Jet Propulsion Laboratory
California Institute of Technology

Evaluating satellite-based X_{CO2} measurements from v11.2 OCO-2 and v11 OCO-3 against ground-based measurements from TCCON and COCCON, and airborne measurements from ATom

IWGGMS Session 4: Calibration and Validation

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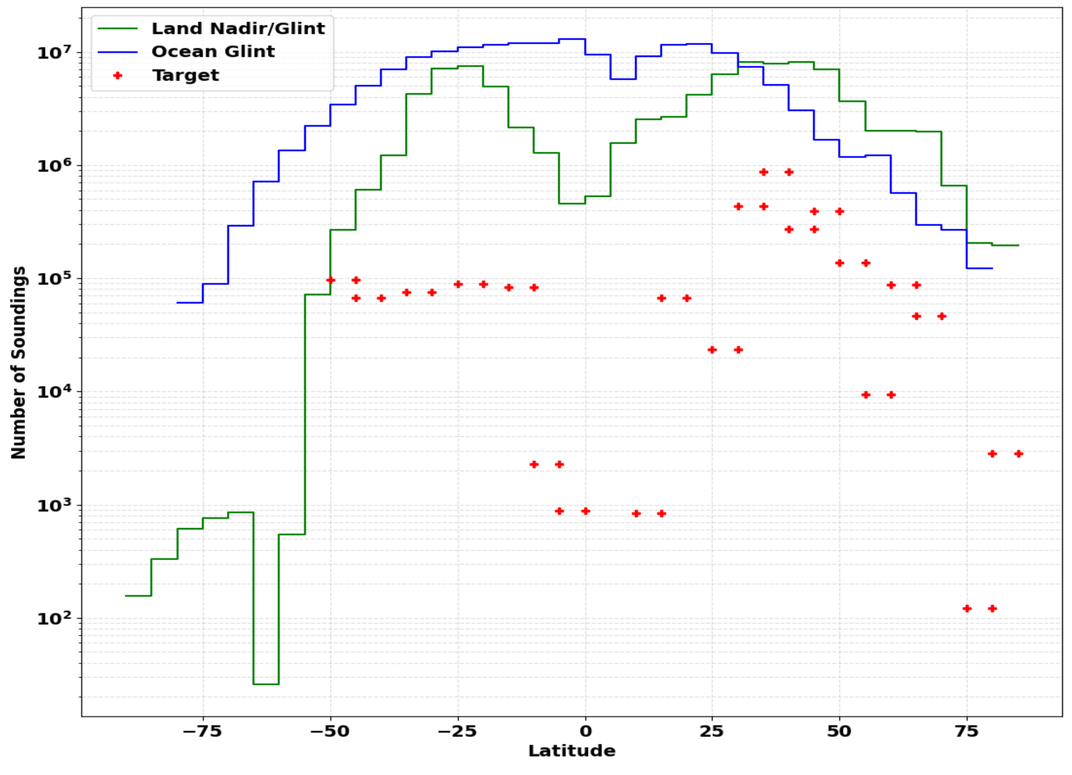
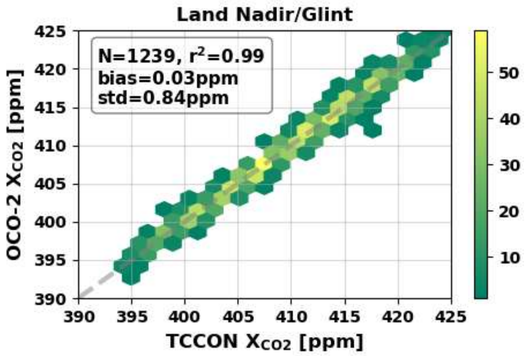
OCO-2/-3 vs. TCCON/COCCON - Introduction

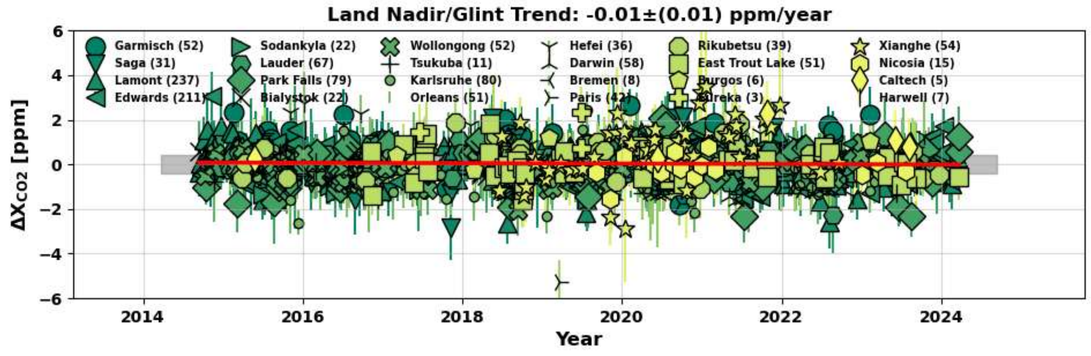
- **Data Used**
  - I. OCO-2 V11.2 (Sep. 2014 – Mar. 2024)
  - II. OCO-3 V11 (Aug. 2019 – Nov. 2023)
  - III. TCCON (GGG2020)
  - IV. COCCON (PROFFAST v1 and v2)

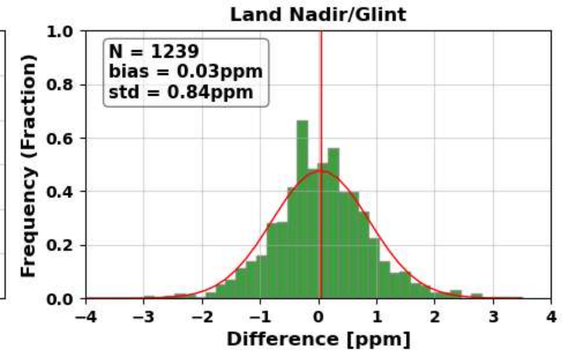
- **Collocation Criteria**
  - I. 2.5° x 5° latitude-longitude boxes around TCCON/COCCON sites (except at specific sites)
  - II. Minimum of 100 good quality OCO-2 soundings required
  - III. TCCON and COCCON XCO_2 (median) within ±1h of OCO-2/-3 overpass time



OCO-2 V11.2 vs. TCCON GGG2020 (x2019)

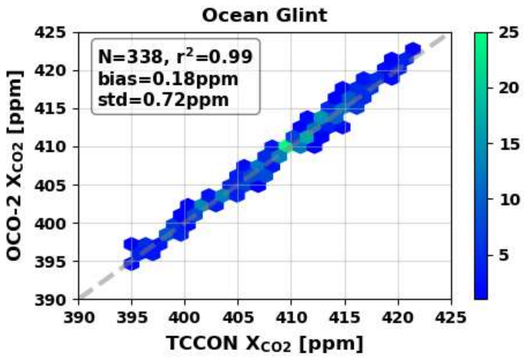


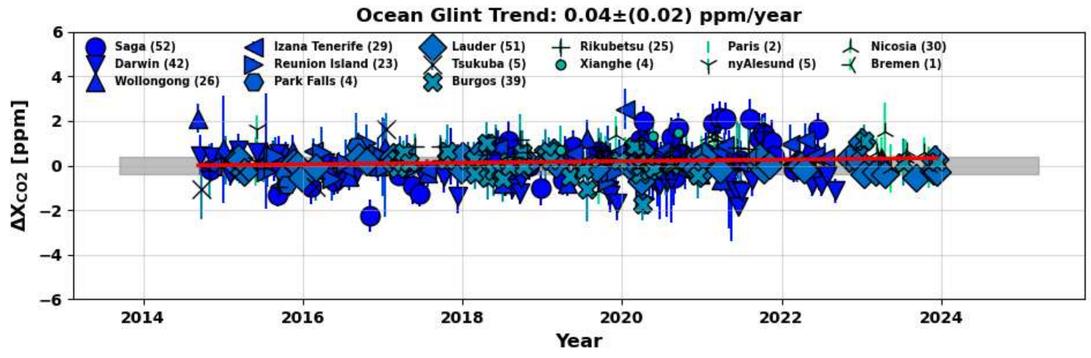


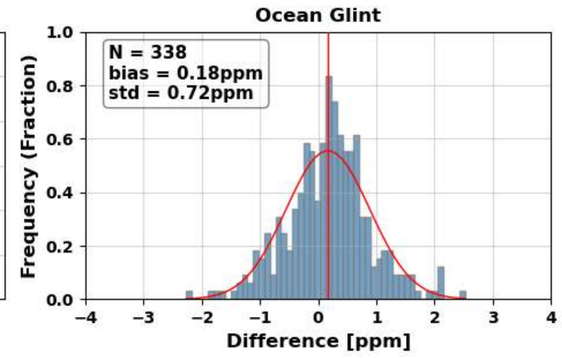


Land Nadir/Glint

The overall bias is slightly positive, but very close to 0 ppm.

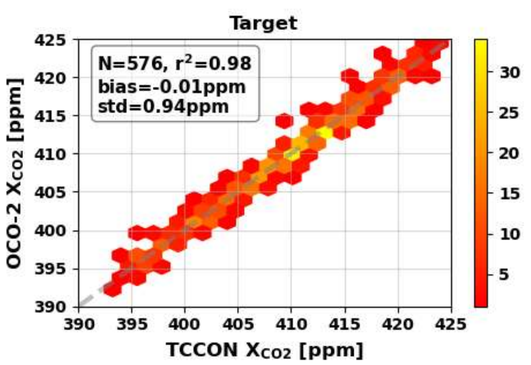


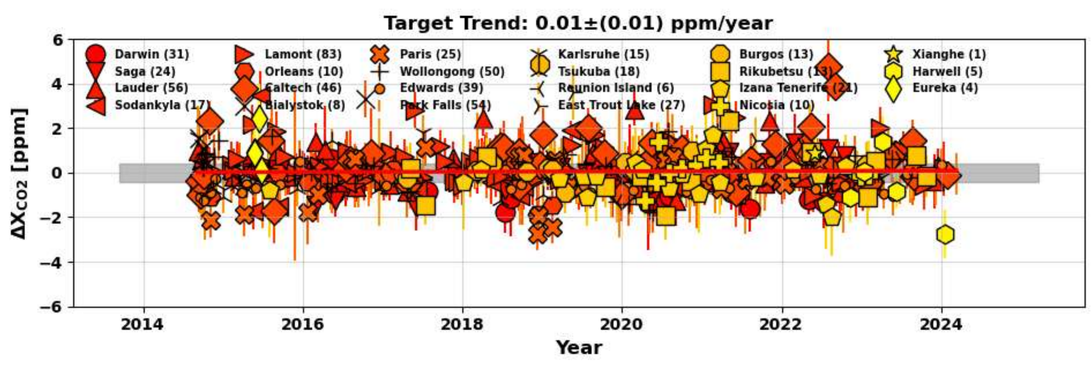


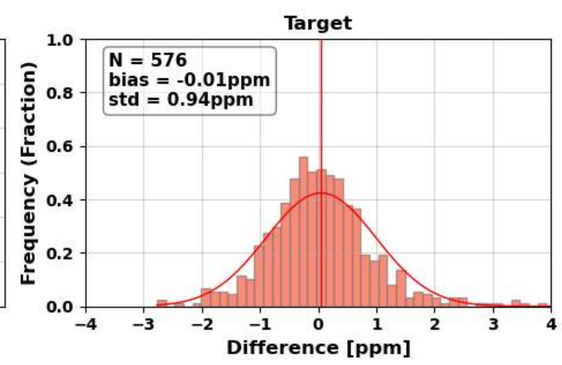


Ocean Glint

The bias is higher than other modes, (though still reasonable given the uncertainty).







Target

The overall bias is slightly negative, but very close to 0 ppm.

