Is GOSAT XCO_2 still useful in the OCO-2 era?

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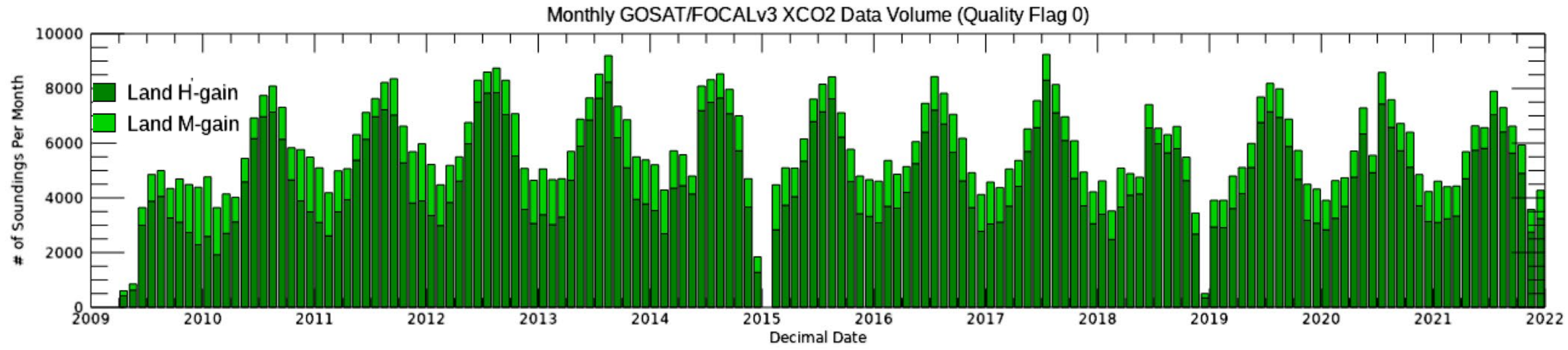
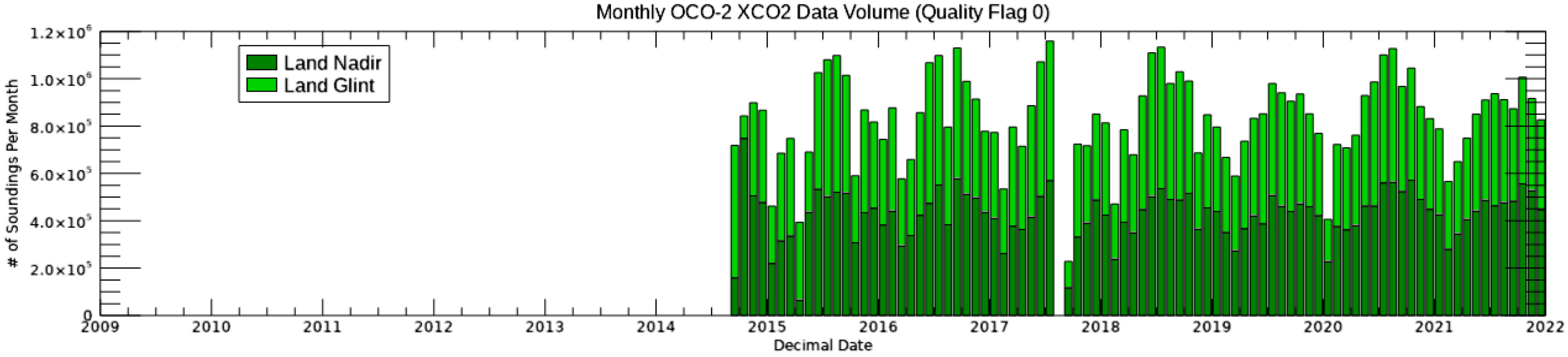
IWGGMS-18, 13 July 2022

Given the current fleet of XCO2 sensors in space, are there questions about CO2 fluxes that we must have GOSAT to answer?



TANSO-FTS on GOSAT

- 6/2009 – Present
- XCO2 Precision ~ 1 ppm
- Averages 5k land, 10k ocean observations / month (ACOS).



OCO-2

- 9/2014 – Present
- XCO2 Precision ~ 0.5 ppm
- Averages 500k land, 1M ocean observations / month.

Pros and Cons of GOSAT

Arguments Against Using GOSAT

- 100x less data than OCO-2
- 2x higher random errors than OCO-2
- Errors not well-characterized

Arguments For Using GOSAT

- Extends record by 5 additional years! Helps place OCO-2 results in context.
- May fill in spatiotemporal holes in OCO-2 record.
- ACOS B9 has well-characterized errors (over land)

Examples of important science publications* using ACOS GOSAT XCO_2 (combined with early OCO-2)

RESEARCH ARTICLE

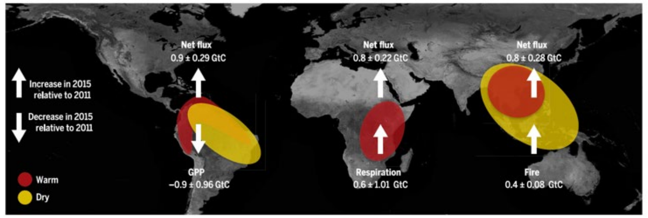
CARBON CYCLE

Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño

Junjie Liu,[1*] Kevin W. Bowman,[1] David S. Schimel,[1] Nicolas C. Parazoo,[1] Zhe Jiang,[2] Meemong Lee,[1] A. Anthony Bloom,[1] Debra Wunch,[3] Christian Frankenberg,[1,4] Ying Sun,[1†] Christopher W. O'Dell,[5] Kevin R. Gurney,[6] Dimitris Menemenlis,[1] Michelle Gierach,[1] David Crisp,[1] Annmarie Eldering[1]

The 2015–2016 El Niño led to historically high temperatures and low precipitation over the tropics, while the growth rate of atmospheric carbon dioxide (CO_2) was the largest on record. Here we quantify the response of tropical net biosphere exchange, gross primary production, biomass burning, and respiration to these climate anomalies by assimilating column CO_2, solar-induced chlorophyll fluorescence, and carbon monoxide observations from multiple satellites. Relative to the 2011 La Niña, the pantropical biosphere released 2.5 ± 0.34 gigatons more carbon into the atmosphere in 2015, consisting of approximately even contributions from three tropical continents but dominated by diverse carbon exchange processes. The heterogeneity of the carbon-exchange processes indicated here challenges previous studies that suggested that a single dominant process determines carbon cycle interannual variability.

on posterior fluxes with OSSEs. The comparison to independent data shows that the OCO-2 and GOSAT X_{CO_2} have consistent error statistics, and the OSSEs indicate that the conclusions from this study are not sensitive to the sampling differences between OCO-2 and GOSAT.



Diverse climate driver anomalies and carbon cycle responses to the 2015–2016 El Niño over the three tropical continents. Schematic of climate anomaly patterns over the three tropical continents and the anomalies of the net carbon flux and its dominant constituent flux (i.e., GPP, respiration, and fire) relative to the 2011 La Niña during the 2015–2016 El Niño. GtC, gigatons C.

