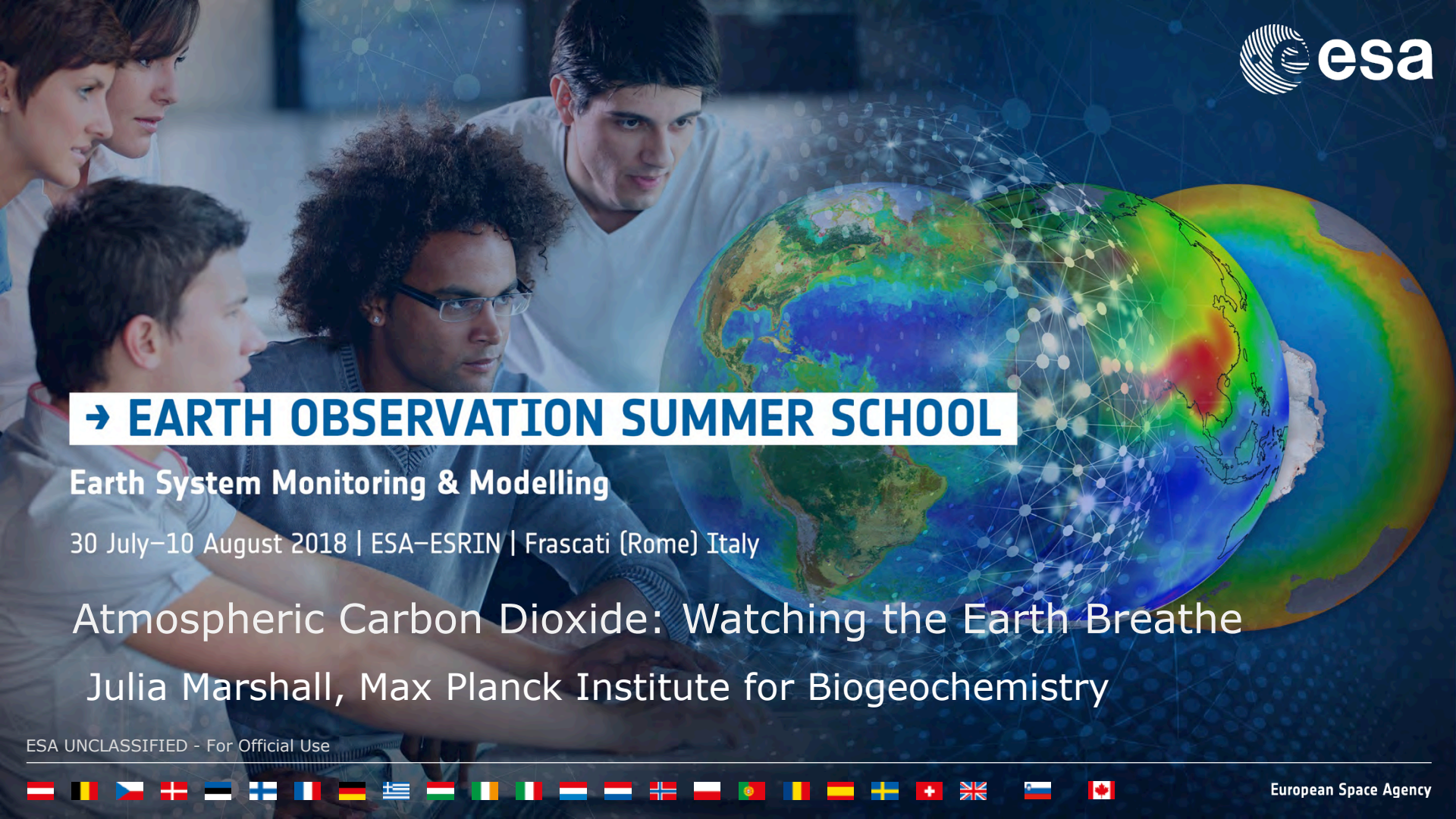


→ EARTH OBSERVATION SUMMER SCHOOL

Earth System Monitoring & Modelling

30 July–10 August 2018 | ESA–ESRIN | Frascati (Rome) Italy

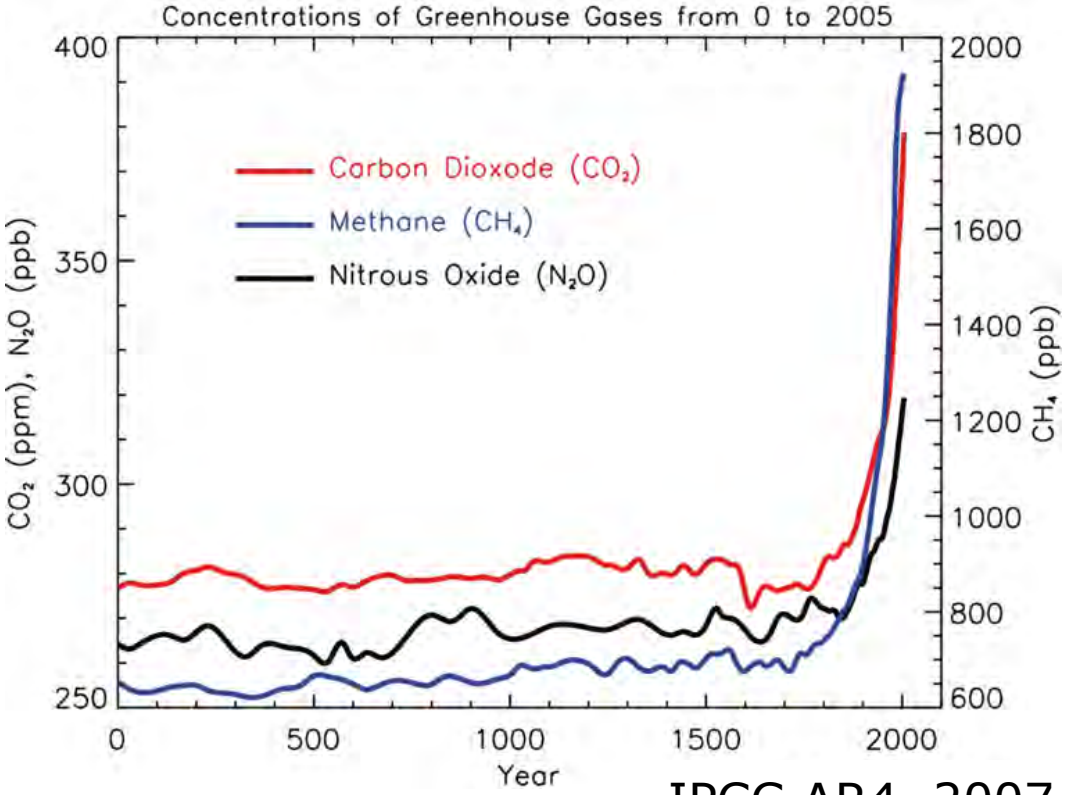
Atmospheric Carbon Dioxide: Watching the Earth Breathe

Julia Marshall, Max Planck Institute for Biogeochemistry

About me

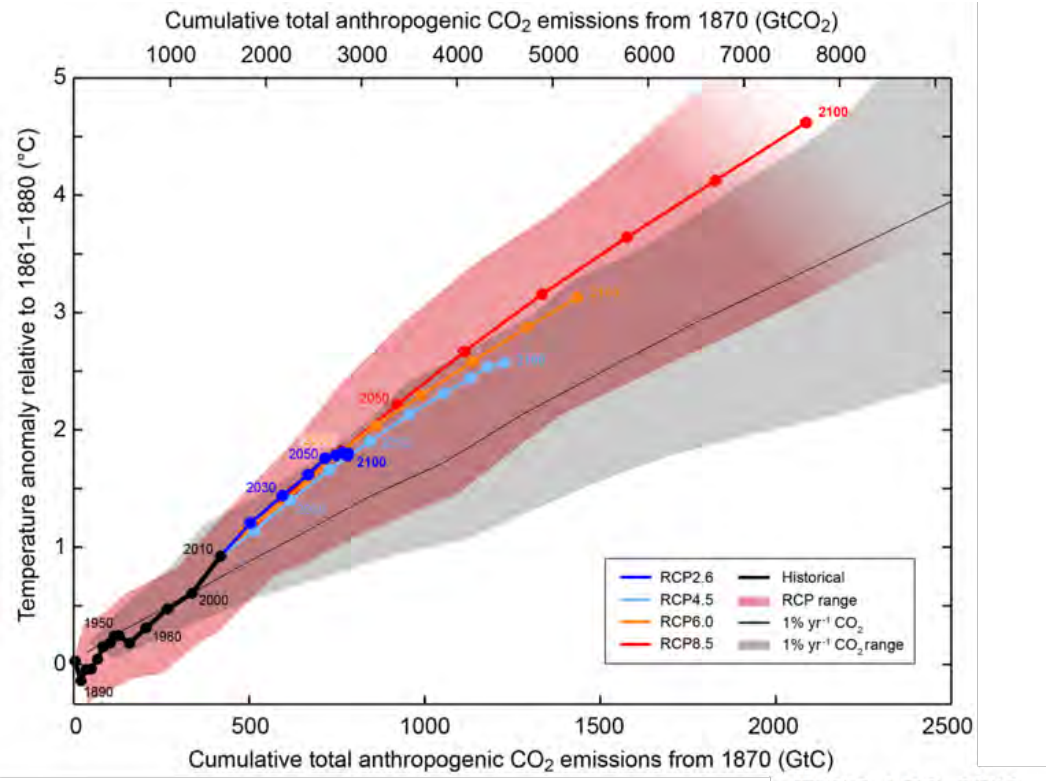
- Group leader at Max Planck Institute for Biogeochemistry
- Originally from Canada
- Did my PhD there on the optical properties of aerosol particles, including both field measurements and modelling
- Moved into modelling after that
- Moved to Germany in 2007 for a two-year postdoc in inverse modelling of greenhouse gases
- …I didn't leave
- Slowly moved into field of remote sensing on a project-related basis at first
- Have two kids

Why do we care about carbon dioxide?



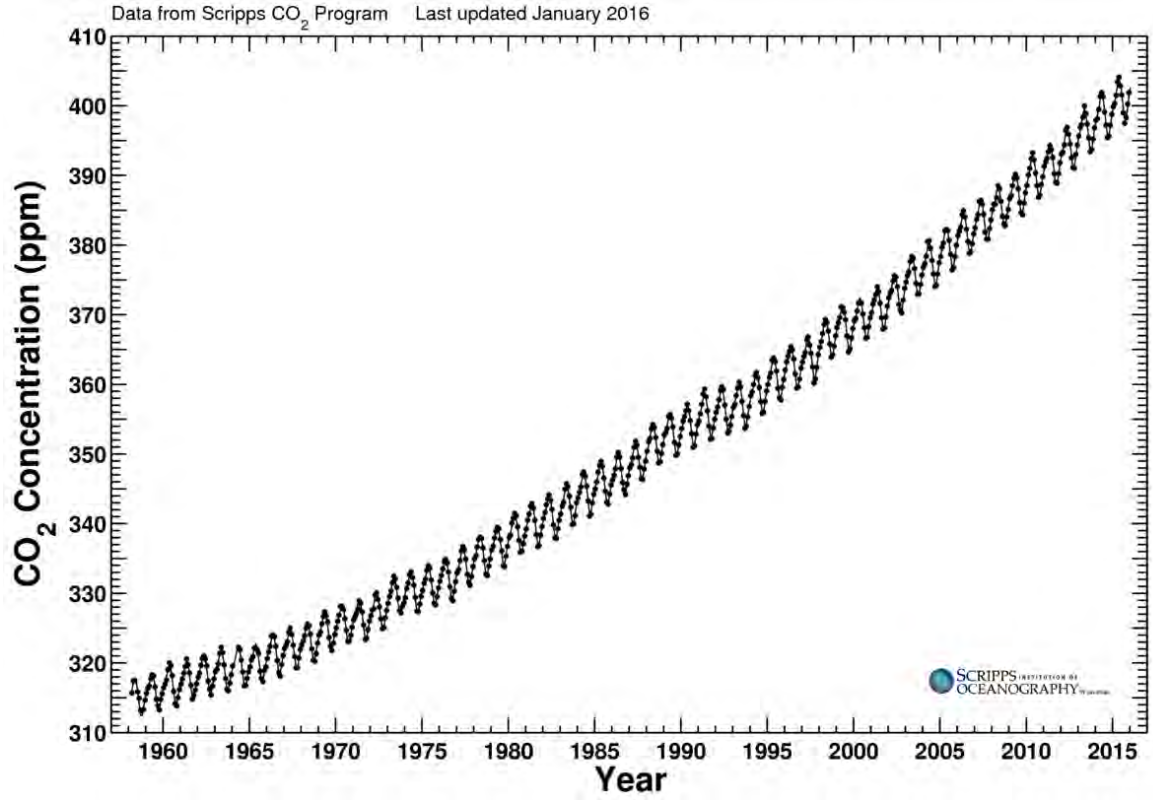
IPCC AR4, 2007

Why do we care about carbon dioxide?

