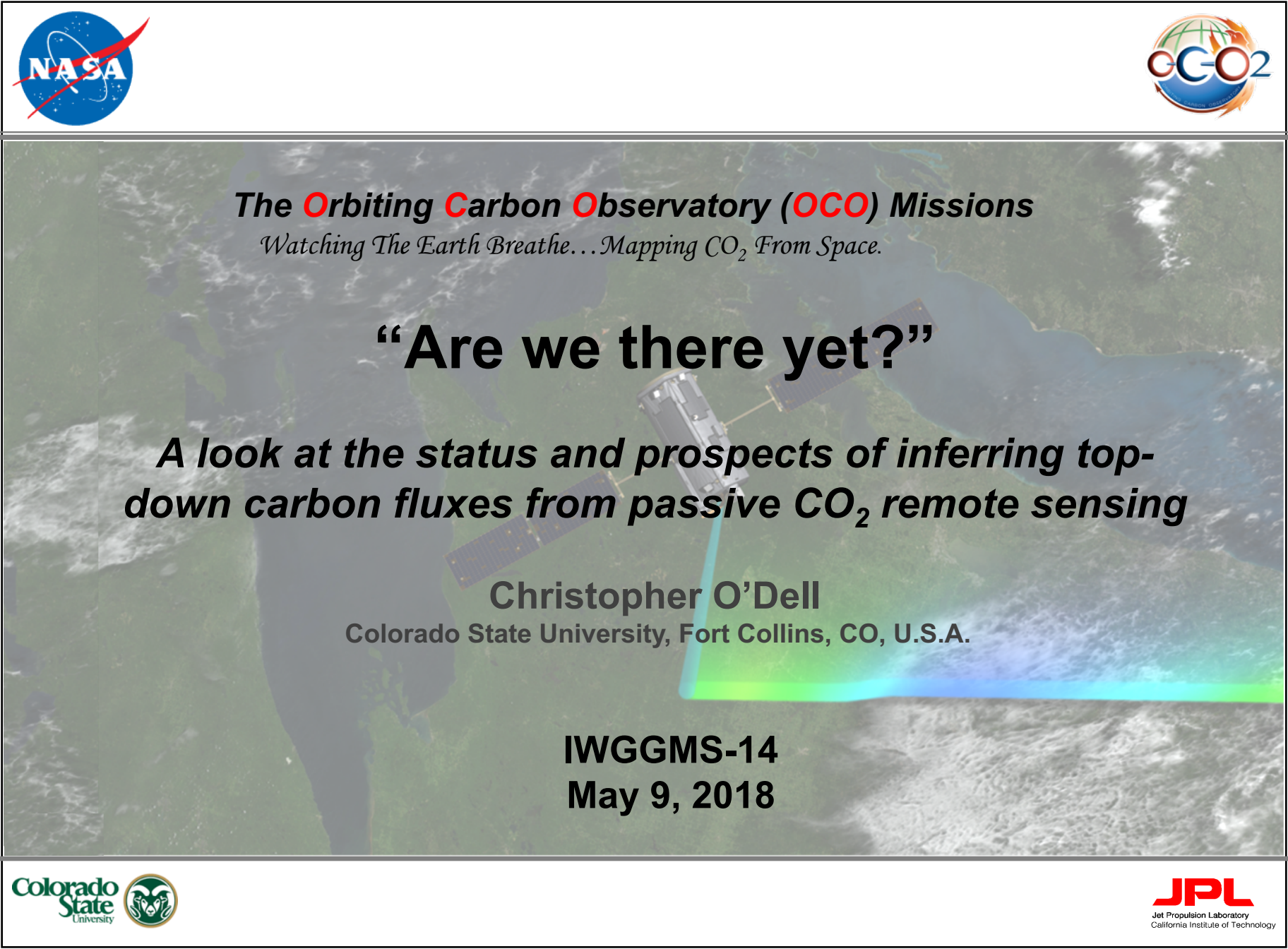

The Orbiting Carbon Observatory (OCO) Missions

Watching The Earth Breathe…Mapping CO_2 From Space.

"Are we there yet?"

A look at the status and prospects of inferring top-down carbon fluxes from passive CO_2 remote sensing

Christopher O'Dell

Colorado State University, Fort Collins, CO, U.S.A.

IWGGMS-14

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Colorado State University

Jet Propulsion Laboratory
California Institute of Technology

With Contributions From

- **Annmarie Eldering, David Crisp, Dave Schimel (**JPL)
- **Paul Wennberg** (Caltech)
- **Robert Nelson, Thomas Taylor, Heather Cronk, Andrew Schuh** (Colorado State)
- **Debra Wunch, Matthaus Kiel** (U. Toronto)
- **Lesley Ott** (NASA GMAO)
- **Sean Crowell** (U. Oklahoma)

What are we trying to do?

Tans, Fung, & Takahashi (1990):

Based on simple inversions using the surface CO2 network, they infer a northern extratropical land sink!

Rayner & O'Brien (2001) :

Simple OSSE (Observing System Simulation Experiment) implies that ***unbiased*** **space-based measurements of CO2 concentration can significantly improve our knowledge of CO_2 sources and sinks on Transcom-sized regions.**

Early 2000s:

U.S. and Japan begin designing & building CO2-measuring satellites.

GOSAT Launches 2009, OCO-2 2014, TanSat 2016

Many satellites now coming! GOSAT-2, OCO-3, MicroCarb, GeoCarb, …

To achieve our goals of CO2 SOURCES AND SINKS from space, we need:

1. **Excellent Level-1 Calibrated Spectra**

2. **Highly accurate retrieved X_{CO2} from those spectra.**

3. **Excellent Source/Sink inversion models with highly accurate transport.**

(this is the topic of a number of current papers in prep or under review)

Past statements on XCO_2 bias requirements

- **Miller et al, 2007**: “Coherent biases on 100-5000 km scales pose the greatest threat...and must be corrected below detectable levels.” Spurious 0.4 ppm interhemispheric gradient leads to 1 Gt/C error in N.H. land sink.

- **Chevallier et al 2007**: “regional biases of a few tenths of a part per million in column-averaged CO_2 can [significantly] bias the inverted yearly subcontinental fluxes.”

