Precision, Accuracy, Resolution, and Coverage: A few insights from GOSAT and OCO-2

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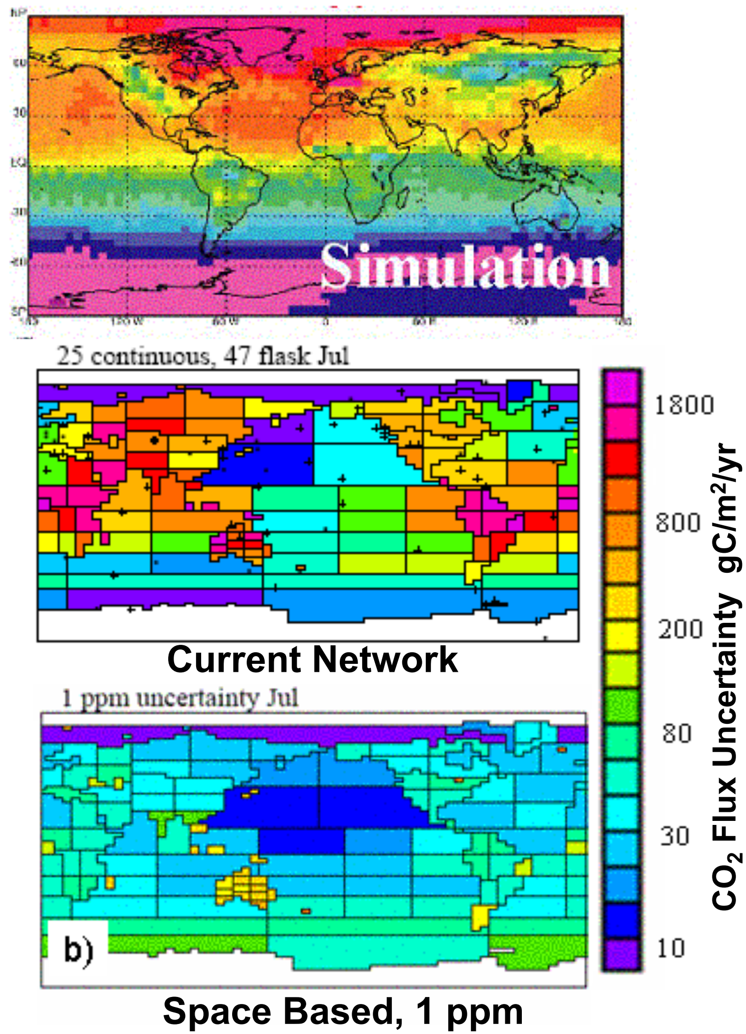
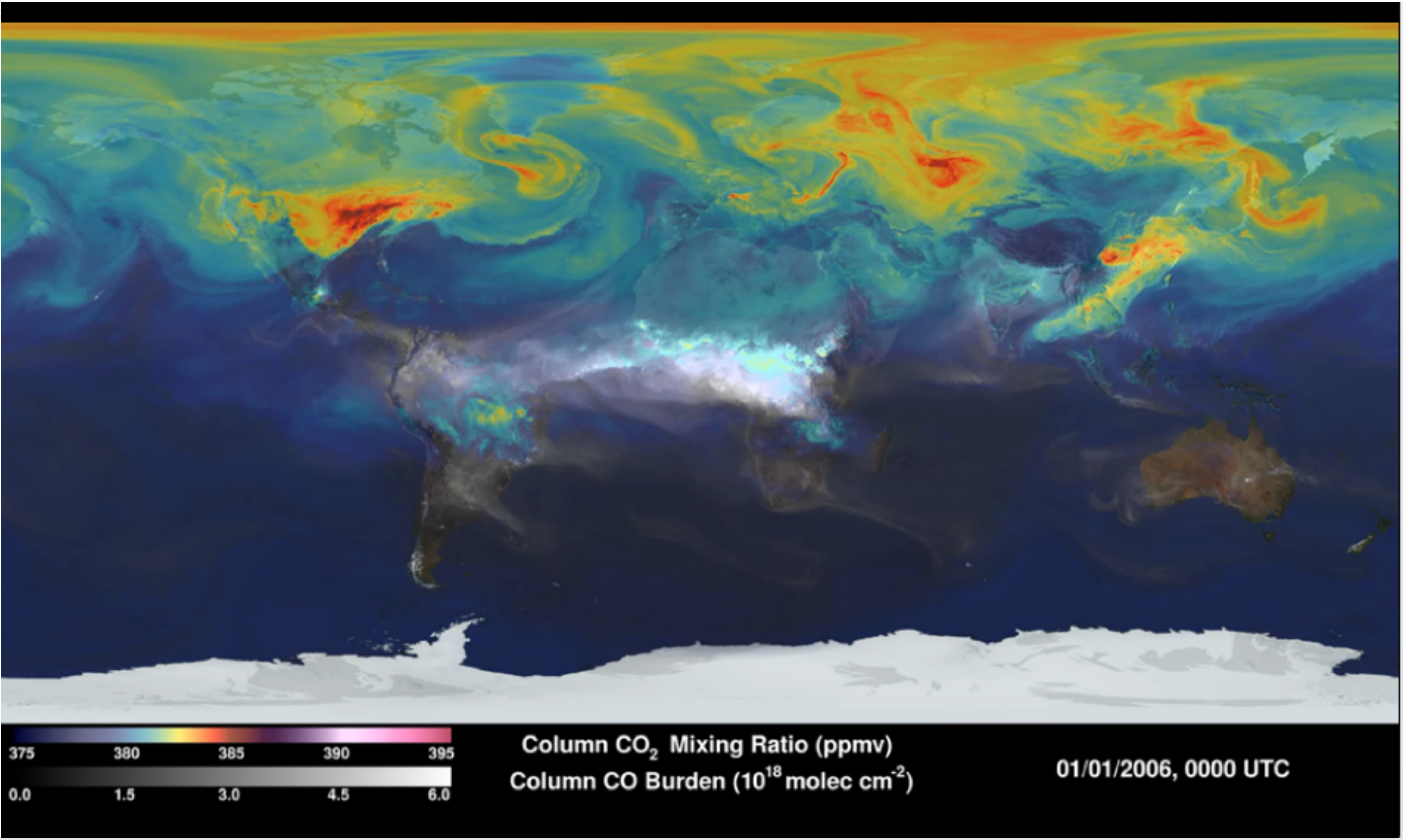
From Crisp et al, IWGGMS-1 (2004)

