GOSAT XCO_2 Products comparison

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GOSAT XCO_2 retrieval systems in this study

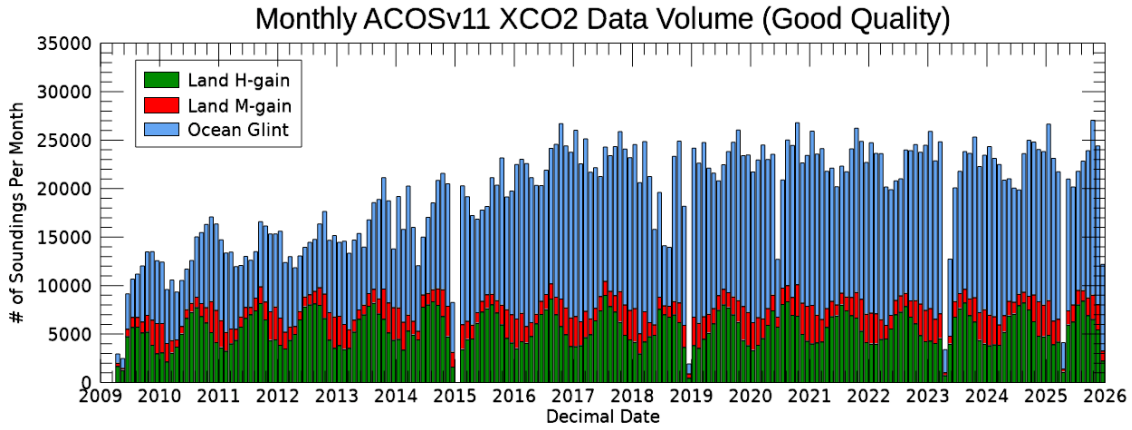
Product	Version	Date Range	Contact	JAXA version	Bias Correction?	Notes
ACOS	V11.0	20090418-20260316	Chris O'Dell (CSU)	v300	Yes (6 regressors, 3 obs modes)	Also used for OCO2+OCO3
U. of Leicester ("OCFP")	V7.3	20090418-20221231	Hartmut Bösch (Bremen), Rob Parker (Leicester)	v205/210	Yes	Being superceded by FusionalP for CO2M
NIES	V3.05	20090423-20260228	Yukio Yoshida, Yu Someya (NIES)	v230.231	Yes (2-3 regressors, 3 modes)	Similar to GOSAT-2 but that is recoded for copyright reasons; GOSAT-GW based on GOSAT-2 retrieval
FOCAL	V4	20090423-20241231	Max Reuter, Stefan Noel (Bremen)	v300	Yes (10 regressors; land vs ocean)	Also used for GOSAT2/OCO2 To be used for CO2M
RemoTeC ("SRFP")	V2.41	20090423-20230831	Andre Butz (Heidelberg)	v300	Ocean only	Reprocessing new version with SRON now (see poster!) Will be RemoTAP for CO2M
JAXA EORC	V3	20090418-20231231	N Kikuchi, K Shiomi (JAXA)	v230.231	No	Partial Column Product; TIR+SWIR

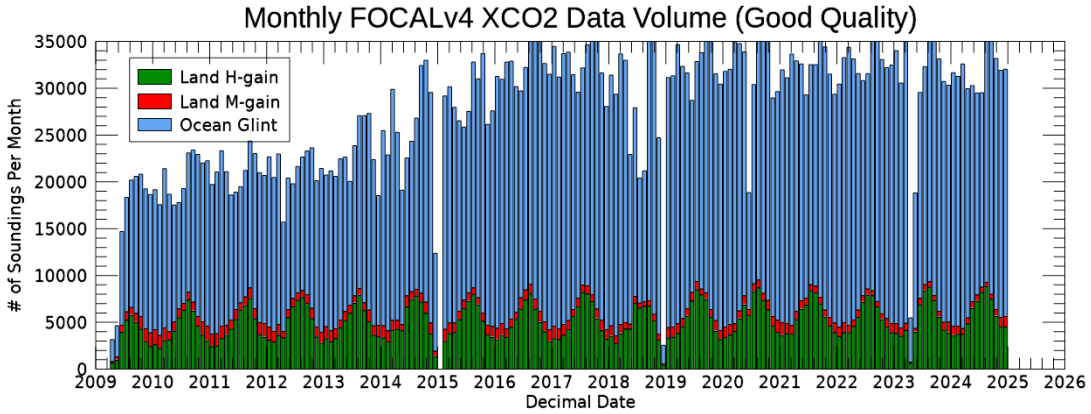
- Only good-quality soundings for each dataset considered.
- Soundings all matched to ACOS L1B sounding_id to enable direct sounding-level comparisons

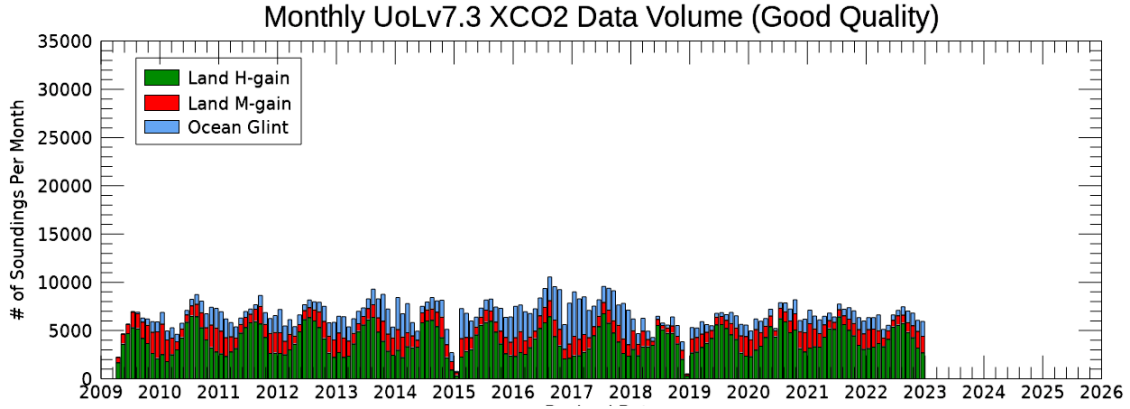
Key retrieval system aspects to consider

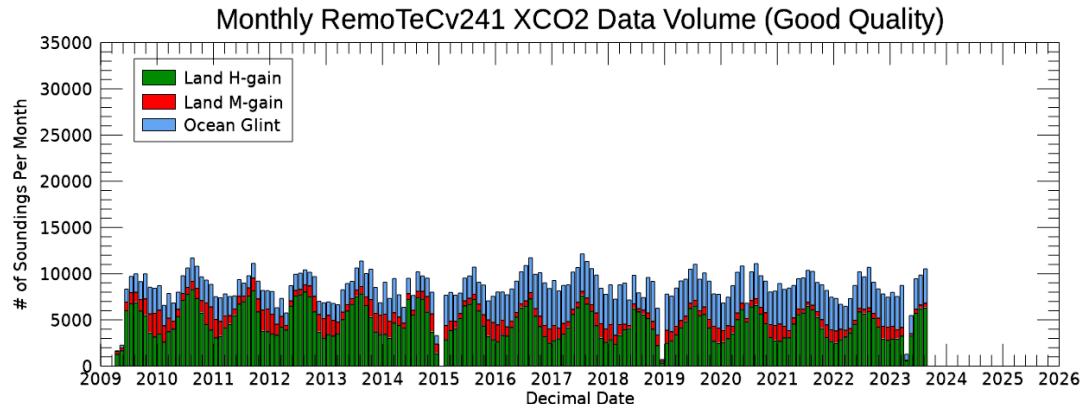
- **Sounding selection**: Which soundings to perform retrievals on?
- **The retrieval** itself: OE vs ML, forward model physics, inputs:
  - Spectroscopy, Meteorology, Solar line list
- Post-Retrieval **Filtering**
- Post-Retrieval **Bias Correction**
- Posterior **Uncertainty Estimate**