- **Lan et al (2017):** “The entire North American Fossil Fuel source (1.6 GtC/yr) is ~0.6 ppm in the column”

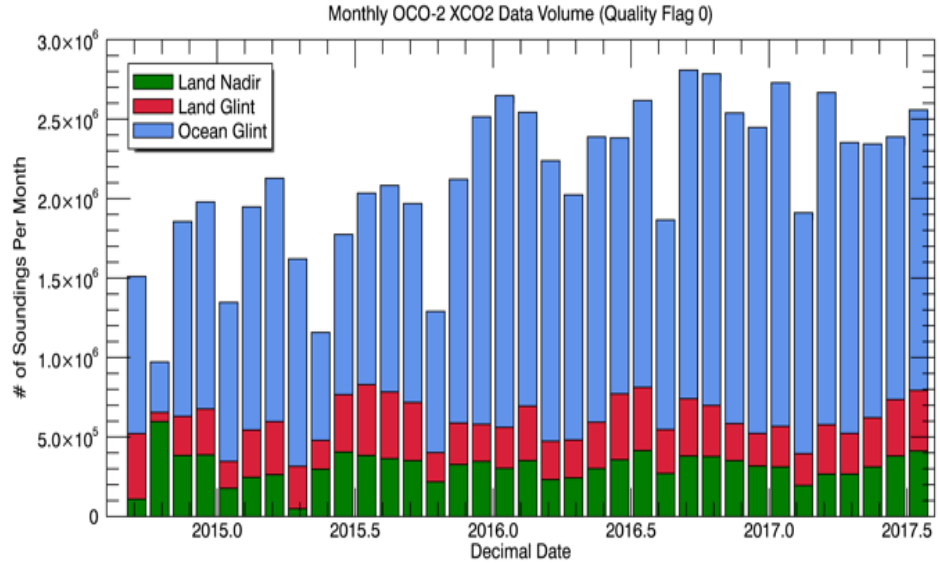
So how small must biases be, to accurately infer regional-scale fluxes?

- These and other studies suggest that spatiotemporal biases must be << 1 ppm.
- Typical numbers thrown around are 0.1-0.5 ppm, with closer to 0.1 highly desirable.
- Beyond this, it really depends on the character of the bias!
  - Very small – will average out
  - Globally constant – don't matter
  - Intermediate scales are most important!

So how are we doing?

The current observing system

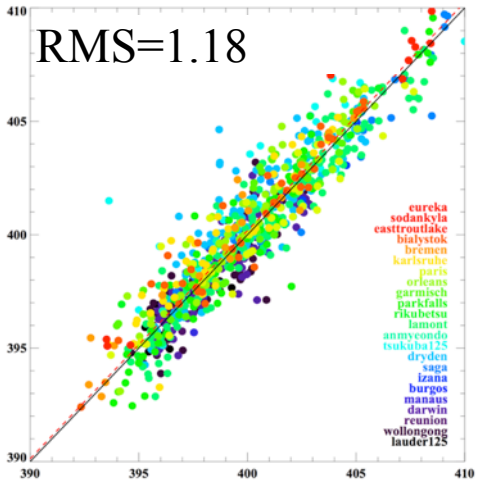
- SCIAMACHY an important pathfinder, data 2002-2012
- GOSAT 2009-Onwards, somewhat sparse sampling.
- OCO-2 returning ~80,000 X_{CO2} measurements per day
- TanSAT, FengYung-3D also recently launched

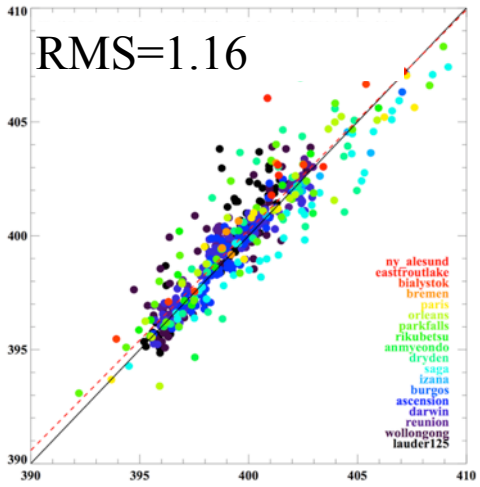


https://disc.gsfc.nasa.gov (keyword OCO-2)

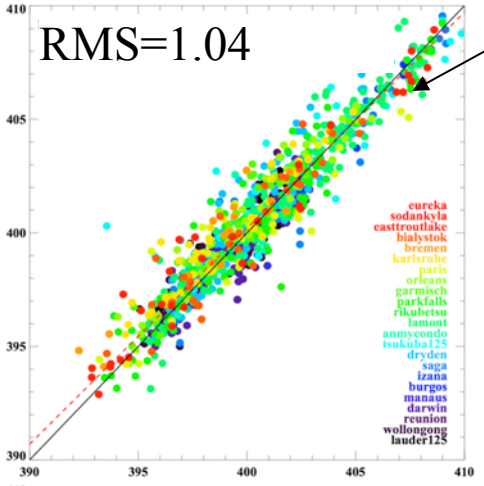
Continuing accuracy improvement

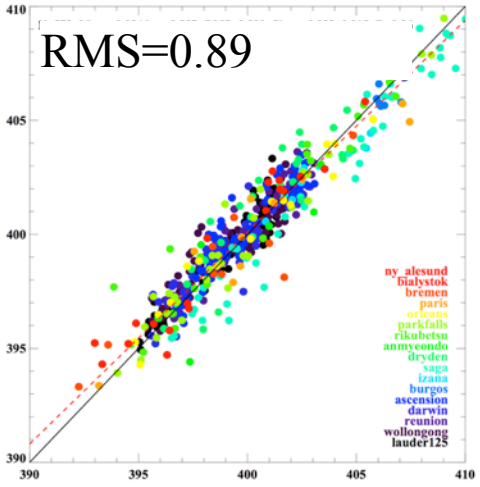
OCO-2 B7





OCO-2 B8





Each circle is one OCO-2 overpass of a TCCON site. All OCO-2 soundings in each overpass have been averaged together.

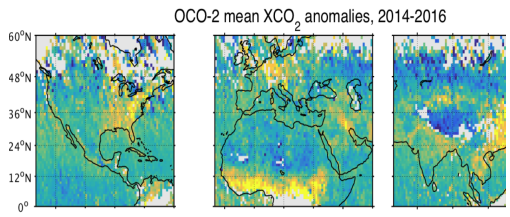
Land (Nadir+Glint)