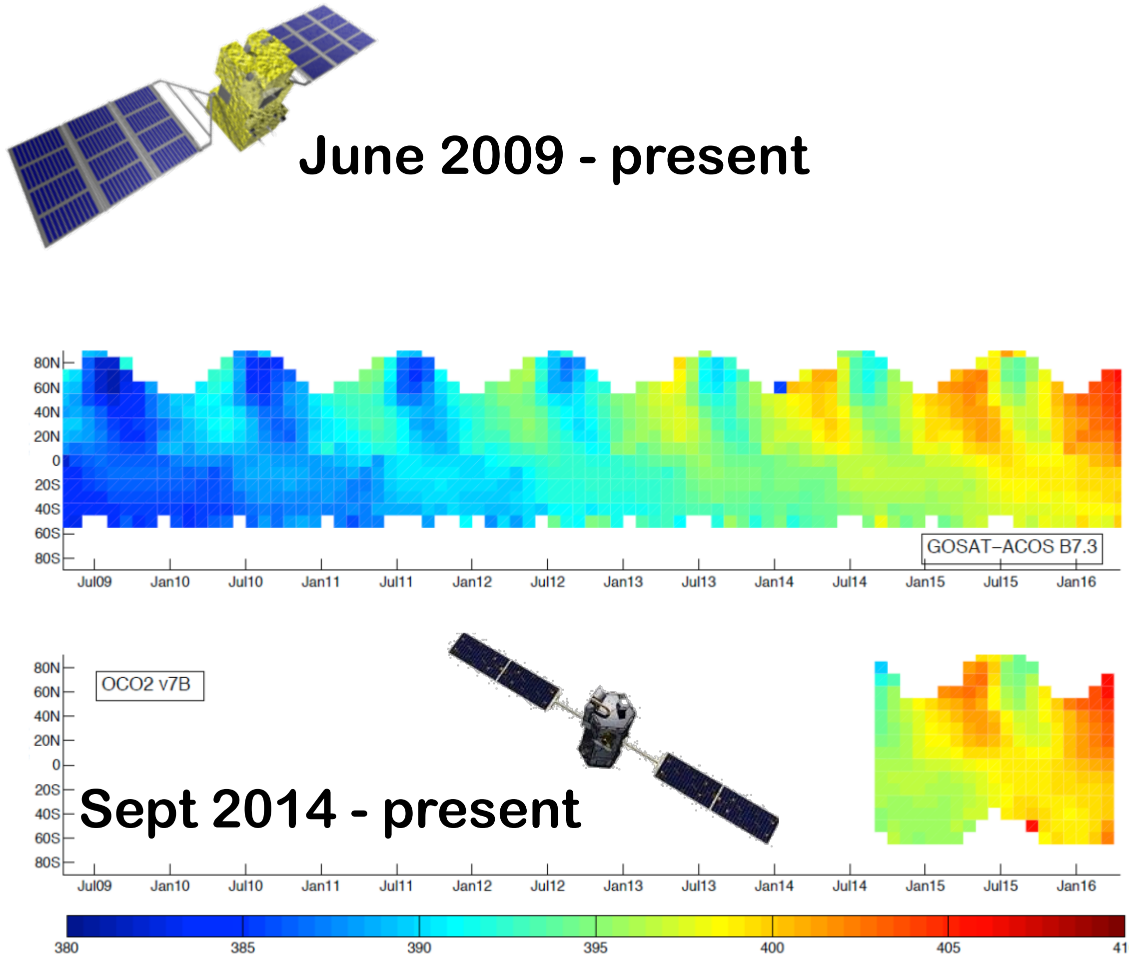
- Space-based measurements of X_{CO2} with precisions of 1–2 ppm (0.3 – 0.5%) will resolve
  - pole to pole X_{CO2} gradients on regional scales
  - the X_{CO2} seasonal cycle in the Northern Hemisphere
- Improve constraints on CO_2 sources and sinks compared to the current knowledge
  - Continental scale flux uncertainties reduced below 30 gC m^{-2} yr^{-1}
  - Regional scale flux uncertainties reduced from >2000 gC m^{-2} yr^{-1} to < 200 gC m^{-2} yr^{-1}