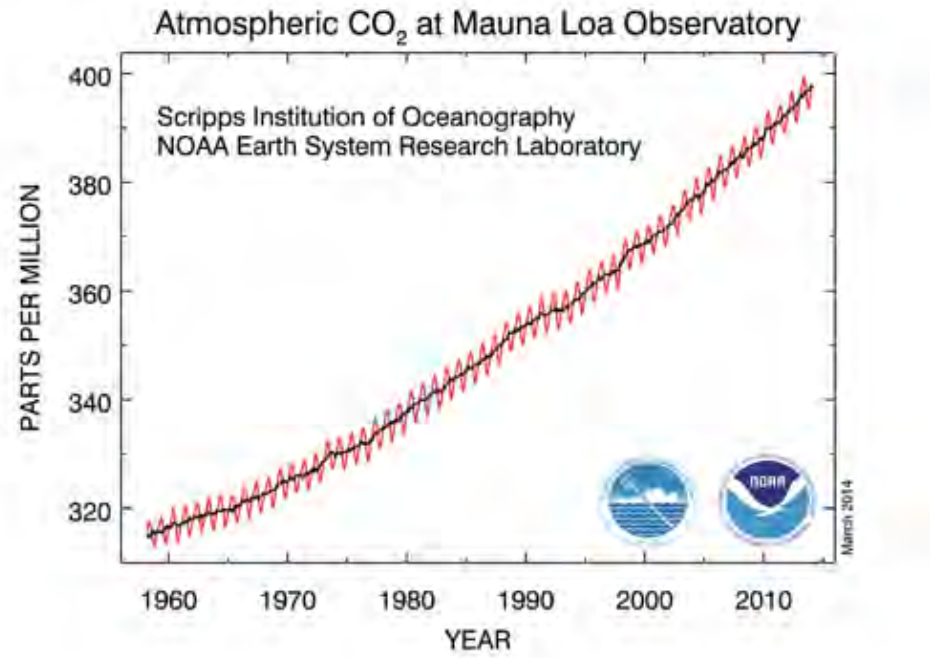


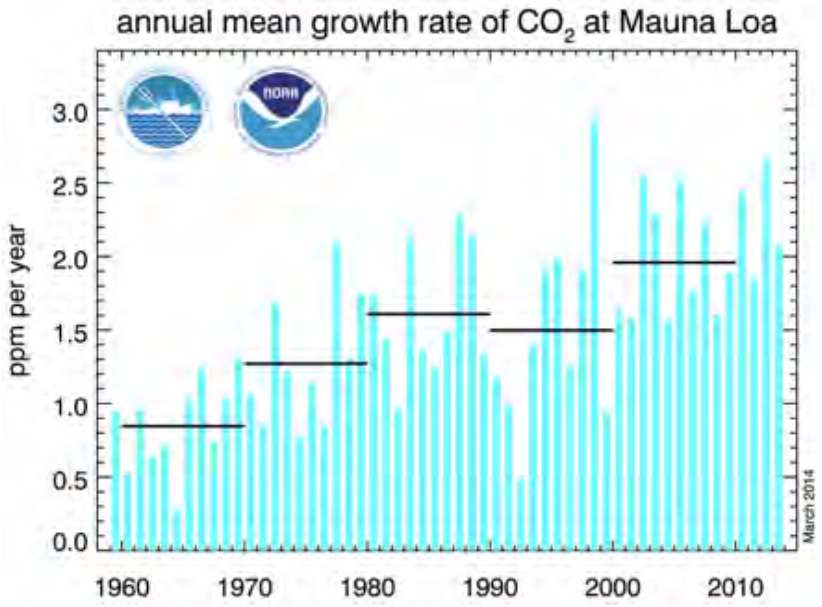
IPCC AR5, 2013

The view from Mauna Loa

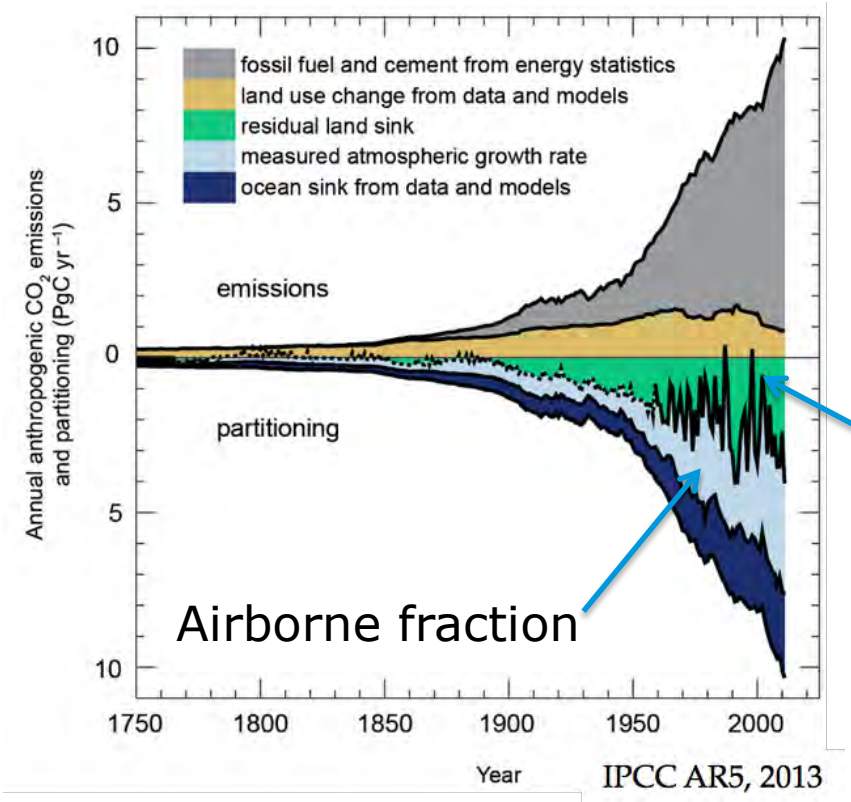


Interannual variability in the growth rate

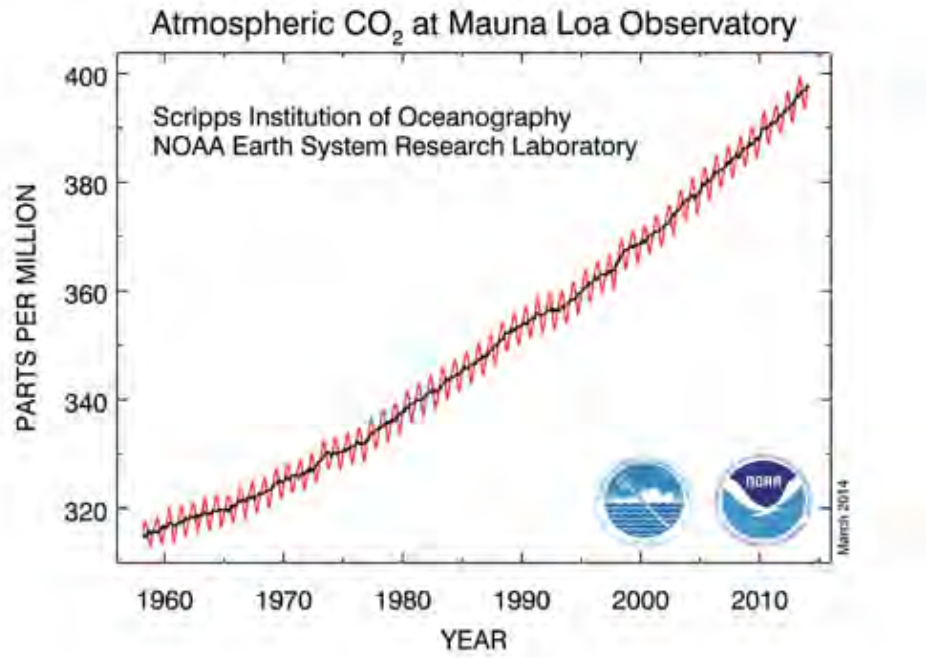


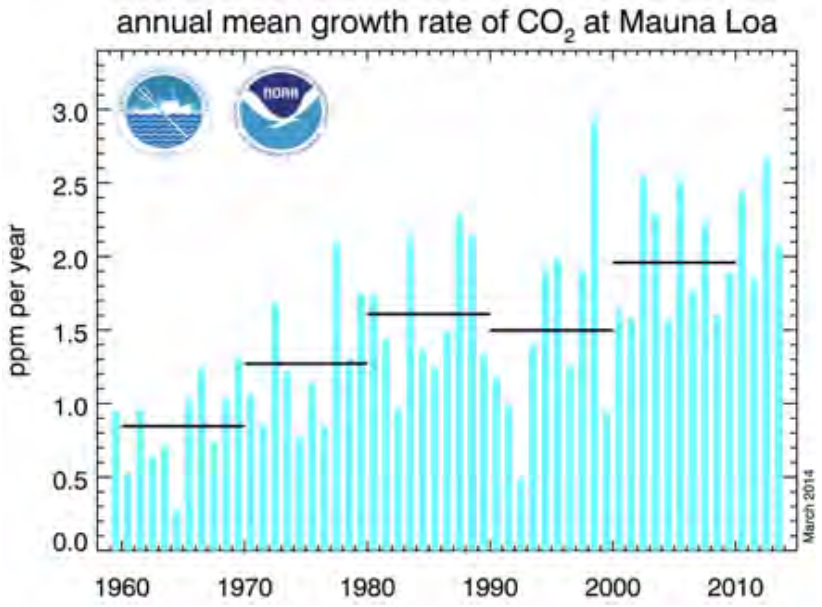


The airborne fraction in the global carbon budget

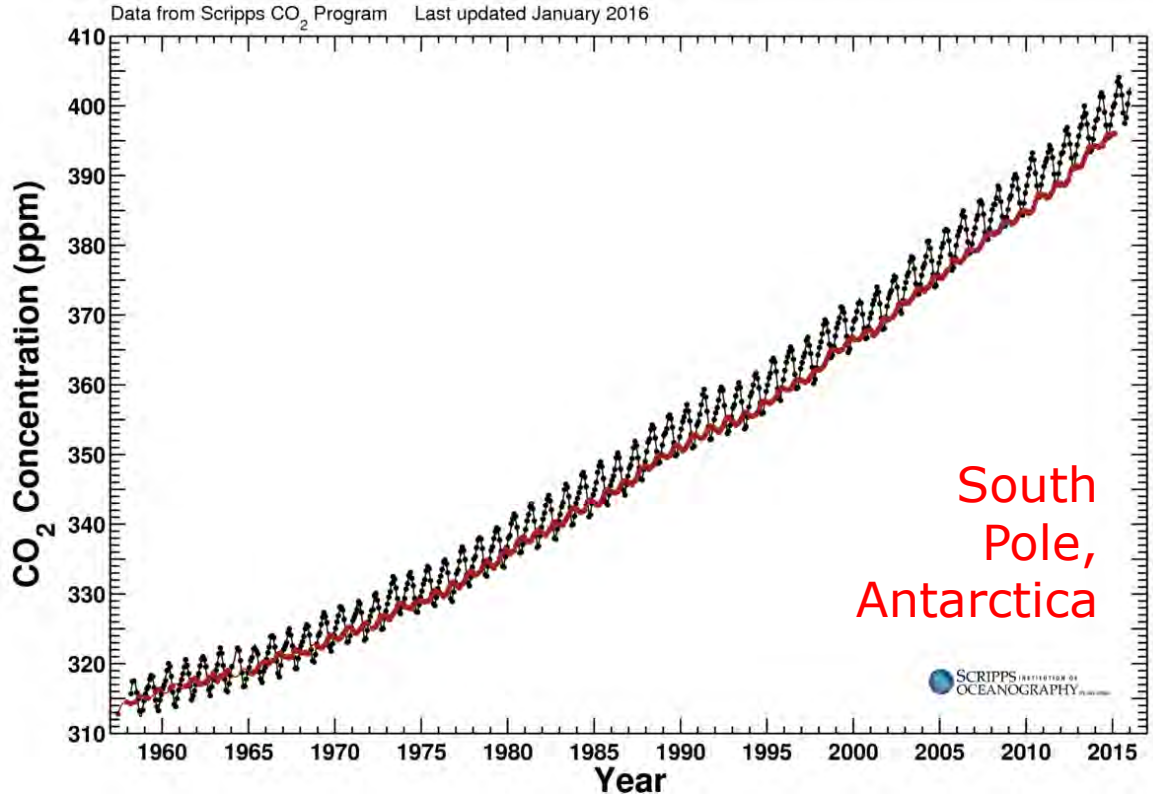


We know this already just from Mauna Loa!





The view from Mauna Loa & the South Pole



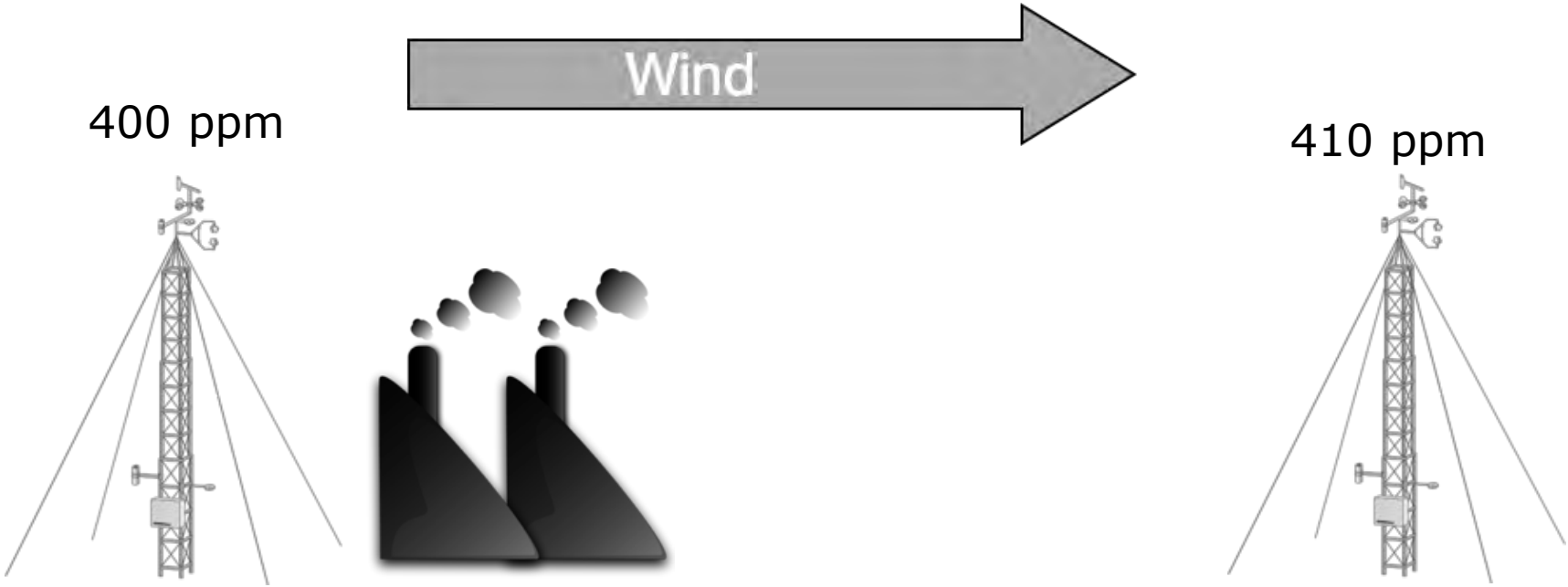
Scientific questions

What are the main feedback processes between the carbon cycle and the climate system?