20% Reduction in Error Variance

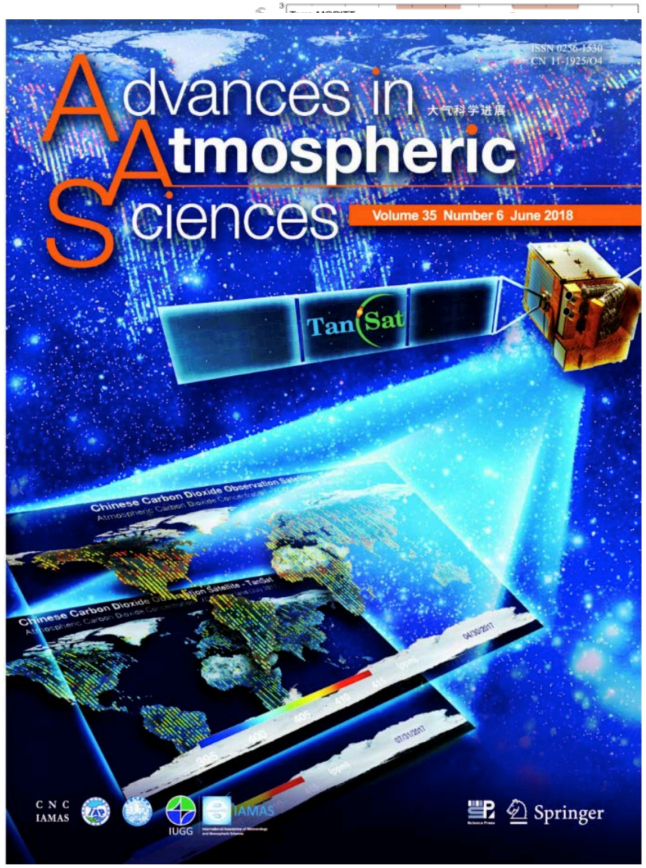
Ocean (Glint)

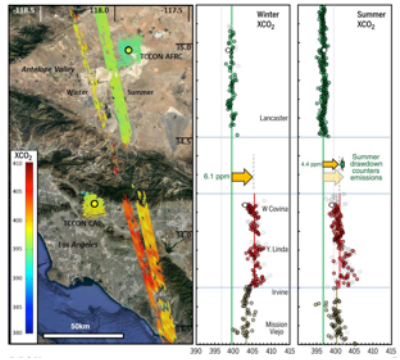
40% Reduction in Error Variance

Notable OCO-2 Science So Far (all B7!)

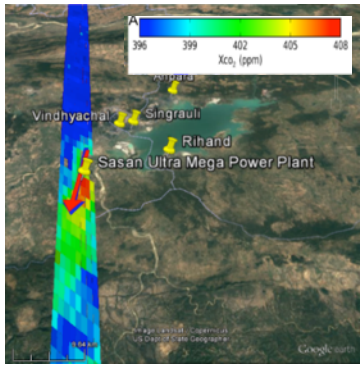


Large-Scale Anthropogenic Emissi
(Hakkarainen et al, GRL, 2016)





Detection of Urban & Volcanic Emissions
(Schwandner et al, Science, 2017)



Quantifying Power Plant Emissions
(Nassar et al, GRL, 2017)

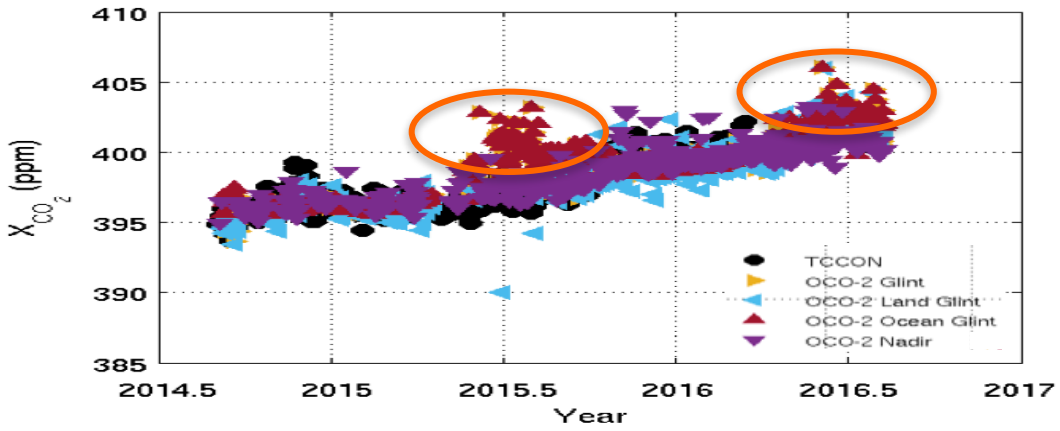
Global SIF Measurements
(Sun et al, Science, 2017)

Tropical Response to 2015-16 El Nino
(Liu et al, Science, 2017)

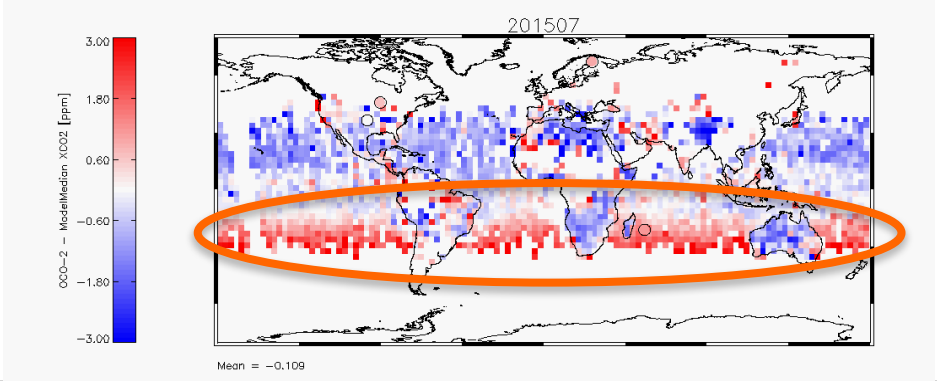
The OCO-2 "southern oceans glint bias" in B7

- High bias seen in southern hemisphere oceans (glint) March-September, relative to models.
- Determined cause was not:
  - Bias Correction
  - Spectroscopy
  - Ocean surface treatment
- Likely cause was tiny AODs in the stratosphere (~0.01), plus stray light in the O_2-A band.

