*The **O**rbiting **C**arbon **O**bservatory (**OCO**) Missions*

Watching The Earth Breathe…Mapping CO_2 From Space.

How good are CO_2 measurements from space? And are they good enough?

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1st CHE General Assembly
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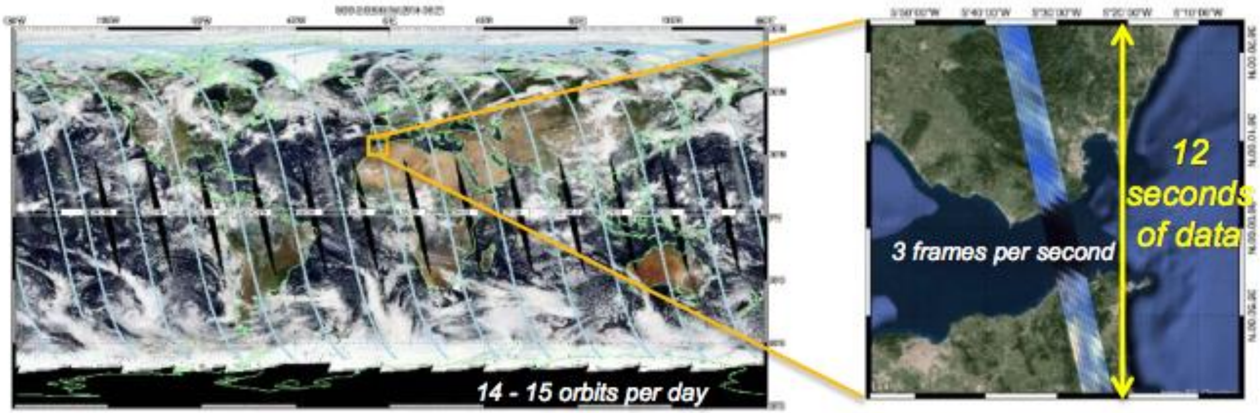
Jet Propulsion Laboratory
California Institute of Technology

With Significant Contributions From

- **Annmarie Eldering, David Crisp, Brendan Fisher** (JPL)
- **Paul Wennberg** (Caltech)
- **Robert Nelson, Thomas Taylor, Heather Cronk** (Colorado State)
- **Debra Wunch, Matthaus Kiel** (U. Toronto)
- **Aronne Merrelli** (U. Wisconsin)
- **Hannakaisa Lindqvist** (Finnish Met. Inst.)

Basic Near-IR Measurement Approach

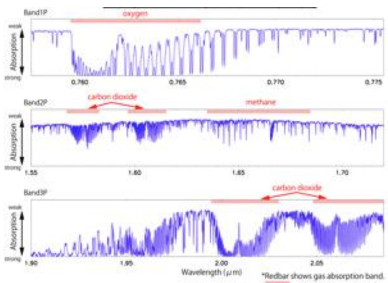


OCO-2 Example

0.765 µm O_2

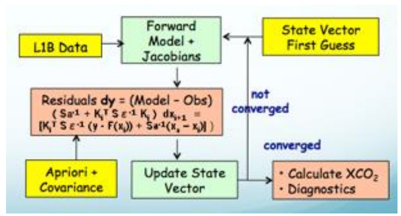
1.61 µm CO_2

2.06 µm CO_2

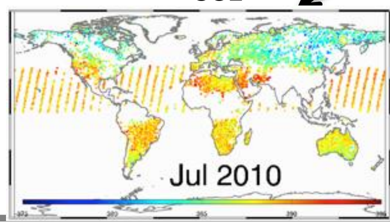


Hyperspectral
Near-Infrared Spectra

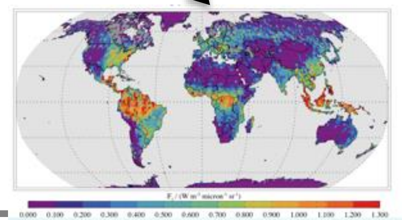
OE Retrieval Algorithm



X_{CO2}



SIF



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To achieve our goals of CO2 SOURCES AND SINKS, 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.**

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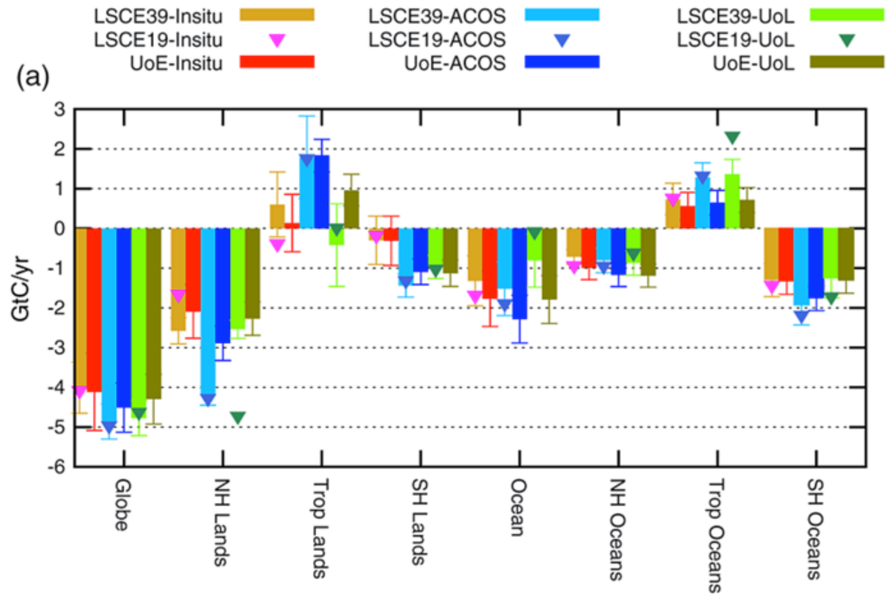
Biases in CO2 measurements can lead to spurious large+regional scale fluxes

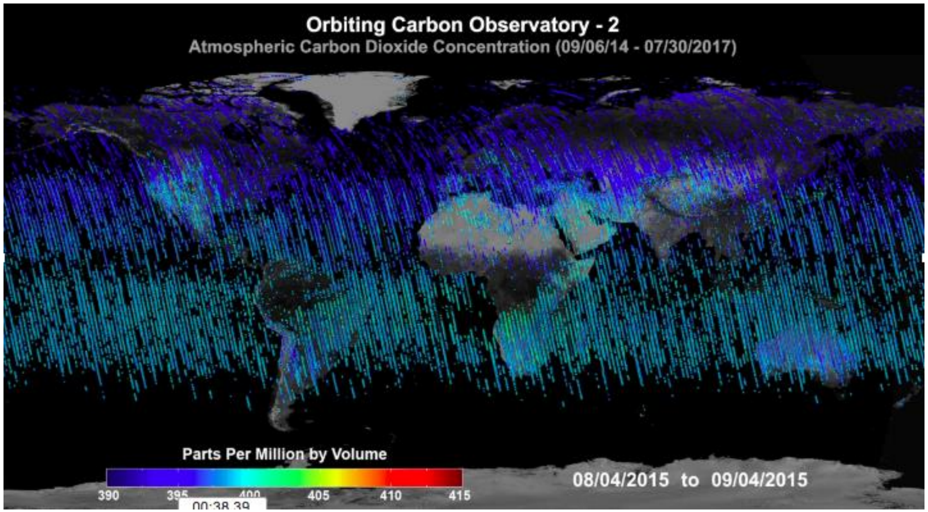
- Basu et al. (2013) found that a 0.8 ppm bias between land and ocean in GOSAT retrievals was enough to turn the global lands from a sink to a source.
- Chevallier et al. (2014) looked at inversions of ACOS and UoL GOSAT data, using mutiple inversions systems.
- Much debate regarding Reuter et al. (2014, 2017) result a larger European sink based on satellite CO2 measurements.

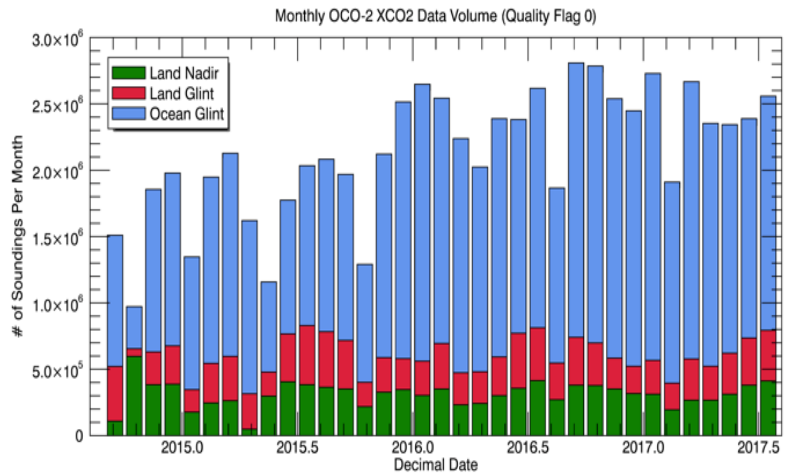


Successes

Data Volume

- OCO-2 now returning about 80,000 full-column measurements of X_{CO2} each day over the sunlit hemisphere
- More data now with improvements in operations and more judicious and effective filtering, in latest version (B8).





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

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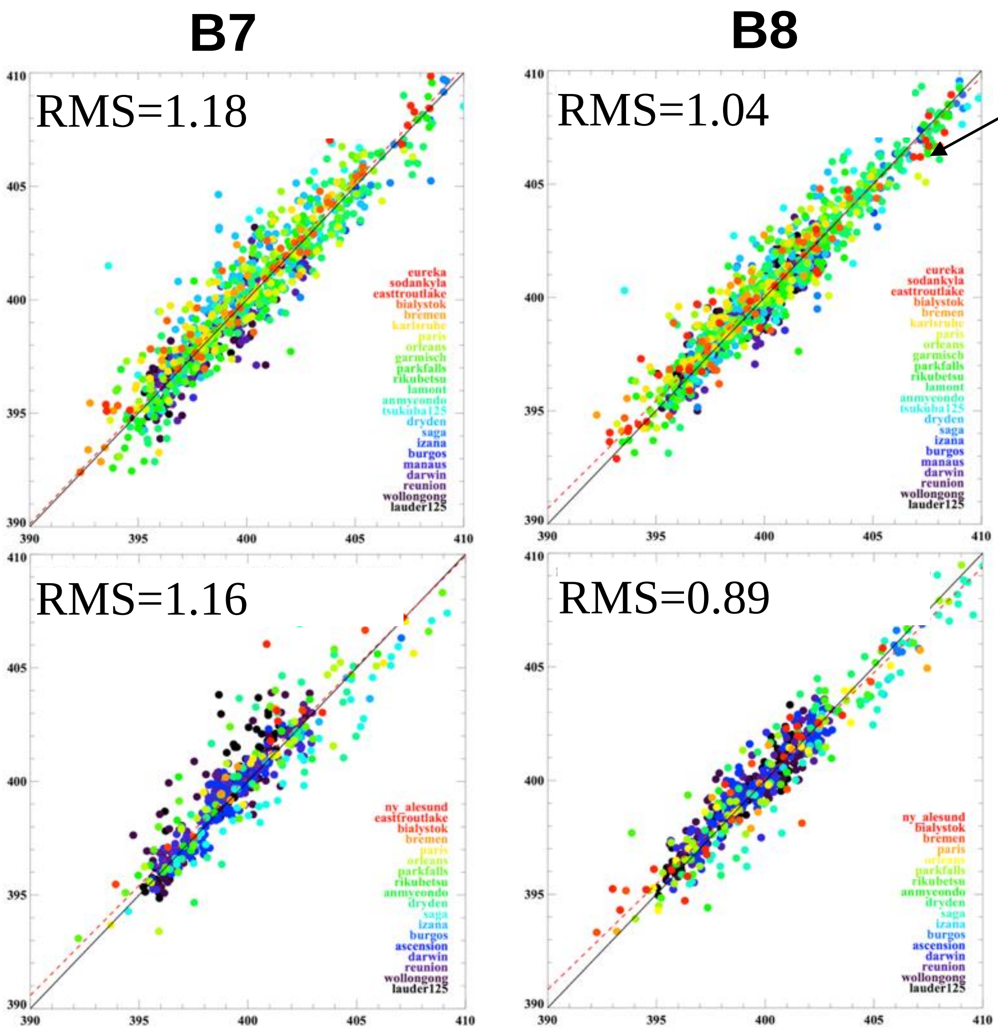
Continuing OCO-2 accuracy improvement