What is the carbon budget of a specific region?

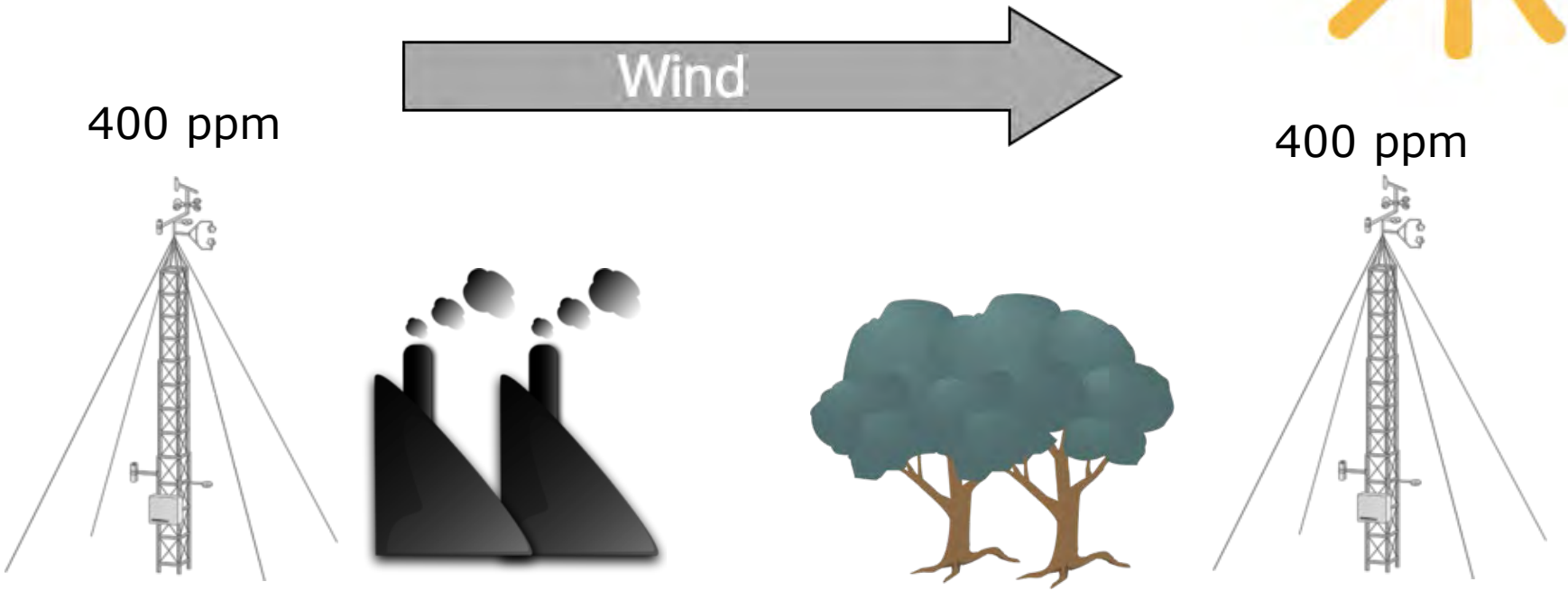
Where, and by which processes, is carbon taken up and released?

Enter inverse modelling



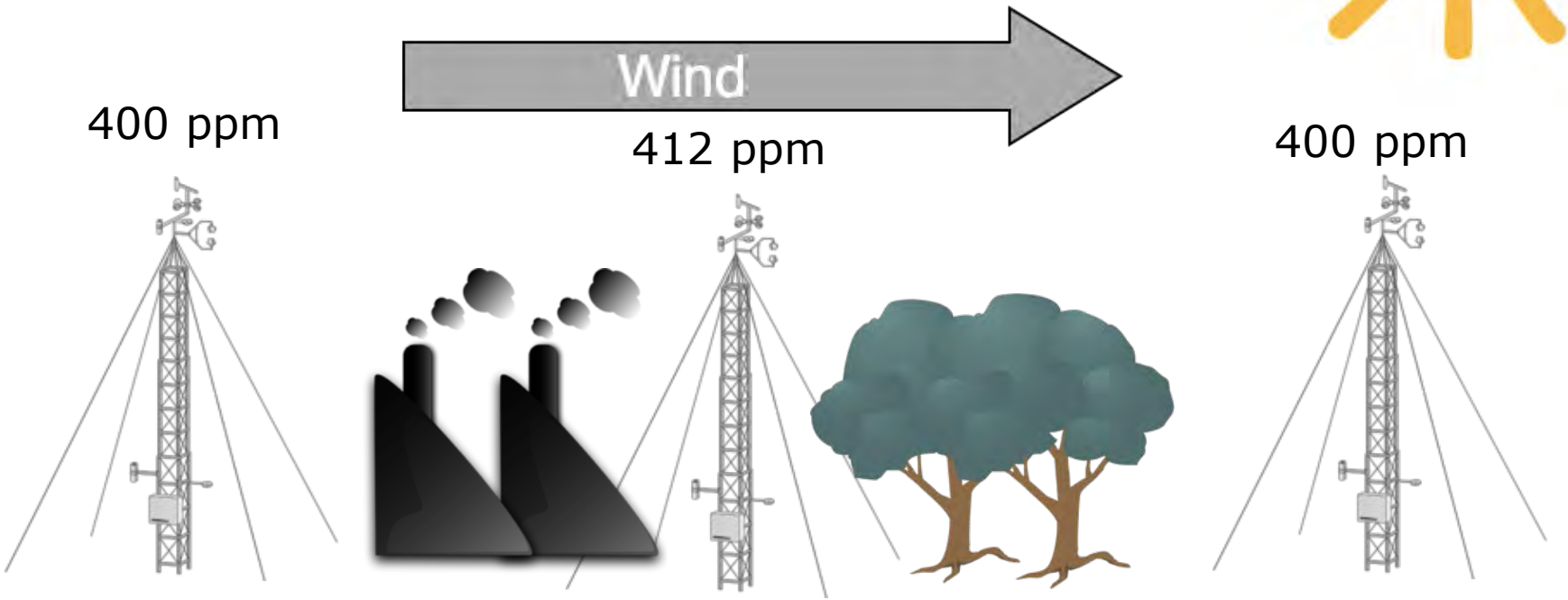
Knowing the wind speed, plus a bit about the dispersion, we can estimate emissions.

Enter inverse modelling



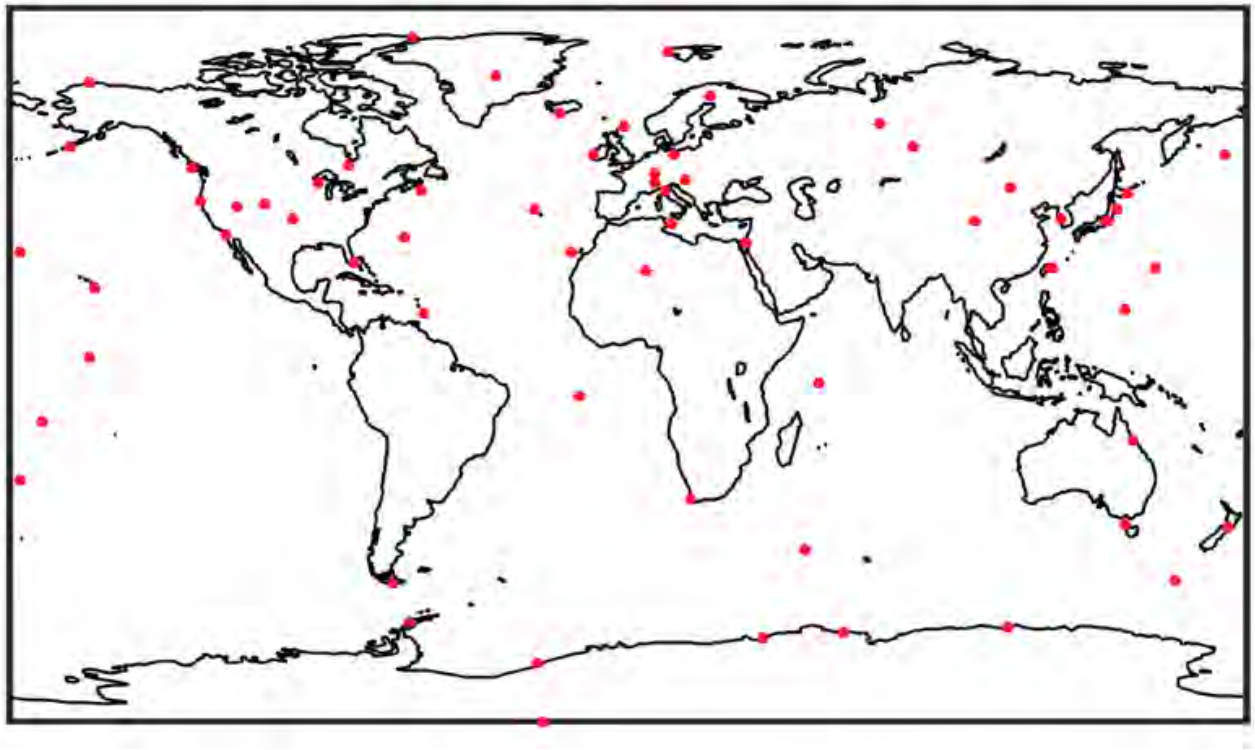
Hmm, now we have a problem...

Enter inverse modelling

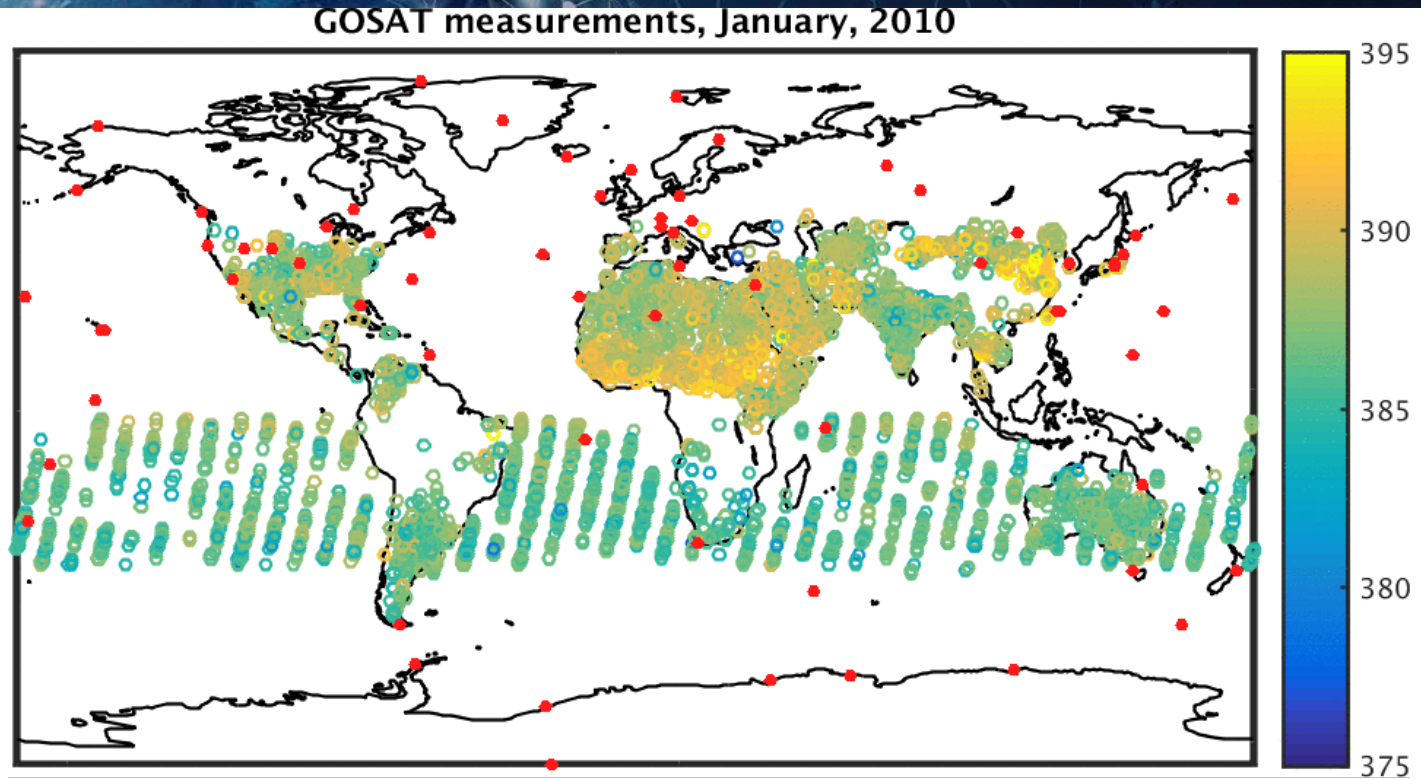


Measurement density really matters!