Wollongong TCCON vs. OCO-2



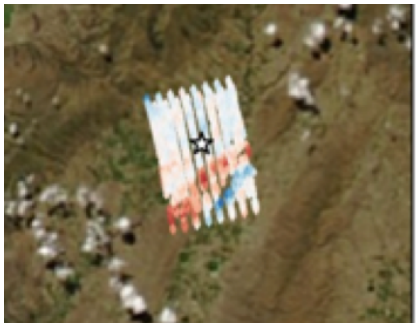
Model Mean vs. OCO-2

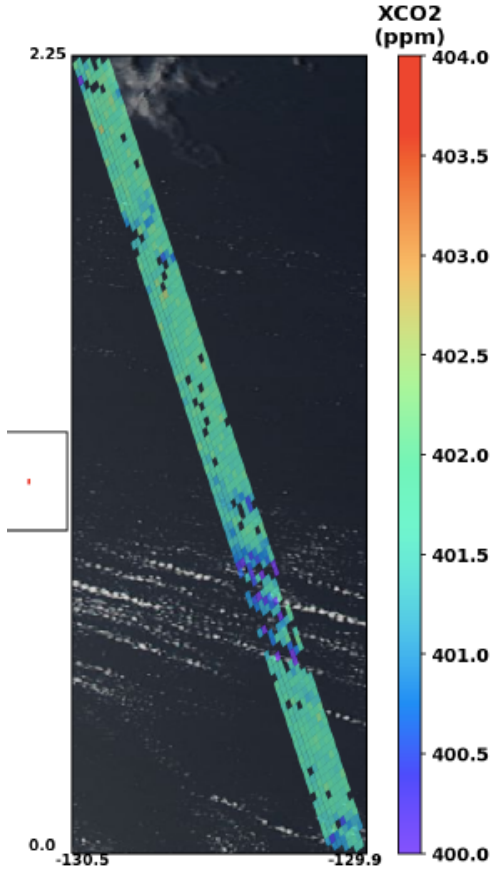


Other possible sources of bias

- Cloud+aerosol induced biases (including 3D effects)
- Pointing-related biases
- Spectral & radiometric calibration
- Prior meteorology related biases
  - e.g. Surface pressure, Temperature profile

Pointing bias errors over Lauder





Cloud-induced errors over ocean

How we deal with Bias

Loosely speaking, our retrieval does this:

$$XCO_{2,final} = XCO_{2,apriori}$$ **Prior**

$$+ (XCO_{2,ret} - XCO_{2,apriori})$$ **Retrieval Update**

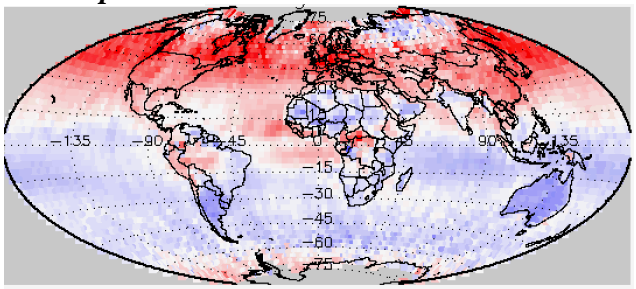
$$+ (\text{Bias Correction})$$ **B.C. Update**

Ideally, our retrieval would do much more "work" than the bias correction. I.e. we want:

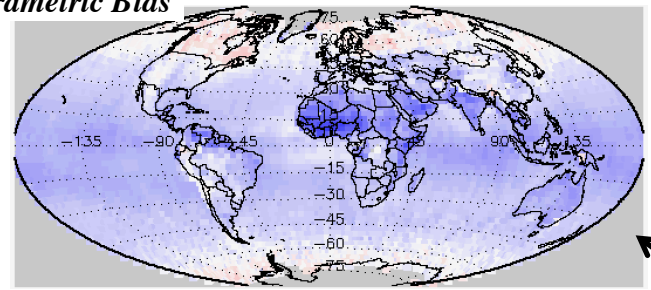
BC Update << Retrieval Update

Bias Patterns and Difference from Models

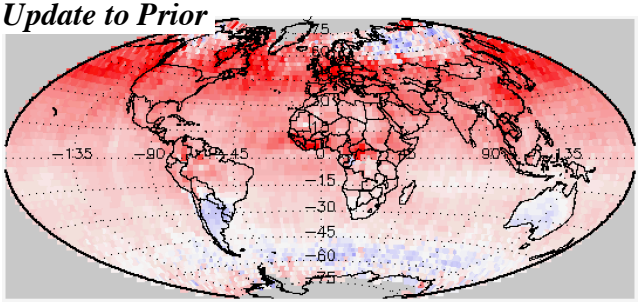
Retrieval Update

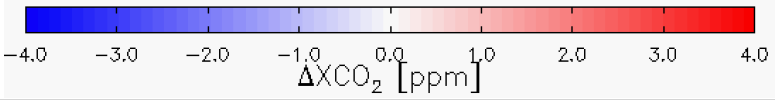


Parametric Bias



Total Update to Prior

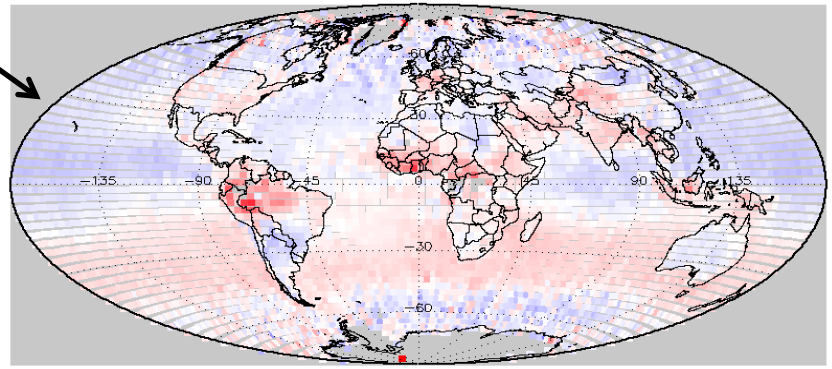




Notes:

- The change from the prior is significant (up to 4 ppm)
- Bias terms are ~ 1-2 ppm
- BUT: The difference from the model reference, after bias correction, is ~0-2 ppm, and generally smaller than the size of the bias correction itself.
- How then do we know if these features are real?

*Total Difference From Model Reference**

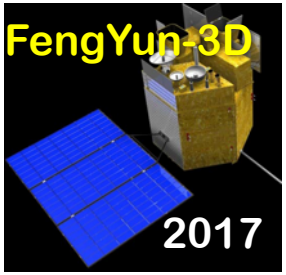


**Model Reference = Mean(MACC, CarbonTracker, Univ. Edinburgh)*

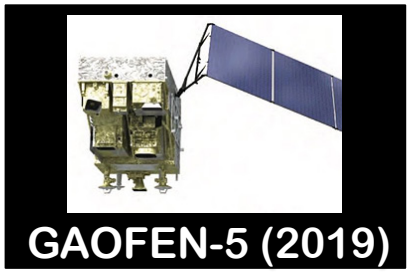
These retrieval issues may affect nearly all of these satellites.

PAST

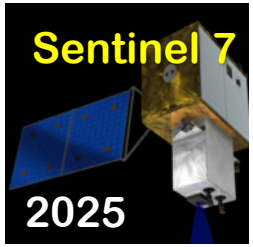
PRESENT



NEAR FUTURE



LATER



Hard Questions to Face

- XCO_2 biases from space still appear too large relative to our desired signals.
- **Is achieving regional CO_2 fluxes from passive space-based observations possible with current systems & retrieval algorithms?**
- **If not, what must be done to make it possible?**
  - Just keep working to reduce XCO_2 biases?
  - Do we need Lidar / other observations?
  - Inverse systems that can better deal with spatially/temporally coherent biases?