Each cirlce 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

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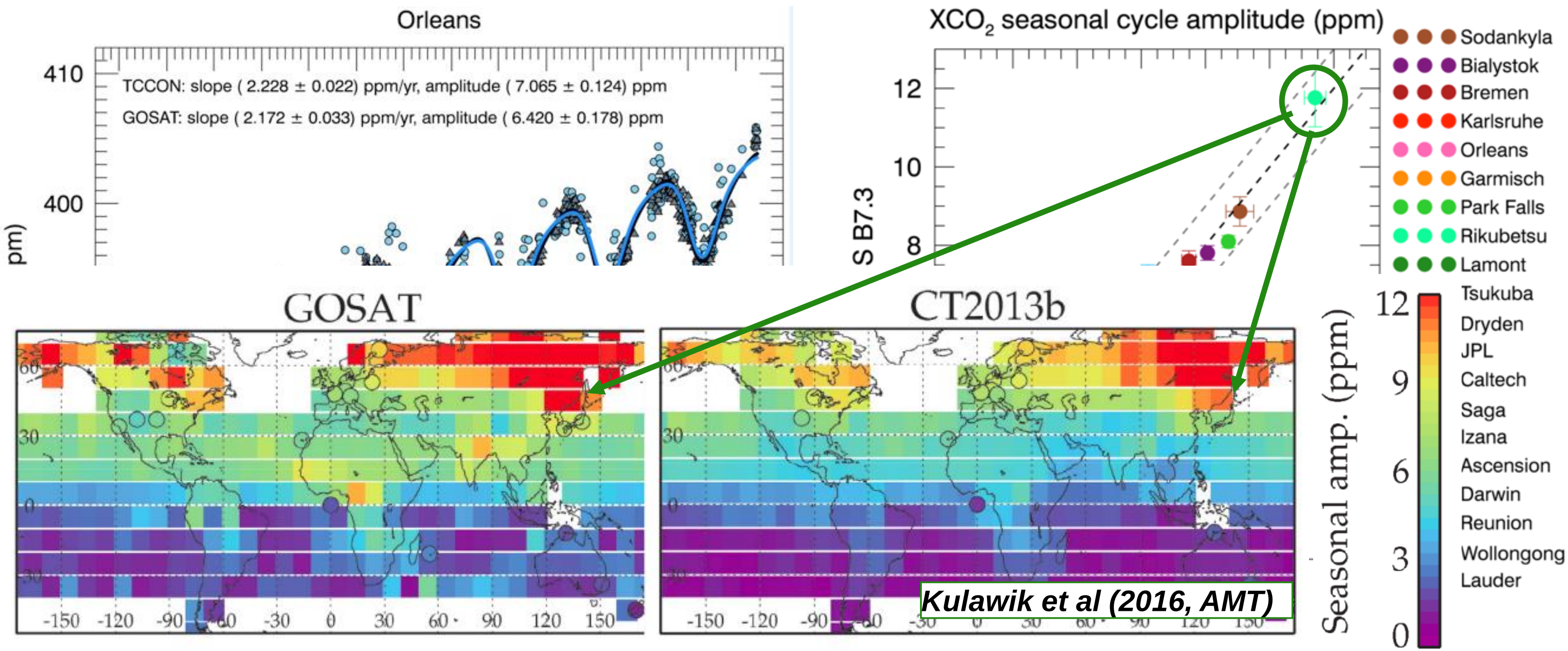
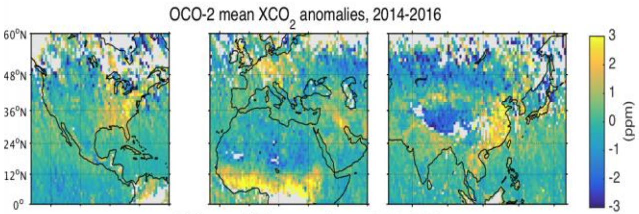
GOSAT has been extremely beneficial

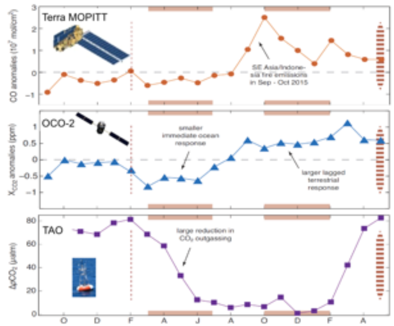


7+ years of GOSAT data show accurate representation of regional CO2 seasonal cycles, as compared to TCCON (*Lindqvist et al., 2015, ACP*).

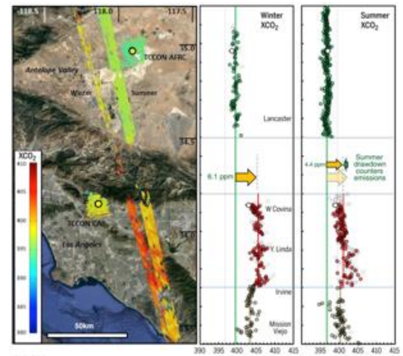
Notable OCO-2 Science So Far (all B7!)



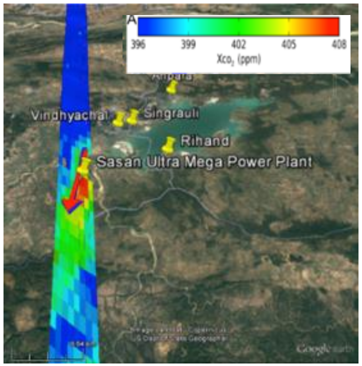
Large-Scale Anthropogenic Emissions
(Hakkarainen et al, GRL, 2016)



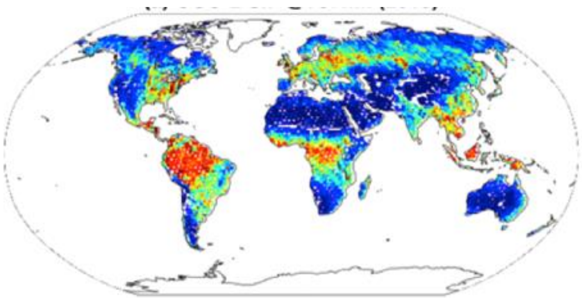
Ocean Response to 2015-16 El Nino
(Chatterjee et al, Science, 2017)



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)

Biases

The basis of satellite bias

- Satellites often have ***imperfect calibration*** (spectral, radiometric, geometric):
  - GOSAT – O_2A 1 had a nonlinearity in the radiometer that caused bias.
  - OCO-2 has thin layers of ice build up on its detectors, that “look” like a stratospheric aerosol particle and caused multi-ppm level retrieval CO2 errors.
  - OCO-2 appears to have slight pointing errors that can also lead to multi-ppm level XCO2 errors.

- ***Spectroscopy*** is incredibly important, and is often overlooked as an important source of bias.

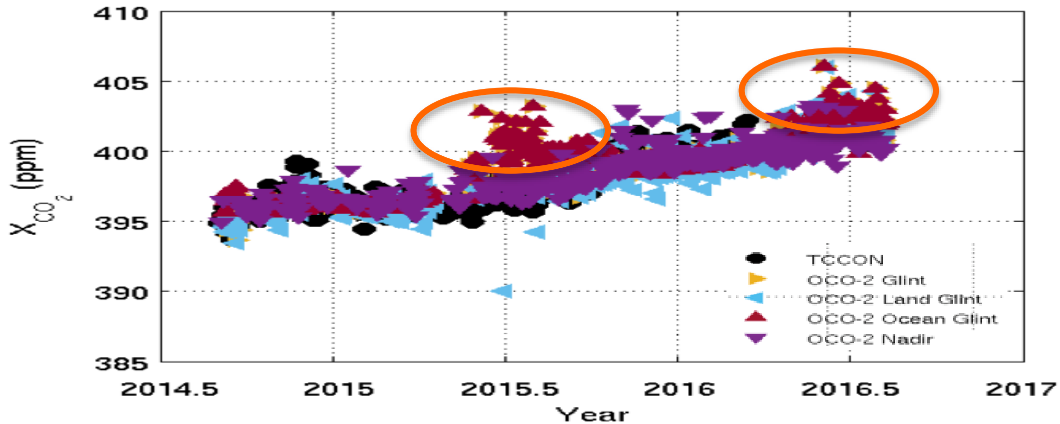
- Even with perfect instruments and spectroscopy, our ***current retrievals exhibit native biases*** of several tenths of a ppm in simulation experiments.

The "southern oceans glint bias" of OCO-2

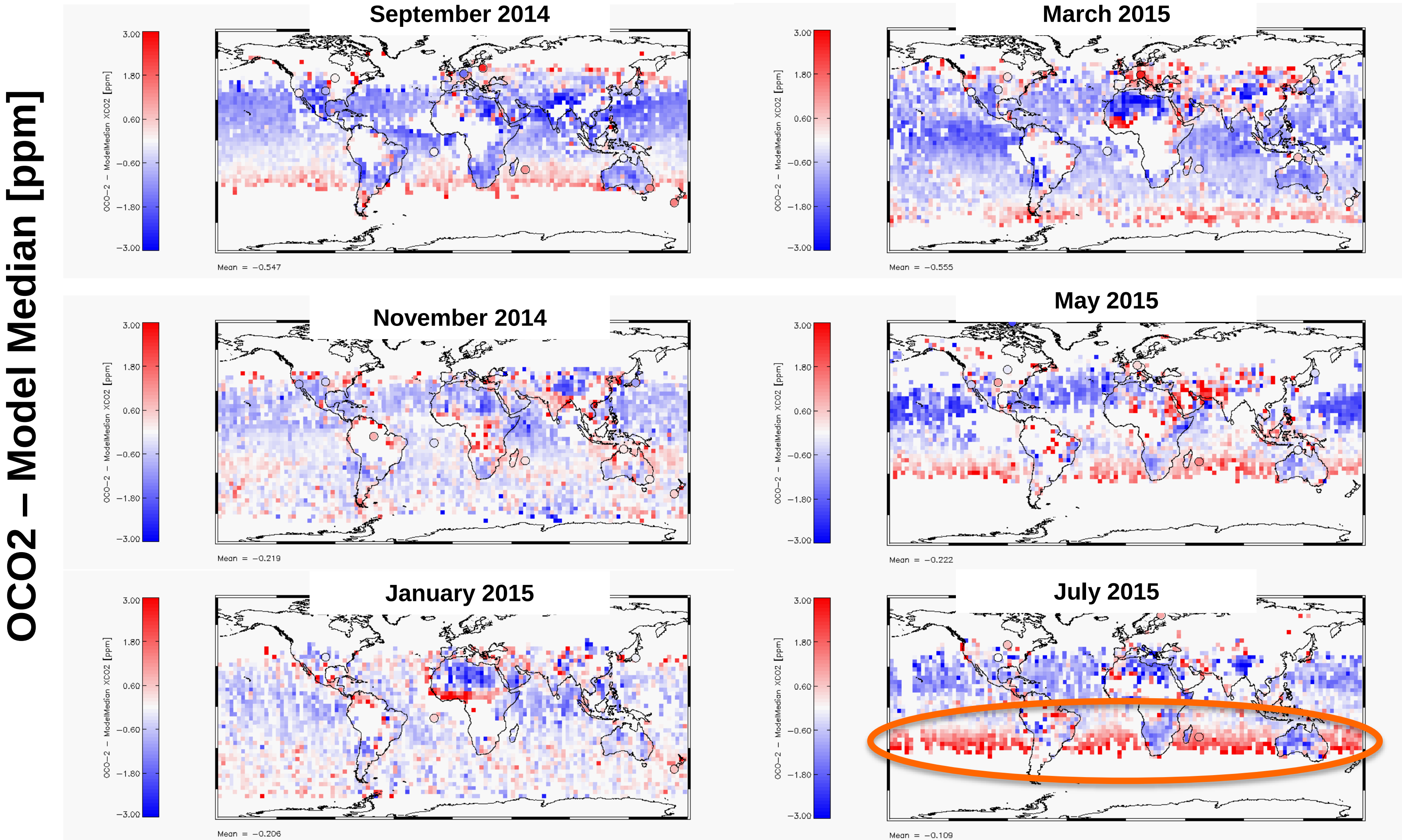
- High bias seen in southern hemisphere oceans (glint) March-September, relative to models.