But the Actual X_{CO2} Field Looked more Like This



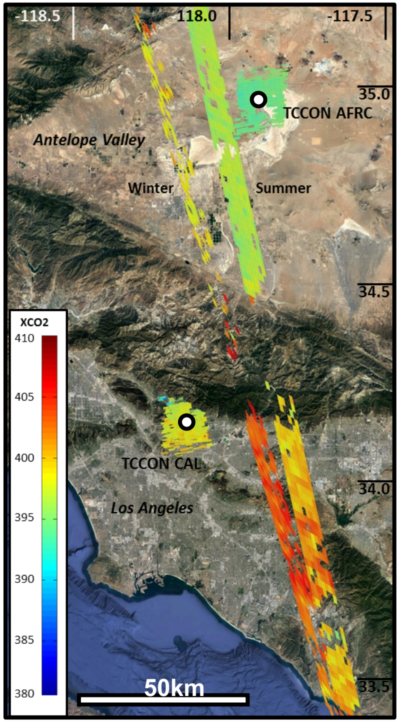
So we Flew GOSAT and OCO-2

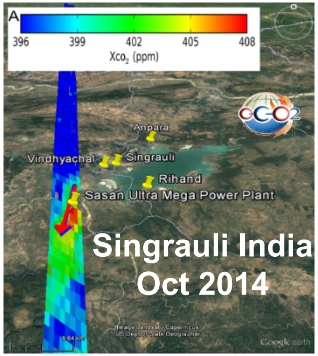


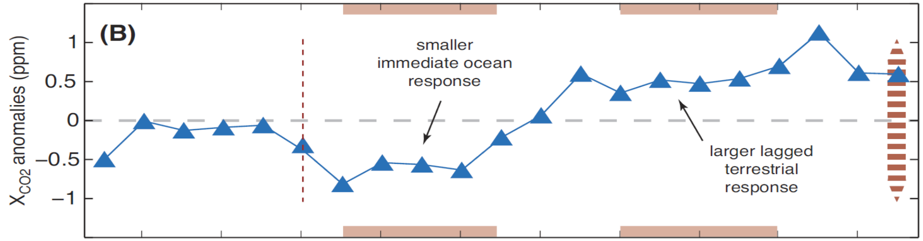
TCCON and other standards have been used to cross validate OCO-2 and GOSAT X_{CO2} to extend the climate data record

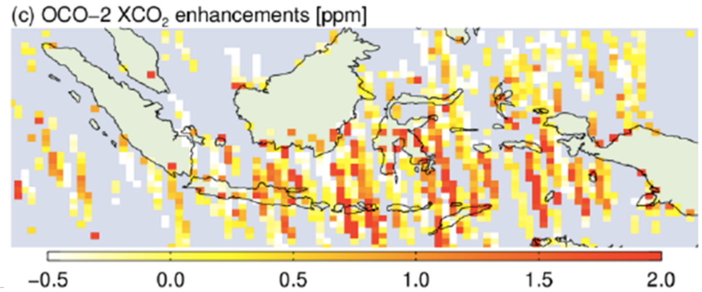
- The magnitude of differences between GOSAT-ACOS B7.3 and OCO2 v7r are within ±1 ppm for overlap regions

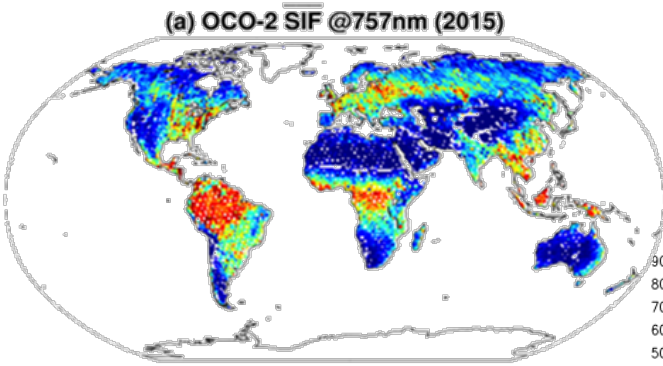
These Systems are Now Being Used to Study the Carbon Cycle