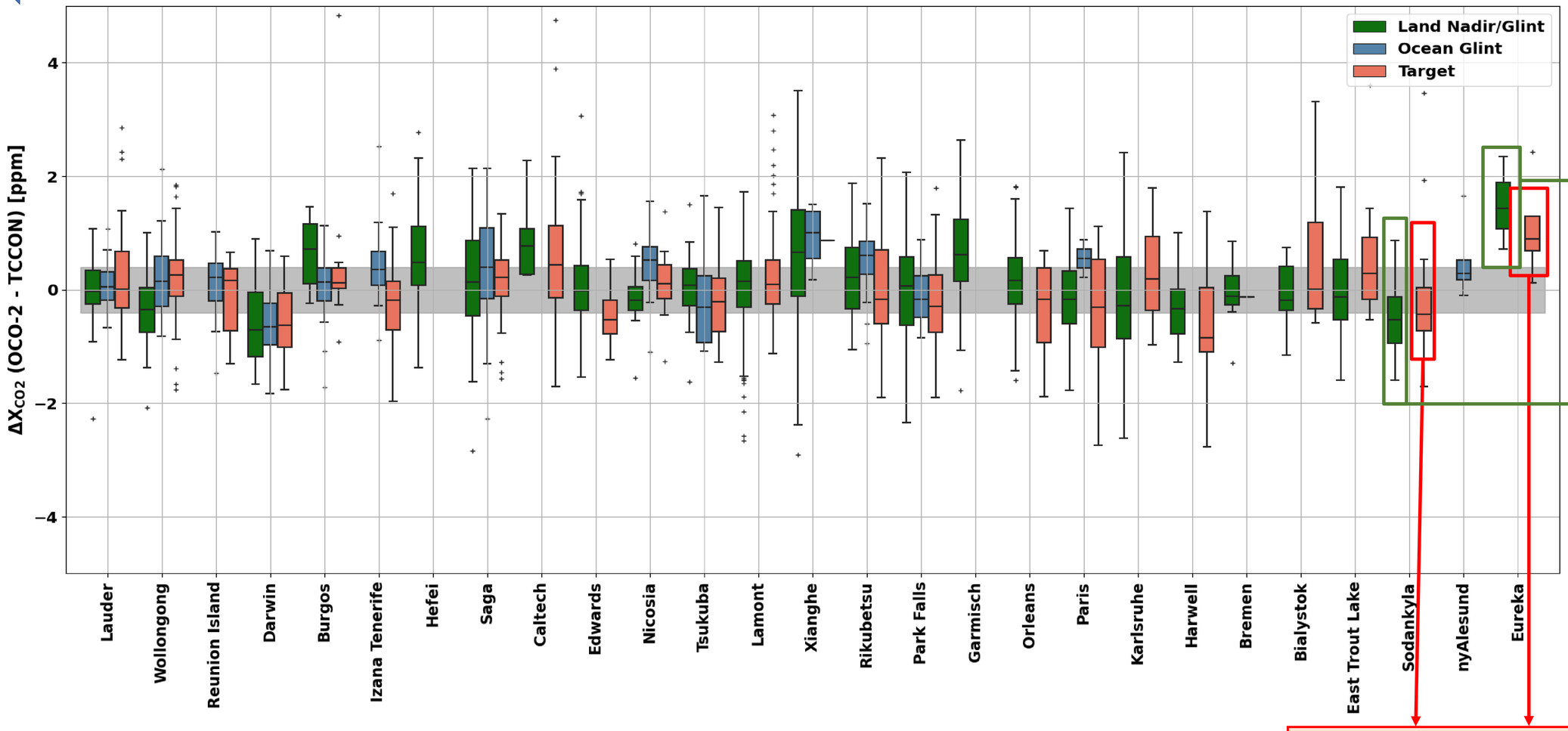
Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	1239	0.03	0.84
Ocean Glint	338	0.18	0.72
Target	576	-0.01	0.94

Aggregated OCO-2 X_{CO2} estimates filtered with xco2_quality_flag = 0 typically compare well with coincident TCCON data at global scales, with **absolute average biases ≤ 0.18 ppm**.

OCO-2 V11.2 vs. TCCON GGG2020 (x2019) – Site-to-Site Differences

South

North



Land Nadir/Glint

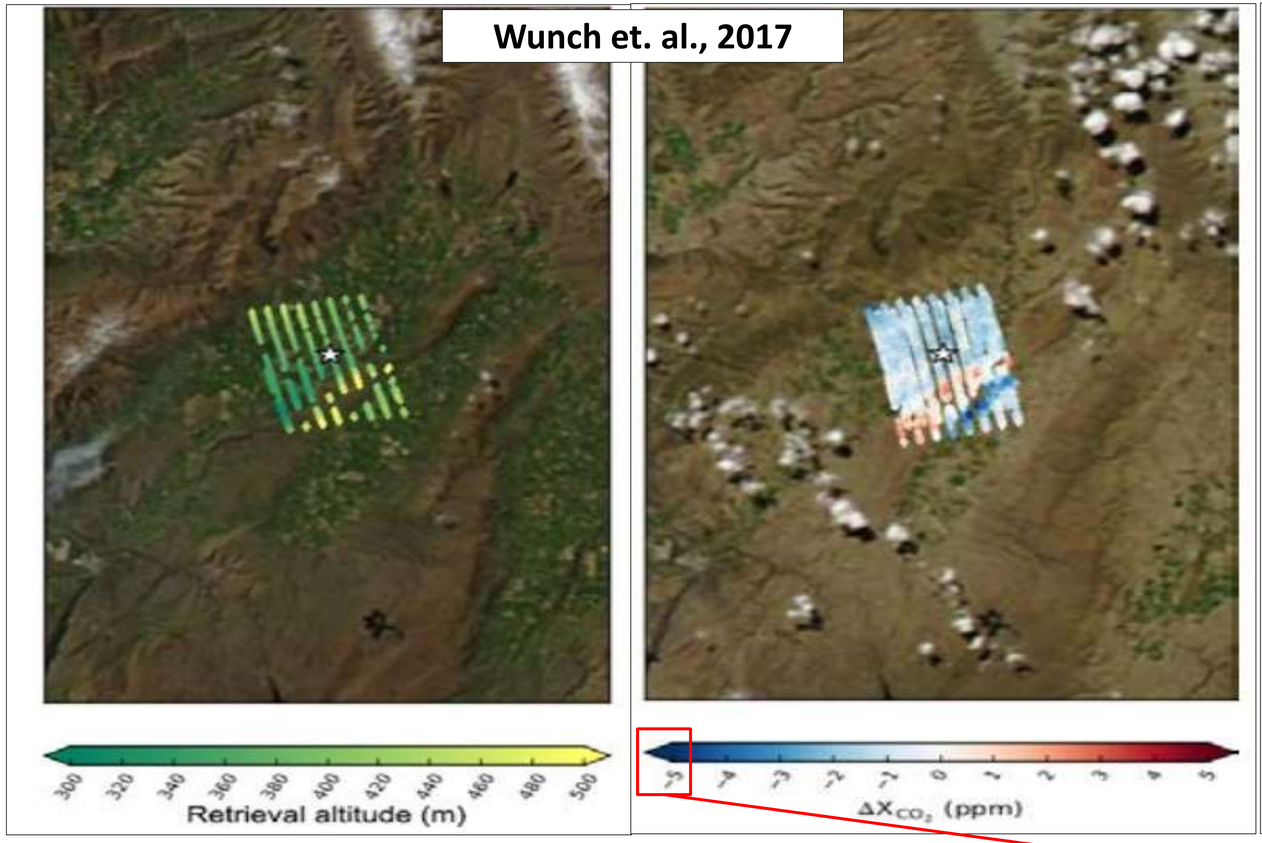
The **largest changes** are for **high northern latitude** sites due to the **DEM** (Copernicus) change.

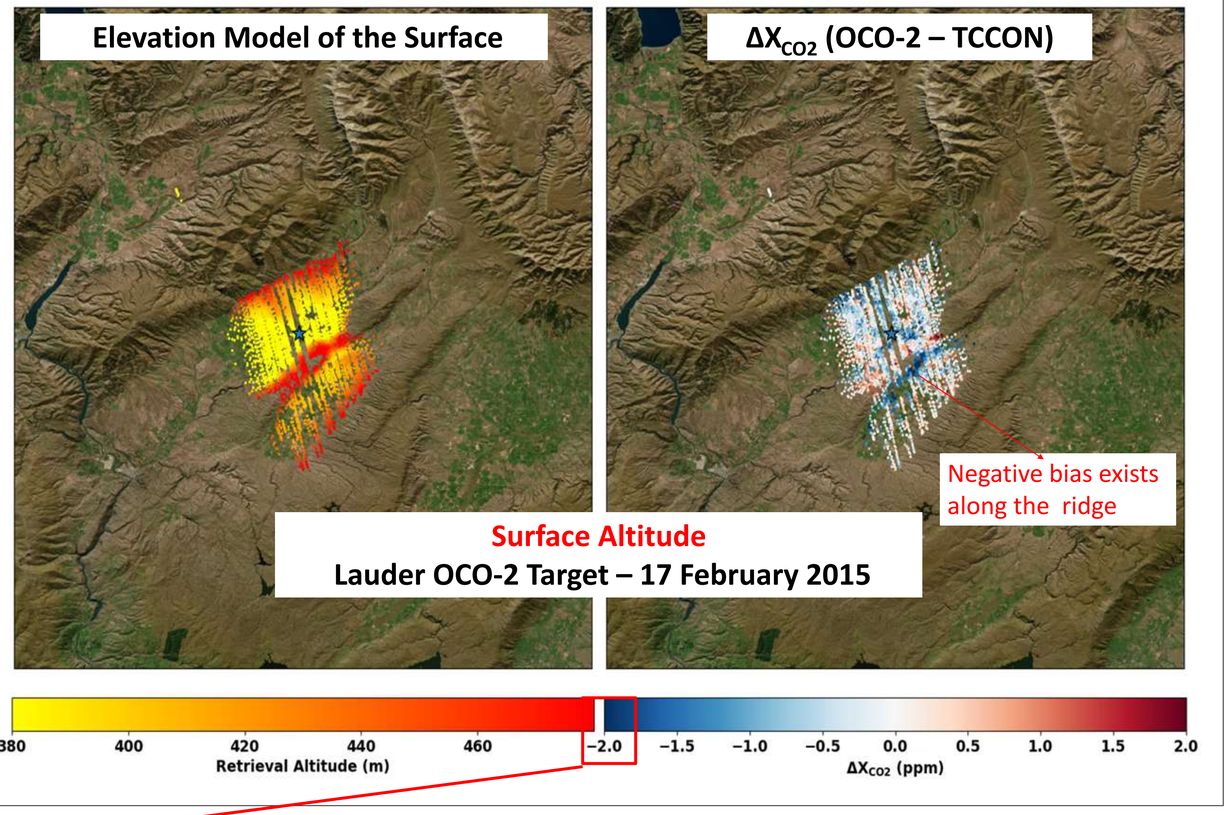
Target

There is a decrease in the bias due to the updated **Global Scaling Factor** and the **DEM**.

- For all observation modes, OCO-2 V11.2 performs well against TCCON.