- Determined cause was not:
  - Bias Correction
  - Spectroscopy
  - Ocean surface treatment

Wollongong TCCON vs. OCO-2



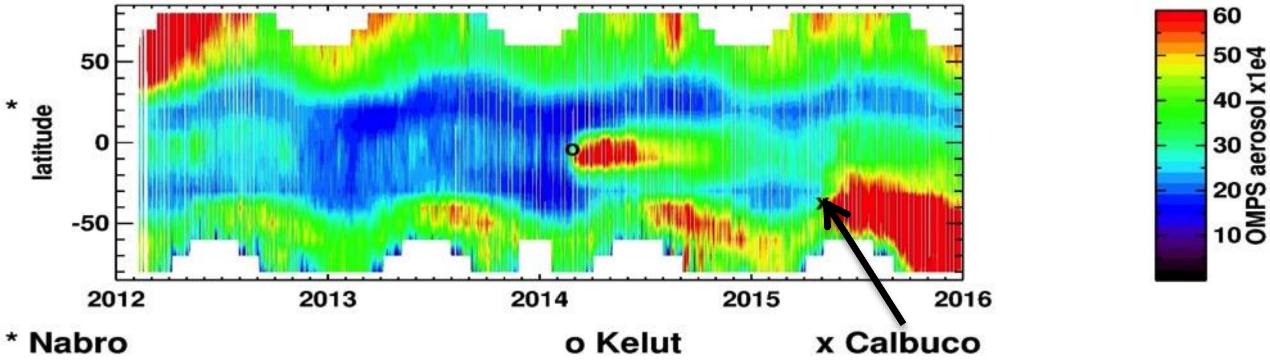
Same problem apparent in model comparisons



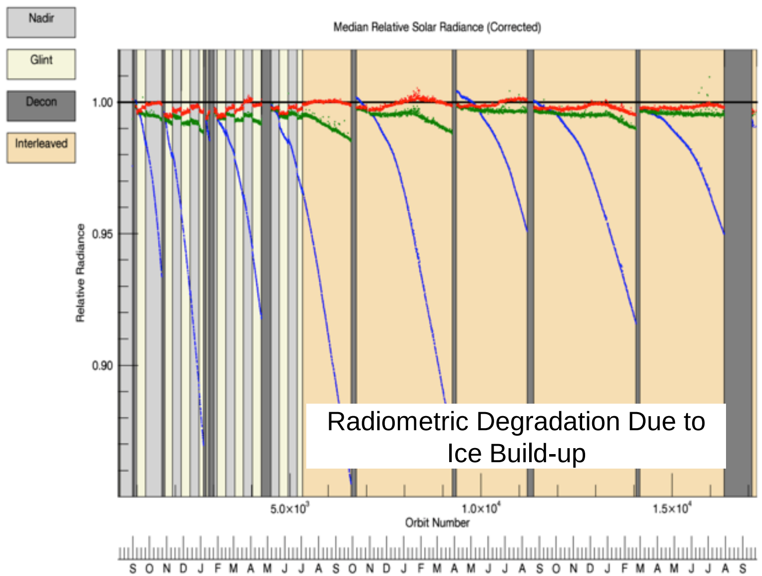
(In-situ constrained models from: D. Baker, S. Basu, F. Chevallier, S. Crowell, L. Feng, A. Jacobson, J. Liu, A. Schuh)

Apparent Causes of Southern Ocean Glint Bias

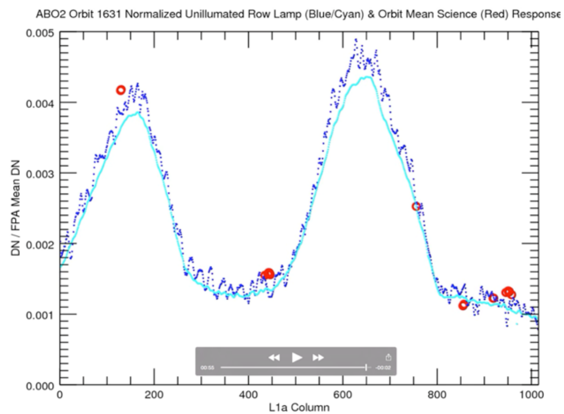
1. Stratospheric aerosols



2. Stray light on band 1 from thin layer of ice on detector.



Leads to stray light pattern on detector:



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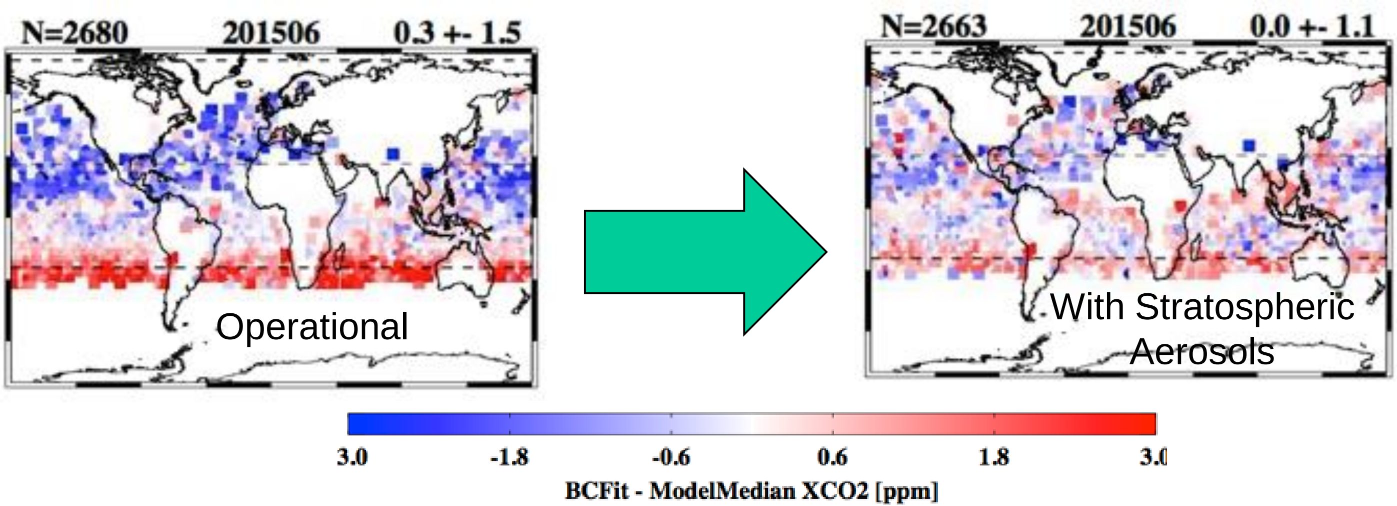
The "Stratospheric Aerosol" Fix

- Sometimes small, high-altitude aerosols from volcanic eruptions and other sources are present in amounts to compromise XCO2 retrieval (AODs ~ 0.01).
- Uncorrected stray light due to ice build-up on O_2 A-band detector can also lead to XCO2 retrieval errors.
- Including a small, sulfate aerosol appears to mitigate both problems.
- Reduces biases over ocean everywhere, and over high-latitude land.



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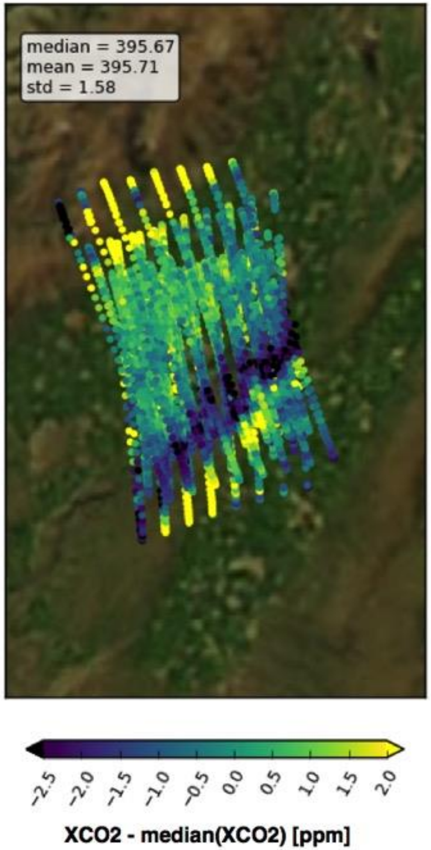
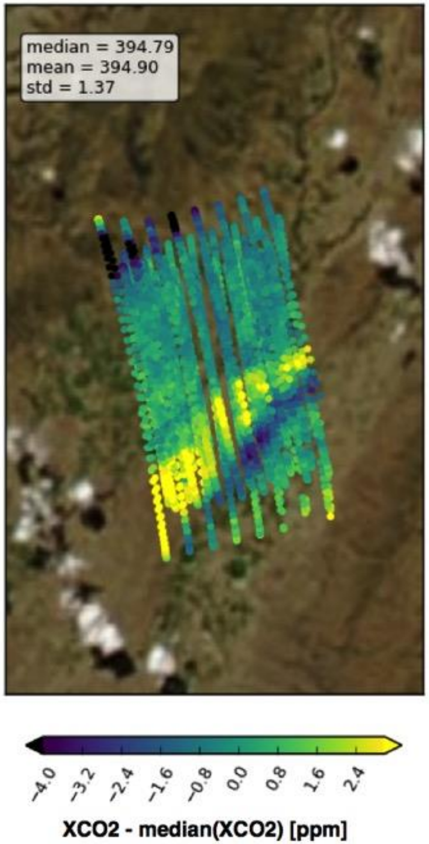
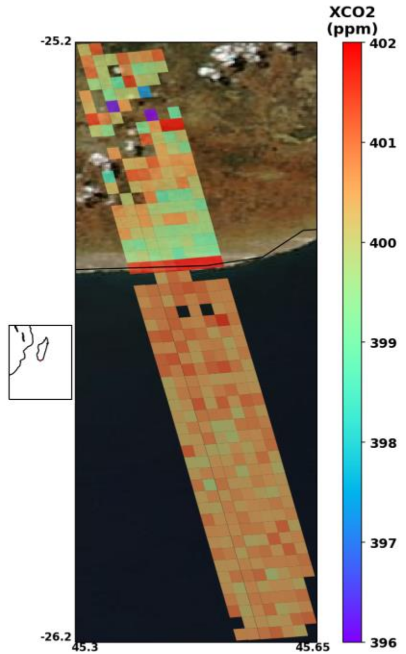
Topography-related bias?

Oct 19, 2014



Feb 17, 2015



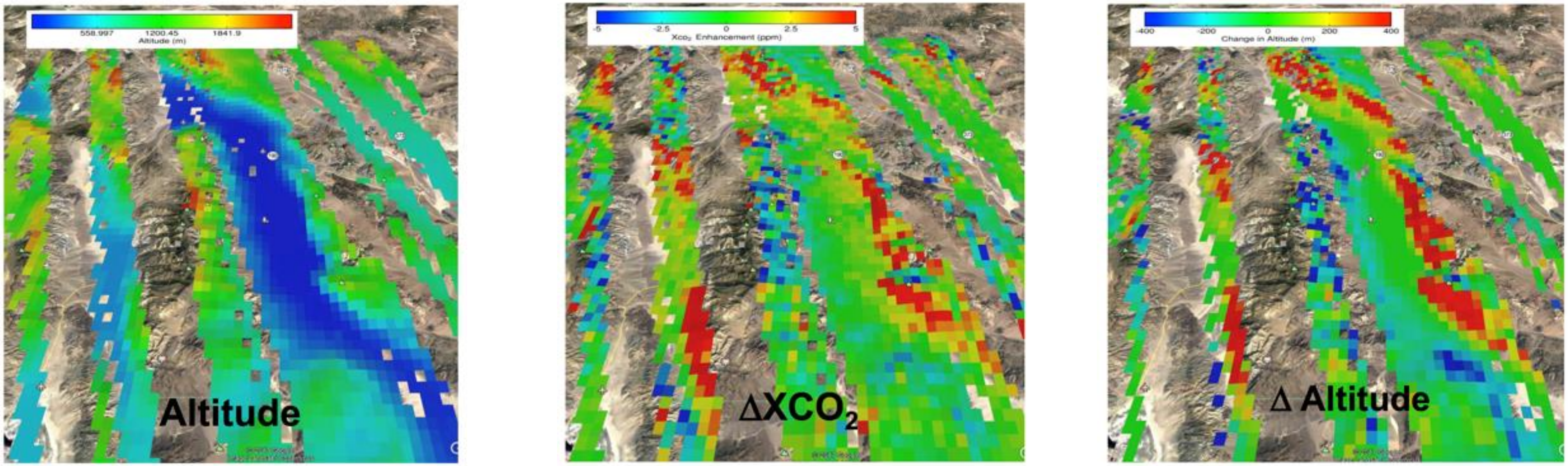


Bias sometimes apparent at bright/dark discontinuity, could be due to slight pointing offset?

Lauder Target observations with gridded B7 X_{CO2}.
Same pattern seen in RemoTeC retrievals.

Matt Kiel & Debra Wunch

Potential solutions show promise (example: Death Valley, USA)

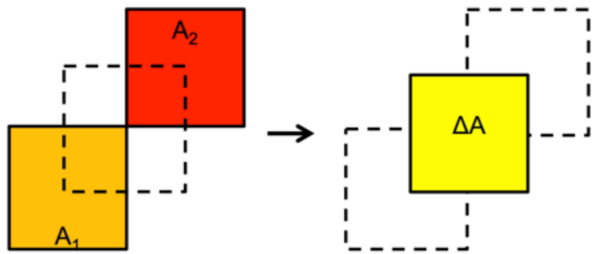


- Small pointing offsets (imperfect pointing knowledge) lead to multi-ppm level XCO2 biases related to ground slope and it's relationship to the satellite view angle.
- This has largely gone unnoticed in OCO-2 data until the last year, as other larger biases took center stage.
- Once these are fixed, we will likely find yet more biases that have been hiding!