One approach: End-to-End CO_2 OSSEs

- Instead of making up synthetic biases that may or may not be realistic, use the REAL RETRIEVAL to create its own biases.
- Invert retrieved XCO2 to obtain fluxes, and compare with the underlying driving fluxes.
- **With the current operational retrieval, and a variety of instrument platforms, and realistic transport error, what is currently possible?**

We can simultaneously test:

- Impact of algorithmic-biases on fluxes
- Impact of instrument-biases on fluxes (imperfect calibration)
- Impact of transport errors on fluxes
- Impact of observing system sampling on fluxes.

Perfect Transport	Perfect Prior Fluxes	Perfect Met (L2)	Perfect Spectroscopy (L2)	Perfect Instrument	Perfect XCO2	Done Before?
Y	Y	-	-	-	Y	Yes
Y	Y	-	-	-	N	Partial
N	Y	-	-	-	Y	Partial
Y	Y	Y	Y	Y	N	No
Y	Y	Y	Y	N	N	No
Y	Y	N	N	N	N	No
Y	N	N	N	N	N	No
N	N	N	N	N	N	No

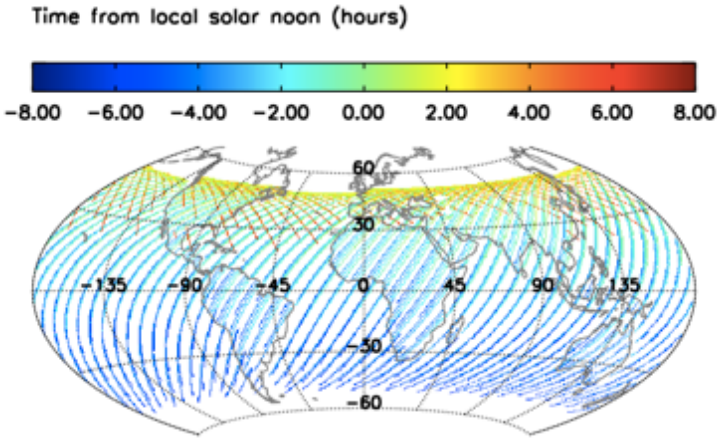
We can simultaneously test:

- Impact of algorithmic-biases on fluxes
- Impact of instrument-biases on fluxes (imperfect calibration)
- Impact of transport errors on fluxes
- Impact of observing system sampling on fluxes.

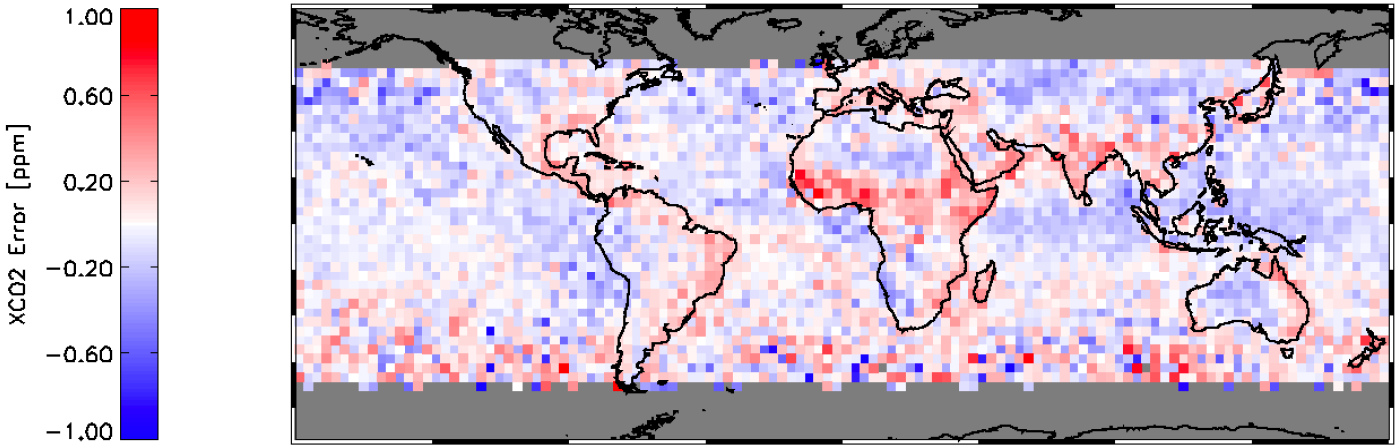
Perfect Transport	Perfect Prior Fluxes	Perfect Met (L2)	Perfect Spectroscopy (L2)	Perfect Instrument	Perfect XCO2	Done Before?
Y	Y	-	-	-	Y	Yes
Y	Y	-	-	-	N	Partial
N	Y	-	-	-	Y	Partial
Y	Y	Y	Y	Y	N	No
Y	Y	Y	Y	N	N	No
Y	Y	N	N	N	N	No
Y	N	N	N	N	N	No
N	N	N	N	N	N	No

Recent OCO-3 Simulations (B8-like)

- OCO-3 noise & sampling from ISS
- CO_2 "Truth" from CarbonTracker
- Operational Cloud-Screening & L2
- Perfect Met, Spectroscopy, Instrument
- Custom Filtering & Bias Correction
- Emergent biases nonetheless!



OCO-3 Simulated Retrieval Errors with custom bias correction



See Eldering, Taylor et al (in prep)