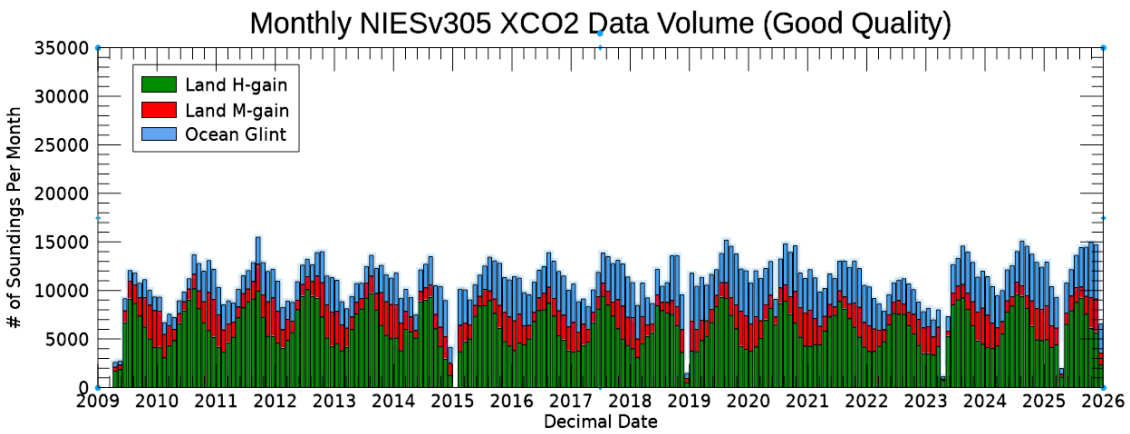
Dataset Sizes & Time Series

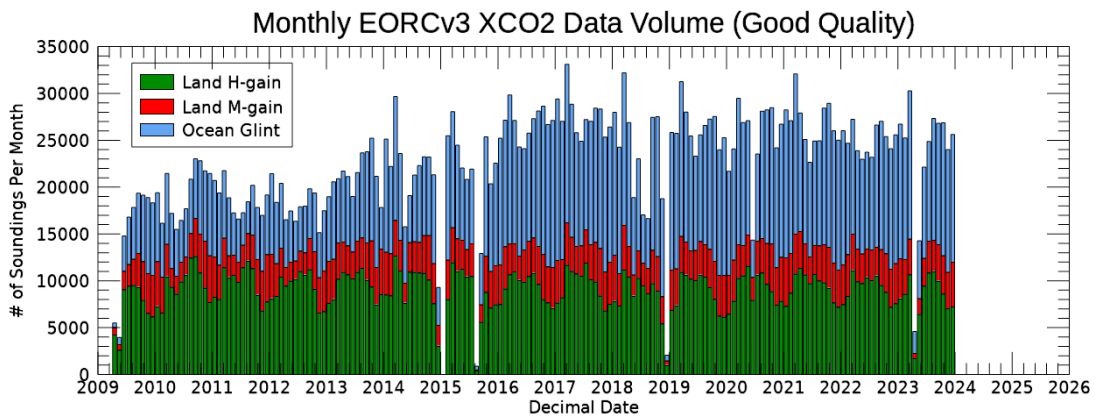






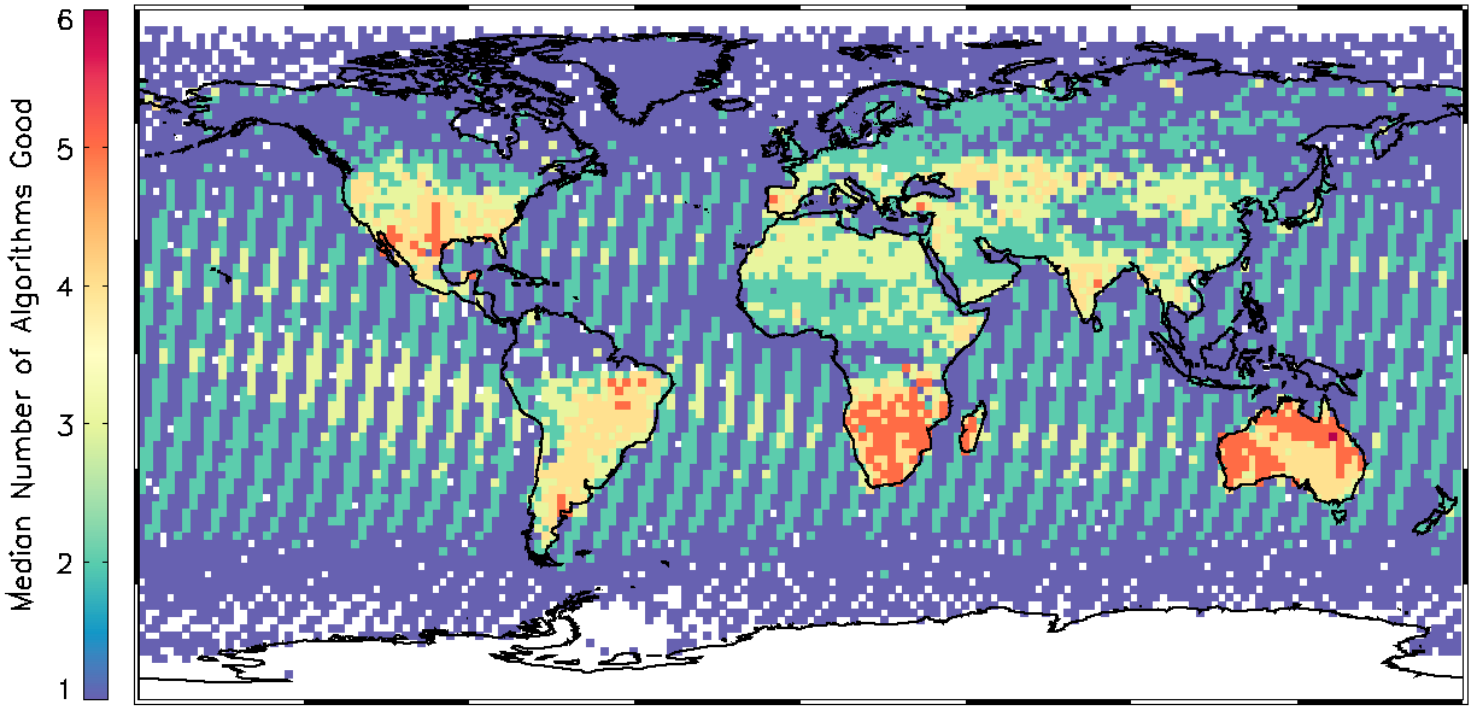




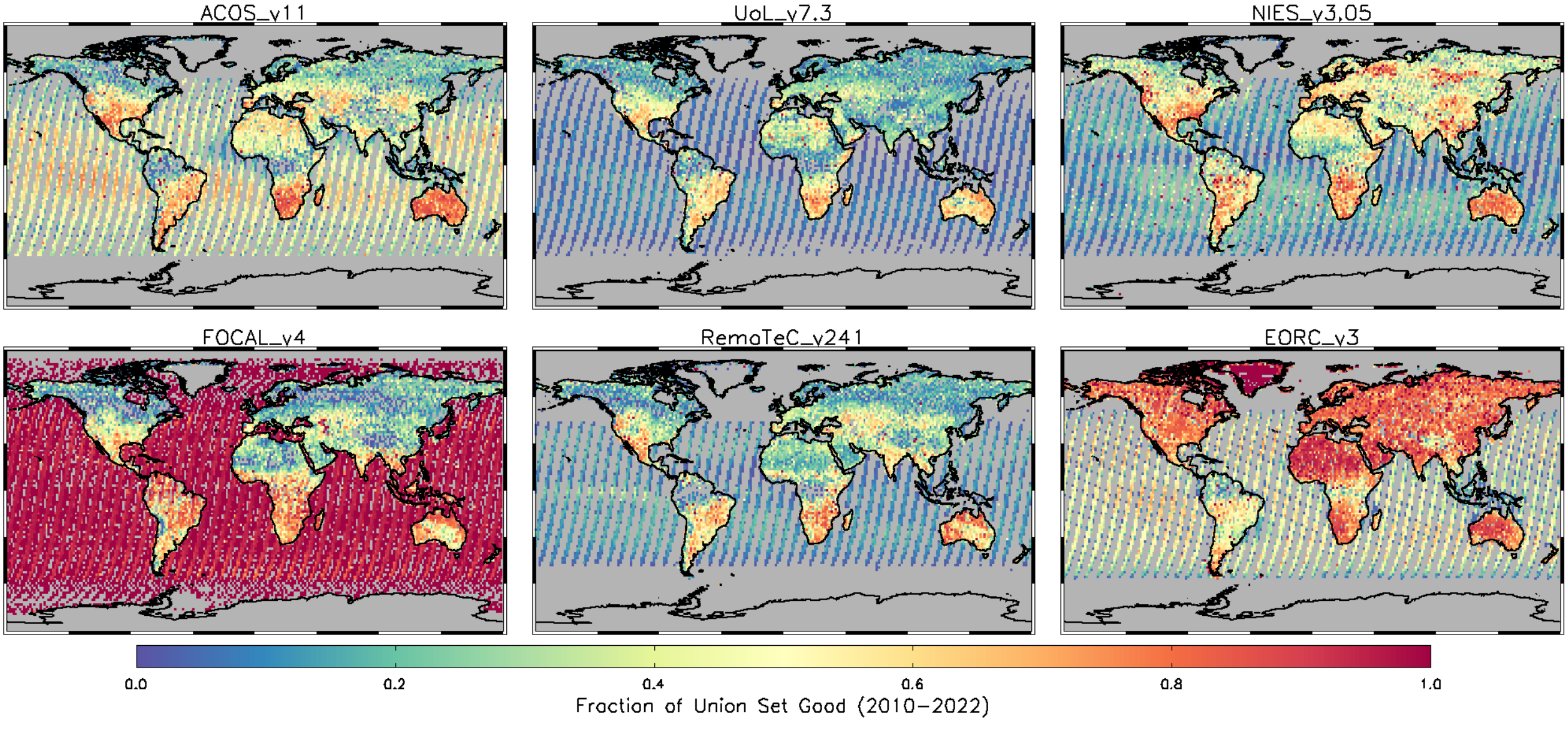


Union of datasets

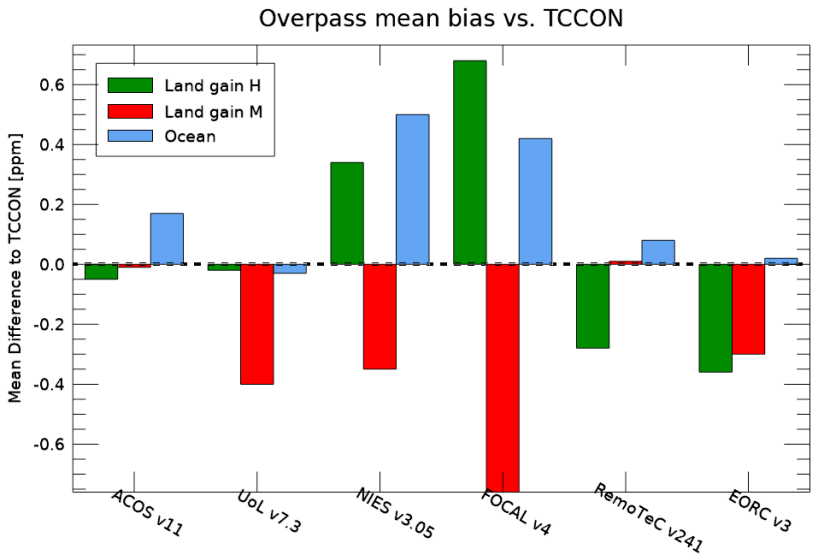
- All unique soundings that were good in ANY dataset.
- Nunion = 7.65M soundings
- Nunion(<=2022) = 6.36M soundings