Current observational constraints (surface)

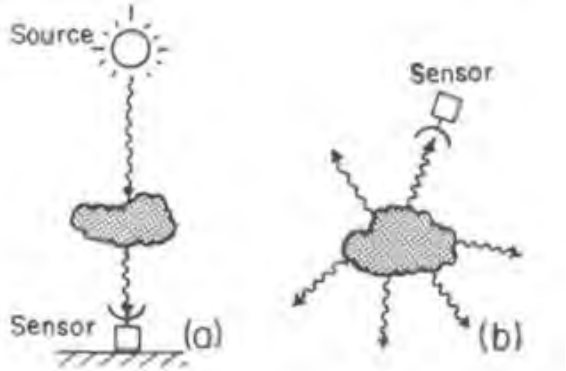


Current observational constraints (surface + GOSAT)



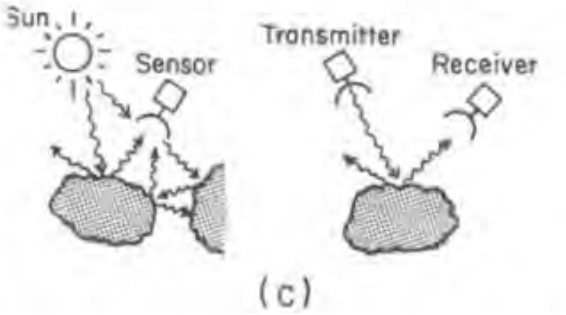
So how are these satellites working anyhow?

Ground-based passive remote sensing (TCCON, NDACC)



Space-based passive remote thermal emission sensing (IASI, AIRS, TES)

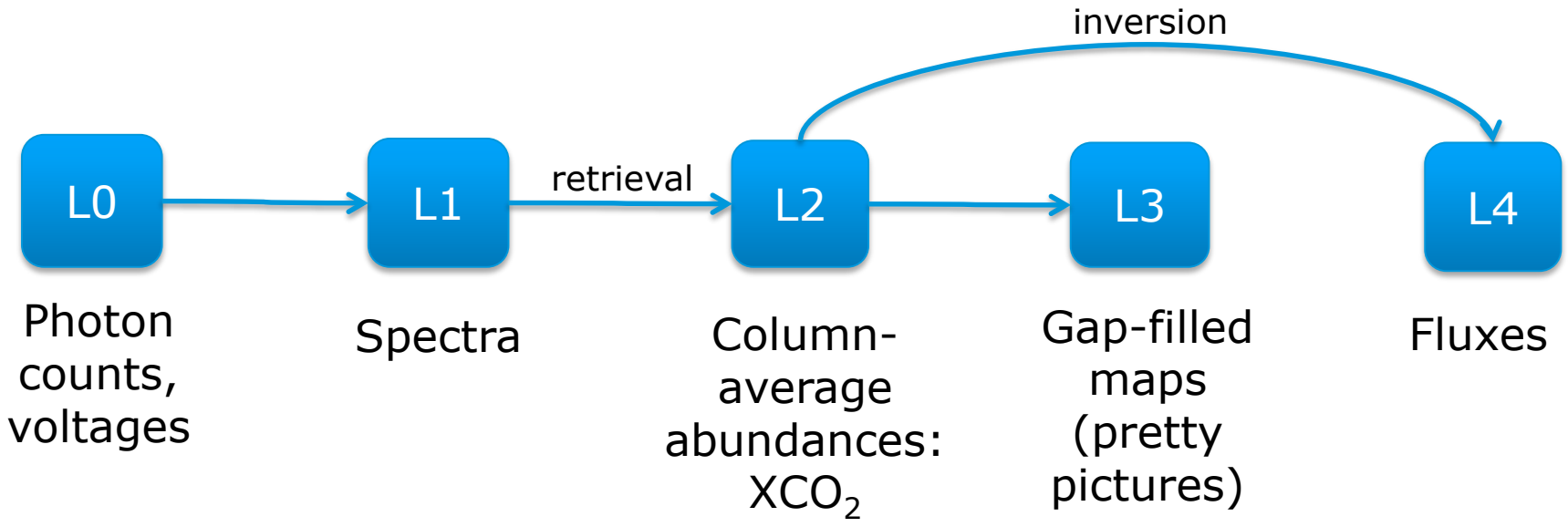
Passive remote sensing, scattering (SCIAMACHY, GOSAT, OCO-2, Sentinel-5P…)



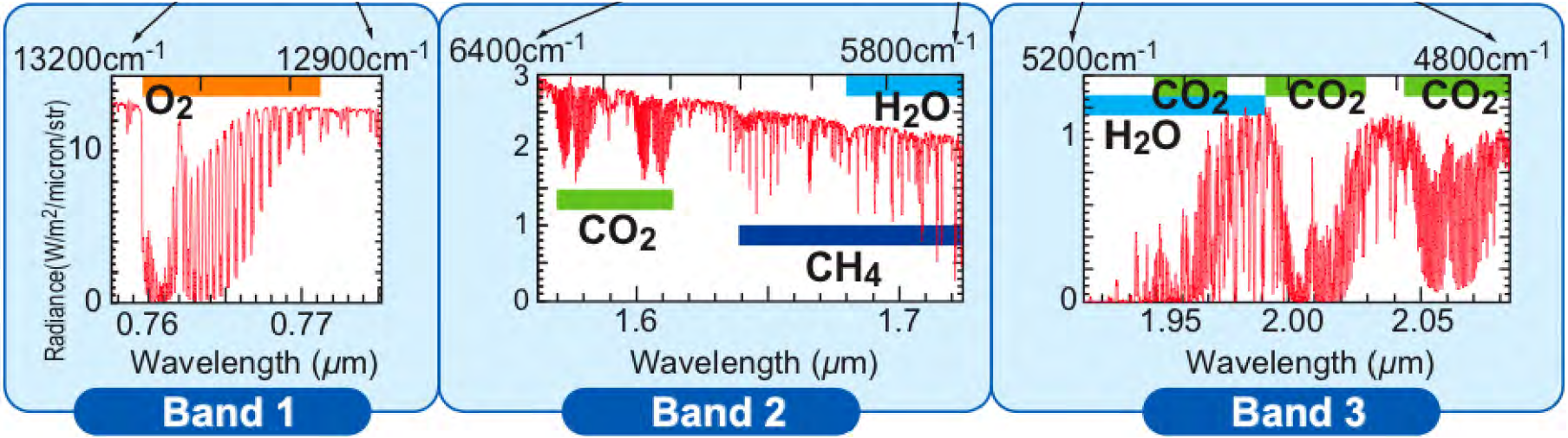
Active remote sensing, scattering ((MERLIN, ASCENDS))

from Stephens

Nomenclature for data processing



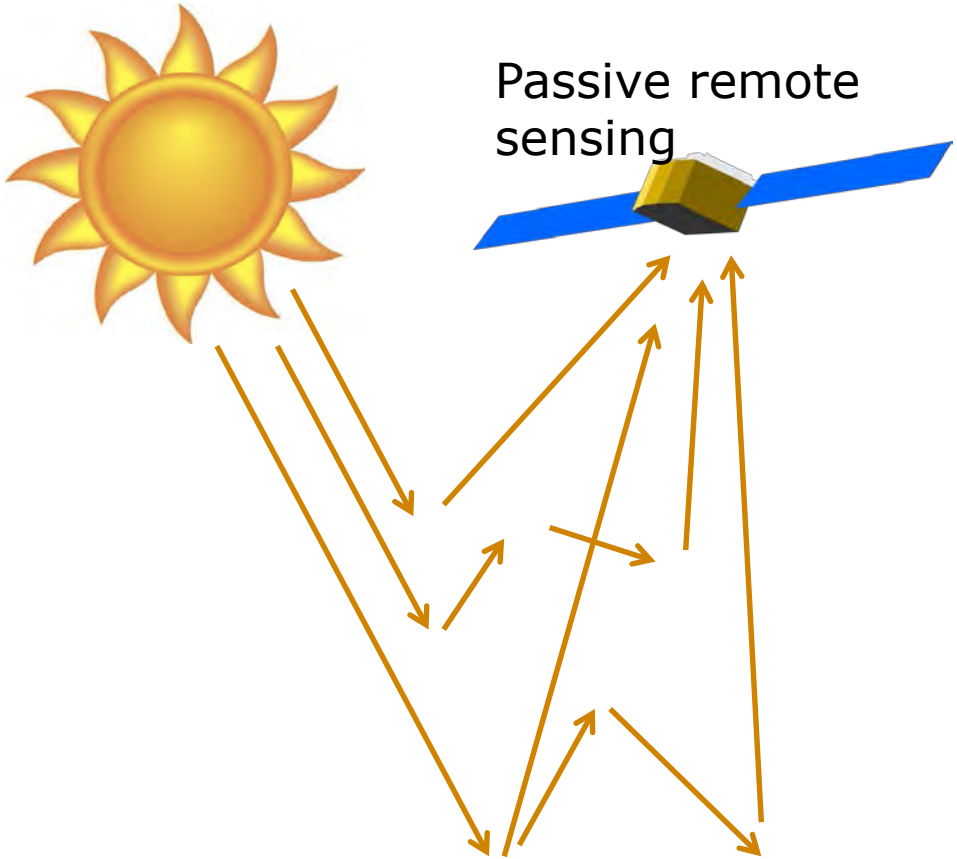
Measurement concept (from GOSAT)



- high-resolution measurement of CO2 at 1.6 and 2.0 μm and oxygen at ~0.76 μm
- this information combined gives a broadband characterization of aerosol

How retrievals work

- A form of optimal estimation
- Using a radiative transfer model (the forward model)
- Start with a prior estimate of the atmospheric state
- Create spectra expected based on this state
- Adjust the atmospheric concentration (and other elements of the state function) until the difference between the measured spectrum and the modelled spectrum (the residuals) are minimized

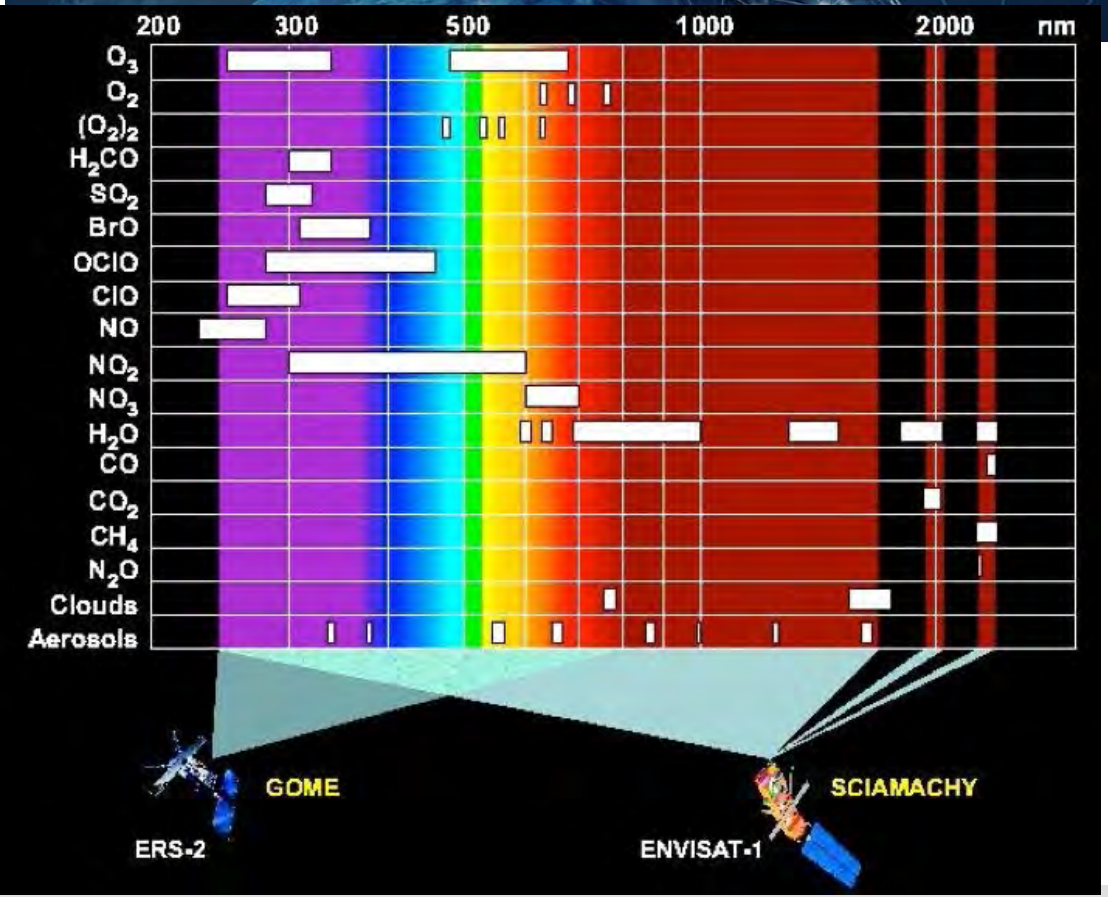


Aerosols (and cirrus) are the single biggest source of error, due to path length uncertainties

Starting with SCIAMACHY

- SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
- Launched on ENVISAT in 2002
- Operated until 2012
- Had relatively large ground-pixels (~30 km x 60 km at nadir) and a broad swath (~1000 km)
- Could measure a lot of species, but first time greenhouse gases CO2 and CH4 were attempted from space