- Define a change in altitude in NE direction:

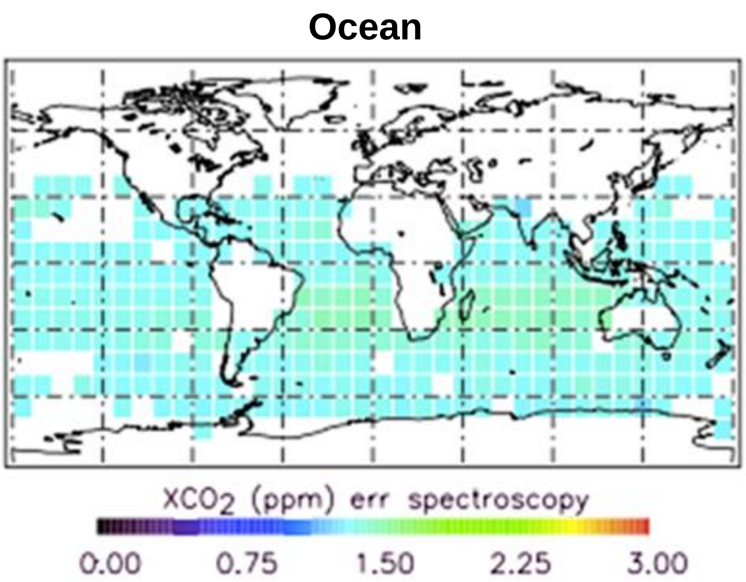
Change in Altitude
$\Delta A = A_2 - A_1$

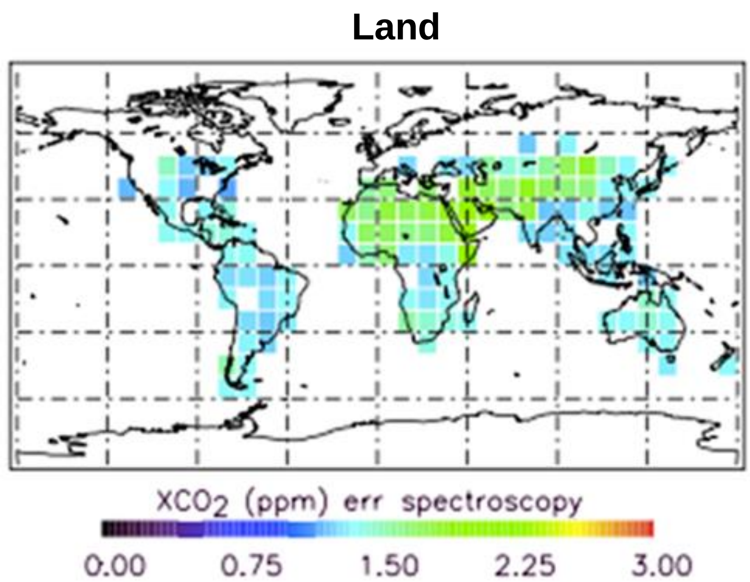
Plotted in dashed grid square



Courtesy Cameron MacDonald (U. Waterloo) and Ray Nassar (Environment Canada)

Spectroscopy errors

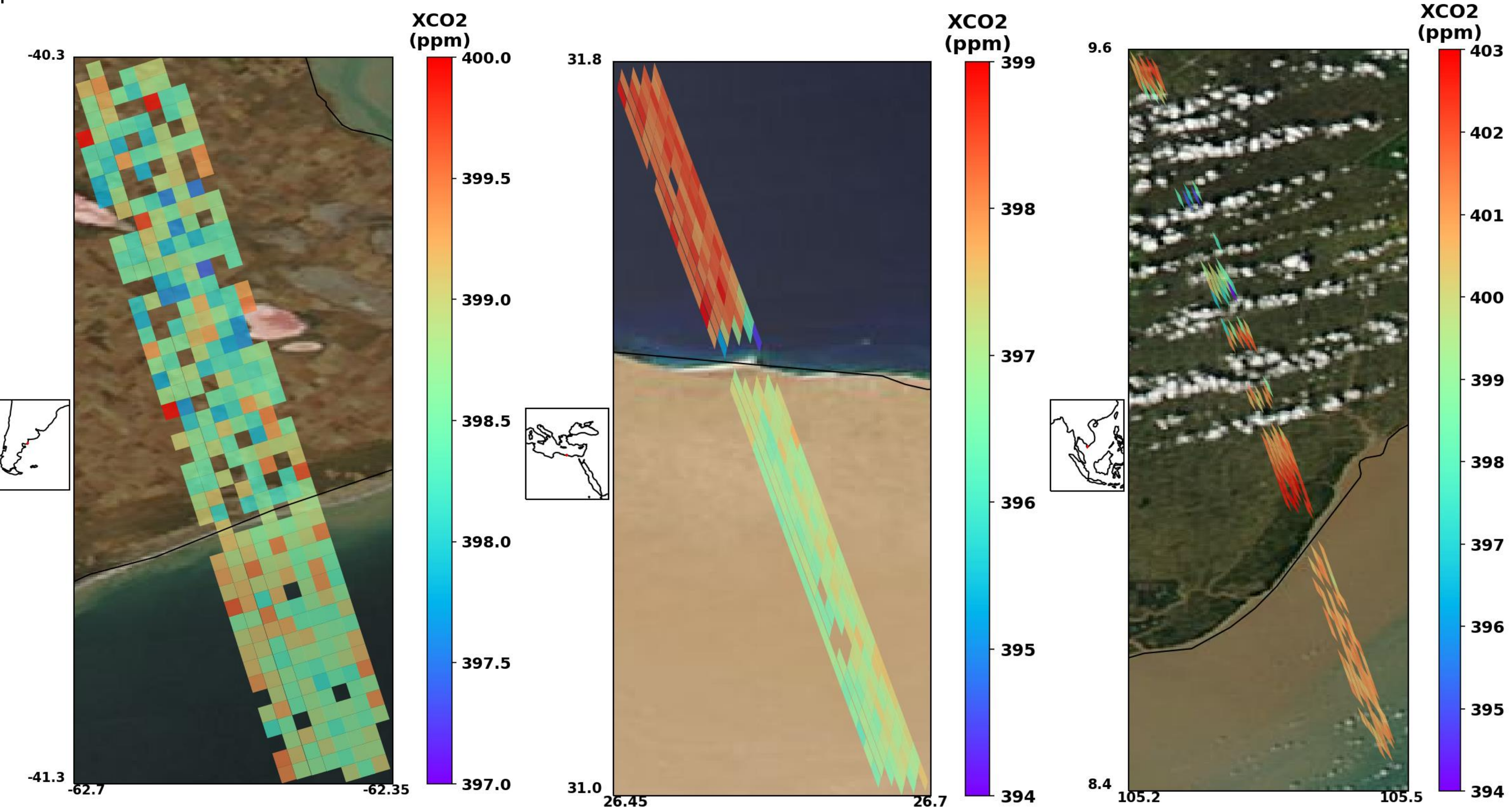




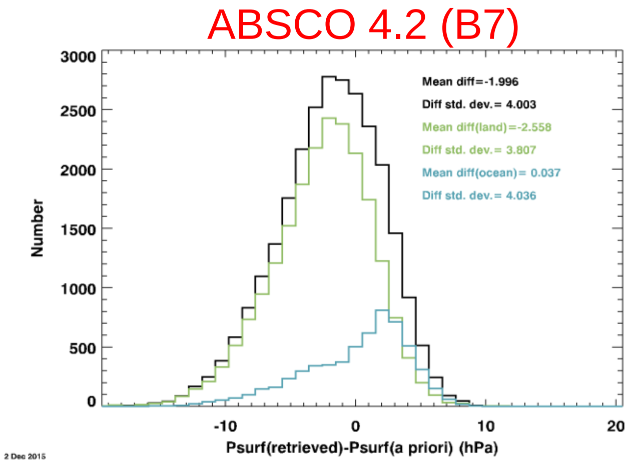
- Theoretical errors induced by spectroscopy as inferred from actual retrievals
- They vary in space & time, and can even induce land-ocean biases.

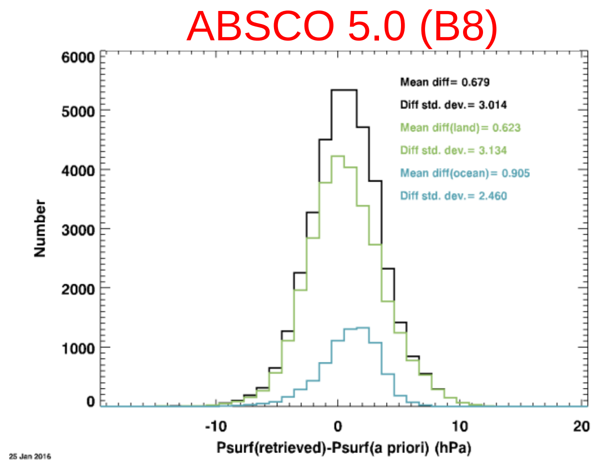
Connor et al., 2016: "Quantification of uncertainties in OCO-2 measurements of XCO_2: simulations and linear error analysis"

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



Spectroscopy Continues to Improve



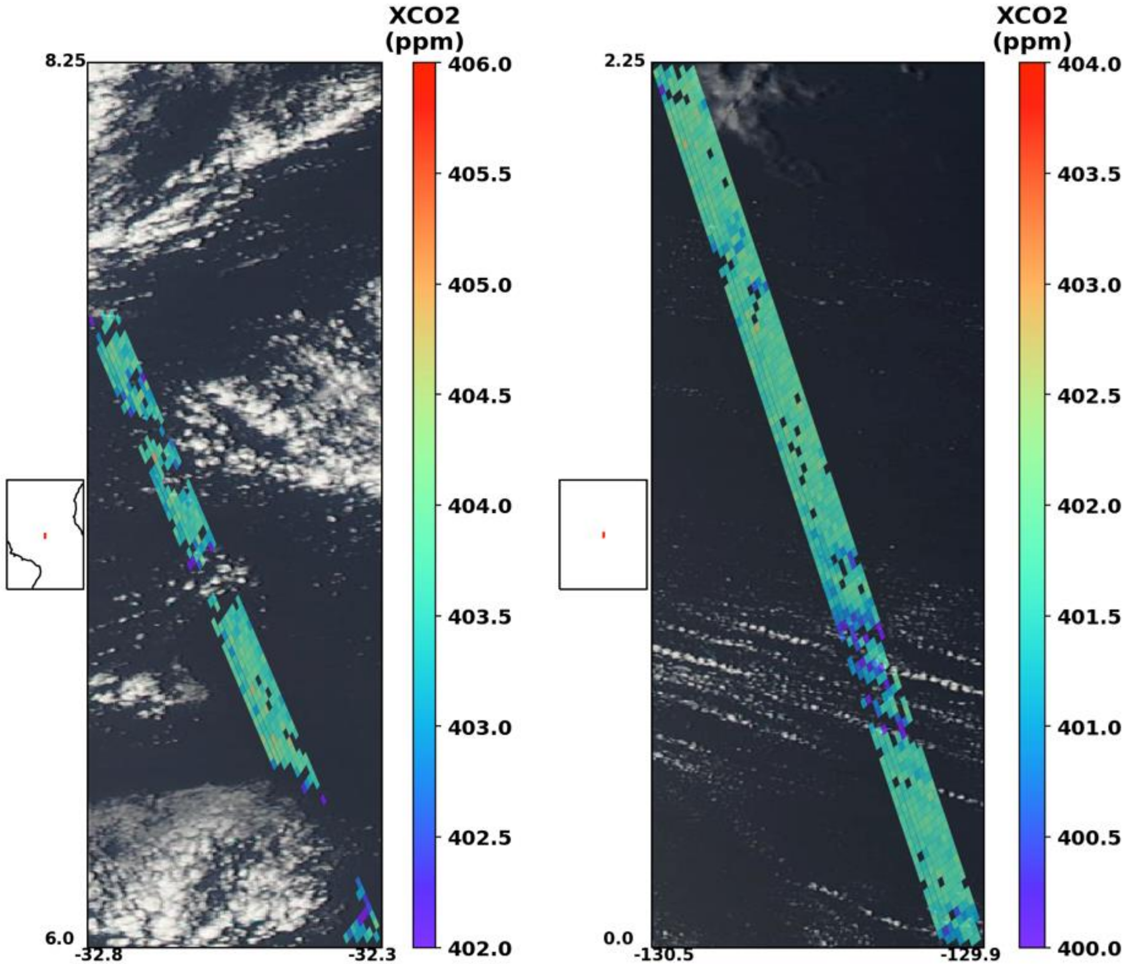


- **O_2A band:**
  - Speed-dependent Voigt from self-consistent multispectrum fits, including line mixing (Drouin et al., 2017)
  - Updated Collision-Induced Absorption
- **CO_2 Bands:**
  - New multi-spectrum fits to wider range of temperatures (Benner et al., 2016; Devi et al., 2016)
  - Updated H_2O Lines