RESEARCH ARTICLE

CARBON CYCLE

Influence of El Niño on atmospheric CO_2 over the tropical Pacific Ocean: Findings from NASA's OCO-2 mission

A. Chatterjee,[1,2*] M. M. Gierach,[3] A. J. Sutton,[4,5] R. A. Feely,[4] D. Crisp,[3] A. Eldering,[3] M. R. Gunson,[3] C. W. O'Dell,[6] B. B. Stephens,[7] D. S. Schimel[3]

Spaceborne observations of carbon dioxide (CO_2) from the Orbiting Carbon Observatory-2 are used to characterize the response of tropical atmospheric CO_2 concentrations to the strong El Niño event of 2015–2016. Although correlations between the growth rate of atmospheric CO_2 concentrations and the El Niño–Southern Oscillation are well known, the magnitude of the correlation and the timing of the responses of oceanic and terrestrial carbon cycle remain poorly constrained in space and time. We used space-based CO_2 observations to confirm that the tropical Pacific Ocean does play an early and important role in modulating the changes in atmospheric CO_2 concentrations during El Niño events—a phenomenon inferred but not previously observed because of insufficient high-density, broad-scale CO_2 observations over the tropics.

from the start of mission operation. OCO-2 retrievals are also being cross-calibrated and cross-validated with measurements and data products from GOSAT (nicknamed "Ibuki"). The GOSAT X_{CO_2} retrievals used in this study were generated by version 7.3 of the ACOS algorithm [GOSAT-ACOS (96, 97)]. Both OCO-2 and GOSAT-ACOS X_{CO_2} data were bias-corrected using the same set of predictors, so that these two satellite data sets could be combined to produce a uniform X_{CO_2} climate data record for use by the carbon cycle science community. See (71) for further details

we adopted a two-step approach for generating the X_{CO_2} anomalies: (i) For each month, individual X_{CO_2} soundings from GOSAT-ACOS and OCO-2 are averaged over prespecified domains (e.g., Niño 3.4, tropical Pacific Ocean, tropical Atlantic Ocean, global) assuming no temporal correlation; and (ii) for an individual month, we find a linear trend that best fits the X_{CO_2} data from 7 years of GOSAT-ACOS and OCO-2 observational records for that month. The X_{CO_2} anomalies are then the residuals from this linear trend. See (71) for the exact mathematical framework and the implication for using both GOSAT-ACOS and OCO-2 together to generate the climatology.

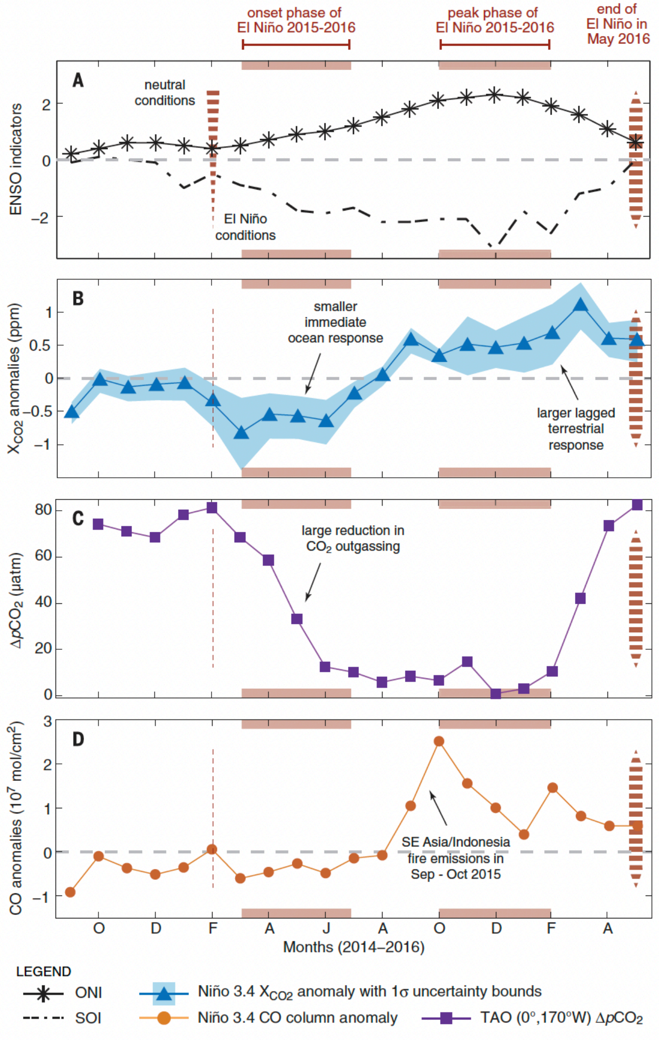


Fig. 2. OCO-2 observes the response of the carbon cycle for an entire El Niño event. (A to D) Temporal evolution of (A) the 2015–2016 El Niño as captured by the ONI and SOI indices; (B) X_{CO_2} anomalies and associated uncertainties in the Niño 3.4 region; (C) ΔpCO_2 from the TAO 0°, 170°W mooring; and (D) the CO total column anomalies in the Niño 3.4 region.

Objective evaluation of surface- and satellite-driven carbon dioxide atmospheric inversions

Frédéric Chevallier[1], Marine Remaud[1], Christopher W. O'Dell[2], David Baker[2], Philippe Peylin[1], and Anne Cozic[1]

[1]Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91198 Gif-sur-Yvette, France
[2]Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA

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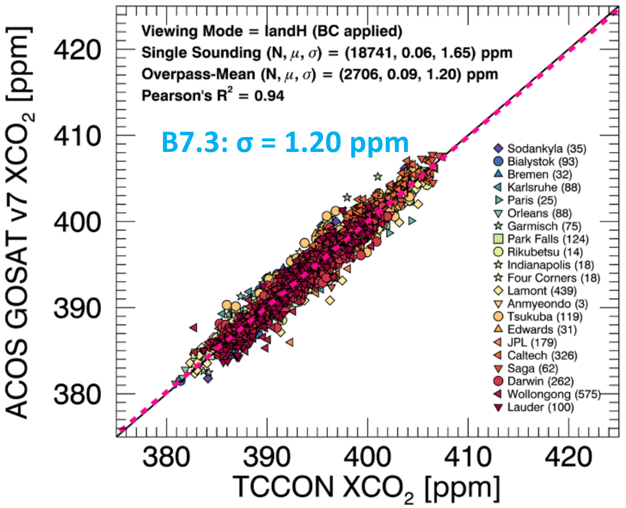
- "Large-scale annual fluxes estimated from the bias-corrected land retrievals of the second Orbiting Carbon Observatory (OCO-2) differ greatly from the prior fluxes, but are similar to the fluxes estimated from the surface network within the uncertainty of these surface-based estimates."