Location Dependent Bias – Lauder



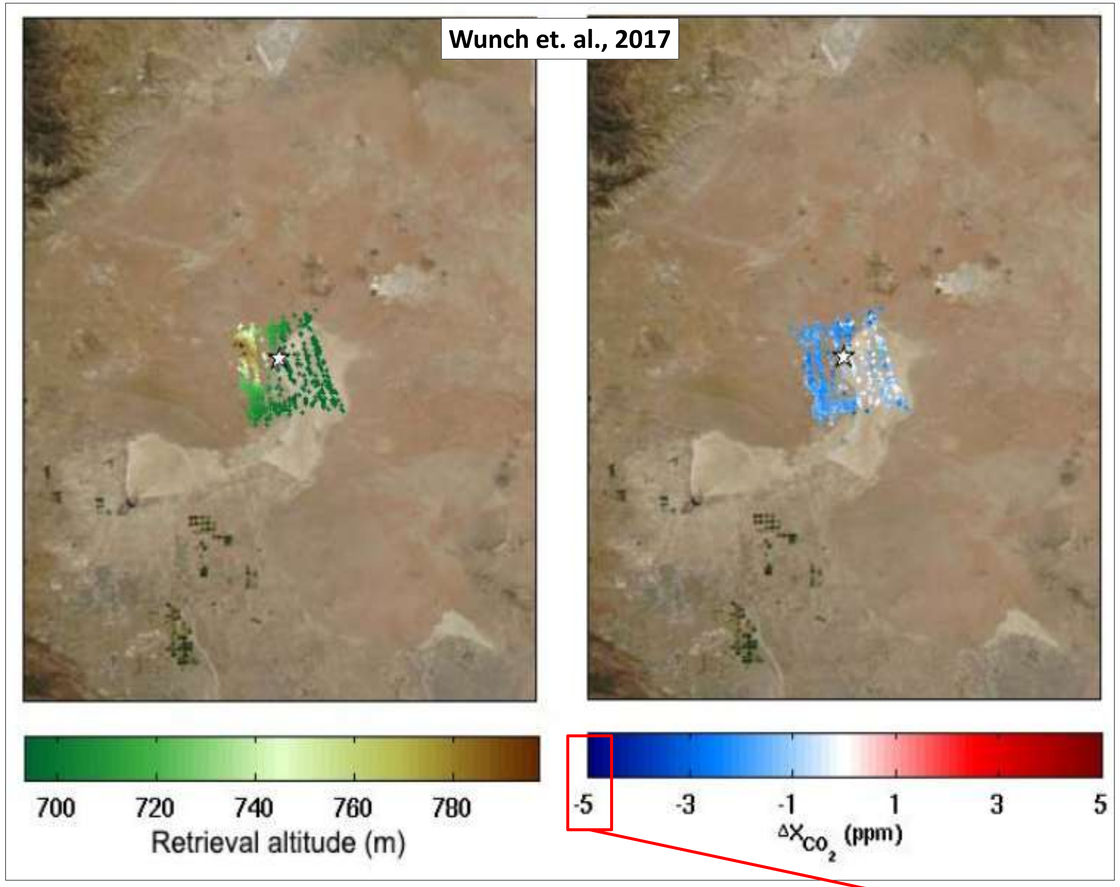


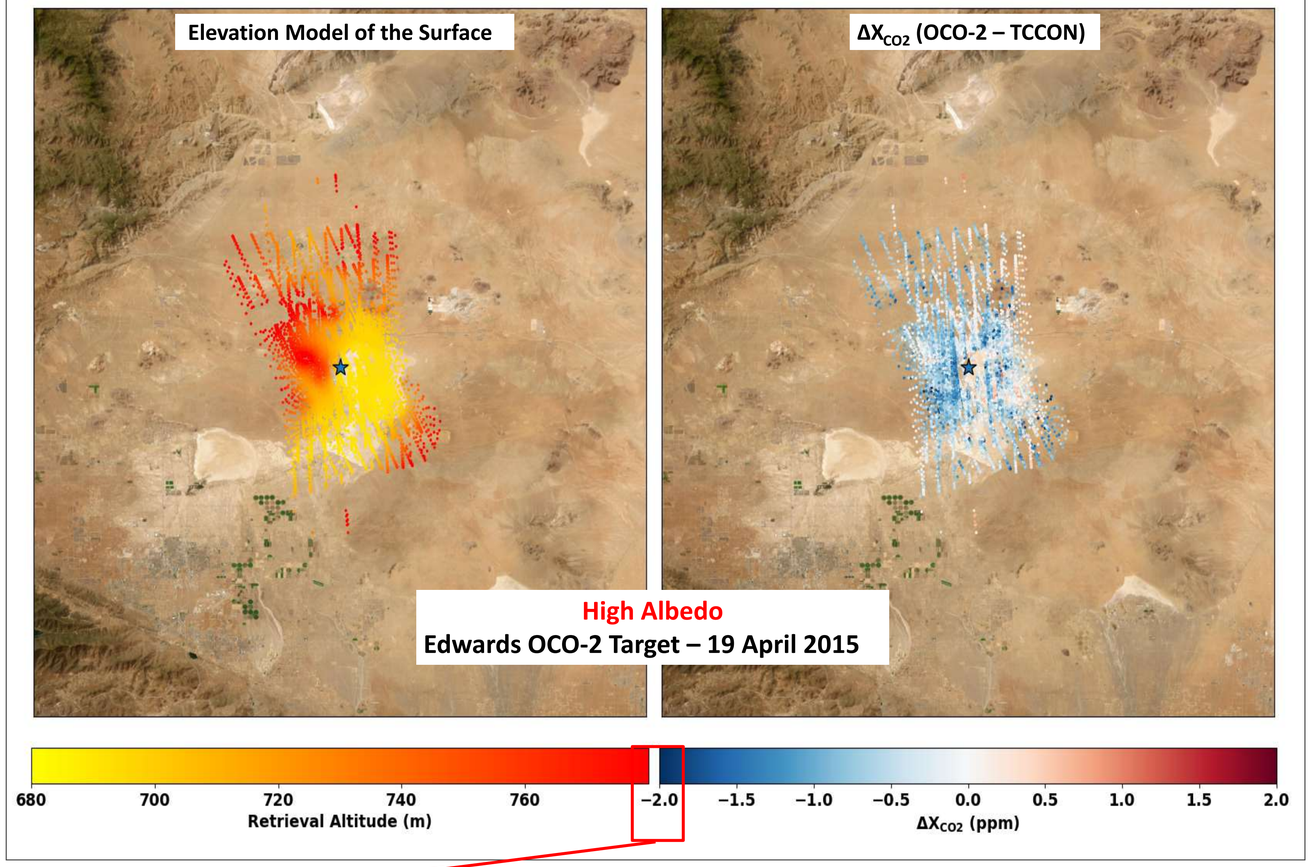
Note different color scales

Location - Dependent Biases – Surface Altitude

- Although, Lauder does not show significant overall bias compared to TCCON, the retrievals can show spurious **spatially correlated errors**.
- The Lauder TCCON station is located in a **valley between rolling hills**. The **surface altitude** is spatially correlated with the changes in X_{CO2} measured during each target-mode maneuver.
- Recreated plots from Wunch et al. (2017) using the V11.1 X_{CO2} dataset indicate lower **ΔX_{CO2}** values, overall.

Location Dependent Bias – Edwards



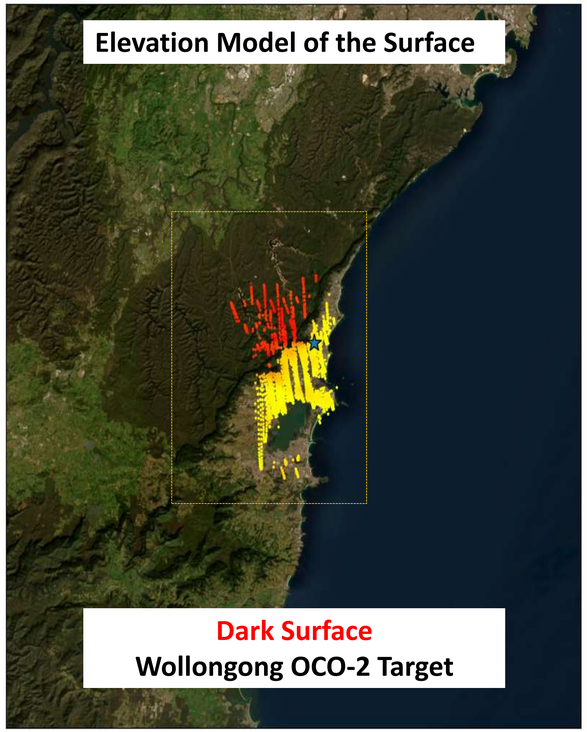


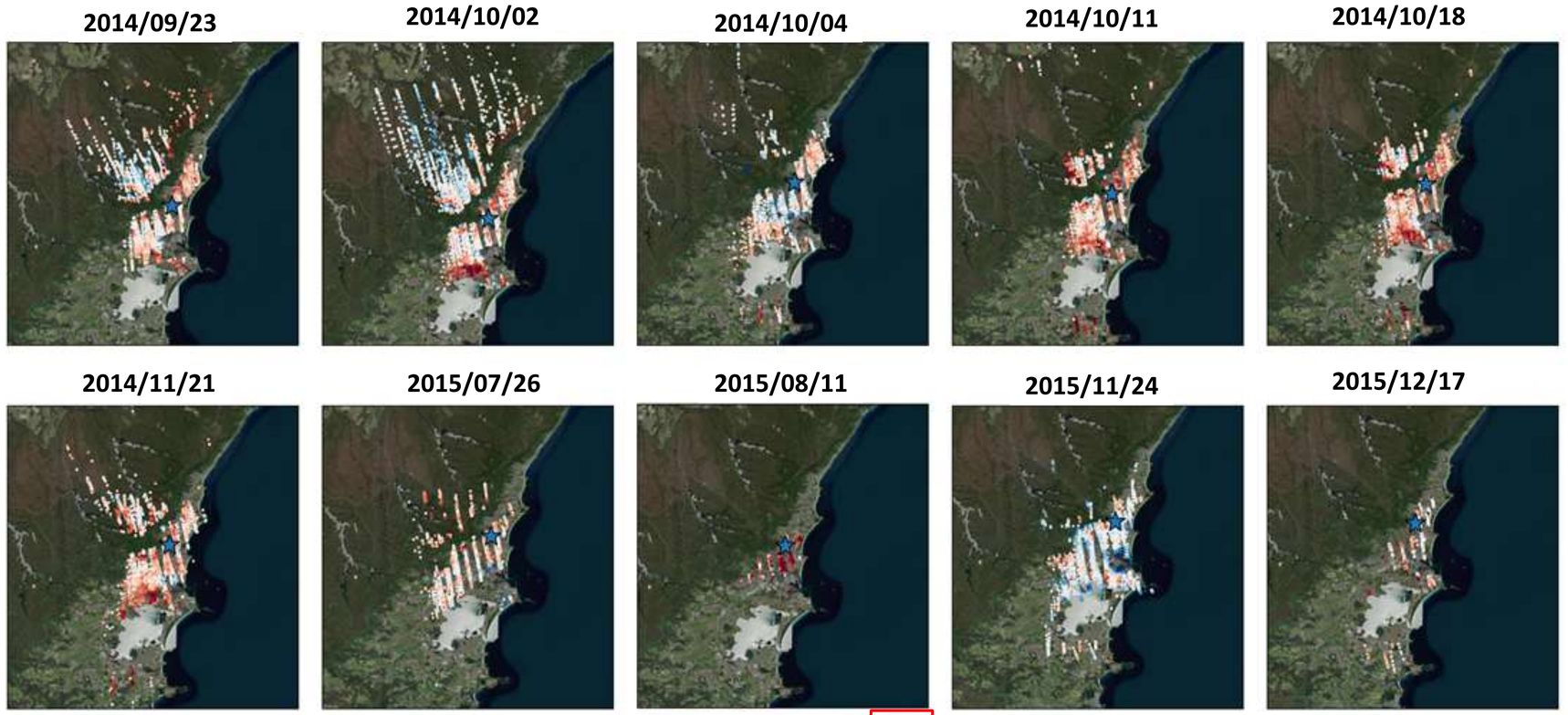
Note different color scales

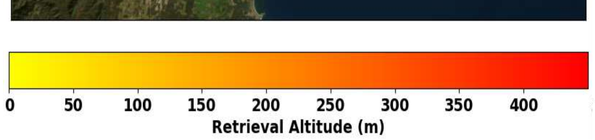
Location - Dependent Biases - Albedo

- The Edwards TCCON station is **situated in the California high desert on the edge of a very bright playa** (high **albedo**), with higher X_{CO2} retrieved over brighter surfaces.
- Significant spurious variability in the OCO-2 X_{CO2} can occur due to **spatial dependence of the target-mode measurements on surface properties** (e.g., albedo, altitude, surface roughness)).
- Recreated plots from Wunch et al. (2017) using the V11.1 X_{CO2} dataset indicate lower **ΔX_{CO2}** values, overall.

Location Dependent Bias – Wollongong



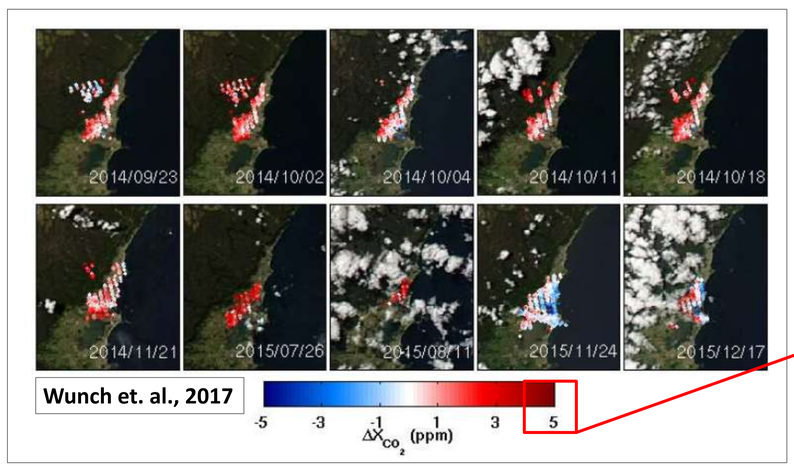




Location - Dependent Biases – Dark Surface

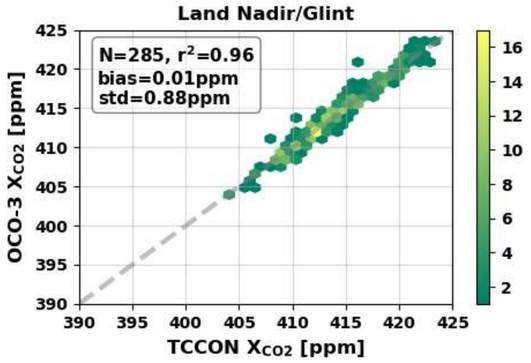
- The Wollongong TCCON station is **situated between the Tasman Sea to the east and the Illawarra escarpment to the west** (region within the box). **OCO-2** X_{CO2} retrievals are **typically biased higher than TCCON**.

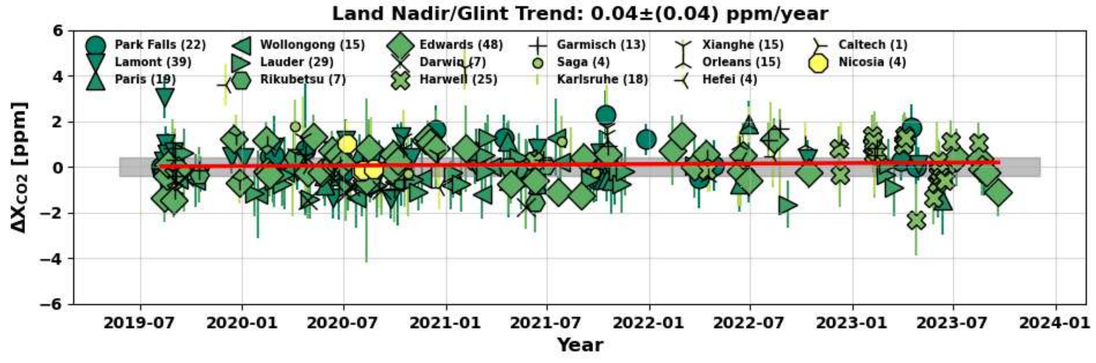
- Recreated plots from Wunch et al. (2017) using the V11.1 X_{CO2} dataset indicate lower **ΔX_{CO2}** values, overall.