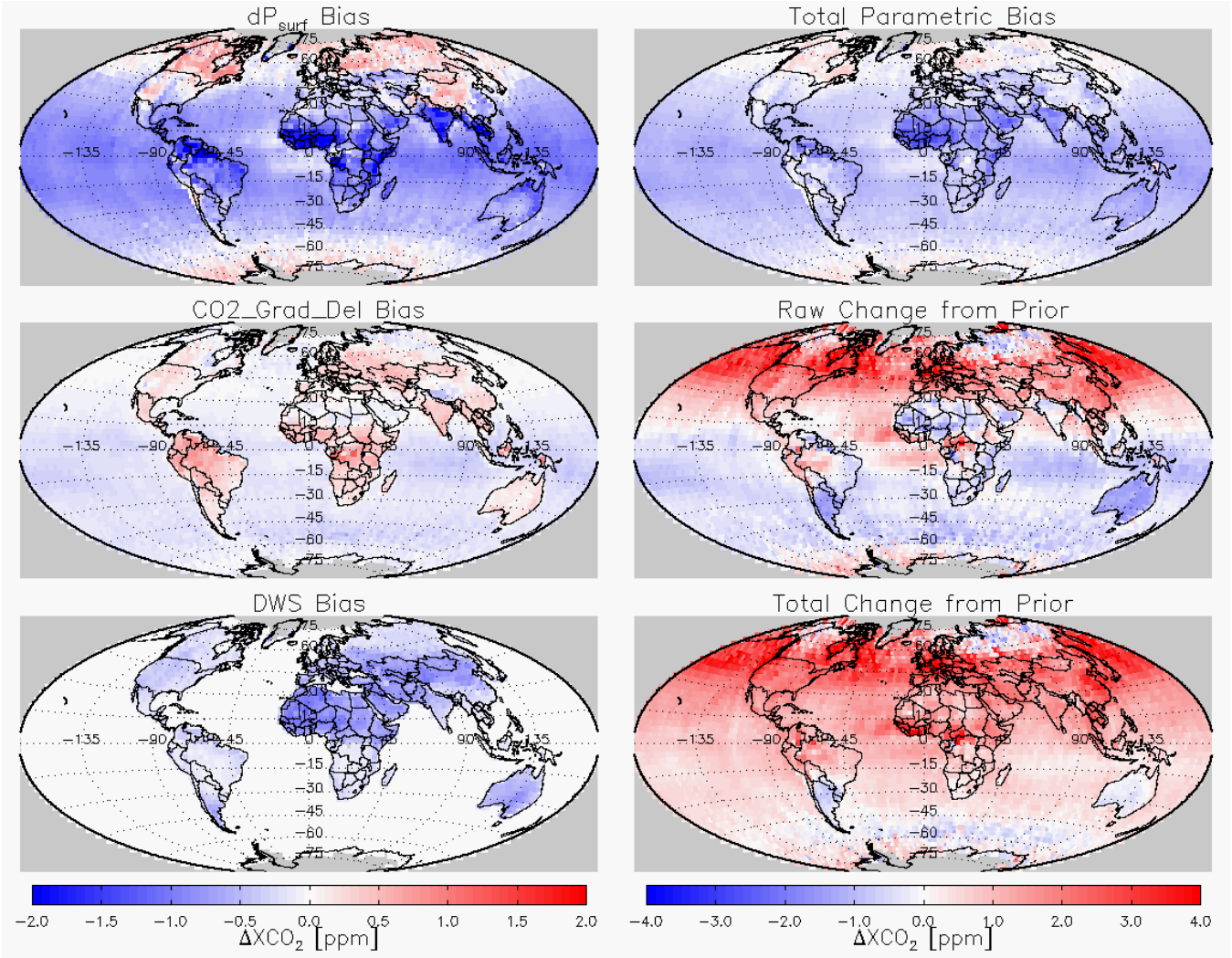
Summary & Concluding Thoughts

- The space-based (passive) X_{CO2} measurement is dominated by systematic rather than random errors (due to calibration & algorithm).
- Regional biases should be less than ~0.3 ppm (possibly much less).
- Highest current biases are on the order of 1 ppm, & regionally coherent.
- "Can we achieve regional-scale CO_2 fluxes over time from current passive space-based obs" is at least partially answerable with an ambitious OSSE study
- If not – we must continue to beat down the errors, and/or find creative solutions.
- We can do this!:
  - With hard work
  - With creative uses of the data
  - With many diligent graduate students!

Thank You!!
Questions?

Latest Version B8 Data:

https://disc.gsfc.nasa.gov (search OCO-2)



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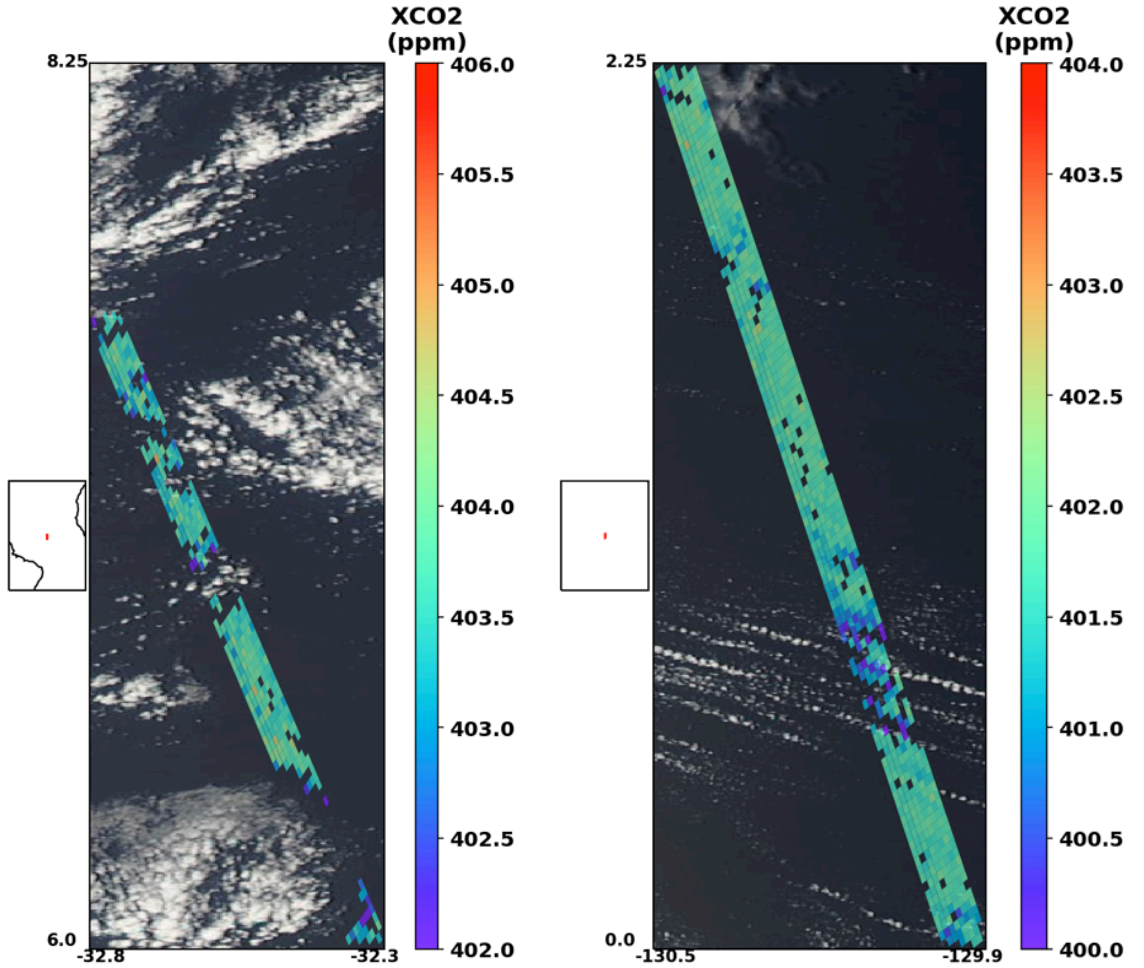
Low biases near clouds over ocean

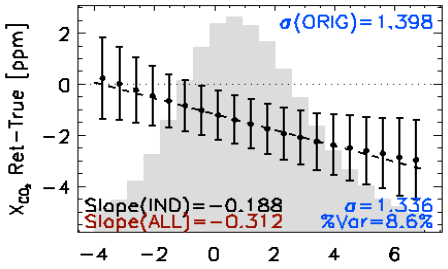
- Fairly frequent
- Could result in a small oceanic low bias
- 3D effects?
- Solutions currently under investigation by OCO-2 cloud team.