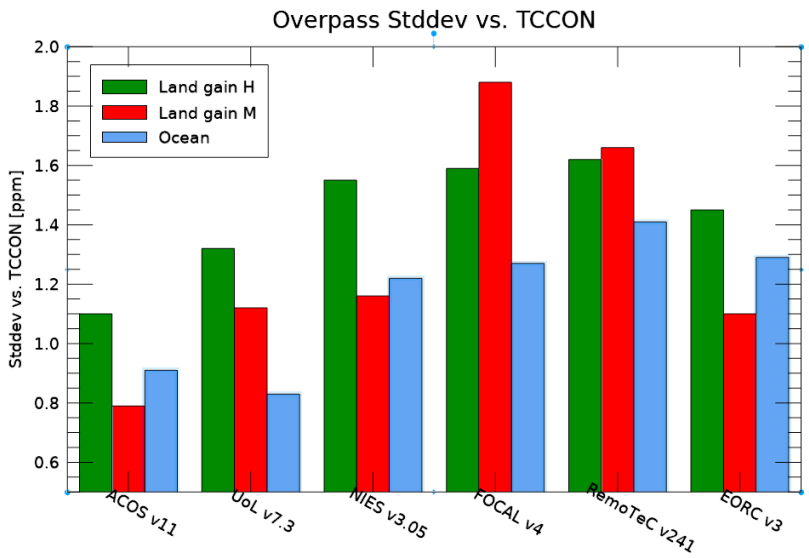


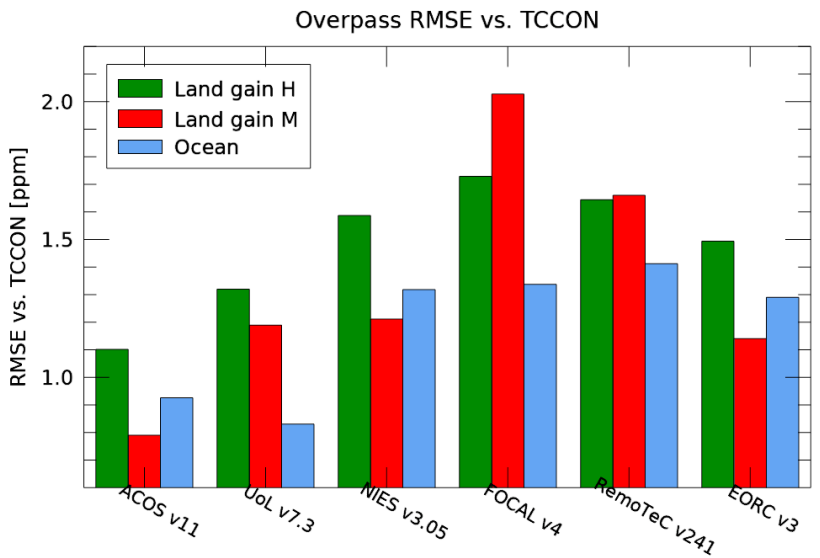
Each Algo's quality flag



High-Level Error Statistics vs. TCCON



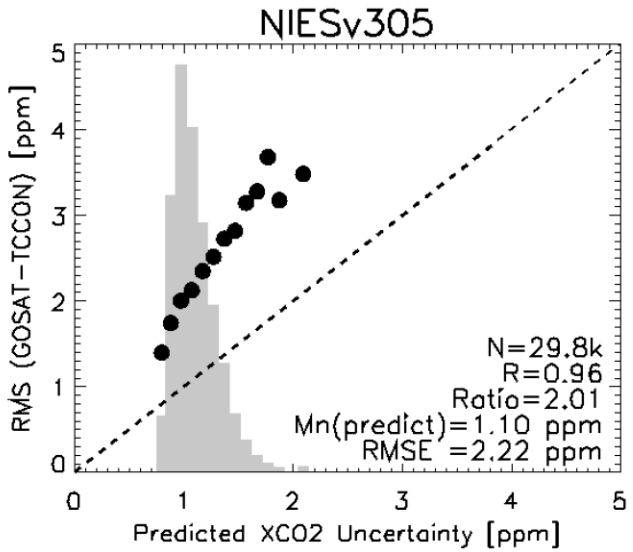


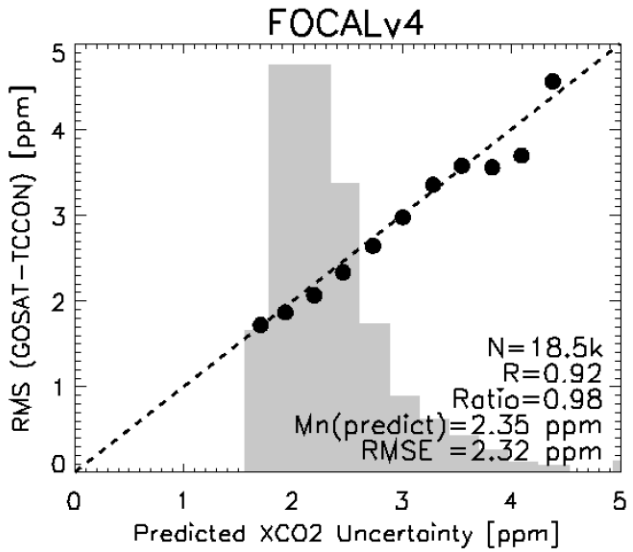


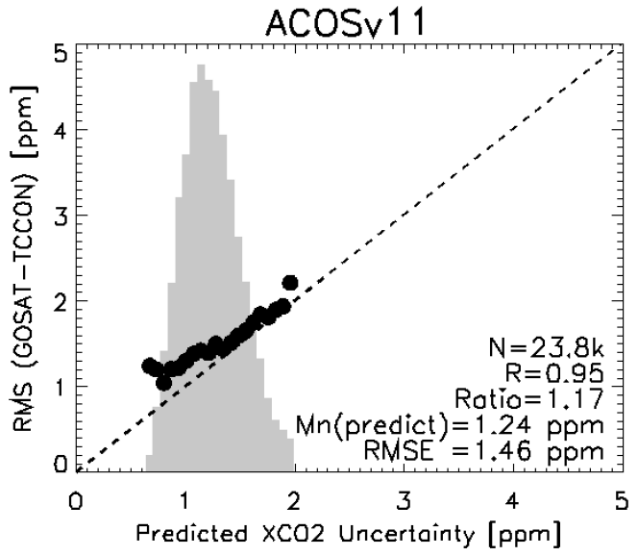
GGG2020: +/- 2.5 deg lat; +- 5 deg lon; +- 2 hours time difference.