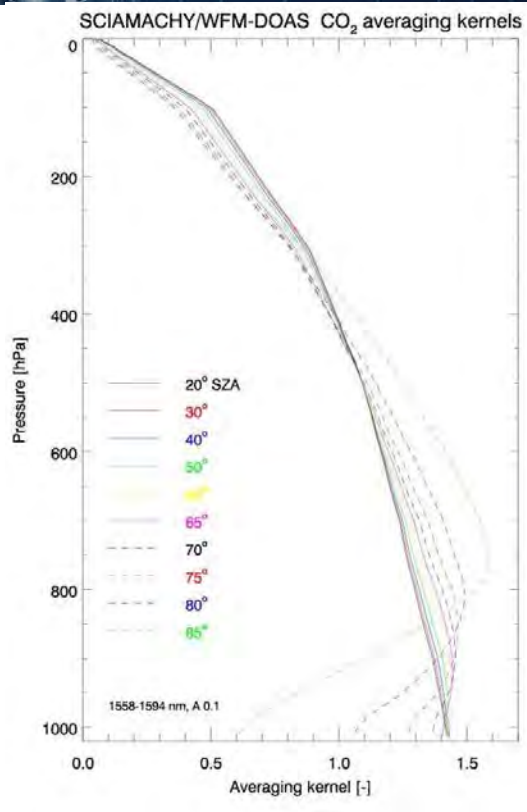
Starting with SCIAMACHY

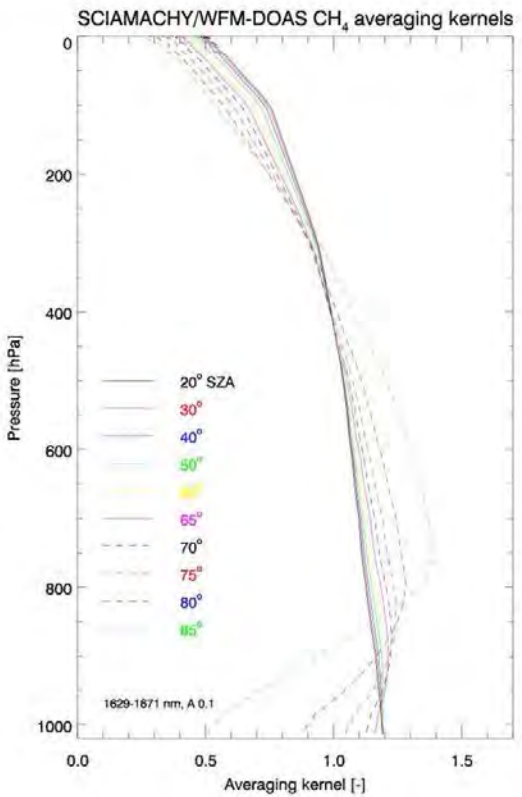


www.iup.uni-bremen.de/sciamachy/

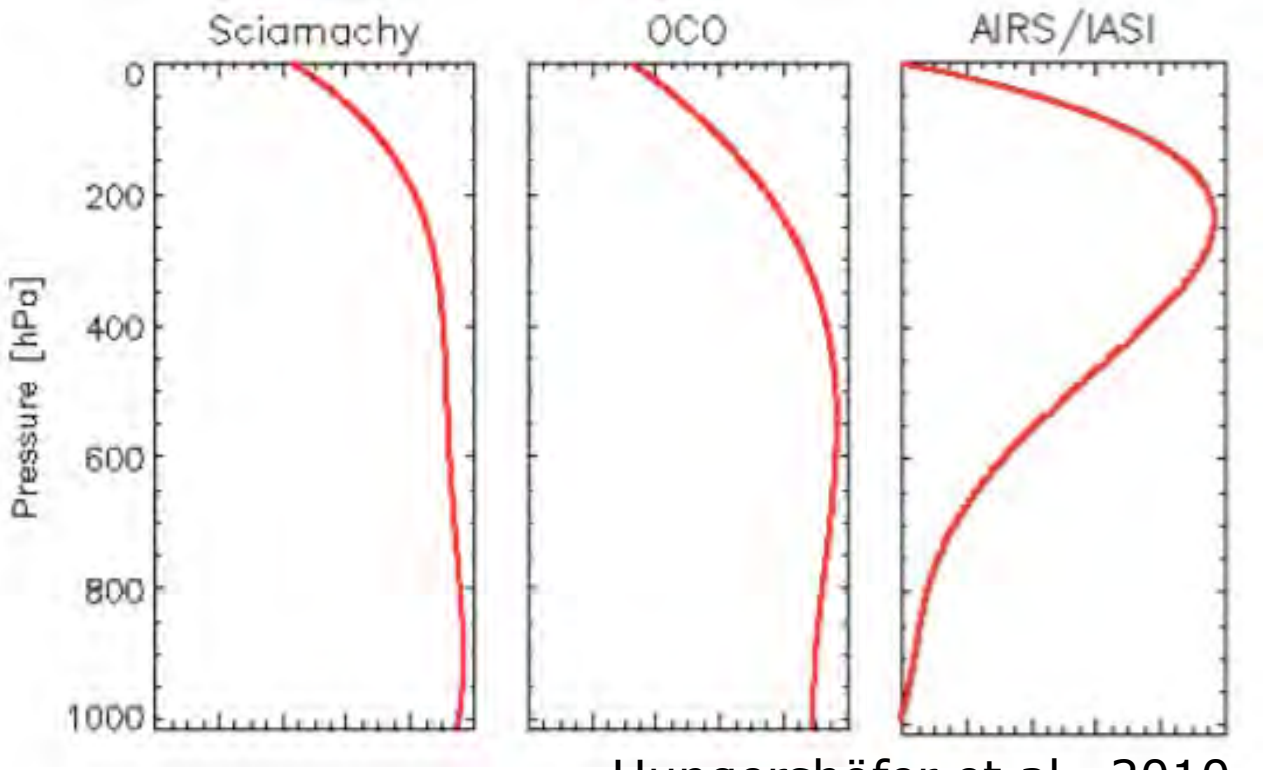
Relatively flat averaging kernel

- Provides relatively good sensitivity in the lower atmosphere
- Fluxes are at the surface, so this is the area we want to see
- Higher up things are more difficult to interpret, and more prone to transport errors



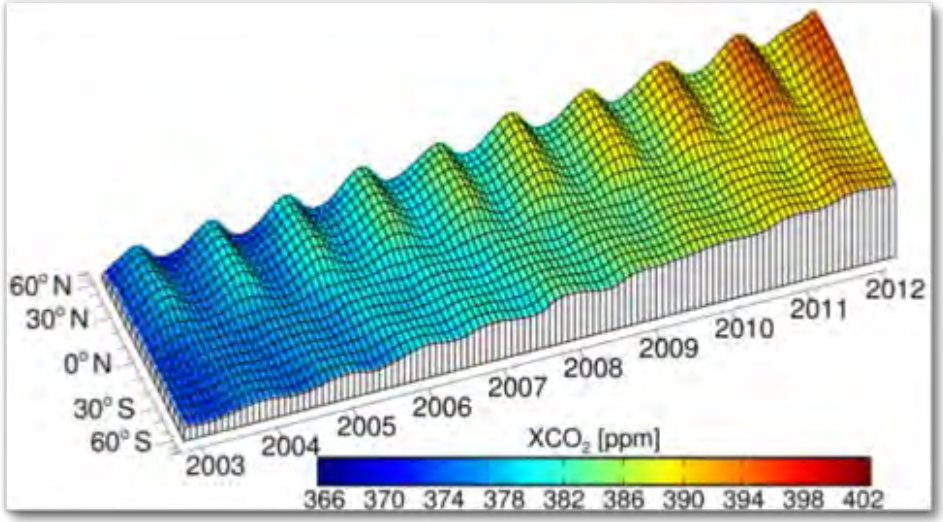


Compare to thermal infrared sensors:

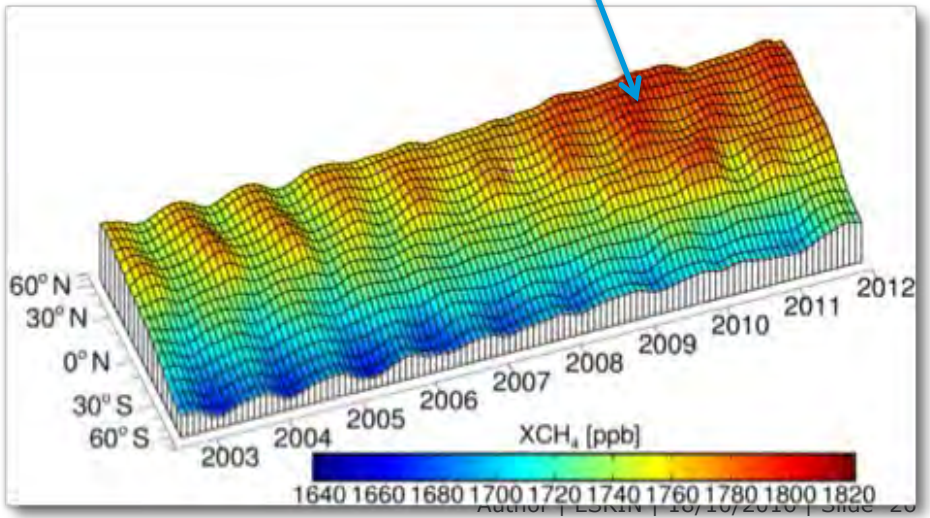


Hungershöfer et al., 2010

Provided a decade of space-borne data

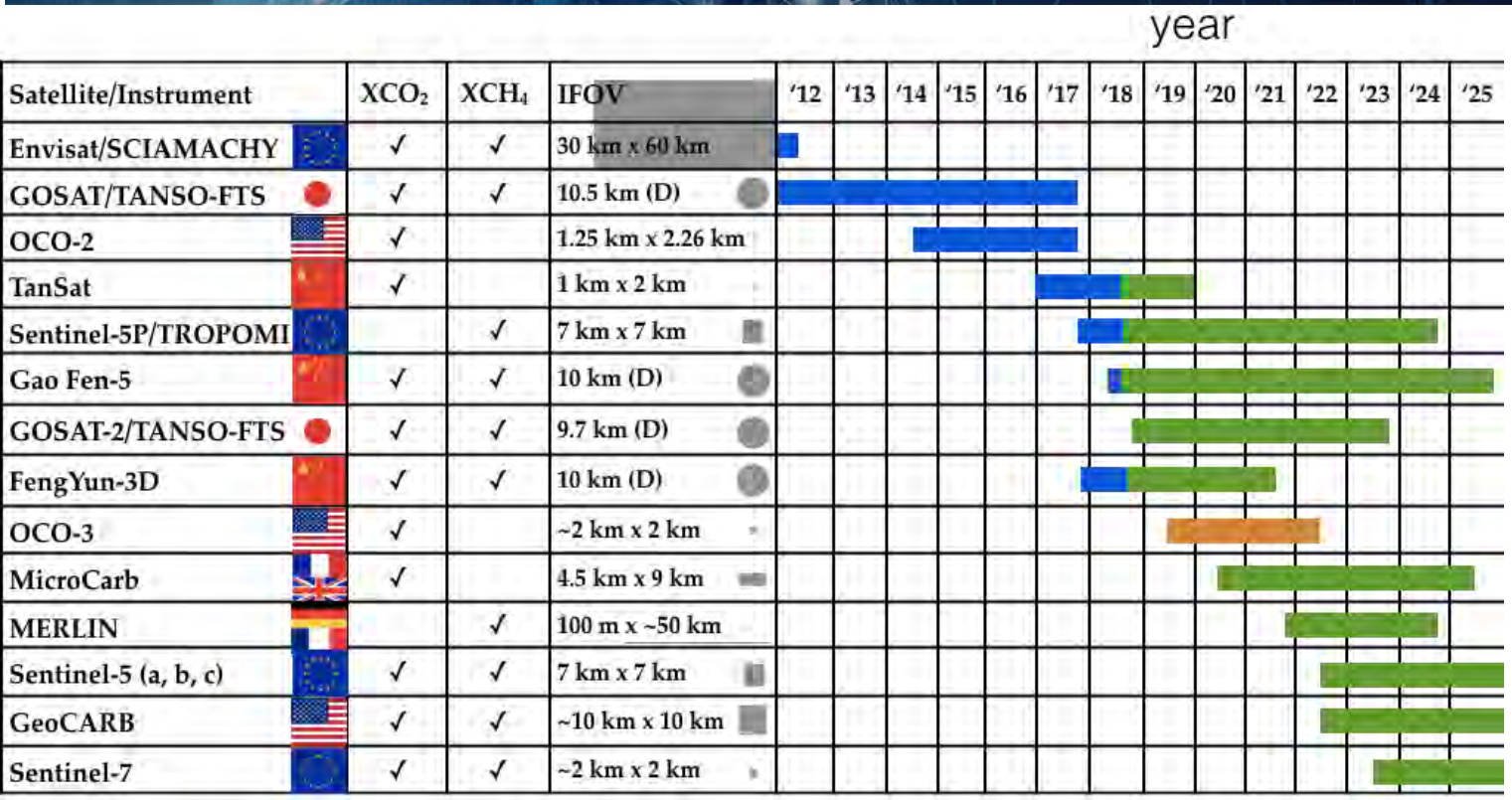


Sensor degradation



www.esa-ghg-cci.org

SCIAMACHY was just the beginning!