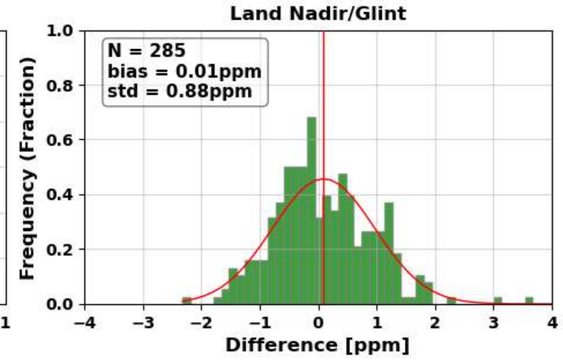


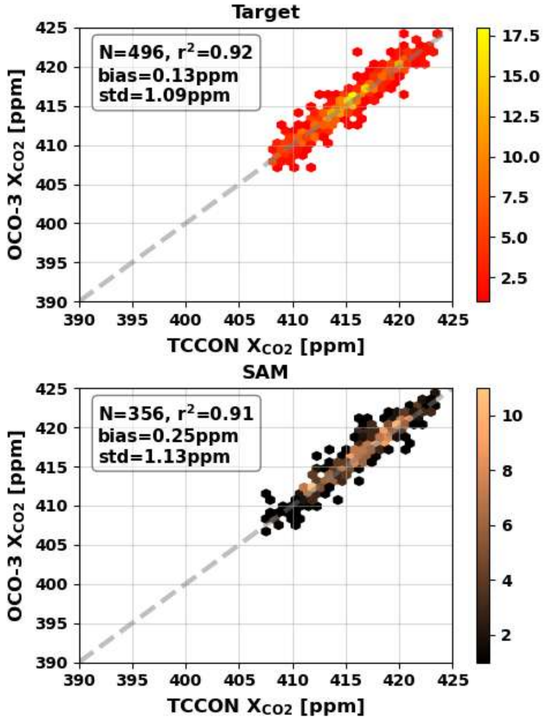
Note different color scales

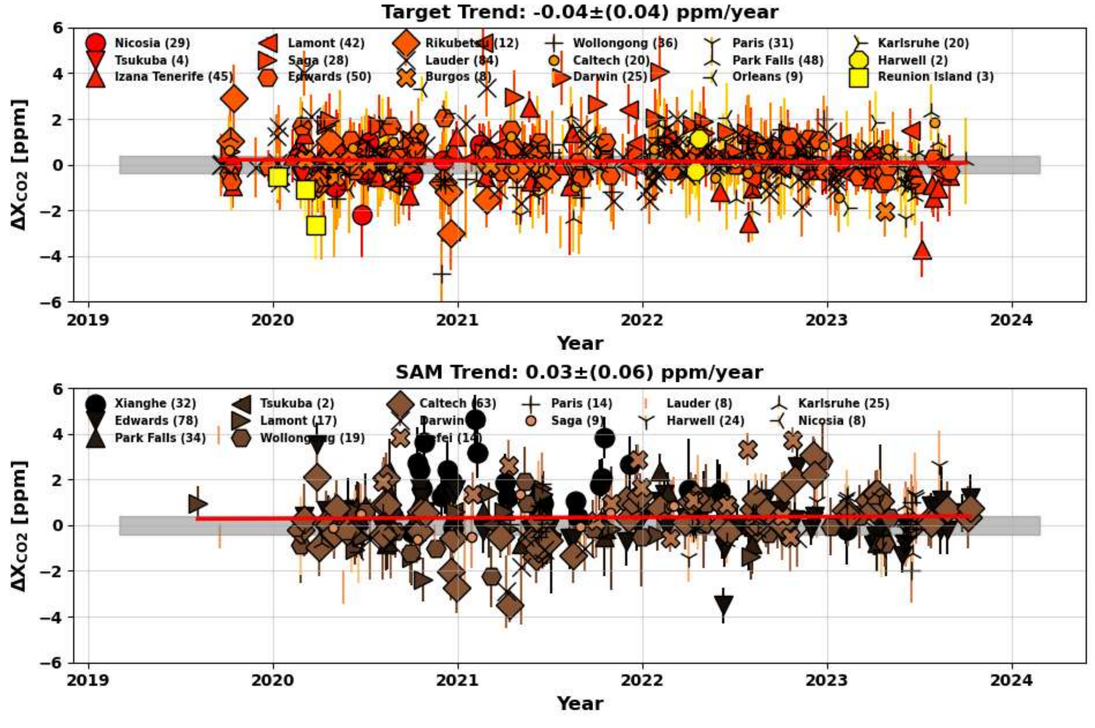
OCO-3 V11 vs. TCCON GGG2020 (x2019)

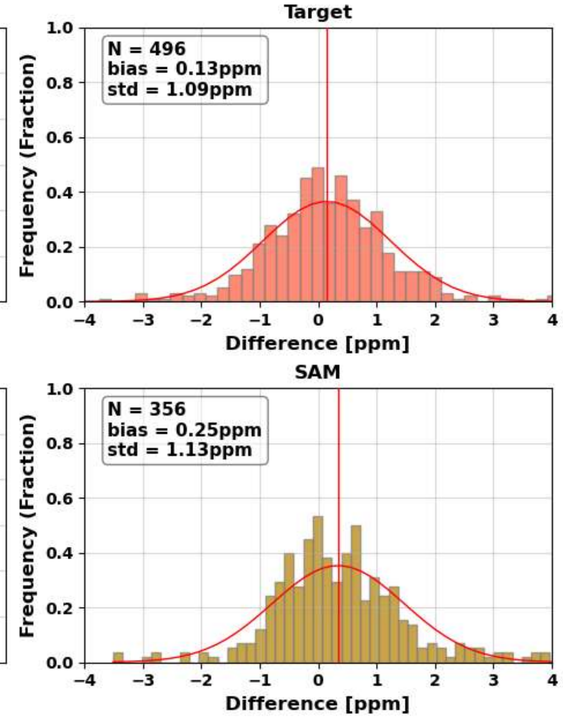












Land Nadir/Glint

The overall bias is slightly positive, but very close to 0 ppm.

Target

Overall, the bias is slightly positive.

SAM

The bias is slightly higher than other modes.

Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	285	0.01	0.88
Ocean Glint	22	0.09	0.62
Target	496	0.13	1.09
SAM	356	0.25	1.13

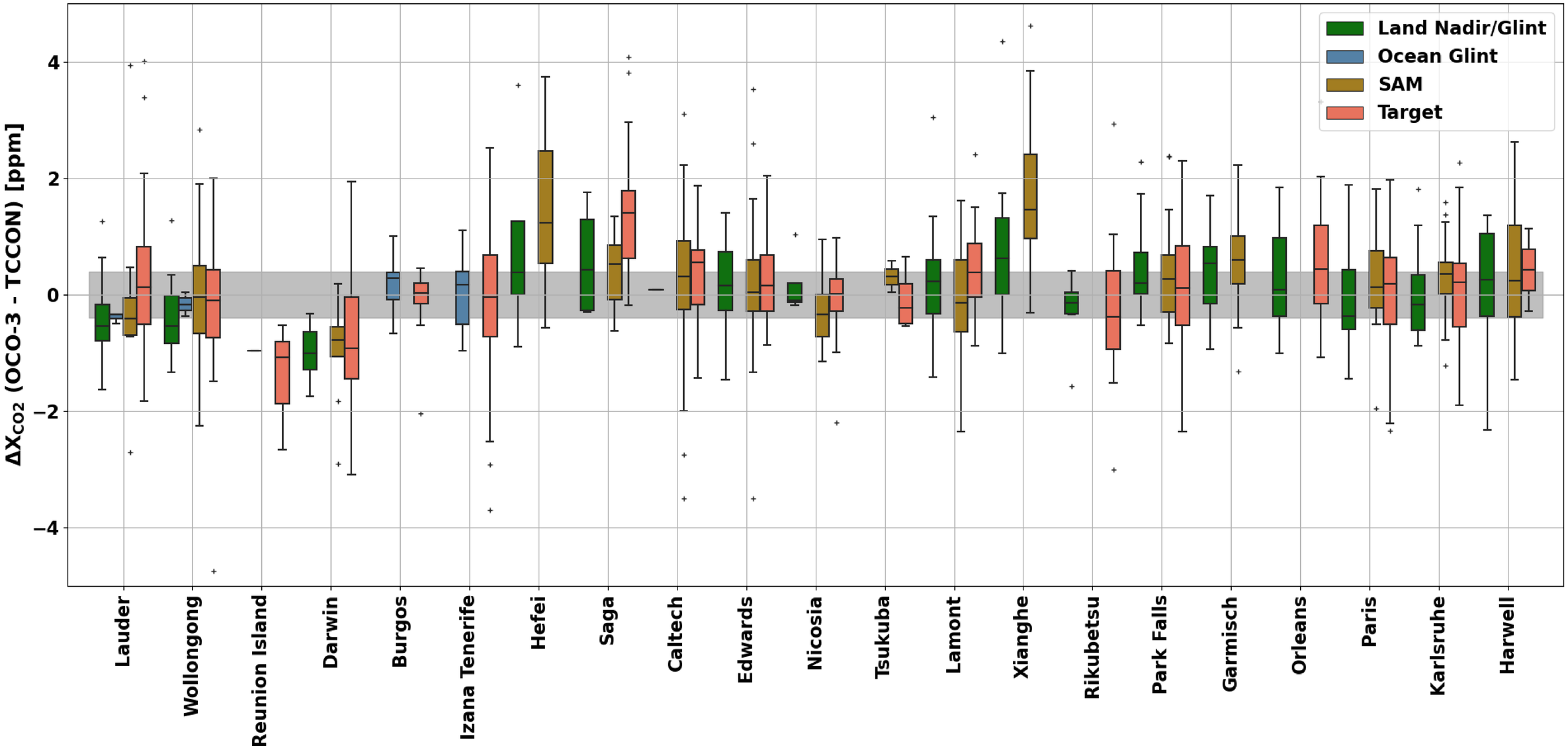
Aggregated OCO-2 X_{CO2} estimates filtered with xco2_quality_flag = 0 typically compare well with coincident TCCON data at global scales, with **absolute average biases ≤ 0.25 ppm**.

Ocean Glint: Limited comparisons are available in this mode.

OCO-3 V11 vs. TCCON GGG2020 (x2019) – Site-to-Site Differences

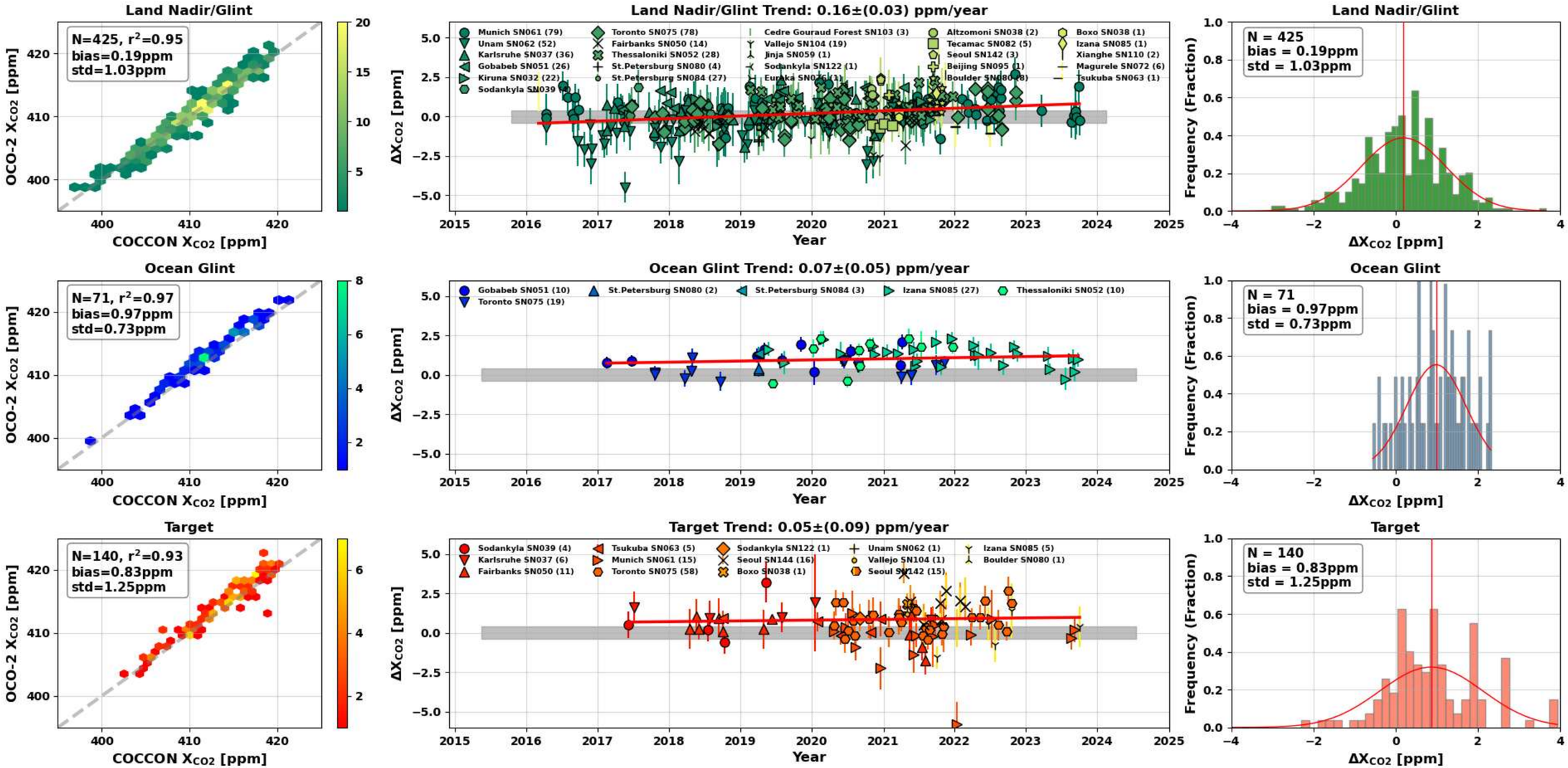
South

North



- For all observation modes, OCO-3 V11 performs well against TCCON, compared to earlier OCO-3 versions.
- Limited comparisons are available in the **Ocean Glint** mode**.**