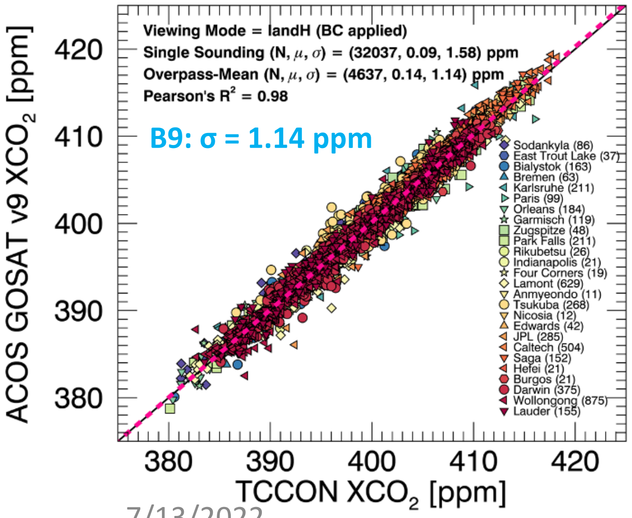
- "The OCO-2-based and surface-based inversions have similar performance when projected in the space of the aircraft data, but the relative strengths and weaknesses of the two flux estimates vary…"

- " In contrast, the inversion using bias-corrected retrievals from the Greenhouse Gases Observing Satellite (GOSAT) … estimates much different fluxes and fits the aircraft data less. "

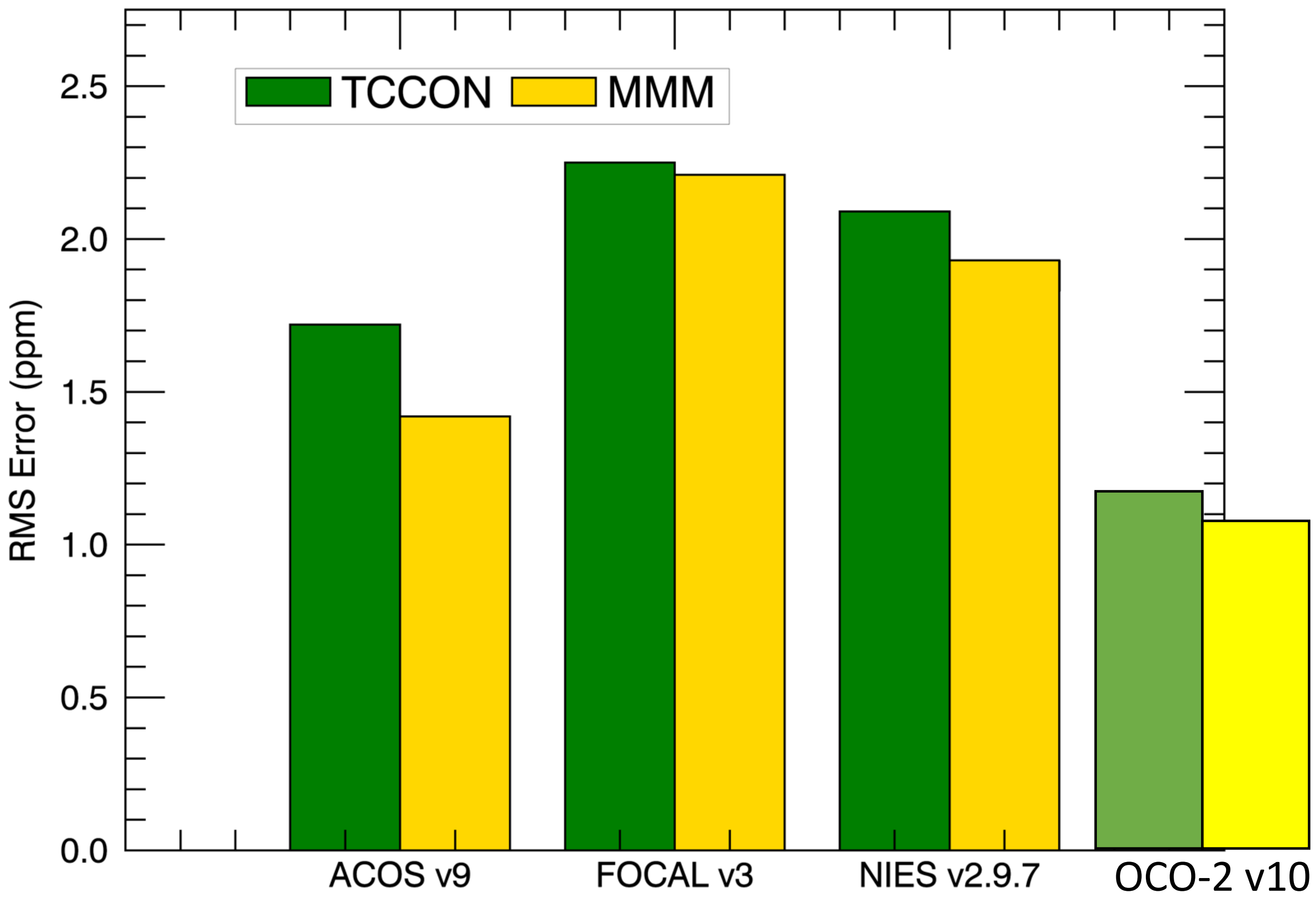
Summary of GOSAT retrievals versus truth (land)

GOSAT vs TCCON (v7.3 vs v9)

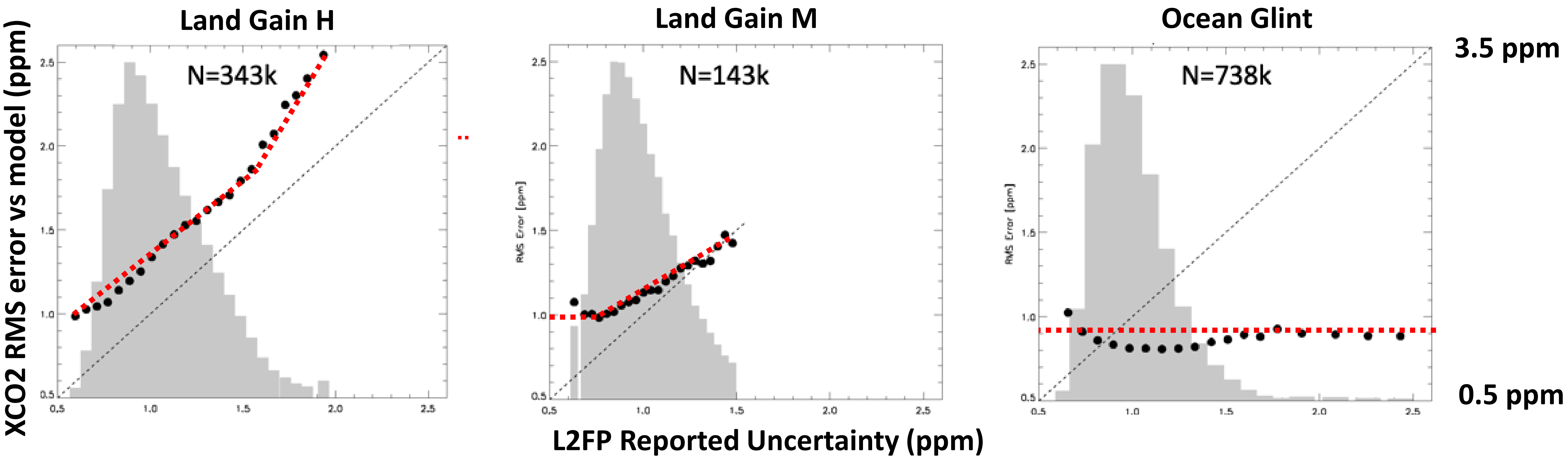




Single-sounding RMS XCO_2 Error [ppm]



Validating XCO2 error from ACOS/GOSAT v9 retrievals against a 4-Model Median Truth Proxy



