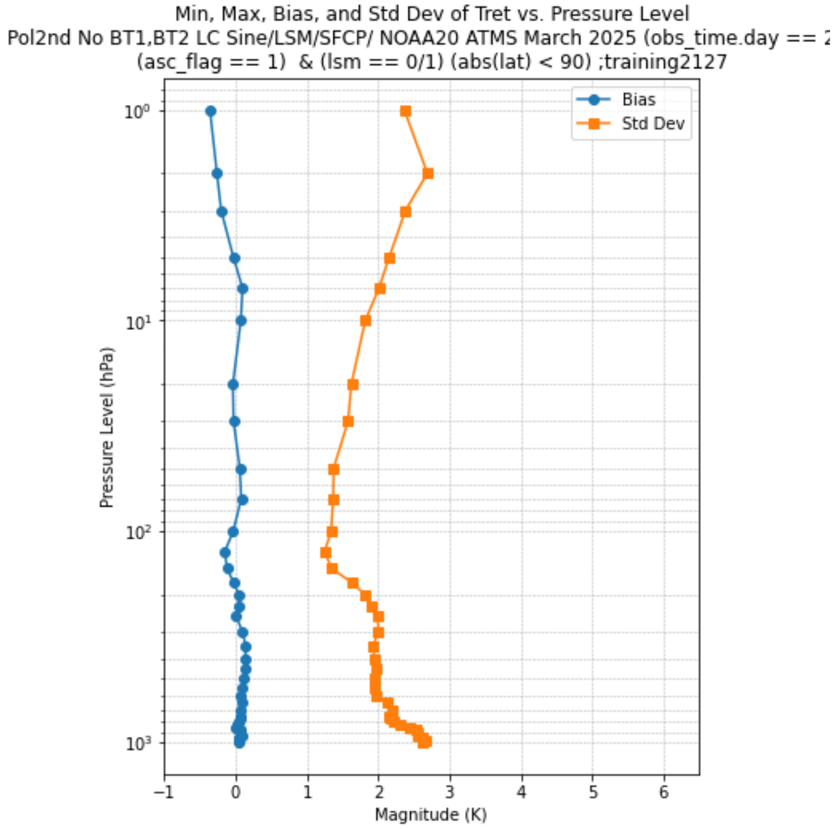
AWS 11-15 similar to ATMS 18-22, ATMS has lower noise

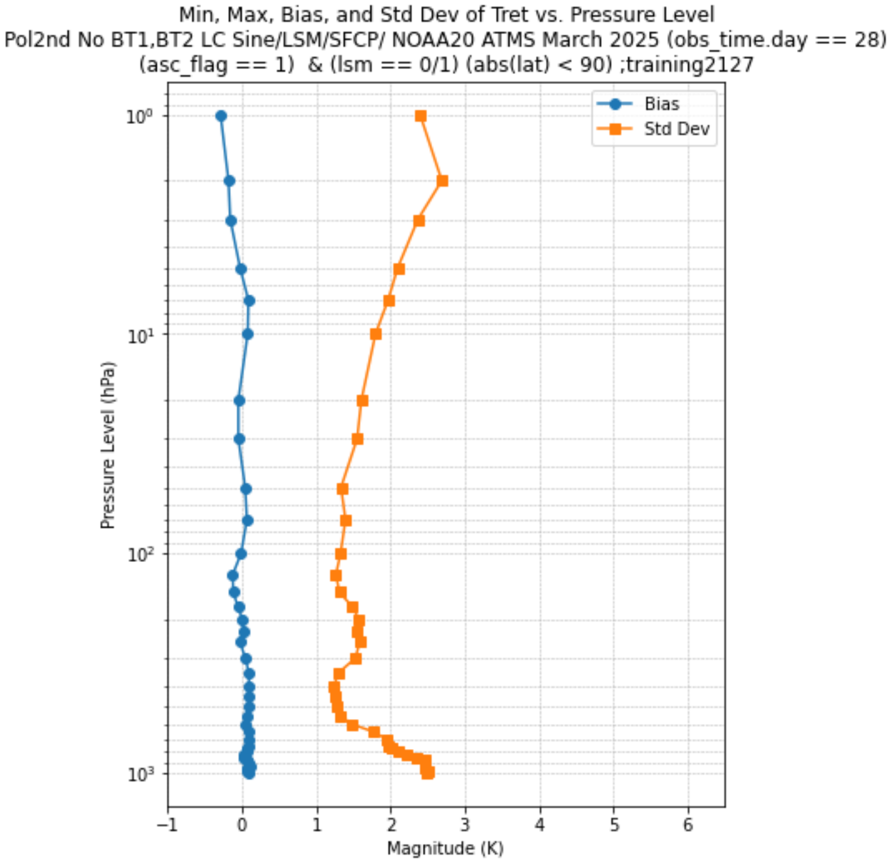
Retrieval Methodology

- Trained against ECMWF Reanalysis for period of March 21 to 27, and apply to March 28, 2025
- Polynomial regression, 2nd order for temperature and 3rd order for water vapor works extremely well – compares to unsupervised neural nets with 3 hidden layers (64,128,64) learning rate .0001 and 50 epochs iterations.
- Polynomial regression is much faster to run different experiments.
- For temperature we found using limb adjusted data is much better.



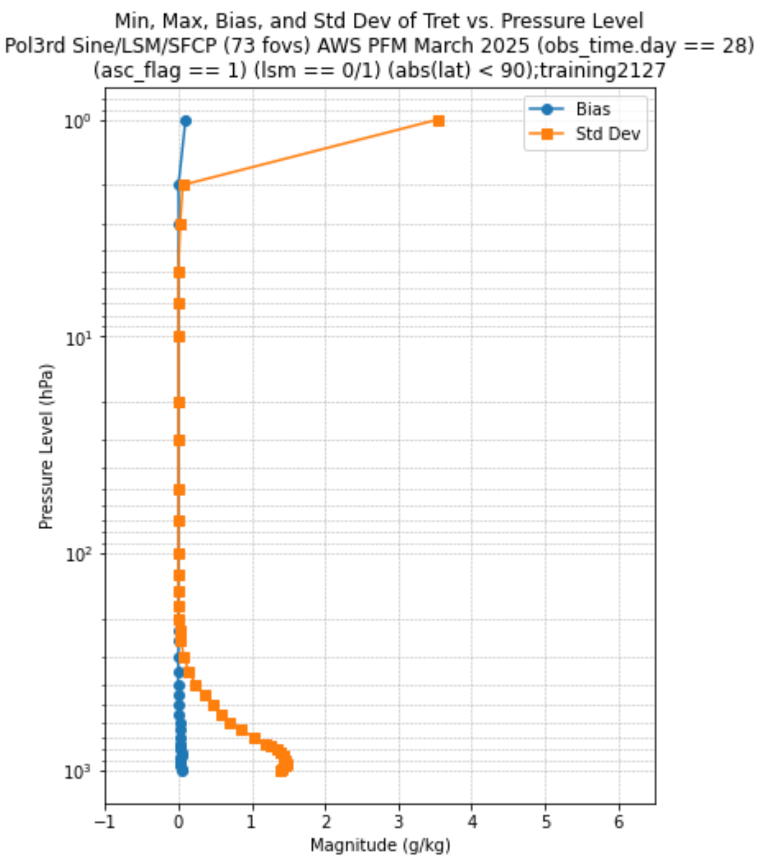
NO LIMB ADJ. With LIMB ADJ.



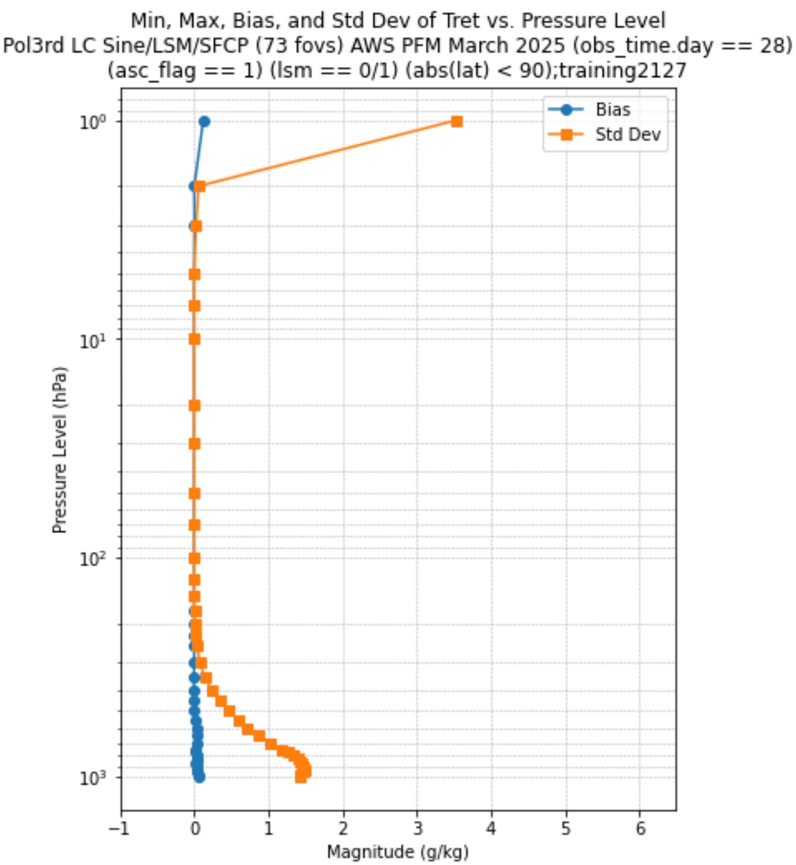


Water Vapor

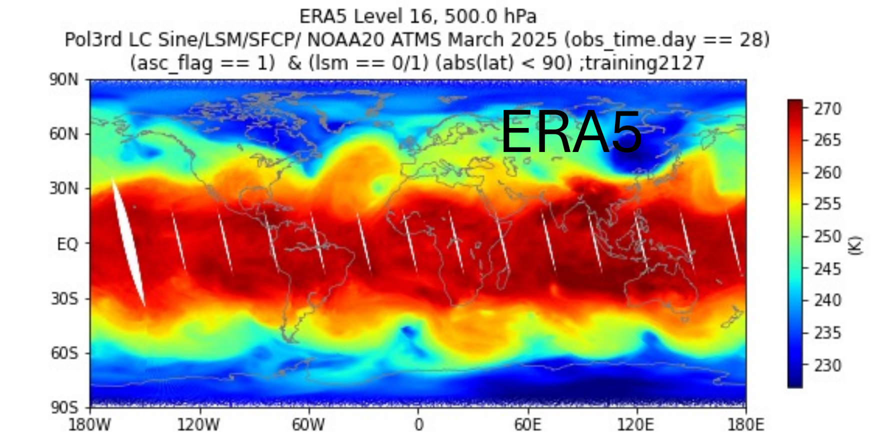
NO LIMB ADJ.

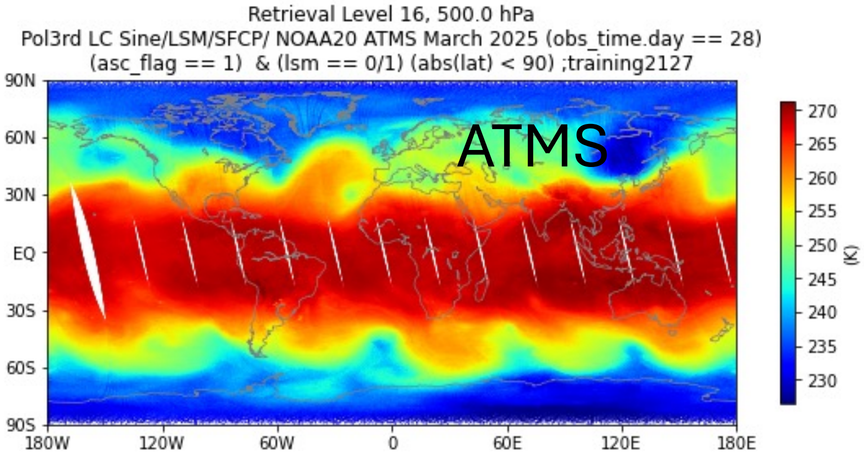


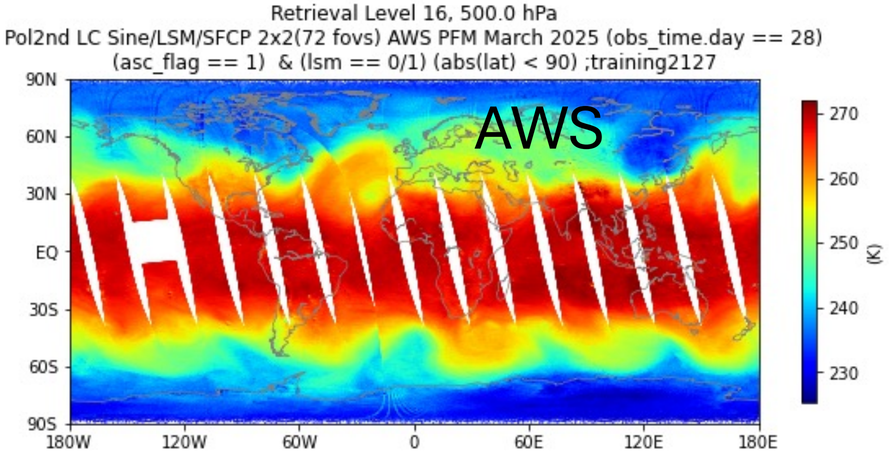
With LIMB ADJ.