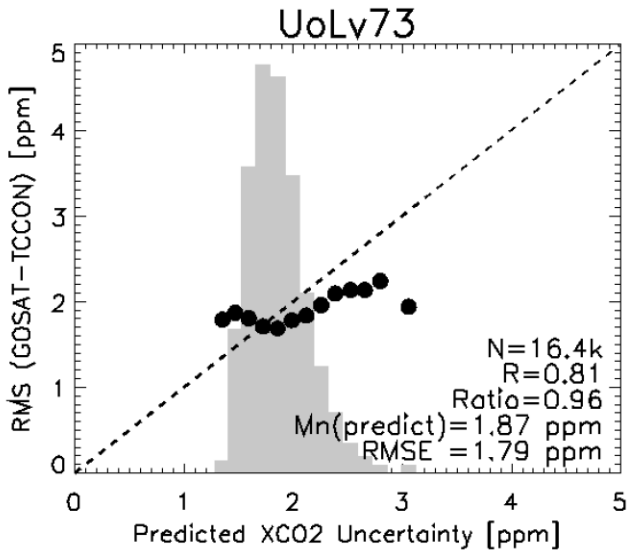
Robustness of Reported Uncertainty

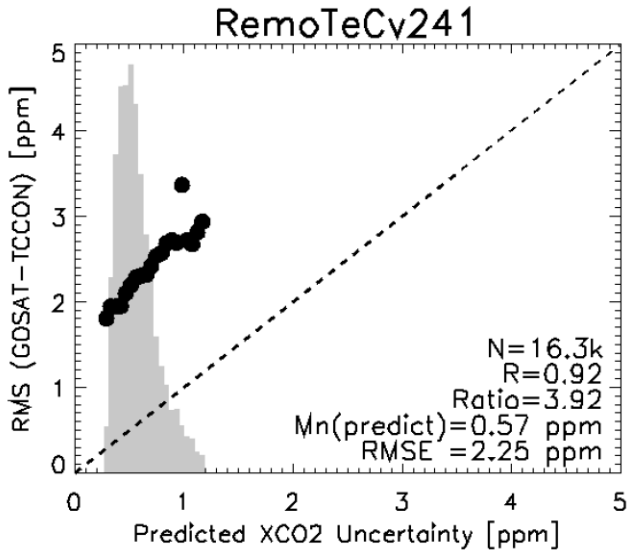
Land gain H, Truth=TCCON

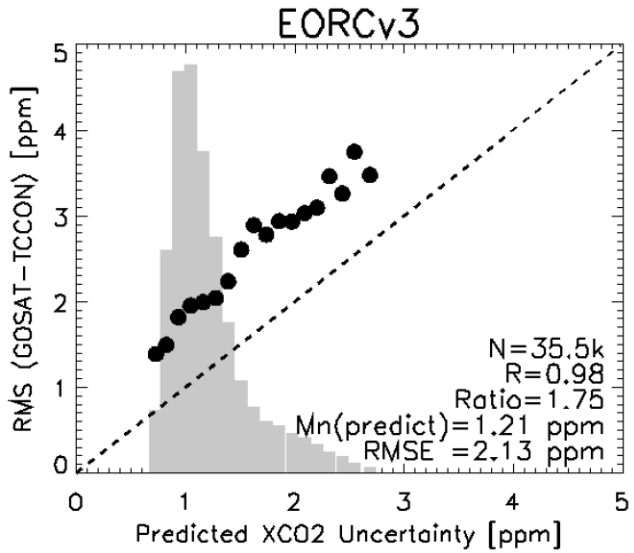






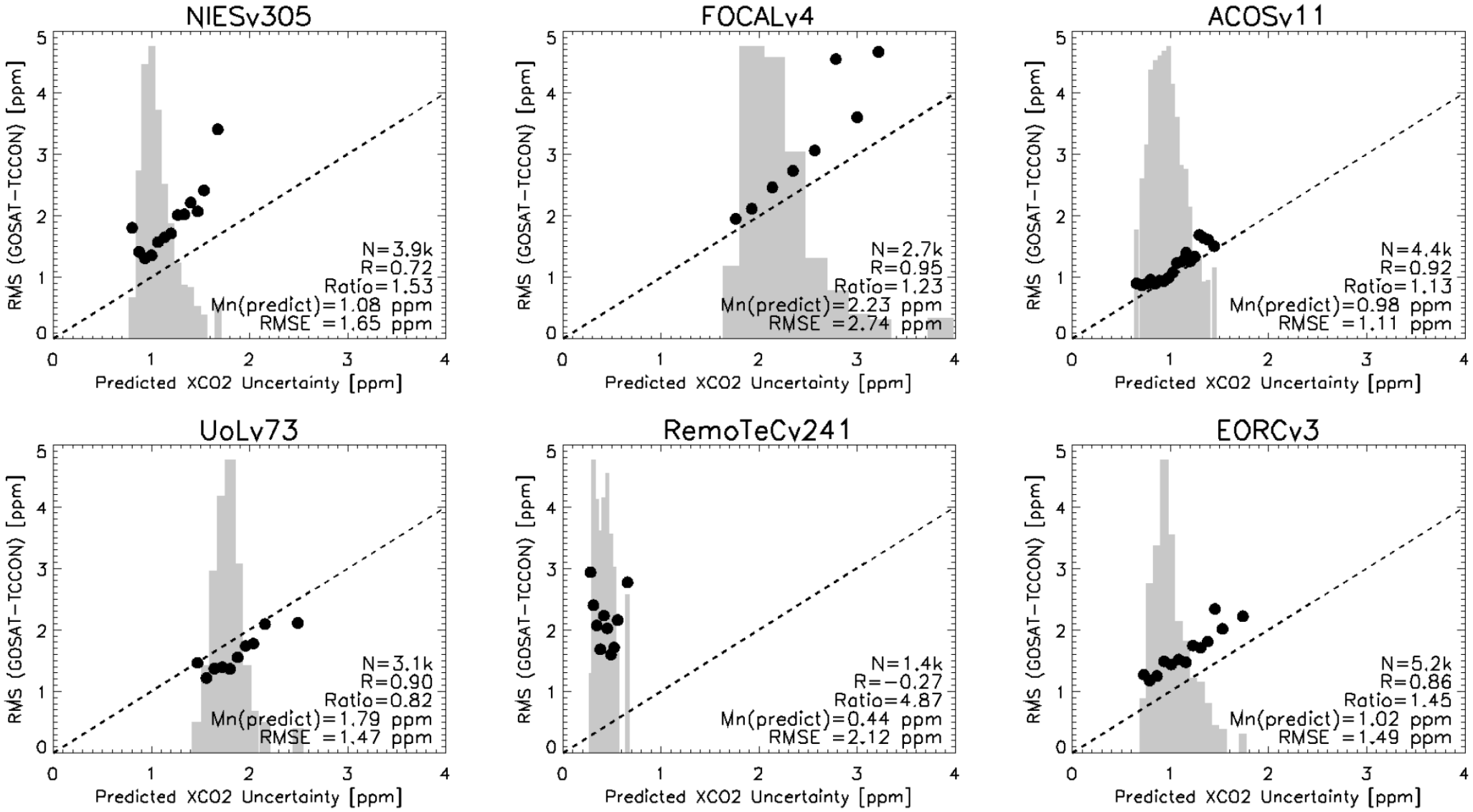






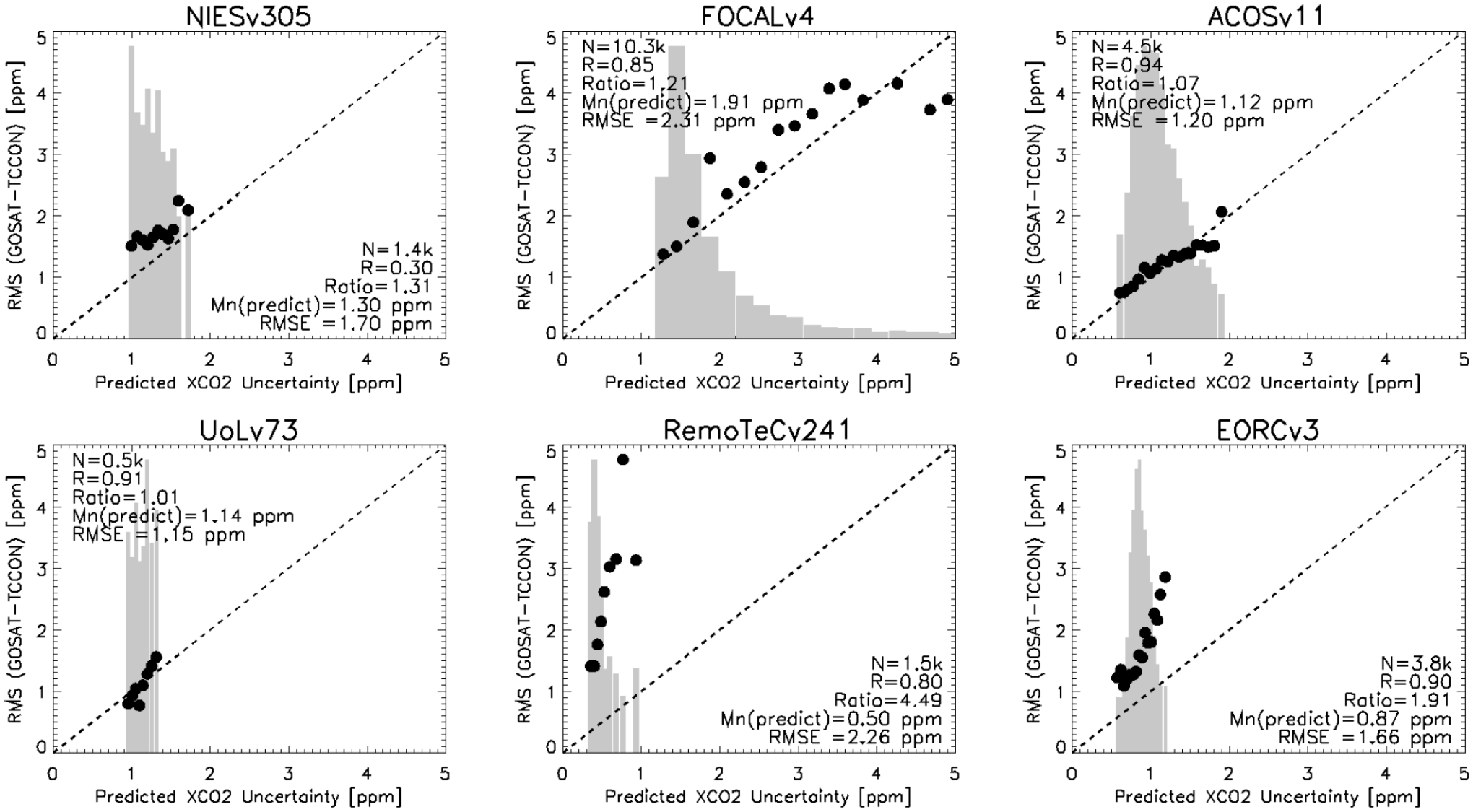
Robustness of Posterior Uncertainty

Land gain M, Truth=TCCON



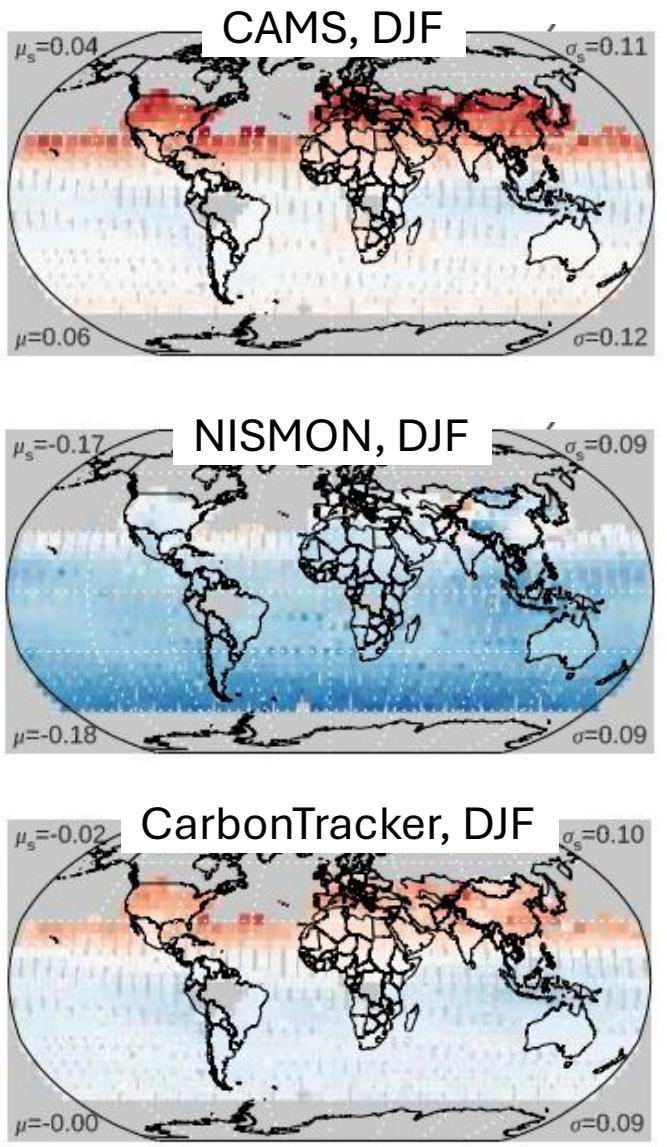
Robustness of Posterior Uncertainty

Ocean gain H, Truth=TCCON

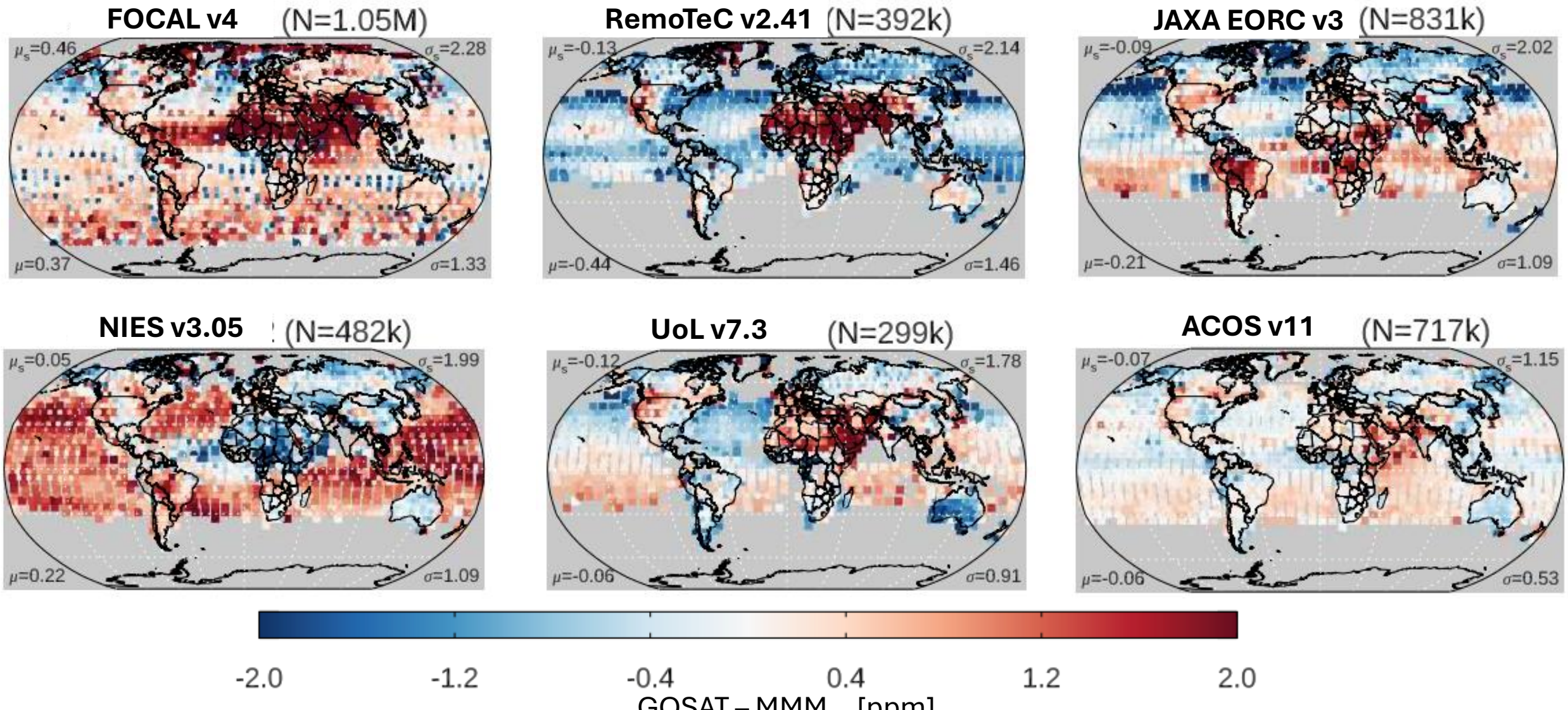


Comparisons to Models

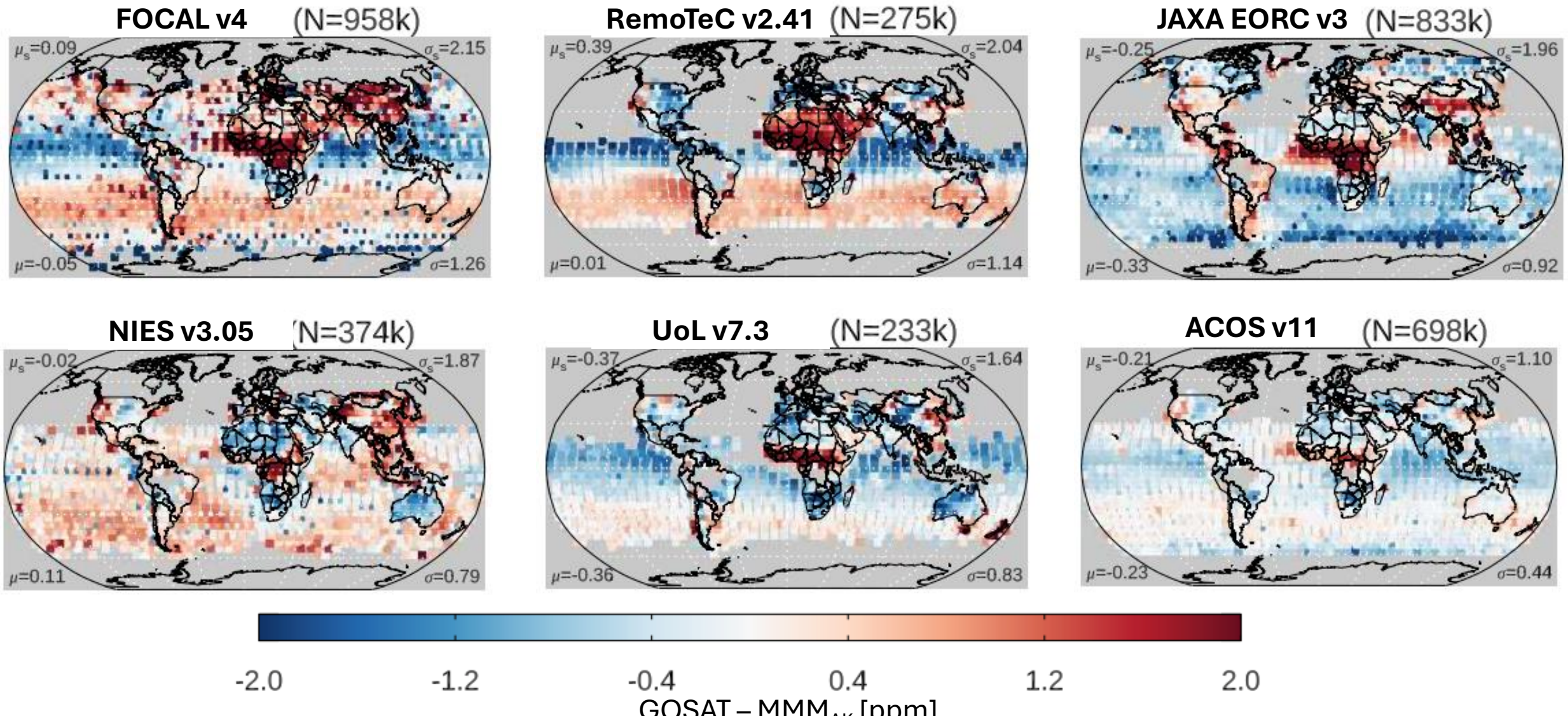
- **Linear interpolation in latitude, longitude, time.**
- **No model-agreement requirement (”Signal Plots”)**
- **5 Models, all assimilating in-situ data:**
  - CarbonTracker CT2022+NRT2025-1 (NOAA) – Andy Jacobson
  - Jena CarboScope s10oc_v2025 – Christian Rodenbeck
  - CAMS v24r1 – Frederic Chevalier
  - Nismon v2025 – Yosuke Niwa
  - University of Edinburgh v8.0 – Liang Feng & Paul Palmer
- **AK correction applied to each (generally small)**
- **“MMM” = Multi-Model Median.**