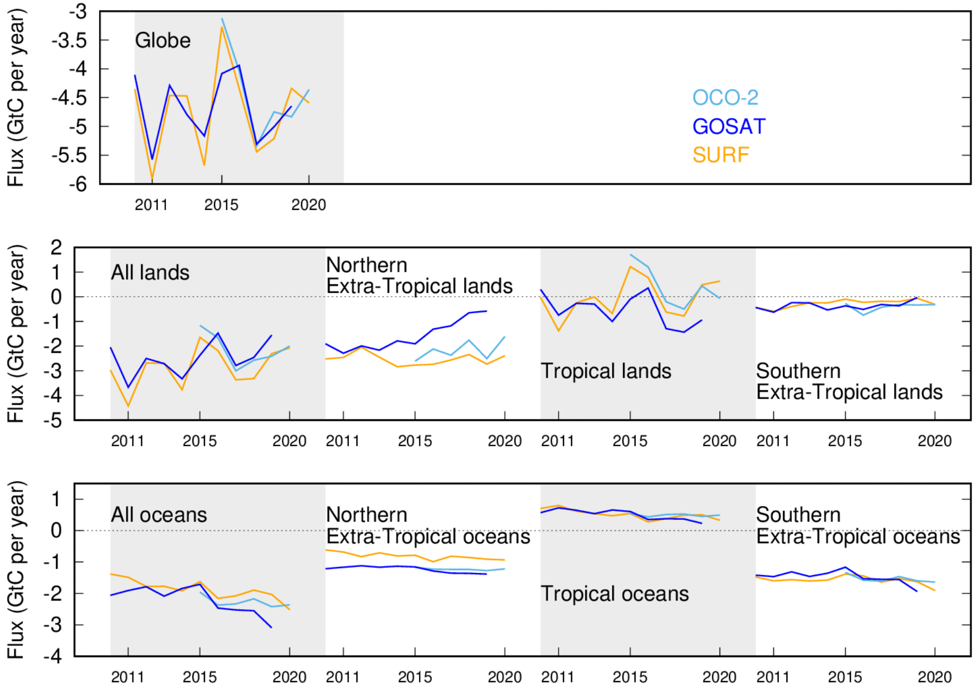
- Values along the 1:1 line indicate that the error vs model is consistent with the reported uncertainties.
- ACOS v9 performs well overall , and has errors that agree reasonably well with theory over land.

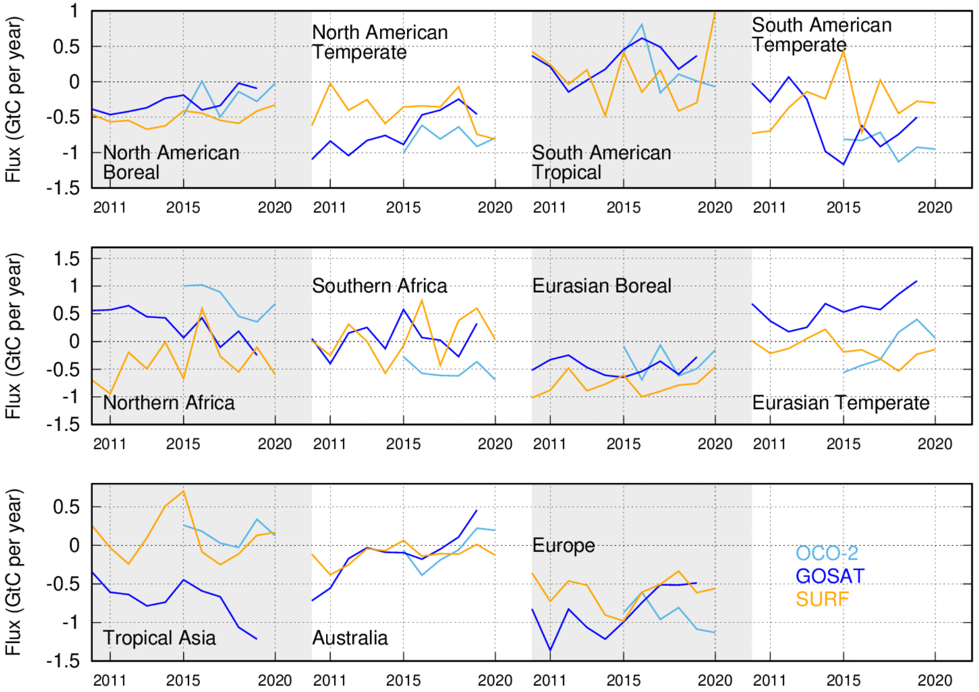
Testing the ACOS/GOSAT v9 XCO2 with these error characterizations.

- CAMS 4DVar inversion system (F. Chevallier), which operationally assimilates both in-situ and OCO-2 data.
- Univ. of Oklahoma TM5 4DVar inversion system (S. Crowell), a participant in the OCO-2 MIP.
- Each run must cover 2015-2018, so OCO-2 results can be compared with ACOS/GOSAT v9 results.

Decade long inversion using CAMS system (F. Chevallier)

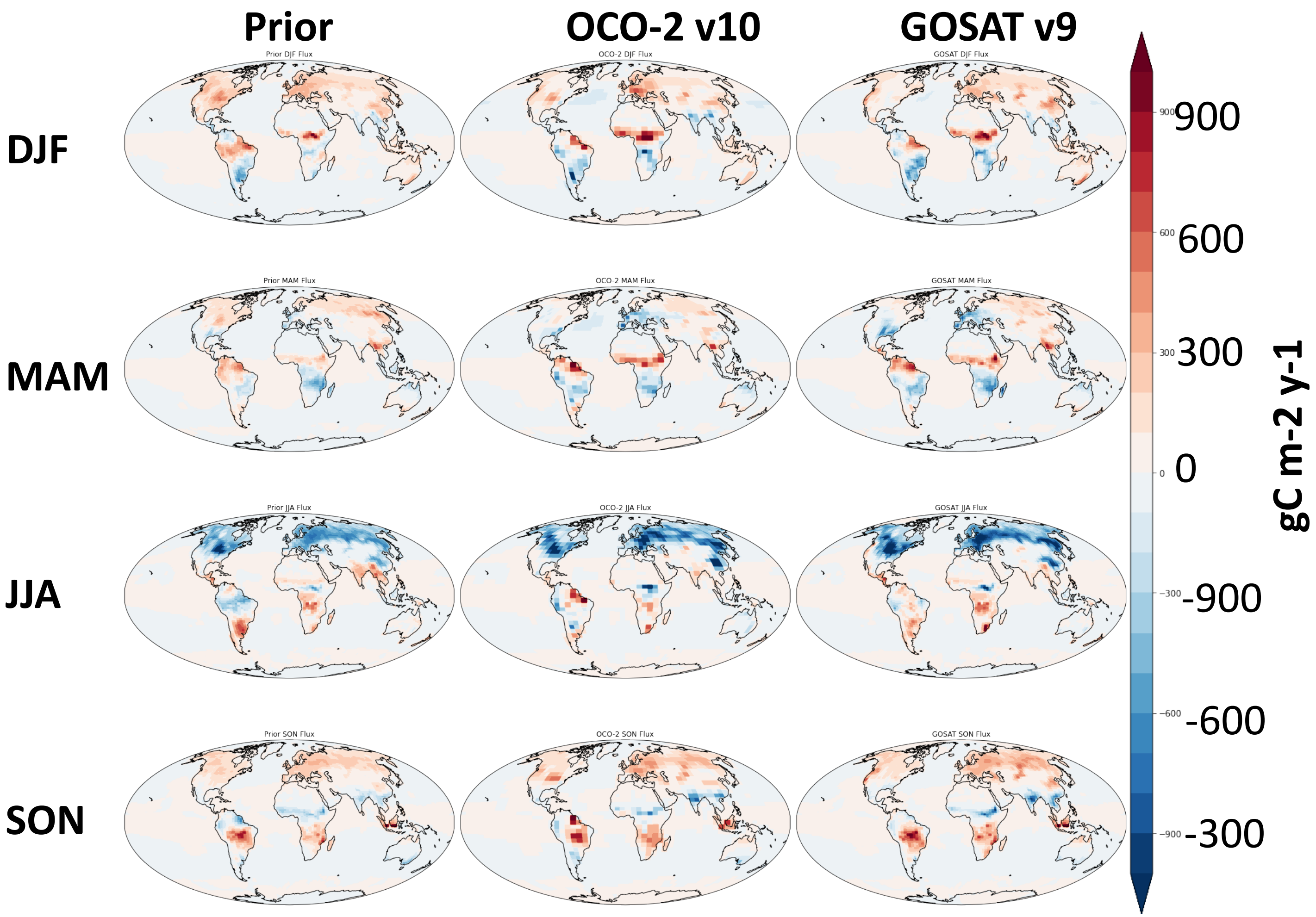
- Three separate runs: Assimilate only surface data, only OCO-2 data, or only GOSAT data.
- GOSAT run shows remarkable fit to independent data like NOAA's annual mean growth rate, surface baseline measurements and aircraft measurements
- GOSAT-inferred carbon budget broadly consistent with those obtained with OCO-2 v10
    - Main difference is a large shift of a sink from Temperate Eurasia to Tropical Asia
- GOSAT ACOS v9 is the first GOSAT dataset that provides reasonable inversion results with the CAMS system
    - Complements OCO-2, and a continuous processing of the GOSAT data with low latency would help operational applications like CAMS.
- CAMS operational satellite based inversion now uses GOSAT for 2009-2014, and OCO-2 for 2015-present (run FT21r2, https://atmosphere.copernicus.eu/sites/default/files/custom-uploads/CAMS255_2021SC1_D1.3.1-2022-2_202206_v1.pdf)