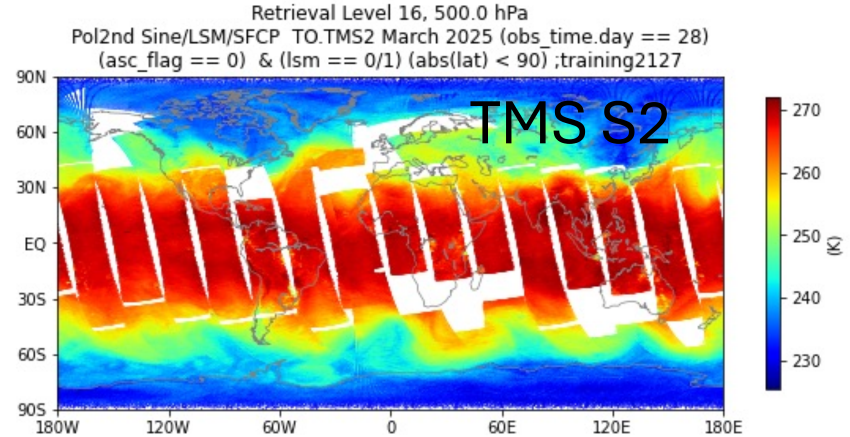


Temperature @500 hPa

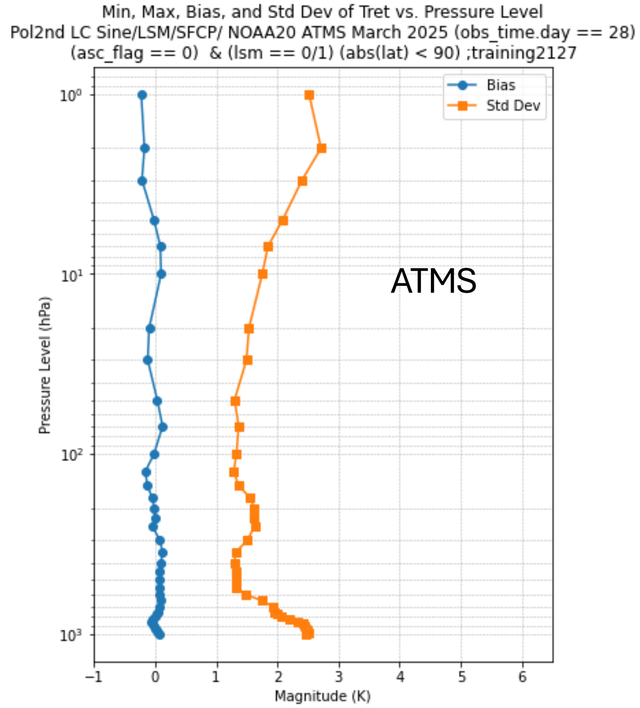


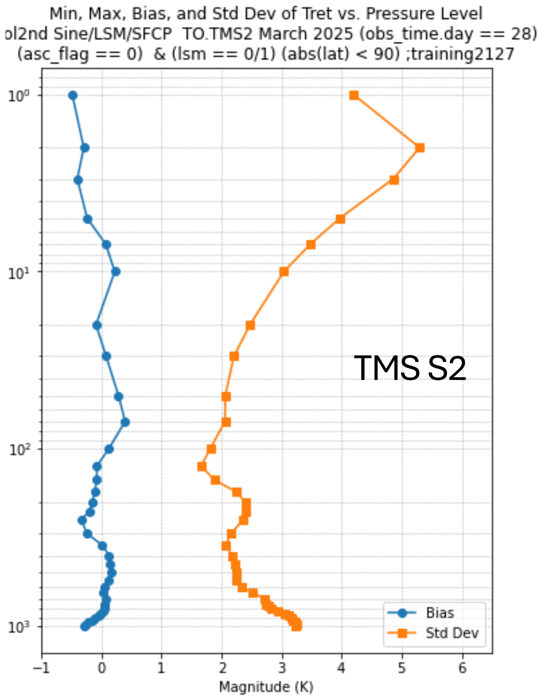


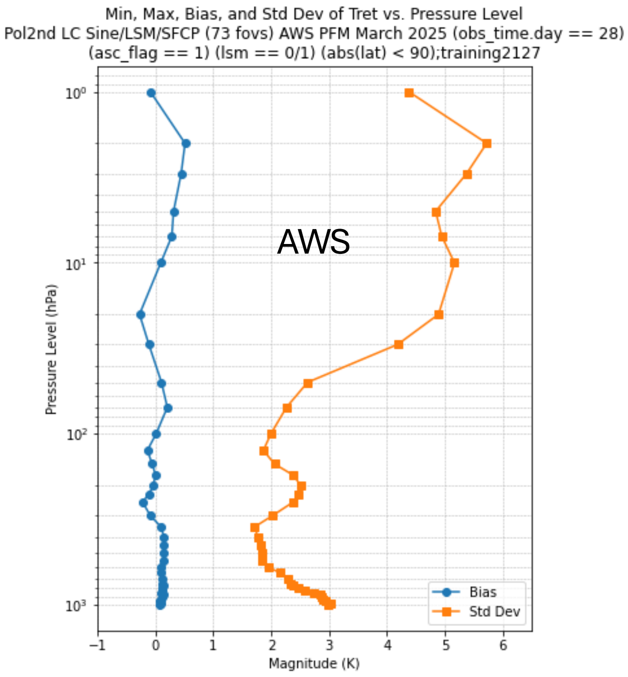




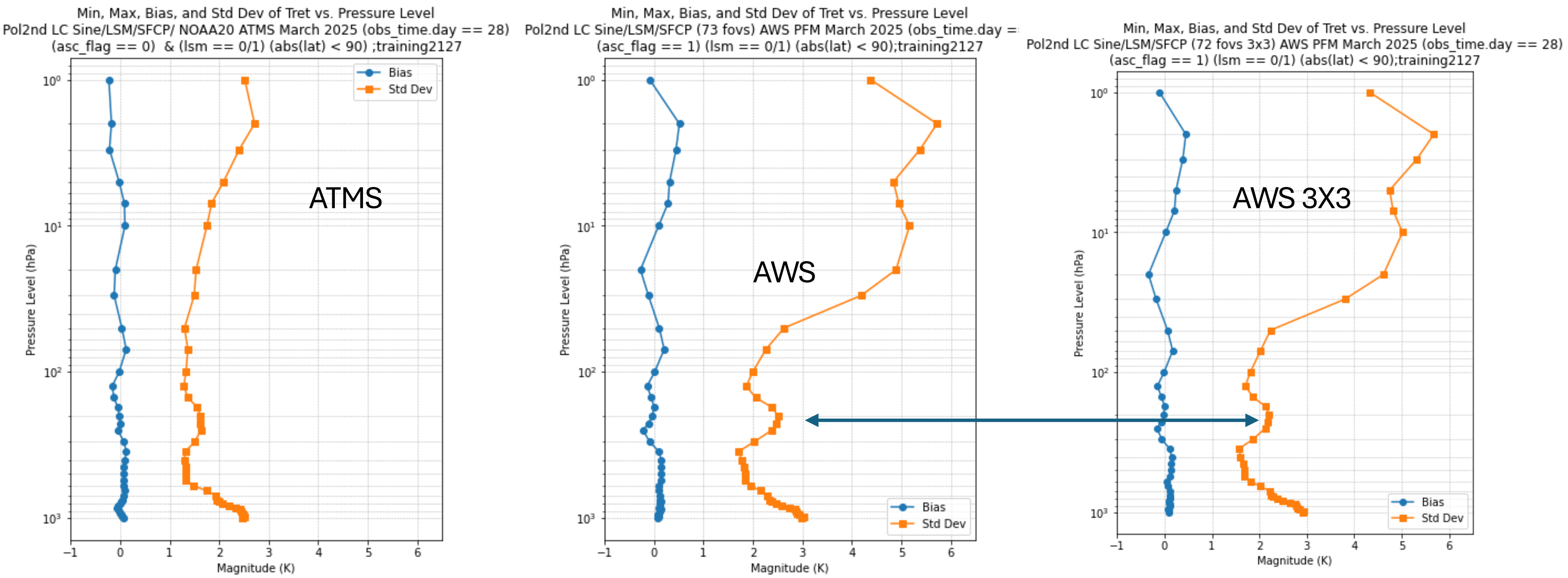
ATMS, TMS, AWS Temperature Statistics







AWS 3x3 averaging



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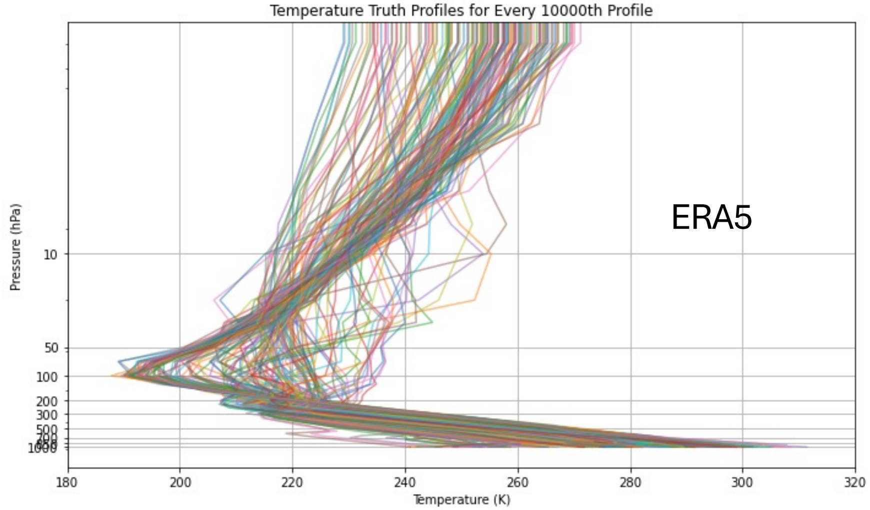
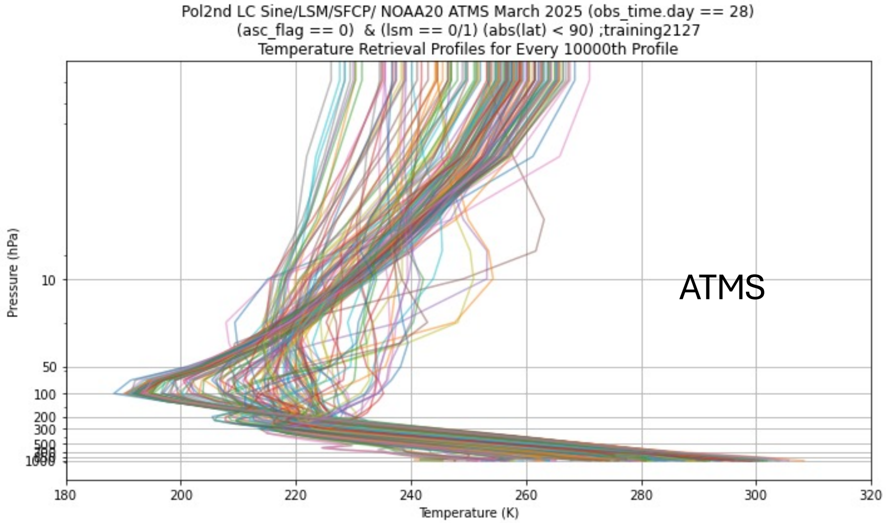
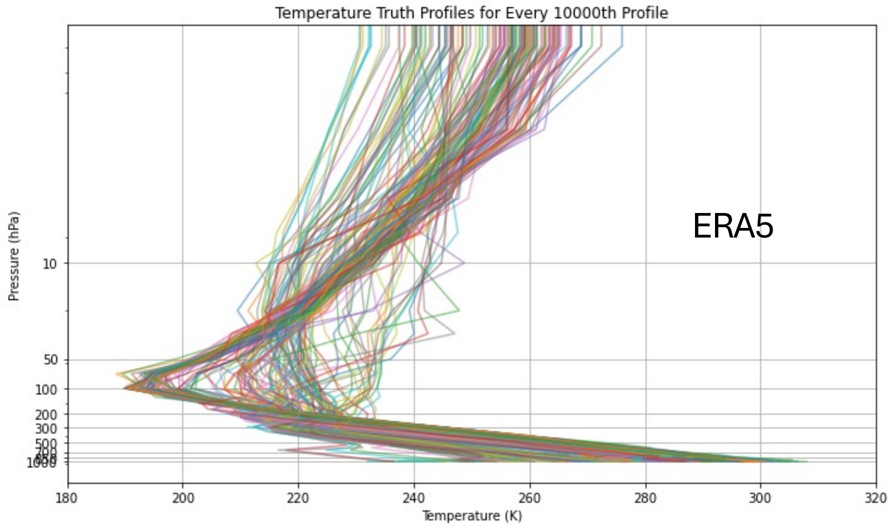
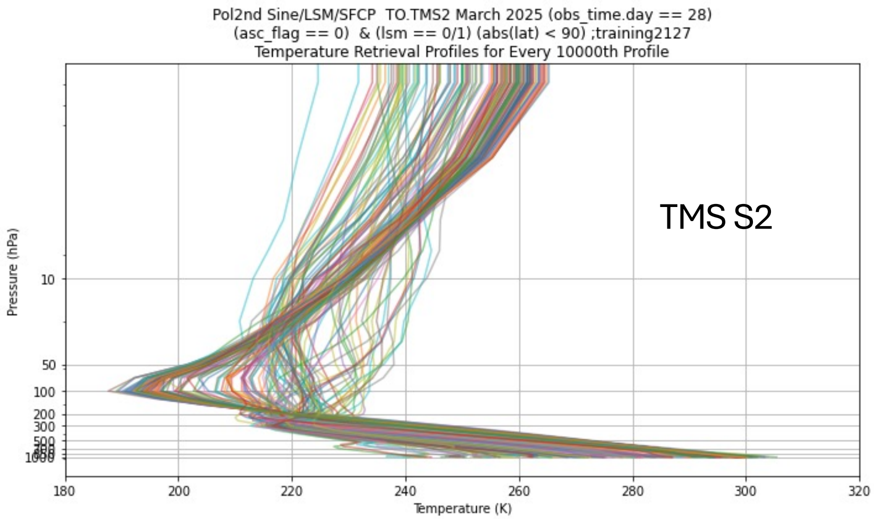
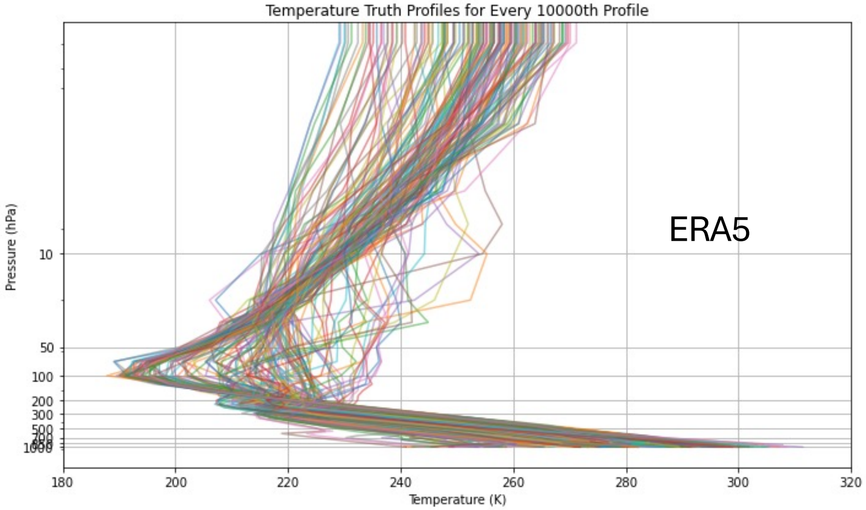


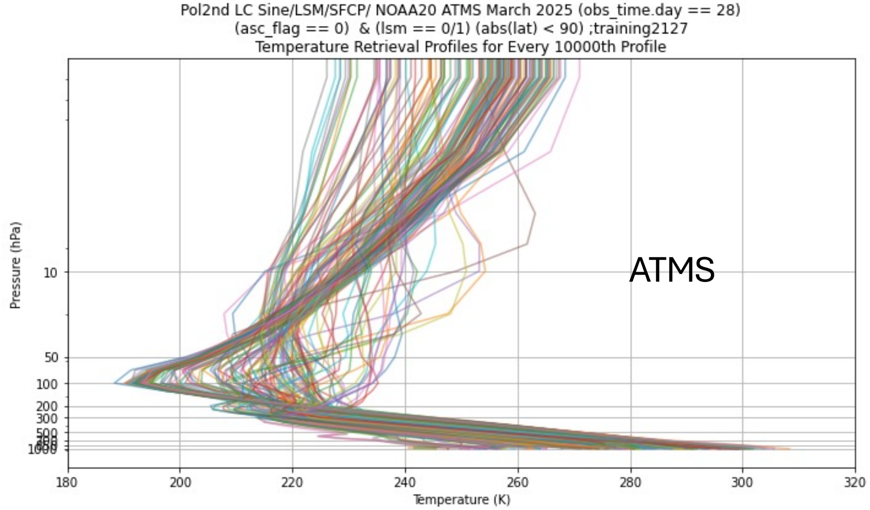




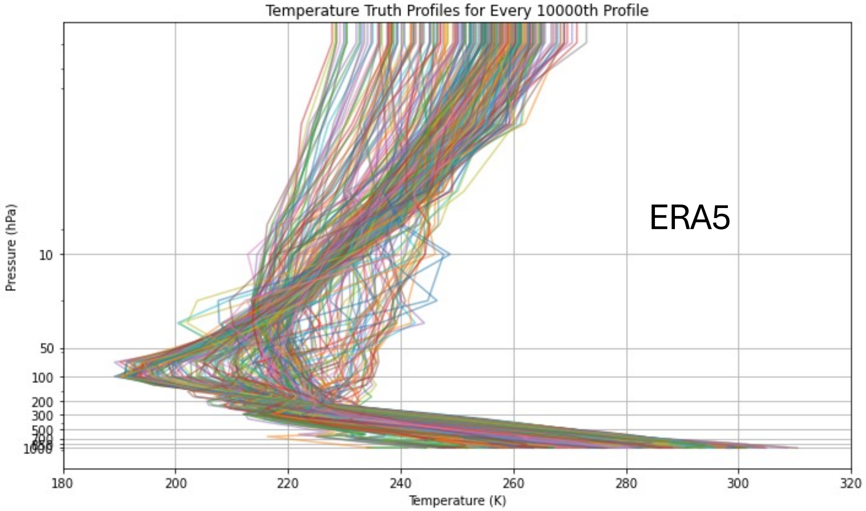




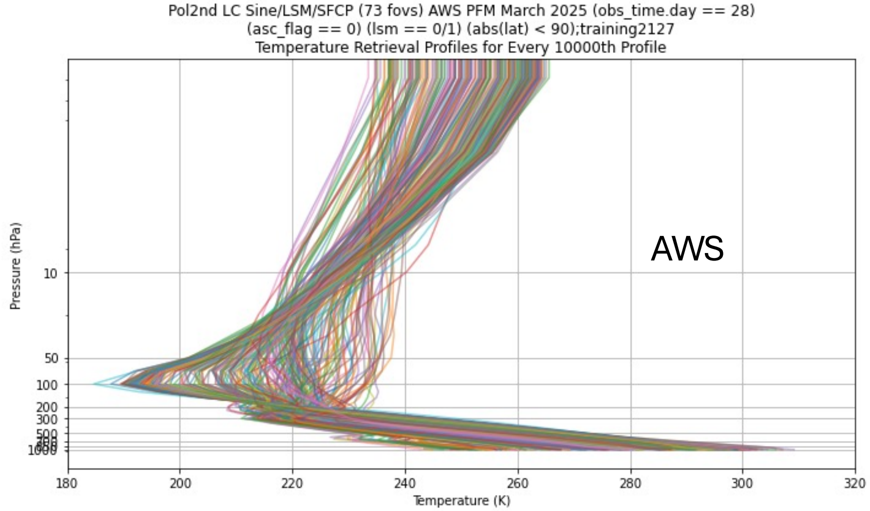
Temperature Truth Profiles for Every 10000th Profile
ERA5
Pressure (hPa)
Temperature (K)