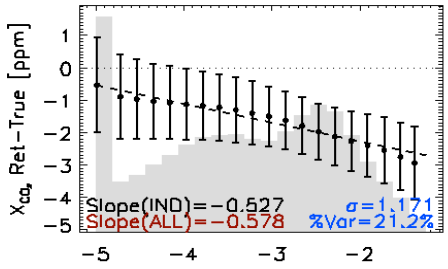


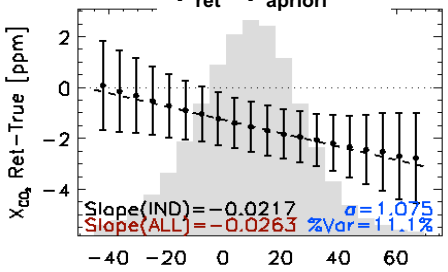
XCO2 Bias Correction Process (OCO-2)

$$X_{CO2}^{BC} = \frac{X_{CO2}^{Raw} - c_1 P_1 - c_2 P_2 - \cdots - FPbias}{global\_offset}$$

Step 1: Regress vs. Bias Predictors



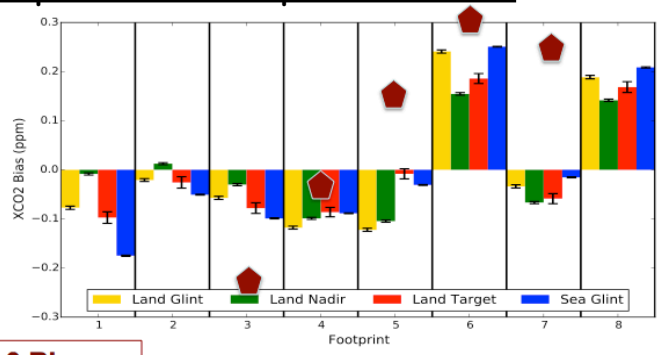




Predictors:

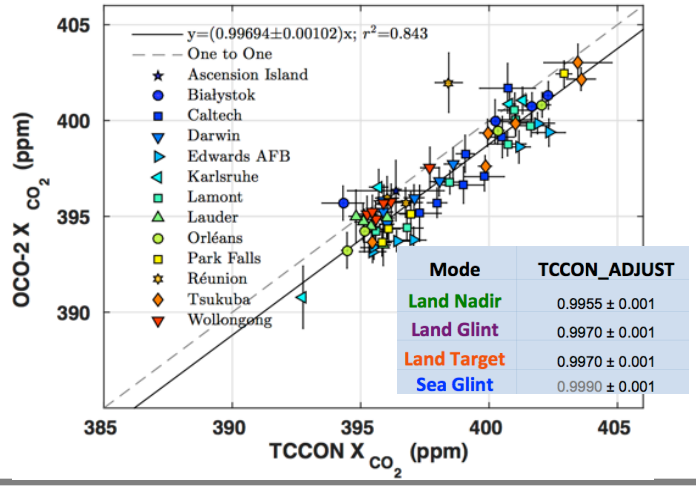
- Surface Pressure Error
- CO2 Vertical Gradient
- Large Aerosol+Water Clouds (land only)