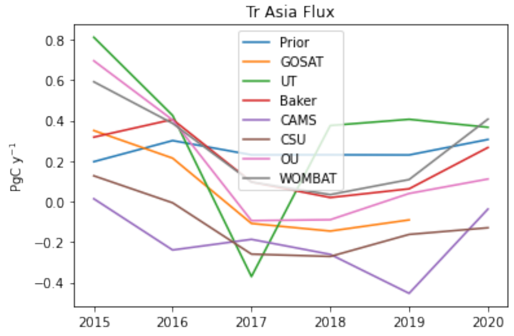




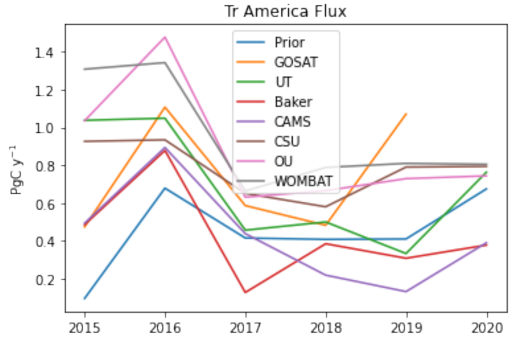
OU inversions on GOSAT v9 compared to OCO-2 v10 MIP (S. Crowell)

- **On broad scales, the GOSAT v9 results seem to fall within the spread of the OCO-2 v10 MIP fluxes.**
- **However, the agreement breaks down at regional scales.**

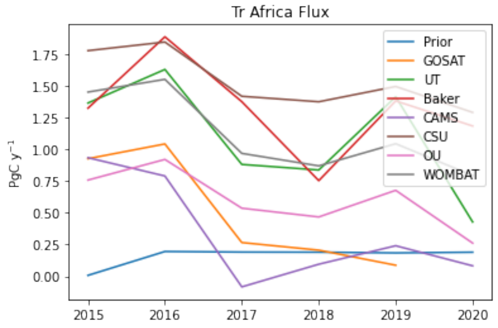




Tropical Asia



Tropical America



Tropical Africa

Summary

- The 2009-Present GOSAT XCO2 record still appears useful, primarily for its additional 5.5 years of data.
- The ACOS GOSAT v9 XCO2, while having somewhat higher errors than OCO-2 v10, still yield inversions that are broadly consistent with OCO-2. This contrasts some earlier findings.
- The other GOSAT retrievals we examined seem to suffer from somewhat higher errors than that of ACOS.
- The OCO-2 team hopes to reprocess GOSAT with ACOS v11 near the end of 2022. Stay tuned.

Additional Material

Tracking the changes to the ACOS L2FP algorithm

Table 1. Updates to recent versions of the ACOS L2FP retrieval algorithm. N/C stands for No Change.

		ACOS v7	ACOS v8/v9	ACOS v10	ACOS v11
1	Spectroscopy	ABSCO v4.2	ABSCO v5.0	ABSCO v5.1	ABSCO v5.2
2	Meteorology prior source	ECMWF	GEOS5 FP-IT	N/C	N/C
3	Aerosol prior source	MERRA monthly climatology	N/C	GEOS5 FP-IT with tightened prior uncertainty	N/C
4	Retrieved aerosol types	water + ice + 2 MERRA types	+ stratospheric aerosol	N/C	N/C
5	AOD prior value (per type)	0.0375	0.0125	N/C	N/C
6	CO_2 prior source	TCCON ggg2014	N/C	TCCON ggg2020	TCCON ggg2020 with updated time-dependent scaling
7	Land surface model	Lambertian	BRDF	N/C	Removal of incorrectly scaled polarized component
8	Ocean surface model	Cox&Munk + per-band Lambertian component	N/C	N/C	Cox&Munk scaled per-band
9	Digital elevation model and land water mask	JPL 2007	N/C	N/C	JPL 2020

OCO-2 cut over to v11 for the forward processing stream on 1-March-2022.