Pol2nd LC Sine/LSM/SFCP/ NOAA20 ATMS March 2025 (obs_time.day == 28)
(asc_flag == 0) & (lsm == 0/1) (abs(lat) < 90) ;training2127
Temperature Retrieval Profiles for Every 10000th Profile
ATMS
Pressure (hPa)
Temperature (K)



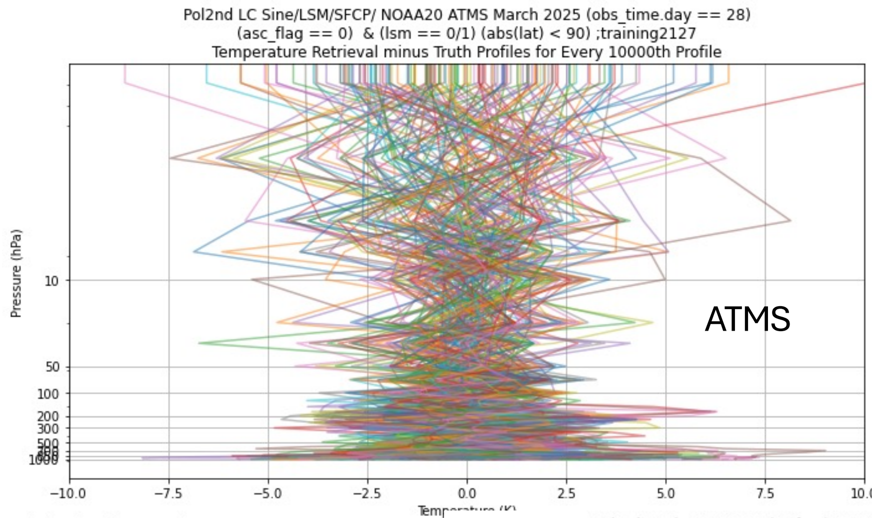
Temperature Truth Profiles for Every 10000th Profile
ERA5
Pressure (hPa)
Temperature (K)

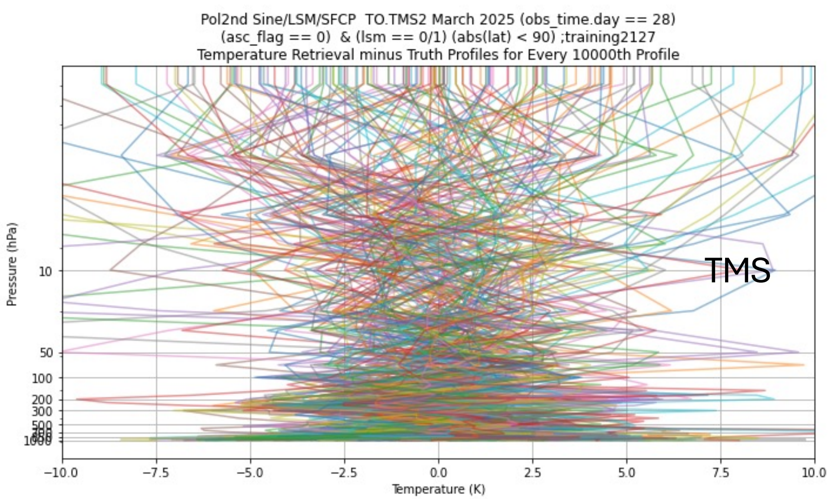


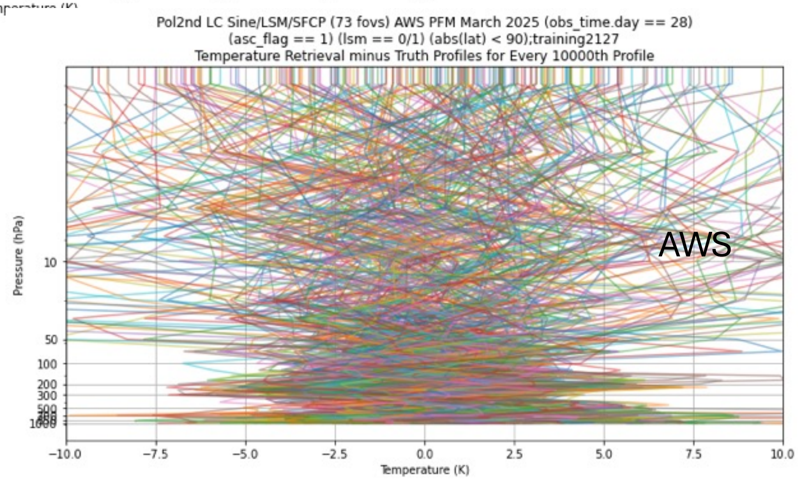
Pol2nd LC Sine/LSM/SFCP (73 fovs) AWS PFM March 2025 (obs_time.day == 28)
(asc_flag == 0) (lsm == 0/1) (abs(lat) < 90);training2127
Temperature Retrieval Profiles for Every 10000th Profile
AWS
Pressure (hPa)
Temperature (K)

Retrieval minus Truth

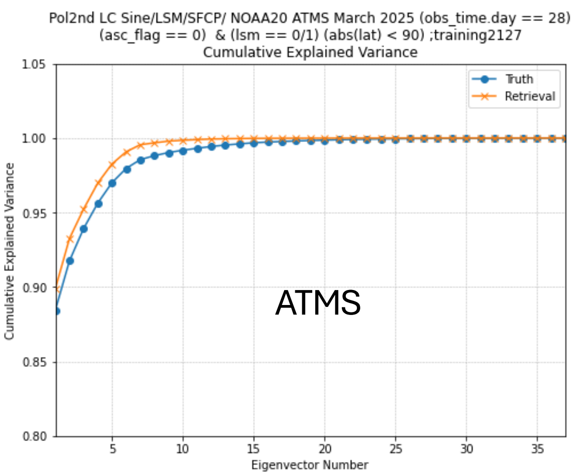
ATMS is much better!!!