JJA, 2010-2022
Mean XCO2 differences vs. MMM



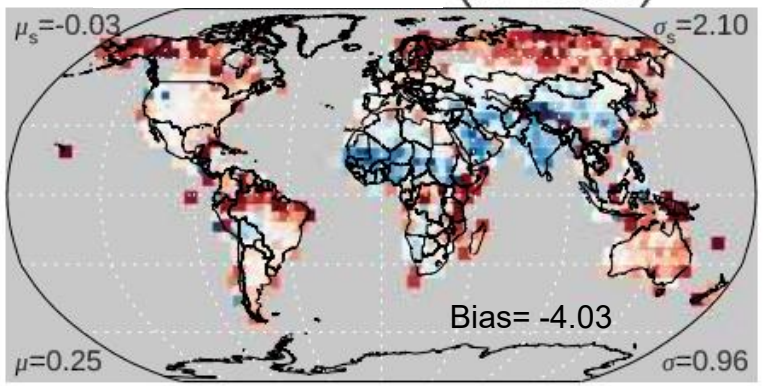
DJF, 2010-2022
Mean XCO2 differences vs. MMM



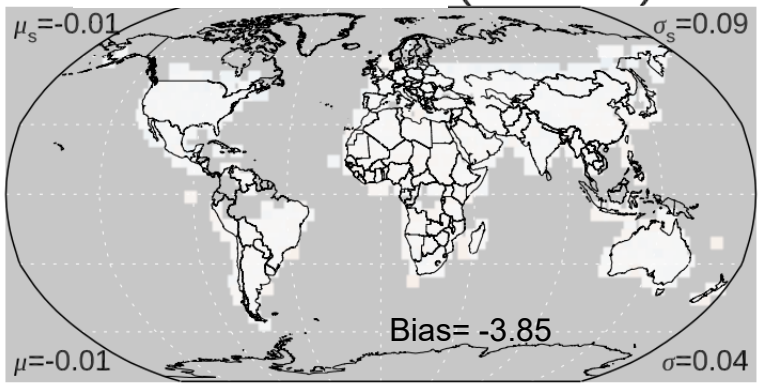
Size of Bias Correction: Land

SON 2010-2022 (offset-subtracted)

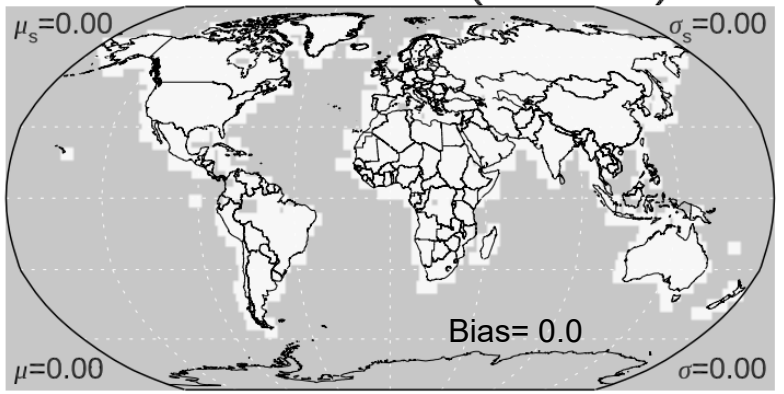
FOCAL v4 (N=248k)



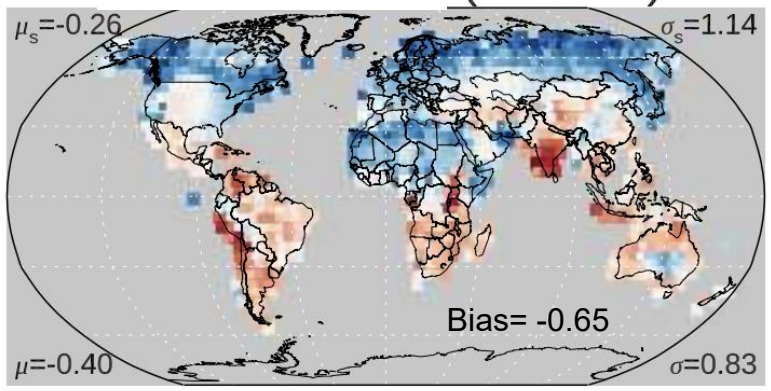
RemoTeC v2.41 (N=236k)



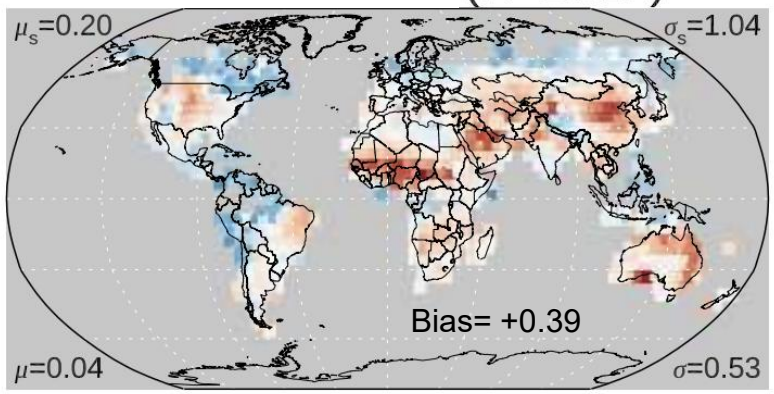
JAXA EORC v3 (N=497k)



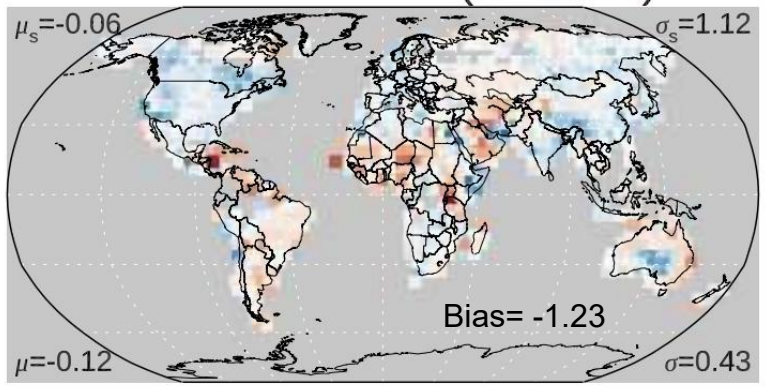
NIES v3.05 (N=339k)



UoL v7.3 (N=211k)



ACOS v11 (N=331k)

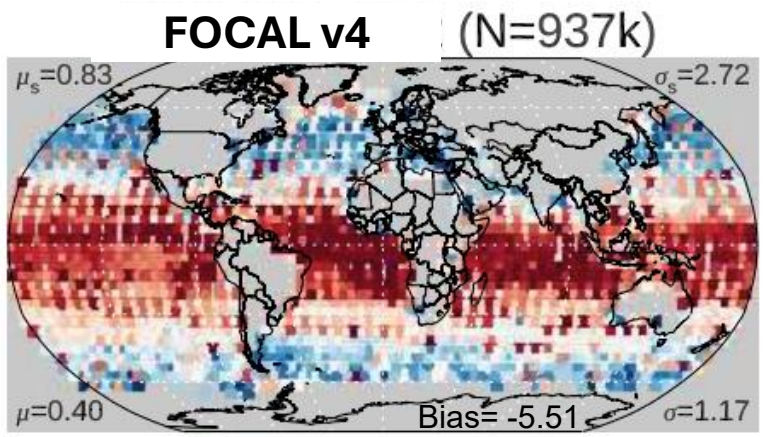


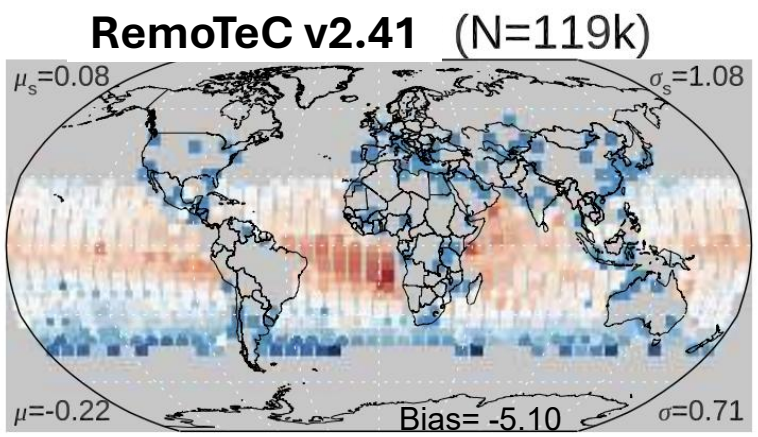
-2.0 -1.2 -0.4 0.4 1.2 2.0

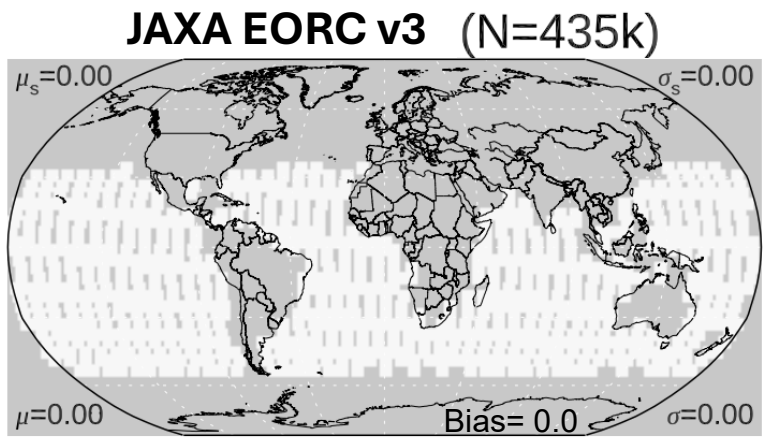
Bias correction (centered) [ppm]

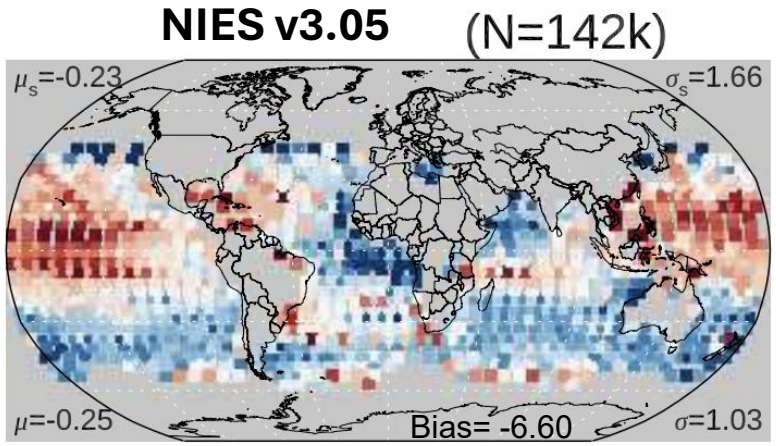
Size of Bias Correction: Water

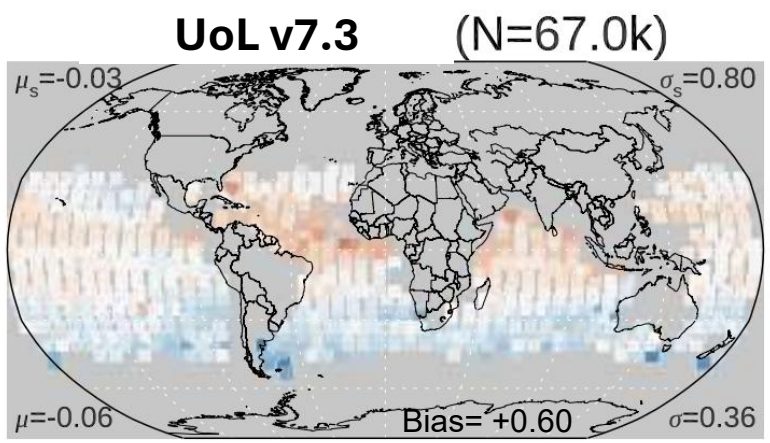
SON 2010-2022 (offset-subtracted)