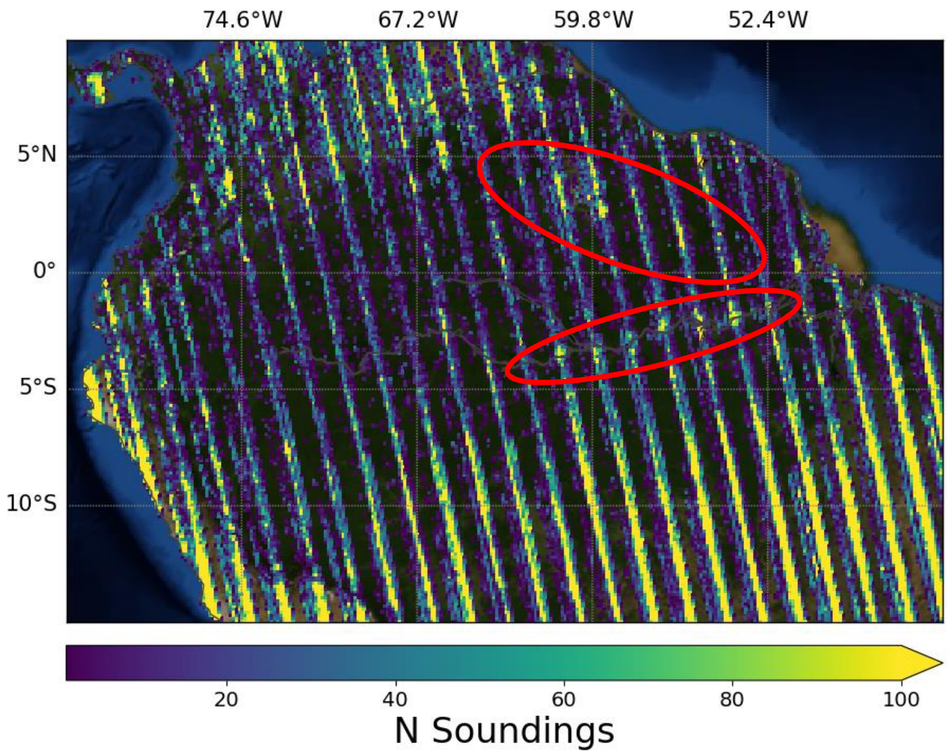
Fig Courtesy Vivienne Payne

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.



Few successful soundings over dark tropical forests



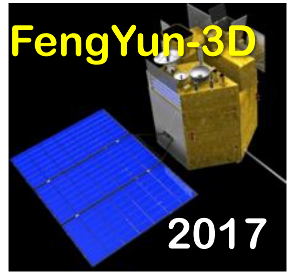
- Persistent cloudiness in these regions limits # of clear soundings to start.
- Darker surfaces are associated with larger errors, and are currently filtered out conservatively.

These retrieval issues may affect nearly all of these satellites.

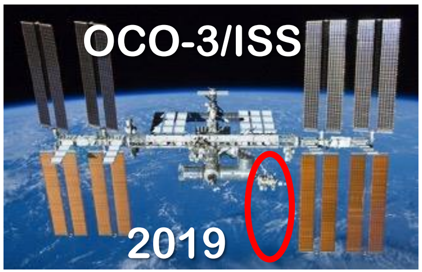
PAST

- 2 Chinese Satellites recently launched
- GOSAT-2, OCO-3 in 2019
- MicroCarb, GeoCarb approved

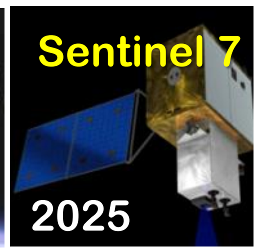
PRESENT

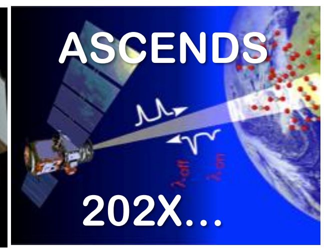


NEAR FUTURE



LATER





Summary & Concluding Thoughts

- The space-based XCO2 measurement (and to a lesser extent XCH4) is dominated by systematic rather than random errors.
- Systematic errors arise due to both problems with the spectra (e.g. calibration), as well as imperfect retrievals due to imperfect spectroscopy, representation of cloud & aerosol scattering, and other effects.
- Bias goal should ideally be less than ~0.3 ppm, to enable measurement of surface fluxes on regional scales.
- Most current biases are less than, or on the order of 1 ppm. They vary strongly with scale, surface features, and clouds. Solutions continue to be found and implemented.
- Further, some biases are native to the algorithm, and can be effectively explored with OSSEs.
- Even with current biases, some scientific studies have been possible with current data.
- The goal bias level is ambitious, but is achievable given sufficient time and investment!

Latest Version B8 Data:

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

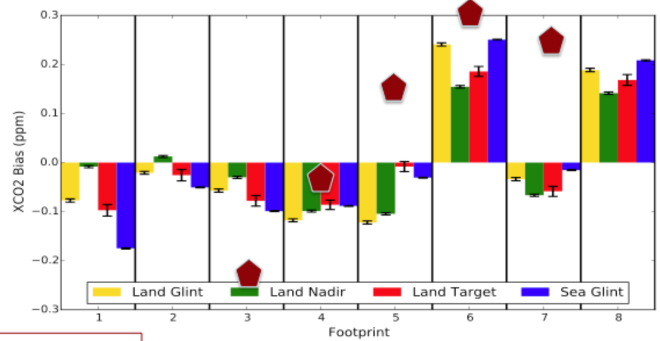
Thank You!!

Questions?

XCO2 Bias Correction Process (OCO-2)

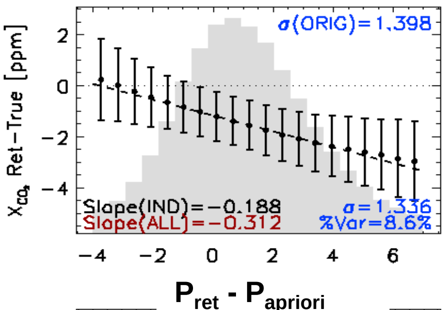
$$X_{CO2}^{BC} = \frac{X_{CO2}^{Raw} - c_1\,\mathrm{P}_1 - c_2\,\mathrm{P}_2 - \cdots - FPbias}{global\_offset}$$

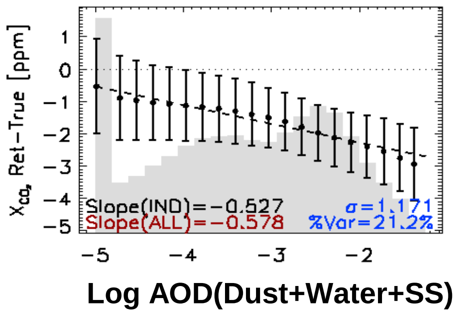
Step 2: Per-Footprint Offset

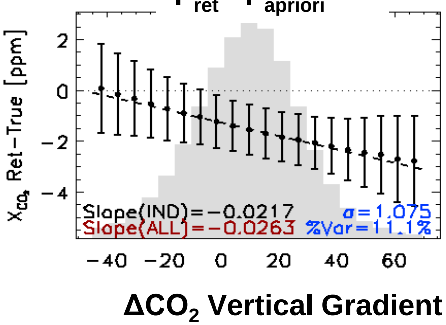


B6.0 Biases

Step 1: Regress vs. Bias Predictors



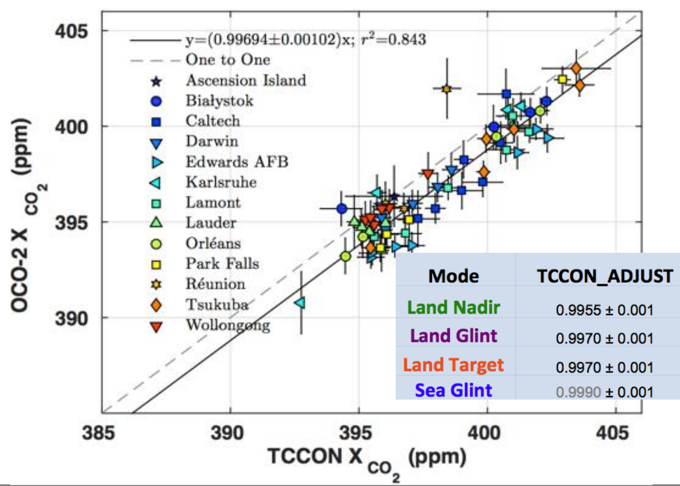




Predictors:

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

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

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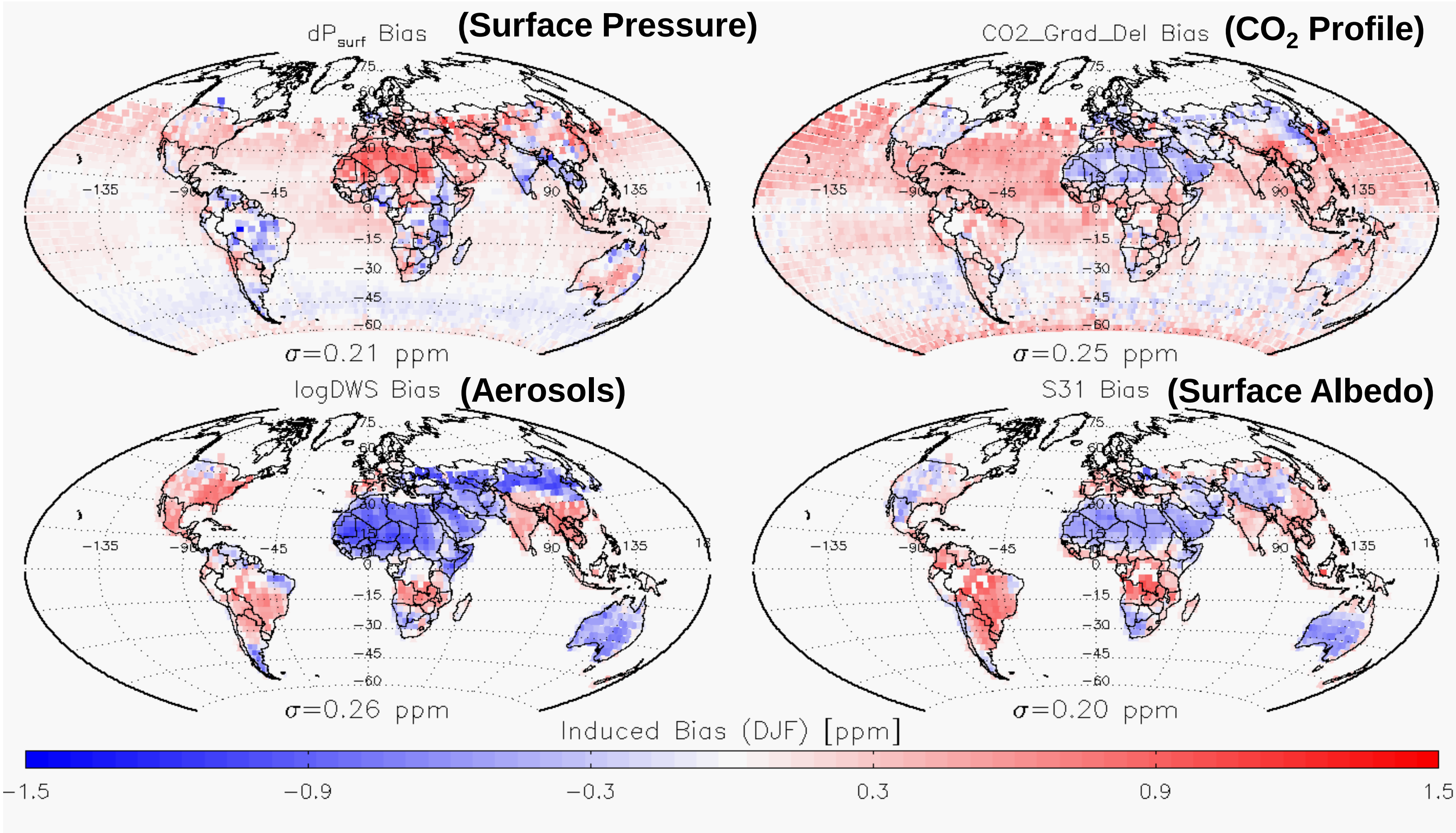
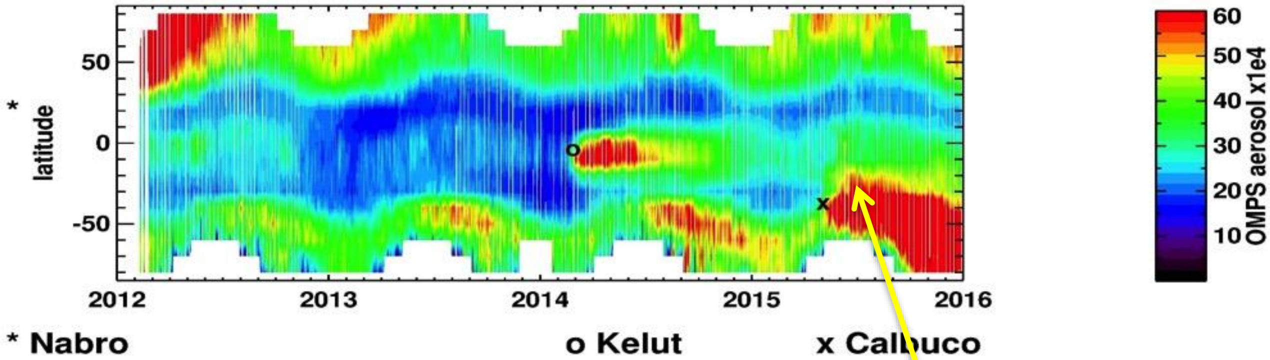
Typical Bias Correction Patterns