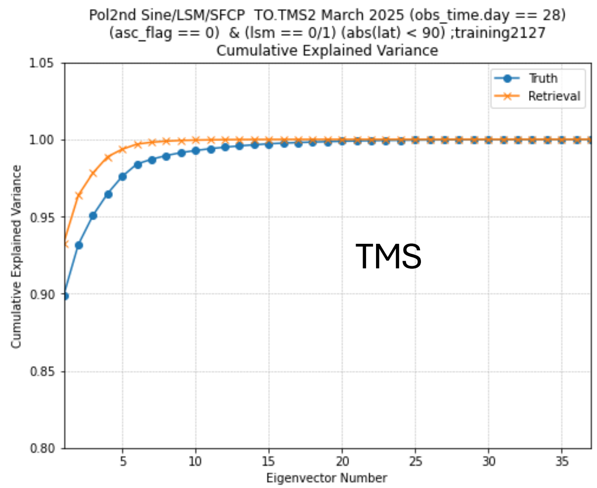


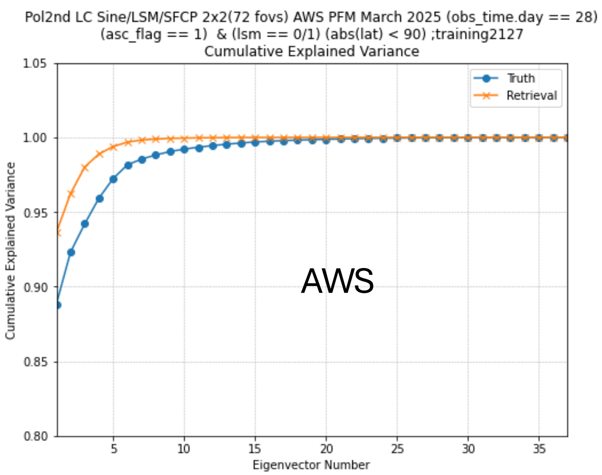




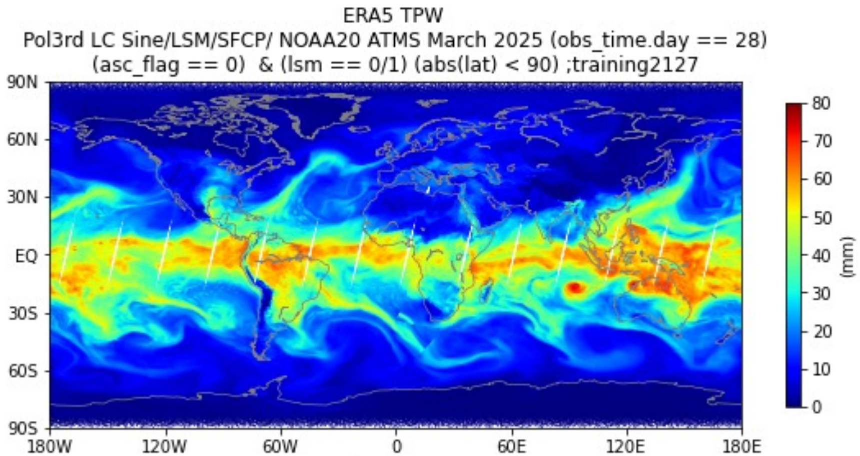
ATMS information content stands out



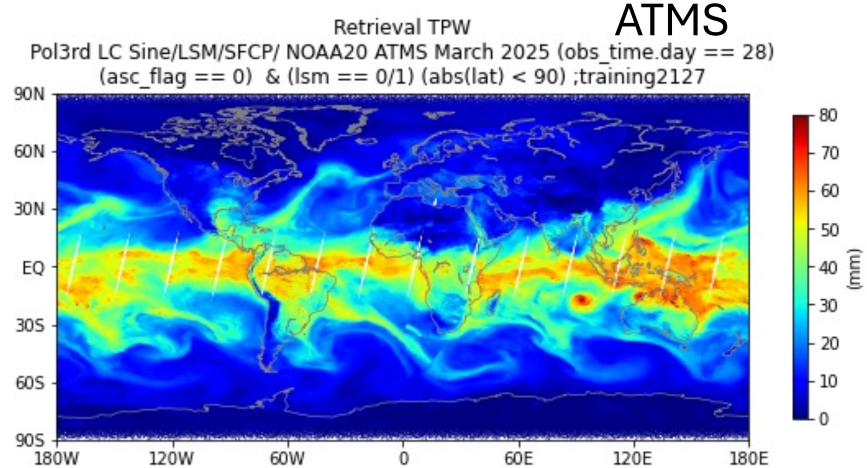


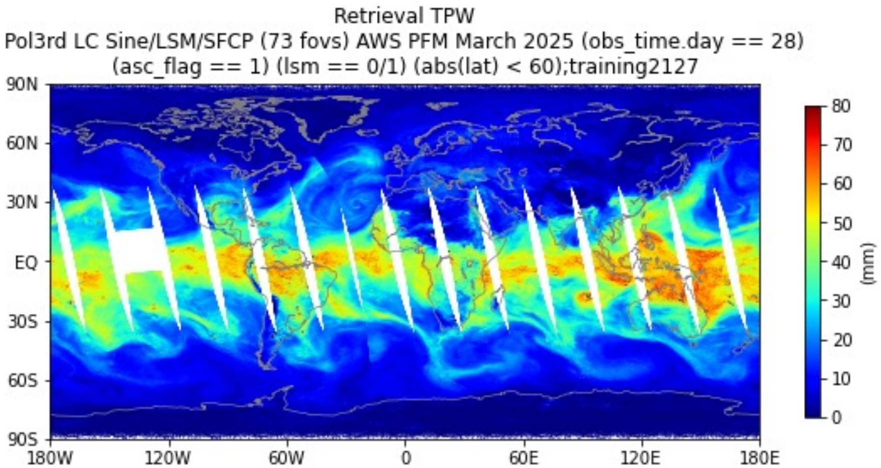


TPW

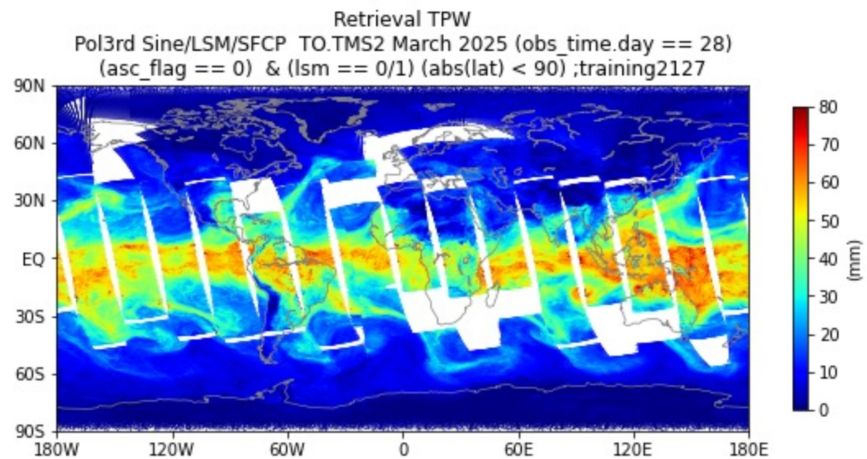


ATMS





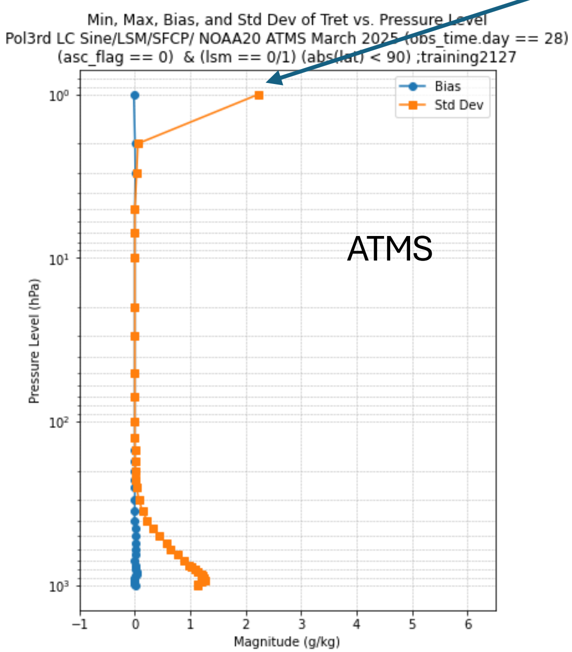
AWS

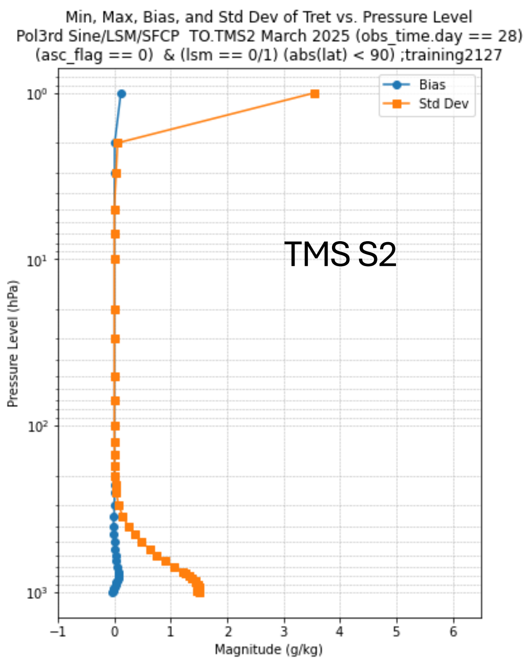


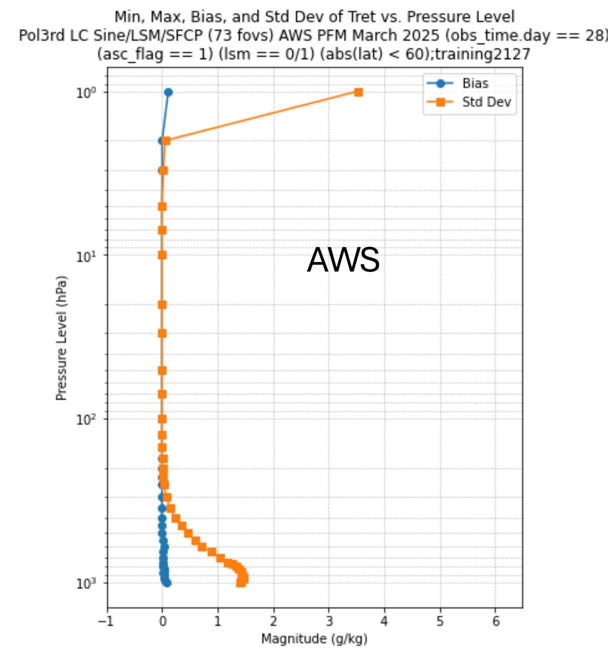
TMS S2

ATMS, TMS, AWS

Top Level is total precip. water TPW Stats



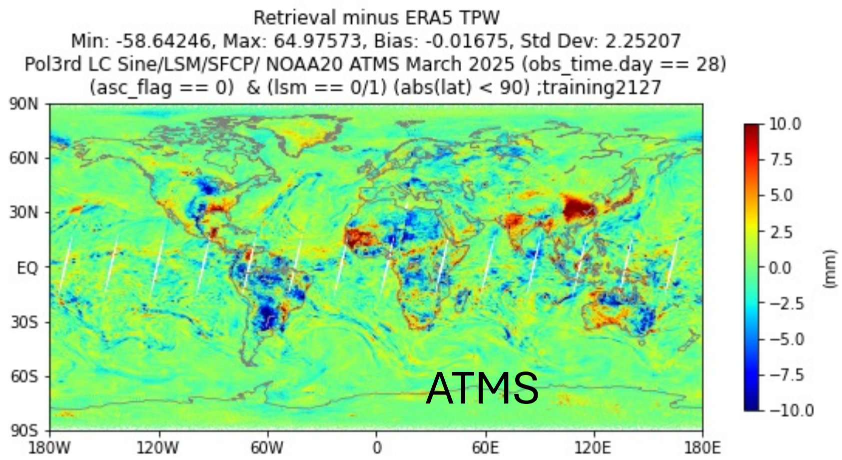


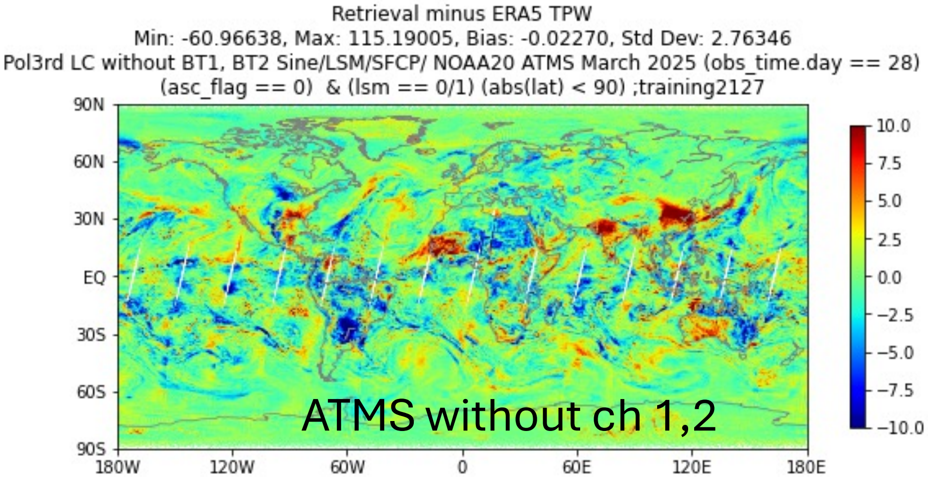


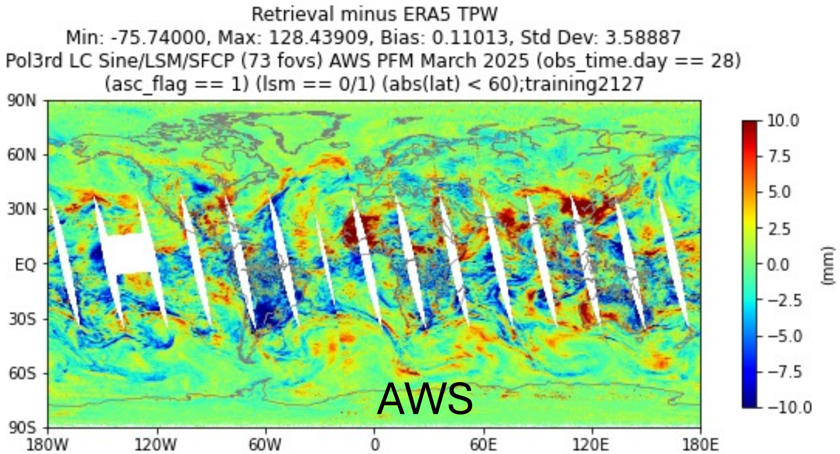
$$\widehat{\mathrm{TPW}} = a_0 - a_1 \times \ln(285 - bl1) + a_2 \times \ln(285 - bl2),$$

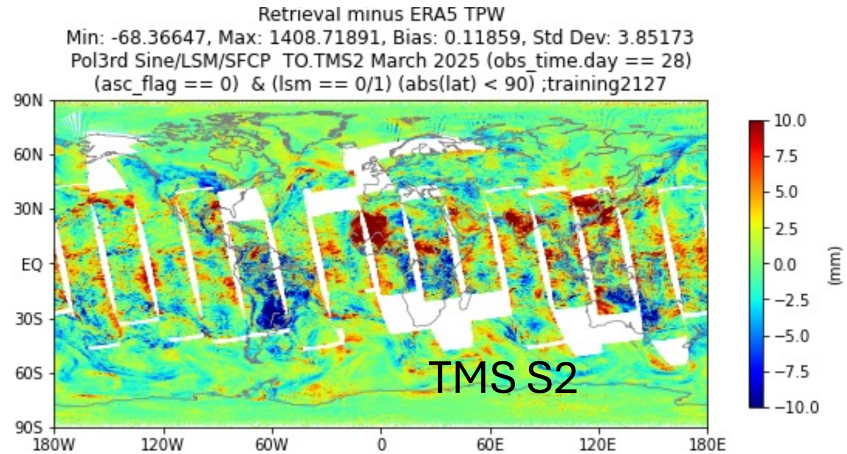
ATMS channel 23.8, 31.4 GHz channels are highly correlated to TPW

TPW Errors


Retrieval minus ERA5 TPW
Min: -58.64246, Max: 64.97573, Bias: -0.01675, Std Dev: 2.25207
Pol3rd LC Sine/LSM/SFCP/ NOAA20 ATMS March 2025 (obs_time.day == 28)
(asc_flag == 0) & (lsm == 0/1) (abs(lat) < 90) ;training2127
ATMS
(mm)


Retrieval minus ERA5 TPW
Min: -60.96638, Max: 115.19005, Bias: -0.02270, Std Dev: 2.76346
Pol3rd LC without BT1, BT2 Sine/LSM/SFCP/ NOAA20 ATMS March 2025 (obs_time.day == 28)
(asc_flag == 0) & (lsm == 0/1) (abs(lat) < 90) ;training2127
ATMS without ch 1,2
(mm)


Retrieval minus ERA5 TPW
Min: -75.74000, Max: 128.43909, Bias: 0.11013, Std Dev: 3.58887
Pol3rd LC Sine/LSM/SFCP (73 fovs) AWS PFM March 2025 (obs_time.day == 28)
(asc_flag == 1) (lsm == 0/1) (abs(lat) < 60);training2127
AWS
(mm)


Retrieval minus ERA5 TPW
Min: -68.36647, Max: 1408.71891, Bias: 0.11859, Std Dev: 3.85173
Pol3rd Sine/LSM/SFCP TO.TMS2 March 2025 (obs_time.day == 28)
(asc_flag == 0) & (lsm == 0/1) (abs(lat) < 90) ;training2127
TMS S2
(mm)

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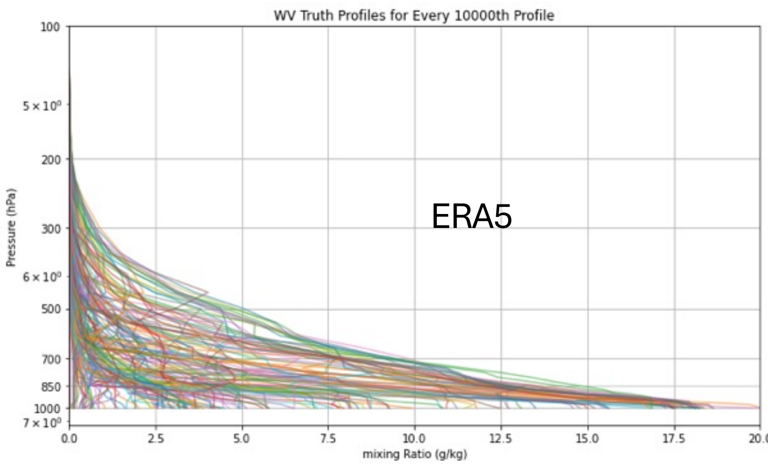

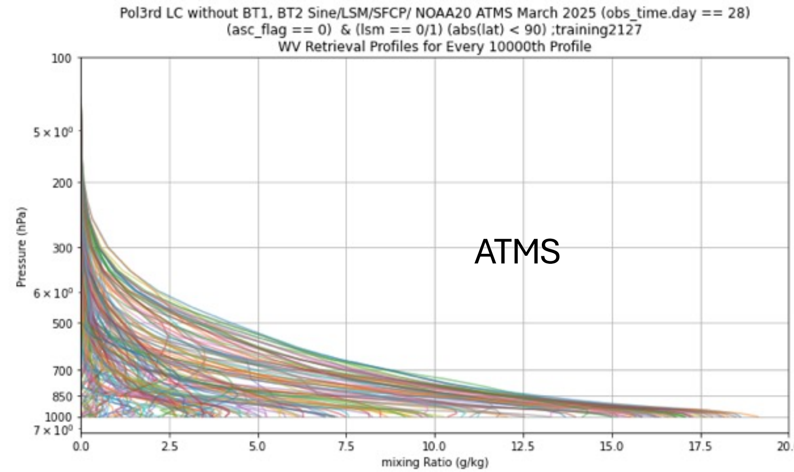

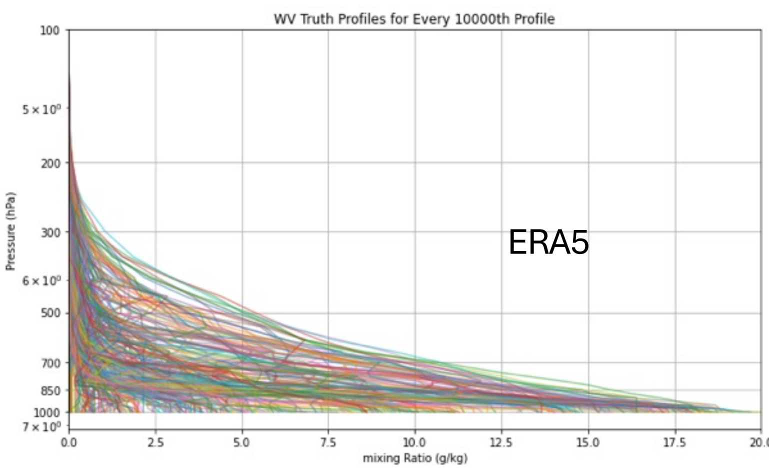

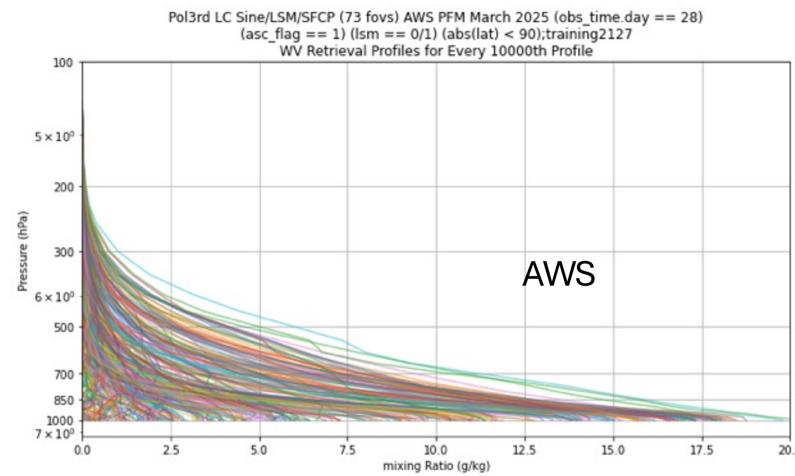

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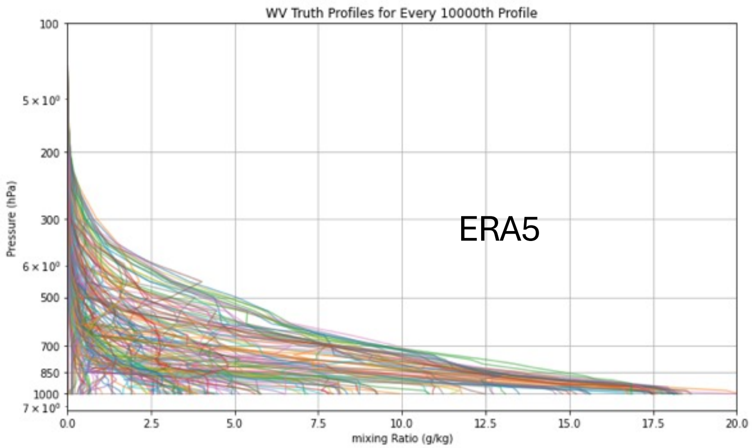
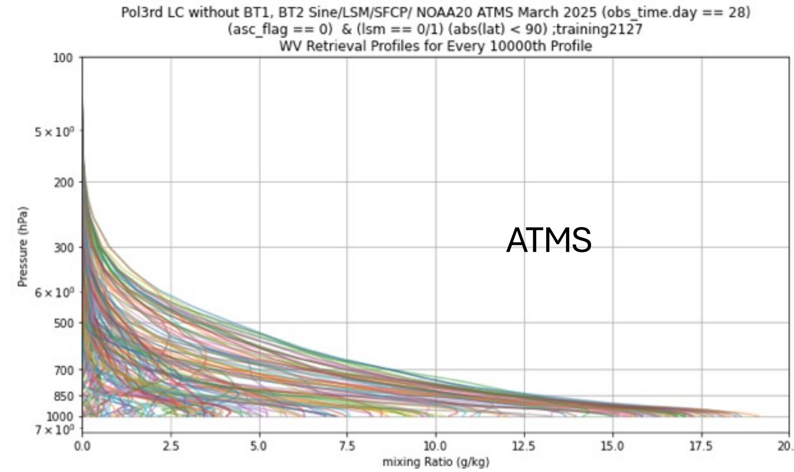
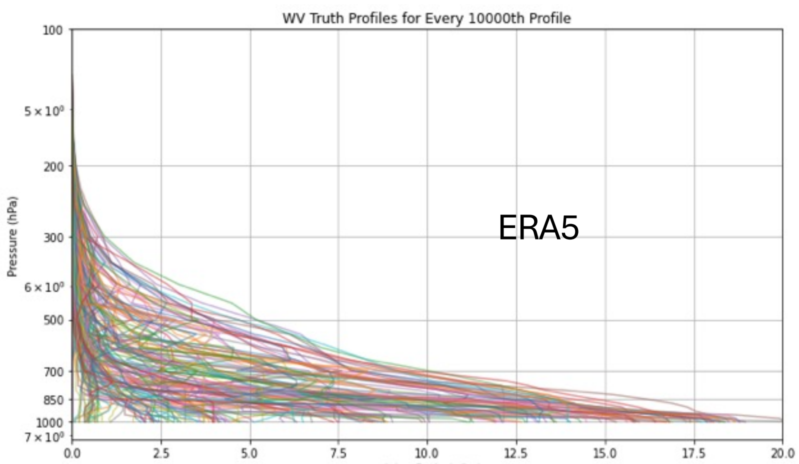
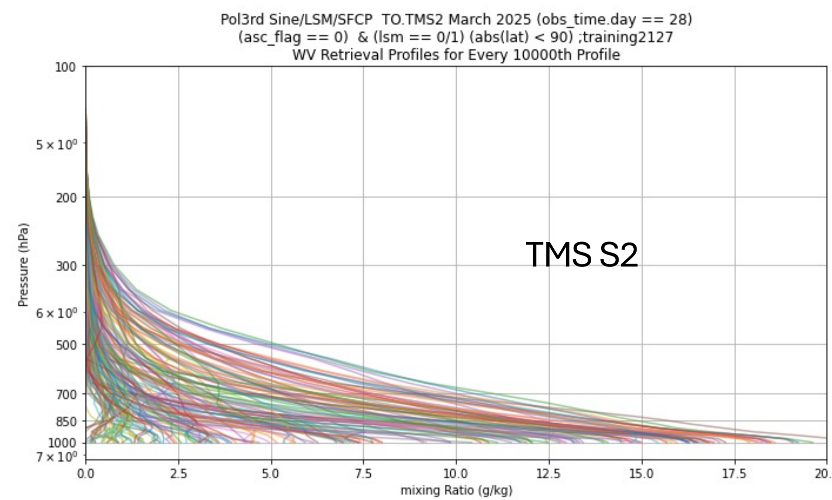