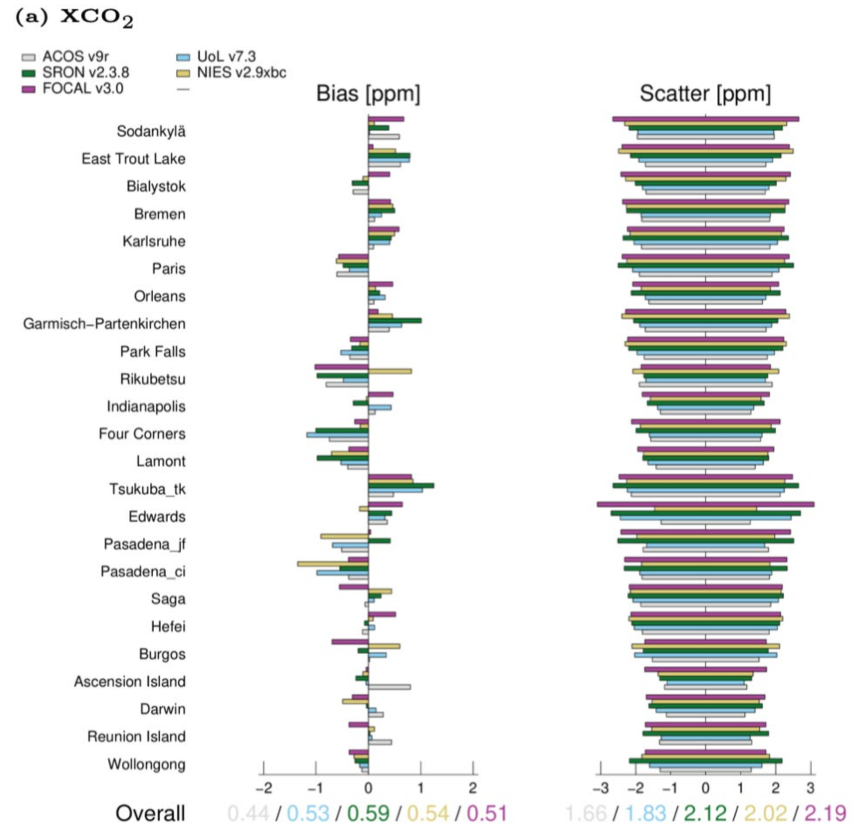
Independent validation of ACOS XCO_2 against "truth"

https://doi.org/10.5194/amt-2022-43
Preprint. Discussion started: 21 March 2022

Atmospheric Measurement Techniques Discussions

Retrieval of greenhouse gases from GOSAT and greenhouse gases and carbon monoxide from GOSAT-2 using the FOCAL algorithm

Stefan Noël[1], Maximilian Reuter[1], Michael Buchwitz[1], Jakob Borchardt[1], Michael Hilker[1], Oliver Schneising[1], Heinrich Bovensmann[1], John P. Burrows[1], Antonio Di Noia[2], Robert J. Parker[2,3],



Atmos. Chem. Phys., 21, 8255–8271, 2021
https://doi.org/10.5194/acp-21-8255-2021

Atmospheric Chemistry and Physics

ACOS performs well relative to other retrieval algorithms.

New approach to evaluate satellite-derived XCO_2 over oceans by integrating ship and aircraft observations

Astrid Müller[1], Hiroshi Tanimoto[1], Takafumi Sugita[1], Toshinobu Machida[1], Shin-ichiro Nakaoka[1], Prabir K. Patra[2], Joshua Laughner[3], and David Crisp[4]

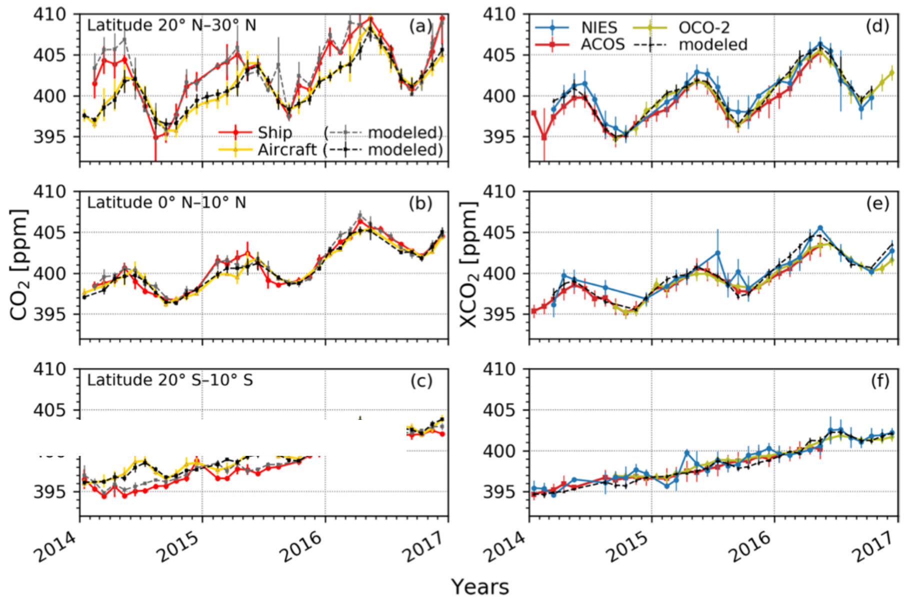
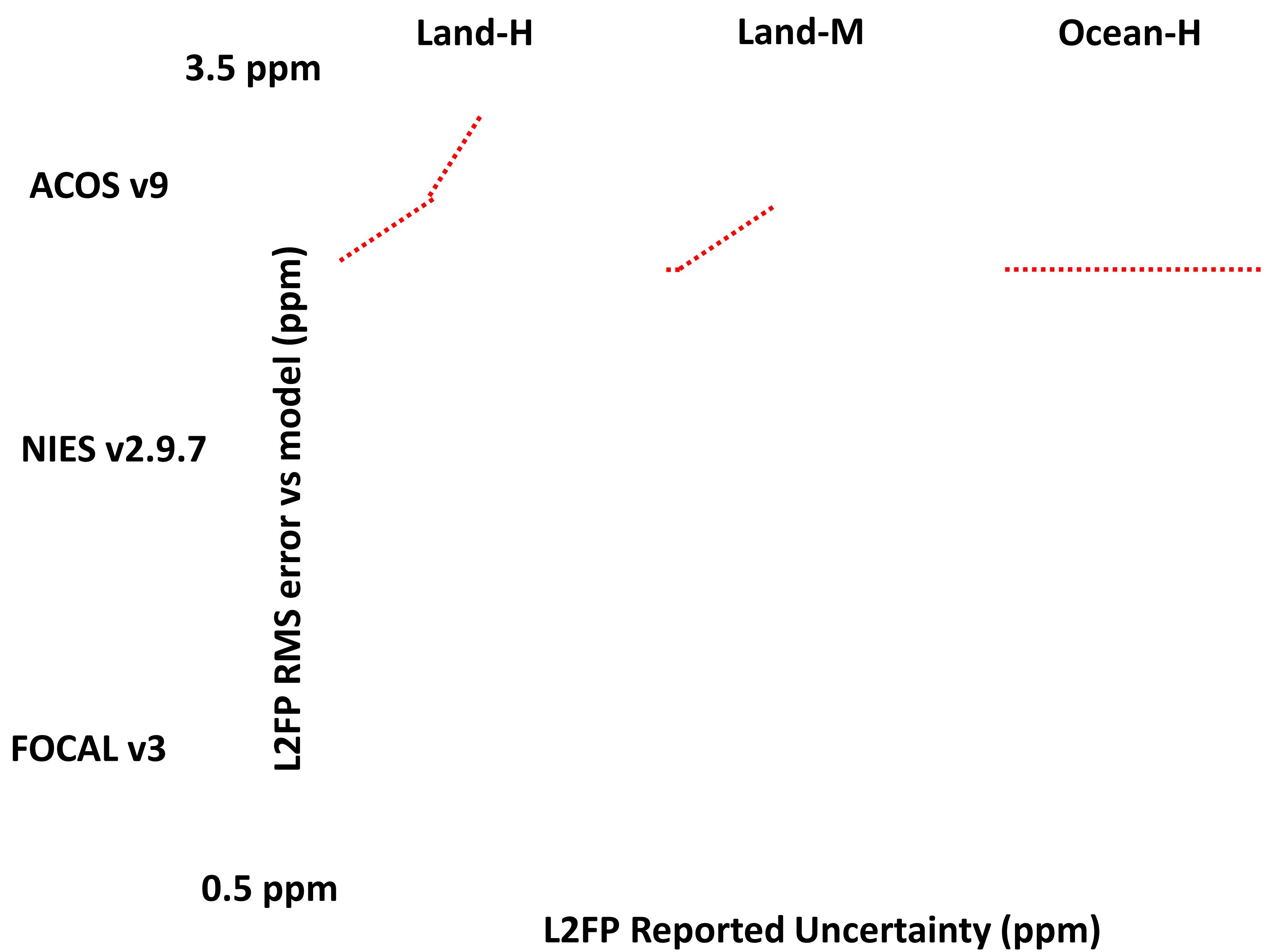