operating

planned

planned/less certain

A note about footprint size

SCIAMACHY: 30 km x 60 km pixel,
1000 km swath

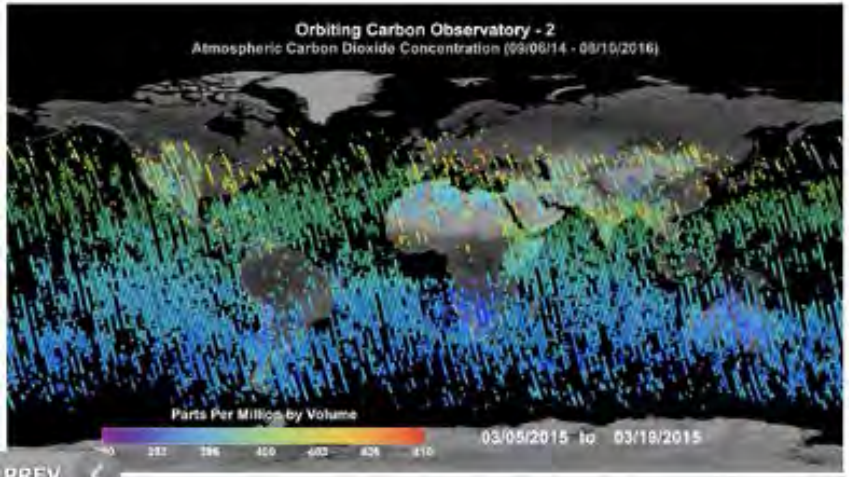
OCO-2: 1 km x 1.5 km,
8-km swath

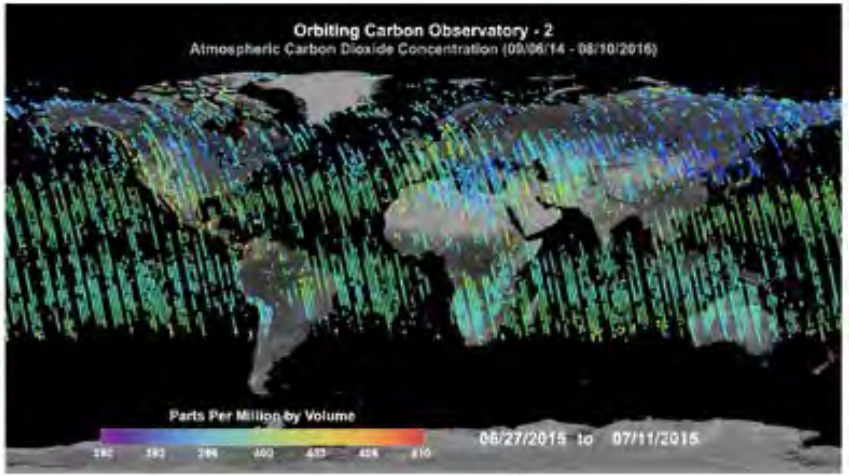
GOSAT:
10.5 km

TROPOMI:
7kmx7km,
2600 km
swath, S5P

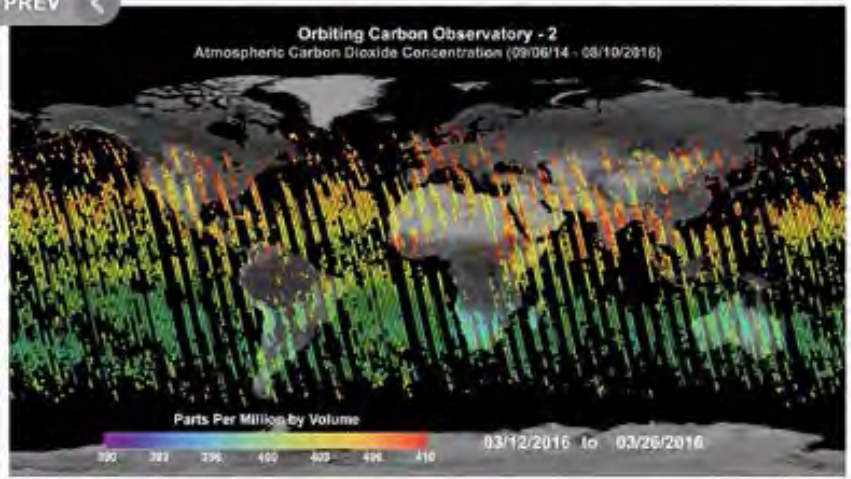
S7C: 2 km x 2 km pixel, 200 km?
swath

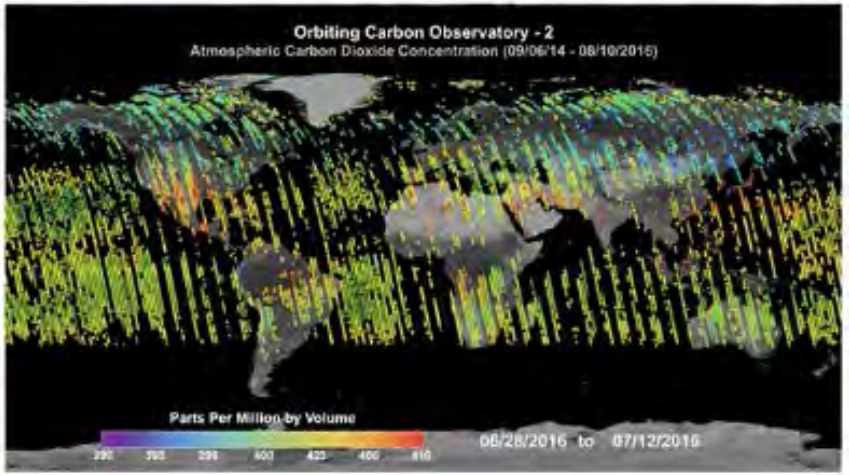
Measurements from OCO-2



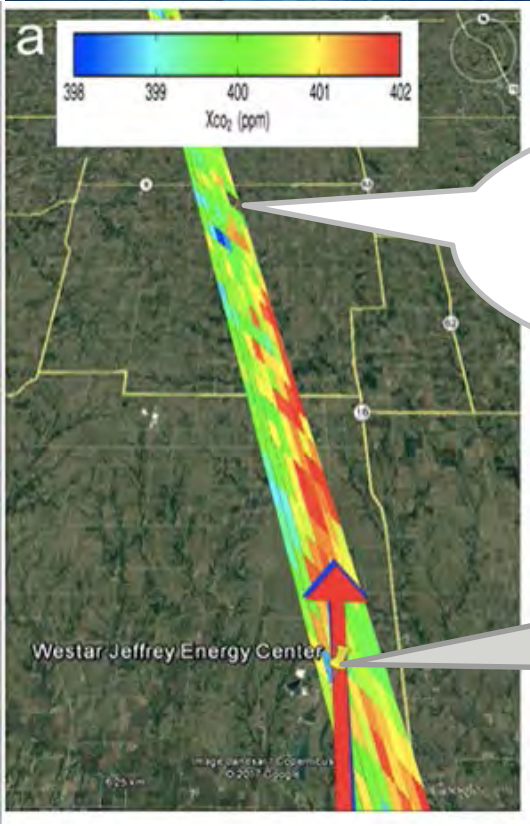


PREV





What this looks like at higher resolution

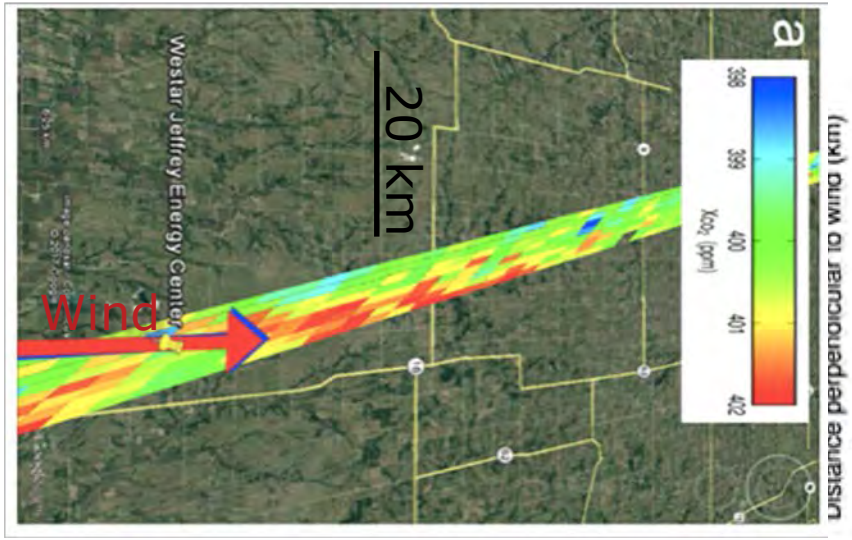


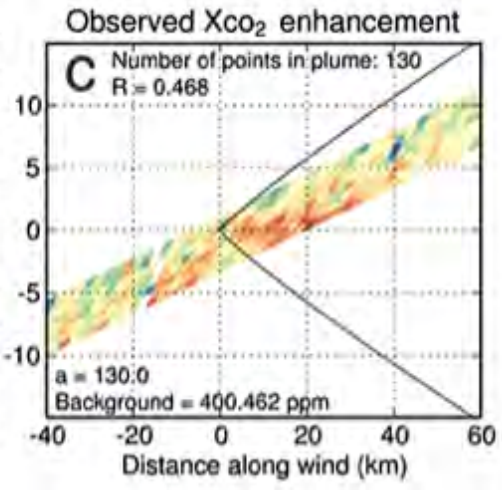
8-km wide swath of total column CO_2 measurements

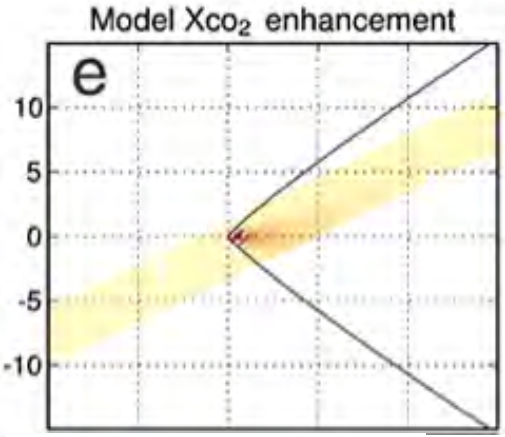
Location of the Westar Jeffrey Energy Center (power plant)

Nassar et al., 2017

Fit to a simple plume model:
1-17% agreement with reported emissions for five power plants worldwide