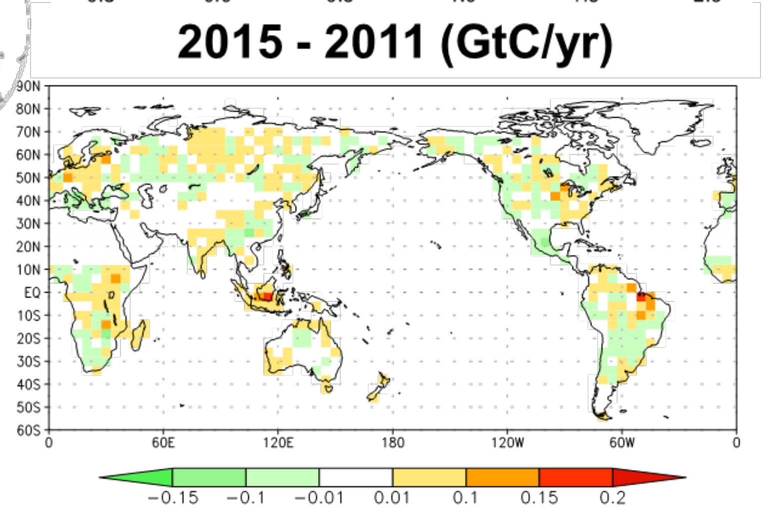


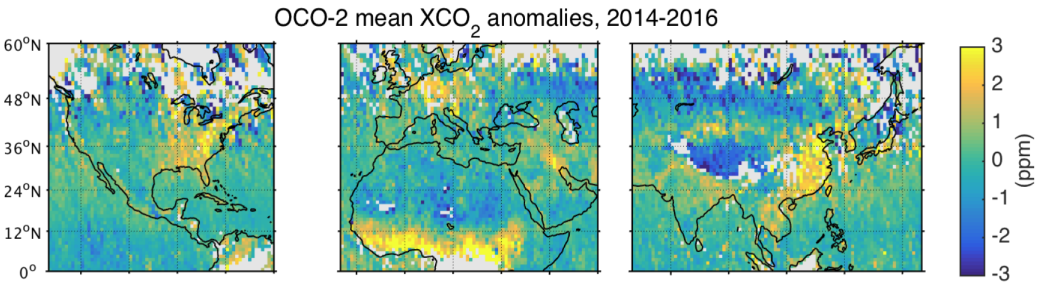










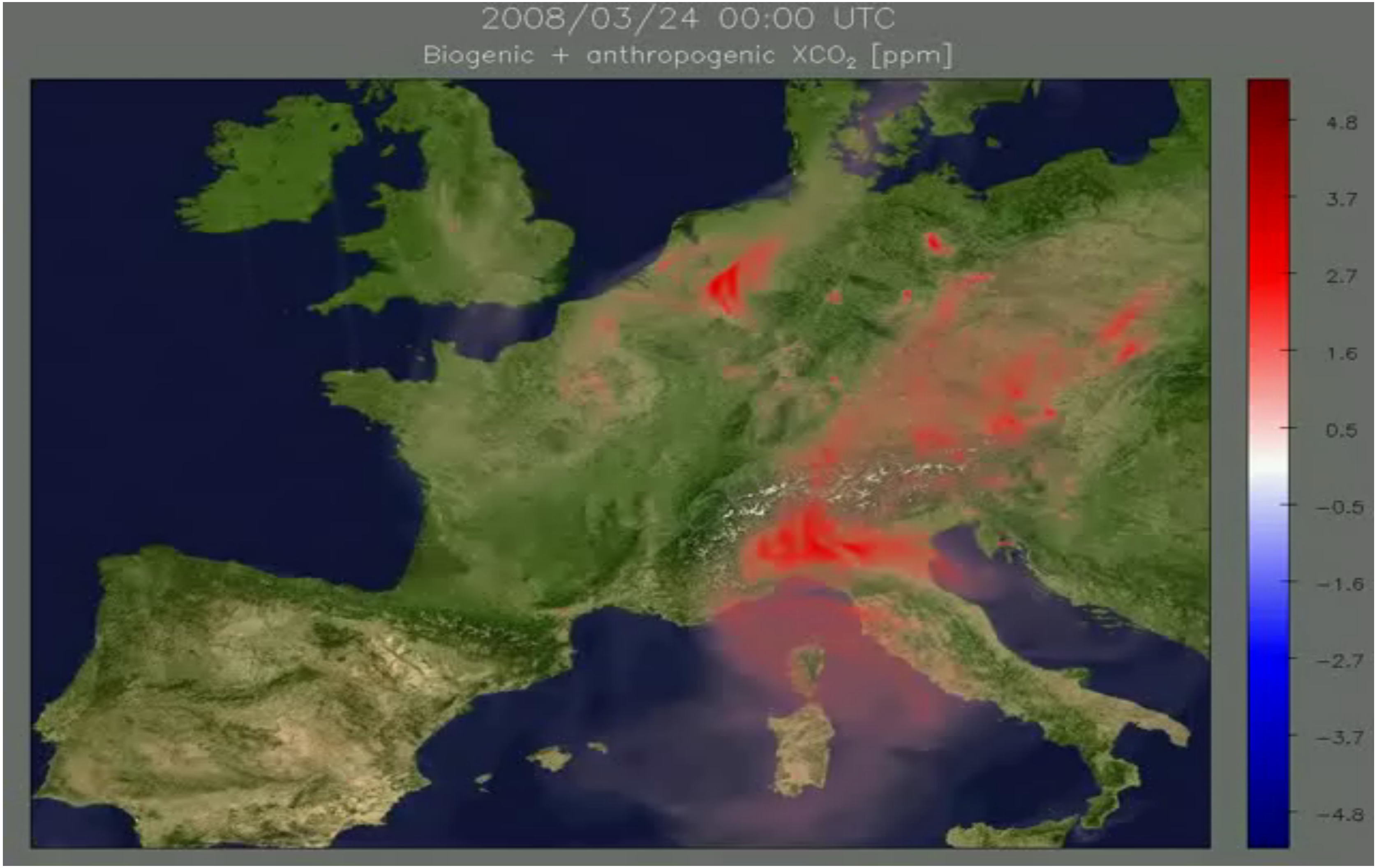


Fast Forward to 2015: COP21

To support the Paris Agreement:

- The overall goal is to develop a sound, scientific, measurement-based approach that:
  - reduces uncertainty of national emission inventory reporting,
  - identifies large and additional emission reduction opportunities
  - provides nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (Nationally Determined Contributions, NDCs)
- In support of these efforts, atmospheric measurements of greenhouse gases from satellites could
  - Improve the frequency and accuracy of inventory updates for nations not well equipped for producing reliable inventories, and
  - help to "close the budget" by measurement over ocean and over areas with poor data coverage
- We now have strong support, but new marching orders

Anthropogenic Emissions

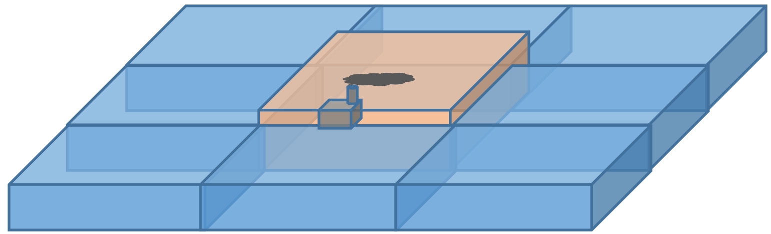


Compact Source Uncertainties Drive Precision

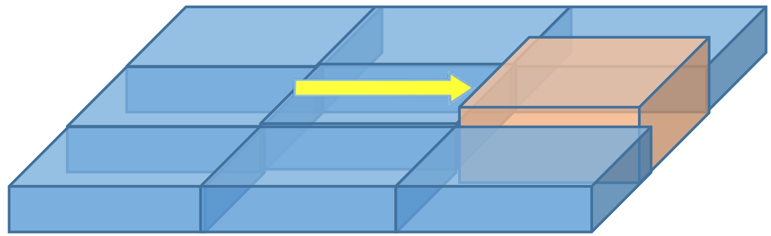
- For emission sources that are smaller than the footprint size, the minimum detectable mass or mass change depends on instrument precision (ΔX_{CO2} or ΔX_{CH4}) and footprint area, A.
- The minimum detectable flux change depends on precision, the effective wind speed at the emission level and the footprint's cross section in the direction of the prevailing winds.