OCO-2 V11.2 vs. COCCON PROFFAST V1 (x2007)



Land Nadir/Glint

The overall bias is slightly positive, but the lowest among all modes.

Ocean Glint

The bias is higher than other modes, (though still reasonable given the uncertainty).

Target

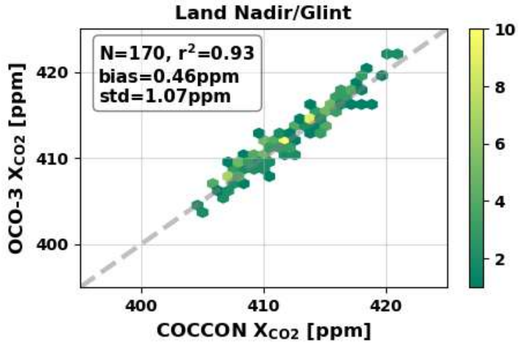
Overall, the bias is high.

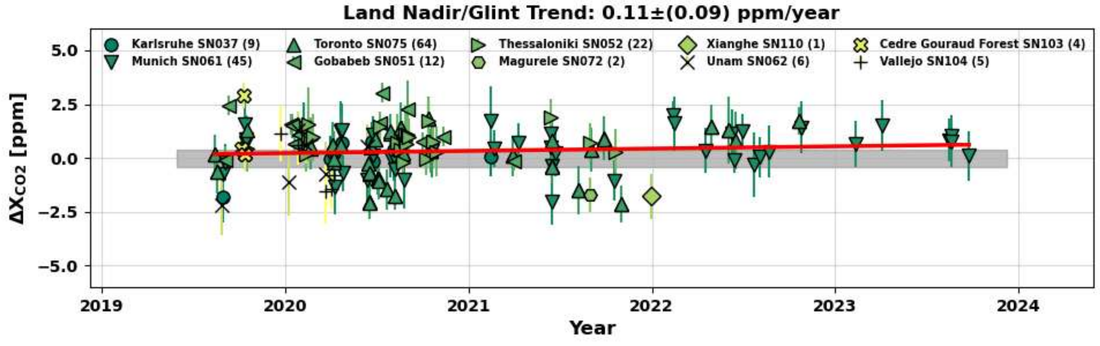
Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	425	0.19	1.03
Ocean Glint	71	0.97	0.73
Target	140	0.83	1.25

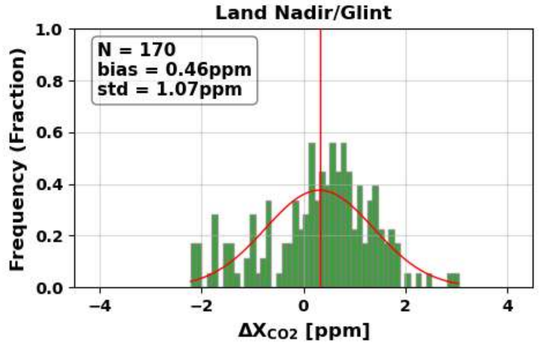
Aggregated OCO-2 X_{CO2} estimates filtered with xco2_quality_flag = 0 typically compare well with coincident COCCON data at global scales, given the uncertainties, with **absolute average biases ≤ 0.97 ppm**.

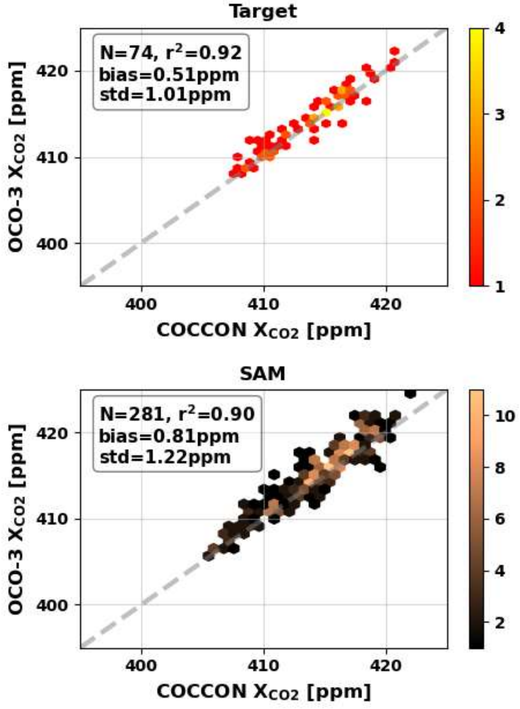
The high bias values are possibly attributable to the use of an older (v1) PROFFAST version-processed COCCON data (on the x2007 scale), consistently available for most sites.

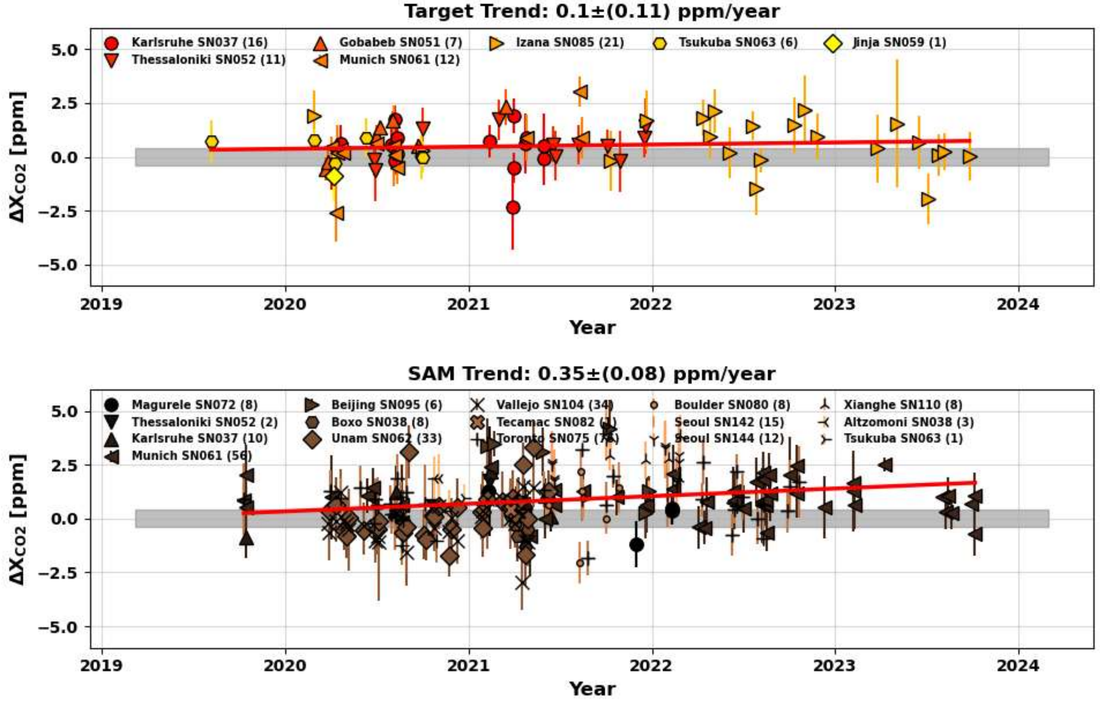
OCO-3 V11 vs. COCCON PROFFAST V1 (x2007)

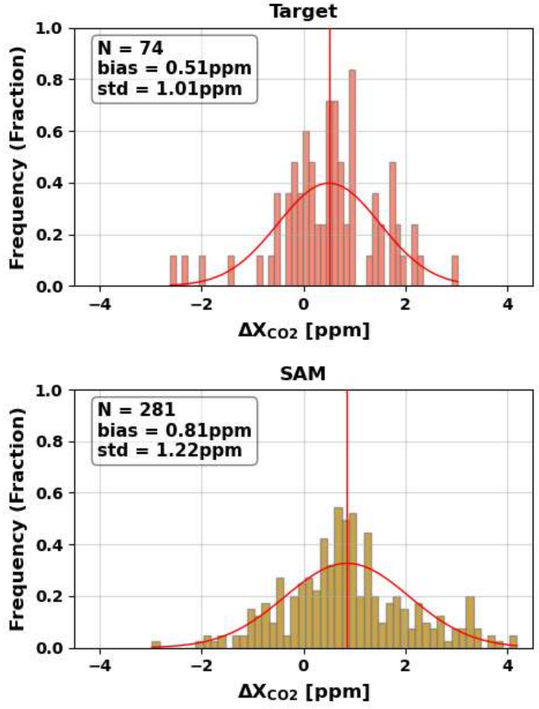












Land Nadir/Glint

The overall bias is positive, but the lowest among all modes.

Target

Overall, the bias is high and positive.

SAM

Overall, the bias is high and positive.

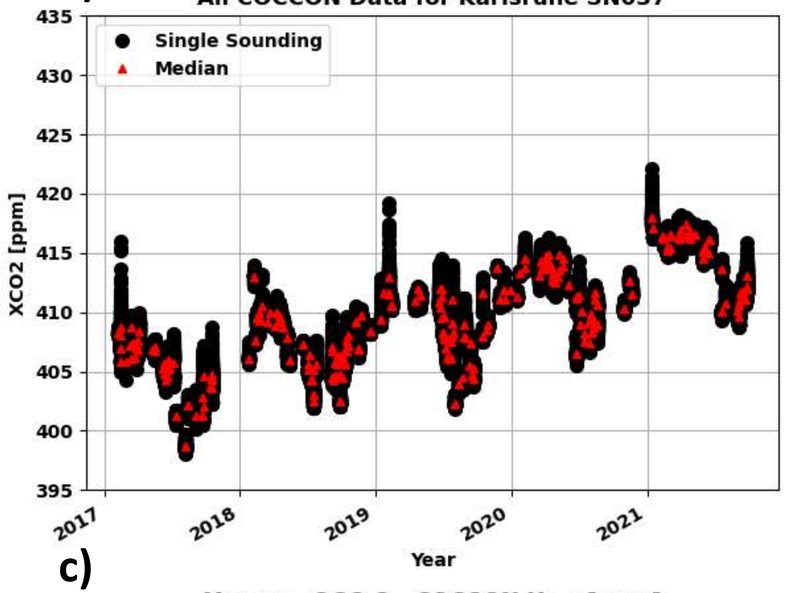
Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	170	0.46	1.07
Ocean Glint	14	0.87	0.47
Target	74	0.51	1.01
SAM	281	0.81	1.22

Ocean Glint: There are very few coincidences in this mode.