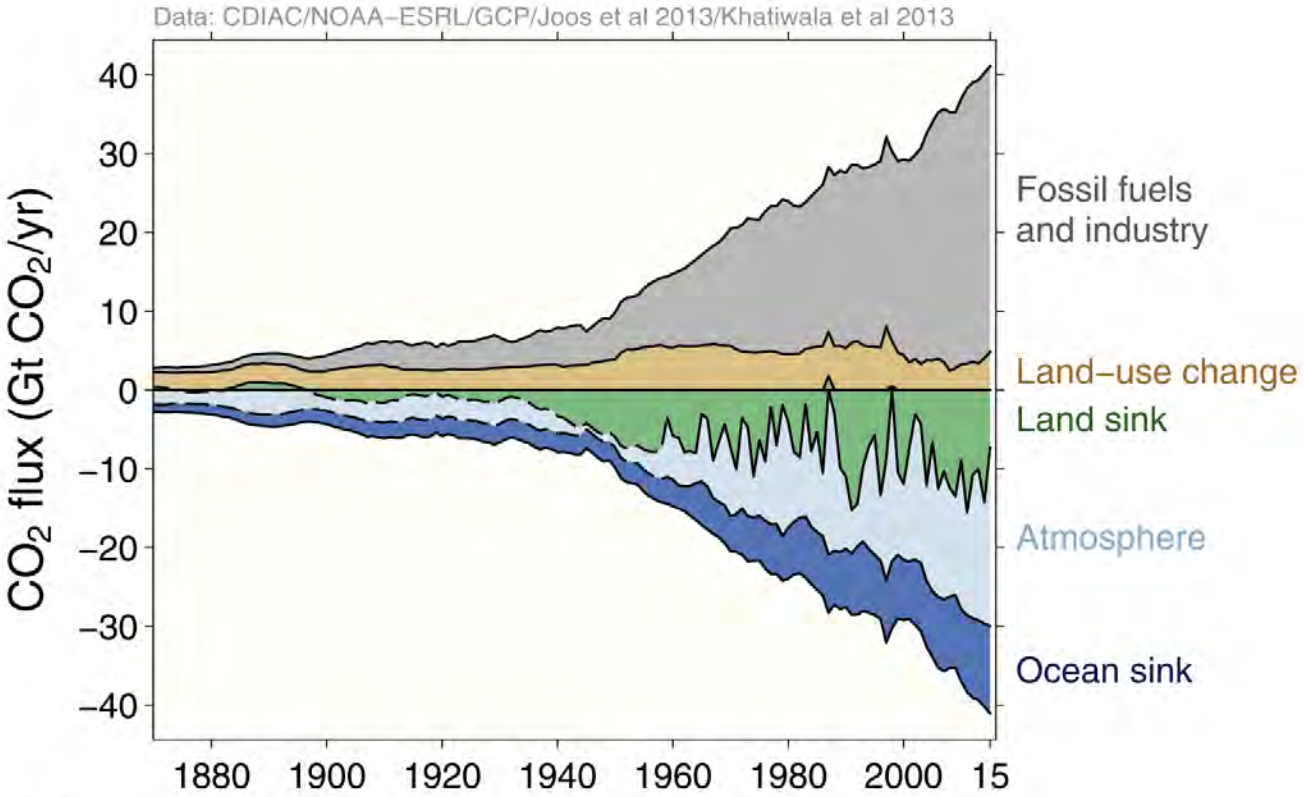


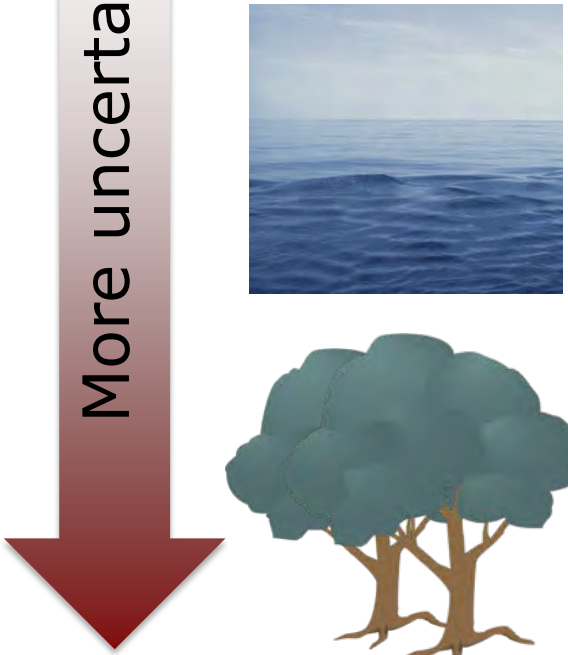
Nassar et al., GRL, 2017

Importance of higher resolution

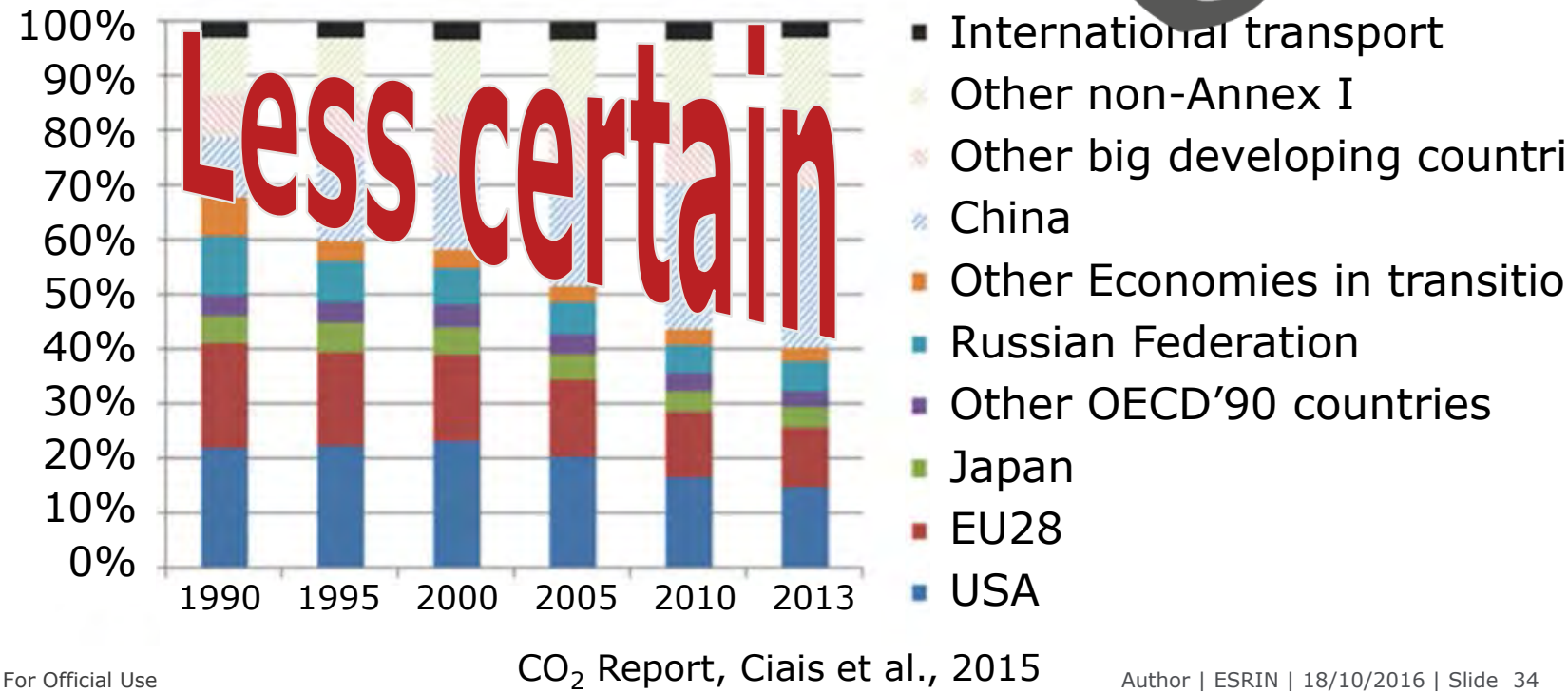
- This provides us with the potential to even monitor anthropogenic emissions directly!
- Generally anthopogenic fluxes are more well-constrained than biospheric fluxes
- However these are better constrained at the national scale, and they are more uncertain in terms of distribution within the country

Some parts of the budget are more certain than others



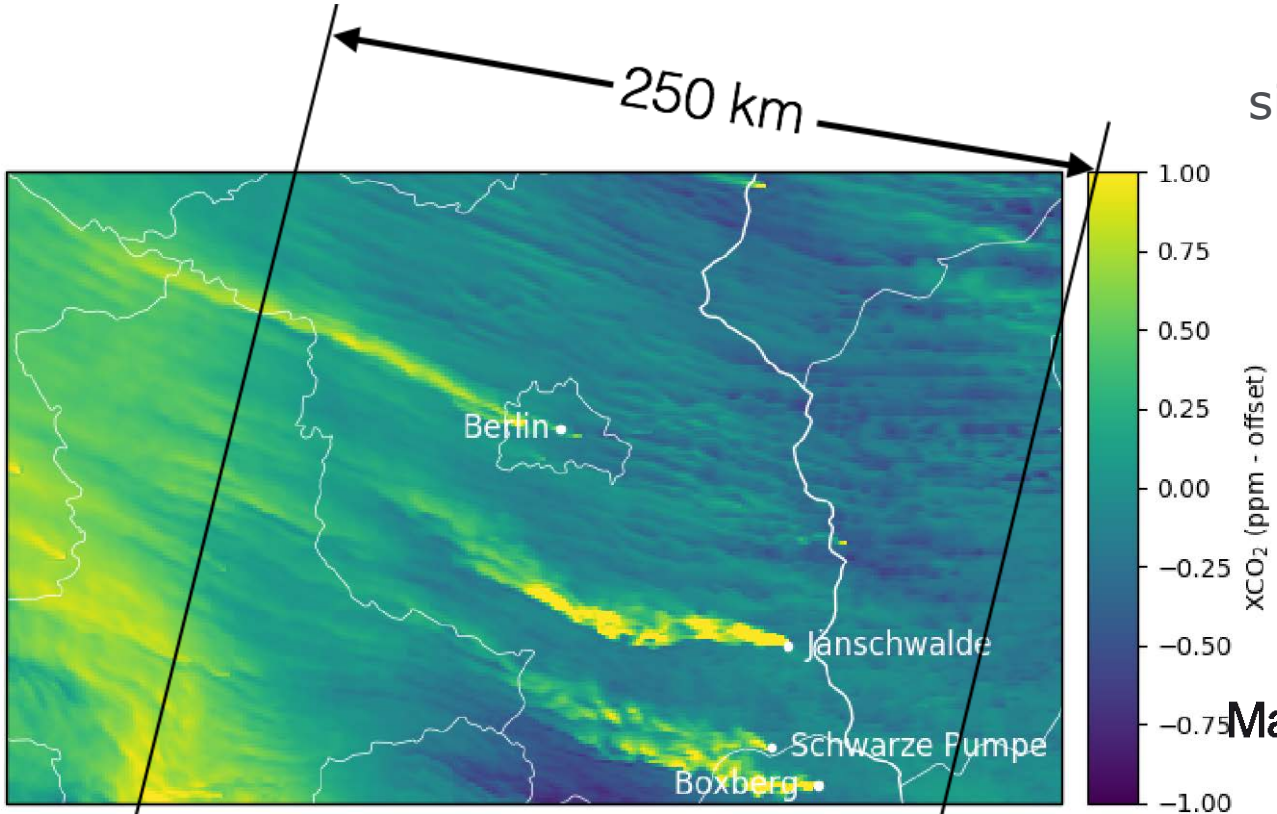


Our "known" anthropogenic emissions are becoming more uncertain



CO_2 Report, Ciais et al., 2015

Now imagine what we could do with a wider swath!



1-km resolution simulations around Berlin, showing variability in total-column CO_2 for one day in July, 2015

Empa
Materials Science and Technology

ETH zürich

Max Planck Institute for Biogeochemistry

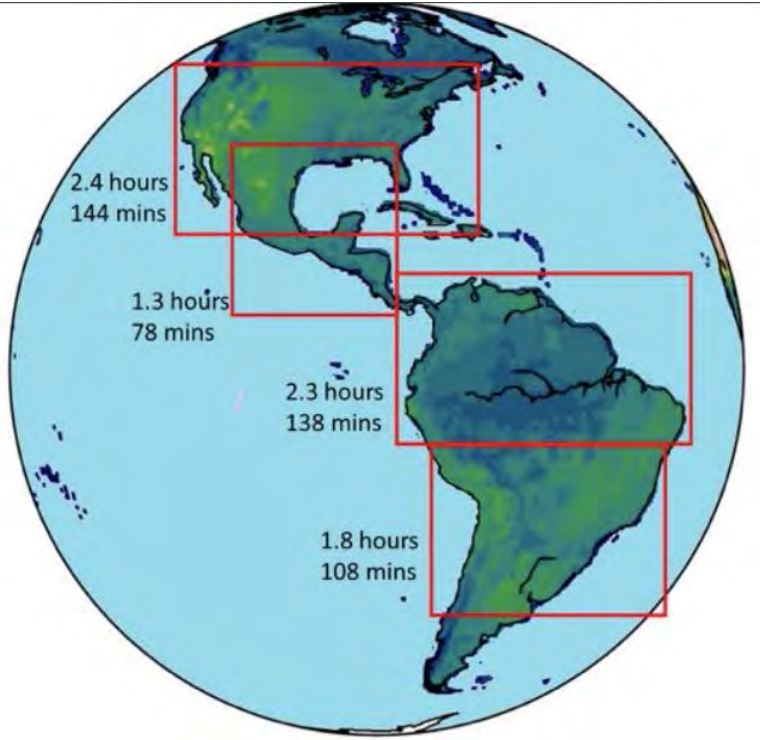
Proposed Sentinel-7 carbon mission

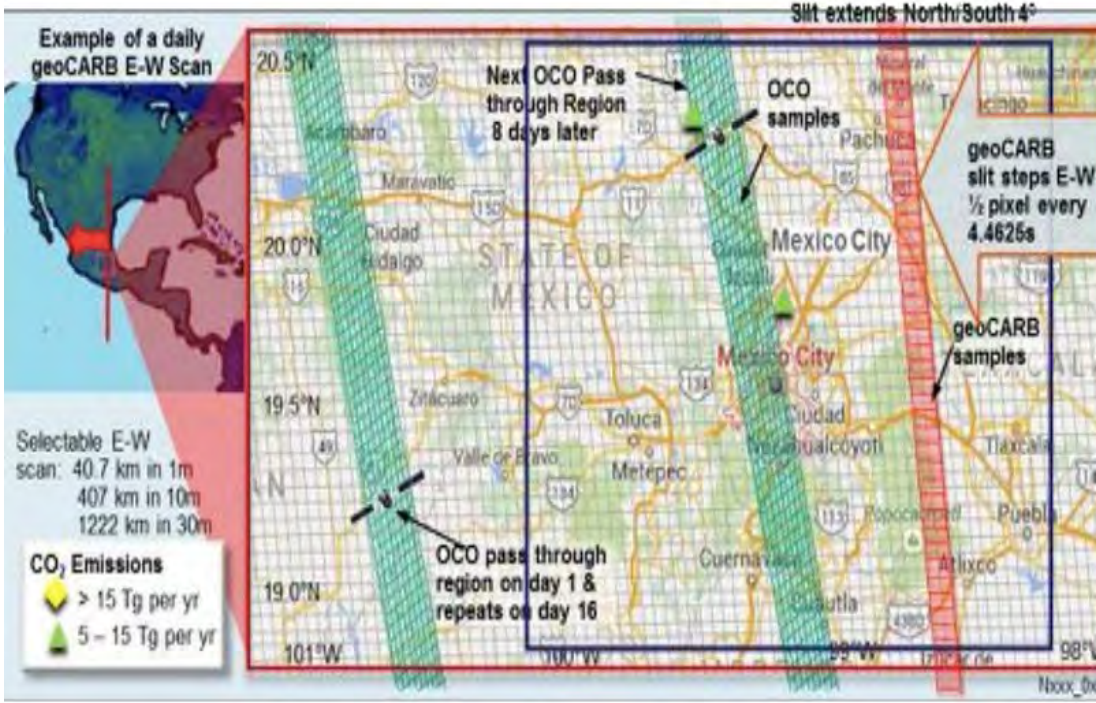
- Proposed European mission with a constellation of imager satellites (launch ~2025)
- Use of additional tracers to separate fossil signal
- Comprehensive modelling system to contribute to 2028 stocktake

Geostationary missions

- Up to now, all missions discussed were using a low-earth, sun-synchronous polar orbit (LEO)
- Lots of gaps in the persistently cloudy (and scientifically interesting) tropics
- Geostationary orbit (GEO) shows some promise
- Upcoming NASA mission GeoCarb is planned here, over the Americas, and there is a proposal for Earth Explorer 10 over Africa as well (feel free to ask for more information)

GeoCarb observing strategy



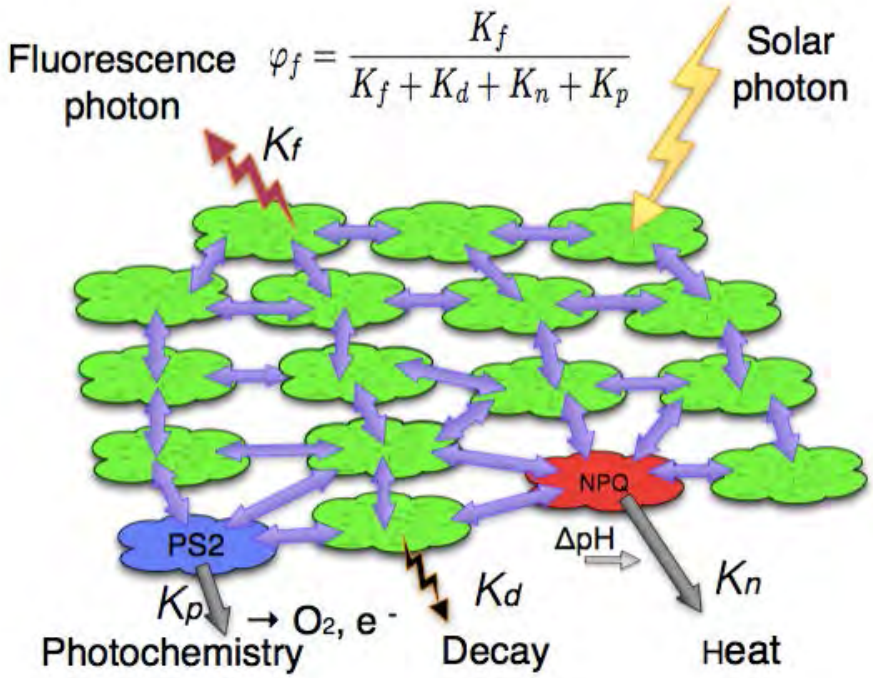


Some problems remain…

- Precision has improved over time, from SCIAMACHY to GOSAT to OCO-2
- Systematic errors/biases remain
- Some can be traced to spectroscopy, aerosol/cirrus contamination, BRDF, etc.
- Ground-based remote sensing is critical for calibration/validation
- Recent correction due to very slight pointing error for OCO-2 that led to elevation-change-dependent errors
- One “correction” led to a nice (and relevant!) by-product…