$$F_{min} = 2 \cdot u \cdot \Delta M_{CO2}(\Delta XCO2_{min}) / L$$

- Detection limits increase with random error, footprint size, and wind speed



ΔM (1ppm X_{CO2}) = 0.016 kT/km^2

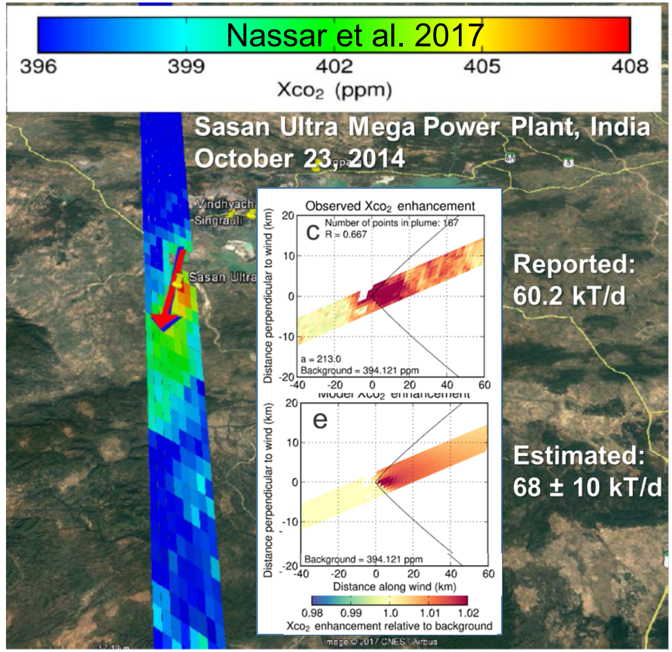


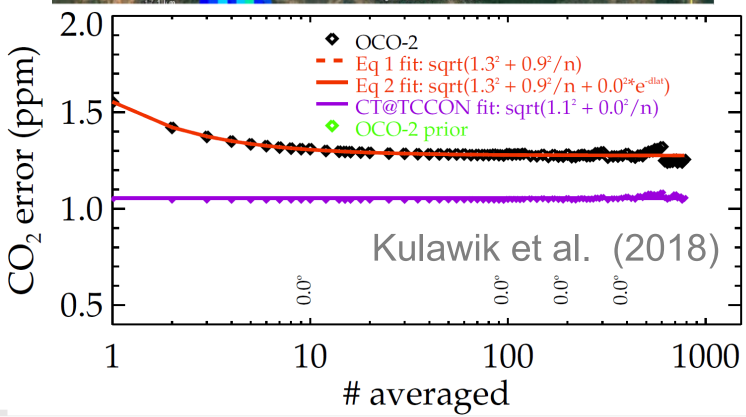
Flux ($MTCO_2$ /year) vs Footprint area and single sounding precision for a 5 km/hour wind

	DXCO2(ppm)				
Area (km^2)	0.25	0.5	1	2	4
1	0.341	0.683	1.37	2.7	5.47
2	0.483	0.966	1.93	3.86	7.73
4	0.685	1.37	2.7	5.47	10.9
10	1.08	2.16	4.33	8.66	17.3
50	2.41	4.83	9.66	19.3	38.6
85	3.14	6.29	12.6	25.1	50.4
1800	14.4	28.9	57.8	115	231

Emissions from Compact Sources: plume models

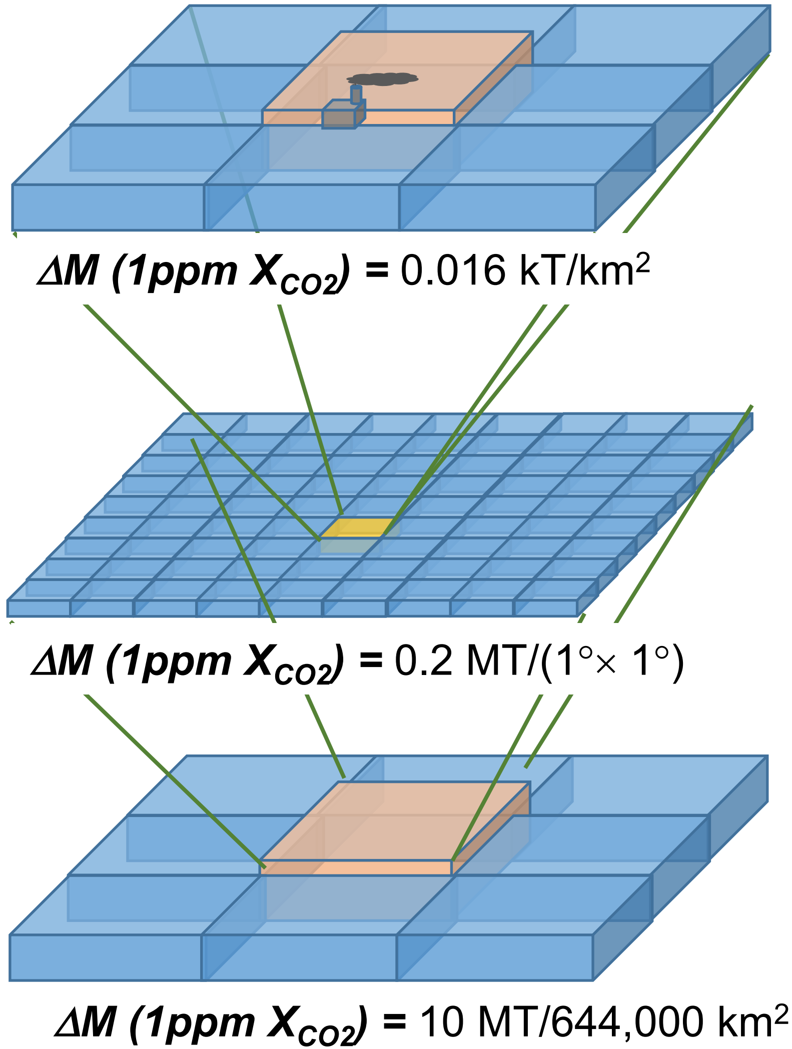
- The OCO-2 (0.5 ppm single sounding random errors) can clearly detect plumes that fall along its ground track
- Plume imaging methods can exploit information from multiple footprints to reduce uncertainties if
  - biases are not spatially correlated
  - footprints within the plume can be discriminated from the background
    - Proxies (NO_2, CO) help for CO_2 plumes
- Averaging typically reduces X_{CO2} anomaly uncertainties (and thus flux uncertainties) by less than a factor of 2
- Wind speed and X_{CO2} uncertainties contribute comparable flux uncertainties