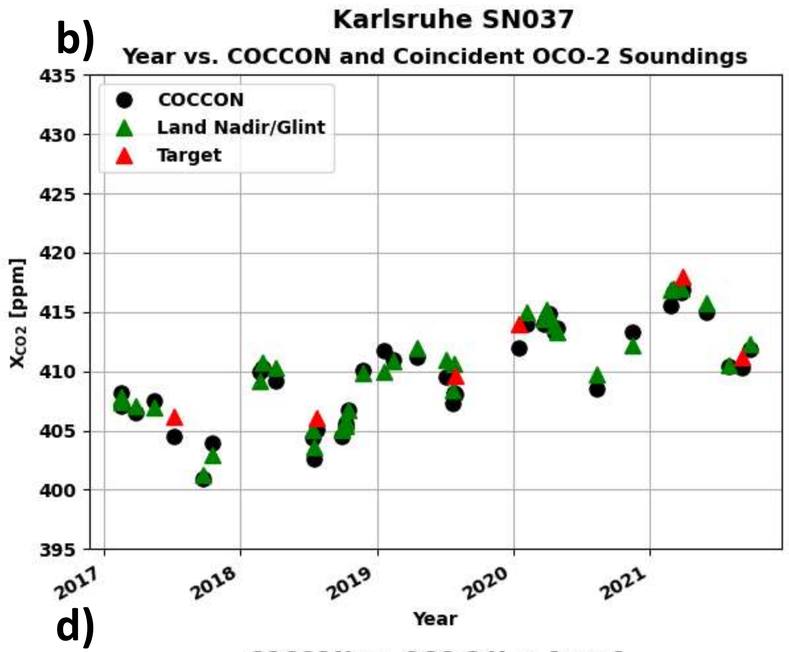
Aggregated OCO-3 X_{CO2} estimates filtered with xco2_quality_flag = 0 typically compare well with coincident COCCON data at global scales, given the uncertainties, with **absolute average biases ≤ 0.87 ppm**. The high bias values are possibly attributable to the use of an older (v1) PROFFAST version-processed COCCON data (on the x2007 scale), consistently available for most sites.

OCO-2 (V11.2) vs. COCCON (V1) - Karlsruhe

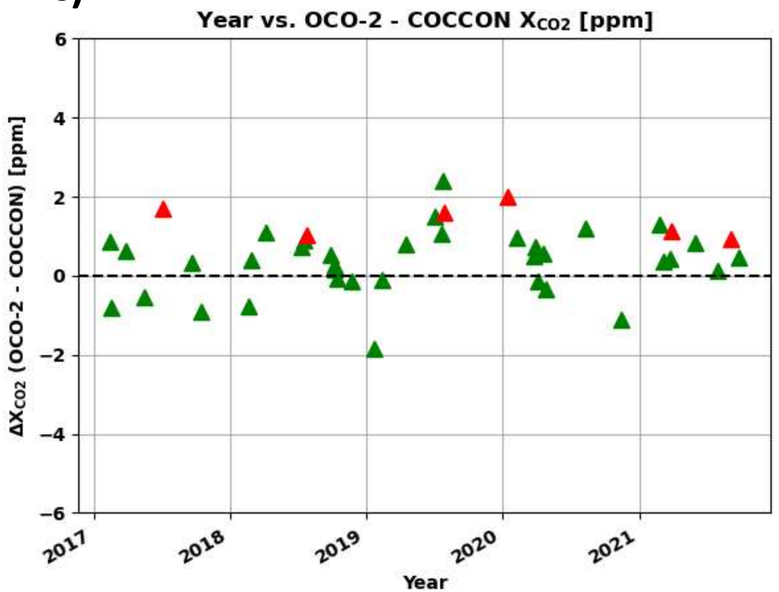
a)



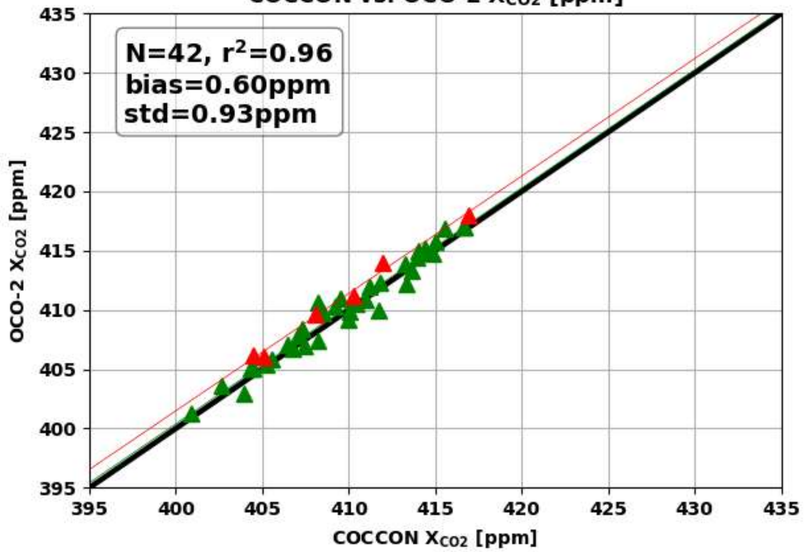
b)



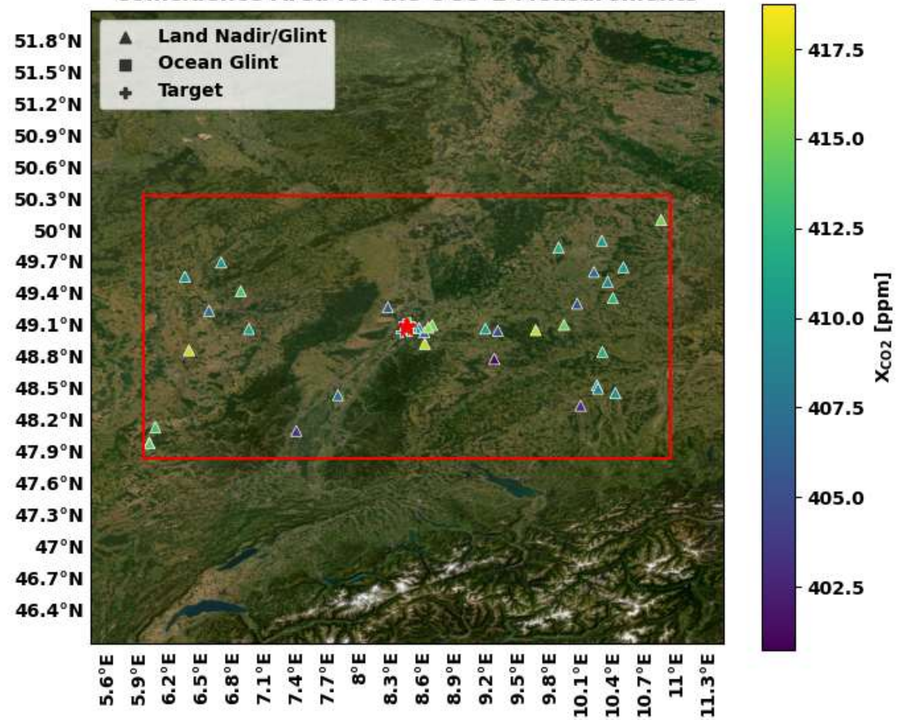
c)



d)



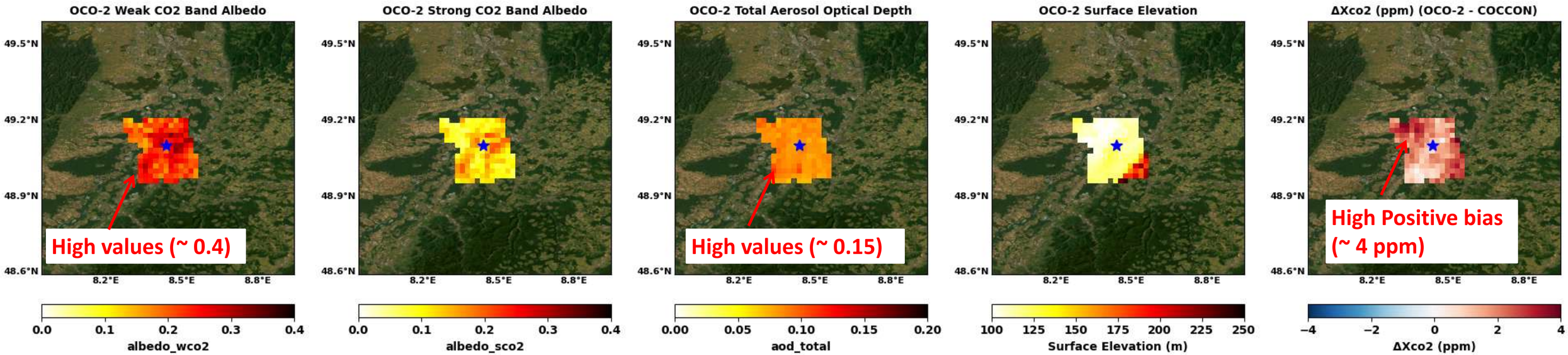
e)



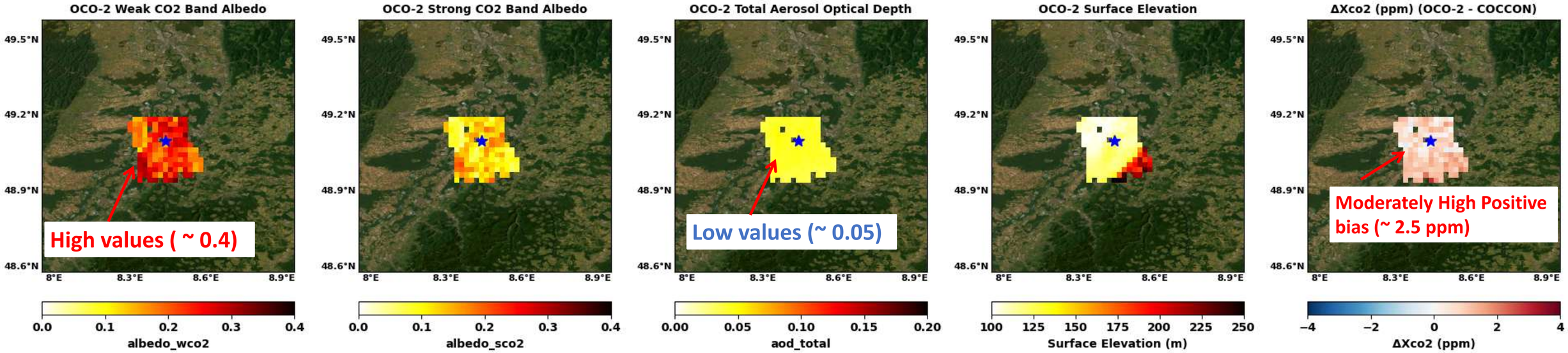
a) **Time** series of all site-specific COCCON data with the red triangles indicating daily median values.
b) **Time series** of the COCCON **median data** (**black circles**) and the **OCO-2 data** (**triangles** colored differently for each mode).
c) **Difference** between OCO-2 and COCCON X_{CO2} measurements (**OCO-2 – COCCON**).
d) **Correlations** between the **COCCON** data and **OCO-2** datasets
e) **Coincidence area** for the **OCO-2** measurements.