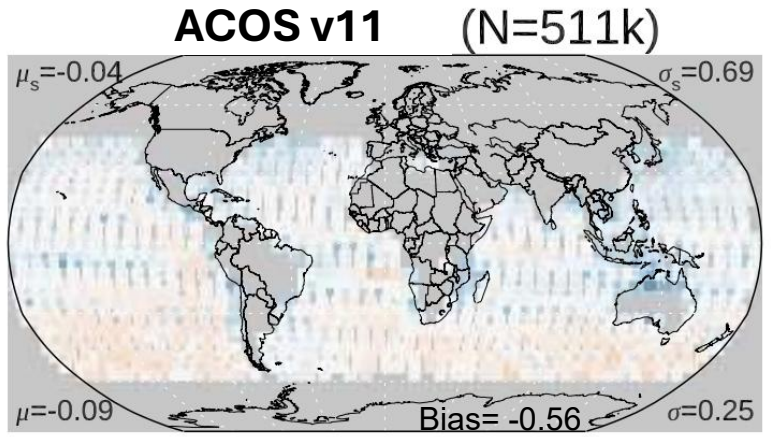


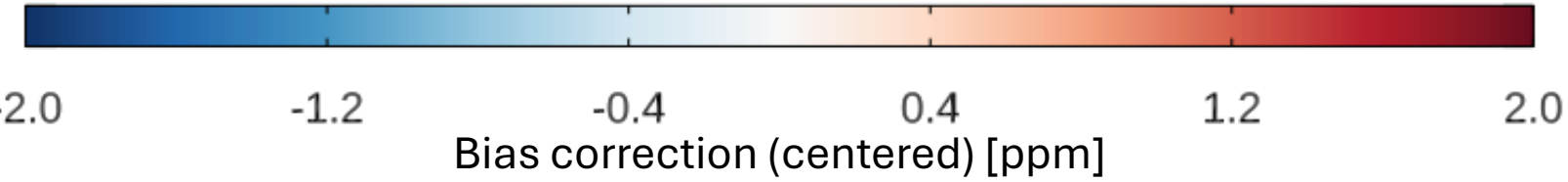




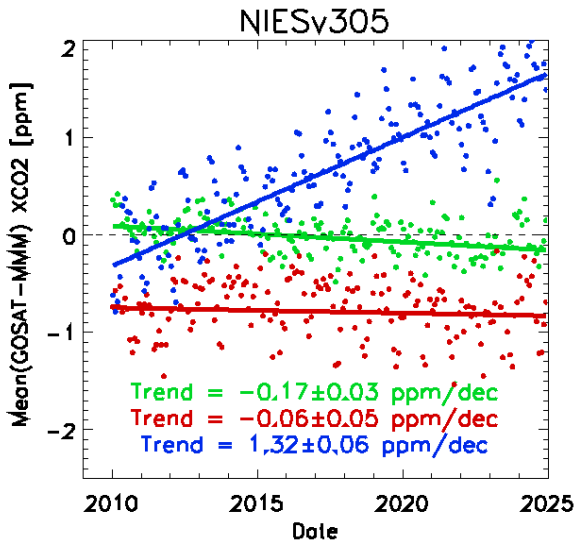


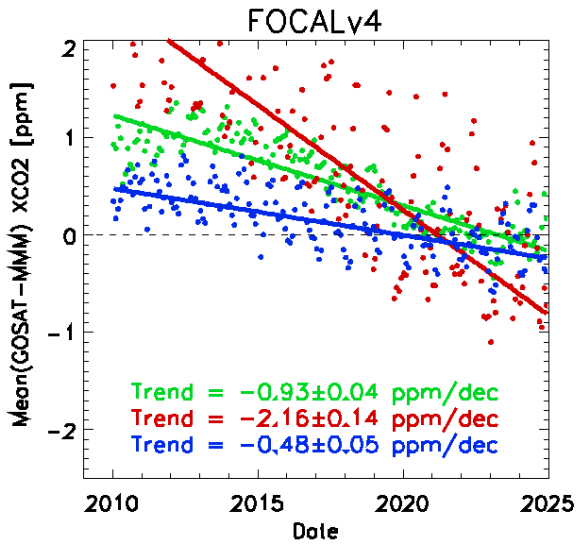


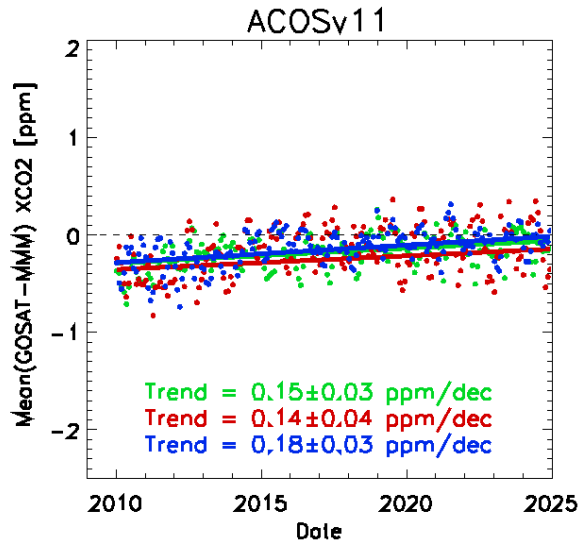


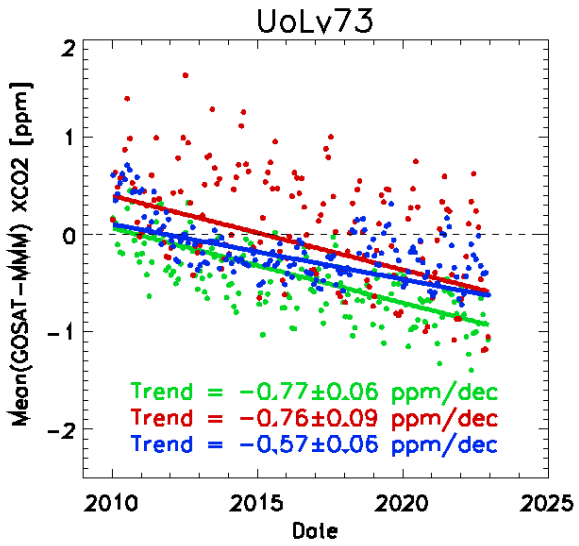


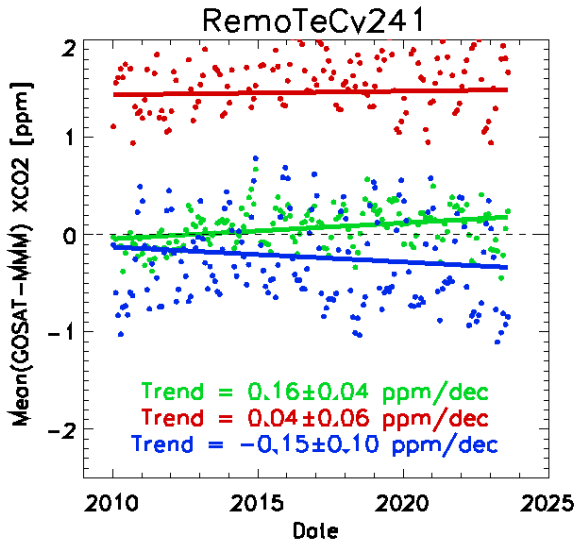
XCO2 Time Trends vs. Multi-Model Median

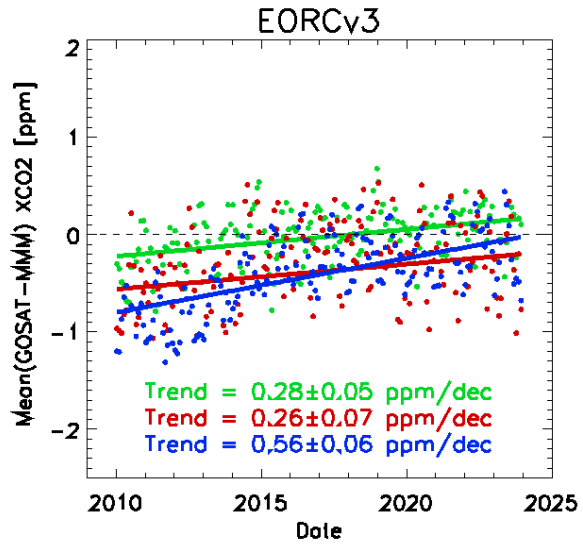








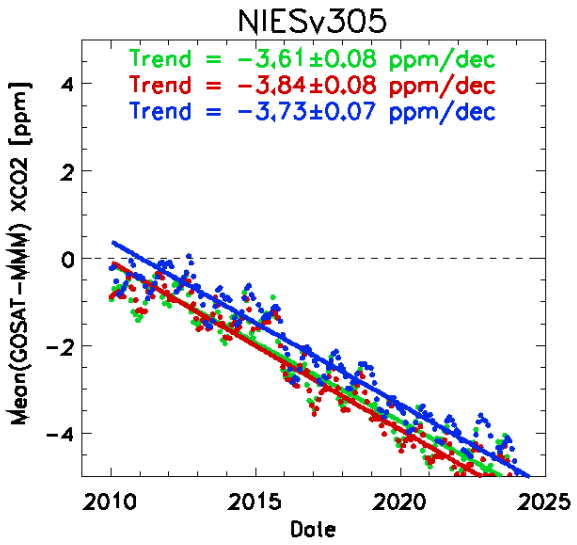


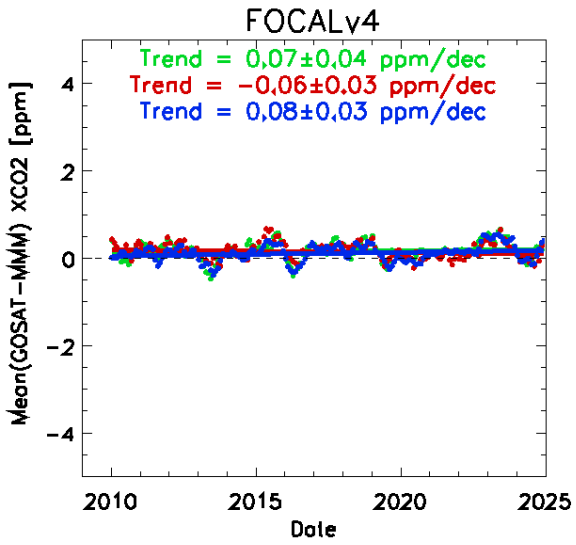


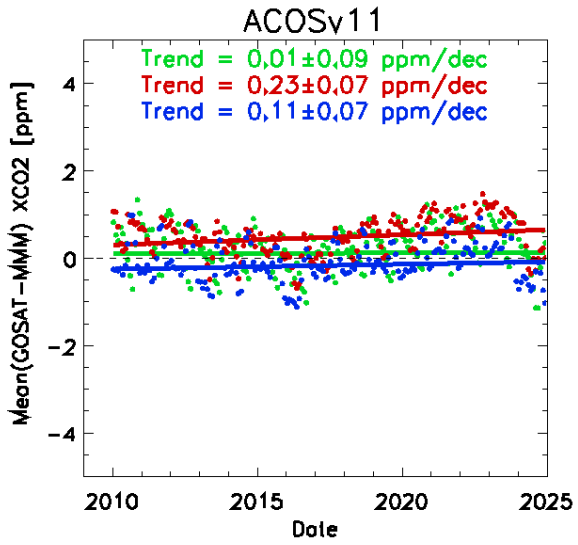
Notes

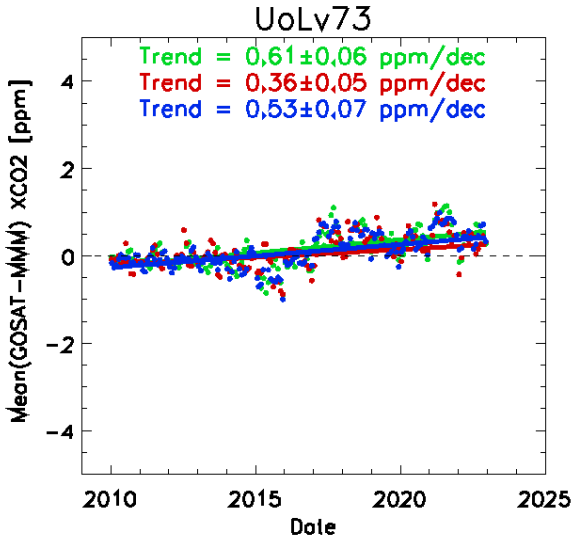
- Several retrievals have large spurious trends, depending on the surface type & gain.
- Results are robust against model removal.