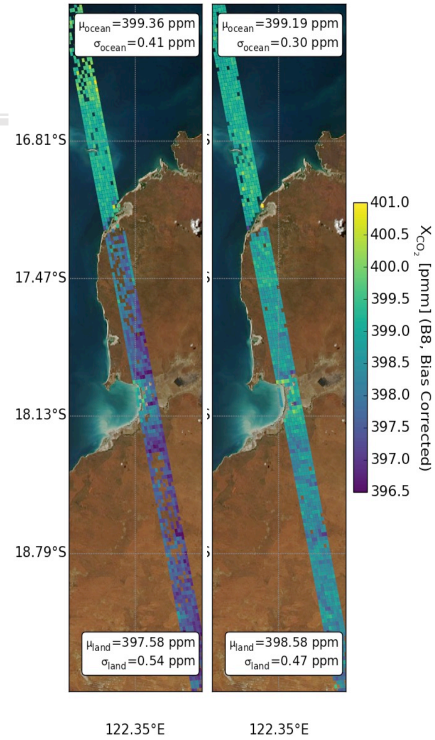
Low Bias Critical for Estimating Fluxes over Extended Areas – like Nations

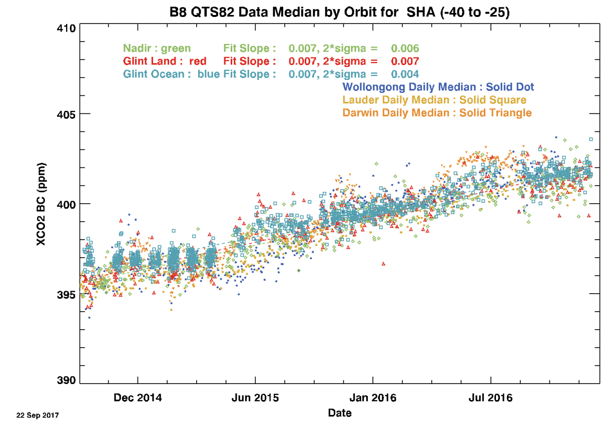
- Over large areas (> 10,000 km^2), random errors average out, but biases are more critical
  - A persistent, 1 ppm X_{CO2} bias between 2 adjacent 1°×1° latitude areas corresponds to a 0.2 Mt CO_2 error
  - A 1 ppm bias between two average-sized countries France, with an area of 643,801 km^2) grows to 10 Mt CO_2
- If our average-sized country is roughly equidimensional, and we assume a mean 10 m/sec wind over this area, this corresponds to a flux error of 3400 MtCO_2/year
  - This is about 10 times the annual fossil fuel CO_2 emissions from France
- Clearly, biases this large are unacceptable for informing fossil fuel inventories



Mitigating the Impact of Biases

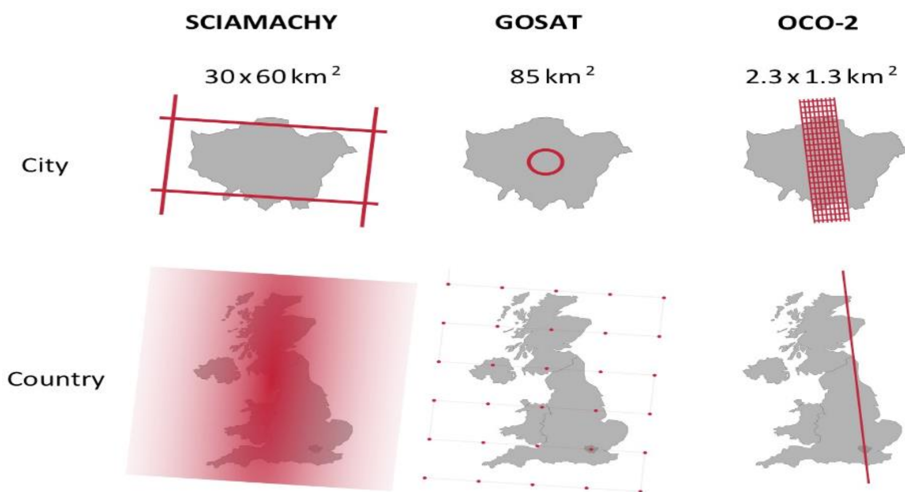
- Fortunately, only spatially and temporally coherent biases operating on the scale of interest can introduce flux errors as large as the one illustrated on the previous slide
  - Biases that are spatially and temporally invariant do not introduce large flux errors, because fluxes are proportional to the product of the anomaly amplitude and the wind, $F \propto u \times \Delta X_{CO2}$
  - Small scale biases often average out
- Some processes can introduce spatially coherent biases
  - surface pressure, air mass dependence, optically-thin clouds and/or aerosols, surface albedo, ...)
- Many of these processes can be identified and mitigated through a well designed calibration/validation program