OCO-2 (V11.2) vs. COCCON (V1) - Karlsruhe

Karlsruhe OCO-2 Target – 6 July 2017

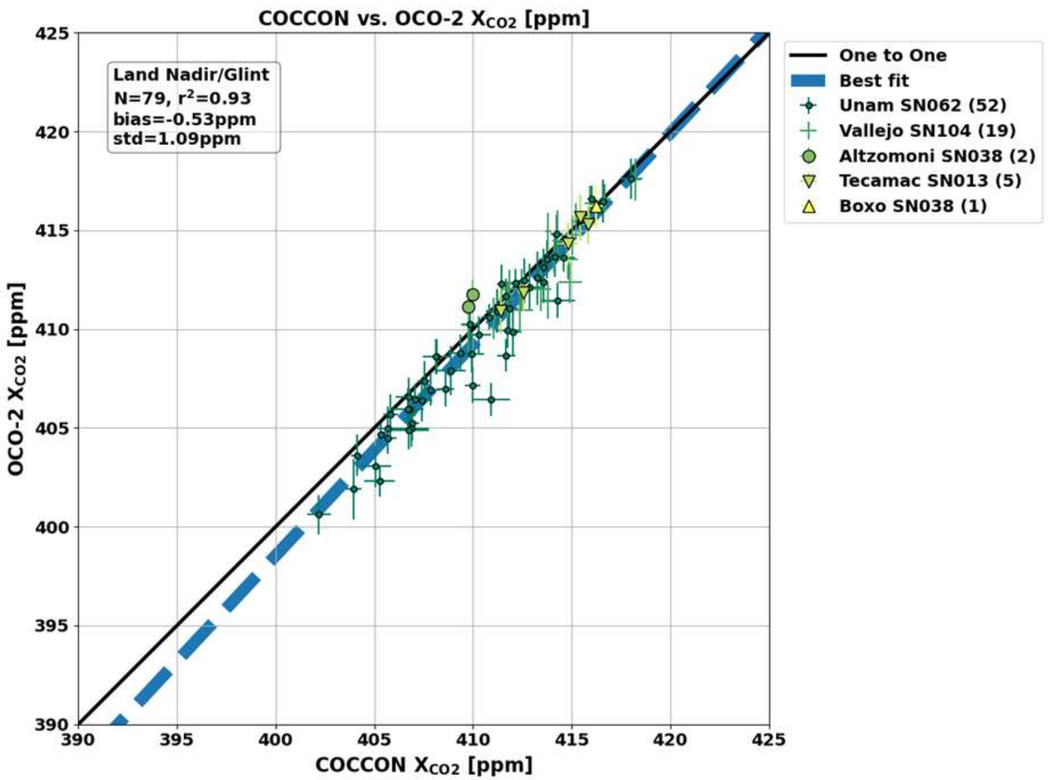


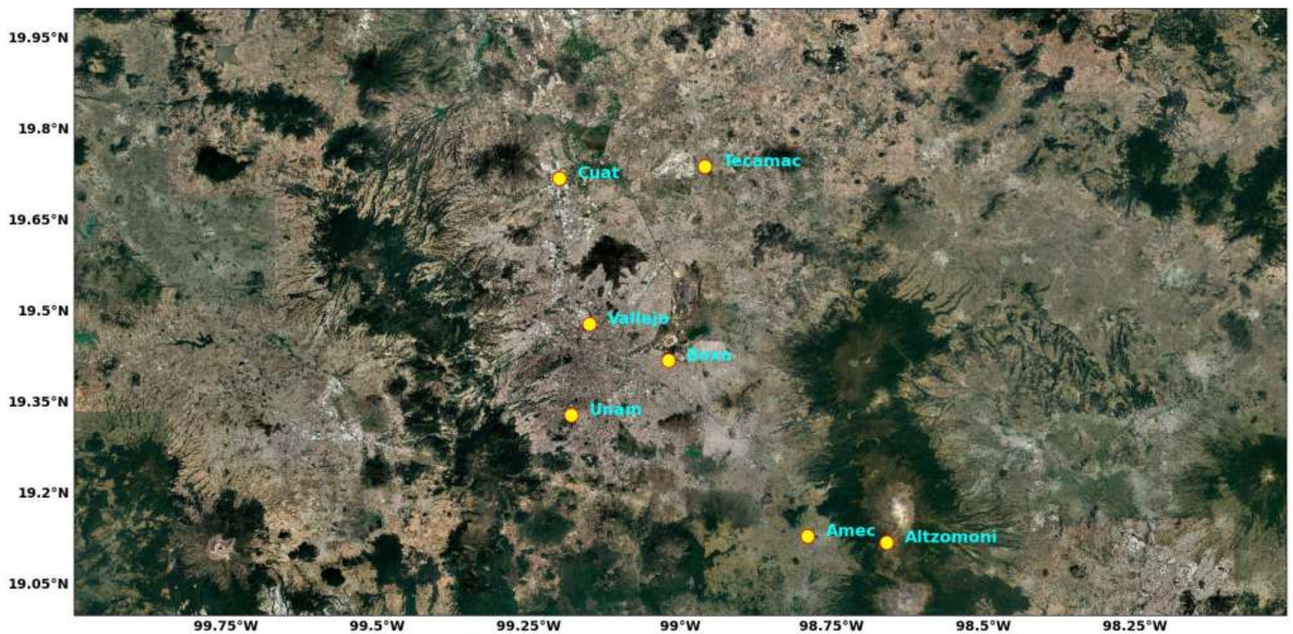
Karlsruhe OCO-2 Target – 3 September 2021



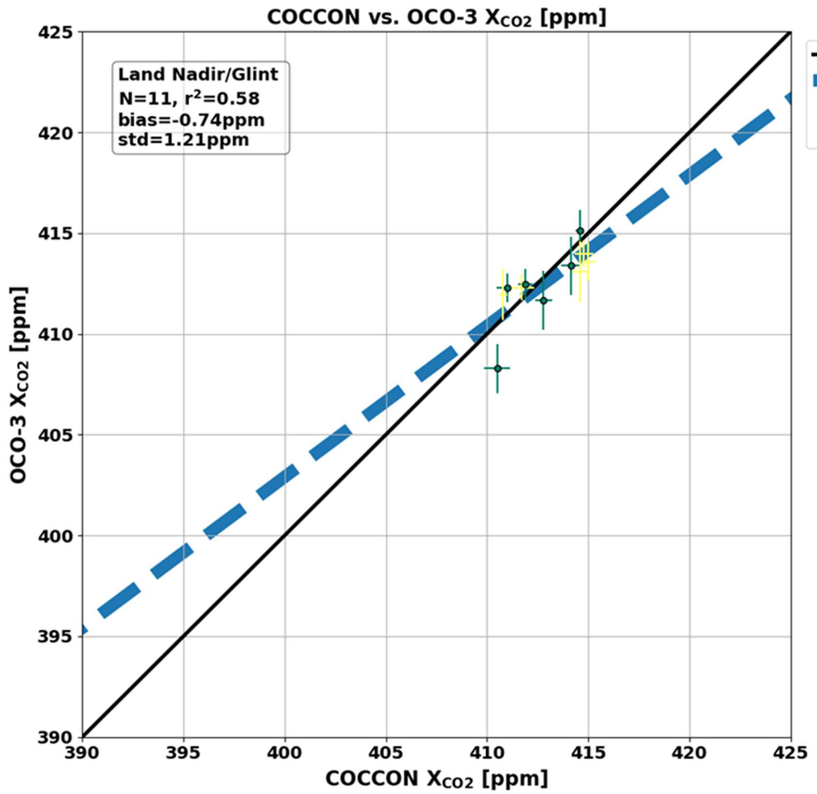
- Data are plotted as 0.02° x 0.02° grid-averaged values.
- High albedo values are reported for the weak CO_2 band on both days.
- High aod_total values are reported on 6 July 2017.

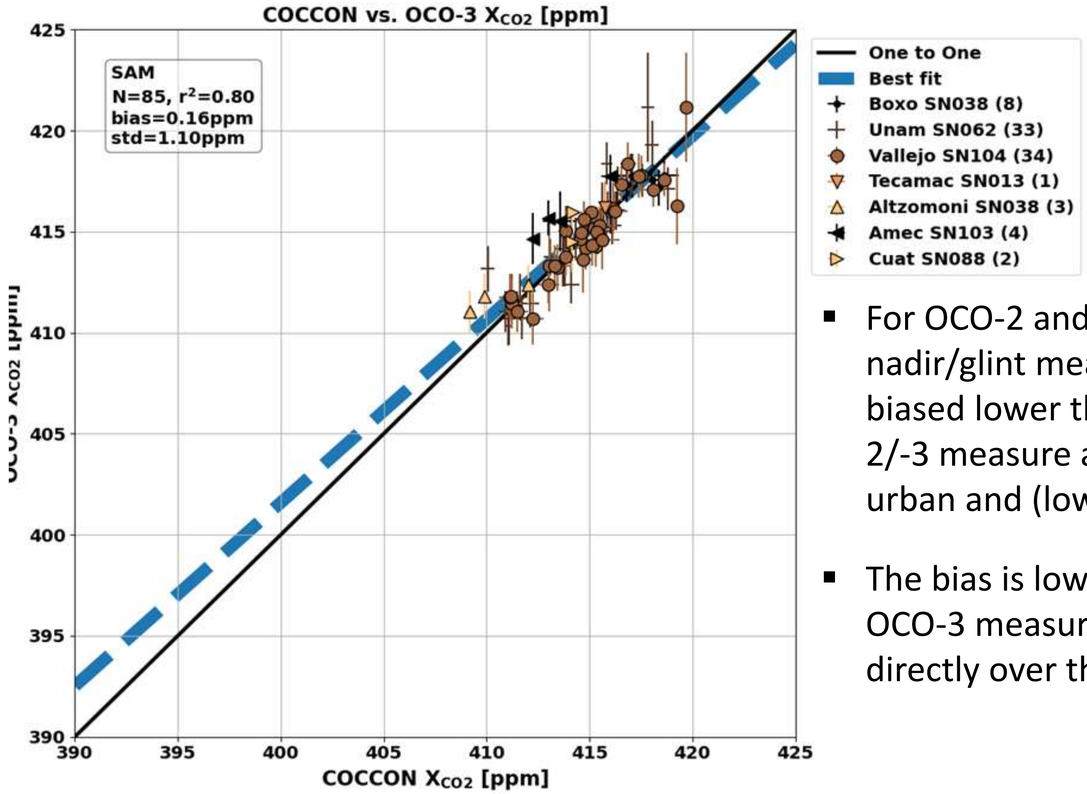
Mexico City Sites





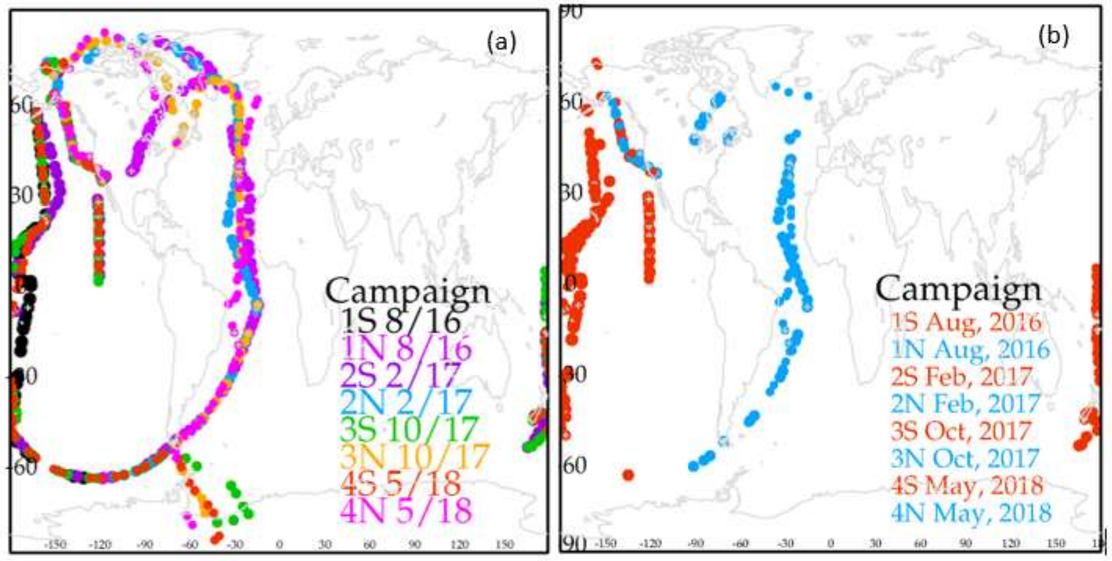
- Data from seven Mexico City Sites – Altzomoni, Amec, Boxo, Cuat, Tecamac, Unam, and Vallejo are used.





- For OCO-2 and OCO-3, the land nadir/glint measurements are biased lower than COCCON as OCO-2/-3 measure a combination of the urban and (lower) background X_{CO2}.
- The bias is low in the SAM mode, as OCO-3 measurements are made directly over the COCCON location.

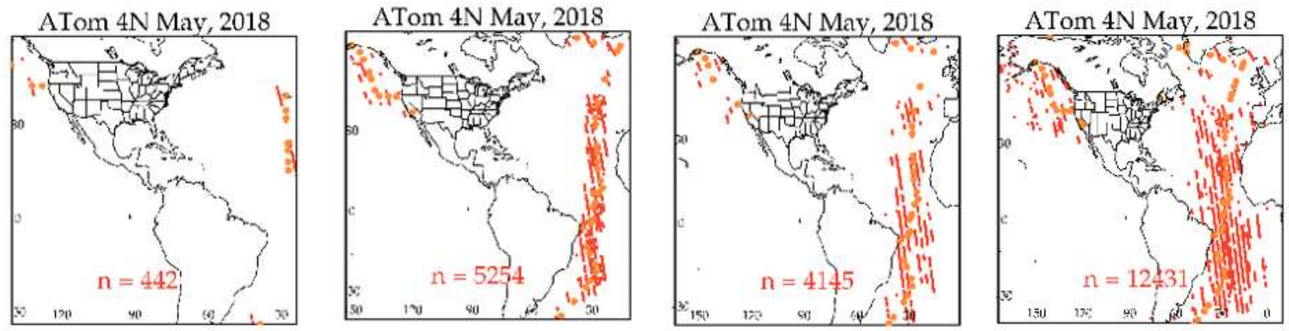
ATom vs. OCO-2 Ocean Glint Data Comparison – Preliminary Analysis



ATom Campaigns: Each dot represents a profile between the surface and 9 or 13 km. The "N" legs are, typically, in the Atlantic, while the "S" legs in the Pacific. The profiles that go up to 13 km are identified with a gray "+" in the center.

Table 1. Systematic error estimates for OCO-2 ocean observations using comparisons to ATom aircraft profiles. The "#_ave" column shows how many ATom observations are matched; "bias" is the mean bias averaged over all campaigns; "bias_stdev" is the standard deviation of the biases for each campaign; "stdev_ave" is the standard deviation of the mean of all observations matching a single ATom measurement minus the ATom measurement; "error_col" is an estimate of the co-location error; "validation error" is an estimate of the error in the aircraft estimate of XCO2; "systematic error" is an estimate of OCO-2 systematic (not random) error.