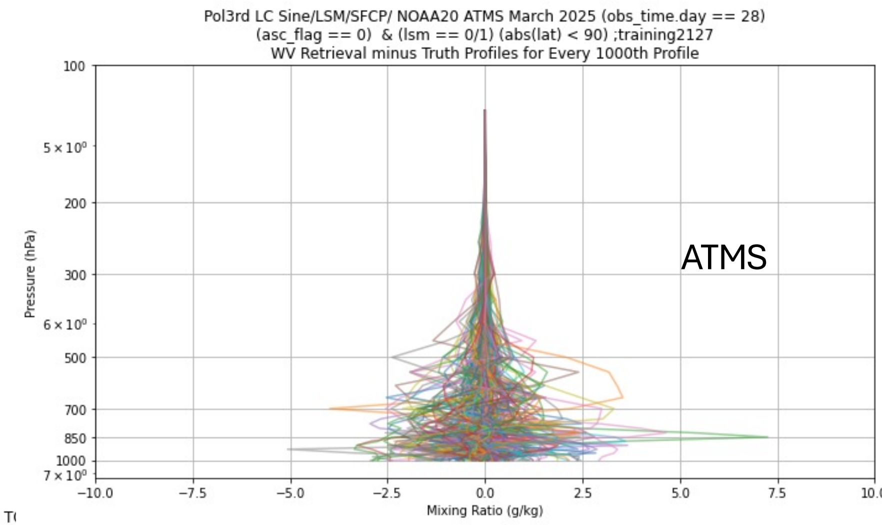


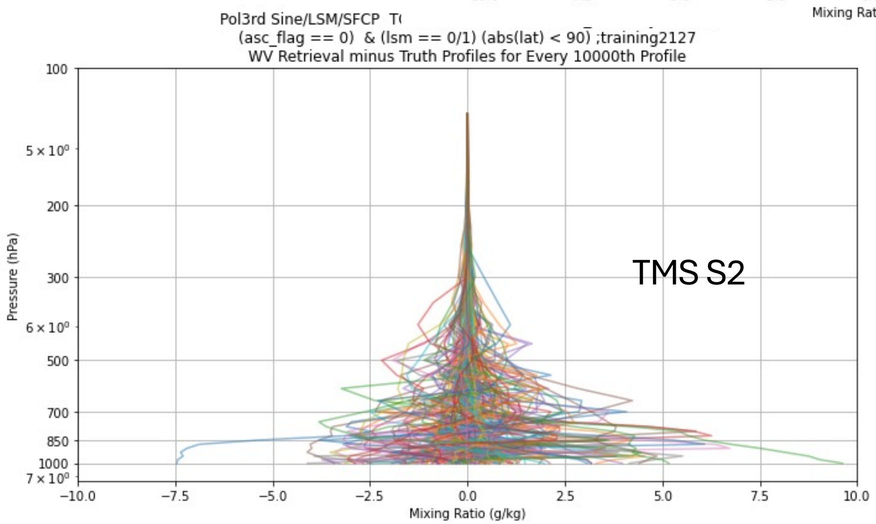


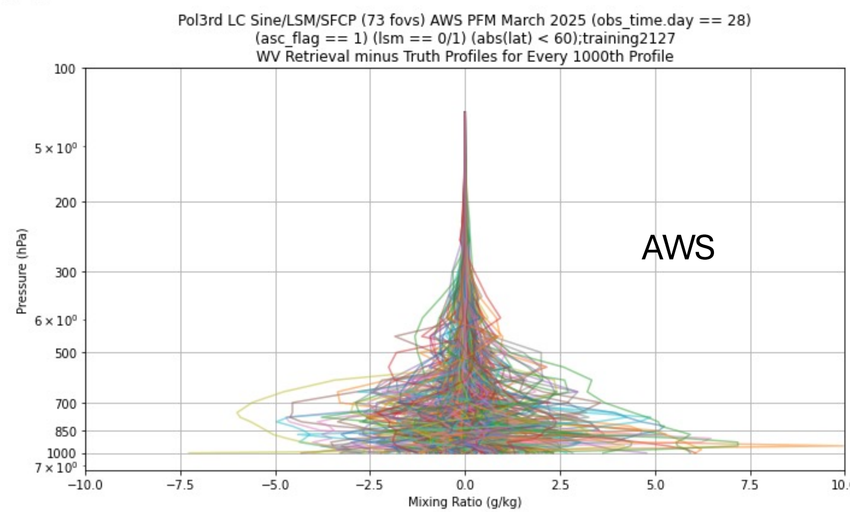


Retrieval minus Truth

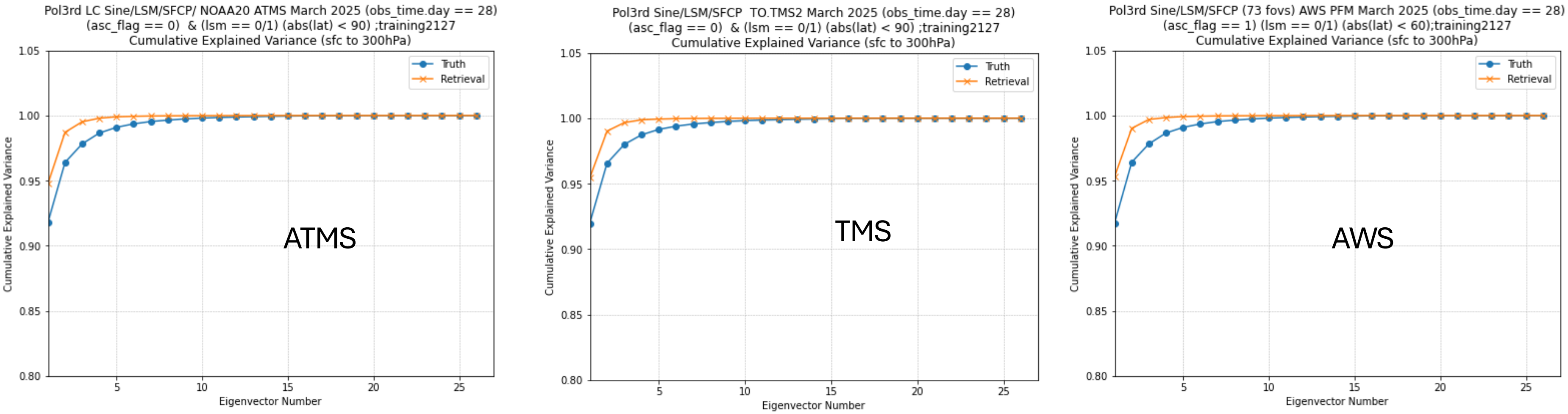
Water Vapor similar



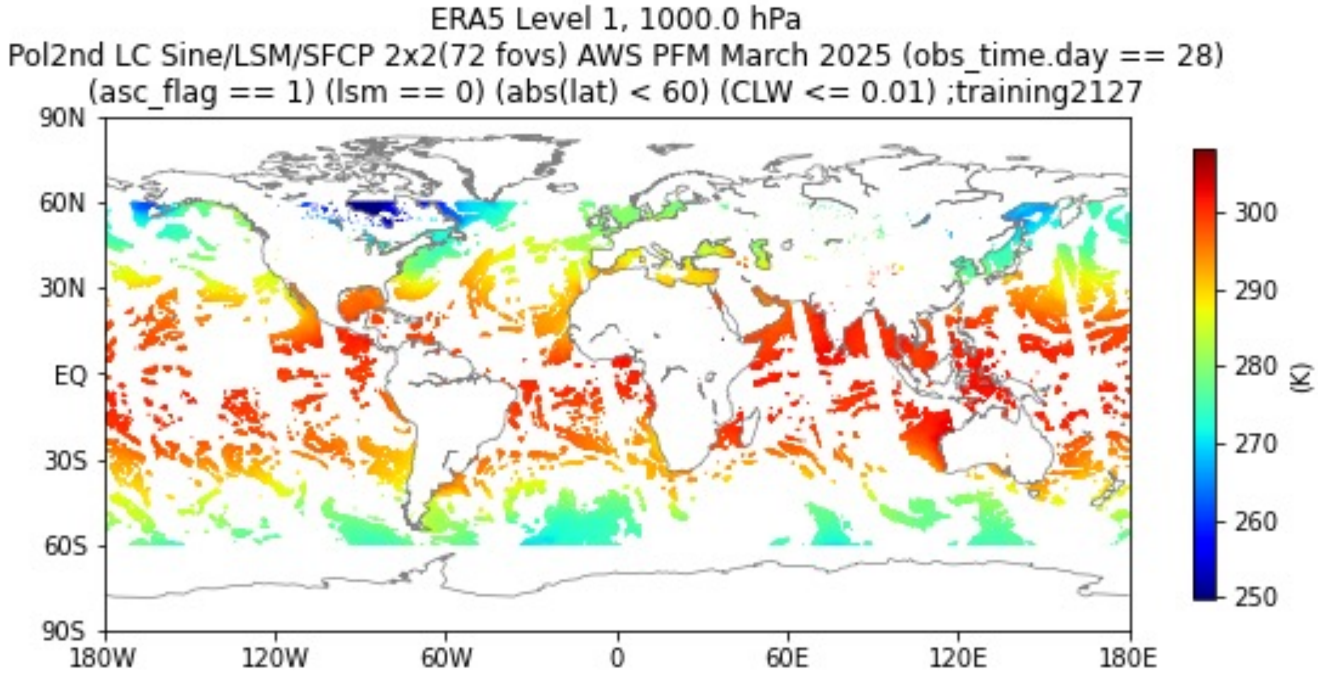




Information content similar for water vapor



Ocean only +-60 lat, Cloud liquid water < 0.01
Super easy cases



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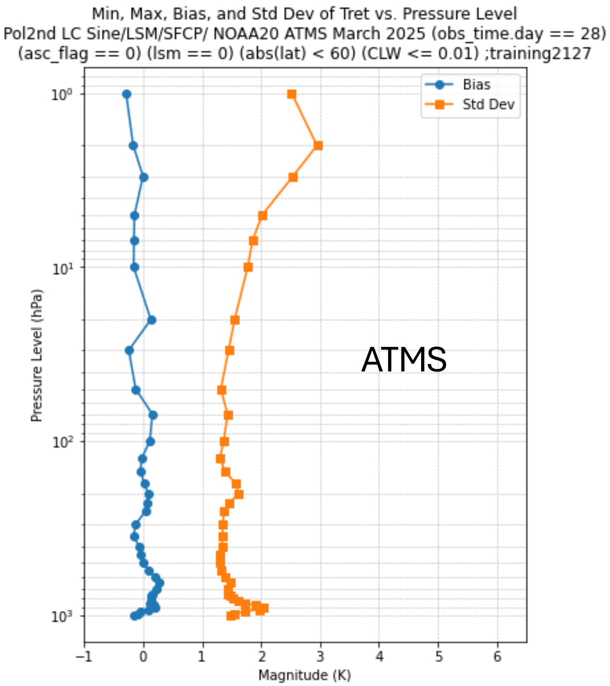
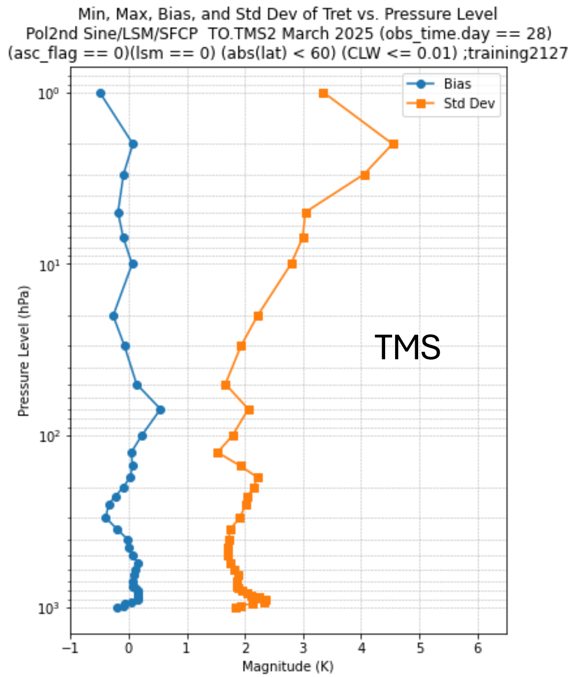
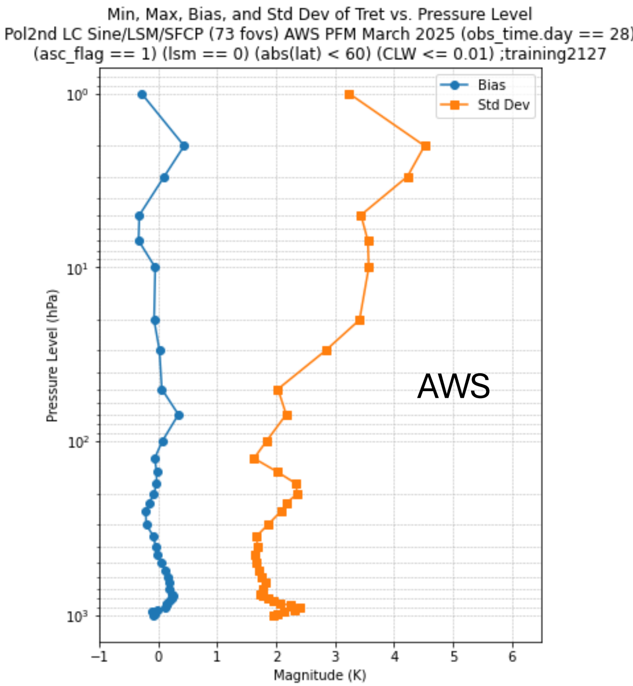
Ocean only +-60 lat, Cloud liquid water < 0.01