Resolution and Coverage: Sampling Strategy

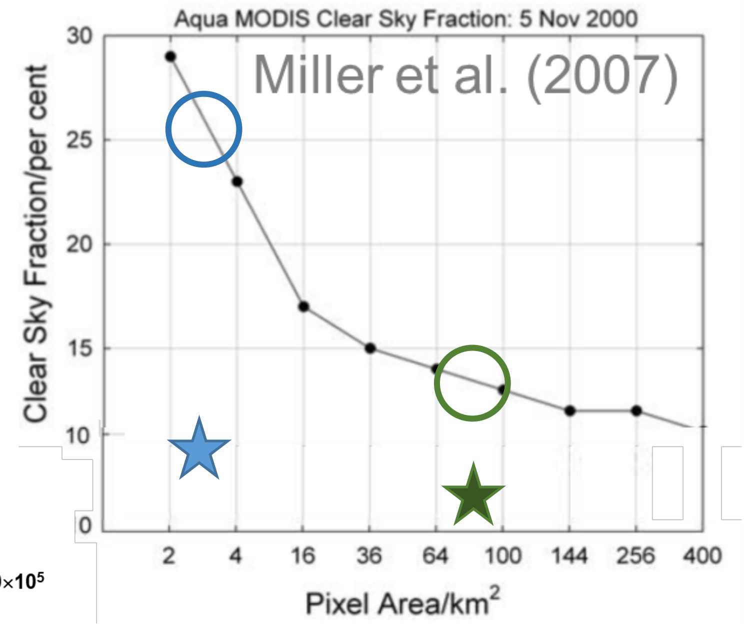
- The resolution and coverage of space based greenhouse gas observations is limited by the spatial sampling strategy adopted
  - The large (30 km x 60 km) footprints used by SCIAMACHY provided good coverage of the Earth, but most were contaminated by clouds or aerosols
  - Systems that collect spatially-isolated sample (GOSAT, Feng Yun 3D, Gaofen-5) cannot resolve localized emissions (plumes) as well as their background
  - Continuous "stripes" like those collected by OCO-2, TanSat, and MicroCarb provide high spatial resolution along a narrow track but there are large distances between sample tracks

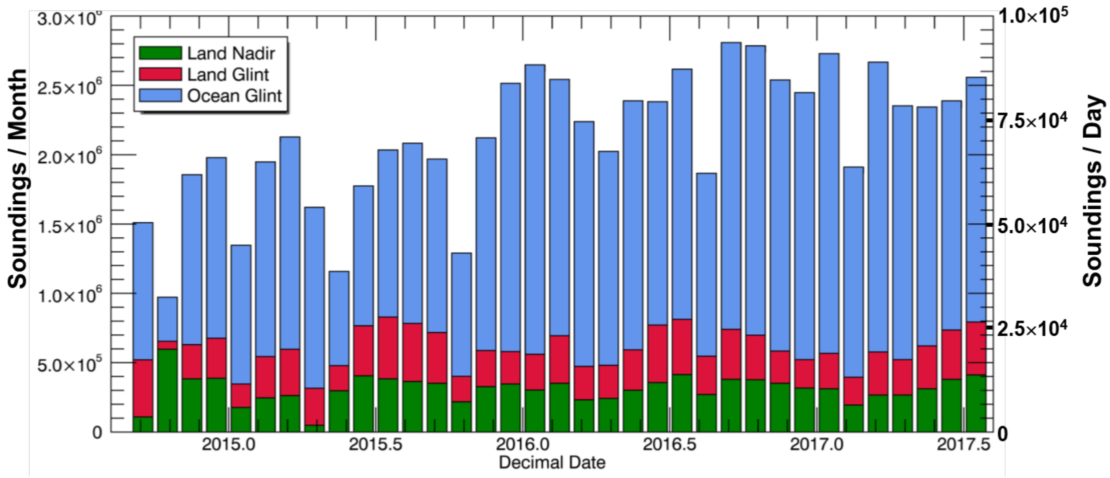


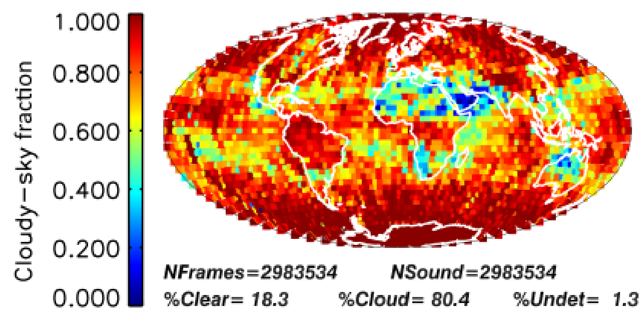
  - Systems that cannot observe the glint spot over the full range of latitudes cannot collect observations over the oceans, which cover 70% of the surface of the Earth
  - Passive solar systems can only collect observations while the sun is up

Resolution and Coverage: Clouds!