	#_ave	Bias (ppm)	bias_stdev (ppm)	stdev_ave (ppm)	error_col (ppm)	validation_error (ppm)	systematic_error (ppm)
OCO2-dynamic	796	0.04	0.23	0.76	0.64	0.24	0.37
OCO2-dynamic-half	**520**	**-0.14**	**0.30**	**0.62**	**0.41**	**0.24**	**0.47**
OCO2-closest-1week	692	-0.04	0.20	0.75	0.60	0.24	0.39
OCO-2-closest-9h	156	-0.07	0.30	0.55	0.20	0.24	0.53



Coincidence Criteria: The OCO-2 (red) matching to 4N ATom (orange) measurements, showing "closest-9h", "closest-1 week", "dynamic – half", and "dynamic" coincidence criteria.

- ATom profiles do not go to the top of the atmosphere. The profiles are extended by CarbonTracker model, by selecting CarbonTracker at the ATom location and time.

- The standard TCCON-matching criteria of 3 degrees latitude, 5 degrees longitude, and 1 hour yields ~ no matches. Thus, we consider several coincidence criteria:
  - **I. Dynamic Coincidence Criteria** (Wunch et al., 2011) with matches within:
    - a. "dynamic" 10 days, 10 degrees latitude, 30 degrees longitude, also matching the atmospheric temperature at 700 hPa within 2K
    - b. "dynamic-half" 5 days, 5 degrees latitude, 15 degrees longitude, also matching the atmospheric temperature at 700 hPa within 2K
  - **II. Geometric Coincidence Criteria:**
    - a. "closest-9h" ± 9 hours, ± 3 degrees latitude, ± 5 degrees longitude
    - b. "closest-1week" ± 1 week, ± 3 degrees latitude, ± 5 degrees longitude

Figures, Table, and Text Credit: *Dr. Susan Kulawik*

Summary

V11.2 OCO-2 vs. TCCON GGG2020

Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	1239	0.03	0.84
Ocean Glint	338	0.18	0.72
Target	576	-0.01	0.94

V11.2 OCO-2 vs. v1 COCCON

Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	425	0.19	1.03
Ocean Glint	71	0.97	0.73
Target	140	0.83	1.25

V11 OCO-3 vs. TCCON GGG2020

Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	285	0.01	0.88
Ocean Glint	22	0.09	0.62
Target	496	0.13	1.09
SAM	356	0.25	1.13

V11 OCO-3 vs. v1 COCCON

Mode	# of Comparisons	Bias (ppm)	Standard Deviation (ppm)
Land Nadir/Glint	170	0.46	1.07
Ocean Glint	14	0.87	0.47
Target	74	0.51	1.01
SAM	281	0.81	1.22

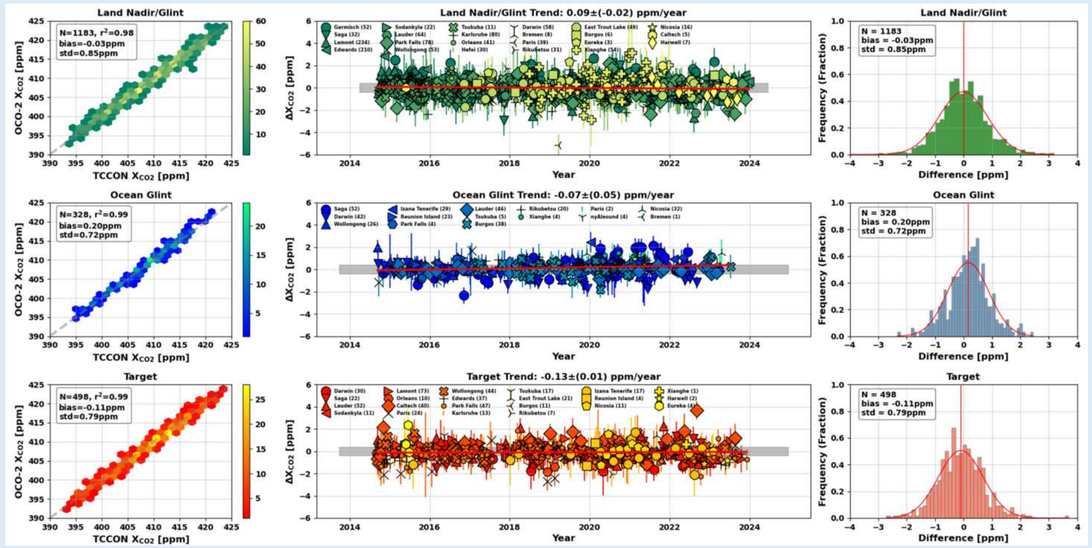
OCO-2 Ocean Glint vs. ATom

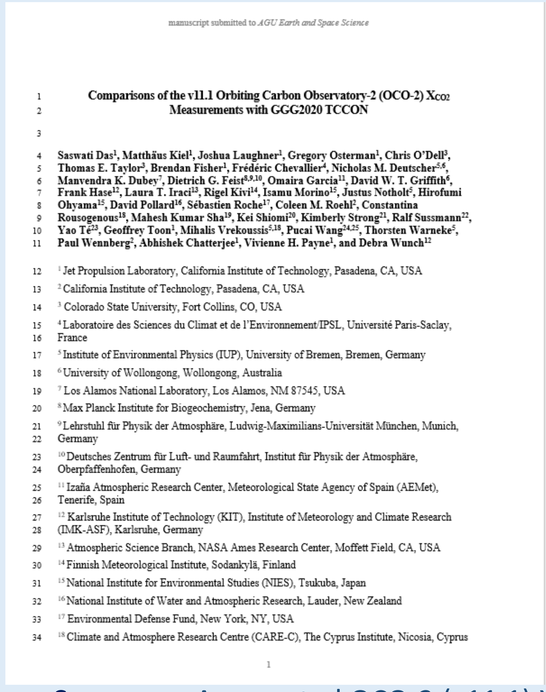
Coincidence Criteria	N	Bias (ppm)	Std (ppm)
OCO-2-closest-9h	156	-0.07	0.55
OCO2-closest- 1week	692	-0.04	0.75
OCO-2-dynamic	796	0.04	0.23
OCO-2-dynamic-half	520	-0.14	0.30

- TCCON continues to serve as the primary validation data source for OCO-2/-3.
- The current comparisons against v1 COCCON provide reasonable results with the given limitations. (Improved comparisons are expected with data for more sites being available in the future, and all COCCON data being available in the v2.4/latest data version.)
- Preliminary OCO-2 (Ocean Glint) vs. ATom comparisons suggest absolute average bias values < 0.15 ppm across all coincidence criteria.

Summary, Paper Update, and Future Work

1. OCO-2 vs. TCCON





Comparisons of the v11.1 Orbiting Carbon Observatory-2 (OCO-2) X_{CO2} Measurements with GGG2020 TCCON

Saswati Das[1], Matthäus Kiel[1], Joshua Laughner[1], Gregory Osterman[1], Chris O'Dell[3], Thomas E. Taylor[3], Brendan Fisher[1], Frédéric Chevallier[4], Nicholas M. Deutscher[5,6], Manvendra K. Dubey[7], Dietrich G. Feist[8,9,10], Omaira Garcia[11], David W. T. Griffith[6], Frank Hase[12], Laura T. Iraci[13], Rigel Kivi[14], Isamu Morino[15], Justus Notholt[5], Hirofumi Ohyama[15], David Pollard[16], Sébastien Roche[17], Coleen M. Roehl[1], Constantina Rousogenous[18], Mahesh Kumar Sha[19], Kei Shiomi[20], Kimberly Strong[21], Ralf Sussmann[22], Yao Té[23], Geoffrey Toon[1], Mihalis Vrekoussis[5,18], Pucai Wang[24,25], Thorsten Warneke[5], Paul Wennberg[2], Abhishek Chatterjee[1], Vivienne H. Payne[1], and Debra Wunch[12]

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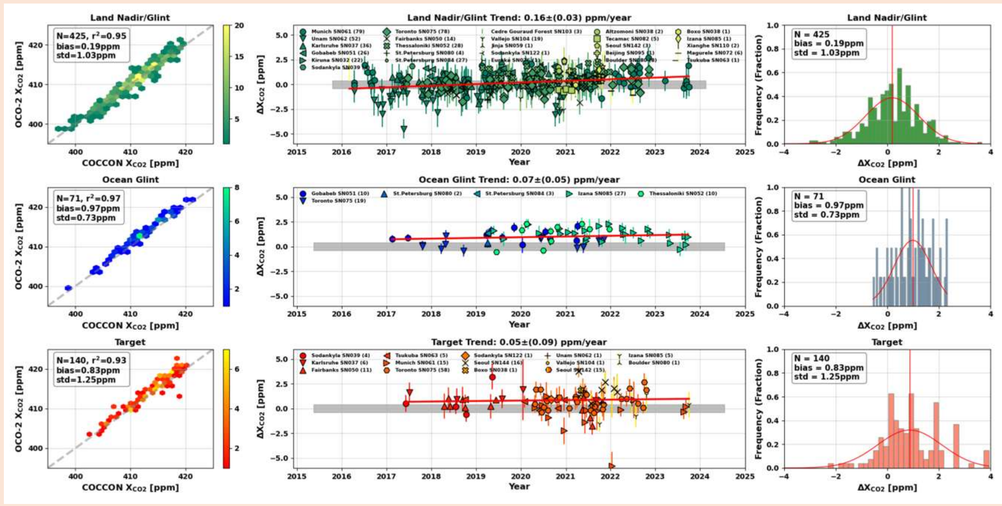
Key Points:

- Dry-air mole-fractions of carbon dioxide (X_{CO2}) from the Orbiting Carbon Observatory – 2 (OCO-2) are evaluated against ground-based data.
- GGG2020-retrieved ground-based measurements from the Total Carbon Column Observing Network (TCCON) are compared with v11.1 OCO-2 X_{CO2}.
- Bias-corrected and quality-filtered OCO-2 X_{CO2} data show absolute average biases less than or equal to 0.20 ppm compared to TCCON globally.

- **Summary:** Aggregated OCO-2 (v11.1) X_{CO2} estimates filtered with xco2_quality_flag = 0 typically compare well with coincident TCCON data at global scales, with absolute average biases ≤ 0.2 ppm.
- Accepted, *AGU Earth and Space Science*

2. OCO-2/-3 vs. COCCON



Validating v11.2 OCO-2 and v11 OCO-3 X_{CO2} Retrievals: Insights from Ground-Based COCCON Measurements

Saswati Das[1], Mahesh Kumar Sha[2], Matthäus Kiel[1], Joshua L. Laughner[1], Gregory B. Osterman[1], Chris O'Dell[3], Thomas E. Taylor[3], Brendan Fisher[1], Robert R. Nelson[1], Bianca Baier[2], Dimitrios Balis[4], Thomas Blumenstock[5], Hartmut Bösch[6], Andre Butz[7], Jia Chen[8], Frédéric Chevallier[11], Alexandru Dandocsi[11], Nicholas M. Deutscher[12,13], Manvendra K. Dubey[14], Darko Dubravica[5], Dietrich G. Feist[10,16,17], Jonathan E. Franklin[15], Matthias M. Frey[5], Omaira García[18], Elaine Gottlieb[15], David W. T. Griffith[12], Michel Grutter[19], Frank Hase[5], Eliezer S. Hernández[18,21], Neil Humpage[13,14], Laura T. Iraci[18], Nicole Jacobs[14], Sujong Jeong[22], Rigel Kivi[23], Morgan Lopez[24], Erin McGee[24], Marios Mermigkas[4], Isamu Morino[25], Justus Notholt[5], Hirofumi Ohyama[26], Thomas Paton[1], Hayoung Park[27], Robert Parker[13,14], David F. Pollard[15], Markus Rettinger[17], Sébastien Roche[28], Coleen M. Roehl[1], Constantina Rousogenous[14], Kei Shiomi[29], William R. Simpson[30], Wolfgang Stremme[18], Kimberly Strong[28], Ralf Sussmann[31], Noemie L. Taquet[28,32], Yao Té[27], Chrysanthi Topaloglou[4], Geoffrey Toon[1], Qianxi Tu[7,8], Mihalis Vrekoussis[5,33], Pucai Wang[20,34], Thorsten Warneke[5], Paul Wennberg[2], Steven C. Wofsy[35], Debra Wunch[36], Minqiang Zhou[37], Elizabeth Spicer[15], Annmarie Eldering[15], Susan Kulawik[38], Abhishek Chatterjee[1], and Vivienne H. Payne[1]

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- **Summary:** Aggregated OCO-2 X_{CO2} estimates filtered with xco2_quality_flag = 0 are typically biased higher than the coincident v1 COCCON data at global scales, with absolute average biases ≤ 1.03 ppm.
- Lower bias values seen when OCO-2/-3 are compared to v2 COCCON.
- Working with the COCCON PIs to receive more data and expand the ongoing analysis.
- Manuscript currently under co-author review.

3. OCO-2 vs. ATom

- Extend the comparison by including aircraft measurements.
- Analyze the V11.2 OCO-2 X_{CO2} data to compare against coincident measurements from the airborne ATom measurements.

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