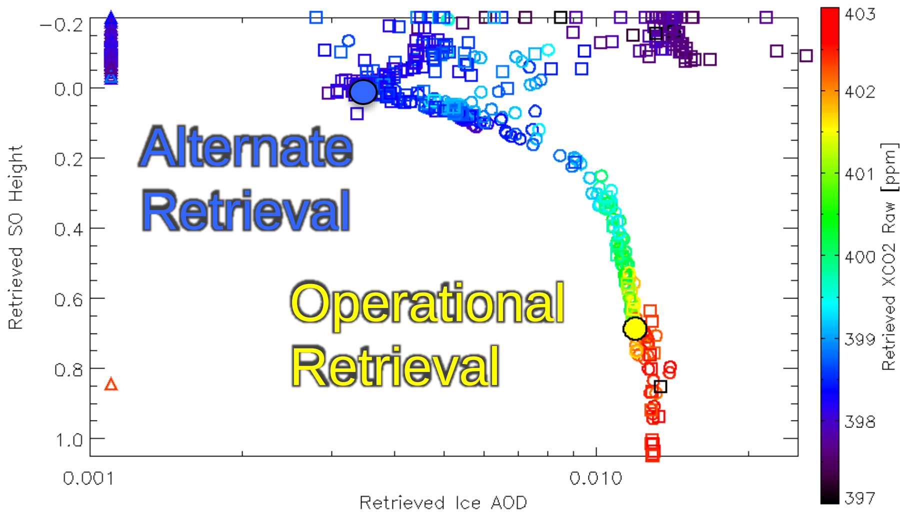
Hypothesis: Stratospheric Aerosols



June 26, 2015 sounding near -28.5 Latitude, 57° SZA

<u>Varied First Guess retrievals show:</u>

- Large range of solutions possible.
- Typical solution:
  - Low sulfate AOD, near surface.
  - Ice retrieved in stratosphere
  - Higher Band 3 chI^2
- Alternate Solution
  - Sulfate moved up near TOA
  - Low/no cloud ice retrieved
  - Lower Band 3 chi^2



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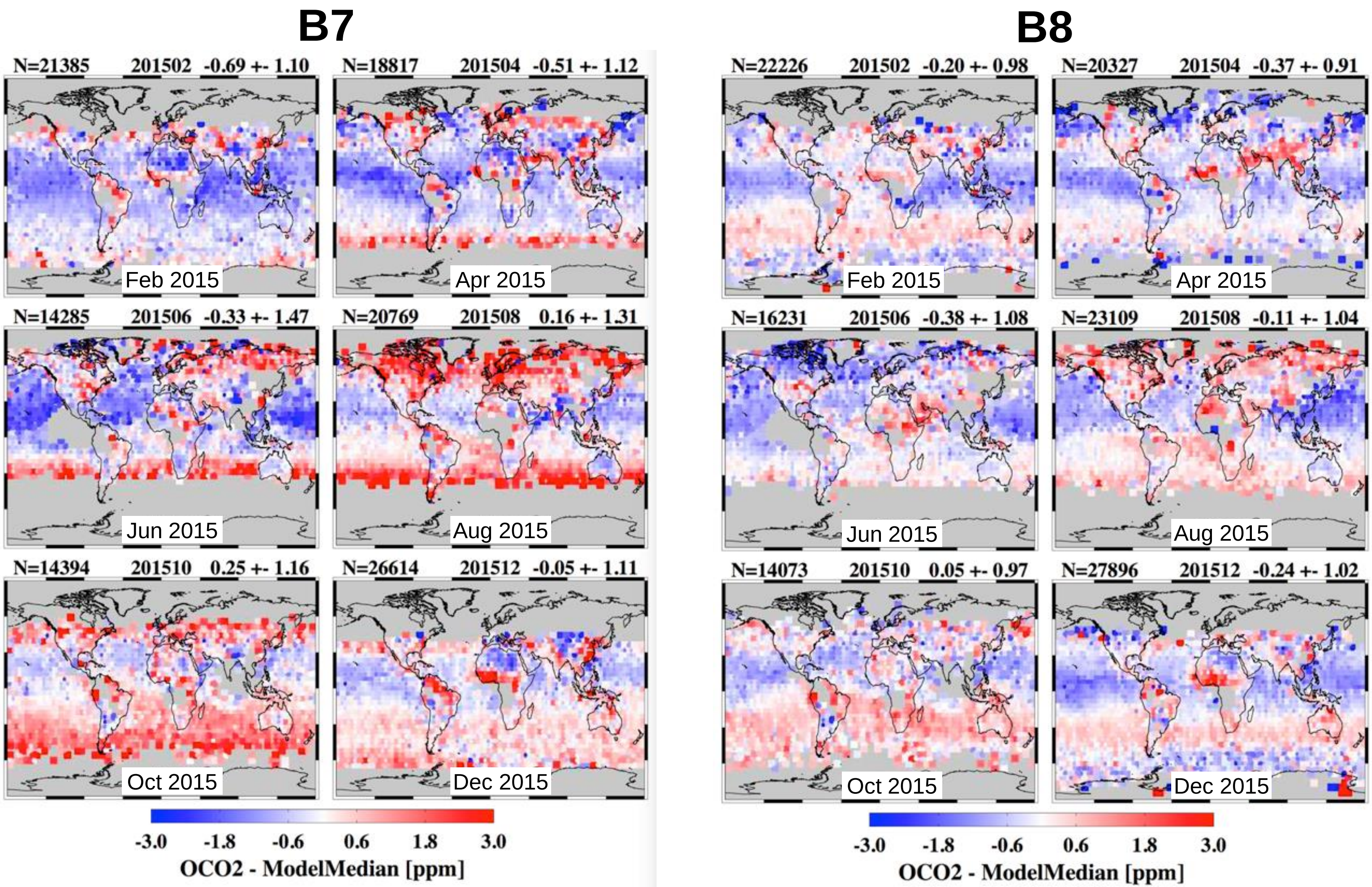
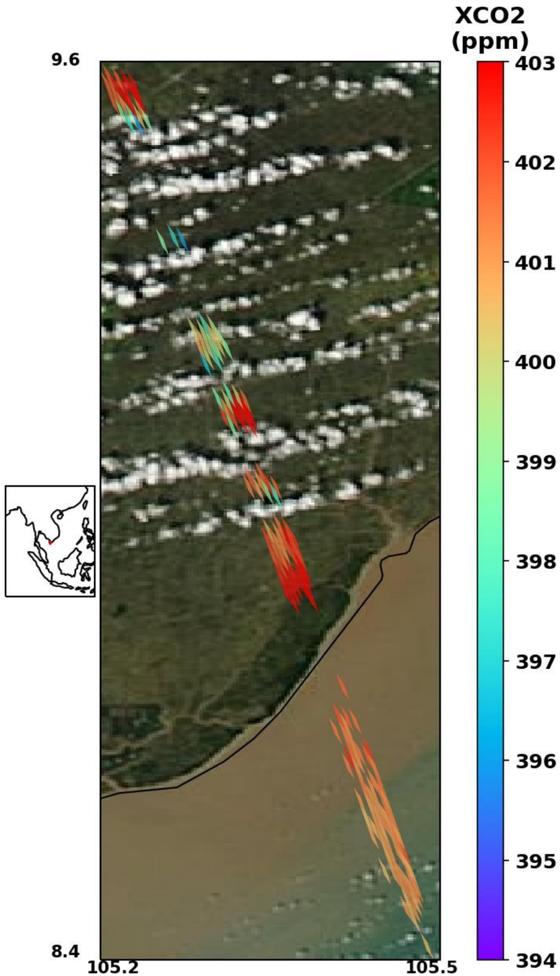
Improved Comparison to Models (2015)



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

Cloud streets! Neat.



Filtering tables

Table 1: Quality Filters Applied to Land Soundings

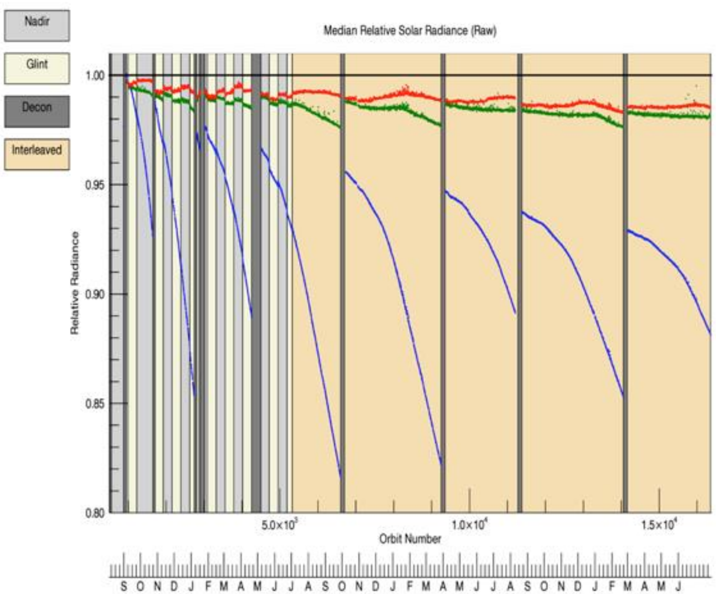
All Land Soundings		
Lite File Field	**Lower Limit** (> or =)	**Upper Limit** (< or =)
Preprocessors/co2_ratio	1.00	1.025
Preprocessors/h2o_ratio	0.88	1.01
Sounding/altitude_stddev	0.0	60.0
Preprocessors/max_declocking_wco2	0.0	0.75
Retrieval/dp	-6.0	14.0
Preprocessors/dp_abp	-10.0	13.0
Retrieval/co2_grad_del	-80.0	100.0
Retrieval/albedo_sco2	0.05	0.6
Retrieval/rms_rel_wco2	0.0	0.25
Retrieval/s31	0.03	0.4
Retrieval/albedo_slope_sco2	-0.00018	0.001
Retrieval/aod_total	0.0	0.5
Retrieval/dws	0.0	0.25
Retrieval/aod_water	0.0005	0.1
Retrieval/aod_ice	0.00	0.04
Retrieval/ice_height	-0.5	0.45
Retrieval/aod_sulfate + Retrieval/aod_oc	0.0	0.3
Retrieval/aod_strataer	0.0	0.02
Retrieval/aod_oc	0.0	0.08
Retrieval/aod_seasalt	0.0	0.125

Table 2: Quality Filters Applied to Ocean Glint Soundings

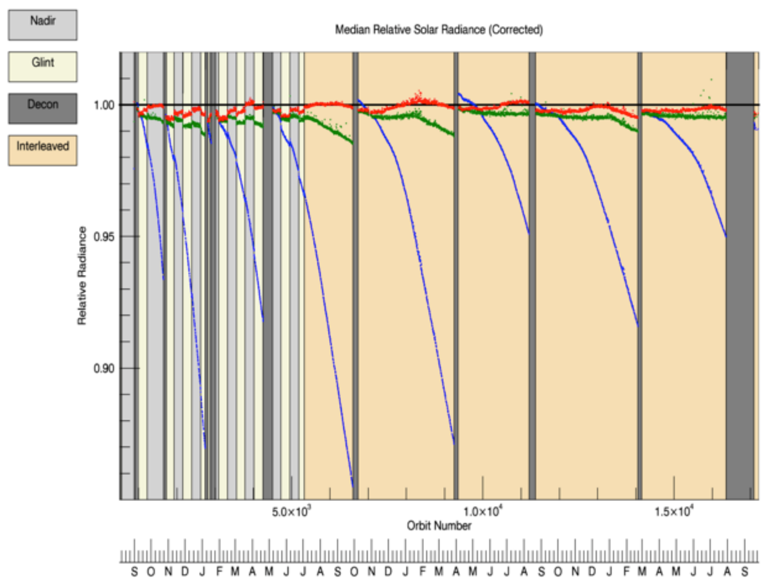
Ocean Glint Soundings		
Lite File Field	**Lower Limit** (> or =)	**Upper Limit** (< or =)
Retrieval/eof3_3_rel	-0.3	0.25
Preprocessors/max_declocking_wco2	0.0	0.2
Preprocessors/max_declocking_sco2	0.0	0.3
Retrieval/albedo_slope_sco2	5e-6	7e-5
Retrieval/rms_rel_wco2	0.0	0.3
Preprocessors/h2o_ratio	0.88	1.01
Preprocessors/co2_ratio	0.997	1.018
Retrieval/dp	-4.0	10.0
Retrieval/co2_grad_del	-20.0	30.0
Retrieval/windspeed	1.5	25
Preprocessors/dp_abp	-50.0	10.0
Retrieval/aod_ice	0.0	0.035