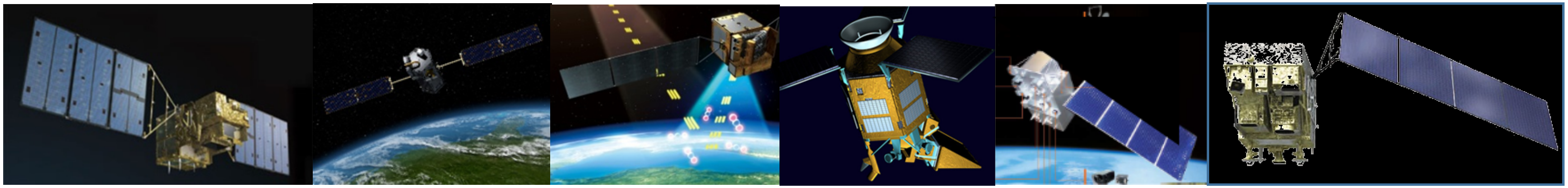
- Early in the evolution of the OCO and GOSAT missions, optically thick clouds were identified as significant limitation on coverage
- Based on MODIS cloud studies, a small footprint was adopted for OCO (and OCO-2) to mitigate this issue



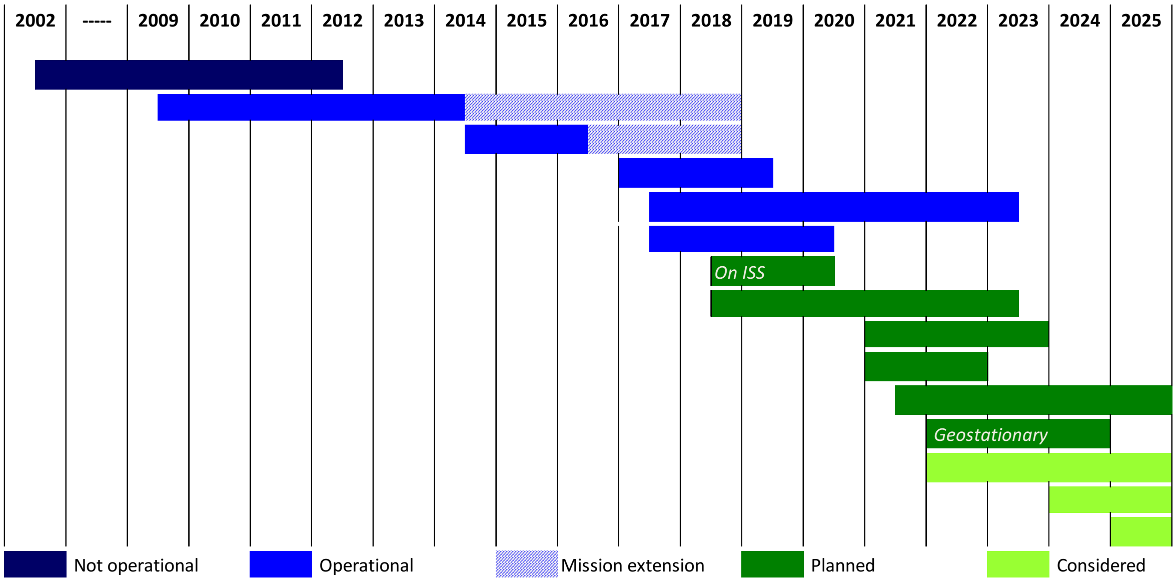




Improving Resolution and Coverage: Combining Data from the Emerging Fleet



Satellite, Instrument (Agencies)	CO_2	CH_4	Swath	Sample
ENVISAT SCIAMACHY (ESA)	●	●	960 km	30x60 km^2
GOSAT TANSO-FTS (JAXA-NIES-MOE)	●	●	3 pts	10.5 km (d)
OCO-2 (NASA)	●		10.6 km	1.3x2.3 km^2
TanSAT (CAS-MOST-CMA)	●		20 km	1x2 km^2
Sentinel 5P TROPOMI (ESA)		●	2600 km	7x7 km^2
Feng Yun 3D GAS (CMA)	●	●		10 km (d)
OCO-3 (NASA)	●		11 km	~4 km^2
GOSAT-2 TANSO-FTS (JAXA-MOE-NIES)	●	●	5 pts	10.5 km (d)
MERLIN (DLR-CNES)		●	100 m	0.14 km (w)
MicroCarb (CNES)	●		13.5 km	40 km^2
MetOp Sentinel-5 series (Copernicus)		●	2670 km	7x7 km^2
GEOCARB (NASA)	●	●		4x4 km^2
Feng Yun 3G (CMA)	●	●		1x1 km^2
GOSAT-3 (JAXA-MOE-NIES)	●	●		
CO2 Monitoring series (Copernicus)	●	●		2x2 km^2



- A broad range of GHG missions will be flown over the next decade.
- We could improve resolution and coverage by combining their results

Improving Resolution and Coverage: Dedicated Greenhouse Gas Constellations

- The coverage, resolution, and precision requirements could be achieved with a constellation that incorporates
  - A constellation of 3 (or more) satellites in **LEO** with
    - A broad (> 200) km swath
    - A small mean footprint size < 4 km^2
    - A single sounding random error near 0.5 ppm and vanishingly small regional scale bias (< 0.1 ppm) over > 80% of the sunlit hemisphere
    - One (or more) satellites carrying ancillary sensors (CO, NO_2, CO_2 and/or CH_4 Lidar)
  - A constellation with 3 (or more) satellites in **GEO** to monitor diurnally varying processes (e.g. diurnal variations in the biosphere, diurnal changes in anthropogenic emissions, SIF)
    - Stationed over Europe/Africa, North/South America, and East Asia
- This constellation could be augmented with one or more **HEO** satellites to monitor carbon cycle changes in the high arctic

Tools Needed to Meet New Requirements

- Sensors with improved precision, spatial resolution, and coverage
  - Improved instrument calibration accuracy and stability
  - Add hoc constellation consisting of the satellites in the “program of record”
  - Dedicated LEO and Geo GHG constellations
- Improved remote sensing retrieval algorithms
  - More accurate description of gas absorption and aerosol scattering
  - Optimized to more fully exploit the information content of solar GHG spectra
- More comprehensive and accurate validation standards
  - Expand and improve ground based in situ, TCCON, AirCore/Aircraft
- Improved atmospheric inversion models
  - Higher spatial resolution
  - More accurate description of both horizontal and vertical transport
  - More complete assimilation of ground-based, aircraft, and space based data
  - Methods to validate estimated fluxes on local, national, and regional scales