Figure 3. Temporal variation of the monthly average CO_2 mixing ratio obtained by ship (red) and aircraft (yellow) **(a, b, c)**, and the column-averaged mixing ratios (XCO_2) from the NIES (blue), ACOS (red), and OCO-2 (olive) **(d, e, f)** in three representative latitude ranges for the northern midlatitudes **(a, d)**, the Equator region **(b, e)**, and southern latitudes **(c, f)**. Results of the ACTM are shown as dashed lines. Error bars represent the standard deviation of the monthly averages.

Validating XCO2 error from 3 GOSAT retrievals against a 4-Model Median Truth Proxy

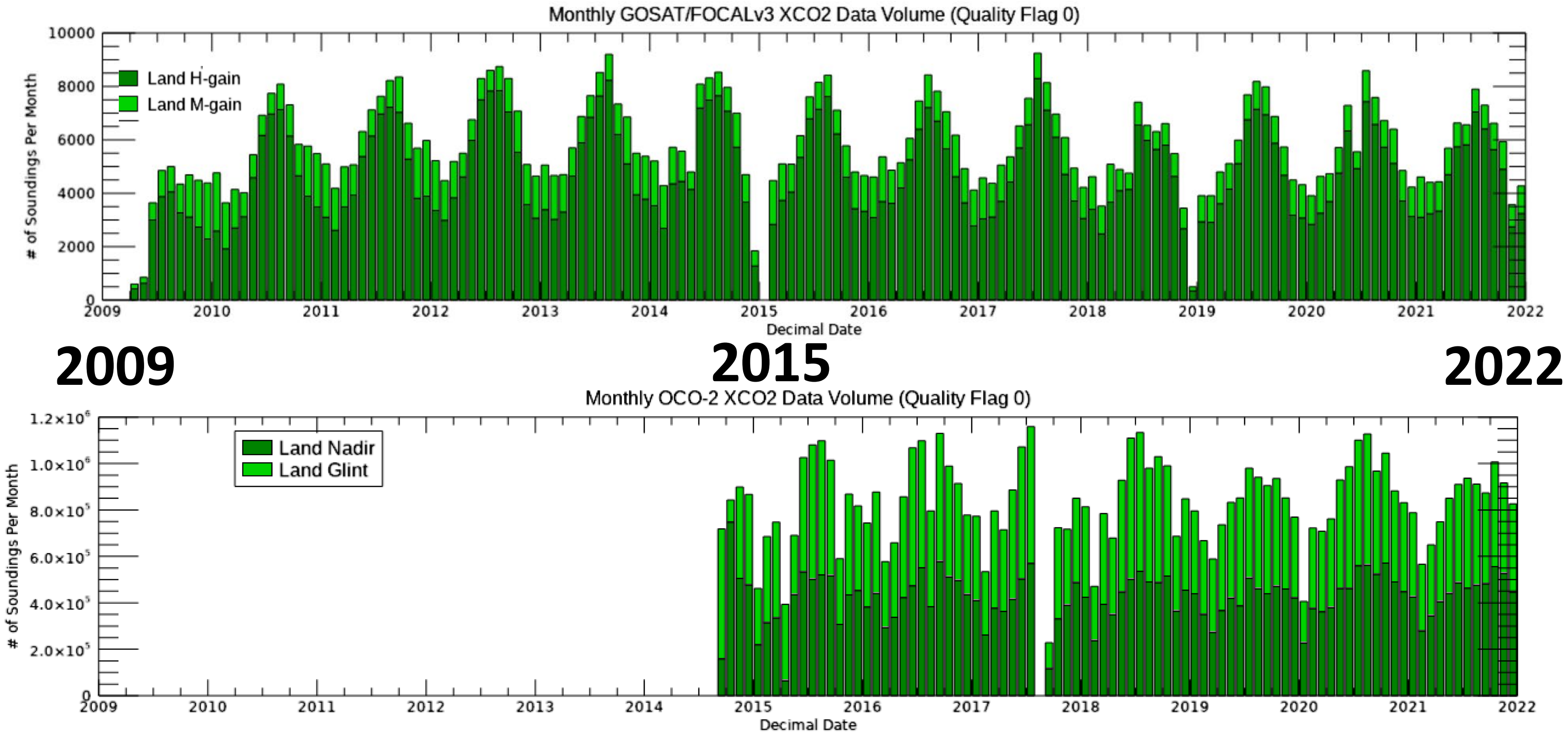


- Values along the 1:1 line indicate that the error vs model is consistent with the reported uncertainties.
- ACOS v9 performs well overall , and has errors that agree reasonably well with theory over land.
- NIES has somewhat higher actual errors, especially for land gain H.
- FOCAL has 2x higher theoretical errors, with actual errors that roughly match that.

dXCO2 statistics (vs models)