A-band radiometric correction

WAS in v7
Note how blue curves do not return to 1



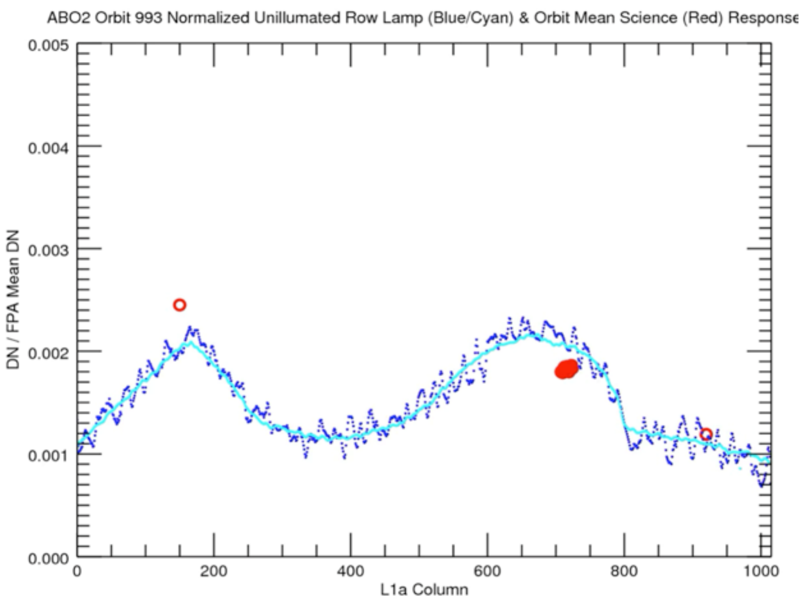
V8 with proper treatment of slow changes in time



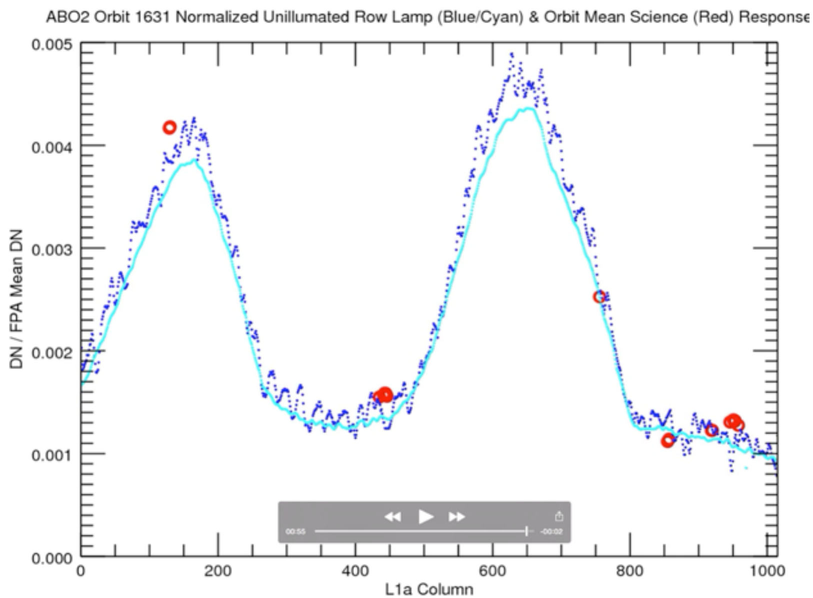
A closer look at Zero Level Offset correction

- ZLO correction changes as ice builds up. It is determined from pixels that are not illuminated, so anything on those detectors is scattered light.

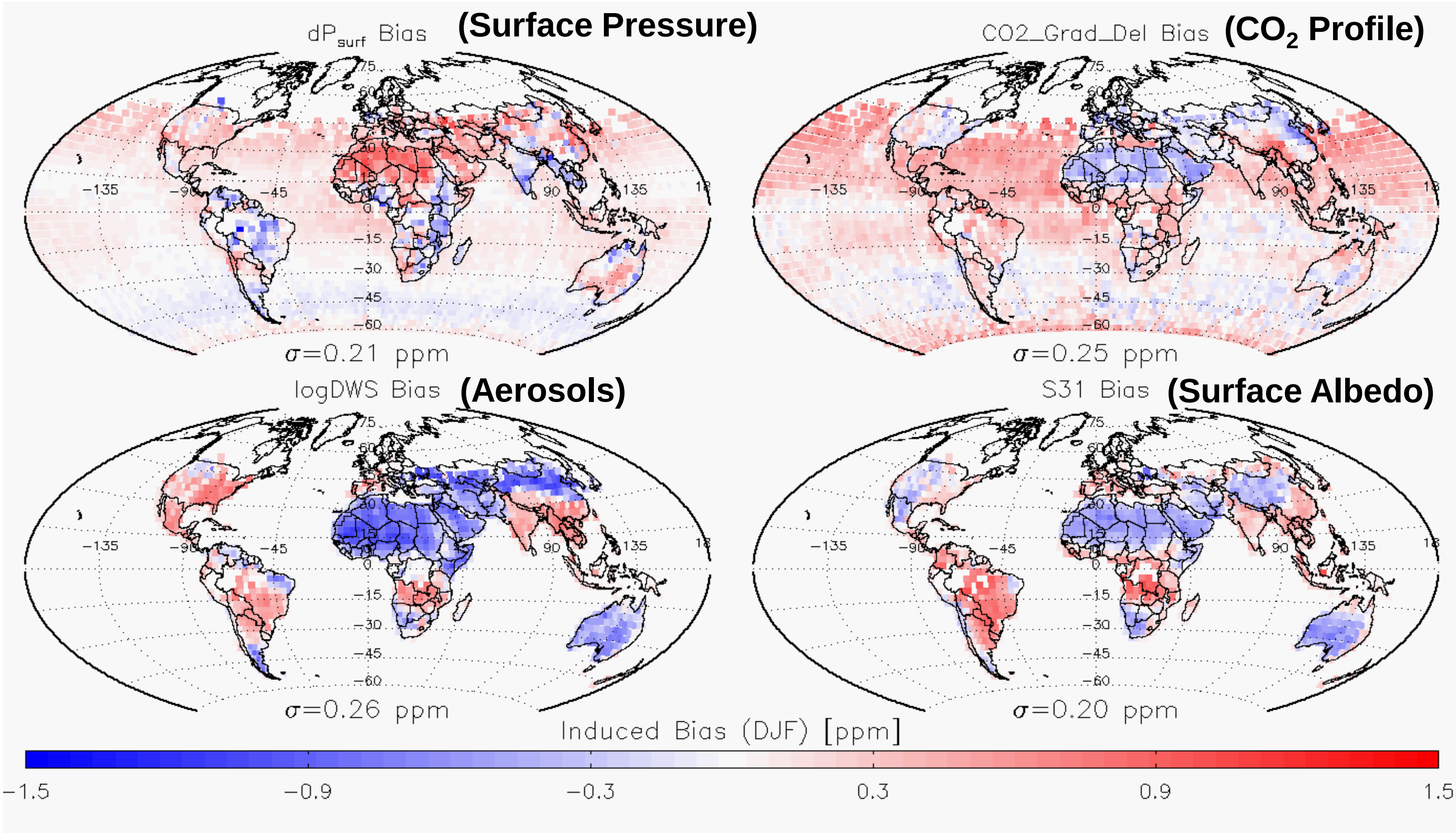
Soon after decon



Later in decon cycle



B7 Bias Correction Patterns

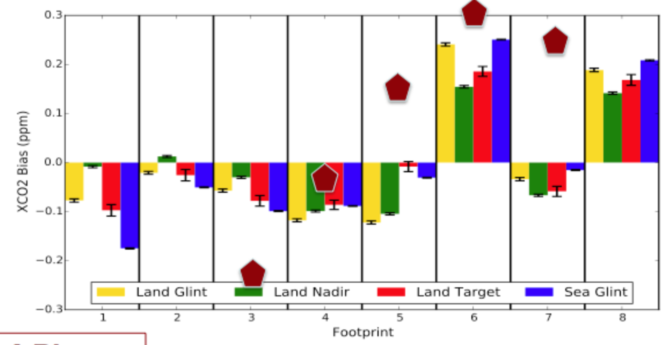


Jet Propulsion Laboratory
California Institute of Technology

XCO2 Bias Correction Process (OCO-2)

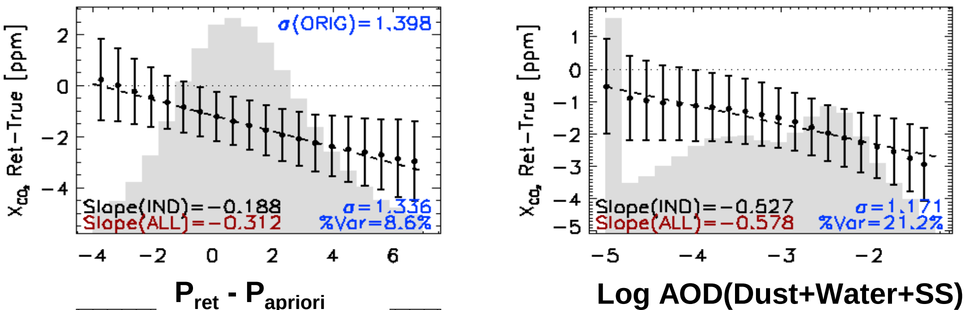
$$X_{CO2}^{BC} = \frac{X_{CO2}^{Raw} - c_1 P_1 - c_2 P_2 - \cdots - FPbias}{global\_offset}$$