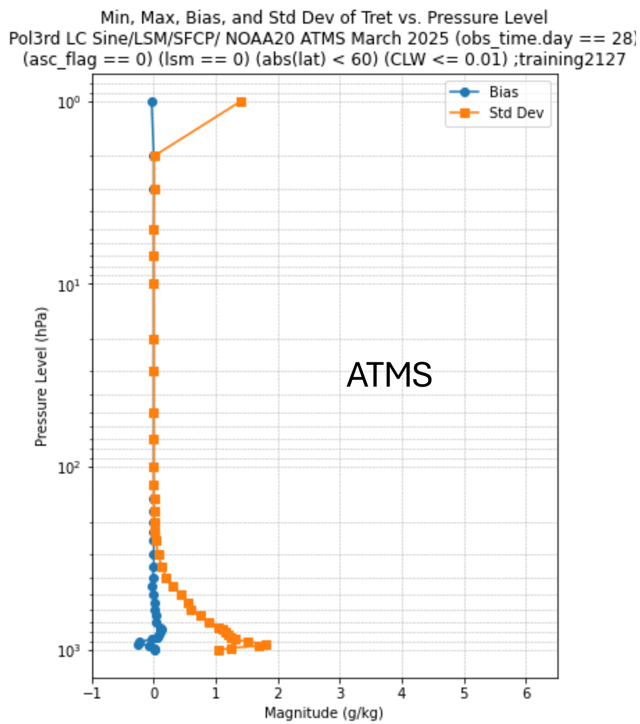


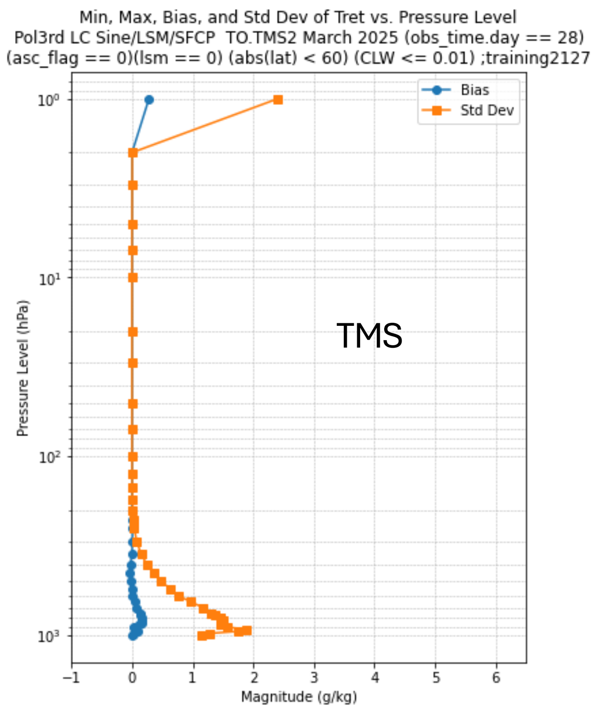


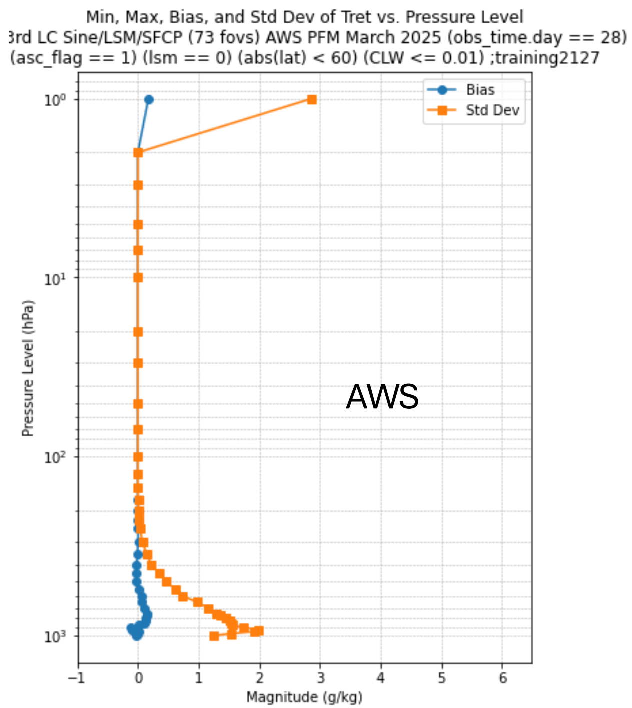


Now TMS (118 GHz) and AWS (50 GHz) are more similar

Ocean only +-60 lat, Cloud liquid water < 0.01



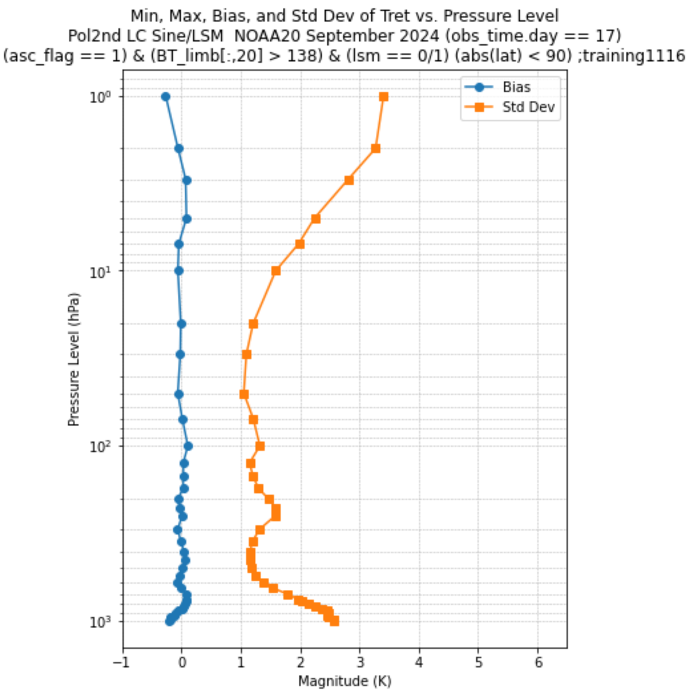




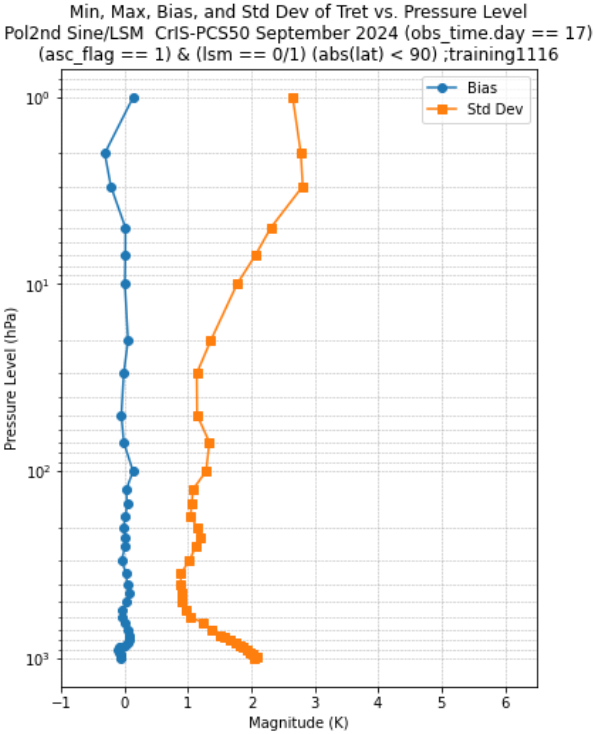
Summary

- ATMS channels 1 and 2 – significantly improve total precipitable water retrievals (but profiles are similar)
- ATMS low noise and additional channels produce higher accuracy temperature retrievals
- Comparing to ATMS, equivalent AWS 50 GHz temperature channels have much larger noise
- TMS and AWS temperature retrievals are similar in troposphere, more so for clear skies (low cloud liquid water).
- ATMS, TMS and AWS water vapor retrievals are similar.
- Polynomial regression works really well!!

BONUS -- What about Hyperspectral Infrared Sounders?

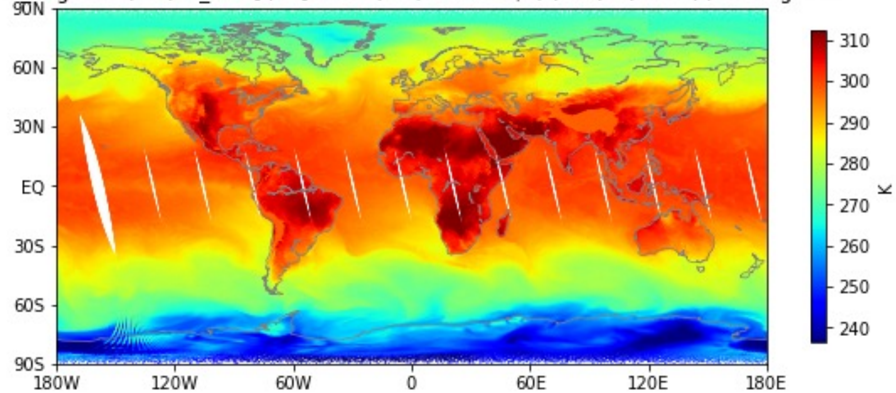


ATMS

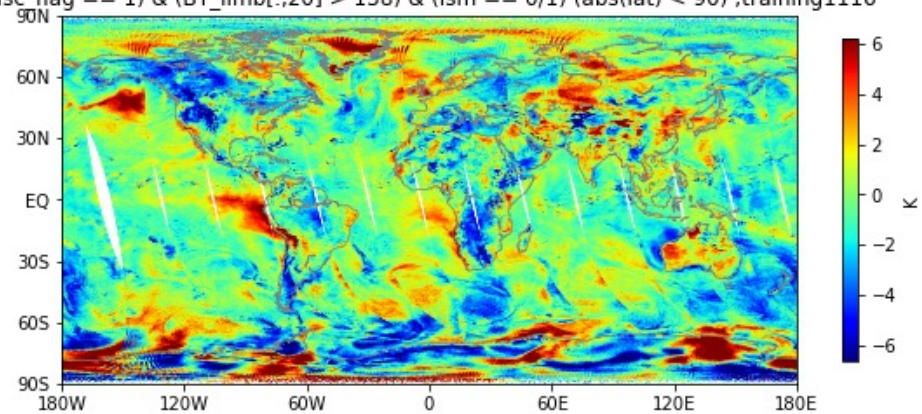


CrIS

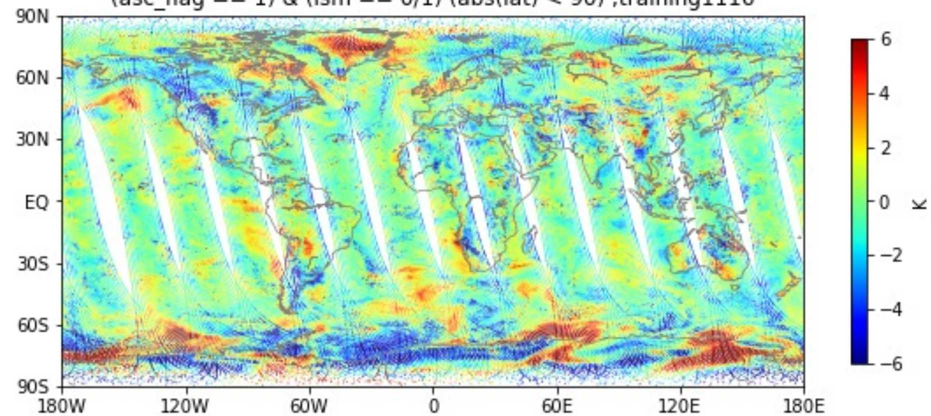
ERA5 Level 1, 1000.0 hPa
Pol2nd LC Sine/LSM NOAA20 September 2024 (obs_time.day == 17)
(asc_flag == 1) & (BT_limb[:,20] > 138) & (lsm == 0/1) (abs(lat) < 90) ;training1116



Retrieval minus ERA5 at Level 1, 1000.0 hPa
Min: -30.60266, Max: 27.20443, Bias: -0.21047, Std Dev: 2.57226
Pol2nd LC Sine/LSM NOAA20 September 2024 (obs_time.day == 17)
(asc_flag == 1) & (BT_limb[:,20] > 138) & (lsm == 0/1) (abs(lat) < 90) ;training1116



Retrieval minus ERA5 at Level 1, 1000.0 hPa
Min: -47.74356, Max: 33.81184, Bias: -0.19728, Std Dev: 2.47317
Pol2nd Sine/LSM CrIS-PCS50 September 2024 (obs_time.day == 17)
(asc_flag == 1) & (lsm == 0/1) (abs(lat) < 90) ;training1116



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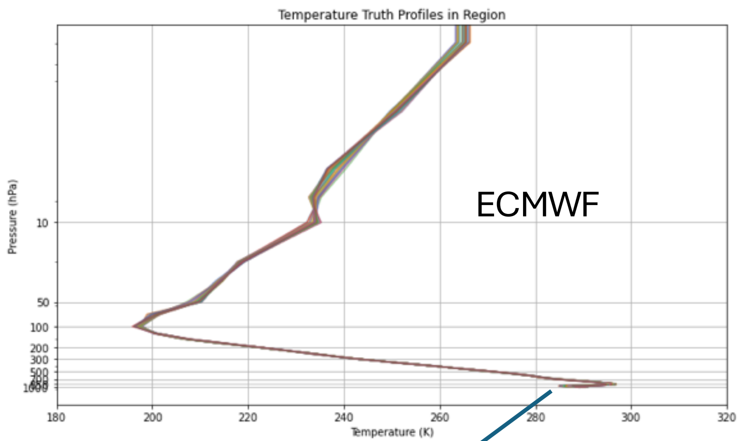

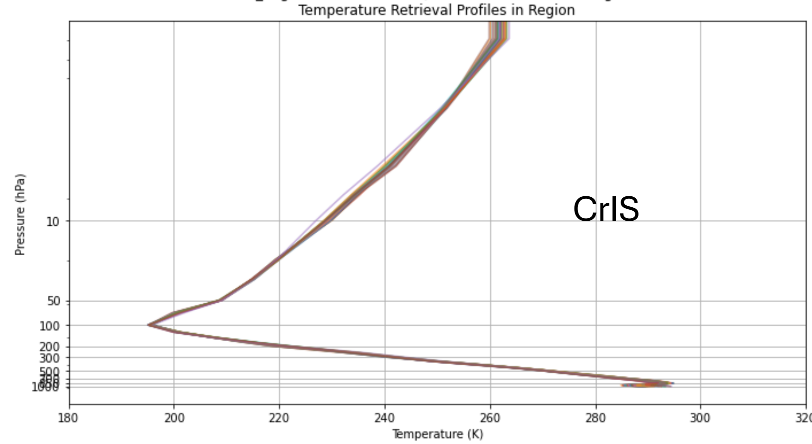

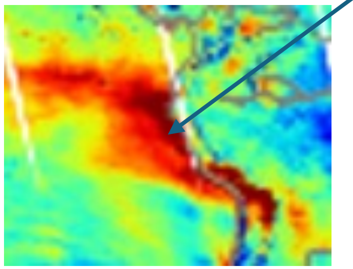

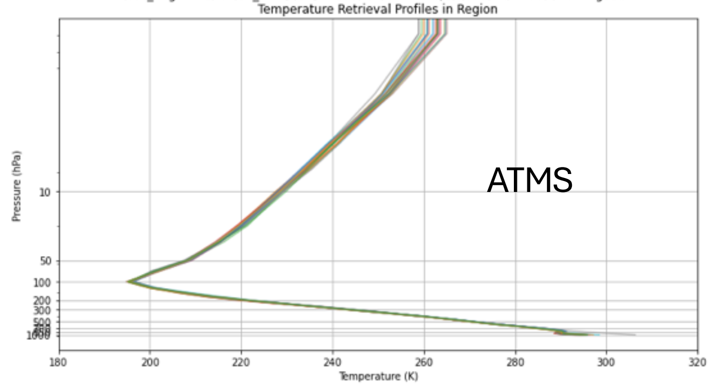

ATMS cannot resolve lower-level inversion

IR Summary

- Hyperspectral IR is particularly important for resolving vertical structure in the lower troposphere.

- Consider a constellation of IR sounders too!! But geostationary is preferable because its achievable – unlike microwave geostationary.