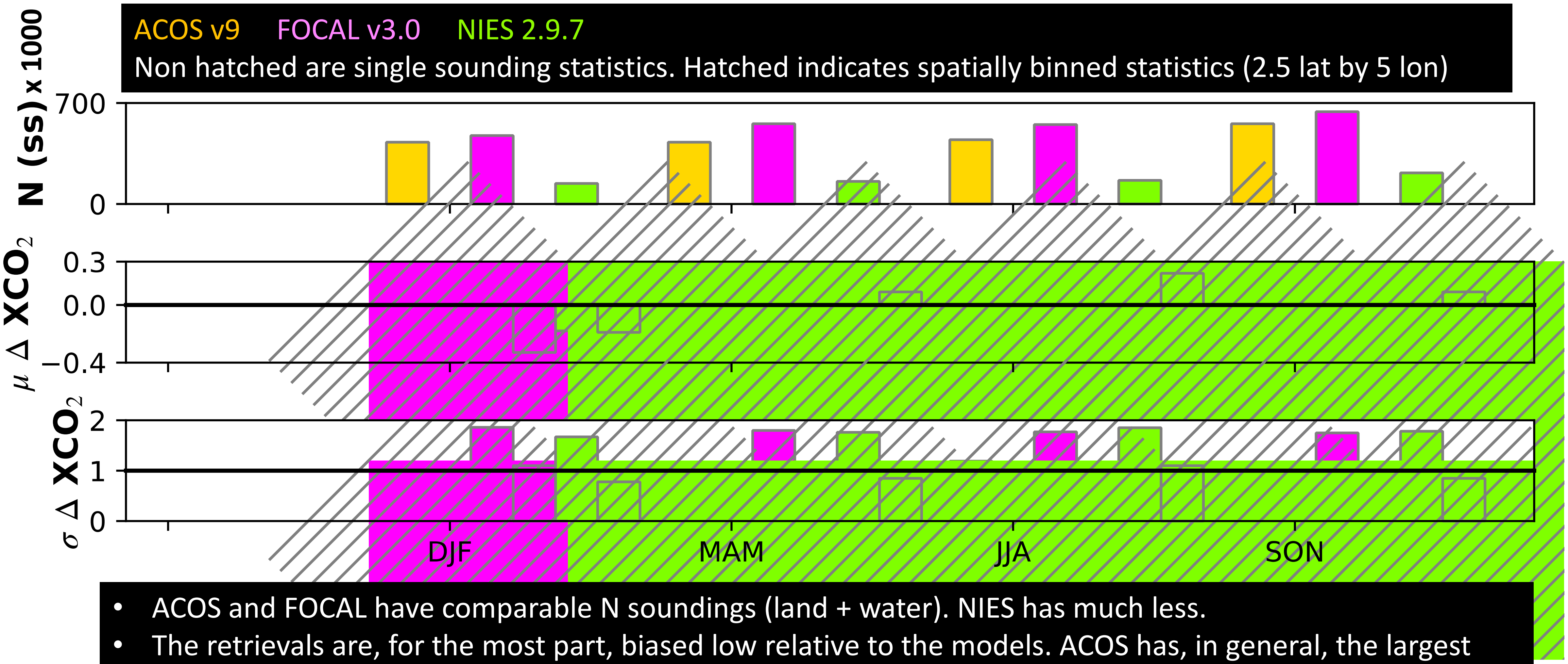
	ACOS v9				FOCAL v3.0				NIES v2.9.7			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
N (SS)	428k	428k	445k	557k	474k	556k	551k	640k	142k	156k	164k	215k
μ (SS)	-0.11	-0.38	-0.22	0.03	-0.31	-0.11	0.05	-0.08	-0.18	-0.03	0.10	-0.11
σ (SS)	1.08	1.12	1.19	1.13	1.86	1.80	1.77	1.75	1.67	1.76	1.85	1.78
N (bin)	2060	2407	2218	2576	2135	2498	2378	2583	1689	2051	1849	2239
μ (bin)	-0.17	-0.26	-0.26	0.05	-0.33	-0.03	0.05	-0.09	-0.19	0.09	0.22	0.09
σ (bin)	0.50	0.54	0.58	0.56	1.10	0.99	0.91	0.81	0.78	0.85	1.10	0.85

It will still be quite a while before the early GOSAT record becomes “insignificant”…



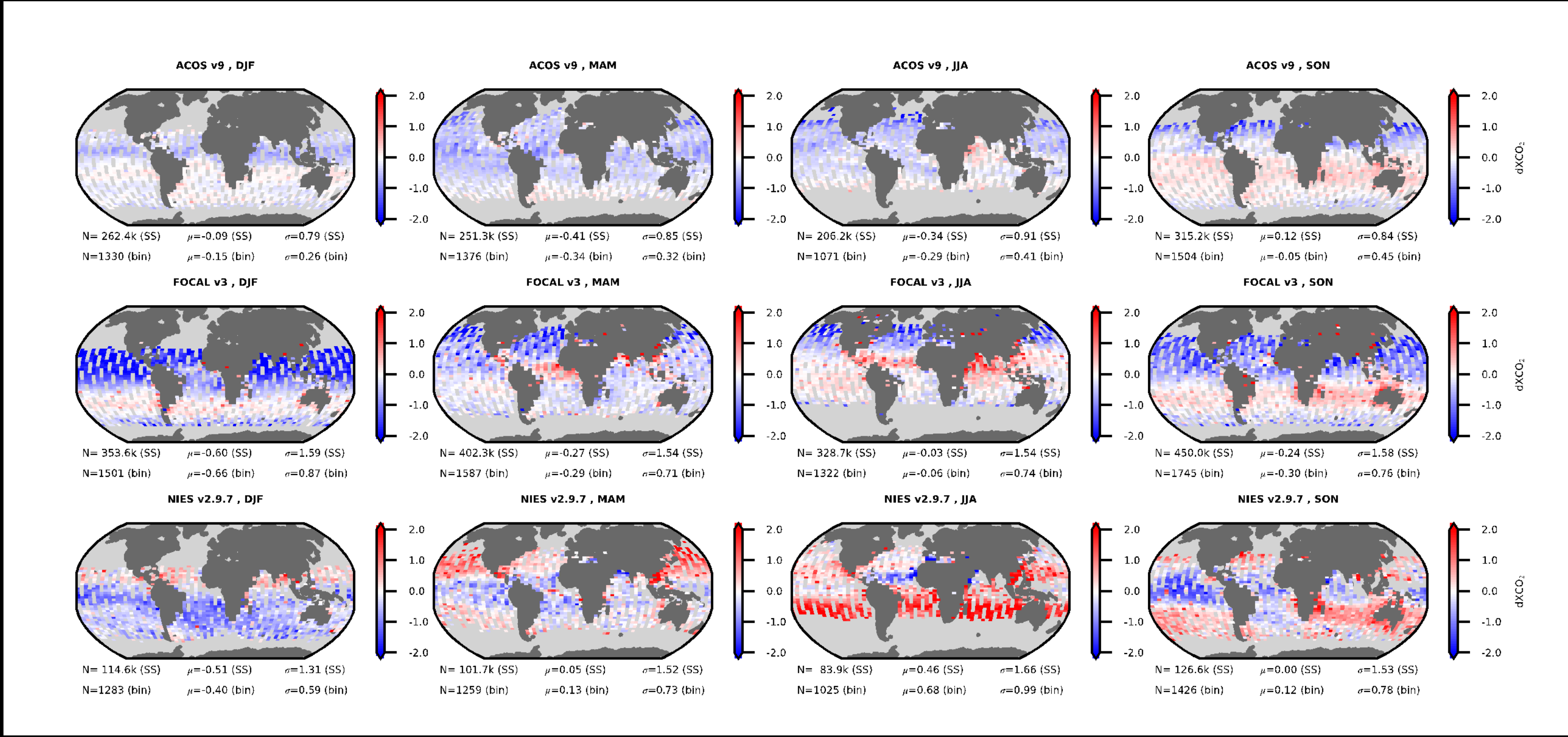
- The extra five years (2009-2014) provided by the GOSAT satellite before the start of the OCO-2 record provide the context necessary for interpreting the interannual variability in the global carbon cycle seen by the OCO-2 satellite.
- How anomalous was the CO2 outgassing seen globally during the 2015/16 El Niño?
- Was the release of CO2 seen during 2015-2016 as compared after 2016 so large because of greater outgassing during the 2015-16 ENSO warm phase, or because of greater uptake during the ENSO cold phase (La Niña) after that?
- The GOSAT data also support one of the key findings from OCO-2: the shift towards greater outgassing in North Africa (D. Baker Inversion)

dXCO2 statistics (vs models)



- ACOS and FOCAL have comparable N soundings (land + water). NIES has much less.
- The retrievals are, for the most part, biased low relative to the models. ACOS has, in general, the largest mean seasonal bias, but as was shown on the maps, the lowest range of bias.
- ACOS has the smallest standard deviation of the dXCO2 (roughly half of FOCAL and NIES).

GOSAT water versus Multi-Model-Median



GOSAT water versus OCO-2 v10