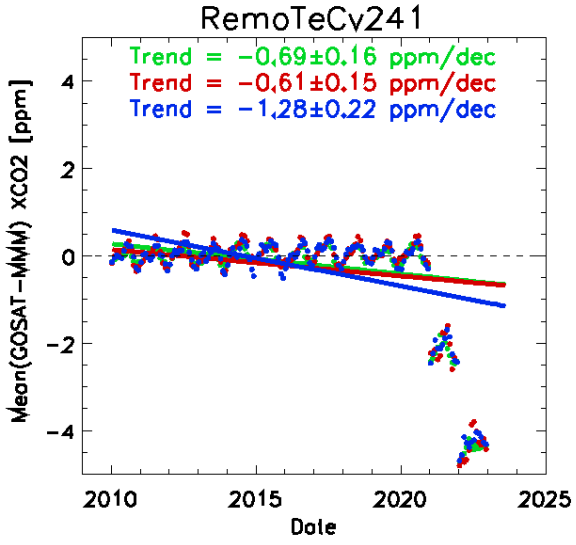
Prior Time Trends vs. Multi-Model Median

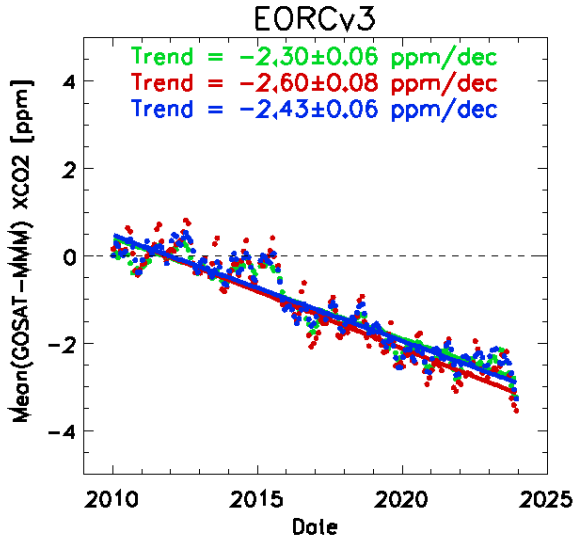












Notes

- FOCAL has the “best” prior in terms of agreement with MMM.
- NIES & EORC priors have significant negative trends (-0.37 and -0.25 ppm/yr, respectively)
- RemoTeC didn’t include the secular increase for 2021-2023.

Findings

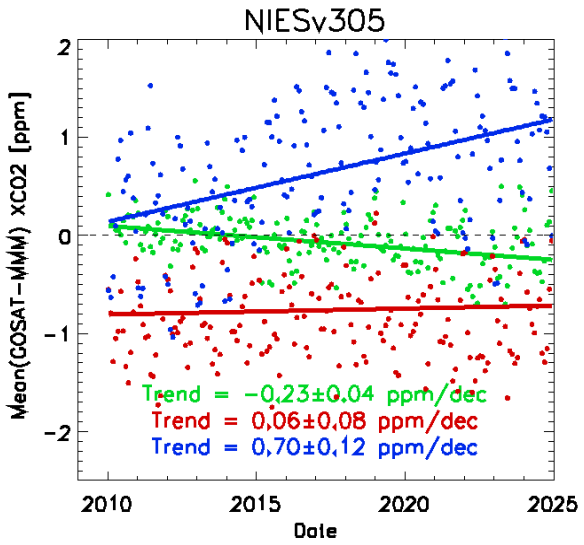
- **Throughput**: Widely varying throughput, especially for ocean data. Most algorithms have similar land gain H, but land gain M (bright/desert) and ocean are widely varying in particular.
- **Accuracy** : Again, wide variations. Some algorithms have 2-3x worse error statistics. This is difficult to evaluate because of the widely varying posterior uncertainty estimates, as well as different throughputs. Ie, will some errors "integrate down"?
- **Stated uncertainty**: Varies by a factor of 4 for the same soundings! One algorithm stands out as far too low; several are high but consistent with their errors. Algs also define stated uncertainty different, e.g. purely noise-based, or including systematic errors as well.
- **Size of Bias Correction:** Large variation, from zero to multiple ppm. Some algorithms (like FOCAL) put more focus on the BC.
- Given that all the algorithms fit spectra using a forward model, there is a surprising variation in performance across these metrics.
- For some algorithms, these results may be pessimistic if not a lot of work has been done for a given algorithm (filtering, BC, GOSAT specificity).

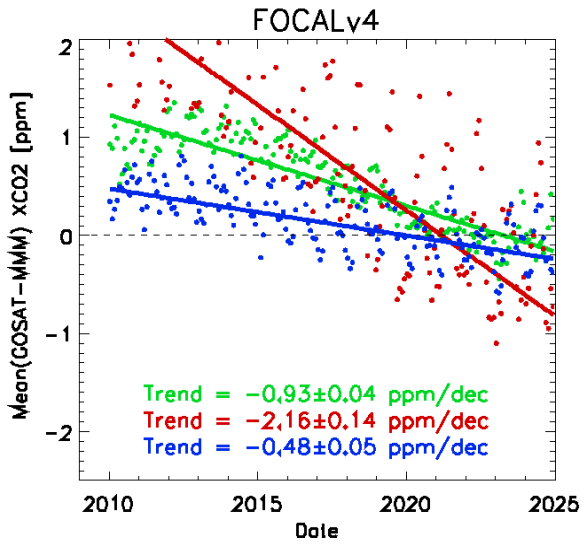
Final Thoughts & Suggestions

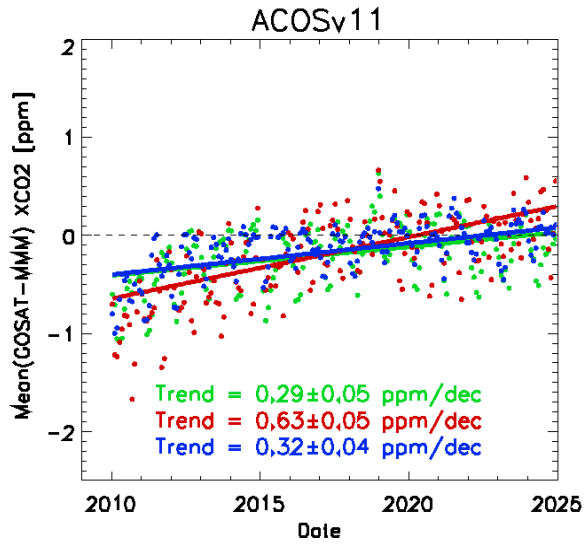
- If assimilated into carbon models, we can expect these datasets to drive large differences in fluxes!
- Each group should carefully evaluate their filters & bias correction, to look for potential improvements.
- Important to look at not only single soundings, but how the data average down.
- An OSSE-based intercomparison still offers the potential to learn even more.

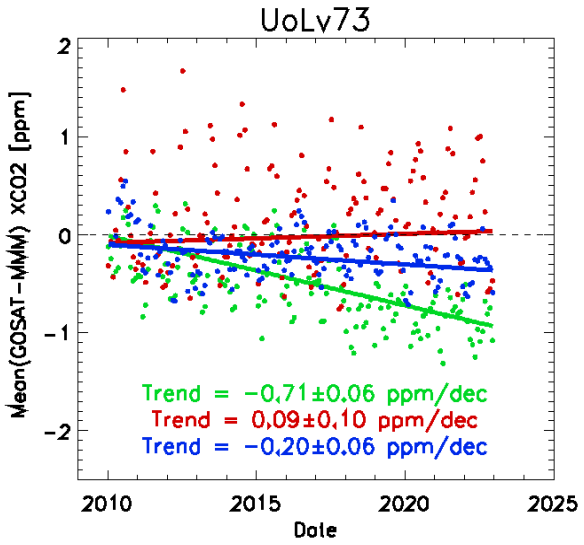
Backup

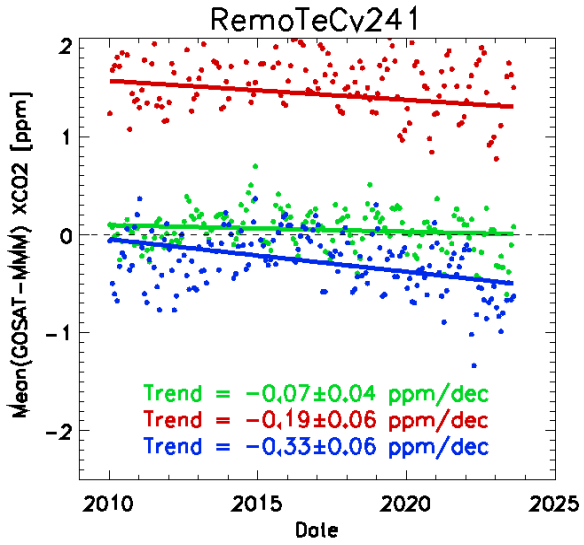
XCO2_Raw Time Trends vs. Multi-Model Median

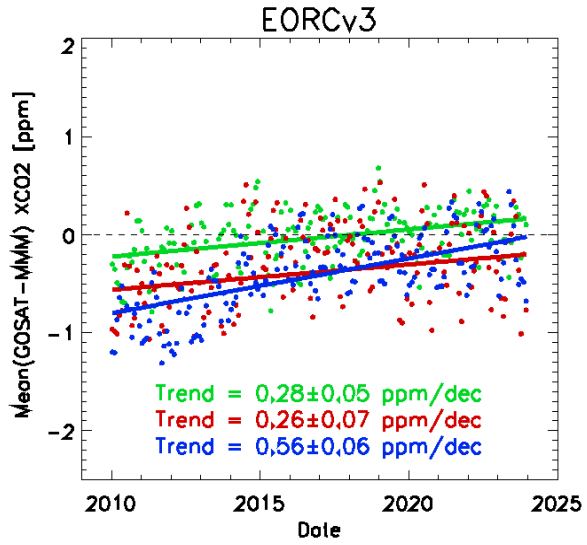












Notes

- Several retrievals have large spurious trends, depending on the surface type/observation mode.
- ACOS,EORC,and UoL have reasonably good consistency across obs modes.
- Results are robust against model removal.