Backup

AWS

Channel		Central frequency (GHz)	Bandwidth (MHz)	NEΔT	Polarisation	Resolution
Name	index					
Sterna-11	1	50.3	180	< 0.6 K	QV	≤ 40 km
Sterna-12	2	52.8	400	< 0.4 K	QV	≤ 40 km
Sterna-13	3	53.246	300	< 0.4 K	QV	≤ 40 km
Sterna-14	4	53.596	370	< 0.4 K	QV	≤ 40 km
Sterna-15	5	54.4	400	< 0.4 K	QV	≤ 40 km
Sterna-16	6	54.94	400	< 0.4 K	QV	≤ 40 km
Sterna-17	7	55.5	330	< 0.5 K	QV	≤ 40 km
Sterna-18	8	57.290344	330	< 0.6 K	QV	≤ 40 km
Sterna-21	9	89	4000	< 0.3 K	QV	≤ 20 km
Sterna-31	10	165.5	2800	< 0.6 K	QV	≤ 10 km
Sterna-32	11	176.311	2000	< 0.7 K	QV	≤ 10 km
Sterna-33	12	178.811	2000	< 0.7 K	QV	≤ 10 km
Sterna-34	13	180.311	1000	< 1 K	QV	≤ 10 km
Sterna-35	14	181.511	1000	< 1 K	QV	≤ 10 km
Sterna-36	15	182.311	500	< 1.3 K	QV	≤ 10 km
Sterna-41	16	325.15±1.2	2*800	< 1.7 K	QV	≤ 10 km
Sterna-42	17	325.15±2.4	2*1200	< 1.4 K	QV	≤ 10 km
Sterna-43	18	325.15±4.1	2*1800	< 1.2 K	QV	≤ 10 km
Sterna-44	19	325.15±6.6	2*2800	< 1 K	QV	≤ 10 km

Table 2: EPS-Sterna channel list and characteristics applicable this study

ATMS

ATMS TDR/SDR Specifications

Channel	Center Frequency (GHz)	Total Bandpass (GHz)	Accuracy (K)	NEDT (K)	EFOV Cross-Track (deg)	EFOV Along-Track (deg)	Polarization
1	23.8	0.27	1	0.7	6.3	5.2	QV
2	31.4	0.18	1	0.8	6.3	5.2	QV
3	50.3	0.18	0.75	0.9	3.3	2.2	QH
4	51.76	0.4	0.75	0.7	3.3	2.2	QH
5	52.8	0.4	0.75	0.7	3.3	2.2	QH
6	53.596±0.115	0.17	0.75	0.7	3.3	2.2	QH
7	54.4	0.4	0.75	0.7	3.3	2.2	QH
8	54.94	0.4	0.75	0.7	3.3	2.2	QH
9	55.5	0.33	0.75	0.7	3.3	2.2	QH
10	57.290344	0.33	0.75	0.75	3.3	2.2	QH
11	57.290344±0.217	0.078	0.75	1.2	3.3	2.2	QH
12	57.290344±0.3222±0.048	0.036	0.75	1.2	3.3	2.2	QH
13	57.290344±0.3222±0.022	0.016	0.75	1.5	3.3	2.2	QH
14	57.290344±0.3222±0.010	0.008	0.75	2.4	3.3	2.2	QH
15	57.290344±0.3222±0.0045	0.003	0.75	3.6	3.3	2.2	QH
16	88.2	2	1	0.5	3.3	2.2	QV
17	165.5	3	1	0.6	2.2	1.1	QH
18	183.31±7	2	1	0.8	2.2	1.1	QH
19	183.31±4.5	2	1	0.8	2.2	1.1	QH
20	183.31±3	1	1	0.8	2.2	1.1	QH
21	183.31±1.8	1	1	0.8	2.2	1.1	QH
22	183.31±1	0.5	1	0.9	2.2	1.1	QH

QV = Quasi-Vertical QH = Quasi-Horizontal Dynamic Range are 0-330 (K) for all channels

The 50 GHz channels are similar, one would expect similar retrieval performance in the troposphere.

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Tomorrow IO TMS

No.	Central frequency	Bandwidth	NEΔT	Nadir IFOV
1	91.655 ± 1.4 GHz	2000 MHz	0.55 K	30 km
2	118.75 ± 3.5 GHz	1000 MHz	0.93 K	25 km
3	118.75 ± 2.625 GHz	750 MHz	0.95 K	25 km
4	118.75 ± 1.875 GHz	750 MHz	0.88 K	25 km
5	118.75 ± 1.25 GHz	500 MHz	0.95 K	25 km
6	118.75 ± 0.75 GHz	500 MHz	0.95 K	25 km
7	118.75 ± 0.375 GHz	250 MHz	1.21 K	25 km
8	118.75 ± 0.125 GHz	250 MHz	1.16 K	25 km
9	184.41 GHz	2000 MHz	0.79 K	15 km
10	186.51 GHz	2000 MHz	0.73 K	15 km
11	190.31 GHz	2000 MHz	0.69 K	15 km
12	204.8 GHz	2000 MHz	0.75 K	15 km

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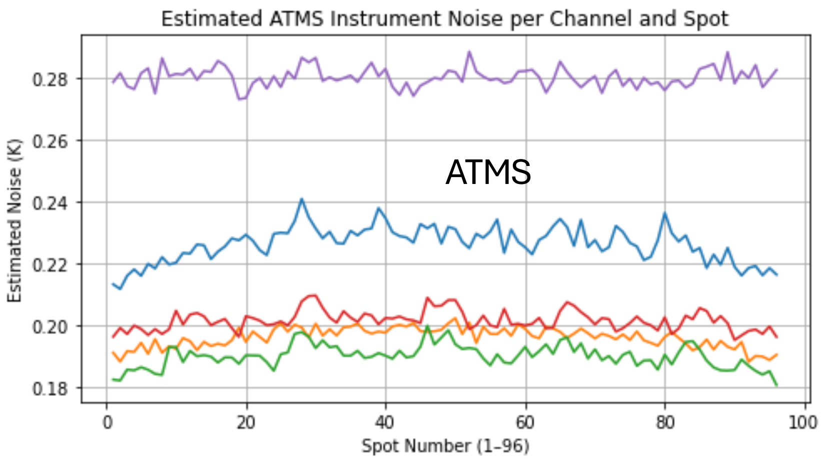
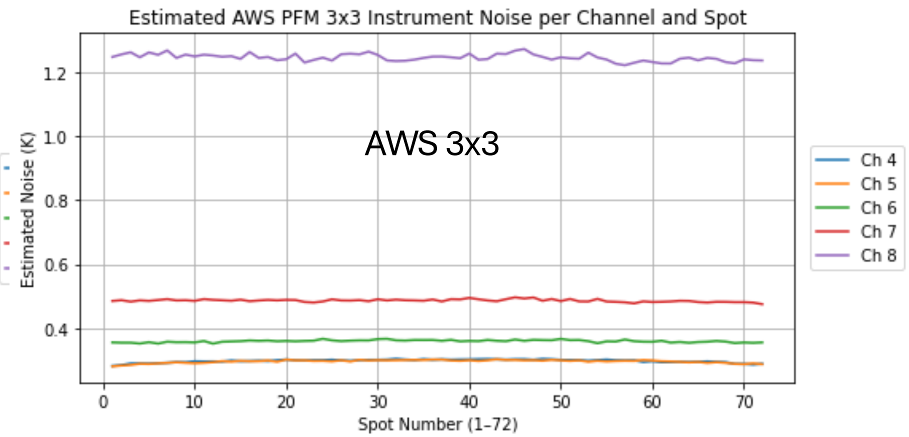
Temperature channels 3x3 averaged AWS





AWS PFM tropospheric sounding channels noise is significantly higher than ATMS. Remember ATMS channel #+2 is similar to AWS channel #

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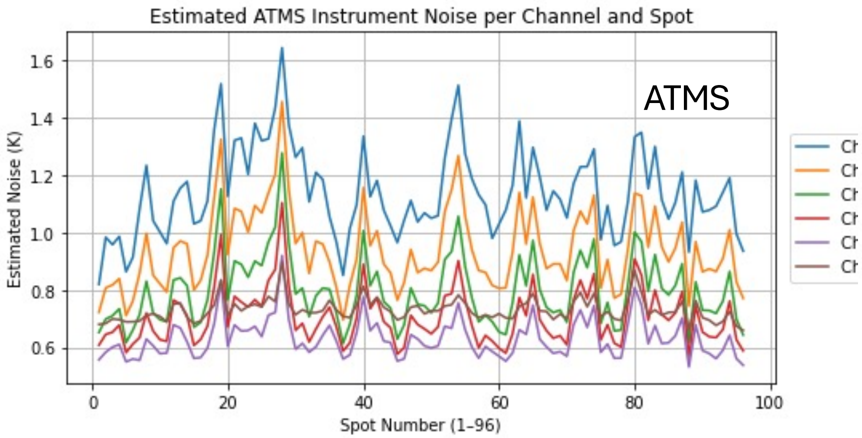
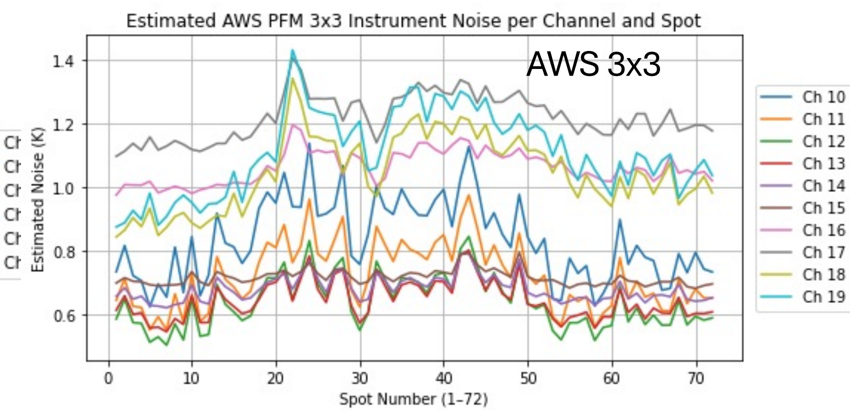
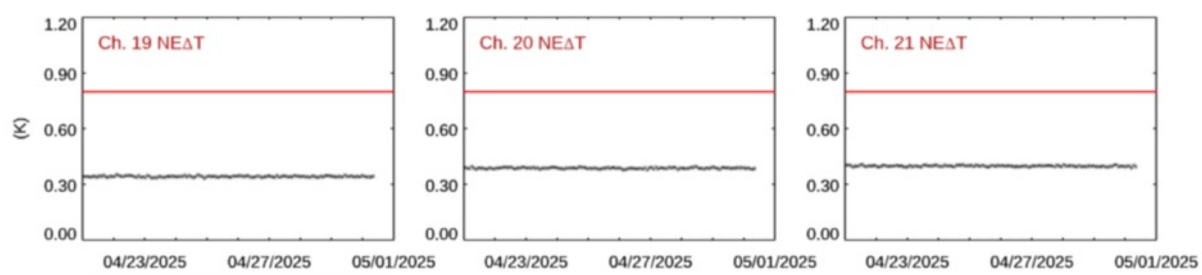
WV Channels 3x3

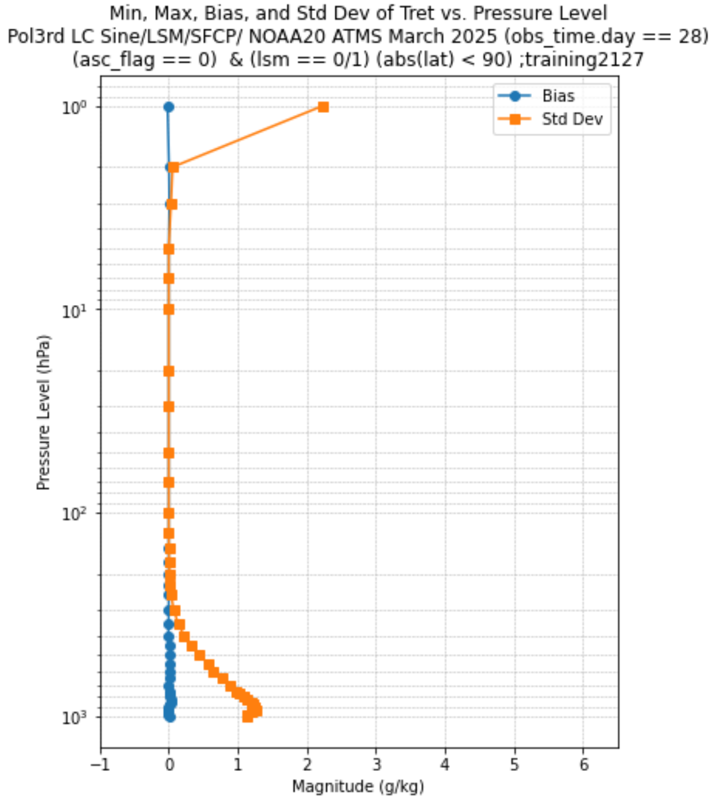


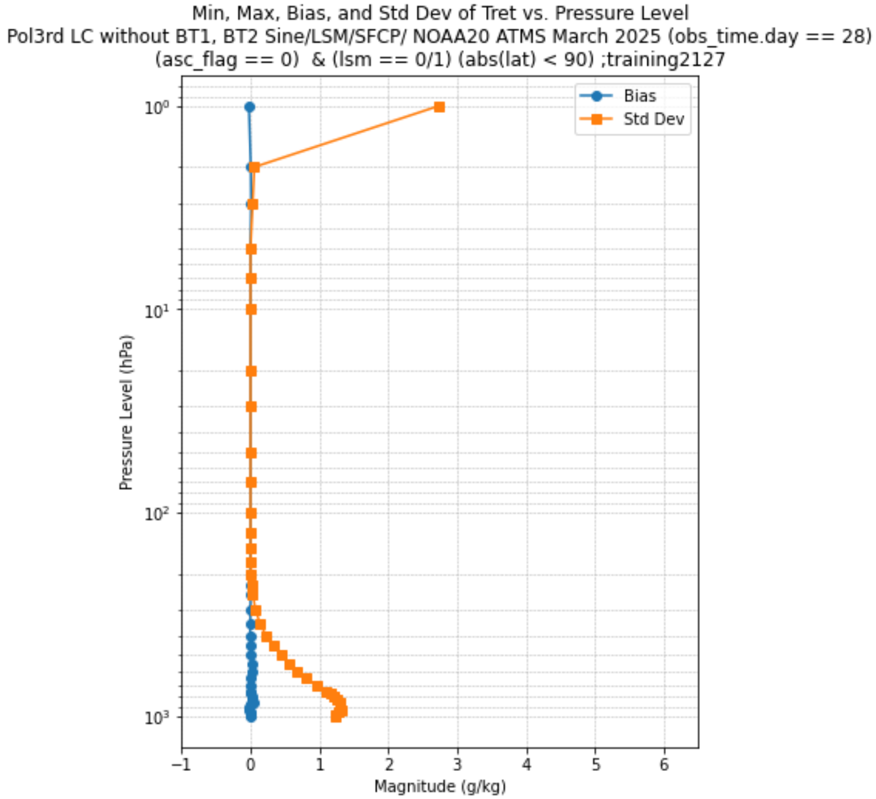


For water vapor channels, the methodology does not compare well with actual instrumental noise because water vapor is very variable – much more so than temperature

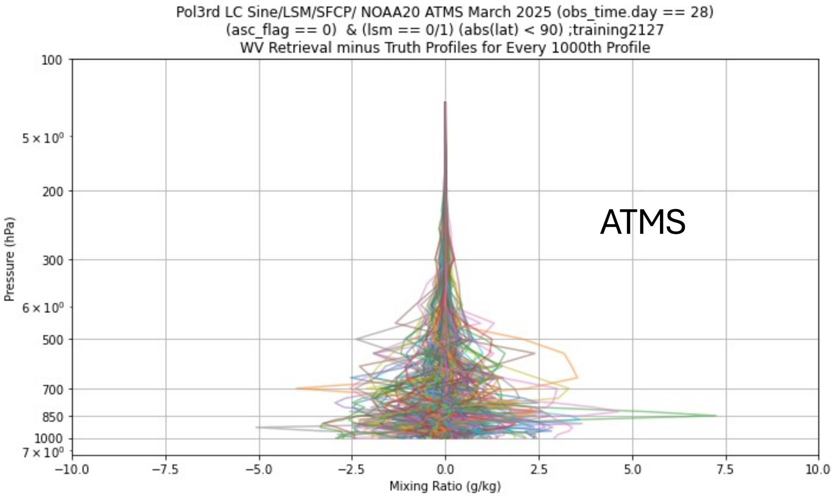


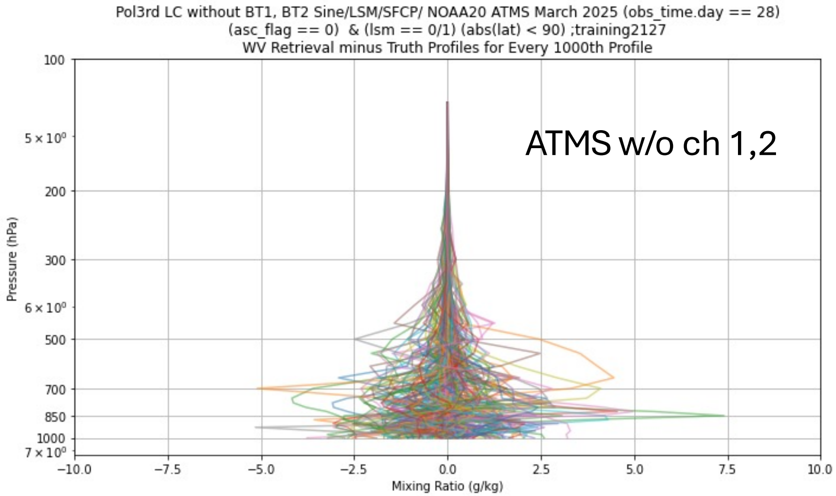
ATMS w/wo 23.8, 31.4 GHz does not impact water vapor profiles