Step 2: Per-Footprint Offset



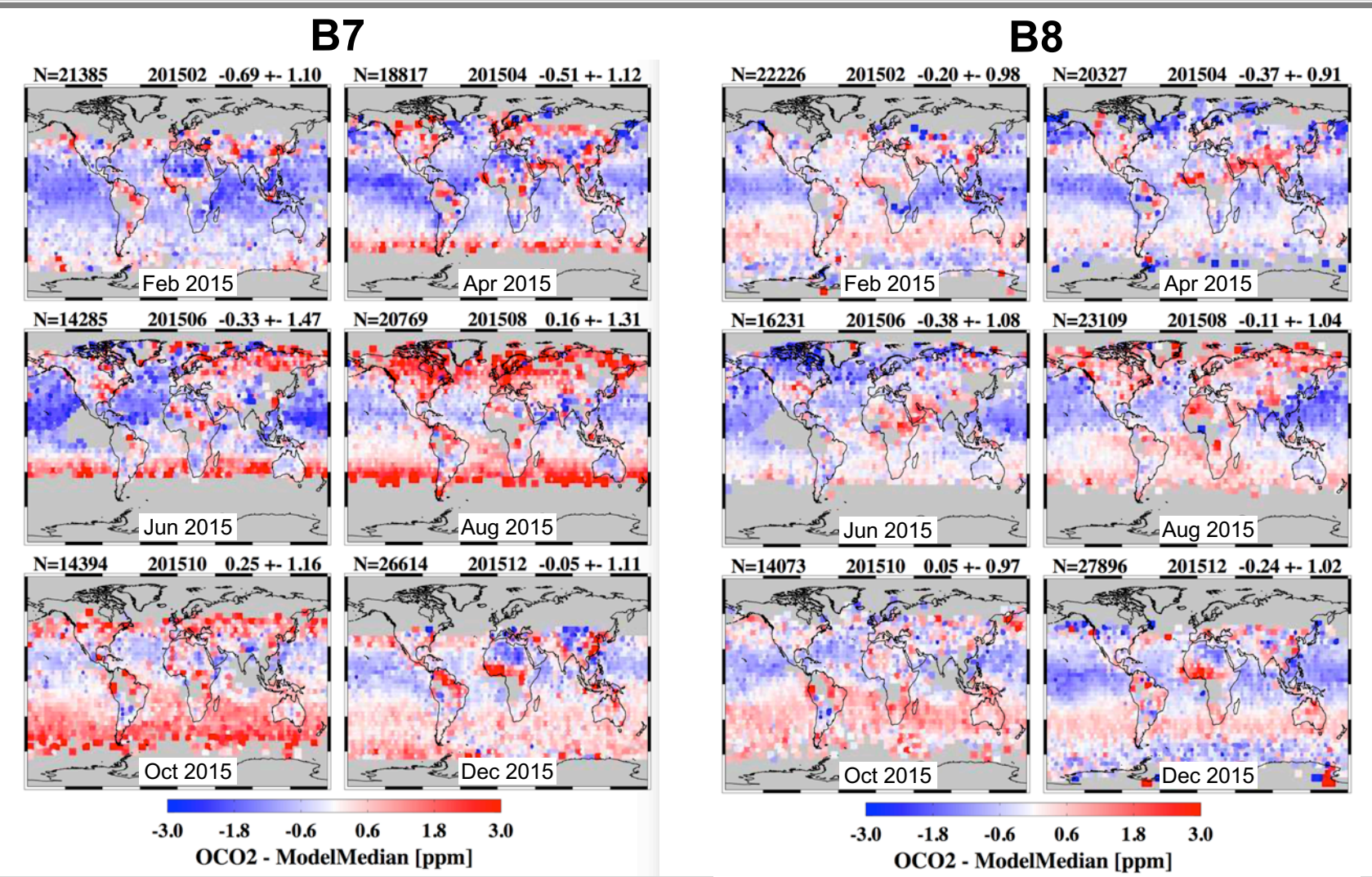
B6.0 Biases

Step 3: Global Multiplier



Mode	TCCON_ADJUST
Land Nadir	0.9955 ± 0.001
Land Glint	0.9970 ± 0.001
Land Target	0.9970 ± 0.001
Sea Glint	0.9990 ± 0.001

Improved Comparison to Models (2015)



(In-situ constrained models from: D. Baker, S. Basu, F. Chevallier, S. Crowell, L. Feng, A. Jacobson, J. Liu, A. Schuh)

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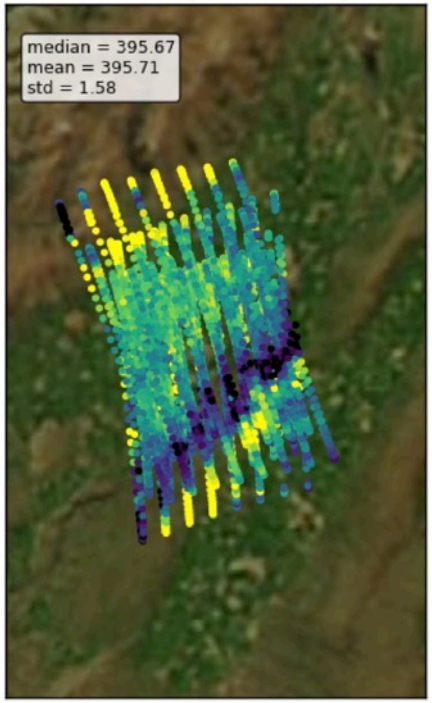
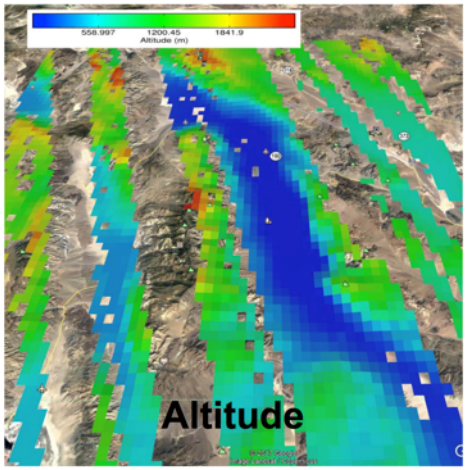
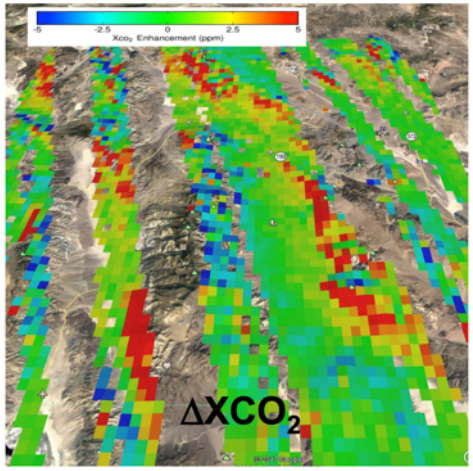
Pointing bias



Lauder, NZ Target
Oct 19, 2014

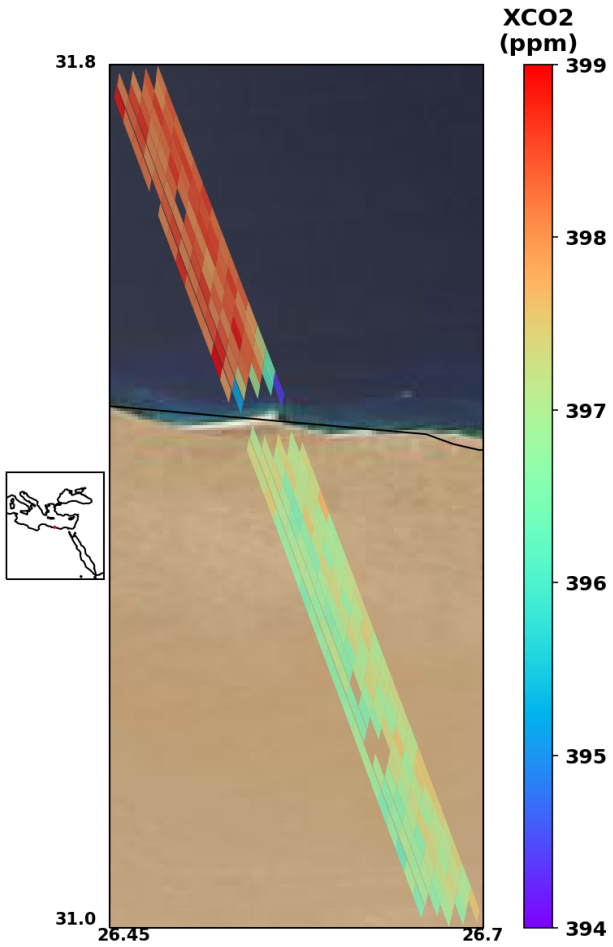




- Small pointing offsets (imperfect pointing knowledge) lead to multi-ppm level XCO_2 biases related to ground slope and it's relationship to the satellite view angle.
- Can lead to "False Plumes" in OCO-2 imagery plots.
- Acts through surface pressure
- Fix underway (summer 2018).

Credit:
Upper left: Matt Kiel, Paul Wennberg, Debra Wunch
Upper right: Cameron MacDonald & Ray Nassar

Land-Ocean Biases, reduced in latest B8 version, still exist



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