Quality Flag statistics over union set
(Date <= 20221231)

Algorithm	Ntot	Tot%	NlandH	landH%	NlandM	landM%	NoceanH	OceanH%	NoceanM	oceanM%
ACOS_v11	2998907	48.9%	865878	45.3%	310792	48.3%	1822236	51.0%	1	0.0%
UoL_v7.3	1055513	17.2%	613021	32.1%	212605	33.0%	229887	6.4%	0	0.0%
NIES_v3.05	1723725	28.1%	944946	49.5%	315675	49.0%	463093	13.0%	11	0.1%
FOCAL_v4	4322735	70.4%	778988	40.8%	151663	23.5%	3382707	94.7%	9377	93.0%
RemoTeC_v241	1352790	22.0%	742541	38.9%	168486	26.2%	441058	12.3%	705	7.0%
EORC_v3	3569803	58.2%	1426062	74.6%	559870	86.9%	1583871	44.3%	0	0.0%
Any	6136678	100.0%	1910467	31.1%	644116	10.5%	3572007	58.2%	10088	0.2%

TCCON Statistics (land H)

Overpass value
(Single Sounding value)

Algo	Nsound	Nover	Mean	Stddev	Stddev (site med)	Median (site rmse)
ACOSv11	20.1k (23.7k)	3447	-0.05 (-0.06)	1.10 (1.53)	0.48 (0.42)	1.13 (1.59)
UoL v7.3	14.8k (18.6k)	2675	-0.02 (-0.04)	1.32 (1.83)	0.54 (0.44)	1.37 (1.90)
NIES v3.05	25.7k (29.1k)	4148	0.34 (0.33)	1.55 (2.19)	0.67 (0.74)	1.69 (2.23)
FOCAL v4	14.6k (18.8k)	2742	0.68 (0.64)	1.59 (2.29)	0.79 (0.55)	1.79 (2.56)
RemoTeCv241	15.0k (18.6k)	2832	-0.28 (-0.28)	1.61 (2.27)	0.68 (0.94)	1.67 (2.41)
EORC v3	34.8k (38.6k)	5372	0.36 (0.43)	1.45 (2.10)	0.46 (0.49)	1.46 (2.24)

TCCON Statistics (land M)

Overpass value (Ns>=3)
(Single Sounding value)

Algo	Nsound	Nover	Mean	Stddev	Stddev (site med)	Median (site rmse)
ACOSv11	3323 (4099)	790	-0.01 (-0.04)	0.79 (1.18)	0.61 (0.73)	0.93 (1.33)
UoL v7.3	2776 (3570)	638	-0.40 (-0.43)	1.12 (1.58)	0.53 (0.91)	1.34 (1.77)
NIES v3.05	2487 (3324)	581	-0.35 (-0.23)	1.16 (1.70)	1.41 (1.29)	1.72 (1.90)
FOCAL v4	1549 (2579)	402	-0.76 (-0.73)	1.88 (3.09)	1.78 (1.19)	2.70 (4.11)
RemoTeCv241	603 (1563)	170	0.01 (0.03)	1.66 (2.15)	1.87 (1.54)	2.09 (2.32)
EORC v3	4541 (5263)	890	-0.30 (-0.36)	1.10 (1.51)	0.75 (0.78)	1.24 (1.46)

TCCON Statistics (ocean H)

Overpass value (Ns>=3)
(Single Sounding value)

Algo	Nsound	Noverpass	Mean	Stddev	Stddev (site med)	Median (site rmse)
ACOSv11	3423 (4046)	575	0.17 (0.09)	0.91 (1.21)	0.60 (0.50)	0.93 (1.26)
UoL v7.3	294 (497)	69	-0.03 (-0.14)	0.83 (1.14)	0.62 (0.49)	0.81 (1.07)
NIES v3.05	794 (1311)	193	0.50 (0.41)	1.22 (1.63)	0.72 (0.64)	1.33 (1.64)
FOCAL v4	7621 (8999)	1143	0.42 (0.35)	1.27 (2.32)	0.44 (0.83)	1.51 (3.49)
RemoTeCv241	743 (1349)	165	0.08 (-0.07)	1.41 (2.30)	0.73 (1.07)	1.27 (2.96)
EORC v3	3088 (3367)	414	0.02 (0.02)	1.29 (1.65)	0.61 (0.76)	1.43 (1.73)

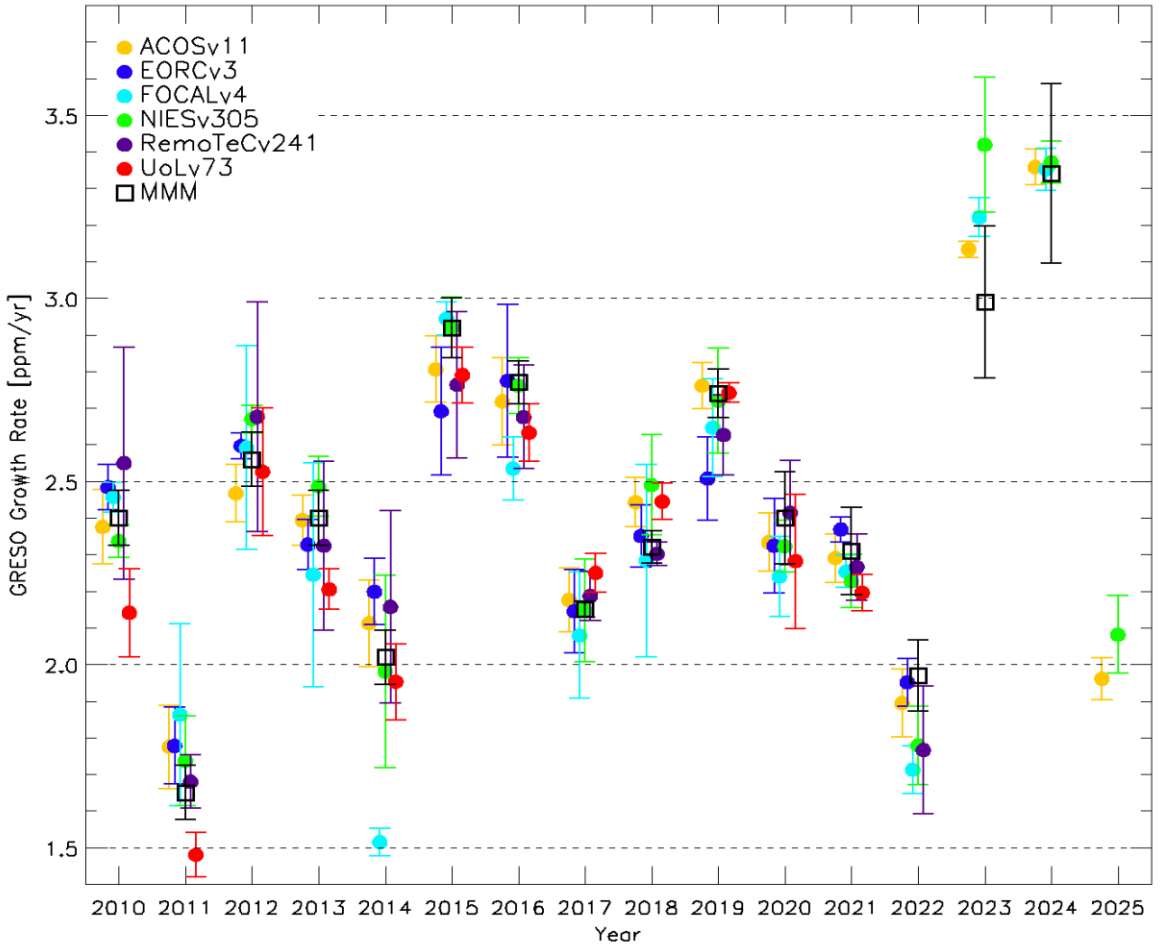
Comparisons to TCCON

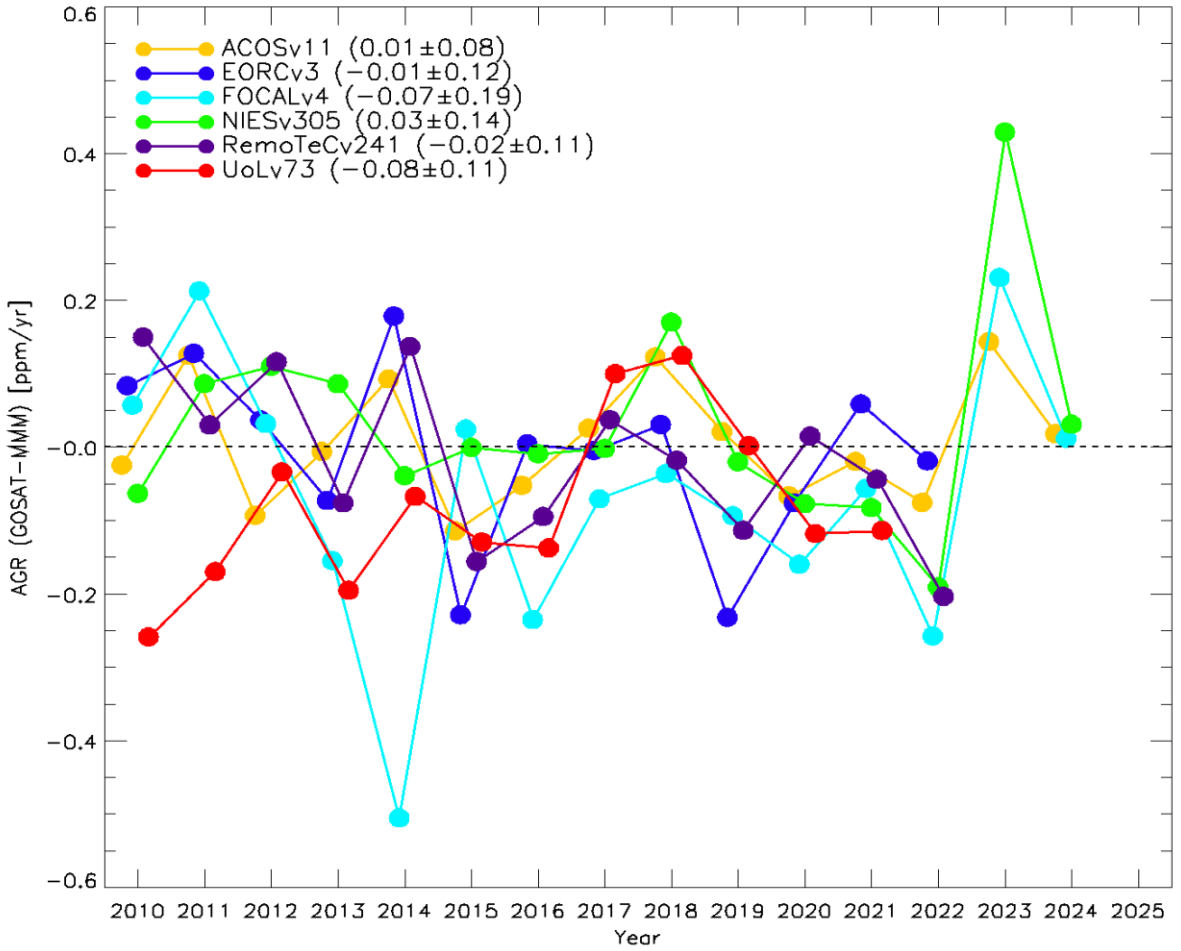
- GGG2020; Wunch-era AK correction applied
- 2010/01/01 – 2022/12/31 so all algorithms have coverage.
- +/- 2.5 deg lat; +- 5 deg lon; +- 2 hours time difference.
- Standard 3-sigma filtering by O'Dell
- All TCCON data available in daily plot form here:
  https://reef.atmos.colostate.edu/~odell/data/tccon/ggg2020/plots/daily_plots/

- Analysis done at both single-sounding level and overpass-mean level.
- An "overpass" requires at least 3 good soundings.

GRESO Growth Rate Analysis

- Use the **GRESO** (Growth Rate from Satellite Observations, Pandey et al 2024, AGU Advances)
- Use the median of Global Carbon Project In-situ models as a reference (Friedlingstein et al., 2026)
- [Left]: Annual Growth Rate estimates ; [Right] : Growth Rate errors relative to Multi-Model Median (MMM)





Retrieval Quality Table*

Top 2
Middle 2
Bottom 2

Product	Good Data Density	RMS vs. TCCON [ppm] (single sound)	RMS vs. MMM (2x3,monthly)	Time Trend vs Models [ppm/dec]	Consistency of reported uncertainty	LandH, LandM, OceanH consistency
ACOS v11	Land					
	Water					
Univ of Leicester v7.3	Land					
	Water					
NIES v3.05	Land					
	Water					
FOCAL v4	Land					
	Water					
RemoTeC v2.41	Land					
	Water					
JAXA EORC v3	Land					
	Water					

** Somewhat subjective!*