With and without channels 1,2

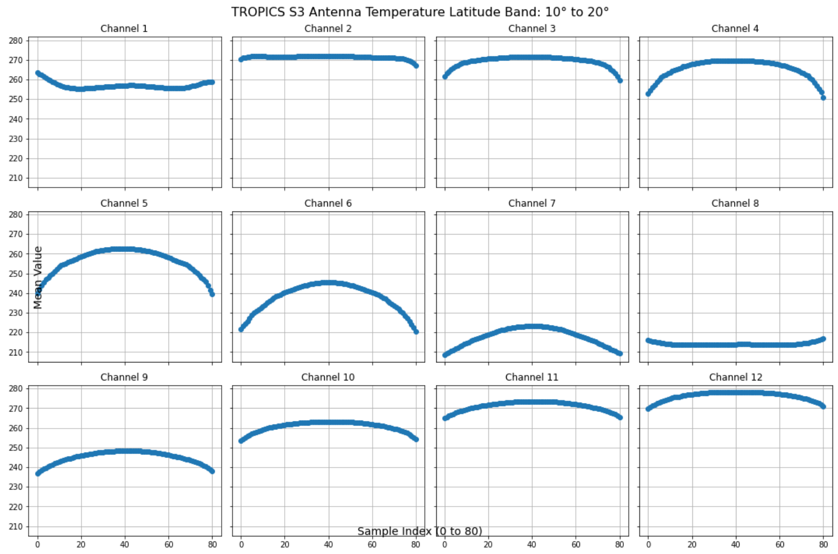




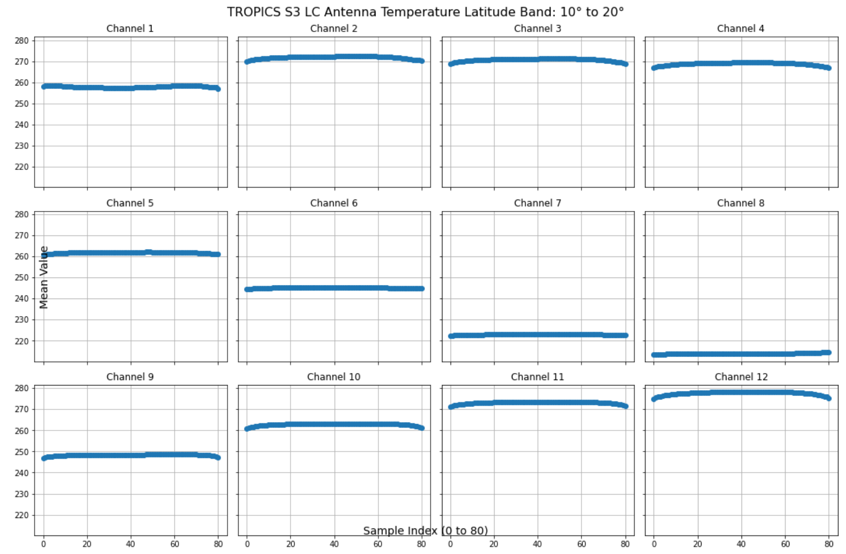
No Impact

TROPICS S3

Original Brightness Temperature

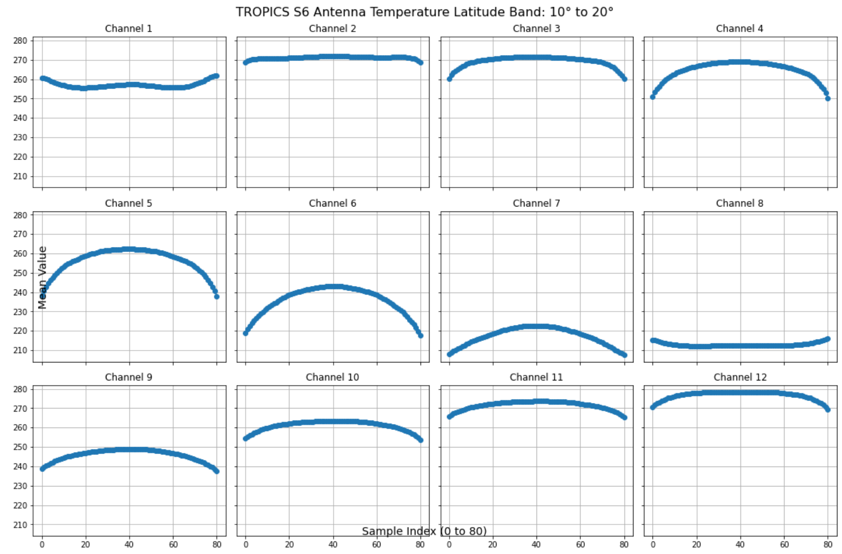


Limb Adjusted Brightness Temperature

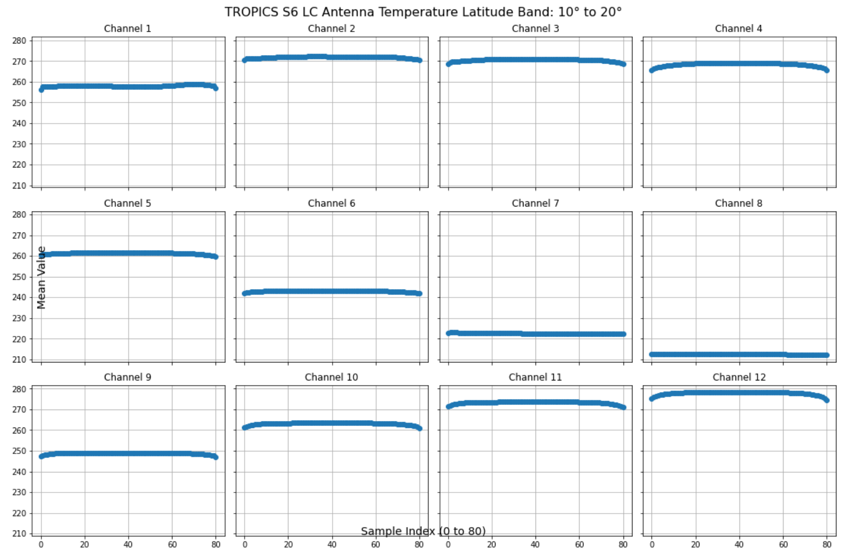


TROPICS S6

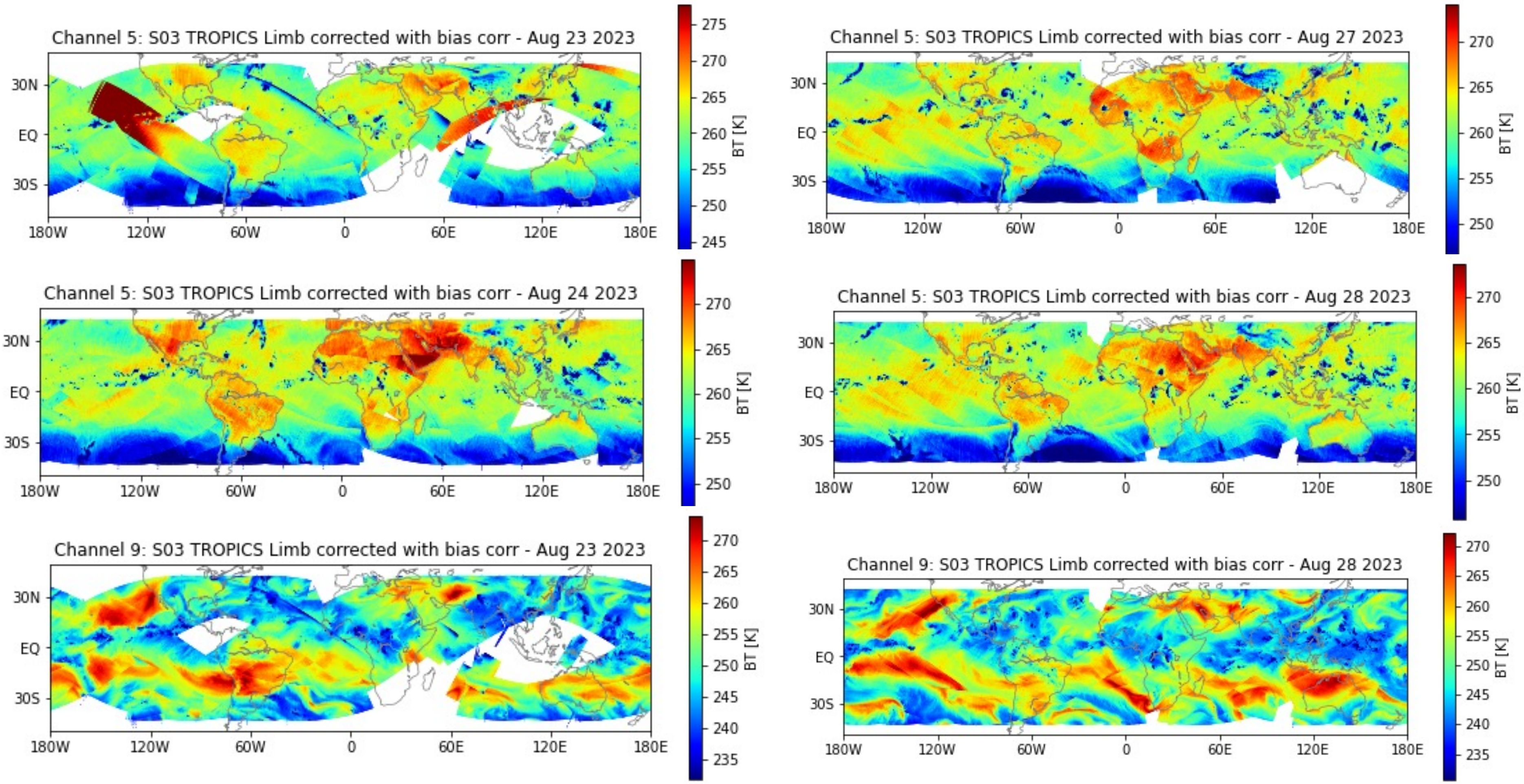
Original Brightness Temperature



Limb Adjusted Brightness Temperature



TROPICS have occasional hiccups



We developed a technique to detect outliers using eigenvectors

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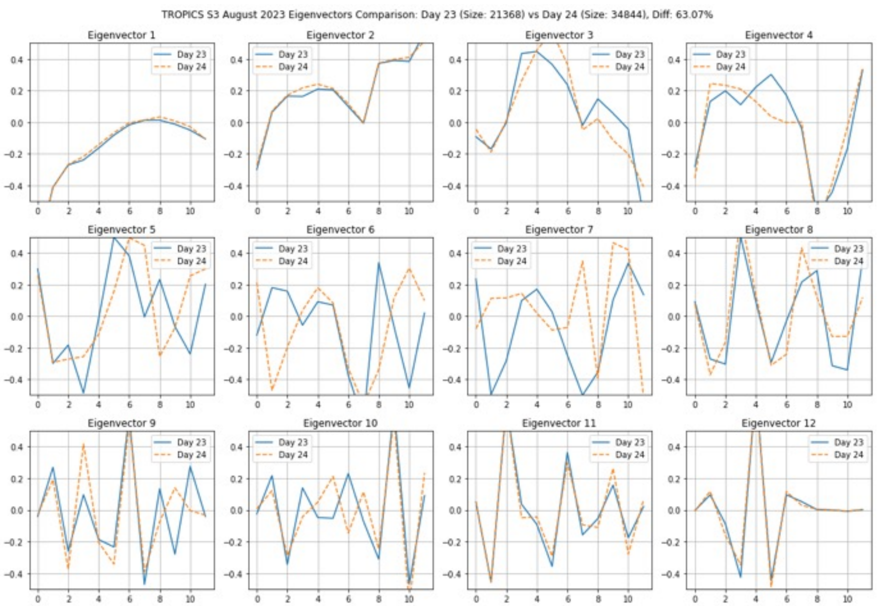
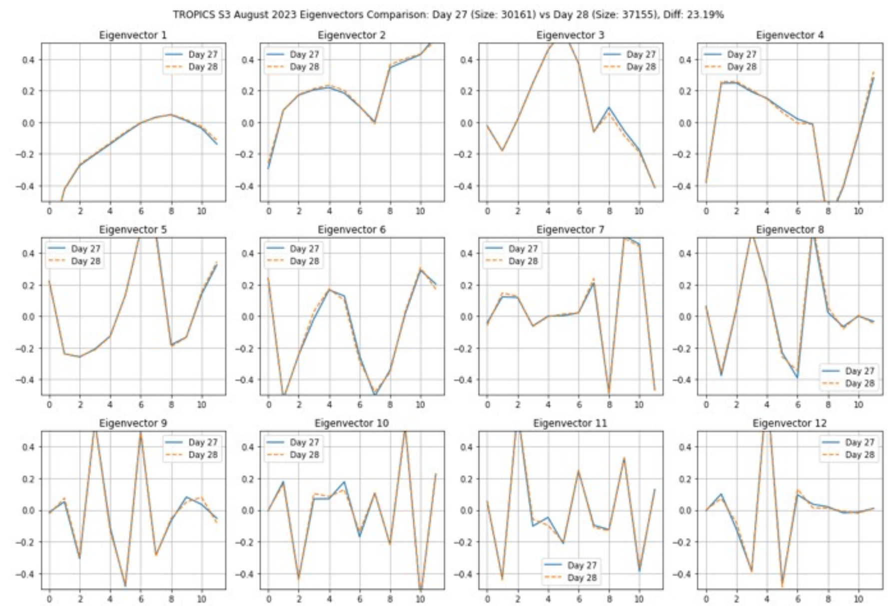
Generate eigenvectors from the brightness temperatures each day, and compare to the day before





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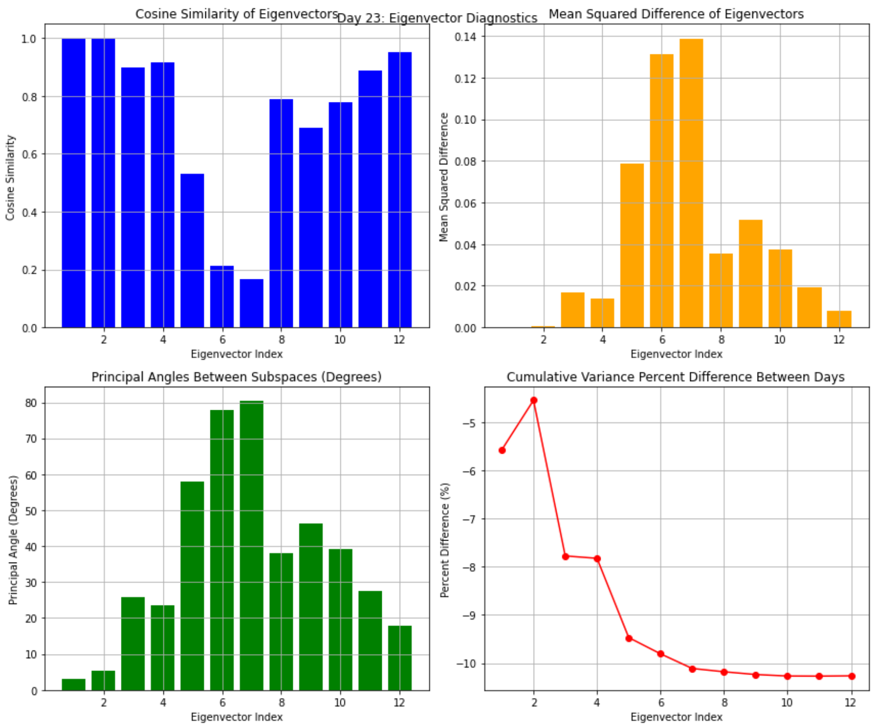
BAD



GOOD