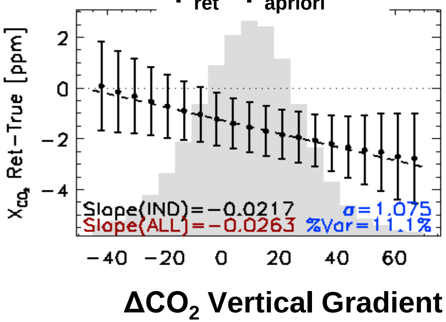
Step 2: Per-Footprint Offset



B6.0 Biases

Step 1: Regress vs. Bias Predictors

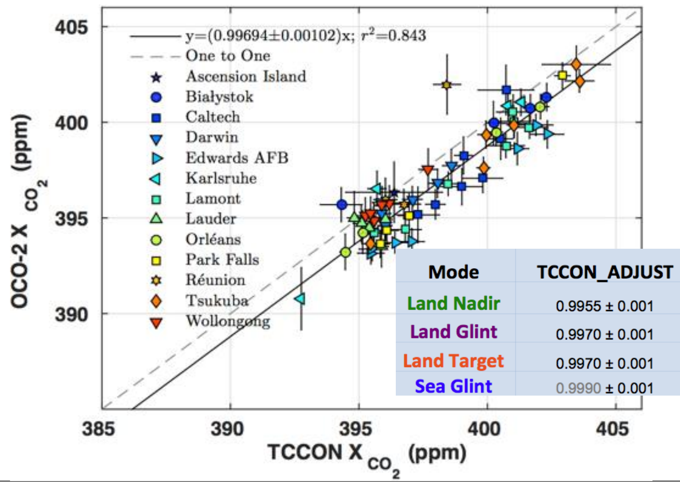




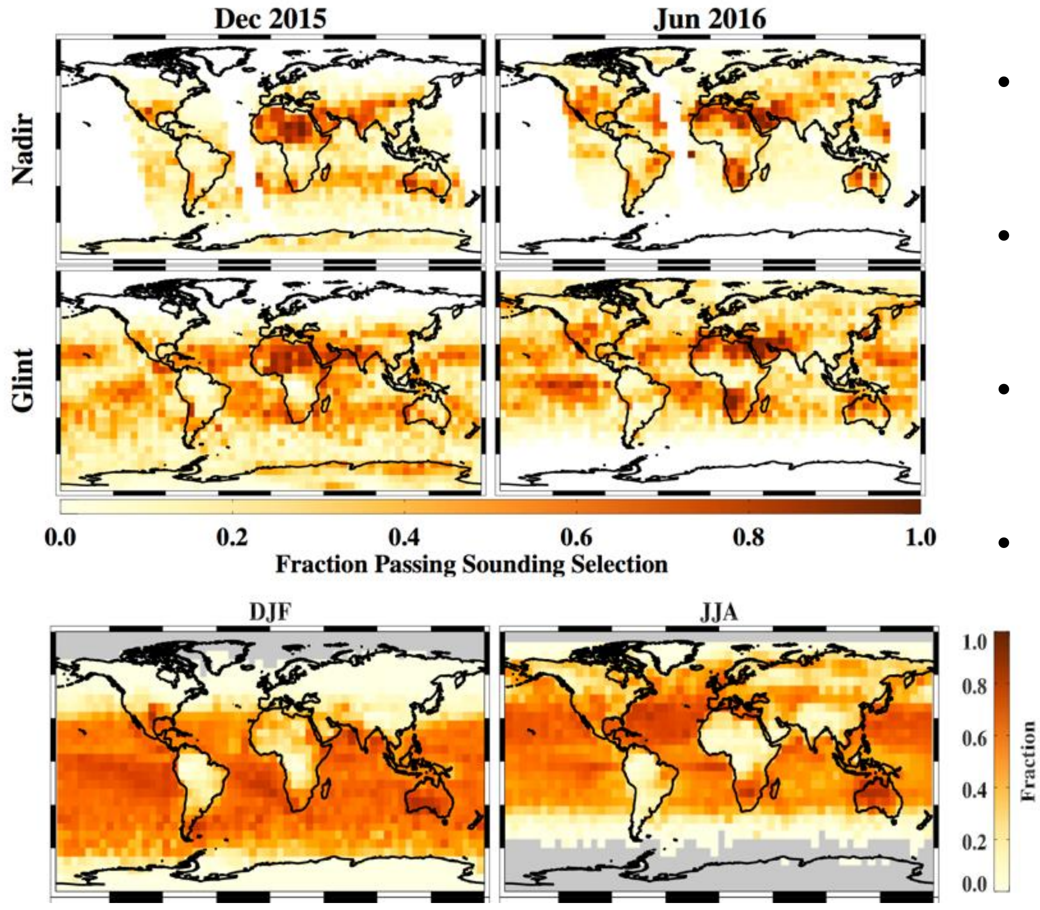
Predictors:

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

Step 3: Global Multiplier



Filtering



Fraction of Retrieved Soundings Passing Quality Filter

- About 20% of soundings pass pre-screening based (clouds, SNR, etc)
- Over ocean, most soundings survive further quality filtering
- Over land, only ~1/3 of soundings survive quality filtering.
- Most soundings over ice & snow-covered surfaces and rainforests are lost due to low signals in the CO2 bands.

Bias Correction Overview

Table 4 Bias Correction Formula (for use on v8.0)

$$XCO_{2\,Corrected} = \frac{XCO_{2\,Raw} - FOOT[fp, mode] \boxed{- FEATS[mode]}}{TCCON\_ADJUST[mode]}$$

where:

	FOOTPRINT BIAS (FOOT) (ppm)							
Footprint (fp)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
ALL MODES	-0.36	-0.15	-0.16	-0.14	0.02	0.33	0.13	0.34

	FEATURE BIAS (FEATS) (ppm)
LAND (ALL)	– 0.36***dP** – 8.5***DWS** – 0.029*(**co2_grad_del** – 15)
SEA GLINT	– 0.23***dP** + 0.09*(**co2_grad_del** + 6.0) [second term only applied when co2_grad_del is less than -6)

	OVERALL DIVISOR (TCCON_ADJUST)	**Method**
LAND GLINT **LAND NADIR** **LAND TARGET**	0.9958	Target is assigned Other modes derived from TCCON paired ND/GL and comparison to models
SEA GLINT	0.9955	Comparison to TCCON, coastlines, model bootstrap, and comparison to models

NOTE! This constant is needed for the L2 standard but not Lite products

	Variable definitions using full/HDF/path for L2 files
co2_grad_del	1e6 * RetrievalResults/co2_vertical_gradient_delta
dP	0.01 * (RetrievalResults/surface_pressure_fph – RetrievalResults/surface_pressure_apriori_fph)
DWS	aod_dust + aod_water + aod_seasalt
aod_dust (1-based)	(AerosolResults/aerosol_types_retrieved[1]) * (AerosolResults/aerosol_aod[1,1])
aod_water (1-based)	(AerosolResults/aerosol_types_retrieved[7]) * (AerosolResults/aerosol_aod[7,1])
aod_seasalt (1-based)	(AerosolResults/aerosol_types_retrieved[2]) * (AerosolResults/aerosol$_{aod}$[2,1])

Parameter Dependencies (Land):

- Good consistency across truth Metrics!
- Same parameters as B7
- S31 dependency gone

		N	Sigma [ppm]	dP	Co2_grad_del	DWS
TCCON:	LandN	106K	1.81 → 1.28	-0.37 (31%)	-0.027 (16%)	-8.0 (4%)
	LandG	76K	1.91→ 1.34	-0.38 (36%)	-0.026 (13%)	-5.1 (2%)
	LandT	314K	1.60 → 1.18	-0.26 (16%)	-0.025 (24%)	-6.9 (5%)
MODELS:	LandN	336K	1.70 → 1.17	-0.34 (27%)	-0.029 (19%)	-8.5 (7%)
	LandG	372K	1.77 → 1.20	-0.34 (29%)	-0.027 (18%)	-8.2 (7%)
SAA:	LandN	275K	1.58 → 0.87	-0.34 (34%)	-0.031 (24%)	-9.9 (11%)
	LandG	286K	1.67→ 0.90	-0.37 (45%)	-0.029 (20%)	-7.9 (6%)
SHA_Mod:	LandN	98K	1.54 → 0.96	-0.35 (29%)	-0.031 (25%)	-8.5 (8%)
	LandG	99K	1.63 → 0.97	-0.36 (30%)	-0.029 (22%)	-9.8 (12%)
Ensemble Statistics		-	-	**-0.346 ± 0.035 (-0.356 ± 0.016)**	**-0.028 ± 0.002 (-0.029 ± 0.002)**	**-8.1 ± 1.5 (-8.2 ± 1.5)**
B70		-	-	**-0.30**	**-0.028**	**-7 to -11**

Excluding land Target →

Bias Correction Overview

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Footprint (fp)	1	2	3	4	5	6	7	8
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	FEATURE BIAS (FEATS) (ppm)
LAND (ALL)	– 0.36*dP – 8.5*DWS – 0.029*(co2_grad_del – 15)
SEA GLINT	– 0.23*dP + 0.09*(co2_grad_del + 6.0) [second term only applied when co2_grad_del is less than -6)

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aod_seasalt (1-based)	(AerosolResults/aerosol_types_retrieved[2]) * (AerosolResults/aerosol$_{aod}$[2,1])

Parameter Dependencies (Ocean Glint):

- Reasonable consistency across truth Metrics. Smaller BC than land.
- Same parameters as B7, but CO2_Grad_Del dependency is nonlinear.

		N	Sigma [ppm]	dP	Co2_grad_del<-6
TCCON:	WL<=2	71K	0.96 → 0.82	-0.24 (24%)	0.063 (1.8%)
	Chris	73K	0.96 → 0.82	-0.23 (25%)	0.066 (3%)
MODELS:	WL<=2	607K	1.00 → 0.78	-0.23 (33%)	0.106 (6%)
	Chris	647K	1.02 → 0.77	-0.24 (36%)	0.104 (8%)
SAA:	WL<=2	324K	0.77 → 0.44	-0.22 (60%)	0.094 (7%)
	Chris	368K	0.80 → 0.44	-0.23 (61%)	0.088 (9%)
SHA_Mod:	WL<=2	155K	0.83 → 0.68	-0.11 (14%)	0.155 (18%)
	Chris	164K	0.83 → 0.67	-0.11 (14%)	0.135 (21%)
Ensemble Stats (Chris) (No SHA_Mod)		-	-	-0.20 ± 0.06 -0.233 ± 0.01	0.098 ± 0.029 0.086 ± 0.019
B70		-	-	-0.08 (there was evidence this was too weak)	0.077

Bias Correction Overview

Table 4 Bias Correction Formula (for use on v8.0)

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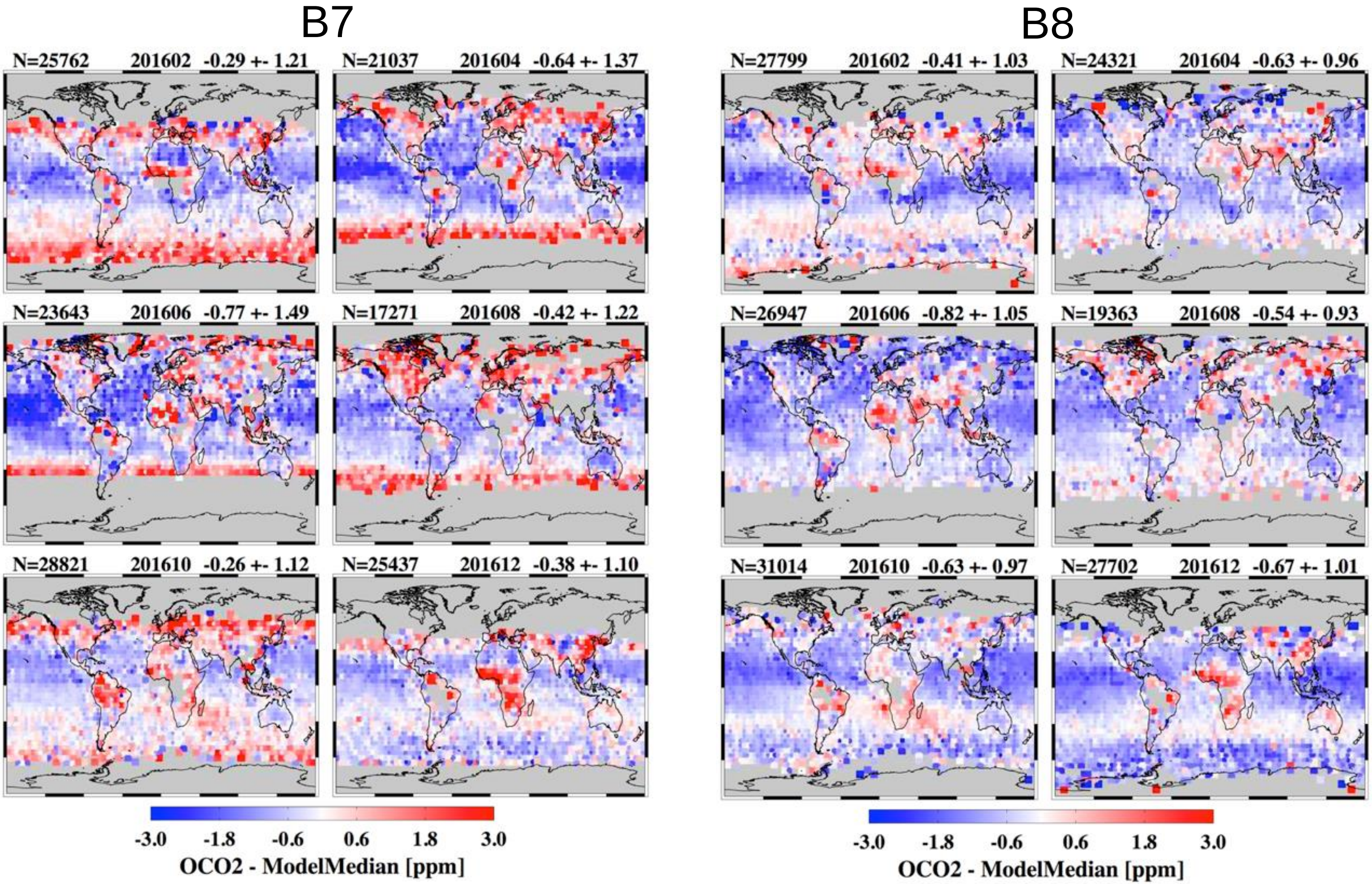
aod_seasalt (1-based)	(AerosolResults/aerosol_types_retrieved[2]) * (AerosolResults/aerosol$_{aod}$[2,1])

Global Divisors

- 0.0001 = 0.04 ppm
- Uncertainty ~0.0004 ppm = 0.15 ppm
- Model appear high by ~0.35 ppm relative to TCCON
  - AK correction not strong enough to explain difference.
  - Inter-model differences up to 0.6 ppm (1σ = 0.2 ppm)
- OCO-2 B8 tied to TCCON.

Comparison to Models (2016)



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