Solar-induced Fluorescence

- Not all photons that reach a plant are used for photosynthesis
- There are protective mechanisms in place to protect the plant from this excess radiation
- One of these results in the reemission of radiation at distinctive wavelengths



Taiz and Zeigler, 2010

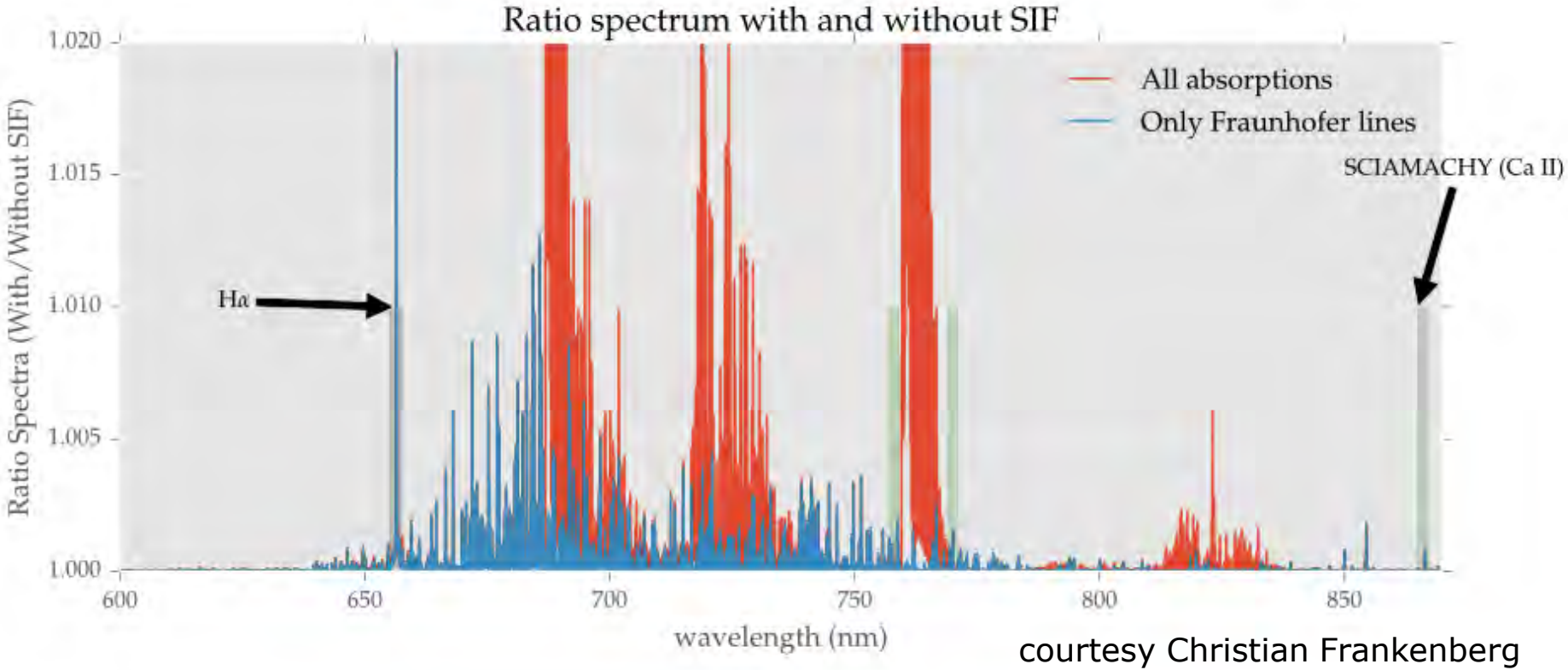
Solar-induced fluorescence

- Plant physiologists have used this emitted radiation in the lab and in the field for years to monitor plant photosynthesis

- The fluorescence is well correlated with GPP (or photosynthetic uptake)…

- From satellite, this can be deduced from the filling-in of the Frauenhofer lines, absorption lines in the O2 A-band

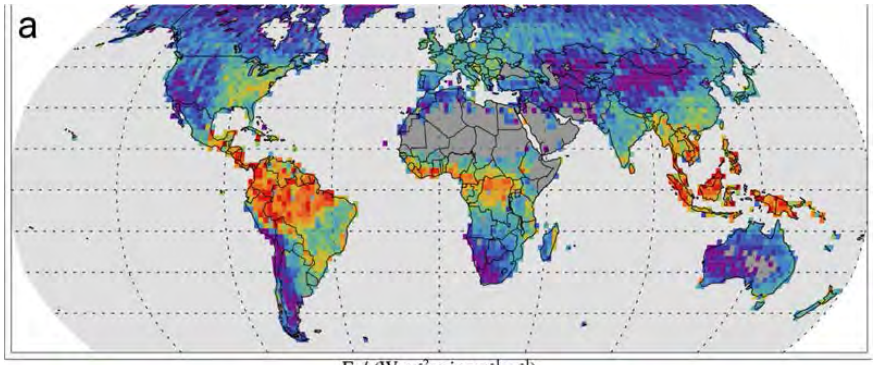
Looking at the Frauenhofer lines



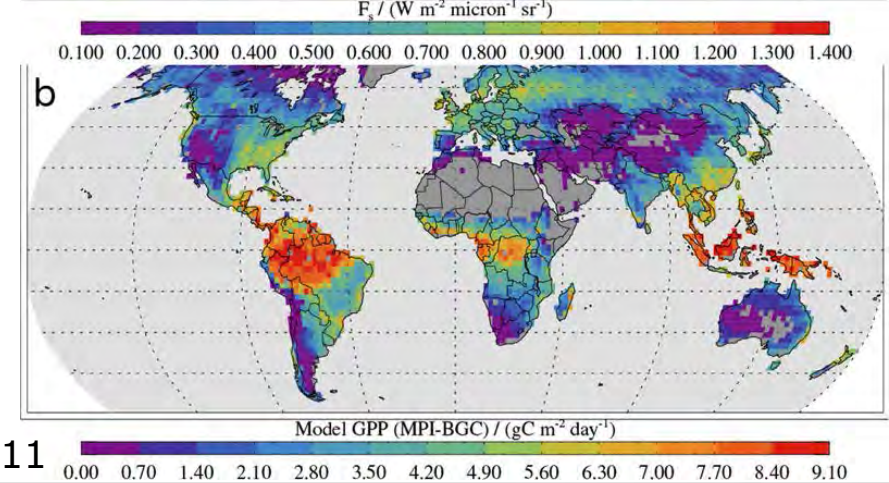
courtesy Christian Frankenberg

Early work from GOSAT:

Fluorescence from Frauenhofer lines from GOSAT

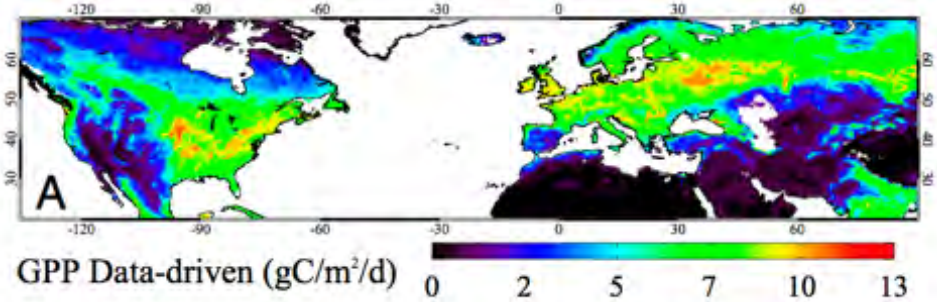


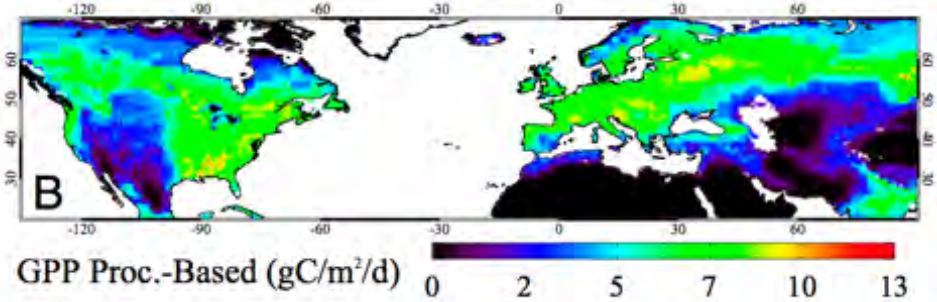
Modelled GPP using machine-learning upscaling of flux tower data

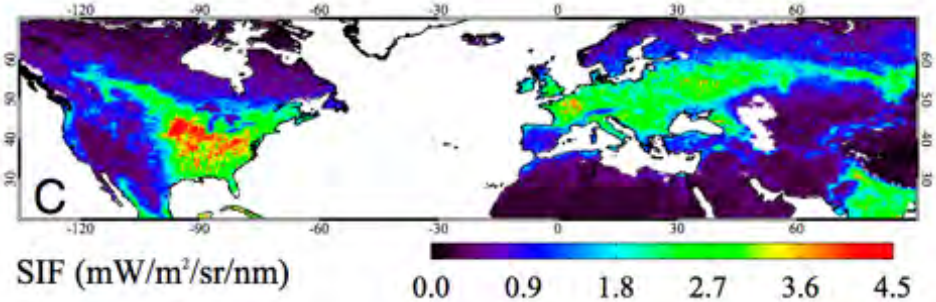


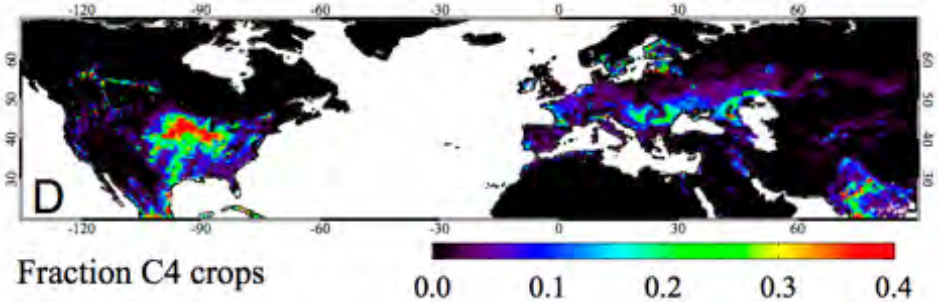
Frankenberg et al., 2011

From GOME-2, some surprising results



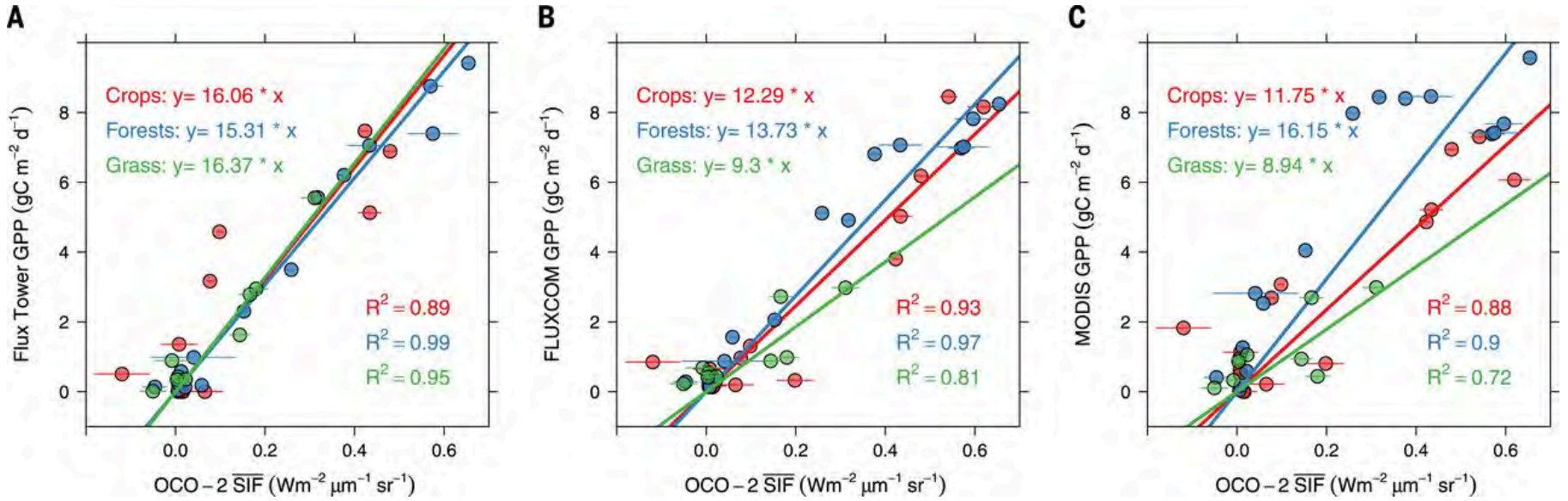






Guanter et al., 2014

GPP vs. SIF



Sun et al., 2017

Conclusion

- Measuring the atmospheric composition helps us understand rapid fluctuations of the carbon cycle
- Passive remote sensing can measure total column carbon dioxide at high precision (~0.5 ppm, or 0.125%)
- Measurement gaps remain in the winter, at night, in persistently cloudy regions
- An array of sensors over the next years will greatly increase the observational constraint
- Some systematic errors remain, but it's getting better…
- Sun-induced fluorescence, relevant for partitioning the processes driving biospheric fluxes, comes "for free"